Design variables for steel and aluminium in high-rise rooftops

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Design Variables for Steel and Aluminium in High-Rise Rooftops

A Thesis

by

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This dissertation reports a case study in the design and construction solutions for a major corrosion failure of the aluminium louvres and steel brackets on the roof and façade of levels 26-29 of the Westfield Tower 2, Bondi Junction. This work was undertaken during early 2005.

Aims:

- Consideration of the roles and responsibilities of designer and engineer working on metallurgical corrosion issues in high-rise buildings
- Undertaking of a literature survey of corrosion issues involving riveting and welding of aluminium and galvanising of steel
- Undertaking of stress calculations for all components to ensure compliance with the requirements of design principles
- Confirmation of the stress calculations through finite element modelling
- Examination of all materials issues in order to prevent re-occurrence of structural degradation and corrosion
- Consideration of relevant environmental effects on the materials
- Implementation of these design solutions using novel aerospace materials and methods
- Prediction of future performance through factorial and matrix method approaches

Outcomes:

- It is hoped that the text provides a documentary basis for future guidance of designers and engineers working in areas related to the subject of the present work.
- It also is hoped that the work on aerospace technologies will broaden the scope of designers and engineers in the potential that these materials and processes have in building considerations.
- The manual stress calculations and finite element modelling confirm that the implemented designs are consistently within design specification and that, from the mechanical perspective, no problems are anticipated.
- Further, since considerable care was taken to ensure that galvanic and other forms of corrosion were avoided through the appropriate use of design, materials, and implementation approaches, no further corrosion has been observed at the site.
- The development of a generic factorial approach and a specific matrix method, applied to corrosion and welding considerations, was informative but these still are at speculative stages owing to the difficulty of obtaining relevant meaningful data and the problem of assigning weighting factors on what is viewed as a fairly subjective basis.

To my father Nadim Melhem,

who inspired the writing of this thesis.

CERTIFICATE OF ORIGINALITY

I hereby declare that this submission is my own work and, to the best of my knowledge, it contains no materials previously published or written by another person, nor material that to a substantial extent has been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at UNSW or elsewhere, is acknowledged explicitly in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation, and linguistic expression is acknowledged.

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I am pleased to acknowledge the valuable assistance of Prof. A.G. Crosky, who kindly agreed to review the technical aspects of the metallurgical content of the thesis.

I also would like to acknowledge and thank my co-supervisor Dr. S. Bandyopadhyay for his guidance and support.

I wish to thank Qantas Airways Ltd., which has been the driving force behind setting the bar higher for my company Perfect Engineering Pty. Ltd., and in directing us to achieve several milestones and accreditations. These achievements have enabled my company to reach this point and to accomplish the end-result of this project.

I also wish to acknowledge and thank Westfield Design & Construction Pty. Ltd. (Bondi Junction), which has had the confidence to select Perfect Engineering Pty. Ltd. as the engineering contractor to take on this mammoth but vital project, and also for the opportunity to undertake this research unreservedly.

I would like to thank my team of engineers and managers who assisted with this project and stayed the course with my unconventional engineering methods and ideas.

I especially would like to thank my mother Samia and my father Nadim. My mother taught me discipline at an early age and the value of hard work and integrity. She has sought tirelessly to instil in me the importance of giving without the expectation of return. My father taught me never to be afraid of taking calculated risks for worthwhile goals. He has instilled in me the importance of ethics and honesty. His motto is *reflect, then action*.

Finally, I would like to thank my beautiful wife Eva, my two lovely daughters Ursula and Rhaneen, who intuitively understood what was required for this dissertation and hence unselfishly provided me with my space. We are expecting a newborn in the family toward the end of this work. I will not mind the noise now that I am done. My wife has provided me with encouragement and inspiration during the writing of this thesis, for which I am forever grateful. I now can spend time with all of you.

ABSTRACT

The present work is not a typical Doctoral thesis in Materials Science and Engineering in the sense that it surveys specific technical literature and reports on the outcomes of a series of experiments. This thesis reports a case study in the design and construction solutions for a major corrosion failure at the Westfield Tower 2, Bondi Junction. The contract was awarded to Perfect Engineering Pty. Ltd. (under my complete guidance) by Westfield Design & Construction Pty. Ltd. in early January 2005. Rectification work, largely on aluminium louvres and steel brackets on the roof and façade of levels 26-29, was completed in June 2005 and the installation has been monitored continuously since then. It must be noted that wherever Perfect Engineering Pty Ltd., appears in the text of this dissertation, the work has been undertaken, researched, designed and approved by me personally. However, Perfect Engineering Pty Ltd is my team and operates strictly under my complete guidance.

The present work is divided into three discrete components:

Section I	Generic Information for the Profession	(Chapters 1-3)
Section II	Field Investigation Technical Considerations	(Chapters 4-8)
Section III	Figures and Appendices	

Generic Information for the Profession

A significant part of the present work attempts to address what is perceived as a need for a document that offers an attempt at comprehensive guidance for the designer and engineer working on metallurgical corrosion issues in high-rise buildings. The approach taken has been to provide coverage of the full range of issues of relevance to professionals working in the field, including research, design, risk management, safety, project management, corporate governance, statutory requirements, compliance, finances, administration, *etc.* These aspects cover the full range of professional responsibilities incumbent on a company undertaking major construction work.

On the technical side, the literature survey is targeted at the specific corrosion problems and their solutions:

a) Types and effects of corrosion
b) Aluminium as a structural material

c) Riveting and welding of aluminium
d) Galvanising of steel

Perhaps the most innovative approaches to these materials issues are consideration of the following technologies:

a) Use of aerospace materials technologies to inform the design, selection, and implementation of aluminium alloys, bolted, riveted and welded
b) Preliminary investigation of factorial and matrix approaches for the assessment of life time and susceptibility to corrosion and welding in high-rise buildings

Field Investigation Technical Considerations

The field investigation reports on all phases of the actual rectification work, including before, during, and after. This material is described as follows:

a) *Chapter 4:* Assessment of causes of failure of louvres and brackets, modifications to design of other structural members, rectification solutions
b) *Chapter 5:* Exposition of the generic factorial approach for estimated service life of components
c) *Chapter 6:* Application of matrix methods to the effects of corrosion and welding
d) *Chapter 7:* Manual calculations of applied stresses and finite element modelling of the same
e) *Chapter 8:* Summary discussion of all relevant issues

Ultimately, the aims of the present work were as follows:

a) Consideration of the roles and responsibilities of designer and engineer
b) Examination of novel design solutions that answered specific problems that had to be solved under stringent constraints
d) Undertaking of stress calculations for all components to ensure that the requirements of general design principles were satisfied
e) Confirmation of the stress calculations through finite element modelling
f) Careful examination of all materials issues such that further structural degradation and corrosion damage would not re-occur
g) Additional critical consideration of relevant environmental effects on the materials, including the potential effects of water, salt, and wind.
f) Implementation of these design solutions using aerospace materials and methods

g) Attempt to predict future performance through generic factorial approach and specific matrix method approaches

Outcomes

a) It is hoped that Chapters 1-3 and the associated following text will provide a documentary basis for future guidance of designers and engineers working in areas related to the subject of the present work. To the author's knowledge, such a compendium of issues and considerations has not been prepared before.
b) It also is hoped that the work on aerospace technologies will broaden the scope of designers and engineers in the potential that these materials and processes have in building considerations. The results of the engineering solutions developed by me personally and my team amply demonstrate the success of these approaches.
c) The manual stress calculations and finite element modelling confirm that the implemented designs are consistently within design specification and that, from the mechanical perspective, no problems are anticipated. To date, further inspections of Westfield Tower 2 bear out this expectation.
d) Further, since considerable care was taken to ensure that galvanic and other forms of corrosion were avoided through the appropriate use of design, materials, and implementation approaches, no further corrosion has been observed at the site. This is in considerable contrast to the situation that I had perceived personally observed upon commencement of the project.
e) Application of a generic factorial approach and a specific matrix method, applied to corrosion and welding considerations, were informative but are considered still to be at a speculative stage owing to the difficulty of obtaining relevant meaningful data and the problem of assigning weighting factors on what is considered to be a fairly subjective basis.

PREFACE

The present work is a culmination of over 20 years of experience in the engineering field, particularly metallurgical engineering. I graduated with my Bachelor's degree in Metallurgical Engineering (Honours) in 1990, with the thesis *Effect of Processing on Performance of Continuous Fibre Reinforced Plastic Composites*. I completed a Master of Science degree 1996, with the thesis *A Study of Abrasive Wear in SiC and Al_2O_3 Particulate Reinforced Composites*. Both degrees were obtained from the School of Materials Science and Engineering, University of New South Wales.

My career path has been oriented around research in metals of a diverse range, particularly secondary processing, with major companies including:

a) *Bradken Consolidated R&D:* Worked in research and development (R&D) of materials used in defence equipment castings.
b) *BTR Engineering:* Managed a team of engineers in R&D in the optimisation of heat treatment processes of metal transmission components and the evaluation of failure claims of vehicle components for Ford and Holden. Managed certain key projects for key clients in quality improvement processes for new prototypes.
c) *Monroe Springs:* Managed a team of engineers in R&D in improvements in Mercedes, SAAB, Ford, and Holden coil and leaf spring design life and serviceability. Held additional position of Manager for the implementation of new quality systems in compliance with QS 9000 and ISO 9001:2000 for all processes.
d) *Sandvik:* Provided technical advice to engineering clients in the latest applications for stainless steel in marine environments for industrial applications and the offshore petroleum industry.
e) *Yeomans Engineering:* Liaised with ANSTO, Qantas, and various government organisations in dual Engineering Manager and Quality Manager position, providing engineering technical services and advice in metal engineering design/fabrication and complex steel alloys.
f) *Perfect Engineering Pty. Ltd.:* Serving as Managing Director for my company, which was formed in October 2003. The company has emerged as a main engineering contractor for mostly Government clients, in particular the Roads and Traffic Authority (RTA), providing innovative solutions for large construction projects with tight time-lines and resource-allocation priorities. Some of the major contracts have involved:

i) M4/M7 Highway
ii) Lane Cove Tunnel
iii) Sydney Harbour Tunnel

Perfect Engineering Pty. Ltd. is a preferred contractor to Qantas, in part due to the company's ISO 9001:2000 accreditation, which is in line with its Quality Management Systems (QMS) and contractor requirements. Perfect Engineering Pty. Ltd., under my guidance has undertaken projects in ground support equipment, including re-design and manufacture of the nose cowl supports traditionally designed and manufactured by Boeing. Perfect Engineering also acts as contractor for other clients, including *Sydney Water*, *Westfield*, *Thiess John Holland*, and *Abi-Group/Leightons*.

I personally have been influenced significantly by my long association and interaction with aerospace organisations, particularly Qantas. Consequently, Perfect Engineering Pty Ltd endeavours to adapt and integrate many aerospace requirements and procedures ranging from engineering through to induction training, on-site compliance, and Safe Work Method Statements (SWMSs) when dealing with aircraft, materials specifications, documentation, and general adherence to various statutory requirements. This approach is designed to give the company the strongest Quality Management Systems (QMS) available. As a consequence, Perfect Engineering Pty. Ltd. is able to adapt aerospace materials and procedures to other applications, as was done in parts of the present work.

I am accredited as a Chartered Professional Engineer (CPEng) and, in response to the associated submission and presentation, which were based on the topic of the present work, Engineers Australia recommended registration on the National Professional Engineer Register (NPER), which also took place. Further, Perfect Engineering Pty. Ltd. maintains strong ties with Engineers Australia through its Professional Development Program (PDP) its *Enterprise Engineering Partnership*" where Perfect Engineering Pty. Ltd. trains its engineers such that they are ready for accreditation in their relevant fields by Engineers Australia.

On a professional and philosophical note, the goal of Perfect Engineering Pty. Ltd. is to provide the best possible engineering services and thus optimal quality and practice. I have attempted to adopt and adapt the strengths and best practices that I have learned from my past employers. While all firms make mistakes, it is my hope that my company is able to learn from them.

On a more personal note, it is my hope that I will be able to return something to the educational institutions, companies, and staff that have provided me with the technical basis for my profession. I hope to be able to contribute aspects of design engineering, safe practice, and professional excellence to the community from which I came and in which I work. Engineering is not just a means of earning a living; it carries a heavy moral obligation to ensure that human safety and life are not put at risk. In our multi-faceted roles as designers, engineers, and builders, we cannot afford to take our roles for granted. We are privileged to be given the responsibility for these tasks, and so, are obliged to practice what we preach.

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ACRONYMS AND ABBREVIATIONS

AA	=	Aluminium Association
AIJ	=	Architectural Institute of Japan
ANSTO	=	Australian Nuclear Science and Technology Organisation
ASCC	=	Australian Safety and Compensation Council
ASTM	=	American Society for Testing and Materials (now ASTM International)
BCA	=	Building Code of Australia
BHP	=	Broken Hill Proprietary Company (now BHP Billiton)
BMU	=	Building Maintenance Unit
BSI	=	British Standards Institution
C/A	=	Cathode-to-Anode Area Ratio
CIB	=	International Council for Research and Innovation in Building Construction
CPD	=	Continued Professional Development
CPEng	=	Chartered Professional Engineer
CRA	=	Conzinc Riotinto of Australia
CSA	=	Canadian Standards Association
CSIRO	=	Commonwealth Scientific and Industrial Research Organisation
CTE	=	Coefficient of Thermal Expansion
DSC	=	Differential Scanning Calorimetry
DSTO	=	Defence Science and Technology Organisation
EA	=	Equal Angle
ECCS	=	European Convention for Constructional Steelwork
EDS	=	Energy Dispersive Spectrometry
EPRI	=	Electric Power Research Institute
ESL	=	Estimated Service Life
ESLC	=	Estimated Service Life of a Component
FEA	=	Finite Element Analysis
GAA	=	Galvanisers Association of Australia
GDP	=	Gross Domestic Product
GMAW	=	Gas Metal Arc Welding
GNP	=	Gross National Product
GP	=	Guinier-Preston
GTAW	=	Gas Tungsten Arc Welding
HAZ	=	Heat Affected Zone
HDG	=	Hot Dip Galvanising
HDGS	=	Hot Dip Galvanised Steel

ICP-AES	=	Inductively Coupled Plasma Atomic Emission Spectrometry
ISO	=	International Standards Organisation
ITP	=	Inspection Test Plan
MIG	=	Metal Inert Gas
NCR	=	Non-Conformance Reporting
NIST	=	National Institute of Standards and Technology
NPER	=	National Professional Engineering Register
NSW	=	New South Wales
NTSB	=	National Transportation Safety Board
OH&S	=	Occupational Health and Safety
PDP	=	Professional Development Program
PFC	=	Parallel Flange Channel
PSL	=	Predicted Service Life
QA	=	Quality Assurance
QMS	=	Quality Management System
QS	=	Quality System
R&D	=	Research and Development
RHS	=	Rectangular Hollow Section
RILEM	=	Réunion Internationale des Laboratoires et Experts des Matériaux
RSLC	=	Reference Service Life of a Component
RTA	=	Roads and Traffic Authority
SAA	=	Standards Association of Australia
SAAB	=	Svenska Aeroplan Aktiebolaget
SAI	=	Standards Australia International
SAXS	=	Small-Angle X-Ray Scattering
SSINA	=	Specialty Steel Industry of North America
SSSS	=	Supersaturated Solid Solution
SWMS	=	Safe Work Method Statement
TEM	=	Transmission Electron Microscopy
TIG	=	Tungsten Inert Gas
UK	=	United Kingdom
UN	=	United Nations
UNSW	=	University of New South Wales
US	=	United States
USA	=	United States of America
UV	=	Ultraviolet
WWI	=	World War I
WWII	=	World War II

THESIS OUTLINE

The present work is divided into three sections. Section I includes Chapters 1-3 and consists mainly of generic information for the profession. Section II includes Chapters 4-8 and consists of information on the field investigation and technical considerations that form the core of the thesis. Section III supplements the text with figures and appendices. The outline of the chapters is as follows:

Section I

Chapter 1 surveys the relevant literature in regard to materials used on high-rise building rooftops and façades and draws comparisons between equivalent materials used in the aerospace industry. This chapter also includes the role of designers, their responsibilities, maintenance recommendations, the extent of metal-related corrosion worldwide, and some elements of previous studies on the basic concepts of factorial approaches to materials.

Chapter 2 presents the origin of the project of the study, the severity of corrosion, and the jeopardy of the structural steel and louvre system on top of a 29 level Westfield rooftop. This chapter focuses on:

a) Investigation and analysis of corrosion problems *in situ* on building rooftops and façades, including design, project management, and implementation of long-term remedial solutions
b) Analysis of the risks to the public, design professionals, construction personnel, and building owners
c) Research and development and an assessment of a factorial matrix as a tool to aid designers in designing and selecting materials to minimise corrosion and ensure long-term structural integrity

The solutions that were used in the field investigation were based on metallurgical and structural strength evaluations and they were implemented using a hand-picked team to ensure that all of the Quality Assurance requirements of ISO 9001:2000 requirements were met.

Chapter 3 presents issues of compliance and the responsibilities of owners and designers. A description of the following issues are presented:

Chapter 7 presents Finite Element Analysis (FEA) data, their interpretation, and some of the implications for specific highly stressed regions. The advantages and limitations of FEA and how use in the future may be incorporated are discussed. Also considered are some of the variables that are beneficial in FEA modelling using inputs in the form of materials issues, such as welding of aluminium, the strength of the aluminium in terms of the heat affected zone (HAZ), and the limitations, advantages, and disadvantages of welding aluminium for structural building applications.

Chapter 8 outlines the discussion and conclusions of the main points of the thesis and summarises the project outcomes.

Section III

This section includes the figures that accompany the text and the appendices that supplement it.

PUBLICATIONS AND PRESENTATIONS

Relevant to some of the work in this dissertation, I have researched and published papers previously on the wear characteristics of 6061 aluminium alloys unreinforced and reinforced with SiC and Al_2O_3 particulate ceramics using various ageing treatments. These materials have been of particular interest over the past three decades in relation to both the aerospace and automotive sectors. I have conducted research, published, and made presentations on these materials to, *inter alia*, CSIRO; ANSTO; the Department of Mining and Metallurgical Engineering, University of Queensland, New Zealand Industrial Research Ltd.; CRA; the Department of Materials Science and Metallurgy, University of Cambridge; DSTO, CIGWELD, BHP, and Mount Isa Mines Ltd.

During the writing of this thesis, I also have presented as part of my application for Chartered Professional Engineer (CPEng) a portion of the present work, which formed an integral part of the requirements for this qualification from Engineers Australia. Some of the other accreditations obtained for myself and my company Perfect Engineering Pty. Ltd. include those from Engineers Australia (development programs for our engineers), SAI Global (ISO 9001:2000), and the NSW Government (OH&S management system). These and the relevant papers that I have published are given in Appendices A to E. It is hoped that the work in the present work will be of value to future engineers, designers, contractors, and others interested in design for the prolongation of the life of various ferrous and non-ferrous metals, whether associated with buildings or in any other field.

a) Materials commonly used on rooftops and their properties
b) Effectiveness of cross-disciplinary experts engaged in the design process
c) Recommendations for safe design (including project management and implementation of a QA system to ensure compliance to stipulated design)
d) Comparison of certain aircraft materials and their design lives when used as building materials and their design life expectancy
e) Effects of corrosion in terms of materials geometry and location
f) General properties of aluminium alloys and their heat treatment
g) Steel coatings, such as hot dip galvanising and its effects on corrosion, service life of the steel, effects of steel design on galvanising, and the effects of welding on galvanising

Section II

Chapter 4 describes the assessment and findings of the site failure on the Westfield rooftop at Bondi Junction. The initial findings from the failure and the challenges to the project are summarised, a proposal of alternative materials and construction methods, in comparison to existing conventional materials and connection methods (including rivets, bolts, aluminium, and structural steel), are presented. Also given are methods for descending the face of the building and some designs of jigging tools that evolved during the progression of the project to ensure successful completion without compromise of either structural or material integrity. Fabricated brackets and steel and other materials to help make the louvre system more rigid are discussed and some recommendations for maintenance to minimise future corrosion are made.

Chapter 5 describes an analysis of the project using an existing factorial approach and compares the results with further assessments in the field. The discussion includes reference to this factorial method and reasons and recommendations are provided to ensure inclusion of variables not traditionally taken into account by many engineers and designers generally.

Chapter 6 includes discussion and illustration of a proposed practical design tool, which is a matrix that may be developed further to help designers predict the probability of achieving a required design life given a combination of materials and environment. This includes graphical representations of how the factorial expression may be delivered to the end-user through a computer-generated interactive matrix. This also includes a detailed discussion the variables and factors that may be applied and how the results could progress to elicit additional factors that may be unforeseen. Both the practicality and limitations of this matrix are presented and discussed.

SECTION I

Generic Information for the Profession

CHAPTER 1. Introduction

1.1 Rapid Materials Developments in Last Century

Man began forging iron around 3000 BC [1]. Since then, for almost over 5000 years, this has been the most popular material ever to be used. Continual improvements to steel and its diversification for various applications and properties are abundant and are ever-continuing into the future. Steel truly is the one material that will serve mankind for generations to come.

Aluminium emerged at a much later date than steel, being discovered in 1821 by the French chemist Pierre Berthier in Les Baux Aluminium [2,3]. At the outset, aluminium was considered to be a precious metal suitable mainly for statues, jewellery, and certain art objects. However, as the price of aluminium fell, this enabled pioneering work and inventions by engineers and designers to make full use of its practical potential.

The phenomenon of age hardening was discovered accidentally by Alfred Wilm in Berlin in 1906 while he was investigating a stronger aluminium alloy to replace brass for the manufacture of cartridge cases [4]. The alloy was named *Duralumin*. Wilm had given a laboratory technician the task of testing the physical properties of various aluminium-copper-magnesium alloys and the technician had left the samples unattended over the weekend. However, the following Monday, the technician found surprisingly high strength in the alloys, which was a result of the Duralumin sample being stored for two days at room temperature, and the phenomenon thus was coined *natural aging*. The research was directed further towards producing high heat treatable aluminium alloys, which were used later for airships, such as the Zeppelins during World War I (WWI), and both civil and military aircraft since World War II (WWII). Aluminium alloys have continued since to be the dominant materials for applications in and construction of subsonic aircraft structures [5].

These alloys were developed further in the United States after WWII, culminating in what is known as alloy 2017 T4, which was used primarily in sheet and plate but mainly aircraft [4]. Further research into aluminium and its benefits has resulted in its use in ships, aircraft, and automobiles owing to its low density and light weight.

The discovery of age hardening has enabled engineers, scientists, builders, and others to use it in many applications due to its versatility. Further, aluminium alloys are used in applications in civil engineering structures due to their wide potential and advantages. However, the properties of steel in this field have not yet been challenged fully by aluminium alloys [6].

Following WWII, another race emerged between the two superpowers the US and USSR during what was commonly referred to as the *Cold War*. This involved a race in defence and transportation technologies that were required for ground, air, and outer space. As a result, further technological advancements occurred on both sides. The result of this race was that many materials were researched and developed metallurgically in order to support the rigorous demands of deep-ocean diving submarines, vehicles, aircraft, and rockets. From this has emerged a new generation and diverse range of strong, lightweight, and corrosion-resistant materials.

Over the last century, developments in metals and alloys have improved the mechanical and chemical properties of these materials. Materials were developed in terms of both strength and corrosion protection. Corrosion protection may be in the form of a coating applied on the metal or the metal has a combination of specially formulated chemical elements for increased corrosion resistance. Although aluminium often is considered a metal that does not corrode easily, this is incorrect. In fact, due to its use in opposition with other metals, the resultant large electrode potential difference causes galvanic corrosion through the establishment of an electrical circuit in the presence of an electrolyte, as indicated by the galvanic series [7].

1.2 Introduction to Basis of Literature Review of Materials and Design Issues for Westfield Building Rooftop and Façade

The work presented in the present work represents both a personal and professional endeavour to correlate and research existing materials and practices for remedial work on steel and aluminium in a complex environment, where virtually all of the components are subjected to various forces of nature, including high wind load, airborne salt, other airborne contaminants, rain, sun, and materials that are far apart in the galvanic series but in contact with one another. These issues are relevant to many high-rise structures, particularly those built according to outdated designs and superseded materials.

Thus, an appropriate starting point for the present work is the acceptance of the reality of widespread and costly structural failures that result from corrosion and its associated factors. This can be considered to be precipitated largely by the increased population and consequent demands for buildings, bridges, aircraft, and other infrastructure. It has been confirmed that, in the US alone, over $300 billion of damage *per annum* is caused as a result of corrosion, which has arisen owing to the lack of knowledge of designers, and that at least 30% of these corrosion-related failures could be avoided by providing simple education to various bodies [8].

Even in that most stringent of industries for adherence to specification and quality, the aerospace, it is considered that corrosion has not been given sufficient attention with respect to structural integrity and that this is the case owing to lack of understanding of the corrosion process and the inability to act upon it [9]. The mere fact that corrosion damage in the crevices of lap joints in Boeing aircraft remains a problem demonstrates the belatedness of its development of a comprehensive corrosion-prevention design handbook to ensure that designers give the same level of attention to corrosion issues as they have to strength, fatigue, and damage tolerance in the past.

The aircraft industry realises that airlines must have the ability to access, inspect, and maintain the structure of aircraft economically and that this incorporates a knowledge of materials selection, finishes, drainage, sealants, and the use of corrosion inhibitors for structural durability [9]. However, there is a disjunction in that the designer does not have full control over corrosion prevention since the final essential step of the inspection and maintenance routine relies on a proper maintenance and corrosion control program by the operator of the aircraft.

It appears that the same problem with regard to corrosion-related failures and maintenance exists in buildings as well. However, the matter in buildings is not as highly dramatised as in the case of aircraft and it is likely that this is reason that the matter is not considered with the same level of urgency. Yet virtually the same principles and processes are applicable to both buildings and aircraft but with one major difference. While aircraft designers consider aluminium for its light weight and corrosion resistance, buildings may employ mechanical joints of welded aluminium. That is, aircraft have relied traditionally on rivets for the connection of the fuselage and wing skins and they have stood the test of time if treated correctly with the appropriate design [10]. If welded joints in aircraft are introduced, then these would require different design approaches to be adopted and a thorough understanding of all of the damage tolerance and safety aspects, including an understanding of predictability of fatigue crack growth.

Steel enjoys the benefits of having these areas generally mapped. Yet, the incorporation of aluminium alloys due to their light weight and corrosion resistance, with certain strength characteristics, is very attractive for use in the fuselage and wing skins. Hence, there is a strong drive toward welding aluminium in aircraft, particularly owing to the significant weight saving in joint design and ease of manufacture of complex shapes [4]. These challenges are formidable, especially in terms of the variable weld stresses across the weld, which ultimately affect the fatigue life [10]. The aircraft industry has been active in initiating an integrated approach to:

a) Correlate actual experimentally tested aluminium alloys with varying ageing treatments
b) Control welding effects through the use of instrumentation to collect reliable stress and strain data to map the mechanical properties, such as in fatigue fracture failure modes

There is an impetus toward the strengthening of aluminium alloys, particularly those that may be used in more structurally demanding applications in aircraft [4,11]. In regards to strengthening aluminium alloys, one particular area of research includes the addition of ceramic particulate reinforcements, where the intention is to determine the effects of the stress fields associated with the dispersants and their effects on the properties when the composites are subjected to various heat treatment cycles. The thermal expansion mismatch between the reinforcement and alloy or the direct strain loading in these alloys encourages precipitation during ageing, which results in further interaction, including movement of dislocations when the alloy is subjected to loading (tensile and compressive). The movement of these dislocations is such that they either will shear through the precipitate or pass completely around it, thus causing more stress.

The direction and outcomes for the design, fabrication/manufacture, and installation of the various metals discussed in the present work have been influenced by the author's previous work in the effects of ceramic reinforcement of 6061 aluminium alloy and ageing treatments on the resultant properties [12-15]. This previous work has served to provide a deeper insight into the parameters that influence the ageing kinetics of aluminium alloys and the associated mechanical and chemical properties.

In the present work, aluminium welding was used in the fabrication of components associated with a bracket and louvre system on an entire Westfield Design & Construction Pty. Ltd. high-rise building façade in Bondi Junction. Therefore, the ageing kinetics and resultant properties of the associated materials are directly relevant to the ultimate performance of the construction. I have ensured that the approach of Perfect Engineering Pty. Ltd. towards its work in buildings would be no different from that used in the aerospace industry, where safety and the optimal performance of materials in the working and operating environment are of paramount importance.

Therefore, the basic requirements to ensure longevity of the materials used in the present project are analogous to the essential steps followed in design in the aerospace industry. However, it is not a simple matter to replace structural steel, often corroded through drainage problems, with lightweight corrosion-resistant aluminium alloys when optimal design requires consideration of a combination of:

a) Rivets, welds, chemical anchors, and bolts as joining solutions
b) Coatings for corrosion inhibition
c) Imperatives of geometry
d) Access demands
e) Future maintenance requirements
f) Aesthetic considerations

Although aluminium represented 70 vol% of the metal used in the project, steel brackets were used primarily to support the aluminium louvres in more than 70% of locations requiring structural support. Although the steel was hot dip galvanised, the zinc coating, in some instances, may not follow the predicted life of protection as expected, which will impact on the performance. Therefore, it is imperative to understand the (time-temperature) kinetics of the effects of varying the parameters and the resultant effects on the physico-chemical properties.

The iron-zinc diagram is presented and is discussed in terms of phase formation in the galvanised zinc coating and how the phases present affect the hardness, brittleness, and ductility of the coating, thereby dictating the coating life. Also, the coating thickness is affected by kinetics parameters and the composition of the steel, particularly when silicon is an alloying element. Hence, the present work includes considerations of both aluminium and steel and their associated technologies for joining and coating.

The advantages and implications of the resultant designs involve consideration of the microstructural and mechanical properties of aluminium and steel. This information is supplemented by load analysis, stress modelling, and prediction of potential for corrosion as tools with the intention of assisting the designer with forecasting performance and enhancing the overall design.

More broadly, the various components of the present work include the following features that are relevant to the roles and responsibilities of building designers:

a) Development of design of brackets, louvres, and other structural components
b) Maintenance of the construction to prolong material and structural serviceability
c) Risk assessments
d) Project management
e) Relevance of ISO 9001:2000 accreditation and adherence to its requirements
f) Drawing parallels in materials selection and processes with the aerospace industry in order to improve the quality of materials and processes, increase design life, and raise design to a higher standard
g) Corrosion, especially crevice and pitting, and the effects of shelter and incline
h) Rivet materials, including steel and aluminium
i) Aluminium alloys and their microstructures, properties, and ageing, especially when welded
j) Steel, particularly the effects of welding on galvanising life
k) Development of a predictive factorial matrix to assist the designer with materials selection and prediction of design life
l) Stress calculations for loading and failure
m) Stress modelling using finite element analysis (FEA)
n) Chemical anchoring and the effects of anchor position and concrete edge distance

Although the serviceability of buildings and life prediction have developed into an area of considerable importance, especially in the last 10 years, it is curious that there does not appear to be any comprehensive studies aimed at providing evidence for the life prediction of building materials under the full range of relevant conditions, including design, processing, fabrication, methodology, installation, performance, and the effects of the environment. This is the intention of the present work.

The designs, approaches, and materials used in the present work were implemented 3 years ago and they have been monitored continuously since completion.

1.3 Aircraft Material Design and Applications

The majority of materials used in aircraft typically are aluminium alloys owing to their combination of high strength, light weight, and corrosion resistance. From the diverse and extensive research in aerospace materials have emerged materials that are abundant and affordable in other sectors, primarily the automotive and building. Aluminium is used largely in applications where moderate structural strength is required, with light weight and corrosion-resistance being secondary considerations.

It must be noted, that during the beginning of the jet age in the 1950s to 1960s, there was little attention paid to corrosion or to corrosion control. Instead, the main criteria for this generation of aircraft tended to be strength and fail-safe attributes [9]. It was not until serious implications regarding corrosion surfaced in these aircraft that the second generation of aircraft in the 1970s and 1980s, with an increased level of corrosion control, enforced design considerations. The current third generation of aircraft now incorporates designs that tend to emphasise mandatory corrosion prevention and control.

Although the design life of the previous generations of aircraft was approximately 20 years, the service life of the new generation of aircraft has been increased to 40 years, largely due to the incorporation of corrosion control [16,17]. Despite this increase, the aircraft industry still uses alloys such as 2024 T3 [11,16,17], which was introduced in 1935, and 7075 T651, which was introduced in 1944 for aircraft structures and was used on tanker and transport fleets built in the 1950s and 1960s. Polmear [11] summarises the typical materials selection for structural members of a typical passenger aircraft, as shown in the schematic in Figure 1.1. This also includes older and newer aluminium alloys that are incorporated in the aircraft. Hence, the Boeing 777 has retained at least 70% aluminium alloys in its structure since the mid 1980s , and the 757, 767 and 747 have retained approximately 78%, 80% and 81% respectively, and this was in correlation with the European Airbus. The impetus, for the continued popular application of aluminium in aircraft was primarily in consideration of lightweight, and this has been dependant upon the continuing rise in the cost of oil. Also, there has been enormous pressure from several countries introducing new legislation to reduce levels of exhaust emissions [11].

However, these particular materials have been the subject of continued corrosion and fatigue. This raises the question as to why alternative and available corrosion-resistant aluminium alloys, with equal strength and fatigue properties, are not used instead of the 2024 and 7075 alloys. This is likely to be a result of the failure of these materials to satisfy all design and performance requirements simultaneously [16,17]. Thus, although the 2024 alloys have relatively good tensile properties, their corrosion resistance is very poor. Also, since these alloys are not weldable, they are used widely with riveted connections. While the 7075 alloys have amongst the highest strengths of the aluminium alloys, their corrosion resistance is poor and they also have low weldabilities.

1.4 Building Designer's Role in Materials Applications

The design life of buildings is subject to the client's requesting the designer to provide a certain service life. Buildings are designed with an emphasis on ensuring that the structural integrity, response to the environment, and general aesthetic requirements remain satisfactory over the life of the building. The key aspect of the design of a building is that it must be functional until the end of its life. There is well documented literature to suggest that most designs of commercial buildings rely on a cross-disciplinary team approach for a project's success [18].

It appears that, despite all of the extensive design planning of a building, the fundamental engineering knowledge often is lacking for many building rooftops and façades, particularly in terms of structural steel design and optimal materials selection. This shortcoming is likely to be due to deficient design that results from:

a) Negligence
b) Insufficient fundamental knowledge of the relation between materials physico-chemical properties and associated performance
c) Insufficient understanding of interactions between materials in apposition
d) Insufficient knowledge of environmental effects

The key conclusion from the preceding is that it is essential to include in the design and construction process the correct engineers and other participants through a cross-disciplinary approach.

1.5 Responsibility in the Case of Litigation

In matters involving structural degradation or failure, particularly by premature corrosion, the question of responsibility arises. It is unfortunate that, by the time such a failure occurs on the outside of a building, and depending on whether it is a catastrophic failure, the evidence of failure may not be traced back to the original design engineer, contractor, or owner. This matter is particularly important when the failure occurs during the ownership of parties that were not the original owners. This matter is complicated further when intervention occurs such that the original design, materials, maintenance, and intentions may have been altered. The questions of liability and litigation costs are critical and they cannot be answered in the absence of sufficient information, which may not be available.

1.6 Consideration of Maintenance and Consequences

The maintenance of a building is an important factor in the consideration of its ongoing life. If designs do not incorporate corrosion maintenance for aluminium and steel structures on the external parts of buildings, then it is highly likely that problems and associated costs will develop. Koch [9] has stated that, traditionally, in aircraft, corrosion has not been given sufficient attention with respect to structural integrity. This probably is due to a lack of understanding of the corrosion process and the inability to predict the initiation and spread of corrosion. Consequently, corrosion is likely not to have been incorporated in damage tolerance assessments and an approach of *find it and fix it* is accepted. Such an approach can lead to extensive corrosion of both structural and non-structural parts, which significantly increases the cost of maintenance. Moreover, as airframes continue to age, corrosion increasingly will affect the structural integrity of these airframes. The same analogy applies to buildings.

The degradation of metals in the atmosphere is well documented, is considered to be a well studied phenomenon, and customarily is represented as in terms of the degradation (measured as weight loss) as a function of the dosage of corrosive agents in the environment [19]. This work is reported principally by weather stations, the majority of which are in Europe and North America [19]. Metals react differently in various environments, which may include corrosive agents such as chlorides in the air, which originate from the ocean and air transfer. These effects are observed commonly in the Australian environment owing to the locations of its major cities being on the coasts [20].

1.7 Repercussions of Poor Design on Corrosion

The costs attributed to corrosion damage have been estimated to be of the order of 3-5% of the gross national product (GNP) of industrialised countries [8]. The total corrosion cost is over $300 billion *per annum* in the US alone and the Specialty Steel Industry of North America (SSINA) estimates that approximately one-third of this cost is avoidable. The knowledge and willingness to invest in corrosion-resistant materials and the use of best anti-corrosion practices from design through to maintenance will aid the achievement of this reduction in corrosion failures. The various countries and industries in which the major corrosion failures have occurred are listed in Table 1.1 below [21]. Figure 1.2 illustrates the cost of corrosion in various sectors of the US economy.

Table 1.1. Major worldwide corrosion failures [21].

Region/Industry	Cost of Corrosion	Reference
Aircraft Industry (North America)	$13 billion per year	[22]
Military Aircraft, (USA)	$3 billion per year	[22]
Aircraft	$100,000 per day lost revenue when grounded for corrosion maintenance/repairs	[22]
Air Force and Navy (Australia)	>$50 million per year	[23]
Army (USA)	$10 billion per year (estimate)	[24]
Army (USS)	$2 billion per year, related to painting and paint removal (estimate)	[24]
Australia	~2% of GDP	[25]
Australia	~$8 billion in 1982	[26]
Automobiles (Finland)	~US$160 per car yearly (~US$300 million in total per year)	[27]
Automobiles (USA)	0.25% of GNP attributed to motor vehicle corrosion (in 1998)	[28]
Automobiles (USA)	$23.4 billion per year cost to American consumers due to: increased manufacturing costs, repairs and maintenance, depreciation (costs of reduced safety not included)	[29]
Bridges (USA)	$30 billion (1999 dollars) to remediate corrosion-induced structural deficiencies	[28]
Old Severn Bridge (UK)	£20 million to mitigate corrosion (projected), with £3 million previously spent on corrosion assessment of suspension cables	[30]
Coast Guard Aircraft (USA)	$20 million per year	[31]
Reinforced Concrete	US estimate of reinforced concrete bridges and car parks due to deicing salts: between $325 million and $1 billion per year	[32]

Region/Industry	Cost of Corrosion	Reference
Restoration of Michelangelo's *David*	~$500,000 (estimate)	[33]
Easter Island Statues	~$10 million in restoration costs (note that the tourism industry associated with these statues reportedly generates several million dollars each year)	[34]
Eiffel Tower (France)	1989 refurbishment costs of 200 million FF; ~50-60 tons of paint are applied every 7 years by some 25 painters as corrosion protection for this >7 thousand ton steel structure; corrosion damage is a major consideration in the maintenance and refurbishment requirements	[35]
Gas Pipeline Industry (North America)	$80 million per year purchased in coatings to coat new pipelines and recoat existing pipelines (1993 reference)	[36]
Restoration of Golden Boy Statue (Winnipeg, Canada)	$6 million for corrosion related repairs (estimate)	[37]
US Army Helicopters	$4 billion spent on corrosion repairs (1998 estimate)	[38]
Japan	0.8-1.0% of GNP (1997 estimate of direct corrosion costs)	[39]
Military (USA)	>$ 20 billion per year	[38]
Military Cargo Trucks (USA)	$850 per truck in replacement parts in the fifth service year; anticipated to escalate to $17,500 per truck in the 11th service year	[40]
Navy (USA)	~25% of total fleet maintenance budget spent on corrosion prevention and control (estimate)	[41]
Nuclear Reactors	£100 million per year (a particular problem of voluminous corrosion product formation on in-reactor steel components)	[42]
Oil and Gas (Agip)	~$0.40 per barrel of oil produced as economic impact of corrosion	[36]
Oil and Gas Production Platforms (North Sea)	60% of all maintenance costs related to corrosion, directly or indirectly (1993)	[36]
Gas and Liquid Transmission Pipelines (USA)	~$7 billion	[29]
Power Generation (USA)	$5-10 billion annually for the US electric power industry; in steam-electric generating plants, corrosion costs exceed 10% of total power cost; ≤50% of outages attributable to corrosion (EPRI estimates)	[43]
Roads, Sidewalks, Bridges (Toronto, Canada)	$110 million is to be spent by this city on the repair of roads, sidewalks, and bridges in 2005, with a backlog of $235 million deferred due to budget constraints	[44]
Statue of Liberty (USA)	Greater than $200 million restoration project (1986), largely necessitated due to corrosion damage, with significant internal galvanic corrosion damage	[45]
Stray Current Corrosion (USA)	5% of total corrosion costs in USA, with most costs arising from electrified d.c. transit system operations	[46]
Switzerland	3-5% of GNP per year or 10-15 billion CHF per year	[47]
USA	~$300 billion per year, for metallic corrosion (~4% of GNP or more than $1000 per	[48]

Region/Industry	Cost of Corrosion	Reference
	person); >⅓ of costs considered avoidable using existing know-how and technology	
USA	$279 billion per year (direct costs), corresponding to 3.2% of the US GDP; indirect costs to the user (society costs) were conservatively estimated to be equal to the direct costs	[29]
USA	$5 billion in 1941 (historical note)	[49]
Water Infrastructure	"I can tell you the cost of not providing basic water for drinking and sanitation will far outweigh the cost of doing so.", attributed to Peter Gleick in Marq de Villiers' book *Water*, Stoddart Publishing Co., 1999	[50]
Water and Wastewater Pipeline Failures (Australia)	$250 million per year.; further cost increases expected as the already aging pipeline system gets older	[51]

In many failures, subsequent investigations fail to determine the actual cause or causes of failure owing to loss of evidence, failure to act promptly, or other reasons, and so the nature of remedial action may be flawed.

1.8 Factorial Approach to Corrosion

Once corrosion in metals has occurred, then the basic causes must be identified in order to:

a) Eliminate the source of the corrosion
b) Select materials and/or processes that are the most appropriate for the minimisation of the effects of corrosion

If the initial design has failed to take into account proper design to counteract the adverse affects of corrosion, then the refurbishment work must not assume that the original material used would have been the right choice in the first place. For instance, corrosion may not be caused necessarily by the environment alone; it also can be influenced significantly by certain fabrication/installation or material properties. Corrosion may be a result of metals' being in contact with one another, such as bolting, riveting, or welding ferrous to non-ferrous metals. In many instances selection of a more suitable material also necessitates various changes to conventional structural shapes or geometry. An example to consider in design is the replacement of steel by aluminium for reasons such as corrosion resistance. Although it is clear that these two materials have different properties, other differences exist. Both steel and aluminium come in different sectional forms. Aluminium generally is extruded and steel usually is not. Aluminium cannot be used for high-strength applications in most cases but its strength is adequate for many other applications.

The improper use of aluminium also can result in problems, particularly in contrast to steel, which generally is considered to be more predictable to the designer. A reduction by two-thirds of iron or steel component by the equivalent in aluminium is an attractive advantage but this is accompanied by a reduction by two-thirds in the stiffness [6,52].

Although direct replacement of a steel part with a duplicate made from aluminium may give acceptable strength under peak loads, the increased flexibility will cause triple the deflection in the part. For instance, where failure is not an issue but excessive flex is undesirable, simple replacement of steel sections with similarly sized aluminium sections will result in a degree of flex under certain loads that may necessitate increasing the thickness of the section. However, this also increases the weight proportionately and so the original advantages may be lost in the re-establishment of the rigidity. Thus, aluminium may be used best by redesigning the dimension of the part to suit its characteristics. Also, since corrosion of aluminium may be even more severe than in steel in the same environment/applications, the proper use of aluminium in buildings will require more than just knowledge of the mechanical properties.

For just over a decade, there has been some considerable interest in issues affecting the service life of buildings. Before that, there was little research performed in the field. In 1996, Frohnsdorf and Martin [53] wrote that *"approximately twenty years ago trying to predict the service life of materials and components for a building was a distant vision, and that today it has been given more serious attention".* Since then, a considerable body of research in the lifetimes of building components has been generated independently by Government and professional organisations, particularly in the US and the UK [54,55].

The pursuit of a standard method for determining the durability and expected service life of building components and materials has derived from the efforts of many organisations, including the American Society for Testing and Materials (ASTM), Réunion Internationale des Laboratoires et Experts des Matériaux (RILEM), and the International Council for Research and Innovation in Building Construction (CIB). Significant progress was marked by the issue of the British Standards Institute (BSI) BS 7543:1992 *Guide to Durability of Buildings and Building Elements, Products, and Components*, the publication by the Architectural Institute of Japan (AIJ) of *Principal Guide for Service Life Planning of Buildings (English Edition)* [56]; and the release of the Canadian Standards Association (CSA) S478-1994 *Guideline on Durability in Buildings* [54,55,57].

ISO 15686 is designed to ensure a proposed design life in which the service life is established from an estimated service life of a building component, building, or other constructed work, such as a bridge or a tunnel [58]. ISO 15686 consists of a group of sub-standards, 15686 – 1 to 15686 – 11, which cover a range of areas related to the service life.

The culmination of the standardisation work in the durability and expected service life of building components and material was the issue of the International Standards Organisation (ISO) ISO 15686-1, *Building and Construction Assets – Service Life Planning – Part 1: General Principles* [59] and ISO 15686-2 *Part 2: Service Life Prediction Procedures* [60], which *deals with the general principles, issues and data needed to forecast service lives, and gives a method of estimating the service life of components or assemblies for use in specific building projects*. ISO 15686-1 [59] also provides a factorial method to determine the estimated service life of a component (ESLC) by adjusting the reference service life by its quality, design level, work execution level, type of environment, in-use condition, and maintenance level.

ISO 15686 proposes the use of the factorial method to forecast the service life and estimate the timing of necessary maintenance and replacement of components in certain conditions [54,55]. This method is based on the *Principal Guide for Service Life Planning of Buildings (English Edition)*, developed by the AIJ, and the work of the CIB, RILEM, and the Standards published in the UK, Canada, and the USA. This method estimates the life of components by adjusting the reference service life using modified factors that relate to the specific conditions of the case. ISO 15686-8.2 *Building and Construction Assets – Service Life Planning – Part 8* [61] proposes the following seven factors to account for differences between the object-specific and in-use conditions:

a) Factor Class A: Inherent performance level (previously called *quality of components*)
b) Factor Class B: Design level
c) Factor Class C: Work execution level
d) Factor Class D: Indoor environment
e) Factor Class E: Outdoor environment
f) Factor Class F: Usage condition (previously called *in-use conditions*)
g) Factor Class G: Maintenance level

Any one or a combination of these factor classes can affect the estimated service life. Owing to the relative newness of the field, many factors affecting the performance/life of even traditional components are not fully understood or researched. The factor class values are, therefore, typically up to the user to set or find, according to ISO 15686. These factor values can be set according to:

a) Experience
b) Manufacturers
c) Test results
d) Feedback from practice through condition assessment
e) Known actions of the environment on specific materials

The critical properties deemed to degrade in the object-specific in-use condition need to be encompassed fully according to ISO 15686. Thus, the service-life planning considerations depend on a series of predicted service lives of components and the projection of maintenance timing and replacement needs.

The factorial method can be used as a guide for the prediction of processes in either new or existing buildings. In the latter case, the assessment aims to identify the residual service life of the components that already are installed. Since the factorial method employs both empirical and subjective inputs, it is likely not to be as accurate as other scientific methods based on observation over time or modelling of performance, according to ISO 15686-1 [59].

The term *predicted service life* (PSL) in ISO 15686 typically means a forecast service life derived from laboratory tests, as described in detail in ISO 15686-2 [60]. The result from this process generally is described as a reference service life (RSL). The RSL is defined as service life that a building or parts of a building would expect in a certain set (reference set) of in-use conditions. The RSL can be derived from manufacturer literature, results of testing, and feedback from practice, according to ISO 15686-1 [59]. However, if another source of information is used to provide the RSL and the procedure involves adjusting factors to reflect project-specific factors, it then referred to as the *estimated service life* (ESL).

When quantitative information is lacking, a grading of the in-use conditions within that factor class can be made. The in-use condition grade, however, is not the same as the value of the corresponding factor; it is a way to quantify qualitative information and use it to estimate the value of each factor. Also, not all of the information for the seven factors must be available for the estimation.

The factorial method can be applied to both components and assemblies. When applied to an assembly, both the components themselves and the interfaces between them must be considered. Two or more agents can act (or counteract) to produce an effect greater or smaller than the sum of their individual effects.

The factorial method is expressed in the following formula:

ESLC = RSLC ·Factor A ·Factor B ·Factor C ·Factor D · Factor E · Factor F · Factor G

where:

ESLC = Estimated service life of a component

RSLC = Reference service life of a component, defined as *a documented period in years that the component or assembly can be expected to last in a reference case under certain service conditions*

ISO 15686-8.2 [61] suggests that all factors should have values in the range 0.8-1.2 or, preferably 0.9-1.1. This narrow range of values is preferred owing to the inherent uncertainty of the method. It may be noted that this provides implicit comment about the meaningfulness of the results obtained by this method. That is, if the method is so uncertain as to skew all of the factors toward unity, then the overall result is likely to be skewed toward unity rather than incorporation of variations according to meaningful relative weightings of the different factors. Further, at present, relevant data are scarce and usually not comprehensive such that the outcomes can be viewed confidently that they indicate the degradation of even similar buildings or components, as indicated in ISO 15686. Therefore, it appears that users are forced to choose the reference service life (RSL) and the factors based on the some arbitrary availability of deterministic data/information.

Materials such as aluminium, however, are extremely complex to predict when compared to steel. Aluminium also is very complex to design with and to ensure that all of the variables satisfy the environmental conditions and loading requirements, as will be discussed in subsequent sections. It is materials such as aluminium used in structural applications that are likely to prove to be extremely difficult to use in the preceding generalised factorial methodology.

CHAPTER 2. Westfield Award of Building Rooftop and Façade Louvre Design and Construction to Perfect Engineering Pty. Ltd.

2.1 Preliminary Holistic Approach to Design and Research and Development

Westfield Design & Construction, Bondi Junction, deemed that Perfect Engineering Pty. Ltd. once again under my complete guidance, would be the most suitable engineering contractor from a list of engineering firms that tendered on the project, in particular due to my background in the field. The goal of the project was to provide appropriate solutions to ensure that the public remained safe from the future re-occurrence of the collapse of the structural louvres on the southwestern section of the building rooftop. Collapse of these louvres due to excessive wind caused their failure and resultant descent from the 29th level of the building into a childcare centre and public footpath below. Fortunately, this occurred on the weekend 23-24 August 2003 and so there were no children or public in the vicinity of the debris during this incident.

In late January 2005, Perfect Engineering Pty. Ltd. was awarded the contract to re-design, refurbish, and provide solutions for the rooftop and façade, which was comprised of structural steel and aluminium louvres. This event was some years after the construction of the building and well before the expected end of its design life. It was determined that, when the building designers chose to incorporate the louvre system on the rooftop and façade, they may have been unaware of and possibly disregarded some basic materials corrosion principles, particularly in regard to the use of incompatible materials. The requirements in the brief of the project were that several alternative solutions to the problems had to be considered and developed and these had to be discussed with the client before proceeding. It was considered that each potential solution should be assessed according to four main criteria, these being:

a) Implementation of the solution without risk to workers, the public on the footpath below the building, and, in particular, the childcare centre directly below on the south side.
b) Preservation of the building aesthetics on the building rooftop and façade so as not to deter from the original architectural design
c) Research and development, design, and construction so that the life of the solution was guaranteed for a minimum of 5 years
d) Implementation of the solution within a strict budget, to be completed in a set period and in a safe manner

This research project evolved from the need to find refurbishment solutions for the building in question and recognition that these findings should be extended to include design recommendations that could be applied by building designers in the future. Therefore, the present work does not intend to provide all of the solutions for an ideal design or that it has covered all potential issues. However, the approach is intended to be holistic in the sense that it attempts to:

a) Identify the key variables and strategies in critical engineering design issues
b) Rectify or re-design the problems in a practical and economical manner
c) Apply sound engineering solutions for similar situations in the future

Inspection of the site revealed that the corrosion process was in the advanced stage, largely owing to the effects of galvanic corrosion. The project was complicated by the diverse range of materials present, the very large areas of the rooftop and façade, and the large amount of metal in place. These factors made it clear that research in materials degradation was a prerequisite of the eventual remedial solutions.

There does not appear to be any pre-existing systematic studies of this nature performed on so many materials used in building rooftops and façades, although there have been other studies on various isolated metals. However, the only industry that had available a body of in-depth and detailed information on materials failures and corrosion was the aerospace industry.

The shortcomings in the original design of the Westfield rooftop and façade at the time of original building construction were such that it is probable that there was no materials specialist involved to select optimal materials to withstand corrosion. This was true particularly in regard to the aluminium and steel structures. Although some of the design may have been suitable for structures in the existing saline ocean environment, the basic concept was flawed in that it neglected:

a) Incorrect use of dissimilar metals in mutual contact, resulting in galvanic corrosion
b) Incorrect use of structural bolts with inadequate galvanised coatings

The majority of the original material on the louvre system on the Westfield building was identified by inductively coupled plasma atomic emission spectrometry (ICP-AES). These data showed that aluminium alloy 6060 was used for the louvre extruded blade profile and 6063 was used for the structural column mullions (Appendix F**)**. These alloys are common materials used in light aircraft and in non-structural applications in buildings, respectively. However, it may be noted that, as discussed in Section 1.3, the aerospace industry is limited in its aluminium design in aluminium largely to 2024 and 7075 aluminium alloys, which are known to have corrosion problems.

The remaining materials on the rooftop and façade were mainly steel, bolts, tek screws, and steel rivets. The substantial literature and case studies in the aircraft industry, combined with its experience, problem-solving documentation, and advanced materials research, provided a suitable basis for the initial facilitation of the project.

Owing to these considerations, a metallurgically compatible and structurally sound system, which included additional internal members to which the louvres could be secured, was designed. This meant that, in certain regions, not only strength but also light weight and, above all, corrosion resistance, were paramount since the building is close to the ocean. External plates and drilling jigs also were designed to facilitate the securing of the louvres to both internal members and the building concrete façades.

Materials alternatives for fixing products were researched, with the observation of the availability of high-performance rivets and bolting devices with strength and corrosion resistance characteristics far exceeding the existing conventional rivets used in the building and in most other buildings. Alternative louvre profiles and alloys with superior strength and corrosion resistance also were researched. These materials had to accommodate the potential effects of welding the structural mullions that support the louvres. Welding was necessary owing to constraints with the existing structural design, size limitations associated with the transfer of the components to the on-site location, and the expectation that the joins would be stronger than the existing rivets.

Guidelines were developed and the client was updated on both the continued findings of the existing deterioration on the rooftop and the proposed rectification matters. Each phase of the project was supported by an overall safety plan. All material was coordinated through regular reports that were prepared on the basis of the research.

On the occasions that the client was dissatisfied with a particular material, design, or process due to aesthetics or safety issue, then alternatives were presented. Each change in material, design, or process required a thorough analysis from the perspectives of strength and corrosion resistance. Incompatible materials were to be eliminated and a new overall design was to be the basis for this remediation work.

An essential element of the design was to ensure a drilling pattern for the concrete façade that would accommodate a suitable number of bolts without compromising, for instance, the edge distance yet preserve the façade's own structural integrity without impairment to existing materials, such as concrete reinforcement (reo) bar. It was essential to avoid procedures that might allow ingress of corrosive macro- and micro-climatic deposits. Also, it was essential to ensure that the aluminium structure would not be impaired or weakened as a result of drilling holes for the bolts.

2.2 Selection of Team to Carry Out Project Requirements

Initially, an engineer very experienced in his field was engaged as Compliance Manager. He co-ordinated all of the work-safe method systems and statements and he inducted the teams for the project. He also was responsible for ensuring that the current requirements pertaining to works conducted on the rooftop, including the Building Maintenance Unit (BMU) and the abseilers suspended by rope were satisfied.

The Project Manager was responsible for co-ordinating and supervising the workshop fabrication activities and the coatings provided by the suppliers. This aspect of the work was critical because it ensured strict compliance with all materials issues, including those done in-house, on-site, and by approved suppliers with certifications from the original manufacturers.

The Quality Manager was responsible largely for ensuring that all materials and processes were consistent with ISO 9001:2000 and for auditing.

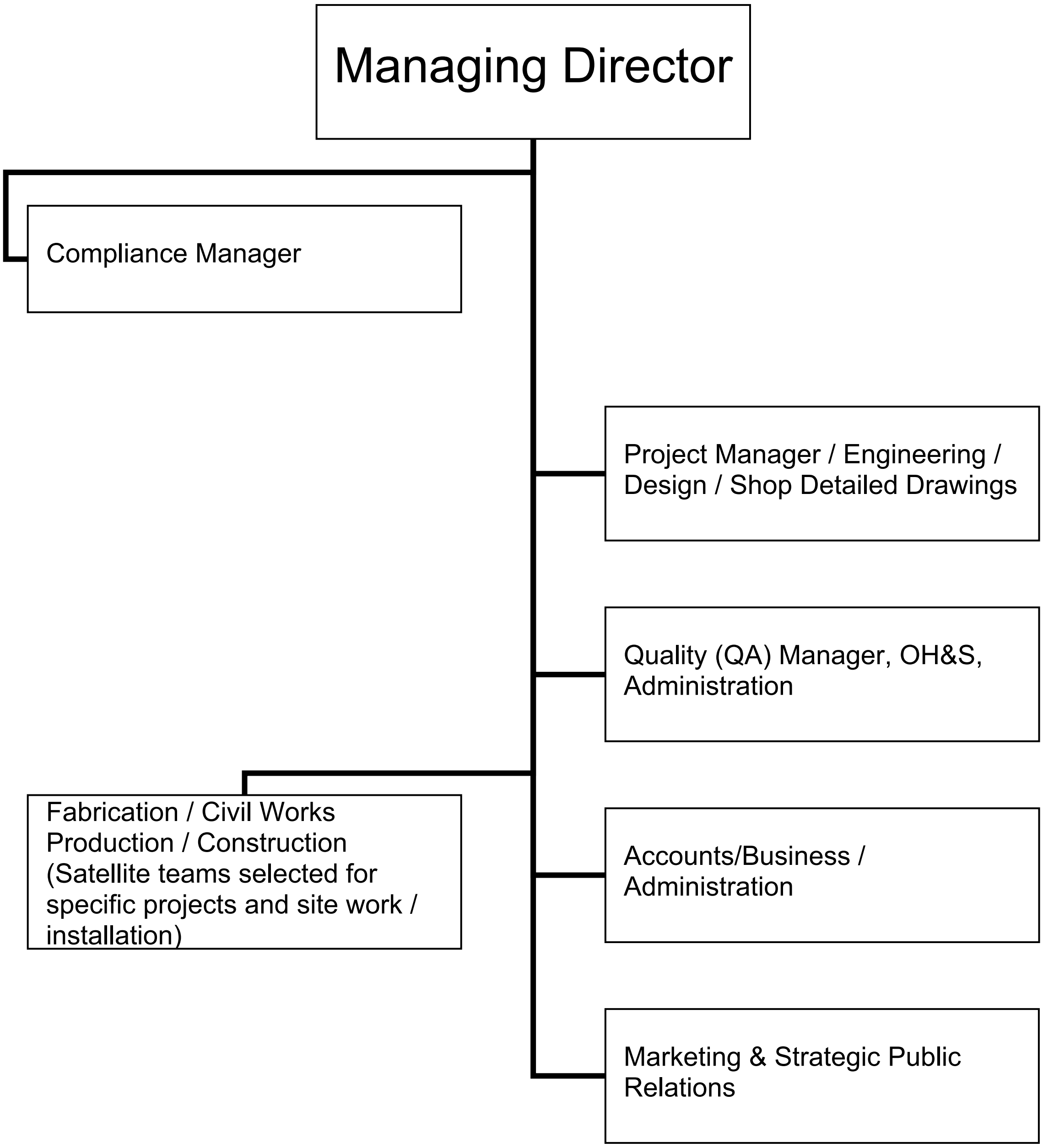
Upon the advice of the three Managers, a team was hand-picked to help execute the project. The basis for acceptance of supplier and team members were:

a) Experience
b) Qualifications
c) Accreditation
d) Attitude
e) Willingness to comply with the standards set for the project

The identities of the suppliers are confidential, although these have been archived in the *Approved Supplier List*, which conforms with ISO 9001:2000 requirements, for which Perfect Engineering Pty. Ltd. is accredited. The company's third-party certifier is Standards Australia International (SAI) Global; the certification number is QEC21503. Copies of all company certifications are given in Appendix D.

2.3 Perfect Engineering Pty. Ltd. Organisation Chart

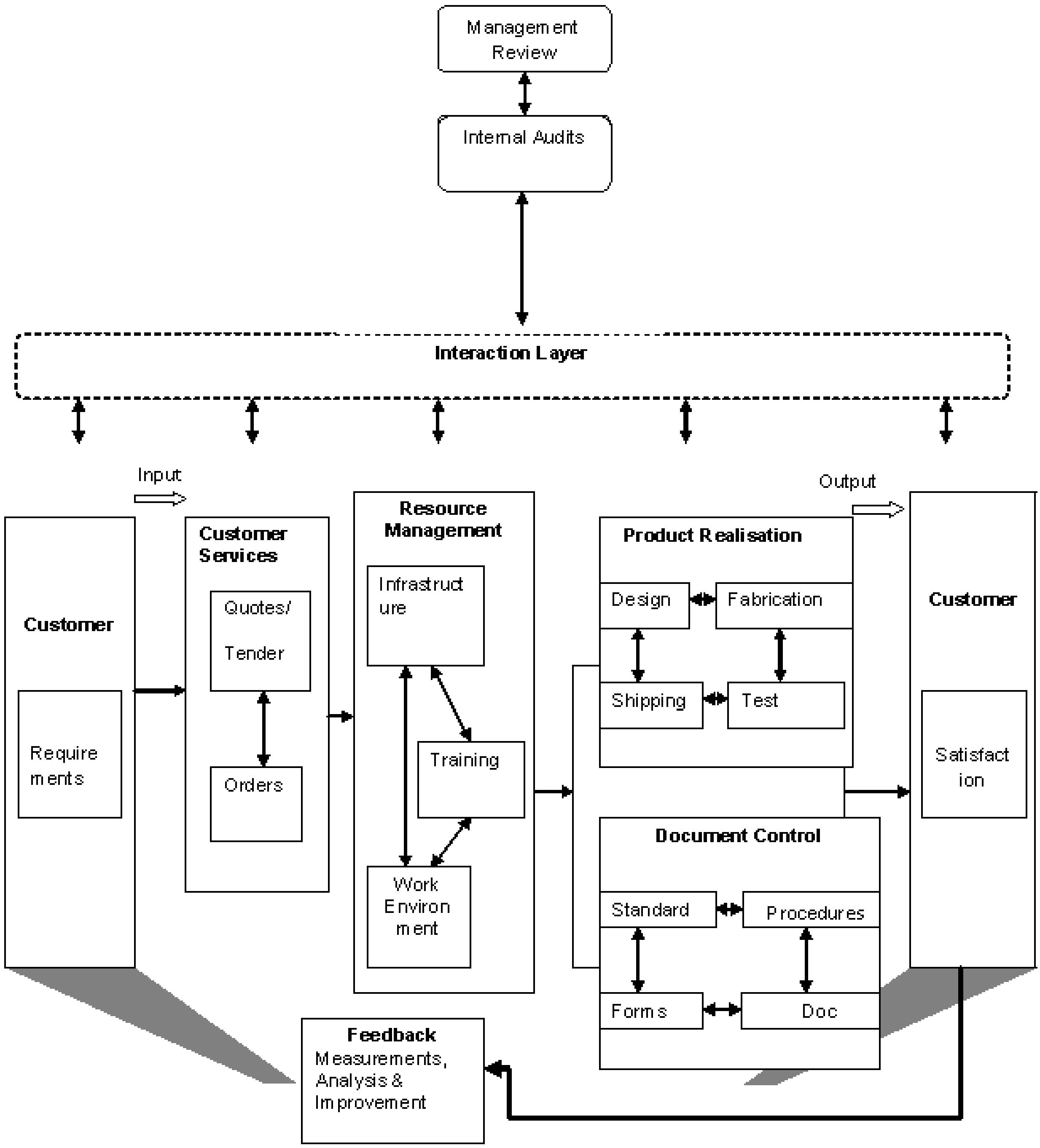
A schematic of the organisation chart of Perfect Engineering Pty. Ltd., showing the project team is shown below.



Schematic showing Perfect Engineering Pty. Ltd. organisation.

2.4 Perfect Engineering Pty. Ltd. Process Core Chart

A schematic of the process core chart for Perfect Engineering Pty. Ltd., showing the company's integration is shown below.



Schematic showing Perfect Engineering Pty. Ltd. integration.

2.5 Intentions and Methodology

It is common to install plant room equipment, especially air conditioning/ventilating and emergency power generating systems, on the rooftop and/or upper levels of high-rise commercial buildings, and this practice invariably involves the use of louvre systems to facilitate ventilation of the equipment. Louvre systems placed on rooftops usually are inset from the building edge, whereas those required to ventilate upper floor plant rooms invariably form an integral part of the building's façade. Since both types of design were present in the Westfield building, solution to the problems involved issues of materials selection and associated considerations as well as independent wind load calculations on the louvres and fixing attachments to ensure loading conditions appropriate to the relevant Australian Standards.

The research was divided into three phases and areas of interest, with objectives as outlined below:

a) Analysis of the corrosion problems discovered *in situ* at the building in question and development of solutions with due regard to design life, installation safety, and cost, with the objective of providing optimal refurbishment solutions to the client
b) Analysis of the risks to the public, design professionals, construction personnel, and building owners associated with compromised louvre system, with the objective of raising awareness with the building industry and policy makers concerning the impact of design, both adequate and inadequate, in the field
c) Extension of the knowledge gained in the aforementioned project phases to develop, through research and the application of a factorial approach for materials permutations and influencing factors, such as design and material selection criteria, heat treatment, and coatings, criteria that can be used by designers as a guide to achieve optimal design life in a variety of environments

It was envisaged further that such an approach for the factorial method, once developed, could be made available to designers in a convenient format, deliverable as an on-line service or as a downloadable application software file. This matrix currently is under development but it requires more research data before a final satisfactory matrix will satisfy all requirements. Some aspects of this work are presented in Chapter 6. The information regarding micro-climate and its direct effects on each material has been the limiting factor to date in the general literature and is beyond the scope of this work.

Phase 1 Methods

Phase 1 was conducted as an engineering project and consisted of the following elements:

a) The conditions of the failed louvres and intact louvres and their associated supporting structures installed on a 29 floor commercial building situated at Bondi Junction, NSW were assessed. The louvres were situated along the external faces of the building at levels 26-28. A rooftop (level 29) structure, providing ventilated protection to cooling towers, also was included in the scope and this structure was set back from the building edge by approximately 3 metres.
b) The installation and metallurgical factors that had contributed to the deterioration and imminent failure of the louvre system were researched.
c) The materials were researched and a schedule for the replacement of components was developed so that it could be used to repair the existing damage and prevent further damage to those components not yet requiring replacement. The compatibility of adjacent metals in a corrosive environment was a critical factor to ensuring success.
d) New supporting structures were designed, component interface details using the compatible materials were chosen, and these designs were refined in collaboration with a view to cross-disciplinary engagement of a structural engineer and or corrosion specialist in aluminium.
e) A risk assessment of the installation methods was undertaken in order to protect the workers and public and to comply with occupational health and safety (OH&S) statutory requirements. This process led to the adjustment of certain elements of the design in order to reduce installation risks.

Phase 2 Methods

From the insights gained during phase 1, it was possible to appreciate the extent of the problems that appeared to be endemic in the design of many modern high-rise buildings in terms of the components and systems supplemental to the core structure. To place these problems into a perspective that can be appreciated by those associated with the construction industry, phase 2 was conducted in order to evaluate the risks to those individuals, organisations, and the public at large. The analysis of risks was confined to considerations of statutory requirements prevailing in New South Wales (NSW), Australia and may not apply to areas of other jurisdiction. The method of research included the following elements:

a) A review of the statutory requirements relating to all stakeholders' duty of care to provide installations that will remain safe for a specified working life that may be less than the building's design life was undertaken. This included an assessment of the transfer of risk from designers to construction personnel to owners, including building maintenance staff, and finally to refurbishment contractors during the course of a building's life.
b) The legal exposure and costs associated with designs that do not meet the statutory requirements relating to safe designs were assessed.
c) The costs of replacing prematurely failing systems compared to the costs of the installation of a more corrosion-resistant system were assessed.
d) An assessment of the additional risks associated with the refurbishment process that would not have been required if there was greater attention paid during the original design.
e) This phase of the research project was conducted primarily using a preliminary approach to the review of statutory regulations, codes of practice, and published industry information.

Phase 3 Methods

Phase 3 examined the factors influencing the performance of the materials considered in phase 1, including required design, materials selection, service life, and environmental risks, such as wind, temperature, humidity, and atmospheric contaminants. Phase 3 was carried out in several stages deploying the following methodologies:

a) A literature review was undertaken in order to ascertain the current status of research in the field of building design and to develop further knowledge of the applications of a factorial approach and subsequent matrix development.
b) Compilation of a comprehensive list of literature available on materials and design for both aerospace and building applications that would be applicable to the existing louvre system and other façades on high-rise buildings.
c) A supplementary list of alternative materials derived from practices in other fields, particularly the aerospace industry, where the use of light and strong alloys and fixing devices has evolved in an environment of keen safety awareness and attention to service life extension was compiled.
d) Materials science knowledge, structural design concepts, processing protocols, and risk assessment techniques were applied in order to develop an appreciation of materials compatibilities, which are complex owing to the factors that influence their behaviour in service.

CHAPTER 3. Literature Review and Considerations

3.1 Overview of Compliance and Responsibilities of Owners and Designers

The high cost of corrosion of metals worldwide and the associated failures can be expected to be reduced significantly by the understanding and application of knowledge collectively in the following areas:

a) Appropriate knowledge and hence design by specification of suitable longer lasting corrosion-resistant metals and coatings for specific applications
b) Use of correct combinations of more than one metal when in mutual contact
c) Design and application of structural components to embrace large structures to withstand heavy wind loads
d) Quality of workmanship and knowledge of fabrication/installation
e) Effects of the environment on not only metals as originally specified but also on ferrous and non-ferrous metals subsequently fabricated, welded, or otherwise installed *in situ*
f) Long-term maintenance and specific recommendations to preserve structures

One of the fundamental factors when considering corrosion is that no one particular metal alone or in combination with other metals will act exactly the same in different environments. The variables involved make it an almost impossible and a daunting task to list all the possible factors that affect each metal, singly or in combination with other metals. Further, there are various implications of factors, such as corrosion and stress, that may alter metals' microstructures during fabrication or installation such that these respond differently in a range of environments that may range from moderate to severe, depending on location. This is why the matrix development as discussed briefly, requires considerably more data inputs before it can be recognised and accepted as a reliable indicator of potential performance. However variables that are relevant to the generation of matrix are illustrated in the expectation that they may serve as a guide to benchmark further development in these matrices.

The major commitment and primary aim of a designer is considered to be the achievement of minimal maintenance (but not neglect) and life-cycle costs while achieving maximal performance and lifetime. This can be done through education of engineers, industry, academic institutions, Government, consumers, and all other parties with a vested interested in ensuring *good practice* in this field.

It is evident that it is essential that there is a significant awareness of the importance of educating engineers about corrosion since at least one-third of these failures could be avoided with suitable materials selection and maintenance programs [8].

In the scope of the present work, it is not possible to provide exhaustive technical information on the design and selection of materials used in rooftops and façades of high-rise buildings. However, it is recognised that there is a dearth of a coherent body of literature reporting these very topics. Therefore, these topics are reviewed broadly and focus on the following:

a) Materials used
b) Some approved methods of joining components
c) Importance of geometry in the performance of materials when exposed to the environment
d) New and improved connection methods that were implemented.

Louvres generally are manufactured from aluminium alloys such as 6063 or 6060 in the T6 condition (explained subsequently). However, 6351 T6 was selected for the structural column support for the louvres because it is slightly superior in chemical and mechanical properties to 6061, which is used widely in aircraft (particularly light aircraft) and in non-structural applications, transport, and ocean-side installations.

The louvres in the mid-section of the façades were reinforced with 6061 sheet metal owing to its excellent bearing and tearing properties, especially when riveting is used. Therefore, it was necessary to extrapolate as much information regarding this material from the aerospace industry about its processing and physico-chemical, mechanical, and corrosion properties in order to understand it better so that it may be applied on other aluminium alloys of similar or close compositions in other industries. Although 6061 may not be suitable as the basis for all of the applications relating to the louvre system, it is an excellent benchmark for further study since the literature on it is large and extensive. In particular, the aerospace industry has a well documented library of information based on case studies and this documented information generally is very useful in helping in the design stage and in aiding remedial work.

The aluminium alloys of interest 6060, 6061, 6063, and 6351, all of which derive from the same family known as the *6000 series*. While 6060 and 6063 have lower strength properties while 6351 is superior. However, the latter's corrosion resistance is not as good as that of 6061. For this reason, powder coating has been used as a corrosion-protection system for the louvre systems fabricated from 6063 and 6351.

There are limitations in terms of the shapes, such as angles, of certain alloys that are available. Consequently, the available replacement alloy will have properties that are different from those specified or expected. It is the responsibility of the designer to understand and accommodate these differences. A common problem that often is not foreseen by designers is that, when one particular member cannot be used since the material properties do not allow it to be extruded into a particular shape or size, then knowledge of the properties of the alternative material is imperative, especially if it is connected to another material. Also, if welding is required for joining one section to another, and the material that was originally supposed to be used is not available in the market, then the alternative material to be chosen must be considered in detail. Although one material may be nearly the same in chemical properties as another or the hardness or tensile properties may be similar, this does not mean that the material will act in a similar manner. Variations of a single chemical element in a ferrous or non-ferrous metal or changes in the heat treatment may change markedly many aspects of the final material properties and designers should be aware of this.

The approach should involve a systematic study of the consequences of each proposed design and these should be assessed scrupulously in terms of these parameters individually and collectively. If only a single hypothetical situation, which may be only a small part of a large population of possibilities and scenarios, is assessed, then knowledge of the impact of this aspect of the design and the result of neglecting it may be absent, misleading, or erroneous.

Selecting a material for a specific application requires that, firstly, it will be structurally safe and suitable for the requirement and, secondly, it will achieve the life cycle required for its intended life. The next step would be to consider the basic parameters required for effective design without compromise to human safety and material integrity. These parameters include consideration of the following effects but they are not limited to the following:

a) Budget
b) Time constraints
c) Diverse range of materials and availability in the market
d) Materials processing/properties variability
e) Workmanship
f) Environment conditions
g) Maintenance

There are many other variables that may impact either directly or indirectly on the life cycle of metals on the external surfaces of a building in the short or long term. Only some of these other variables will be discussed in the subsequent sections.

3.1.1 Designer's and Professional Engineer's Responsibilities

Designers are generally engineers with some form of formally recognised academic qualification and accreditation from a recognised institution, such as a reputable and recognised engineering body. One such body, the only one in Australia, is Engineers Australia. The professional responsibilities of an engineer/designer, including the ethical responsibilities and general conduct, are detailed in Section 3.1.4.

One of the main tools to help the designer or owner achieve the aims of a project is to ensure that a recognised professional engineers in the relevant specialist areas is employed for each task. Accreditation with Engineers Australia provides some level of confidence to the owner and the general public that the ultimate design will rest with a person who is qualified to work in that particular field since they have been assessed after acquiring their formal qualifications, and so the owner may have the assurance that the engineers have the experience and expertise to execute such projects.

The duties of the design engineer are very diverse with regard to the overall design. This engineer will have to use direct knowledge and expertise or he must engage others to make important engineering decisions. The engineer will either work to existing conceptual plans provided by the client and that may require some modification and certification by himself at the end of the project or the engineer must design from the initial stage and certify as required. The designer should stipulate on the drawings or list of engineering specifications relating to the materials specified in the project that the materials and fabrication should adhere to relevant Standards and he should specify these Standards.

As an example of the approach a designer may make, the welding of steel and specification of subsequent galvanising requires the designer to understand the importance of the steel composition in order not to compromise the zinc coating. In general, the higher the silicon content of the steel, the thicker the zinc coating must be [62,63]. It is well known that, the thicker the zinc coating is, the better the corrosion protection will be since the zinc life is dependent on the thickness. However, when welding wire is high in silicon content, this will ensure that the weld metal will react more with the zinc and result in a thicker zinc coating. The Galvanisers Association of Australia (GAA) draws on data from the Australian Standard AS 2312 *Guide to the Protection of Iron and Steel against Exterior Atmospheric Corrosion* and states that high-silicon steels may increase coating thickness by two to three times and yield a rough surface finish that may be brittle. Another disadvantage lies in the aesthetics owing to the resultant uneven colour spread. However, if the steel itself is high in silicon and the welding consumable is lower in silicon, then the weld region will receive less zinc, which may affect the overall estimated life of the component, although the GAA states that this is not necessarily the case.

There is another consideration with metals that are high in silicon content, which is that, not unexpectedly, most galvanisers in Australia galvanise according to Australian Standards. Unfortunately, much overseas imported steel is purchased from certain steel suppliers owing to its relatively low cost and these steels may not be manufactured using strict quality requirements that do not allow compliance with these Standards. It is these steels that often are defective in terms of the overall properties that are required in the engineering field. To ensure consistency in welding and general materials, the designer must stipulate that the steel and consumables must meet the Standards of a particular code.

The designer will incorporate the framework and consequently the foundations of the overall construction. In the situation where the designer may not have accreditation and specific knowledge in certain metals, then other consultants and experts in their respective fields must be called upon to approve materials selection or materials applications. Inevitably, the designer will have to ensure that a cross-disciplinary approach engaging relevant experts in order to ensure adherence to every aspect of the requirements of the construction. If this approach is taken from the onset of design, this is likely to ensure that the construction will yield a favourable outcome for the owner and, more importantly, for the safety of individuals and the public in surrounding areas and the environment.

3.1.2 Risk Management Implications

In most modern societies, the protection of the population from injury or harm is provided by complex systems of law, Standards, codes of practice, and industry guidelines. Underpinning the legal mechanism is the concept of *duty of care* and, should it be shown that any person is injured through the disregard of another's duty of care, then the consequences can be serious.

In Australia, each State and Territory is responsible for OH&S legislation in its own jurisdiction. Consistency between these jurisdictions and international Standards is maintained through the Australian Safety and Compensation Council (ASCC), which is a Federal Government initiative [64].

Edited Extract from ASCC Website

Through a partnership of government, unions, and industry the ASCC leads and coordinates national efforts to:

a) Prevent workplace death, injury, and disease
b) Improve workers' compensation arrangements
c) Improve the rehabilitation and return to work of injured workers

The ASCC also:

a) Provides a national forum for Commonwealth, State, and Territory governments, employers, and employees to consult and participate in the development of policies relating to OH&S and workers' compensation matters
b) Promotes national consistency in the OH&S and workers' compensation regulatory framework

The ASCC is not a regulatory authority and does not make or enforce laws. OH&S laws in Australia operate in each of the State, Territory, and Commonwealth jurisdictions and they are administered by each jurisdiction's OH&S authorities. The State and Territory OH&S legislation provides the mechanisms to deal with protection of people in the work environment and the public affected by work being carried out. Where the general public may be placed at risk through activities or situations not covered by workplace-related OH&S legislation, there are other legal mechanisms that cover specific risk areas, such as the various State and Territory Public Health Acts and the Building Code of Australia (BCA), which is a federal Code that has been awarded legislation status by all jurisdictions [65]. The BCA has been developed to ensure safe and responsible building design and it encourages innovation and flexibility in design by allowing application of expert qualification of design techniques. The

Code also provides a parallel prescriptive design mechanism that refers to subsidiary design Standards published by bodies such as Standards Association of Australia (SAA), and certain building and services regulations where appropriate.

A recent addition to the BCA and building regulations is intended to close the gap between original design responsibilities and ongoing maintenance responsibilities. According to this, building owners must carry out essential maintenance and, although certain specific systems are specified for maintenance, it also is necessary for the owner to establish what other essential elements are required to be maintained to provide a safe environment. Records of essential maintenance must be kept and penalties apply for non-compliance. In this regulatory environment, it would appear to be reasonable for a building owner to require that the designer/builder issue an essential maintenance manual upon handing over the building for occupancy. Harm caused to people that can be attributed to failure to comply with any of the various legislation and codes referred to above is likely to result in legal action against those responsible. This failure to comply may be considered to be evidence of neglect of duty of care and/or professional misconduct. Penalties associated with such charges range from significant fines and damages to imprisonment.

Clearly, given the wide range of legislative mechanisms in place to protect people from harm, there is no field of endeavour that could be considered safe from legal action should anyone neglect his professional responsibilities and duty of care. It also should be noted that the initial legal penalty may be only the tip of the iceberg since damage may extend to loss of reputation, loss of certification to practice, and cessation of business.

When considering building design, it is apparent that risk exposure begins with architects and engineers but flows through to building owners, operators, maintenance staff, and repair contractors. It can be seen that this responsibility can be transferred through the building's life and it can be appreciated that it is difficult to establish where responsibility begins and ends.

A recent legal case in Queensland (*Woolcock Street Investments versus CDG Pty. Ltd.*, 2004) surprised many by the High Court finding that a designer could not be held accountable for losses incurred (due to design issues) by a subsequent owner once the building ownership had been transferred from the original owner.

A short summary of comments regarding the case was published on the web site of leading law firm, Allens Arthur Robinson [66]. An extract is given below:

Extract from Allens Arthur Robinson

Introduction

Woolcock Street Investments v CDG Pty. Ltd. [2004] HCA 16 (Woolcock Street Investments) will undoubtedly be remembered as one of the more significant decisions handed down by the High Court in 2004. In it, the court was asked whether a builder or architect of a commercial building can be held liable to a subsequent purchaser of the building for defects in the building's design or construction that cause the subsequent purchaser 'economic loss'. The court decided that a builder or architect cannot be held so liable.

Key Facts

So far as they are relevant to the issue, the facts are straightforward. A trustee company engaged an engineering firm and a civil engineer to provide services for a commercial building project the trustee company was engaging in.

In 1992, the building, a commercial warehouse and office complex, was purchased from the trustee company by Woolcock Street Investments. The sale contract contained no warranties that the building was free of defects, nor, under it, did the trustee company purport to assign to Woolcock Street Investments any rights it may have had against the engineering firm or the civil engineer. Woolcock Street Investments did not retain an expert to inspect the building, or inquire of the tenants or their agents whether the premises had any structural defects.

By 1994, substantial structural damage had occurred to the building because of settlement of the foundations. The foundations had been designed by the engineering firm with the assistance of the civil engineer. Woolcock Street Investments brought an action in negligence against the engineering firm and the civil engineer for the economic loss Woolcock Investments had suffered as a consequence of the damage to the structure of the building.

The High Court ruled that Woolcock Street Investments did not have any contractual conditions with the engineering firm or the civil engineer with reference to safeguarding itself by ensuring that the sale contract contained warranties or even an assignment of any rights the original owner may have had in regard to claims for defects. Woolcock Street Investments also did not seek to engage inspections of the premises prior to purchasing, so it became vulnerable as a result. The engineering firm and civil engineer therefore were not found to be liable in this instance.

Whilst this finding sounds like good news for designers, the conditions of the finding were quite specific and addressed only commercial loss in a situation where the original design responsibility boundaries were not clearly defined. Injury to the public resulting from design or construction deficiencies may result in a different ruling. Therefore, this example represents one possible legal outcome for a specific situation. Basically, the High Court held the view contrary to that of most commercial situations, where a duty of care may be owed by a designer, engineer, or builder for private dwellings since it is assumed that the average homeowner does not have the resources or experience to make comprehensive examinations of premises due to the limited resources at their disposal. Hence, the ordinary homeowner should be entitled to rely on the experience and expertise of architects, engineers, and builders. From this, it can be concluded that it is much safer to practice outstanding design and demonstrate duty of care than to take the risk of the alternative.

Perfect Engineering Pty. Ltd. Case-Specific Project

In the case of Perfect Engineering Pty. Ltd. and the client's building, it was evident that the louvre system was originally not designed with either longevity or ease of maintenance in mind. As a consultant and engineering contractor, on behalf of Perfect Engineering Pty. Ltd., my main concern was the development of solutions with the following attributes:

a) Implementation of design and ensurance of complete project management of work to be executed without risk to repair workers while maintaining a high level of standards in materials and workmanship
b) Implementation without risk to the public
c) Longevity of the finished job and hence continued safety through maintained structural integrity
d) Economy
e) Absence of inconvenience to building users

In order to enact the key elements a) and b) above, it was necessary to consider all requirements of the OH&S legislation and Quality Assurance (QA) requirements of ISO 9001:2000. For this, Perfect Engineering Pty. Ltd. carried out full risk assessments and quality audits, which involved developing Safe Working Method Statements (SWMS) for the application of every possible safety precaution. A number of innovative construction techniques was used, including rope access during abseiling for drilling and component placement on the buildings out-face. It is clear that this required extensive safety procedures to protect both workers and the public below. From the QA perspective for this project, key procedures were established, including quality objectives, corrective and preventative actions, management review meetings for changes in design and various associated implications as a result of design changes, internal audits, product realisation plans, traceability protocols, and updating of the approved supplier list in cases of severe non-conformance.

To ensure element c) above could be implemented, it was necessary to consider new structural fixing techniques and metallurgical compatibility all materials that could be substantiated in order to comply with our duty of care to provide a safe building in accordance with all codes and regulations. Integral to the design was the need to consider those OH&S management issues described above so that the design itself complemented the efforts to ensure safety in installation and safety in ongoing operation of the installed system. Such considerations now are described commonly by the term *safe design* and the practice recently has been promoted strongly by the ASCC in its published recommendations [64]. This publication refers specifically to building design and, while the recommendations are not intended for inclusion in the legislation, it is interesting to note the ever-increasing focus on linking safety into all facets of design.

Recommendations for Safe Design and Risk Limitation

As a result of this project and the observations made with regard to the increasing demands on designers to develop safe structures, it is recommended that:

a) Building designers should engage a wide range of professionals to increase substantially the knowledge brought to the design table. This will not only prove valuable in achieving a better end-result but, more importantly, the practice will do much to prove that, where specific practice is not prescribed in building codes and Standards, then the designer has complied with the legal requirement to engage expert opinion. The example learned from the present project is the outcome of the lack of involvement by material science experts in the original building design. Had materials science experts been consulted, then many of the materials compatibility problems that resulted in accelerated corrosion would not have occurred.

b) Building designers should begin to identify those components of buildings that will require periodic maintenance in order to maintain integrity for the whole design life of the building.
c) Following identification of those components referred to above, building designers should prepare maintenance recommendations for the building owners so that the components comply with the BCA's essential maintenance requirements.
d) Where periodic maintenance is required, ensure that safe design principles are used so that maintenance workers in the future of the building are not exposed to risky maintenance tasks that could be made safer and more convenient.

Engineers and designers must not experiment since human lives are at risk. According to Martin and Schinzinger [67]:

[*W*]*e suggest that engineering should be viewed as an experimental process. It is not, of course, an experiment conducted solely in a laboratory under controlled conditions. Rather, it is an experiment on a social scale involving human subjects*.

3.1.3 Project Management

The stage subsequent to that of design usually is the project management stage. The designer should specify on the drawings or list of specifications which are to be the basis of the construction project for subsequent contractors or project managers who will be responsible for organisation and execution of the entire project, which involves the purchase, fabrication, and installation of each component to be used. The ongoing maintenance, if required, also should be specified by a relevant accredited authority and this stage often is missed or not included in most designs and project management plans.

The handover from the designer to the contractor generally represents a large gap in communication. As a result of this, there may be a lack in conformance to specifications. This is the basis for attempts to assign the blame once litigation between the designer and the contractor or project management team occurs. It is in these instances that a system is required to ensure that not only the procedures and specifications are adhered to but also an inspection and audit are undertaken at certain intervals during the project. One such system is the implementation and use of ISO

9001:2000, which involves a quality management System (QMS); this is discussed in more detail in Section 3.1.5. This system, if adhered to and rigorous auditing is conducted at regular intervals, can prove to be very fruitful. It would be in the owner's interest to specify that these audits be conducted and checked against the ISO 9001:2000 QMS.

There is no doubt that the ultimate responsibility for the initial design and essential forewarning of additional precautions in engineering practice lie totally in the hands of the designer. In the present work, the designer is defined as the one who will be designing in terms of structural design, not in terms of the architectural design. Architectural design may be a prior conceptual design but does not take on the responsibility for the final structural detail. However, it is incumbent on the designer to take into account the aesthetics that are stipulated by the architect and/or owner. If the designer is not also the contractor, then he may not generally have control over the complete execution of the remaining project.

The present review highlights some of the most pertinent considerations for design and execution of projects for both owner and designer, who must consider carefully the construction of large masses of steel and other metals towering on high-rise buildings over the public.

There definitely is a gap in design knowledge when steel and aluminium are compared. The reason for this may be that structural engineers usually design in accordance with the general steel design codes and assume that aluminium will be applied according to the relevant codes; however, the codes for aluminium change so rapidly compared to those for steel that maintaining currency is a challenge. The ultimate distinction between the two metals is that, while steel can be considered more or less a constant, aluminium alloys are rapidly changing materials with more variations in their compositions and processing such that the standard of knowledge is unlikely to achieve the constancy of that of steel.

3.1.4 Professional Engineers' Practice Accreditation and its Relevance

The following two extracts have been taken from the Engineers Australia web site and they are reproduced for reference in the present work only [68] These describe the attributes of professional engineers as defined by Engineers Australia and the National Professional Engineering Register. Each recognises competence and excellence in the field.

Professional Engineers – Chartered Professional Engineer (CPEng)

Membership of Engineers Australia is offered in various grades. Membership denotes experience and recognition as an engineer and is a means by which purchasers of engineering services can determine the experience level of the practitioner. The Chartered title is exclusive to Engineers Australia and is based on competence. The title is offered at the professional engineer, engineering technologist, and engineering officer level. The title stands for the highest standards of professionalism, up-to-date expertise, quality and safety, capacity to undertake independent practice, and to exercise leadership within the engineering team. An engineer who is a member of Engineers Australia at the Chartered level is committed to maintaining the currency of their skills and knowledge and meeting established ethical standards. Purchasers of engineering expertise can be assured that Chartered Engineers are competent to be licensed in foreign jurisdictions and practise internationally.

National Professional Engineering Register – NPER

NPER is a simple, consistent, national database to which any person or organisation can refer when particular engineering and engineering related skills are required [68]. It identifies those persons whose academic qualifications, cumulative and current experience and competencies, and commitment to ethical conduct and continuing professional development are of the standard considered appropriate by the profession for independent professional practice. NPER is divided by areas of practice and registration in an area of practice on NPER is based solely on the demonstrated professional competence of the applicant. As with Chartered Engineers, engineers registered on NPER are committed to maintaining the currency of their skills and knowledge, meeting established ethical standards, and are competent to be licensed in foreign jurisdictions and practise internationally.

Continued Professional Development in Australia – CPD

Engineers Australia is a body that encourages professional engineers to undertake CPD activities in order to maintain and extend their knowledge, skills, and judgement [68]. Engineers Australia does not approve of CPD to be undertaken on an *ad-hoc* basis. In general, practitioners must confirm their involvement in 150 hours of continuing professional development over the period of 3 years. Continuing professional development activities must relate to the practitioner's area of practice. Compliance with this requirement is subject to periodic random audit.

Code of Ethics

All members of Engineers Australia are bound by a Code of Ethics [68]. The first tenet of the Code of Ethics obliges members to place the welfare, health, and safety of the community before sectional or private interests. Other tenets of the Code bind members to act with honour, integrity, and dignity and to be aware of the social and environmental consequences of their actions. The most secure protection for the community lies in the fundamental requirement of the Code that members must practice within the limits of their personal and professional competence and in the assurance that they will be subject to effective disciplinary action if they fail to observe that constraint. Engineers Australia's Code of Ethics and disciplinary procedures are another guarantee that Australian engineers are competent to be licensed in foreign jurisdictions and practise internationally.

3.1.5 ISO 9001:2000 and its Relevance

One tool that is likely to assist the client in achieving the aims of a project is to ensure that the designer, project manager, contractor, and others are working within a guided and disciplined framework that incorporates a QMS that is internationally recognised. In Australia, one such QMS, which is an integral part of one with the most stringent requirements, is in the aerospace industry. This QMS is ISO 9001:2000.

In today's global marketplace, serious and dedicated organisations are utilising ISO 9001:2000 as a means to provide a uniform QMS and to facilitate the design, development, production, and servicing of their management system to meet their customer's needs more effectively. In order for a company to be successfully accredited to ISO 9001:2000, companies need to have a solid awareness and demonstrated objective to meet the requirements of the Standard and to provide evidence of an effective management system. ISO 9001:2000 represents an international consensus on quality management practices, with the objective of ensuring that an organisation can achieve customer and regulatory quality requirements consistently. This Standard helps companies adopt internationally accepted good management practices, with the goal of helping them to improve the quality of their products and services while improving company operations. To be certified to the Standard, a company must implement a QMS that encompasses all of the company's activities, including:

a) Engineering drawings with all of the correct information
b) Updated, approved, and filed engineering drawings
c) Assessment design validation
d) Certifications
e) Corrective and preventative action reports
f) Internal auditing
g) Minuted meetings
h) Correct hiring and training
i) Customer interaction
j) Vendor management
k) Selection of approved suppliers and documentation of the reasons for selection of service/product and service delivery processes and procedures.

This focus on quality is supported by the commitment to values, customer focus, and continual improvement. Naturally, the aim of this Standard is not to detail a plan how to run a company but it is to provide a structure that can aid to *personalise* the company operations.

Accreditation reduces risk for business and its customers by assuring them that accredited bodies are competent to carry out the work that they undertake. Companies with accreditation to ISO 9001:2000 are required to operate at the highest standard and require the teams and suppliers that they select to comply with appropriate international Standards. ISO 9001:2000 certification extends to the manufacturing and service organisations in the regulated and unregulated industries. A few of these are as follows:

a) Aircraft and Spacecraft
b) Automotive
c) Marine Craft
d) Nuclear Fuel (Fission and Fissile Material)
e) Mining Products
f) Petroleum Products
g) Iron, Steel and other Metal Products
h) Glass and Ceramic Products
i) Water
j) Transportation and Logistics
k) Medical Devices
l) Optical Products
m) Software Development

Basic Outline of Perfect Engineering Pty. Ltd. Quality Procedure

The procedure adopted by Perfect Engineering Pty. Ltd. is applicable to all quality related records, including but not limited to the following:

a) Audit reports
b) Management review records
c) Corrective and preventive action records
d) Records of personnel training and induction
e) Calibration reports
f) Design approvals
g) Inspection and testing records
h) Product non-conformance reporting (NCR) and disposition records
i) As-built drawings
j) Subcontractor supplied documentation and records
k) Contract review records
l) Inspection and test plans
m) Quality plans
n) Delivery dockets

Some of the procedures for the handling of key records that are retained in order to meet the company's quality, statutory, and commercial requirements are as follows:

a) Access/security for some records restricted to management
b) Customer project files and confidential customer information retained in the archive cabinet, restricted to authorised personnel
c) Protection of electronic records using passwords
d) Disposal at the termination of the nominated retention time by suitable methods specified by the manager
e) Retention of important hard-copy records in the security of the main office, with restricted access

3.1.6 Retention Times for Quality Records

Table 3.1 summarises the record-keeping procedures and tenures for Perfect Engineering Pty. Ltd.

Table 3.1. Perfect Engineering Pty. Ltd. retention times for quality records.

Type	Records	Retention Period	Location	Accessed by
Commercial Records	Quotations	7 Years	Archive Cabinet	Administration & Management
	Tenders	7 Years	Archive Cabinet	Administration & Management
	Customer Orders	7 Years	Archive Cabinet	Administration & Management
	Purchase Orders	7 Years	Archive Cabinet	Administration & Management
	Invoices - Creditors	7 Years	Archive Cabinet	Administration & Management
	Invoices - Debtors	7 Years	Archive Cabinet	Administration & Management
	Payroll	7 Years	Archive Cabinet	Administration & Management
	Taxation	7 Years	Archive Cabinet	Management
	Customer Financial Information	Indefinite	Archive Cabinet	Management
Training Records	Staff	Indefinite	Archive Cabinet	Management
Inspection & Traceability Records	Customer Project File	Indefinite	Archive Cabinet	Administration & Management
	Incoming (Purchase Order)	7 Years	Archive Cabinet	Administration & Management
	Final (Packing Slips)	7 Years	Archive Cabinet	Administration & Management
Quality Systems Records	Audit Reports	7 Years	Archive Cabinet	Management
	Corrective Action Requests	7 Years	Archive Cabinet	Management
	Review Minutes	7 Years	Archive Cabinet	Management

3.2 Aircraft Design Life and its Relevance to Building Design

Researching in aircraft materials and the various associated forms of corrosion as a result of manufacture, installation procedures, and environment is an excellent starting point for any engineer interested in metal corrosion. Many of the findings in aircraft can be extrapolated to incidents involving metals in other fields, such as buildings. This is particularly the case for metals used on the façades of high-rise buildings and rooftops, which often are situated in severe environmental conditions and have certain wind load patterns in the vicinity. An aircraft is subjected to airborne contaminants and high winds when flying over oceans, sand in countries with deserts, and fluctuations in temperature in the range –70°C to 70°C [69]. Thus, it is worthwhile to examine how aerospace engineers implement their initial designs and future maintenance of metal components.

The problem-solving techniques applied by aerospace engineers benefit engineers in many disciplines as a result of the generous budgets allocated for resources and research. Many airline organisations operate using an ISO 9001:2000 QMS. The Boeing fleet has provided an immense amount of service data over the years and this has been used continuously to upgrade safety, durability, performance, maintenance, and production of new-generation airplanes [9]. Design documents for fatigue performance and damage tolerance were developed in the 1970s, resulting in reduced fatigue problems and structures more tolerant of damage. The success of these design documents prompted a major effort in the late 1980s to develop a complementary design document for corrosion prevention.

Figure 3.1 shows some of the typical causes and sources of corrosion, which are divided into the two main categories of manufacturer and operator [70]. The first potential source of corrosion is in the basic design process. Materials selection, finishes, and structural configuration can have a significant impact on the corrosion performance of an airplane. During the design phase, attention must be paid to the basic principles of corrosion-conscious design, such as the selection of corrosion-resistant materials, the avoidance of dissimilar metals in contact, crevices, stresses, sealing, use of corrosion inhibitors for structural durability, fluid drainage, and easy access to provide the airlines with the ability to inspect and maintain the structure economically.

Boeing's *Design for Corrosion Prevention* [70] is based on continuous materials and process development and tests by Boeing and suppliers as well as on the monitoring of corrosion improvements implemented on production airplanes. The data resulting from an increasingly mature and expanding fleet facilitate the continued assessment of corrosion prevention. The recommended guidelines, which give the key design elements over which a designer has control, help to ensure long-term corrosion control of airplane structures, airplane safety, and long life with minimal maintenance and re-work requirements.

The lifetime and maintenance requirements are affected significantly by the occurrence of corrosion. Most structural behaviour, *e.g.*, static strength and fatigue performance, can be predicted and validated accurately by analysis and testing. However, corrosion behaviour can be confirmed only by real-time exposure. Corrosion is a serious and costly problem that is not predictable or easily detectable in many instances. Airlines spend large amounts of time and money repairing corrosion, particularly in ageing airplanes. A greater concern is the insidious nature by which corrosion can degrade structure such that fail-safe and/or load-carrying capability may be lost unless the operator continually takes corrective action through an effective corrosion control program. Such concerns should impress upon the designer the great responsibility associated with designing for corrosion prevention. These considerations must be co-ordinated with many other design elements. The wealth of information Boeing has at hand from past experience has provided the information necessary to improve new designs and production models continually.

3.2.1 Overview of Typical Aircraft Corrosion Modes

A diverse range of materials comprise the modern aircraft of today, and these have special design and maintenance constraints. Generally speaking, the aerospace industry has stringent guidelines on the construction of aircraft, with particular attention paid to selection of materials and a detailed list of associated problems and solutions. In fact, the aerospace industry may be considered to be one of the strictest industries in assuring compliance with one of the highest standards ever set. One of the most widely used materials existing in a typical aircraft is aluminium alloys owing to their high strength-to-weight ratios. Fortunately, there is an established body of literature on failures associated with aluminium alloys, including and the reasons for their corrosion and subsequent failures.

Crevice corrosion occurs when a corrosive fluid enters and is trapped between two surfaces, such as a joint, a delaminated bondline, or under a coating [4,7,9,71-75]. When unchecked, both pitting and crevice corrosion can develop readily into exfoliation corrosion or intergranular stress corrosion cracking. Exfoliation corrosion is a form of intergranular corrosion where corrosion attack occurs along the grain boundaries of elongated grains, causing a leaf-like (de-lamination and swelling) separation of the metal grain structure [76]. This form of corrosion often initiates at unprotected end grains, such as at fastener holes and plate edges and has a high vulnerability to exfoliation since the holes provide a pathway for the electrolyte to the most susceptible short transverse endgrain of the alloy [76].

Pitting and crevice corrosion are the most common forms of corrosion in the 2000 and 7000 series aluminium alloys [5,9]. These are also the principal aluminium alloys used in aircraft construction. Pitting corrosion produces deterioration of the airframe structures in localised areas and can have high penetration rates [4,9]. Pits often create stress concentrations that can reduce the fatigue life of a component. Crevice corrosion, by itself, is more destructive than pitting corrosion [4]. The detrimental aspect with crevice corrosion is that, since the corrosion takes place at the base of the crevice, it cannot be seen as it happens.

Grain boundaries have higher energies than within grains and so intergranular stress corrosion cracking occurs when stresses are applied perpendicular to the susceptible grain boundaries [4,7,9,70,77]. More so than pitting and crevice corrosion, the susceptibility to exfoliation corrosion and intergranular stress corrosion cracking depends on alloy type, heat treatment, and grain orientation. Another common form of corrosion is fretting corrosion, which occurs when two surfaces rub at high frequency and low amplitude in the presence of a corrosive environment. Galvanic corrosion occurs when dissimilar metals that are not close in the galvanic series are in direct contact. Isolation of the different metals, which can be accomplished by proper design and assembly, can prevent both forms of corrosion from occurring.

More detail regarding the specific modes of corrosion mentioned above will be illustrated subsequently.

3.2.1.1 Crevice Corrosion Most Common in Aircraft

Crevice corrosion is a localised form of corrosion in which moisture is retained in the crevice geometries for prolonged periods of time, thereby ensuring localised attack in specific areas with reduced oxygen potential in their vicinities (see Sections 3.5.3.3 and Figure 3.17). Crevice corrosion damage in the lap joints of aircraft skins has become a major safety concern, particularly after the Aloha Airline incident. Corrosion damage to aircraft fuselages is an example of atmospheric corrosion. In 1988, a 19 year old Boeing 737 aircraft, operated by Aloha, lost a major portion of the upper fuselage near the front of the plane in full flight at 7,300 metres altitude [78]. The extent of damage is shown schematically in Figure 3.2. The original fabrication process utilised cold bonding and so fasteners were used to maintain surface contact in the joint. This allowed the bonding adhesive to carry/transfer load between skin panels. The adhesive was breaking down and so corrosion in the joints resulted in disbonding, causing the fasteners to carry loads for which they were not designed. The repeated pressurisation cycles led to the formation of cracks at the fastener holes. The growth of the existing and undetected cracks in the fuselage skin was accelerated by the presence of corrosion in the joints and was due primarily to an inefficient and an ineffective airline maintenance program. Therefore, an additional reason for this catastrophic failure included inexperienced inspectors and knowledge. This particular airliner flew almost exclusively on short runs between Hawaii's islands, so the aircraft was subjected extensively to metal fatigue since the body of a plane goes through a stressful pressurisation cycle on every flight. The cabin is pressurised after takeoff so that passengers can breathe an atmosphere close to that at sea level even though the air outside the plane becomes progressively thinner with altitude; the cabin is depressurised as the plane descends for landing. The Aloha planes also have a high exposure to corrosion because the airports that they use are near saltwater.

As a result of this, there was evidence in this particular aircraft of multiple site-fatigue damage, leading to structural failure [78]. The National Transportation Safety Board (NTSB) investigation report issued in 1989 indicated that the catastrophe was due to the failure of the operator's maintenance program to detect corrosion damage [79]. Earlier in 1981, a similar aircraft had suffered an in-flight break-up with more than one hundred fatalities. Investigations pointed to corrosion-accelerated fatigue of the fuselage skin panels as the failure mechanism [80].

The three basic types of aircraft fuselage lap splices are shown in Figure 3.3. A particular aircraft design normally incorporates two or three different types of splices in the fuselage. The fuselages of commercial aircraft typically are constructed from 2024 T3 aluminium alloy [11] and figure 1.1. The lap joints are riveted and sealed by some manufacturers, whereas others employ a combination of riveting and adhesive bonding [81,82]. Corrosion damage in the crevice geometry of the lap joints is highly undesirable. Fatigue cracking in the Aloha case was not anticipated to be a problem, provided the overlapping fuselage panels remained firmly bonded together [83].

Corrosion processes in this crevice geometry and the subsequent build-up of voluminous corrosion products inside the lap joints lead to pillowing, a dangerous condition whereby the overlapping surfaces are separated, as shown in Figure 3.4. The prevalent corrosion product identified in corroded fuselage joints is aluminium oxide trihydrate, with a particular high volume expansion relative to aluminium, as shown in Figure 3.5. The build-up of voluminous corrosion products also leads to an undesirable increase in stress levels near critical fastener holes. Rivets have been known to fracture due to high tensile stresses resulting from pillowing [84]. Corrosion damage on commercial and military aircraft, such as the pillowing in lap splices described above, is becoming a major concern in the context of the global ageing aircraft problem.

At the turn of the century, 64% of the U.S. commercial carrier fleet were least 20 years old [80]. In 1970, the average age of this fleet was under 5 years. It is well known that the costs and safety risks associated with aircraft corrosion damage are the highest in ageing fleets. Lengthy and detailed inspection and maintenance procedures, as part of periodic checks and overhauls, represent a substantial portion of the corrosion costs.

3.2.1.2 Accelerated Corrosion in Rivets in Ship Hull of *Titanic*

Robert Baboian is a corrosion consultant and he has concluded that the *Titanic* was held together by 3 million rivets made with a type of iron that was different from that of the hull plates [85]. He states that, since the ship was finished, it sat in seawater for a year until the inside was furnished. The dissimilar metals of the hull and rivets in connection with the electrically conductive seawater may have created a circuit that slowly corroded and weakened the rivets. It was assumed that the *Titanic* collision with the iceberg could have popped the weakened rivets, which would explain a clinking sound reported by survivors. The factors which most probably caused the failure and subsequent sinking of the *Titanic* are summarised as follows:

A) During the year in seawater, there is a strong possibility that stray currents from d.c. equipment caused accelerated corrosion.
B) The rivet iron was different from that of the hull plate iron by design. The rivet iron needed to be malleable at high temperatures and therefore contained a higher level of slag inclusions.
c) During the year at dockside, corrosivity of the rivet iron therefore could have been higher than that of the hull plate iron. Galvanic corrosion of the rivet iron is likely during that period of time.
d) Photos and video taken by Robert Ballard during his 1985 and 1986 expeditions to the *Titanic* show preferential corrosion of the rivets in some areas.
e) Inspection of the *big piece* that was retrieved from the ocean bottom also shows this same preferential corrosion in some areas.

All of this evidence points towards weakening of the hull/rivet structure, thereby enhancing the rivet-popping mechanism that caused the *Titanic* to sink.

The high concentrations of slag made the rivets brittle at low temperatures and prone to fracture. Further, there is evidence of shortages in skilled labour during construction. At the time, steel rivets were replacing iron rivets due to the former's higher strength and the availability of machines to install them. However, a shortage of skilled labour and the use of inferior rivets appear to be associated causes for the sinking of the *Titanic*.

3.2.1.3 Various Types of Failure Associated with Rivets

Amongst the oldest types of fasteners are solid rivets and these consist of a shaft and a head [86]. The head is deformed at one end with either a hammer or rivet gun. The head may be either rounded or countersunk and, for this reason, access is required from both sides of the structure. Solid rivets are used in applications where high safety is required, such as in structural parts of aircraft, bridges, cranes, and buildings. Solid rivets in aircraft typically are made of aluminium, titanium, and nickel alloys. Steel rivets are used in bridges, cranes, and buildings. Blind rivets are used in applications requiring only one side to be accessed. These rivets are tubular with a mandrel through the centre and they are inserted through a hole drilled to connect the parts together. The mandrel is drawn into the rivet, expands the blind end by flaring against the reverse side, and then breaks off at the designed break point. The mandrel thus is encapsulated at the blind side and the remainder of the mandrel is dislodged. Blind rivets usually are not used in critical structural applications owing to their low load-carrying capabilities compared to those of solid rivets.

However, with both types of rivets, the key information lies in the actual materials' mechanical and chemical properties. The major disadvantage with blind rivets is that they have a tubular cross-section that obviously is smaller than that of a solid rivet. This means one blind rivet is not as strong as one solid rivet of the same diameter. Therefore, compared to solid rivets, design with blind rivets requires the use of:

a) Greater number
b) Larger diameter
c) Stronger material

A rule of thumb is that the number of blind rivets needs to be increased roughly in the proportion of five blind rivets for three solid rivets of the same diameter [86].

The literature for blind rivets is not as exhaustive as those for solid rivets and bolted joints. However, it is reasonable to assume that, under ideal conditions, design considerations for blind rivets and solid rivets or bolts are effectively the same, provide the preceding points are factored in. That is, the design of joints and the calculations of stress distribution are discussed using a generic approach.

In a riveted joint, a rivet is forced into a hole connecting two plates or beams [86]. Although aircraft use unheated rivets, when heated rivets are used, as the rivet cools, tension develops in the rivet and the plates are forced together. In bolted joints, high-strength bolts are inserted into connecting holes between plates or beams and then tightened to an initial percentage (typically ~70%) of the allowable bolt tensile strength.

For bolts, the hole generally is slightly larger than the diameter of the bolt and this is taken into account.

In the present work, the following assumptions are made in the calculations of rivet strength [86]:

a) The rivets and bolts completely fill the connecting holes.
b) The applied loads are carried equally by the rivets or bolts.
c) The rivet or bolt shear stress is distributed uniformly over the cross-sectional area.
d) The tensile load carried by the plate also is distributed equally across the plate material.
e) Frictional stresses are negligible.

The first four of the preceding assumptions do not affect the stress calculations significantly [86]. However, it is known that there can be significant friction between plates riveted or bolted together. This friction may represent a significant component of the load applied to a joint. Although some countries, such as France, take the friction into account in stress calculations [87], this is ignored in the present case on the basis of small relative degrees of movement of the components.

There are two basic types of riveted and bolted joints, these being lap joints and butt joints [87]. The present work considers only lap joints since butt joints were not used. A lap joint is shown in Figure 3.6. The distance between the rivets within a row in a riveted or bolted joint pattern is known as the *pitch*. The distance between rows in a riveted or bolted joint pattern is known as the *back pitch*, *transverse pitch*, or *gauge*. The first row (row 1) of a pattern is the row that is closest to the applied load. As a general guideline for steel or aluminium plates, the minimum pitch is three times the diameter of the rivet or bolt and the minimal edge pitch (distance from the nearest rivet to the edge) is one and half times the rivet or bolt diameter.

Joint Failure

There are a number of ways in which a riveted (bolted) joint may fail. There are basically three main modes of failure to be considered, and are as follows:

a) *Rivet Shear:* As shown in Figure 3.7, which gives a side view of a lap joint, the rivet or bolt area between the two main plates is in shear [87]. The formula for the strength of a joint in rivet shear is obtained by using the definition of the shear stress, which is the force parallel to the area in shear divided by the area. Thus, if the cross-sectional area of the rivets or bolts is multiplied by the allowable shear stress for the rivet or bolt, then the shear strength is obtained.

$$P_{rivet\ shear} = N\,(\tfrac{1}{4}\cdot\pi d^2)\,\tau_{all}$$

where:

$P_{rivet\ shear}$ = Shear strength of riveted or bolted system
N = Number of rivets or bolts in shear (in a lap joint or in a butt joint with one cover plate)
π = 3.1415
d = Diameter of rivet or bolt
τ_{all} = Allowable shear stress for rivet or bolt

b) *Rivet/Plate Bearing Failure:* This is compression failure of either the rivet or the plate material behind the rivet.

As shown in the middle diagram in Figure 3.8, when the top main plate is considered, it is pulled into the fixed rivet [87]. This puts the plate material behind the rivet into compression and, if the load is large enough, the plate material may fail in compression. From the rivet's perspective, the plate is pulled into it and this puts the rivet into compression. Again if the load is large enough, the rivet material may fail in compression. Which material fails first in compression depends, of course, on the maximal allowable compressive stress for the rivet or bolt and plate material.

To determine the load that will cause failure, again, the area under shear stress is multiplied by the stress. In this case, it is common practice to take the area in compression as the vertical cross sectional area of the rivet, as shown in Figure 3.9, for both the area of the rivet in compression and the area of plate in compression.

$P_{bearing} = N(d \cdot t)\sigma_{all(c)}$

where:

$P_{bearing}$ = Compressive strength of riveted or bolted system or plate
N = Number of rivets or bolts in compression
d = Diameter of rivet or bolt
t = Thickness of plate
$\sigma_{all(c)}$ = Allowable compressive stress for rivet or bolt or plate

c) *Net Section Failure:* This is a tensile failure of the plate material normally at the rivet row positions [87]. That is, the plate will fail first where the holes are in the plate. As is shown in Figure 3.10, if the plate material is cut at rivet row 1, the plate material is in tension. To determine the applied load that the plate can carry before it would fail in tension, the area under tension is multiplied by the allowable tensile stress. This area is the cross-sectional area of the plate, which, if solid, would be the width of the plate times the thickness of the plate ($A = w \cdot t$). However, since the plate is cut at rivet row 1, the diameter of the rivet must be subtract from the width of the plate (since the area of the plate is reduced by the rivet holes).

$P_{row1} = (w - d \cdot n)\sigma_{all(t)}t$

where:

P_{row1} = Tensile strength of plate at rivet row 1
w = Width of plate
d = Diameter of rivet
n = Number of rivets in row
$\sigma_{all(t)}$ = Allowable tensile stress on rivet or plate
t = Thickness of plate

The formula for net section failure at rivet rows beyond row 1 has to be modified somewhat owing to the fact that the rows beyond row 1 do not carry the entire load since some of the load is transferred to the second plate.

There are several other ways that joints may fail, including shear-out failure, which may occur if a rivet is placed too close to the end of the plate and the plate material behind the rivet fails in shear [87]. If proper placing of rivets is maintained, this mode is not normally a problem. Therefore, if the strength of a joint is to be determined, the load needs to be calculated using the three main modes of failure. The lowest load that causes the joint to fail is considered to represent the strength of the joint.

Referring to Figure 3.6, calculation of the shear failure involves all nine rivets [87]. Similarly, calculation of the bearing failure also involves all nine rivets, although failure will occur at the load commensurate with either the rivet or plate allowable stress, whichever is the lower. The load for bearing failure will be higher than that for shear failure only if the plate compressive load is lower than that of the rivet compressive load. Net section failure involves plate failure in tension. At row 1, where there is only one rivet, the plate will fail here if the tensile properties of the plate are less than those of the rivet, but its failure load will be intermediate between that of shear and plate bearing failure.

The calculations then become more complex as rows 2 and 3 are approached [87]. The reason for this is that rows 1 and 2 carry different loads from each other. Row 2 does not carry the entire load since the load is transferred to the bottom plate by the rivet in row 1. Since there are nine rivets in the pattern and it is assumed that the rivets equally share the load, then 1/9 of the load is transferred to the bottom plate. Therefore, row 2 carries 8/9 of the load, which suggests that the load to failure for row 2 will be only slightly lower in row 1. Finally, net section failure in row 3 is such that that the previous rows 1 and 2 transfer 3/9 of the load to the bottom plate, leaving 6/9 of the load for row 3. The load to failure in tension here will be higher than that for rows 1 and 2. In summary, the lowest load to failure is for the nine rivets in shear, followed by row 2 (2 rivets), which is higher. The next highest load to failure is row 1 (1 rivet) and the highest value for load to failure is row 3 (3 rivets).

Since the riveted plate has holes in it, it is inevitable that the characteristics of the plate are changed and the strength is compromised [87]. The area of the plate multiplied by the given material stress yields load greater than that calculated with the nine holes. If the load of the plate without holes is divided by that of the plate with holes, then this will be the ratio of efficiency, *i.e.*, joint strength/plate strength as a percentage. This will provide an indication of the actual plate strength the plate with holes will yield.

Therefore, the simplified assumption that all of the rivets carry equal loads is incorrect and so the joint may fail in several ways, such as plates failing through a line of rivet holes or with all the rivets failing in shear [86,88].

3.2.1.4 General Rivet Properties and Recommended Installation Procedures

The following procedures and recommendations for blind rivets are from the supplier of aerospace blind rivets [86]:

Parts generally fastened by rivets are flat parallel surfaces, where both the rivet clinch and head provide adequate space for the rivet driver during clinching. When a blind rivet is set, a self-contained mechanical feature expands the rivet's shank, securing the parts being joined. These rivets are most often installed in joints that are accessible from only one side. Blind rivets also are used to simplify assembly, improve appearance, or decrease cost where both sides of the joint are accessible. Blind riveting offers portability, which is valuable for large assemblies. Blind rivets should be used where:

a) Fastener removal is not necessary for maintenance.
b) High vibration exists.
c) A temporary fastener is needed.
d) Uniform clamping is desirable.
e) Repairs to fasteners for field use by untrained personnel are needed.

Diameter: This is based on the measurement of a blind rivet's shank, usually in 0.030-0.125 inch (0.762-3.175 mm) increments. Grip range is the range of material thickness that can be joined properly with a blind rivet of a given length. Manufacturers furnish specific recommendations.

Design Considerations: Joint design factors that must be known include allowable tolerances of rivet length versus assembly thickness, type and magnitude of loading, hole clearance, and joint configuration.

Tools for Installation: Power tools install most rivets efficiently. Manual installation tools can be used efficiently with little or no training. Blind rivet joints usually are loaded in shear, which the rivets can support better than tensile loading. Rivets subject to vibration perform more efficiently if manufacturer-specified minimal hole clearance is maintained. Materials can be as thin as 0.020 inch (0.508 mm) with some rivets. If one component is of compressible material, rivets with extra-large head diameters should be used on that side of the application to distribute the load over a larger area. Originally for fastening applications where only one side of the workpiece is accessible, these rivets often are used in other applications to reduce assembly time. Break-stem blind rivets consist of a body and mandrel. To set the rivet, the placement tool engages the mandrel and provides an axial pull. This causes the mandrel head to upset the tail of the rivet, forming a blind head. When the mandrel reaches its designed tensile load, it breaks at a predetermined point on its shank. The portion in the tool is then discarded.

Rivet Advantages: Some advantages of rivets, compared to threaded fasteners, include:

a) Lower initial rivet cost
b) Lower labour costs
c) Shorter machine times to set the rivets in parts
d) Joinability of dissimilar materials of various thicknesses
e) Availability of a variety of finishes ,such as plating, parkerising, and painting
f) Ability to serve as fasteners, pivot shafts, spacers, electric contacts, stops, and inserts.
g) Ability to fasten parts that are painted or have other finishes

Rivet Disadvantages: Tensile and fatigue strengths of rivets are lower than bolts of comparable diameter and machine screws with nuts. The allowable tensile loads of blind rivets of certain diameter can exceed 2300 lbs (1045 kg). Rivets are fasteners that are the least susceptible to vibration loosening. This is the reason why aircraft manufacturers rely heavily on rivets. While riveted joints are weatherproof, they are not normally sealed against air or water under pressure. A sealing compound, rivet coating, or special washer may be used but at added cost. Rivets produced in volume are not made normally with the same precision as screw-machine parts. Normal tolerances on major dimensions are 0.005 inch (0.127 mm), although closer shank-diameter tolerances can be obtained. Rivets should not be used where dimensional variation must be maintained as low as 0.001 inch (0.025 mm).

3.3 Commercial Building Design Life

The building construction industry is one of Australia's largest industries and this applies to the remainder of the world. Buildings also account for 46% of the energy use in Europe and the built environment is the largest consumer of materials resources [89,90]. For example, in the UK, 70 million tonnes of building materials go to waste each year. The environmental impact of construction, use, and demolition of the built environment is enormous. Much of this is due to ineffective communication in the building chain, thereby lowering quality, increasing costs, and requiring unsustainable resource and energy consumption.

Consequently, 75% of the world's energy resources are consumed by the built environment, with its complex matrix of buildings, activities, and transportation [89,90]:

a) 36-45% of a nation's primary energy consumption is used in buildings.
b) 40% of the annual raw material consumption (by weight) is used in building construction.
c) 20-26% of landfill waste originates from building construction, renovation, and demolition

Designers and other decision makers require service life planning as a tool to help aid in optimisation of resource use by ensuring that the building will last for the lifetime that the building user wants without incurring large unexpected expenditure [18,89-91,]. This means that unnecessary wastage of inappropriate material must be minimised and consideration of the environment should be a pertinent factor in the design. After all, the main aim of service life planning is to ensure that the design is capable of lasting for the specified period. The design life is the number of years that the building users require the building to last. The specified length of time that e building must last ultimately will be in the hands of the designer, who also has to ensure that the design will allow it to be functional until the end of its life. As mentioned before, this must take into consideration a number of performance requirements, including functionality, environmental impact, and cost over the specified design life.

3.4 Product Life Cycle Assessment

When deciding on the design life of a building, many important issues must be considered and integrated carefully in the design. One very basic yet extremely important aspect is that the overall cost of building materials may be considered from the point of view of a materials life cycle [91]. As shown in Figure 3.11, this includes the extraction of raw materials from the earth, various stages of production or manufacture, fabrication and installation, gradual degradation over time, demolition, and its final removal, possibly to landfill. All of these processes individually or collectively consume energy and add pollutants to the environment, including water and air. Also, raw materials extraction equates to earth depletion and this can be mitigated partially if materials are recycled.

The embodied energy of a material represents the energy expended in its production, as mentioned above [91]. The chart as shown in Figure 3.12 compares the embodied energies of virgin materials *versus* those of recycled materials. When a material is recycled, embodied energy is lower because the energy necessary for extraction is eliminated and the energy consumed in manufacture is reduced somewhat, depending on the material. For example, this illlustration shows that the embodied energies of virgin concrete and recycled concrete are virtually the same, whereas the production of aluminium is highly energy intensive while the embodied energy of recycled aluminium is much lower. It may be noted that the embodied energy of recycled steel is almost exactly the same as that for aluminium.

Overall, building design and construction are considered to involve very complex and detailed management of people and resources, especially in the commercial sectors, where numerous practices dictate the overall construction. Not only is there a requirement to stay within budget and time but, more importantly, there is an obligation to observe human and environmental safety practices. Generally, large and complex projects require a certain re-direction of resources and individuals in order to achieve the desired outcomes. It is expected or assumed that, once the contractor has been approved, he in turn will choose the approved subcontractors, suppliers, vendors, and teams to carry out the requirements of the project. There are several variables in which the probability of some adverse incident may occur in the building in the future owing to the incorporation of non-compliant procedures and non-compliant materials. This is likely to be a result of one or more of the following five very basic areas:

a) Inappropriate design
b) Budget constraints
c) Inappropriate contractors
d) Incorrect material
e) Incorrect workmanship

The client specifies the requirements of the project, its expected life cycle, and its overall budget. Based on these parameters, the initial step is in the design, which then relies on the services of additional teams, including architect, structural engineer, project manager/contractor, fabricator/installer, and others.

3.5 Cost of Corrosion

The costs attributed to corrosion damages of all kinds have been estimated to be of the order of 3-5% of industrialised countries' GNPs [8]. In 1978, metallic corrosion was estimated to cost over $300 billion *per annum* in the US alone [92]. As much as one-third ($100 billion *per annum*) of this loss is avoidable and could be saved by the broader application of corrosion-resistant materials and the application of the best anti-corrosive practices, from design through to maintenance.

According to the SSINA:

The staggering present cost of corrosion to the U.S. economy could be sharply reduced by wider application of longer-lasting corrosion-resistant materials like stainless steel. Material selection and substitution in the wide range available today should be a major commitment, and a primary aim should be to assure less maintenance and better total life cycle costs.

3.5.1 Determination of Cause of Corrosion Failure

A prominent feature in corrosion failures is that subsequent investigations are required to determine both the reason for failure and the most appropriate remedial action. Failure analysis can be extremely complex, especially if the initial groundwork in identifying the cause of failure is not acted upon immediately. This is analogous to a murder scene, where the information must be gathered as soon as possible so that as many pieces of evidence in the puzzle are included to form a complete diagnosis of the cause of incident. The fewer the number of missing items of evidence, the easier it is to extrapolate existing information and form a reasoned conclusion based on the existing information, experience, and/or relevant literature.

3.5.2 Basic Metallurgical Factors that Contribute to Corrosion

A definition of corrosion is the actual process of surface degradation or deterioration of metals or related materials [74]. The process begins with the metal losing both electrons and ions, thereby providing them to the surrounding environment, such as an electrolyte. The metal ions that have been provided by the metal either dissolve in the electrolyte or combine with ions of the electrolyte to form a surface deposit.

A metal that loses its electrons (oxidation) is termed the *anode* [7]. The metal that gains electrons (reduction) is termed the *cathode*, provided there is an electrical connection between the two metals for electron transfer. The above three factors (anode, cathode, and electrolyte) must be interconnected and act simultaneously if corrosion is to occur. The fourth requirement is that the anode and cathode must be in physical contact to allow transfer of electrons. If only one of these factors is missing, then corrosion cannot occur, as when the cathode reactants are depleted, the anode products are saturated, or the electrical connection is interrupted.

Corrosion can be also considered on a microstructural level. Each phase present in a metal is comprised of a certain composition and structure and so each phase has its own electrode potential. Thus, corrosion may occur when the anode and cathode sites exist in two-phase alloys when the metals are exposed to an electrolyte. This will be discussed in more detail in the subsequent sections. The main factors that affect corrosion due to microstructural changes and stresses in metals are described briefly.

Heat treatment may affect the corrosion rate by altering the microstructure of the metal. For instance, certain steels, which are in their hardened condition, such as quenched steel, develop certain microstructures depending upon their composition [93]. Even a single phase has a certain corrosive rate because, in some instances, the grain boundaries may act as the anode and the grains act as the cathode. If the temperature is increased, then some phases may coalesce, thereby reducing the number of grain boundaries associated galvanic cells and so the corrosion. However, while grain boundaries usually are anodic, they may act as cathodic in other cases.

In aluminium alloys, when only a single phase is present, the corrosion rate is low [94]. However, the precipitation of a second phase enhances corrosion. When these fine precipitates agglomerate in aluminium alloys, the corrosion rate decreases markedly but not to the same level as a single phase.

Also, stress in metals affects the corrosion rate significantly. In general, metals that have been cold worked have more highly stressed areas than annealed metals. This results in more rapid corrosion of the former.

In summary, for corrosion to occur, the requirements are a difference in electrical potential between the anode and cathode; the presence of an electrolyte, which usually is water or condensation, especially when contaminated with chloride salts; and mutual contact between the metals.

3.5.2.1 Wet Corrosion

Ashby and Jones [73] describe the loss of material by oxidation through two different conditions, dry and wet. Dry conditions involve mild corrosion and wet conditions enhance corrosion. For instance, steel corrodes very quickly in water and this is an example of wet corrosion. Aerated water encourages iron atoms (see Figure 3.13) to pass into solution and is described as follows:

In the presence of water, iron will dissolve and provide Fe^{++} ions to the solution, leaving behind two electrons ($2e^-$) [73]. This is the anodic reaction. These electrons then are conducted through the metal to a place where oxygen reduction can take place to consume the electrons. This is the cathodic reaction. This reaction generates hydroxide ions (OH^-), which then combine with the iron ions (Fe^{++}) to form a hydrated iron oxide, $Fe(OH)_2$. Instead of forming on the surface, which may give protection, it often forms in the water, giving no protection.

Voltage Difference

The voltage difference acts as a driving force for wet corrosion because it involves the flow of electrons (see Figure 3.14) [73].

At the cathode: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

The metal becomes positively charged as the oxygen converts to hydroxide and, when the voltage reaches +0.401 V, the reaction stops.

At the anode: $Fe \rightarrow Fe^{++} + 2e^{-}$

In each case the number of electrons produced equals the number of valence ions [7].

Iron ions form and, as a result of leaving behind electrons in the metal, the voltage of decreases until it reaches –0.440 V, at which point the reaction stops [73]. If the cathode and anode are physically connected, electrons flow from one electrode to the other, the potentials fall and both reactions start again. The reaction driving force is 0.440 V – (–0.401 V) = 0.841 V.

There are three points to make:

a) The greater the driving force for oxidation, the more the potential for oxidation.
b) The anode corrodes in a bi-metal situation. That is, the metal that is anodic (which has a larger negative corrosion voltage) will corrode. For instance, in a copper/zinc combination, the zinc is the anode and therefore it corrodes. In the iron/zinc combination, the zinc is the anode and so it corrodes. However, in a magnesium/zinc, combination, the magnesium is the anode and it corrodes.
c) Corrosion takes place more easily in dilute solutions.

Further examples of the preceding are given in Section 3.5.3.

One way of avoiding galvanic corrosion is to place a non-conducting layer between the two metals so that electrons are not able to flow from the anode to cathode [73]. The presence of a protective oxide film also can change affect the situation. For example, in pure water aluminium is stable because the resultant film is protective. In seawater aluminium corrodes rapidly because the chloride ion tends to break down this film. Figure 3.15 shows the rate of metal loss for various metals in pure water.

3.5.3 Typical Modes of Corrosion

3.5.3.1 Galvanic Corrosion

Galvanic corrosion is where two metals have different electrode potentials, with one being anodic and the other being cathodic [95-97]. The anodic reaction (*viz.,* corrosion) will take place at the more electronegative metal while the cathodic reaction will take place on the less electronegative metal. This is a localised mechanism by which metals can be preferentially corroded. This form of corrosion has the potential to attack junctions of metals or regions where one construction metal is in contact with another. Frequently, this condition arises because different metals are more easily fabricated into certain forms, where one item may be required to be extruded from aluminium and another item is typically is made from stainless steel owing to its strength and abrasion resistance. Galvanic corrosion is inevitable in this instance since the aluminium is considered as anodic and the stainless steel is considered as cathodic.

Three conditions must exist together for the galvanic corrosion to take place. The following three conditions are as follows [96]:

a) The galvanic or electromotive series ranks metals according to their potential, shown in Table 3.2. These data can be used to determine that the anodic or active metals at the negative end of the series, such as magnesium, zinc, and aluminium alloys, are more likely to be attacked than those at the cathodic or noble metals at the positive end of the series, graphite and platinum [96]. The critical point is the difference in potential of the two materials being considered as a joined pair. A difference of hundreds of millivolts is likely to result in galvanic corrosion but only a few tens of millivolts is unlikely to be a problem.
b) The two different metals must be in electrical contact with each other. This is very common as the two metals may be bolted, welded, clamped, riveted, or even just resting together in contact.

Table 3.2. Galvanic series in flowing sea water, showing voltage differences between various alloys [96].

GALVANIC SERIES
In Flowing Seawater

Alloy		*Voltage Range of Alloy vs. Reference Electrode**
Magnesium	**Anodic or Active End**	-1.60 to -1.63
Zinc		-0.98 to -1.03
Aluminum Alloys		-0.70 to -0.90
Cadmium		-0.70 to -0.76
Cast Irons		-0.60 to -0.72
Steel		-0.60 to -0.70
Aluminum Bronze		-0.30 to -0.40
Red Brass, Yellow Brass, Naval Brass		-0.30 to -0.40
Copper		-0.28 to -0.36
Lead-Tin Solder (50/50)		-0.26 to -0.35
Admiralty Brass		-0.25 to -0.34
Manganese Bronze		-0.25 to -0.33
Silicon Bronze		-0.24 to -0.27
400 Series Stainless Steels**		-0.20 to -0.35
90-10 Copper-Nickel		-0.21 to -0.28
Lead		-0.19 to -0.25
70-30 Copper-Nickel		-0.13 to -0.22
17-4 PH Stainless Steel †		-0.10 to -0.20
Silver		-0.09 to -0.14
Monel		-0.04 to -0.14
300 Series Stainless Steels ** †		-0.00 to -0.15
Titanium and Titanium Alloys †		+0.06 to -0.05
Inconel 625 †		+0.10 to -0.04
Hastelloy C-276 †		+0.10 to -0.04
Platinum †	**Cathodic or Noble End**	+0.25 to +0.18
Graphite		+0.30 to +0.20

* These numbers refer to a Saturated Calomel Electrode.
** In low-velocity or poorly aerated water, or inside crevices, these alloys may start to corrode and exhibit potentials near -0.5 V.
† When covered with slime films of marine bacteria, these alloys may exhibit potentials from +0.3 to +0.4 V.

c) The metal junction must be bridged by an electrolyte. An electrolyte is simply an electrically conducting fluid. Almost any fluid falls into this category, with distilled water as an exception. Even rain water is likely to become sufficiently conducting after contact with common environmental contaminants. If the conductivity of the liquid is high (a common example is seawater), the galvanic corrosion of the less noble metal will be spread over a larger area; in low conductivity liquids the corrosion will be localised to the part of the less noble metal near the junction.

When a galvanic couple forms, one of the metals in the couple becomes the anode and corrodes more quickly than it would if in isolation; the other metal becomes the cathode and corrodes more slowly than it would if in isolation [96]. However, when contact with a dissimilar metal is made, the corrosion rates will change, where corrosion of the anode accelerates and corrosion of the cathode will decelerate or even stop. Since the electrolyte in environments near the ocean contain salt, it is appropriate to examine the seawater galvanic series, which is given in Table 3.2, in order to predict which metal will become the anode and how rapidly it will corrode.

The seawater galvanic series is a list of metals and alloys ranked in order of their tendency to corrode in marine environments. If any two metals from the list are coupled together, the one closer to the anodic (or active) end of the series will be the anode and thus will corrode more quickly, while the one toward the cathodic (or noble) end will corrode more slowly.

For example, an aluminium alloy, which has a voltage range between –0.70 to –0.90 V (an average of –0.80 V), coupled to a lead, which has an average voltage of –0.22 V, will result in an aluminium anode and lead cathode, with a voltage difference of 0.58 V [–0.80V – (–0.22V)]. The voltage difference and the ratio of the surface areas of the anode and cathode are the major factors that affect the severity of galvanic corrosion [96]. Corrosion of the anodic metal is both more rapid and more damaging as the voltage difference increases and as the cathode area increases relative to the anode area.

The effect of the cathode-to-anode area ratio, C/A, is illustrated in Figure 3.16 for a rivet in a plate. In both couples A and B, aluminium is the anode and stainless steel is the cathode [96]. The C/A in couple A shows that the aluminium rivet is relatively small, which gives a large C/A. In couple B, the situation is reversed, where the stainless steel rivet is small, and so the C/A is small. Corrosion of the aluminium rivet in couple A will be severe. Although the potential difference is the same in both instances, the corrosion of the couple with the smaller C/A will be much less owing to the larger cathodic material.

The simplest means of reducing galvanic corrosion are as follows [96]:

a) All parts should be made of the same material or a non-metallic and non-absorbent insulator should interpose the two dissimilar metals to prevent current.
b) The critical smaller parts should be made from the more cathodic metal so that they will be protected (low C/A).
c) The galvanic couple can be painted or otherwise coated, ensuring that either or both of the couples are painted but allowing the C/A ratio to be as large as possible.

If only the corroding member (the aluminium rivet) of couple A were painted, there still would be a large bare cathode, which would make corrosion of the rivet even worse if the paint coating were scratched because the C/A would be even higher than if the anode weren't painted [96]. In such cases, it often is good practice not to paint the anode in order to ensure that the cathode area is not reduced further in size relative to the anode (in cases when the painted anode is scratched).

However, if the area of the anode is small with respect to the cathode, then the current will be concentrated in a small area, and the effect at each point could be very large. This area effect can be very important when protective coatings are used to prevent corrosion of mixed metal systems. If the anode is coated and there is a small defect in the coating or it becomes damaged (explained above), then the relative exposed anodic area will be small and rapid corrosion at the coating defect would more likely occur.

Making use of knowledge in galvanic effects can assist the designer in avoiding corrosion. For example, if a steel member of a structure is being damaged by contact with silicon bronze, one method to prevent or divert galvanic corrosion from the initial area between two metals is to connect a third metal that is more anodic than either of the other two [95]. The third metal in this case could be magnesium, zinc, aluminium alloy, or cadmium. It is well documented that zinc corrodes preferentially to both of the original members of the couple. In cases where a metal, such as the steel, is protected, the preferentially corroding metal is called a *sacrificial anode*. Such anodes are used commonly together with coatings to control corrosion on the underwater surfaces of boats, ships, and other marine structures.

The same principle can be used to protect steel in marine atmospheres if the anodic metal is applied to the steel as a coating. In this way, zinc galvanising and aluminium coatings are used extensively to protect steel in marine atmospheres.

3.5.3.2 Area Effect

As discussed in the Section 3.5.2.1, the relative areas of the anode and cathode have a pronounced effect on the amount of corrosion that occurs. It is common practice to use stainless steel fasteners to fix aluminium sheeting or signs. However, if aluminium screws are used to fix stainless steel, the screws probably would corrode rapidly.

An apparent contradiction of this area effect occurs when such a component comprised of two metals is only partly wetted, for example, with a stainless steel bolt in an aluminium plate where water collects in the corner at the edge of the bolt but the remainder of the plate remains dry [97]. In this case, the effective area of the less noble aluminium is only the wetted region, which may be of a size similar to that of bolt section that is wetted. Thus, it is possible for the aluminium plate to be attacked galvanically only in the region immediately surrounding the bolt. In summary, it is only the wet area that is relevant.

3.5.3.3 Crevice Corrosion

As discussed in Section 3.2.1.1, crevice corrosion damage in the lap joints of aircraft skins has become a major safety concern, particularly in aircraft fuselages. Usually, the detection and meaningful monitoring of crevice corrosion represents a major challenge. Crevice corrosion geometries, such as lap joints in the fuselage, illustrate a graphic example of hidden corrosion, as shown in Figure 3.17.

Consequently, the base of the crevice is anodic and the mouth is cathodic, giving the oxidation reaction (corrosion) for the metal M:

$$M \rightarrow M^+ + e^-$$

This reaction takes place at the base of the crevice while the following reduction reaction occurs in water at the mouth of the crevice:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

Geometry plays a large role in crevice corrosion [74,97]. Crevice corrosion is a localised form of corrosion and some common examples of such affected geometries include flanges, gaskets, disbonded linings/coatings, fasteners, and lap joints. Stagnant solutions play an important role in the establishment of highly corrosive micro-environments inside such crevices. A metallic material tends to assume a more anodic character in a stagnant crevice solution compared to that of the bulk surface, which is exposed to the bulk environment. Therefore, crevice geometries that inherently retain water for prolonged periods of time generally take longer to dry and so the corrosion will be more focused in these areas. The corrosion product is insoluble and so excludes oxygen completely, which increases the electrical potential. This eventuates into a pit, with corrosion's accelerating in the oxygen-deficient areas. Basically, corrosion may take place anywhere in the vicinity of the joint as long as it is in a position where there is metal ion deficiency.

3.5.3.4 Pitting Corrosion

Pitting corrosion (Figure 3.18) is a localised form of corrosion where the bulk of the surface remains unaffected [73-75]. Pitting often is observed in situations where resistance against general corrosion is conferred by passive surface films. Localised pitting attack is found where these passive films have broken down.

Within the pits, an extremely corrosive micro-environment, which may bear little resemblance to the bulk corrosive environment, tends to be established [73-75]. For example, in the pitting of stainless steels in chloride-containing water, a micro-environment essentially generating hydrochloric acid may be established within the pits. The pH within the pits tends to be lowered significantly, together with an increase in chloride ion concentration, resulting in the electrochemical pitting mechanism reactions in such systems.

The detection and meaningful monitoring of pitting corrosion usually represents a major challenge. Pitting failures can occur unexpectedly and with minimal overall metal loss. Furthermore, the pits may be hidden under surface deposits and/or corrosion products. Monitoring pitting corrosion can be complicated further by recognising a distinction between the initiation and propagation phases of pitting processes [98].

3.6 Effects of Design Geometry on Corrosion

Coastal wind patterns determine how far sea salts are carried inland. Generally, locations within 8 to 16 km of salt water are considered coastal since the wind can carry the salt much further than 16 km [99]. Higher temperatures also increase corrosion rates. Paradoxically, the most corrosive environments are those that have little or no rain because heavy rainfall serves to remove corrosive deposits from exposed surfaces. That is, removal of accretions of corrosive deposits from metal surfaces is an important consideration in corrosion control. The major design criteria are as follows [100-103]:

a) Surface roughness
b) Sheltered and horizontal surfaces

c) Crevices
d) Time of wetness and drainage paths
e) Debris build-up from bird droppings
f) Complex surfaces
g) Rivets
h) Joints
i) Sharp edges
j) Inaccessible positions
k) Overlapping of non-compatible materials

Surface Roughness

Prolonged corrosion cannot occur unless corrosive substances adhere to a surface. A smooth surface makes it difficult for contaminants to adhere and makes manual and heavy rain-washing more effective. A rough surface accumulates more contaminants and is less easily cleaned.

Sheltered and Horizontal Surfaces

Dirt and contaminants accumulate on sheltered components or horizontal surfaces because rain may not be able to remove the contaminants. Horizontal or sheltered surfaces in general should be avoided unless rain or manual cleaning is likely.

Crevices

Crevice corrosion can occur when water and corrosive contaminants remain trapped in narrow gaps and salt (chloride) is present in the environment. Problems can be avoided by eliminating narrow crevices that can accumulate moisture or by sealing them with a weld or sealant.

Time of Wetness and Drainage Paths

Time of wetness can be an issue for areas of the structure that trap or retain water or debris (see Figures 3.19 to 3.23). These areas include horizontal plates or elements or configurations that form pockets at the junctions of two or more members. Such configurations should be avoided if possible or, if necessary, drainage paths should be provided.

Debris Build-up from Bird Droppings

Debris build-up also can occur from nesting birds. If possible, access to the interior of structures should be screened to keep birds from nesting inside.

Complex Surfaces

Steel structures or fixings with complex surfaces are more difficult and expensive to clean and coat.

Rivets

Conventional steel rivets occasionally corrode internally and hence are difficult to protect due to their extremely complex shape and protruding features, which establish effective crevices.

Joints

It is best to eliminate or minimise joints as far as possible. It also is best practice to seal joints where possible to avoid open trough situations.

Sharp Edges

Edges tend to show coating breakdown well before the general flat surfaces of steel in corrosive atmospheres (see Figure 3.24). It is best to grind these surfaces down prior to coating or galvanising.

Inaccessible Positions

This generally is considered to represent poor design or bad practice and must be avoided where possible.

Overlapping of Non-Compatible Materials

This should be avoided wherever possible owing to the potential for galvanic corrosion. The separation of different metals is an essential aspect of avoiding this (see Figure 3.25) [104]. It is particularly important when materials need to be exposed to oxygen for the surface to be replenished to form a protective oxide layer, as in the case of aluminium.

The design of structures is based largely on data and functional requirements that can be quantified, potentially leading to the estimation of the life expectancy. The selection of a protective system involves many factors, which vary according to the type of structure, its complexity, its function, the general environment, the influence of micro-climates, and the effects of environmental changes (natural and otherwise) [104].

Other factors affecting selection are more subjective, such as time to first maintenance, planned maintenance schedule to cover the required life of the structure or plant, thickness of coatings, *etc.* These should be viewed with caution because the degree of variation may differ between one coating system and another. The design of structures usually can influence the choice of protective system. Conversely, it may be appropriate and economical to modify the design to suit the preferred protective system, such as in designs for safe and easy access to and around structures to facilitate maintenance.

3.7 Basic Processing of Aluminium

Aluminium is a metallic element that comes from the ore bauxite, which gets its name from Les Baux, France, where it was discovered in 1821 [2,3,105]. Today, bauxite is found predominantly in tropical and sub-tropical regions. Two to three tons of bauxite are required to make one ton of alumina, depending on the grade of the bauxite. While the mining process is relatively simple, the process to extract the aluminium from the bauxite is complex. There are two successive stages, where a chemical leaching process extracts alumina or anhydrous aluminium oxide from the bauxite, followed by the Hall-Héroult electrolytic process to reduce the alumina to aluminium. While aluminium is used sometimes in its commercially pure form, most applications involve the addition of small quantities of other metals to create alloys with special properties. Certain alloying elements will increase the strength or corrosion resistance while others enhance specific properties, such as machinability, ductility, weldability, and strength at high temperatures. Regardless of the alloy, the aluminium content is usually above 90 per cent.

3.8 Re-Use and Retention of Aluminium in Louvre Façades on Buildings

During the past 30 years, the use of aluminium in buildings has grown continuously. This is due to a number of key performance advantages arising from the materials characteristics of aluminium [93,105,106-113]. Aluminium cladding façades act as radiant thermal shields for the building envelope. In summer, they reduce solar radiation absorbed by opaque elements. In winter, they provide a thermal buffer and wind screen, thus minimising thermal losses. Year round, they reduce sound transmission through the building envelope and protect building materials from rainwater, environmental pollution, and heat stress due to seasonal temperature variations. Aluminium cladding material can withstand natural forces, such as wind pressure, earthquakes (elastic character), gravity (own weight), solar radiation (chemical deterioration caused by ultraviolet (UV) radiation), and thermal expansion/contraction. Bare, coated, perforated, or specially extruded aluminium also is used for solar control systems. Aluminium has excellent structural strength in terms of wind load, dead load, buckling, and deflection. In coastal areas that are subject to hurricane damage, structural strength is essential for personal survival as well as resistance to wind damage and windborne debris. Specific aluminium alloys also are used in the vicinity of coastal regions due to their high corrosion resistance.

3.8.1 Properties of Aluminium

The properties of aluminium are summarised below [11,93,105-113]:

a) Non-toxic, non-magnetic, incombustible with no sparking, therefore inherently safe and healthy
b) Long service life, requiring limited maintenance over the entire building life, high durability, and corrosion-resistant properties when alloyed with certain metallic elements
c) Low specific weight (one third that of steel), high strength-to-weight ratio allowing architects to minimise load-supporting structures
d) Density approximately one third that of steel, varying in the range 2600-2800 $kg \cdot m^{-3}$ in different alloys
e) Young's modulus approximately one third that of steel, varying in the range 68.5-74.5 GPa for different alloys
f) Coefficient of thermal expansion approximately twice that of steel, varying in the range 19-25 $\cdot$ $10^{-6}°C^{-1}$ for different alloys
g) Very good heat conductor that rapidly dissipates heat
h) Melting point approximately half that of steel, at ~660°C
i) High reflectivity and low emissivity
j) Considerable design flexibility, with capability of being rolled, forged, extruded, and cast to various shapes
k) Considerable workability, being able to be sawn, cut, bent, and welded both in the workshop and on-site

l) Capacity to be anodised, powder coated, or otherwise coated with various colours to meet certain aesthetic and decorative needs whilst increasing the durability and corrosion resistance and improving cleanability
m) High intrinsic value and low recycling costs
n) Repeatedly recyclable, resulting in significant savings in energy and natural resources without diminishing its properties (required energy for recycling is only 5% of energy used for primary production with electrolysis; ~30-40% of all aluminium existing today is recycled)
o) Light, thereby minimising overall energy in terms of handleability, transportation cost, and applications.

Most importantly, through alloying with elements, such as Cu, Mg, Si, and Zn, aluminium can attain approximately the strength of steel while remaining one-third as heavy [11,93,105-113].

3.8.2 Effect of Ageing on Properties of Aluminium

As discussed in Section 3.5.2, heat treatment of metals and aluminium affects many properties, including corrosion in some alloys. The effects of heat treatment are numerous and therefore knowledge of the heat treatment of aluminium alloys and precipitation hardening may assist the designer to use these materials for their advantages or exclude them for particular applications owing to their limitations. In certain situations, it is unavoidable to weld aluminium, where riveting, bolting, or adhesive bonding is not an option. Although aluminium may have the specified properties when it arrives from the manufacturer, subsequent thermal treatment, such as during welding, can alter the microstructure and so change the properties of the material. It therefore is imperative to understand the influence of heat treatment and welding on aluminium and the effects these have on the general microstructural properties and, in particular, strength, if it is to be used in applications involving structural requirements.

To obtain high strength in aluminium alloys, compromises may be required. For example, the need for a high yield strength necessitates the selection of a heat treatable alloy (see Section 3.8.3) [4]. However, if a medium or low strength is sufficient, then a non-heat treatable alloy (see Section 3.8.4) or commercially pure aluminium may be selected. The latter alloys are both easier to fabricate and not as sensitive to thermal treatments.

Pure aluminium has very low strength and a 0.2% proof yield at ~30 MPa. However, it is very ductile, with ~30-40% elongation [6]. Its mechanical properties will increase if it is cold worked to a yield of ~100 MPa but the ductility will decrease to only ~3-4%. Pure aluminium also is highly corrosion resistant since it has just a single phase. These types of materials are most likely to be found in applications for which there is little structural demand. Aluminium can be strengthened and hardened by alloying and additionally by heat treatment and/or cold working.

For some non-ferrous alloys, age hardening, also known as *precipitation-hardening*, is the most important strengthening process [107]. For an alloy to be precipitation hardenable, it must have decreasing solubility of an alloying element with decreasing temperature, as shown in Figure 3.26 [108]. Although this condition is met by most binary aluminium alloys, many alloys acquire little precipitation hardening in practice, and these alloys are not classified as heat treatable, as is the case for aluminium alloys with magnesium, manganese, or a combination of the two [97].

The first step in the heat treatment of aluminium alloys is the production of a supersaturated solid solution (SSSS) and its retention at room temperature [11]. This usually is accomplished by a high-temperature solution treatment followed by a downward quench. A typical alloy that can be age hardened usually would have a composition between points F and H (along the solvus line), as shown in Figure 3.26, although most age hardenable alloys are chosen from compositions with solute concentrations lower than F [107]. Maximal hardening in commercial alloys occurs when there is a critical dispersion of Guinier-Preston (GP) zones, intermediate precipitates, or both. In some cases, the alloys are cold worked after quenching and before ageing. This procedure increases the dislocation density and provides more sites at which heterogeneous nucleation of intermediate precipitates may occur.

From Figure 3.26 it can be seen that if alloy 4 is heated to point M, any excess β will be dissolved and the structure will consist of a homogenous α solid solution. If the alloy is quenched to room temperature and β is not able to precipitate, a SSSS is obtained with the excess β solute trapped in solution. It is this SSSS that must be retained after quenching in order to achieve an increase in strength [107].

The SSSS then is allowed to decompose at room temperature by natural ageing or at some intermediate temperature, typically around 200°C, in order to produce a fine dispersion of sub-microscopic and/or microscopic intermediate precipitates by artificial ageing [11]. This process is known as *age hardening* and is discussed further in Section 3.8.8.

3.8.3 Heat Treatable Aluminium Alloys

Heat treatable wrought aluminium alloys belong to three main alloy systems. The best known of these and the earliest to use commercially is the Al-Cu-Mg system typified by the *Duralumin* alloys [11]. The other two main systems are Al-Si-Mg and Al-Zn-Mg. The heat treatable wrought alloys can be summarised as follows:

a) 2000 Series Systems Al-Cu and Al-Cu-Mg
b) 6000 Series System Al-Si-Mg
c) 7000 Series Systems Al-Zn-Mg, Al-Zn-Mg-Cu

Depending on the age hardening characteristics that enhance their mechanical properties, these alloys are classified into two groups:

a) Those having medium strengths and that are readily weldable (Al-Si-Mg and Al-Zn-Mg)
b) Those having high strengths and that have been developed primarily for aircraft construction (Al-Cu, Al-Cu-Mg, and Al-Zn-Mg-Cu), most of which have very limited weldability.

Aluminium alloys 6061, 6351, 6063, and 6060 are some typically heat treatable alloys, all of which belong to the Al-Si-Mg system [110]. Alloy 6061 offers good strength, formability, and corrosion resistance. 6351 has excellent strength and good corrosion resistance. 6063 and 6060 have excellent corrosion resistance although 6063 has a higher strength than that of 6060.

These alloys exhibit medium to high strengths with good corrosion resistance [4]. Table 3.3 lists the compositions of these common 6000 series alloys. The alloying elements that, when added to aluminium, respond to heat treatment are magnesium, silicon, copper, and chromium. These elements, either between themselves or in conjunction with aluminium, form phases that have limited solid solubilities in aluminium at room temperature but that have increasing solubilities with increasing temperatures [109]. Heat treatable alloys will be discussed further in Section 3.8.11.

Table 3.3. Typical chemical composition of 6061 and other 6000 series aluminium alloy [11,105,107,109,114].

Alloy	Elemental Analyses (wt%)				
	Mg	Si	Cu	Cr	Al
6061	0.8-1.2%	0.4-0.8%	0.15-0.04%	0.04-0.35%	Balance
6351	0.2%	0.7-1.3%	0.1%	0.2%	Balance
6063	0.45-0.9%	0.2-0.6%	0.1%	0.1%	Balance
6060	0.35-0.60%	0.3-0.6%	0.1%	0.05%	Balance

In 6061, magnesium and silicon both combine to form precipitates of magnesium silicide (Mg_2Si) [110]. Also, copper is added in order to improve the mechanical properties and chromium is added in order to counteract the adverse effect of the copper on the corrosion resistance.

The aluminium-rich portion of the Al-Mg_2Si system is shown in Figure 3.27 [108]. During artificial ageing (T6 temper), the precipitates of the intermetallic compound (Mg_2Si) form and these strengthen the alloy. A consequence of this temper treatment is that the yield strength can be increased to ~250 MPa. The process of precipitation in certain alloys will be discussed subsequently in Sections 3.8.7 to 3.8.10.

3.8.4 Non-Heat Treatable Aluminium Alloys

The wrought non-heat treatable aluminium alloys that do not respond well to strengthening by heat treatment contain magnesium and/or manganese as the major alloying additions. Improved strength is obtained by strain hardening, which usually is by cold working during fabrication together with dispersion hardening. The non-heat treatable alloys and their principal alloying elements are as follows [11,93,106-113]:

a) 1000 Series ≥99 wt% Al
b) 2000 Series Cu
c) 3000 Series Mn
d) 4000 Series Si
e) 5000 Series Mg
f) 6000 Series Mg + Si
g) 7000 Series Zn

3.8.5 Temper Designations for Aluminium Alloys

The ISO has attempted in the past to unify the nomenclature for all aluminium alloys. Unfortunately, this has been unsuccessful owing to the continued use of various nomenclatures in different countries. Therefore, the present work adopts the temper designations of the US Aluminium Association (AA), which include the letter designations for different tempers applied to wrought and cast products [97,105,111]. This system is based on the sequences of mechanical and/or thermal treatments used to produce various tempers:

a) F As-fabricated alloy without further heat treatment or strain hardening following conventional cold working, hot working, or casting
b) O Wrought alloys that have been annealed to lower strength or cast alloys that have been annealed to improve ductility
c) H Wrought alloys that have been strain hardened to increase strength
d) W Naturally aged alloys with an initial unstable temper
e) T Stable alloys that are thermally treated with or without strain hardening

The alloys tempered with a T treatment, the T is followed by a number from 1 to 10, with each number indicating a specific sequence of basic treatments. For example, T6 is a solution-treated and artificially aged alloy; it applies to alloys that are not cold worked after solution heat treatment. The mechanical properties of alloys in the T6 condition are improved by precipitation heat treatment.

3.8.6 Ageing Characteristics – T6 Heat Treatment of Aluminium Alloys

As mentioned previously, aluminium heat treatments involve quenching from a temperature in the single α field (typically from ~500°C) to a temperature below the solidus temperature [107]. The quench should be as rapid as possible and is best accomplished in cold water of sufficient volume in order to ensure that sufficient heat exchange takes place. Rapid cooling is necessary in order to retain the maximal amount of alloying elements in solid solution; it also temporarily stabilises a lattice vacancy concentration much higher than the equilibrium concentration at room temperature. Therefore, if the alloy is rapidly quenched to room temperature (below the solvus line along points F to H in Figure 3.26), α will exist as a homogeneous solid solution whilst the precipitation of β is suppressed. This condition is thus termed *supersaturated solid solution* (SSSS), and the alloy is ductile and in a meta-stable state. This condition is sometimes termed solution treated.

3.8.7 Microstructural Changes Due to Precipitation and Ageing

Following quenching, the alloying elements remain in solid solution. However, these dissolved elements are in a metastable condition, so the alloy decomposes slowly at room or a slightly elevated ageing temperatures [93,112]. The alloying constituents that are precipitated in a non-equilibrium form are referred to as *GP zones* or *transitional precipitates*. The GP zones are coherent or partially coherent with the matrix such that strain fields are set up in their vicinity, resulting in hardening. The equilibrium precipitates produced by over-ageing always are non-coherent and therefore produce less hardening.

The explanation for the preceding is as follows [113,115,116]. The solution-treated alloy will develop coherent precipitates upon being held for a length of time at room temperature or slightly above. The nucleation and growth of the GP zones start immediately after quenching by a clustering process in which the solute atoms, together with some aluminium atoms and some excess vacancies, converge to form the GP zones. The initial stages of this process take place very rapidly and it is probable that the initial nucleation takes place almost instantly. The rapid nucleation results from the presence of an excess concentration of vacancies owing to the quench. The alloy thus becomes harder and its yield and tensile strengths increase but there usually is a corresponding decrease in ductility, as shown in Figure 3.28.

Ageing accelerates the precipitation of a second phase [93]. Detailed studies have produced the following interpretation of the age hardening phenomenon. Figure 3.29 shows the supersaturated atoms distributed at random. After an incubation period, they tend to accumulate along specific crystal planes in the manner indicated in Figure 3.29b. The concentrations of solute atoms in other regions therefore are lowered and so supersaturation decreases, providing a more stable crystal structure. At this stage, the precipitates are coherent with the matrix. As a result, the matrix is strained and dislocation movement occurs with difficulty across these distorted regions. Consequently, the metal becomes harder and more resistant to deformation under high stresses.

3.8.8 Ageing Sequence

The ageing sequence has been established according to two observations that derive from transmission electron microscopy (TEM) and electrical resistivity studies [113].

These show that the ageing sequence in unreinforced and reinforced Al-Cu-Mg composites from ingot alloys is as follows:

SSSS → GP Zone → S' (Al_2CuMg) → S (Al_2CuMg)

a) SSSS = Supersaturated solid solution
b) GP Zone = Coherent Guinier-Preston zone
c) S' = Semi-coherent intermediate phase
d) S = Incoherent equilibrium phase

Rack *et al.* [112] have shown that the characteristics and general sequence of precipitation in 6061 are as follows:

a) SSSS
b) Formation of Si clusters
c) Coherent Al-Mg-Si GP zones
d) Disordered partially coherent β'' (<100> $_{Al}$ needles)
e) Ordered coherent β' (<100> $_{Al}$ semi-coherent hexagonal needles, *a* = 0.705 nm, *c* = 0.405 nm)
f) Equilibrium β-Mg_2Si (platelets, rods, *c* = 1.215 nm)

Thomas [117] has shown that the first indication of ageing in Al-Si-Mg alloys is the formation of silicon clusters, suggesting that the ageing sequence for most heat treatable alloys, *i.e.*, 6000 series, follows the same pattern.

3.8.9 Overageing

A continuation of the local segregation process over long periods of time leads to further precipitation and overageing or softening [107] (see Figure 3.29c). The equilibrium phase at this stage loses its coherency and forms a distinct interface with the lattice. Coherency distortion lessens considerably and so the strength and hardness decrease spontaneously. A high-angle boundary is likely to exist between the second phase and the matrix, thereby allowing the precipitated phase to be viewed with optical microscopy. The growth of the second phase generates larger areas that have little means of slip resistance, so marked softening occurs. The electrical conductivity decreases initially during ageing owing to lattice distortion caused by coherency strain, but this increases when overageing occurs.

3.8.10 Effect of Ageing on Corrosion

When a single phase is present, the corrosion rate of an age-hardenable aluminium alloy is low (see Figure 3.30). However, the corrosion rate is increased significantly upon precipitation of a second phase. The corrosion rate increases with continued growth of the precipitates but it eventually decreases again owing to the coalescence of the precipitates and consequent reduction in the surface area of the galvanic cells (*viz.*, grain boundaries). In some alloys, the maximal corrosion rate corresponds approximately to the overaged condition, as shown in Figure 3.30 [94].

Further, there usually are differences in the electrical potentials between regions in an alloy when one section receives thermal treatment different from that of the remaining alloy [11]. Welding (see Section 3.8.11), which is a form of ageing, can provide this situation, thus yielding a difference in potential of up to 0.1 V between the weld bead, the adjacent heat affected zone (HAZ), and the remainder of the parent alloy.

3.8.11 Effect of Welding of Aluminium

Some consideration must be given to fusion welding because this affects all alloy post-treatments and results in an irreversible decline in strength and corrosion resistance in some alloys. The coefficient of thermal expansion of aluminium is twice that of steel [6], so the former is prone to distortion and stress inducement if proper welding procedures are not followed. Due to aluminium's high thermal conductivity [118], much of the heat present during welding diffuses into the surrounding parent metal. The shorter the time taken to complete a weld, the less the heat diffuses into the parent metal. So, if more intense and concentrated energy is used, then there is less heat diffusion into the surrounding metal, allowing welding to be done more quickly. These considerations allow the conclusion that the aim of fusion welding is to produce deep and narrow welds that are produced quickly.

Non-heat treatable wrought aluminium alloys usually undergo some level of cold working in the mill and so subsequently are supplied with a strain hardened (H) temper. Metal inert gas (MIG) and tungsten inert gas (TIG) fusion welding produce an as-cast structure in the fusion zone, which lacks the strain hardening of the parent metal [88]. This can be mitigated through the use of a filler metal or rod with higher solute level than in the alloy composition, so this can provide some strengthening to the fusion zone. More to the point, the welding process also causes the HAZ to be heated above the annealing temperature and so the material in this region is softened. The width of the HAZ may be minimised through the use of appropriate welding practices, such as the use of stringer weld beads and minimisation of heat input. However, in many cases it is difficult to avoid high heat input and a wide HAZ will result. Fortunately, welding of non-heat treatable alloys does not appear to have a significant effect on the resistance to corrosion.

In age hardened aluminium alloys, the situation is more complex than for wrought alloys. The microstructures of the fusion zone and HAZ differ from that of the parent alloy. At least the outer part of the HAZ is overaged and consequently softened, so this must be taken into account when considering the strength of the joint. However, these microstructural changes may affect the corrosion resistance. While 6061 is not affected and 6063 only negligibly, the corrosion resistance of alloys with Cu may be adversely affected [88]. Of the heat treatable wrought aluminium alloys, the Al-Si-Mg alloys are the easiest to weld [11]. For this reason they are used widely for structural components in welded assemblies [119].

The common filler metals 1100, 4043, 5254, 5356, and 5556 can provide resistance to corrosion [88]. However, in order to produce the best resistance to corrosion, it is best to use a filler metal that is closest in composition to the parent metal. This will help reduce the galvanic corrosion of the weld and/or the parent metal, so the correct choice of filler metal is important. That is, the filler metal must have a solution potential as close as possible to the solution potential of the aluminium alloy being welded. The solution potentials of the aluminium alloy series are categorised in the following order:

a) Anodic: 7000 > 5000 > 6000 > 3000 > 1000 > 4000
b) Cathodic: 2000

Ideally, the filler metal should be cathodic relative to the parent metal so that the area of the smaller area (weld) is the cathode and the larger area (parent metal) is the anode [88]. If the situation reversed, then rapid corrosion will occur.

A summary of some typical tensile strengths of heat treatable alloys in their temper condition and as-welded condition have been selected from the literature, in particular from ship design literature [120-122], and summarised as shown in Table 3.4. These alloys are used widely for structural applications in architecture owing to their adequate strength and corrosion resistance.

Table 3.4. Typical tensile strength properties of heat treatable groove welds [105,118,120-127].

Alloy	Parent Alloy Tensile Strength (MPa)	As-Welded Tensile Strength (MPa)
6063-T6	170-245	130
6061-T6	275-310	140
6061-T4	241	130
6351-T6	275-330	140
6060-T5	110-175	90

Figure 3.31 represents some of the compositional limits of the common 6000 series alloys showing contours for peak aged condition T6 and the corresponding yield strengths.

Several studies of the strength reduction across welds in aluminium alloys have been reported. The first tests carried out by Hill [128] involved plates with longitudinal welds at the centre using 6000 series alloys. Although the level of strength reduction depends on the temper condition of the parent material, Hill [128] found reductions in the yield strength in the range 33-50%. As shown in Figure 3.32, the data revealed that, within the entire zone $2b_r$, there is a region close to the weld, which was called the *reduced strength zone* b_r This region comprises of half of the HAZ and is associated with a reduced limiting stress $f^*_{0.2}$. The value of b_r was determined to be 19 mm and that this was associated with a decreased elastic limit $f^*_{0.2}$, which is shown in Figure 3.33, relative to the parent metal.

Mazzolani [6,52] also studied welded joints of 5086 and 7020, as shown in Figure 3.34, producing the average values given in Figure 3.35. The residual tensile stresses at the welds were ~100 MPa, with equilibrating compressive stresses of 30-50 MPa at the end(s) of the members. This work showed that heat treatment plays a major role in the distribution of the strength. Where 5086, which is non-heat treatable, exhibited a reduction in yield strength at the weld of ~10%, 7020, which is heat treatable, showed a reduction in yield strength at the weld of ~40-50%.

Figure 3.36 illustrates the strength of the joint of a fillet weld [6]. Since the strength of the joint is reduced relative to that of the parent metal, then the effect of heat must be considered in these computations. Figure 3.37 shows the extent of the HAZ and the elastic limits of the reduced zone $f^*_{0.2}$ relative to the elastic limit of the unaffected parent metal $f_{0.2}$. The mechanical properties gradually decrease across the reduced strength zone of the weld (b_r) and reach a minimum at its centre (see Appendix G).

It is important to note that the width of the HAZ and thus b_r depends on the welding procedure (temperature, voltage, velocity, number of passes, thickness of joint, *etc.*) and so, for commonly used MIG and TIG fillet welding procedures, it has been found that the b_r typically has a relatively constant value of ~25 mm [6].

A key assumption for fillet welds is that the simple tensile and compressive stresses are uniform in the effective fillet area, which usually is considered to be the depth of the throat section of the fillet multiplied by the length of the fillet [6]. As shown in Figure 3.38, the depth is the lesser height of the triangle inscribed in the cross-section of the fillet, where stress fields are exerted on the fillet in different directions, and the length is assumed to be the length of fillet. The force that acts on the joint perpendicularly to the axis of the fillet causes perpendicular shear or perpendicular stress in terms of the direction of projection (see Appendix G).

Owing to the complex loading behaviour of fillet welds, the European Convention for Constructional Steelwork (ECCS) has tabulated experimental coefficients ψ that give the ratios between the transverse and longitudinal strengths of fillet welds. These are given in Table 3.5 for a number of aluminium alloys.

Table 3.5. Experimental coefficient ψ, which gives ratio between transverse and longitudinal strength of fillet weld values, as suggested by ECCS European Standard [6].

Parent Metal	**Condition**	**Weld Metal**	***ψ***
7020	T6	5356	0.69
7020	T6	4043	0.68
6082	T6	5356	0.64
6082	T6	4043	0.64
6061	T6	5356	0.64
6061	T6	4043	0.64
6061	T5	5356	0.67
5083	0	5356	0.71
5454	H24	5356	0.67

The use of these factors in calculation of the design strength of fillet welds is shown in Appendix G.

As specified in ships' rules and guidelines [120-122], consideration should be given to critical or extensive weld zones as regards yield strength because the localised reduction in strength relative to that of the parent alloy occurs near welds. The strength of butt-welded aluminium alloys is dependent on the use of welding wires of compatible strength. As with fillet welds, the extent of the HAZ commonly is assumed to be ~25 mm. In fact, this HAZ extent is so well established that it is recognised by what is known as the *1 inch rule*, where the softening is assumed to extend in all directions a distance of 25 mm.

Guidance also can be obtained from sources such as CSA Standard CAN3-S157-M83 (R2002), *Strength Design in Aluminium*, which also suggests that the zone affected by welding be taken to extend a distance of 25 mm each side from the centre of the weld. The available literature and evidence for the 1 inch (25 mm) rule for the HAZ is convincing.

Avoidance of Stresses in Welds

One method of avoiding stresses in welds is to avoid the incorporation in the design of abrupt changes in thickness [120-122]. These thickness changes concentrate stresses in the areas such as welds. Generally, gaps between workpieces of >1.5 mm are not recommended. Although gaps larger than this may be relatively easy to fill, these will introduce excessive stresses due to thermal contraction. Good alignment prior to welding also will minimise stresses, which in turn will prolong the weld life.

Ensurance of Appropriate Conditions for High-Quality Welds

Aluminium is extremely sensitive to hydrogen contamination [120-122]. Consequently, the presence of moisture will result in defective welds resulting from porosity. Whilst welding outdoors, care must be taken in the event that it is humid. In such cases, pre-heating is required.

Clean Joints for Welding

Joints should be clean because aluminium is sensitive to many types of contamination [120-122]. Greases and oils can be removed with the use of a clean cloth saturated with acetone. However, acetone is a polar solvent and so a non-polar solvent also may be useful. One such commercial solvent is *Shellite*. Since aluminium has a passive oxide layer, it must be removed prior to welding [120-122]. Chemical, mechanical, and electrical means are available for this purpose. Welding should take place shortly after such cleaning in order to avoid re-formation of the oxide layer.

Welding Consumables

Welding generally is carried out with argon or a mixture of argon and helium gases. If an appropriate filler metal is used, then many problems can be avoided. For example, a welding filler metal of higher alloy content than the parent metal will aid against metal cracking [120-122]. Other methods of reducing cracking or hot cracking include the use of rapid welding speeds, modification of the joint design, preheating the parent metal to reduce the cooling rate, reducing the stress level by changing the restraining jigs or fixtures, and ensuring that the correct width-to-depth ratio is used in the weld cross- section.

Pre-Heating Aluminium Prior to Welding

The pre-heating temperature must not be too high because, if it is, then a weld pool may develop and become difficult to control [120-122]. For materials up to 8 mm thickness, 100°C pre-heating temperature normally would suffice. For larger sectional thicknesses, 350°-400°C is required so that the weld can cool so as to minimise the possibility of stress cracking. To reduce the possibility of stress cracking further, it is beneficial to use 1.6 mm filler rod, tungsten electrode, and pulsed welding. Typical heat input values of 0.8-1.6 $kJ\cdot mm^{-2}$ are adequate, with the lower end of the range being for thinner materials.

Effect of Additional Heat during Welding on Aluminium

The additional heat from welding may coarsen the microstructure to the overaged condition in the HAZ, which is detrimental to the alloy strength [11]. Again, in order to minimise this potential, it is advisable to weld with low heat input and to ensure that the material does not remain at a high temperature for too long. This may be achieved by designing or planning the welding sequence so as to weld on cold materials at all times.

3.9 Hardness and Tensile Strength Relationship in Welded Aluminium Alloys

Malin [129] has determined that joints welded under various conditions show a direct relationship between hardness and tensile strength and that the average hardness gradient may be used as an indication of the strength of welded joints. Burch [130] also studied the effects of welding speed on the strength of 6061 T4 aluminium alloys and he also concluded that there is a relationship between hardness and tensile strength.

Hardness also can be used to interpret the effects of the HAZ adjacent to a weld. Of particular interest to most designers is the width of the HAZ in aluminium alloys, and this may be determined from hardness measurements across the weld. Malin [129] has stated that the narrower the HAZ, the higher the joint strength.

The rate of heating during welding also affects the width of the HAZ, as evident from Standards that recommend the most rapid heating possible [131]. Slow heating results in a wider HAZ and a weaker weld joint.

3.10 Hot Dip Galvanising (HDG)

Hot dip galvanising is used widely to protect steel from corrosion. The zinc coating that is applied during galvanising is anodic to steel and thus provides sacrificial protection [62]. Upon atmospheric exposure, the zinc coating develops a protective layer of insoluble zinc oxides, hydroxides, and carbonates, depending on the environment. When the protective layer has stabilised, reaction between the coating and its environment slows considerably, thereby resulting in long coating life.

An example of galvanic protection using galvanised iron sheet is shown in Figure 3.39 [73]. In galvanising, iron or steel is coated with a layer of zinc. The zinc then acts as the anode and the steel doesn't corrode even when exposed. Even if the coating is broken, zinc will corrode preferentially relative to steel [73].

Galvanising provides a robust coating that is highly resistant to wear and impact during transport, installation, and service [62]. Unlike organic coatings that tend to shrink away from sharp corners or can be difficult to apply to complex shapes, galvanising ensures an essentially even coat over all surfaces accessed by the molten zinc (melting point ~420°C). Importantly, it protects the steel substrate until the zinc has corroded away, unlike conventional paints, where corrosion of the steel can progress unobserved underneath the paint film. The corrosion rate of galvanising is very low compared with that of steel, as shown in Table 3.6.

Table 3.6. Comparative corrosion rates (mass losses) of zinc and steel over 2 years [62,132].

Environment	Location	Zinc:Steel Corrosion Rate
Arid	Phoenix, AZ	17:1
Rural	State College, PA	22:1
Light Industrial	Monroeville, PA	28:1
Industrial	East Chicago, IL	52:1
Marine	Kure Beach, NC	80:1

Both Australian Standard AS/NZS 2312:2002 and the International Standard EN ISO 14713:1999 *Protection Against Corrosion of Iron and Steel in Structures – Zinc and Aluminium Coatings – Guidelines* provide considerable information on the corrosion rate of zinc under various conditions of atmospheric service. In addition, over the last few decades, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) has carried out extensive mapping to establish the corrosivity of the Australian climate. It is important to note that, while the service life estimates in these two Standards are consistent, they do not extrapolate beyond 25 and 20 years, respectively. However, based on extensive case histories and the fact that the service life of galvanising is related directly to the zinc thickness, extrapolation well beyond 25 years is possible.

3.11 Service Life of Galvanising as a Function of Zinc Coating Thickness and Steel Thickness

The service life of any particular post-fabrication galvanised item is dependent on the thickness of the zinc coating [132]. However, the coating thickness must be increased along with the thickness of the steel, as shown in Table 3.7. This is particularly important for sharp edges and complex shapes, where conventional paints may not provide adequate cover. For in-line galvanising, the process restricts the galvanising thickness to allow the steel to retain ductility for further manufacturing.

Table 3.7. Variation in galvanising thickness with steel thickness [62,132].

Steel Thickness (mm)	Local Galvanising Thickness (μm)	Average Galvanising Thickness (μm)	Galvanising Coverage ($g{\cdot}m^{-2}$)
Sheet Products	--	14	100
≤1.5	35	45	300
1.5 to ≤3	40	55	390
>3 to ≤6	55	70	500
>6 to ≤9	70	85	600
>9 to ≤12	85	125	900

There are many reports of the corrosion of steel and zinc in the atmosphere [62,132]. Many of these define the performance in terms of five corrosion categories, from C1 (the most benign) to C5 (the most severe). They are summarised in Table 3.8.

Table 3.8. Effect of environment on corrosivity [62,132].

SO 9223 Corrosion Category	Typical Environment	Average Zinc Corrosion Rate ($\mu m{\cdot}year^{-1}$)	AS/NZS 2312 Corrosivity Description
C1	Few alpine areas, dry interiors	<0.1	Very Low
C2	Arid/rural/urban interiors, occasional condensation	0.1-0.7	Low
C3	Coastal, high-humidity interiors	0.7-2	Medium
C4	Seashore (calm), swimming pools	2–4	High
C5	Seashore (surf), offshore	4–8	Very High

It may be noted that these data provide only generalised guidance and other factors, such as specific micro-climates and unwashed areas, may have an influence [6].

3.12 Service Life of Galvanising as a Function of Silicon Content in Steel on Zinc Coating Thickness

Individual elements in steel may influence the reaction between molten zinc and steel, which can result in alteration of the structure, thickness, and general characteristics of the zinc coating [63]. Early in the 20th Century, several investigators researched the iron-zinc binary phase diagram [133-135]. The version proposed by Raynor [136], shown in Figure 3.40, gives the following phases: α, γ, Γ, δ_1, ξ, δ, and η. Each of these phases may be present in a galvanised coating, depending on composition, temperature, and time. Consequently, these variables will affect the hardness, brittleness, and ductility of the coating. That is, the life span of maintenance of the coating thickness and quality is dictated by parameters including the composition of the steel, composition of the galvanising, the temperature, and the time at temperature.

The α phase region (solid solution of Zn in α-Fe) is stable at low concentrations of Zn. The solubility of Zn in α-Fe at low temperatures (250°C) is at the minimum of 4.5 wt%. As the temperature increases, the solubility of Zn in α-Fe increases until, at 623°C, it achieves a maximum of 20 wt%. The effect of dissolved Zn on the lattice parameter of α-Fe (body centred cubic) has been investigated by other researchers owing to the interest in the hardness of this phase [63]. From this, it is clear that Fe is capable of dissolving Zn at typical galvanising temperatures. The ramifications of this are as follows:

a) Since the steel is capable of dissolving Zn, care must be taken not to affect the former's properties by alteration of its alloy composition.
b) The partial solubility of Zn in α-Fe facilitates chemical bond formation and consequent adherence of the galvanising layer.

Examining the phase diagram on the Zn-rich side, it can be seen that, at a wide galvanising temperature range of 440°-490°C, the equilibrium phases are Γ, δ_1, ξ, and η. Of these, the first three show homogeneity regions of mutual partial solubility. The ramifications of this are as follows:

a) If the galvanising layer consists of η-Zn, it will not leach Fe from the steel
b) It is more likely that the galvanising layer will contain Γ, in which case some dissolution of the steel by Γ could occur, further assisting bond formation. However, again, care must be taken not to alter the steel alloy composition.
c) Under equilibrium conditions, the galvanising layer could consist of one of the following:
   - A homogeneous solid solution of Γ
   - A mixture of α-Fe + Γ
d) Under non-equilibrium conditions, the galvanising layer could consist of one of the following:
   - Pure Zn
   - A homogeneous solid solution of δ_1 or ξ
   - A mixture of Γ + δ_1 or δ_1 + ξ or ξ + η

The microstructures of typical galvanising layers consist of a grey colour deriving from [63]:

a) Two thick layers of δ_1 and ξ

b) Thin layer of Γ

Examining the subsolidus compatibilities in the phase diagram, it is clear that the most probable arrangement of the order of the phases (layers) is:

α-Fe (base) – Γ (thin) – δ_1 (thick) – ξ (thick) [– η (if it were present)]

It is obvious that galvanising is a non-equilibrium process. Therefore, kinetics are important, as is demonstrated by the fact that the immersion time can change the thicknesses of the layers. That is, brief immersion results in the ξ layer's being thicker than the δ_1 layer. Conversely, prolonged immersion reverses this trend.

However, the effect of silicon in steel is important, particularly, when the silicon content is high [63]. This can result in a significant reaction between the steel and molten zinc, yielding a microstructure consisting of δ_1 + ξ, although a very thin layer of shiny η-Zn may be present. Here, the subsolidus compatibility between α-Fe and Γ is absent.

It may be noted that the ductility of galvanising layers decreases significantly in the presence of ξ [136].

3.12.1 Design for Incorporation of Proper Venting and Drainage

Hot dip galvanising involves the complete coating of steel with corrosion-inhibiting zinc, which forms a metallurgical bond with the base steel [62,63,132,137]. The advantage of this process is that both interior and exterior surfaces will be protected from corrosion if the correct design procedures and dipping procedures are followed. The process typically involves hot caustic degreasing (removing oil, other organic residues, and paint), hydrochloric acid pickling (removing mill scale and corrosion by-products), rinsing (removing prior cleaning and acid residues), flux solutions (conditioning the surface), zinc bath dip (at 455°-460°C), and finally chromate quenching (passivating the zinc surface to prevent early oxidation).

Molten zinc must be allowed to flow freely without impediment and this may be achieved with proper design [62]. The most desirable fabrication design is one that is structurally robust but also provides complete access by the liquid.

Webs in columns and beams, such as strengthening gussets, should have the internal corners cropped or holed to ensure that no zinc build-up occurs in angles or corners;

air-locks and ash entrapment also must be eliminated. If long structural lengths of steel require galvanising, then the designer also must be ready to examine alternative methods, such as double-end dipping. Another method involves the design of spliced sections, where either the section is too large or the means of transport to the intended site does not permit such a size.

Also, since welding stresses may cause distortion during galvanising owing to stress release, the galvanising of welds should be minimised where possible. The preferred alternative is bolting, and so splicing may be an appropriate solution. However, there are disadvantages to bolting in terms of corrosion, as discussed in Section 3.6.

In any case, a well considered design will ensure that the galvanising will impart the intended properties as a result of the use of methods involving proper dipping, draining, and venting.

3.12.2 Design for Drainage

The following design aspects are recommended for gussets, as shown in Figure 3.41 [62,137]:

a) Where gusset plates are used, generously crop corners in order to facilitate free drainage. When cropping gusset plates is not possible, holes with a minimal calculated diameter must be placed in the plates as close to the corners as possible.
b) To ensure unimpeded flow of liquids, all stiffeners, gussets, and bracing should be cropped to the minimal calculated size.
c) Continuous welding should be used in order to avoid moisture traps.
d) Water-soluble cutting fluids only should be used during drilling.
e) Holes with the relevant diameters in the end-plates of rolled steel shapes should be used in order to allow molten zinc access during immersion in the galvanising bath and drainage during withdrawal.
f) Alternatively, appropriately sized holes can be placed in the webs within a small distance (calculated) of the end-plate.
g) To facilitate drainage, end-plates should have holes placed as close to interior corners as possible.

3.12.3 Bevel Sizes

According to Figures 3.41 and 3.42, the requirements for bevel sizes are as follows:

a) Bevel cuts for angles and channels = 25% of flange width
b) Bevel cuts for I beams and columns = 25% of half the flange width
c) Bevel cuts for right-hand side end plates = 25% of half the widest side

3.12.4 Hollow-Section Columns

For hollow sections, *i.e.*, rectangular hollow sections (RHS), when both internal and external surfaces are to be galvanised, at least one filling and draining hole must be provided, with a vent diagonally opposite to allow the exit of air during immersion.

3.12.5 Weld Quality

Both structural and aesthetic aspects of welding may be affected by the galvanising process. The GAA has made the following recommendations [62,63]:

a) The silicon content of welding rod or wire should be low and of similar metallurgy to the parent metal.
b) Welds should seal joins where possible so that liquids in the pre-galvanising stage are not expelled during the galvanising process.
c) Slag left on the metal will prevent proper conditioning of the surface by the solutions applied.

SECTION II

Field Investigation Technical Considerations

CHAPTER 4. Field Investigation Technical Considerations

4.1 Overview of On-Site Findings of Failure

Figure 4.1a shows a satellite view of the vicinity of Westfield Tower 2, Bondi Junction and Figure 4.1b shows an aerial view of the rooftop on Level 29 of Tower 2, the childcare centre, and the surrounding streets. A schematic drawing of typical louvre locations on the building and the extent of damage is shown in Figure 4.2. The initial assessment involved inspection of the damaged structural louvre panels on the southwestern side of the rooftop, as shown in Figure 4.3. The childcare facility faced south, which is to the left of this photograph. Louvre panels that had detached from the structure and fallen from level 29 down to level 28 are shown in Figure 4.4.

Permanent damage to the louvre sections mounted on the sides of the building was observed on the north and east sides. While winds blowing from the harbour/ocean from the north deposited airborne seawater, high wind loads generally came from the west. The structural louvres on the southwest corner of the rooftop had been damaged severely by the heavy winds of August 2003 since the majority of the connecting structures had corroded severely and given way.

4.2 Summary of Initial Consideration for Site Work

Although the level of damage was significant, the difficulty of rectification was compounded by the fact that the client did not have any building plans or drawings. Initially, even obtaining bearings on the interiors of levels 26-28 was difficult since there were no windows or views to assist with locating position or direction (see Figure 4.5). Further, all of the louvres that required replacement or strengthening were blocked with aluminium cladding on the internal faces so that it was awkward to inspect the extent of damage. It immediately became clear that the original design had not considered subsequent access and maintenance issues.

The initial impressions of the difficulties involved in rectification are as follows:

a) The total area requiring correction was large.
b) There were no building plans or drawings.
c) Sight and access were restricted.
d) All items had to fit in the goods lift owing to the undesirable costs associated with crane and helicopter use.

e) Work near the edges and on the faces of the building was required, posing serious safety issues.
f) There were many variables involved in the re-design and refurbishment.
g) There was risk of collapse of the structural louvres on the rooftop.
h) It was difficult to navigate within the building, which was a particular problem when arranging to meet others on site.
i) Parking in the shopping centre basement was restricted and generally unavailable.
j) The project was constrained by scheduling issues dictated by working above a childcare facility and within a given period (6 months) specified by Westfield.

Further, it was necessary to identify constraints on potential engineering solutions posed by other factors. The following were identified as being the most critical:

a) Most work had to be performed 26-28 floors up on the side of the building.
b) There was a danger of debris falling onto the public below.
c) The aesthetics of the building façade had to be preserved or enhanced.
d) There were inevitable cost and time constraints that precluded total replacement.
e) Other contractors and maintenance staff were working in close proximity.

It was clear that undertaking such a project required careful planning, clear goals, and a disciplined approach. After careful consideration, it was concluded that the project could be completed successfully and so a tender was submitted.

4.3 Observations, Challenges, and Proposed Solutions for the Project

The louvre structure on the southwest corner of the rooftop on level 29 had been torn apart by the very strong winds on the weekend of 23-24 August 2003. Two entire louvre panels were detached completely from their support frame. The anchors holding the base equal angles, which supported the louvre system, had failed in shear. The bolts were severely corroded. Considerable forensic evidence was unavailable because the inspections were carried out approximately 1 year after the incident of August 2003 had occurred.

There was permanent deformation of the vertical dividing mullions on both the east and north louvre panels on level 29 (see Figure 4.6), probably as a result of the fact that they were restrained only at the tops and bottoms.

All of the pop rivets and fixing screws, which were the primary fixing attachments for all of the louvre panels, were corroded severely. Figure 4.7 shows some of the typically corroded mandrels and pins inside the aluminium rivets that were taken from the southwest corner where the panels had failed. Corrosion was more severe in the steel mandrels but, in many cases, it had progressed into the aluminium sleeves as well. The replacement rivets that were to be used to re-attach the aluminium louvres are shown in Figure 4.8. These rivets are comprised of an aluminium alloy sleeve (5056) and aluminium alloy mandrel (7075).

Following the initial inspections, the following observations were made:

a) Since no engineering drawings or specifications were available, these would be required for reference and planning purposes and for off-site construction (see Appendix H).
b) Westfield specified that it preferred long-lasting, corrosion-resistant, and lightweight metal on the façade, where possible, instead of bulky structural steel in order to retain the aesthetics of the building.
c) The existing louvre structures were made of bronze anodised aluminium sections. Each panel was ~3660 mm height by 1770 mm width. The mullions were comprised of two C-shaped extruded aluminium sections that were bolted together. The heads of the louvre panels were attached principally at the mullion positions to a galvanised steel wind beam with steel rivets.
d) The extruded aluminium louvres were fixed to the mullions with self-tapping screws. The bite of the screws had ~10 mm engagement into the screw flutes.
e) The sills of the louvre frames were originally fixed only to a 35 mm x 35 mm x 5 mm equal angle with 5 mm pop rivets of the type mentioned above (steel/aluminium) at ~1 m intervals.
f) The upper section of the louvre system on the rooftop was comprised of rounded brackets attached by self-tapping screws.
g) The louvres to replace the entire southwest corner had to be manufactured because suitable identical or similar louvres were not available in the marketplace (see Figure 4.9). Appendix I compares the original and new louvres.
h) Some designs required approval from an independent external structural engineer, such as in the welding of two L-shaped angles of varying sizes back to back but positioning them in such a way as to match the exact dimensions in all three directions for bolting and securing the louvres.

i) The noise attenuators or baffles on level 28 were corroded severely, especially on the eastern and northern sides. The sheet metal that was directly beneath the baffles and that overlapped the aluminium sections was corroded as well (see Figures 4.10 and 4.11).
j) The access to some areas of the interiors of levels 26, 27, and 29 was restricted owing to the presence of aluminium-clad sheets and sound attenuators or baffles.
k) Certain areas were extremely difficult to access and so special jigs had to be devised using on-site measurements.
l) The structural steel sections needed strengthening and bracing on the eastern side of the rooftop.
m) The steel cradle structure, shown on the left of Figure 4.12, is the BMU located at level 26. The difficulty of access to the louvres can be seen.
n) Owing to the large size of the BMU, it would not fit in between the outwardly sloping concrete columns on the face of the building, as shown in Figure 4.12. Consequently, window abseilers were trained according to the Perfect Engineering Pty. Ltd. QMS for work on levels 27 and 28. This involved calculation of a safety factor and development of a SWMS for the descent down the façade by the abseilers (see Appendix J). It was possible to use the BMU for work level 26, where the building façade was flat.

A schematic illustration of the basic operations during site work and a description of the positions of the louvres on the façade are given in Figure 4.13.

One of several new louvres being manufactured in the workshop with mullion framing is shown in Figure 4.9. This was used as a prototype prior to formal fabrication. The mullions or frames were manufactured using aluminium 6351 T6 (Appendix K) and the louvre profiles were made of aluminium 6063 T6 (see Appendix I). The final fabrication step was powder-coating since the original louvres were powder coated and this would enhance corrosion resistance (see Appendix L).

Replacement of the corroded rivets was a particular concern. Considerable R&D and Testing failed to reveal a rivet with the desired strength and corrosion resistance. Ultimately, the aerospace rivet [138] shown in Figure 4.8 was selected on the basis of its excellent shear and tensile strengths (see Appendix M). When this was tested on site, the differences between this blind rivet and more conventional ones were evident. It can be used in high-vibration applications and in materials with thickness variations as great as 3/8 inch (9.53 mm). Over 10,000 rivets were used on site. Some of its characteristics are as follows:

a) Flush installation ensures that the fastener is painted easily if required; more importantly, it allows it to resist water and salt, thereby improving the corrosion resistance.
b) Sleeve expands during installation, ensuring a tight fit and filling the hole to create a weather-resistant joint.
c) Flush pin break eliminates the need for grinding or filing.
d) Solid-circle lock ensures maximal strength and resistance to vibration, which ensures no pin pushout.

The sleeve was aluminium alloy 5056 with clear chromate and the pin was aluminium alloy 7075 with gold chromate (see Appendix M). Typical installed values in nominal grip for diameter 3/16 inch (4.76 mm) were as follows:

a) Tensile Strength: 2.2 kN
b) Shear Strength: 3.1 kN
c) Pin Retention Strength: 0.2 kN

There were other practical considerations as well.

a) Although the project was completed in under 6 months, the QA paperwork required an additional 2 months for final sign-off.
b) Owing to the varied nature of the work, a range of experienced tradesmen was selected to work in the different areas. On average, there were eight to ten men employed full-time at any one time.
c) I had decided that all workshop fabrication and other supplier activities, which were the direct responsibility of Perfect Engineering Pty. Ltd., had to be managed under the company's accredited ISO 9001:2000 QMS.
d) All fabrication and supplier activity had to be scheduled and co-ordinated so that deliveries and implementation were done sequentially and effectively.
e) All services and materials provided by suppliers required certification and traceability.
f) In some instances, materials, such as the rivets, were ordered from interstate or US. The expected shipment times and potential delays had to be considered in the scheduling.
g) All personnel had to undergo strict safety inductions prior to entry on site.

h) Since the project was divided into several stages, SWMSs were completed for each project undertaken, with all individuals taking responsibility for the tasks at hand.
i) All documentation, including SWMSs, weekly audit checklists, daily safety logs, project attendance logs, electrical equipment register, security register, Westfield environmental health and safety (EH&S) weekly logs, *etc.* were completed and archived as required. Strict compliance with these procedures ensured that there were no accidents or injuries during the tenure of the entire project.

A report on the work carried out on the louvres on levels 26-29 and the structural members on the periphery of the rooftop on level 29 was prepared for Westfield. Some of the key components of the report are summarised below in order to provide a brief overview of the integrity of the louvres and structural members and the general condition of the steelwork on site prior to commencement of the project. The report also highlights major long-term corrosion remedies and structural strengthening incorporated in order to certify a 5 year guarantee for the structural integrity of the entire project provided that Westfield adheres to certain measures. To provide Westfield with further confidence, Perfect Engineering Pty. Ltd. also has provided supplementary engineering certification for 5 years on the structural work, as determined by an external structural engineering firm that has co-operated on and inspected the project periodically since commencement of the project in early February 2005.

The intention of the report to Westfield was to provide a basic and succinct description of the project, without being an in-depth or technically detailed report, although it was specified that these details could be provided if requested. The report included a set of basic engineering drawings for establishing direction and reference to proposed new brackets in various locations, ascertaining various aspects of sourcing of materials, fabrication, strength, and corrosion (see Appendix N). The report focused on the important aspects of the overall project, including the periodic maintenance schedule that Perfect Engineering Pty. Ltd. recommended to the client. The report included proposals for precautions and recommendations for maintenance that must be taken so that the 5 year guarantee would not become void in specific areas. The report also specified that Perfect Engineering Pty. Ltd. would inspect in February of each year (for an example, see Appendix O) and detailed procedures for these inspections were provided. In fact, Perfect Engineering Pty. Ltd. inspects the site two times *per annum* in order to determine the potential for corrosion or structural problems due to wind.

4.4 Causes of Corrosion and Failure and Engagement of Other Experts in the Field for Initial Assessment

It was concluded initially that the principal cause of typical failures in the structural sections were due primarily to severe corrosion, which subsequently resulted in the failure of structural sections, especially in the louvre panels in the southwest corner of the rooftop (Figure 4.14). The extent of corrosion was a result of two factors:

a) Airborne salt from the harbour/ocean
b) Use of inappropriate combinations of materials in contact

Since it was clear that corrosion was the main issue, I engaged the services of two independent experts:

a) Corrosion specialist from the School of Materials Science and Engineering, University of New South Wales
b) Aluminium engineering specialist from the Australian Aluminium Council (AAC) in the field to assess the situation.

Both experts confirmed my findings and supported the solutions proposed by me and the work that I deemed were to be undertaken by Perfect Engineering Pty. Ltd.

The main conclusions about the causes of failure which I had assessed were as follows:

a) *Corrosion 1:* Non-structural grade bolts, which may or may not have been zinc coated, corroded (see Figure 4.15).
b) *Corrosion 2:* Aluminium and steel, which have a difference of 0.15 V in the galvanic series, were in contact with one another and underwent galvanic corrosion.
c) *Fatigue:* The bolts failed in fatigue owing to the repeated cyclic stress from wind loading.

A typical example of galvanic corrosion can be seen in Figures 4.16 and 4.17, where steel cladding extending from the base of baffles enveloped the mullion faces. Since steel, with the larger surface area, is cathodic and it covered the anodic aluminium, the presence of an electrolyte (seawater) resulted in galvanic corrosion. The corrosion residue covered the surface and hindered oxygen access to the aluminium, thus enhancing the corrosion. The solution was to isolate and remove all material in contact with the aluminium mullions and to expose them to air. Consequently, it was not necessary to replace any steel cladding of the mullions adjacent to the hobs under the louvres. This was particularly important in the regions where the baffles reside.

Since the purpose of the baffles is to minimise noise, Westfield stipulated that very few (six) of them could be removed from each of the louvre sections from the cooling tower section on level 28 facing north, south, and east. The corrosion in these baffles was excessive, as shown in Figure 4.18, which indicates that these areas were unduly exposed to airborne contaminants. It also is possible that the corrosion was enhanced as a result of the effect of the chemicals used with the nearby equipment, which required chemical dosing of the water used with it.

The remaining mullions were cleaned of corroded debris falling from the baffles and washed thoroughly, as shown in Figure 4.19. The corroded mullion section on the remaining north side was inspected for structural integrity and considered to be safe. Consequently, this section was primed with *Emerbond* and two coats of *Emerclad*, a special coating for aluminium that has a total of 10 year guarantee from the manufacturer.

At the commencement of the project, chemical analyses were performed on the louvres in order to ensure that compatible materials would be used so as to eliminate or reduce galvanic corrosion (see Appendix F). All materials associated with the louvres, particularly the rivets, were researched carefully and selected to be compatible with the existing aluminium and steel materials. For example, with aluminium alloys, not all mating aluminium alloys are compatible with each other and so there may be a compromise. Although aluminium alloys with percentages of ≥2.0 wt% copper (*e.g.*, 2000 series) have high tensile strength, they are subject to corrosion and will undergo pitting corrosion [9].

4.5 Scope of Works on Project

I had organised the project into several discrete stages for Perfect Engineering Pty Ltd to undertake.

4.5.1 Structural Brackets Secured Internally on Level 28 to Support Louvres

The key structural positions for each of the louvres of level 28 were identified and these were strengthened from the inside with newly fabricated high-strength structural brackets that were hot dip galvanised for optimal protection against corrosion. Each individual bracket was made to match detailed shopfloor drawings to precision ±1 mm for the frame and ±0 mm for the nuts that were welded on the frame.

A U-shaped bracket was used for each of the central upper positions of the louvres, as shown in Figure 4.20. The new bracket connected to three sections of the horizontal mullions whilst an existing smaller central upper bracket, which was in good condition, secured the fourth horizontal mullion connection.

Figure 4.21 (left side) shows the lower central bracket that was positioned to connect to the bottom of the three vertical mullion sections. It can be seen that the central bracket is original and the two adjacent brackets were manufactured by Perfect Engineering Pty. Ltd. The positions of these brackets were determined on the basis of engineering calculations of wind loads on the spans of the louvres.

Additional brackets, shown in Figure 4.22, were made to secure the remainder of the horizontal mullion sections from the inside since many of lower brackets were either corroded or deemed no longer capable of supporting the louvres.

The upper brackets were secured to the concrete roof via *Hilti* M16 and M12 chemical anchor bolts [139]. The lower and additional brackets were secured to the concrete hob adjacent to the louvre sill using *Hilti* M12 chemical anchor bolts. It must be noted here that throughout this project, all of the anchor rods used were *Hilti* HAS steel bolts and all of the chemical capsules were *Hilti* HVU adhesives.

4.5.2 Corroded Structural Parallel Flange Channel (PFC) Supporting the Louvres on Level 29

The entire parallel flange channels (PFCs) under cover on level 29 and their associated bolts were severely corroded, as shown in Figure 4.23. These PFCs were re-designed and engineered depending on where they were to be installed in order to be able to carry the required load imposed by the wind conditions (see Appendices P and Q). The newly fabricated and spliced PFCs (see Figure 4.24a) were also hot dip galvanised (see Figure 4.24b). The louvres on level 29 were dependent completely on these PFCs and the upper and lower brackets connecting them for load bearing. Therefore, the newly fabricated and galvanised upper and lower brackets also were hot dip galvanised. The cleats on to which these PFCs were connected were wire brushed thoroughly and primed with *Emerbond* and coated with two layers of *Emerclad*.

4.5.3 Structural Beam above Building Maintenance Unit (BMU) on Level 29

The beam above the BMU area was a major structural beam that held up a section of the roof on the western side. If the existing corrosion were to continue at the observed rate (see Figure 4.25a), it is likely that the beam would have ceased to provide sufficient support. This was an example of poor design. Consequently, the beam was wire brushed back thoroughly to bare metal, primed with *Emerbond*, and coated with two layers *Emerclad* (see Figure 4.25b). Further, additional support was provided to the beam by incorporating a large equal angle, which was hot dip galvanised and chemically anchored into the wall directly underneath the beam (see Figure 4.25c).

4.5.4 Replacement of Bolts, Nuts, and Rounded Brackets on Level 29

All non-structural and zinc plated nuts and bolts in the structural PFCs on level 29 were replaced with structural 8.8 grade steel nuts and bolts, which are hot dip galvanised. (see Figure 4.26). Also, *Hilti* hot dip galvanised M8 chemical anchor bolts were used with the existing equal angles on the hobs holding the louvres on level 29 at positions 300 mm apart.

The old brackets holding the PFCs to the mullions all around level 29 were rounded and found to exhibit cracks of ~2-3 mm depth at the radius (see Figure 4.27). The cracks in the original brackets were due to stresses imposed during the bending. It was evident that crack propagation has traversed approximately half the thickness. The brackets were secured merely by 6 mm tek screws and one bolt fixed upside down so that the nut sat on the top face of the PFC, as shown in Figure 4.28. The bolt arrangement facilitated its corrosion. Both of these defects represented additional examples of poor design.

Consequently, new L-brackets were fabricated using two separate sections at right angles and butt welded to achieve deep penetration welds for high strength (see Figures 4.29 and 4.30). These new brackets were used to replace all of the original brackets on the PFCs. The welds were positioned at a 45° angle so that any deposits would wash off easily and not establish a corrosion site on the weld. The tek screws that were used to attach the old rounded brackets to the mullions were replaced with hot dip galvanised M8 bolts, which passed through the entire mullion for additional strength, and secured on the opposite side (see Figure 4.31).

It is important to recognise that the work of suppliers must be subject to continual scrutiny. Figure 4.32 shows some of the initial galvanised PFCs which were designed and manufactured by Perfect Engineering Pty. Ltd. and galvanised by a reputable and nationally recognised galvaniser, is certified to AS/NZS ISO 9002 *Quality Systems*. The work of this supplier was not acceptable.

Prior to installation, all components were audited and recorded as satisfying all of the dimensional and surface requirements as stipulated by the designs. Upon examination of the galvanised structural steel, it became obvious that several items had been chipped. The reason that this was important was that the chipped areas, which expose the underlying steel, are vulnerable to corrosion. The chipping was due to either the use of an incorrect application temperature or mishandling during galvanising or transport. The galvanised components were rejected and the galvanisers were instructed to strip the items to bare metal and re-galvanise them.

4.5.5 Aluminium Alloy Strips 6061 T6 and 6060 T5 to Hold Louvres in Place

The presence of loose louvres, as shown in Figure 4.33, presented a serious structural problem. Consequently, retaining strips of 6061 T6 aluminium were placed in the centres of the louvre panels. This alloy was determined to be the best aluminium strip in terms of the combination of strength and corrosion resistance. However, it also was observed that the best shape available for use in the corners was manufactured using 6060 T5, which was determined by calculation to be able to give adequate support. Consequently, the corners were restrained with angle strip of this alloy. The angles were 60 mm x 25 mm x 3 mm, welded to equal angle of the same alloy of size 100 mm x 100 mm x 6 mm, and chemically anchored in concrete.

Although both 6061 and 6060 have high corrosion resistances, the strips additionally were powder coated with Dulux Duratech 900 Chalk USA for added corrosion protection and colour match (see Appendix L). The strips themselves were secured using 3 mm thickness aluminium plates, as shown by the grey rectangles that can be seen in Figure 4.34. These plates were powder coated. The bolts shown were of high tensile grade steel and threaded through to internal brackets specifically made to secure these louvres. Although the bolts were galvanised, extension of the threaded length required coating with cold galvanising (aerosal cold gal; see Appendix L). This is a 98.5% zinc-rich aerosol spray that contains durable epoxy resin and sacrificial zinc pigment. This is used commonly for long-term protection of steel surfaces against corrosion and is recommended for use with steel in cases of severe corrosion.

4.5.6 Attachment of Specialised Aluminium-Grade Rivets onto Aluminium Alloy Strips to Secure Louvres in Place

Aerospace-grade rivets of structural aluminium grade, having a sleeve body of 5056 aluminium with clear chromate and body or mandrel of 7075 aluminium with gold chromate, were used. These rivets have exceptionally high tensile and shear properties (see Appendix M). Most importantly, they do not encourage corrosion (see Figure 4.8a and Appendix M). The existing rivets had aluminium sleeves but steel mandrels. It was the steel mandrel that was corroding and leaving the aluminium sleeve with unsuitable tensile and shear properties capable of accommodating loading. The intention of riveting each louvre with strip was primarily to ensure that, if the existing corroded screws, which pass through the screw flutes of the louvre blades and connect the louvres to the mullions, as shown in Figure 4.35, failed, the rivets would retain the louvres securely. In this case, the existing screws, which also were corroded severely, no longer would pose a risk, even if the screws were to fail (see Figure 4.36).

4.5.7 Securing of Existing Aluminium Angle at Base of Louvres on Level 29

Hot dip galvanised M8 high tensile hexagonal head bolts also were bolted onto each of the single vertical mullions from the outside to the inside, passing through the brackets connected to the PFC (see Figure 4.37) at the top, and through the equal angle at the base for added strength to ensure that the wind load would have no bearing on the louvres (see Figure 4.38). Figure 4.38b shows the *Hilti* M8 chemically anchored bolts in the existing equal angle and through the concrete hob. This dual bolting system, which went through the mullion and into the equal angle, combined with, chemical anchoring of the equal angle, provides triaxial strength characteristics.

4.5.8 Structural Rectangular Hollow Section (RHS) Columns on Level 29

All of the vertical RHS columns exhibited holes at the tops and these allowed water to reside inside the columns. Figure 4.39 shows one such column, located on the south face near the western side, where it was corroded severely owing to water retention within the interior of the column. Therefore, the corroded RHSs were replaced with new RHSs that were hot dip galvanised, as shown in Figure 4.40.

(Note: *An important aspect of quality assurance also applies to site supervision. During work on this section, in the absence of supervision by Perfect Engineering Pty. Ltd., the column shown in Figure 4.39 was removed by an external fabricator. He asked the consulting structural engineer, who had been engaged to certify the structural components as a secondary check on the company's work, whether he could cut the RHS, weld it on site, and spray the sections with coldgal, which is a zinc-rich spray. The structural engineer agreed to this procedure. When this became known to Perfect Engineering Pty. Ltd, the structural engineer was informed that this practice was incorrect, it was not approved, and that the fabricator must remove the RHS, make a new one, and hot dip galvanise it to specification.*)

The holes in the tops of all of the RHS columns were plugged with a two-mix steel putty, as shown in Figure 4.41. The water in the columns was drained from the bottom by drilling a 6 mm hole in the column bases, as shown in Figure 4.42. The bases of the RHS columns were primed with *Emerbond* and coated with two layers of *Emerclad*; all of the bolts were replaced with new ones. The six main RHS columns on the eastern side originally had large galvanising holes in the bases, as expected. However, these holes had become obstructed partially in some instances with an accretion of residue and corrosion products. These holes were cleared, as shown in Figure 4.43.

The 6 vertical RHS posts on the east side were supported inadequately by severely corroded bolts on the vertical baseplates adjoining the concrete hob, as shown in Figure 4.44. The baseplates, which secured the RHS's to the hob, were separated from the hob by gaps of ~10-15 mm owing to this corrosion. The RHS baseplates were strengthened further by replacing the existing bolts with new hot dip galvanised *Hilti* M20 HSL bolts, which were used to pull the baseplates flush with the hob, as shown in Figure 4.45.

4.5.9 Structural Strengthening of RHS Columns Using Cross-Bracing on Level 29

To provide extra support for the structural RHSs on the east side of level 29, several RHS members, both designated as NTS2 in the drawings were fabricated, spliced, hot dip galvanised, and erected on site. Additional bracing was extended from the louvres and chemically anchored to the concrete wall with *Hilti* M20 chemical anchor bolts, as shown in Figures 4.46 and 4.47. Another section that was not structurally secure was the centre area, surrounded by louvres on level 29 (see Figure 4.46). As shown in Figure 4.48, a channel designated NTS1 in the drawings for reference was designed and constructed in order to encompass three of the existing PFCs diagonally and to be tied to the main PFC on the east side (the existing braced channel was secured a concrete wall). In this way, the structural work in the central area was secured (see Appendix Q).

4.5.10 New Louvre Panels for Southwest Corner

Figure 4.49 shows the new set of louvre panels that was fabricated and installed on site. These louvres had a special profile specifically pressed from 6063 T6 and the mullions were of 6351 T6 C-channel section (100 mm x 25 mm x 3 mm), which is even stronger than 6061 T6. Prior to this, the existing louvres were chemically analysed, as mentioned earlier in Section 4.4, and found to consist of either 6060 or 6063 aluminium (see Appendix F). However, as discussed in Sections 3.1 and 3.8.3, 6351 T6 has superior corrosion resistance and strength.

The challenge presented was that the new louvre panels had to be manufactured with a profile similar to that of existing louvres, which were 30 years old and are no longer available. It was decided that the new louvres would be welded individually to the mullions in order to provide extra strength. Therefore, this eliminated the need to incorporate screws or rivets that connect these louvres to the mullions.

Wind load calculations were undertaken in order to ensure that the profile would not introduce any undue loading (see Appendices P and Q). This design was superior to the original in that 6351 was used instead of the original 6063 in the mullions largely owing to the superior properties of 6351.

The calculations for the new louvres were based on wind loading using the extreme windward pressure according to AS 1170.2 *Structural Design Actions – Wind Actions*. Although the ultimate wind pressure was determined to be 1.28 kPa, the line load (force of wind acting over the length of the angle) was found to be only 0.11 kN. This suggests that the deflection in the louvre blade also would be low, and the calculations confirmed only a 0.43 mm deflection over a span of 4100 (unitless). Hence, the loading on the welded sections at the joints were calculated to be only 0.15 kN. These calculations will be discussed subsequently.

Figure 4.50 shows louvre panels fabricated from existing louvres. Some parts can be seen to be primed with the red *Emerbond*. This was done at Westfield's request. These parts as well as the base equal angle, according to my recommendations, were coated subsequently with *Emerclad* by Westfield. Other louvre panels were powder coated as a precaution and for aesthetic reasons. This treatment has a 10 year guarantee.

This new louvre panel section received additional structural support in response to the unusually high wind loads experienced regularly on the southwest corner. As shown in Figure 4.51, several hot dip galvanised supports were either welded or bolted to the existing cross-brace facing west. The main brace visible in this view was chemically anchored to the hob with *Hilti* M18 bolts. The south side, which faced the childcare facility, was reinforced with an additional hot dip galvanised PFC. The columns were fabricated and chemically anchored on site using *Hilti* M18 bolts to support the new section of louvres, as shown in Figures 4.52 and 4.53.

4.5.11 Refurbishment of Weld-Damaged Louvre Panels above Building Maintenance Unit (BMU)

The louvre panel above the BMU adjacent to the southwest side was dismantled and a new one was fabricated by welding the louvres onto a new frame, as shown in Figure 4.54. New brackets and strips were installed in order to increase the strength. The louvre materials were powder coated for aesthetic and corrosion-resistance purposes.

4.5.12 Securing of Parapet to Hob and Louvres

The parapet on level 29 was loose in many sections. The bolts that held the parapet in place were largely ineffective since many had pulled out. As shown in Figure 4.55, *Hilti* hot dip galvanised M8 bolts were chemically anchored to the concrete and the cladding was secured using washers to avoid pull-out or ripping of the cladding. The cladding thus was pulled tight against the concrete hob. The cladding was riveted into the mullion from the side facing outwards, as shown in Figures 4.56 and 4.57, which show the parapet before and after being riveted, respectively. This not only secured the parapet but it ensured that the louvres received additional structural support, as shown in Figure 4.58.

The main reason that the parapet was loose in many areas was due to the fact, when painters, electricians, and other tradespeople descend in the BMU along the side of the building, they frequently hit the cladding with the BMU, as suggested by Figure 4.59.

4.5.13 Securing of Louvres on Main Louvre Sections

As shown in Figure 4.60, abseilers worked on the outside of the louvres on levels 27 and 28 since the louvres on level 29 were accessible from the rooftop and the BMU could access only level 26. 6061 T6 aluminium strips were riveted in the centres of the louvre sections where the main vertical mullions met, as shown in Figures 4.61 and 4.62. The strips were riveted to each louvre blade and the strips were riveted to the mullions at every second louvre span distance (see Figure 4.36).

Special jigs were made and married up with the brackets during fabrication so that specially made and threaded high tensile grade bolts would pass through the strip on the outside, through the mullion, and into the brackets (upper U-shaped brackets and lower brackets, as discussed previously), which were positioned on the inside of level 28 (see Figures 4.63a and 4.63b for the upper brackets and Figure 4.63c for the lower brackets).

High-alloy grade M8 bolts were selected because the shank was threaded beyond the existing thread region and the high strength would tend to compensate for any degradation caused by the threading. A second reason was their corrosion resistance.

The brackets had six holes each, with nuts that were welded to the face with the holes and positioned so that each bolt would align and thread through to secure it in place, as shown in Figures 4.64 and 4.65. Figure 4.64 illustrates the lower C-bracket and Figure 4.65 shows the upper U-bracket.

Table 4.1 lists the types, locations, and quantities of the designated types of brackets that were used.

Table 4.1. Summary of common brackets designated and designed for internal and external use.

Level 28 Internal Brackets

Support facade louvres

	N	E	S	W
1	1 UBc , 1 LBc & 3 LB	1 UBc , 1 LBc & 3 LB	1 UBc & 3 LB , 1 LBc (EA 40 X 40 X 6)	1 UBc , 1 LBc & 3 LB
2	1 UBc , 1 LBc & 5 LB	1 UBc , 1 LBc & 3 LB	1 UBc , 1 LBc & 3 LB	1 UBc , 1 LBc & 3 LB
3	UBc , LBc - PLATE & 2LB	1 UBc , 1 LBc & 3 LB	1 UBc , 1 LBc & 3 LB	1 UBc , 1 LBc & 3 LB
4	1 UBc , 1 LBc & 7LB - L Shaped	NA	1 UBc , 1 LBc & 3 LB	NA

UBc	13
UBc - plate N3	1
LBc	12
LBc - plate N3	1
LBc - EA 40x40x6	1
LB sides	40
LB - L shape	7

Legend:

N = North

E = East

S = South

W = West

1 = Bracket position commencing on left-hand side

2 = Bracket position adjacent to 1

3 = Bracket position adjacent to 2
4 = Bracket position terminating on right-hand side
UBc = Upper bracket centre
UBc - plate N3 = Upper bracket centre (with plate for hob fixing)
LBc = Lower bracket centre
LBc - plate N3 = Lower bracket centre (with plate for hob fixing)
LBc - EA 40 x 40 x 6 = Lower bracket centre (with equal angle)
LB sides = Lower bracket (on left or right side)
LB - L shape = Lower bracket (L-shaped)

Figure 4.64b shows a mullion being treated with *Emerbond* and *Emerclad* (see Appendix (L). The original condition of this member in the corroded state is shown in Figure 4.17. Also, the mullion has been given a special type of bracket, as shown in Figure 4.64b, on the right side. This acts as a claw, holding the mullion with special rivets of aluminium with high tensile/shear properties.

The two large brackets, as shown in Figures 4.64a and 4.65a, are typical representations of those used for each louvre section, and the dimensions of the upper brackets are summarised in Table 4.2 (refer also to Appendices H and N for bracket positions). Each bracket was to be made of a different configuration owing to the internal configuration and space available.

Table 4.2. Dimensions of upper brackets at different locations around building.

Location	Upper Bracket Centre (UBc) Dimension (mm)						
	A	B	C	D	E	F	G**
N1	550	891	250	1020	125	125	--
N2	800	888	430	770	170	260	--
N3*	N/A	N/A	N/A	N/A	N/A	N/A	--
N4	550	891	250	1025	125	125	--
E1	550	891	250	1015	125	125	--
E2	1050	396	250	1000	125	125	--
E3	550	891	250	1025	125	125	--
S1	550	891	250	1025	125	125	--
S2	1050	396	250	1000	125	125	--
S3	1050	396	250	1020	125	125	--
S4	550	743	250	1020	125	125	--
W1	550	861	250	1020	125	125	--
W2	850	692	250	825	125	125	200
W3	550	891	250	1020	125	125	--

* N3 is a Telecon control room. The condition of the brackets in this room was excellent, with no trace of corrosion. This section was totally enclosed except for one face that had a louvre system.

** These measurements were not assessed individually owing to the variation in the B dimension. The absent measurements were in the range 120-160 mm.

The nuts were welded on the inside of the brackets because it was virtually impossible to thread a nut onto the bolt from the inside, especially when the section of the mullion being tightened was either sitting behind a hob or a wall (see Figure 4.65d). This method actually held the whole louvre section and tied it into the brackets on the inside. This method had to be applied for every bracket around the building.

The drawing of Figure 4.65a shows another typical detailed sketch that was done on site for the critical dimensions for the upper U-bracket connecting the mullion from the internal of level 28 using six bolts. The brackets shown in Figures 4.65c and 4.65d had to be designed to ensure that the louvre system behind a concrete wall would be secured. The brackets had to be detailed on site as did the adjoining plates (for the lower brackets). The one shown in Figure 4.65d was ~300 mm x 300 mm, it was secured with eight bolts, and it was located behind a wall. This location could not be accessed by hand and was difficult to see from any angle. The top bracket were constructed similarly. These descriptions illustrate the complexity and level of precision required to achieve each different requirement throughout the project.

The upper brackets were the principal members supporting the majority of the wind pressure forces acting on the louvre system from the outside. Therefore, the dimensions and locations of the chemical anchor bolts and the sizes of the angles were extremely important to the design. The main issues are illustrated in Figure 4.33, showing loose louvres requiring support, and Figure 4.63, showing jigs to marry with upper brackets for bolting. The upper brackets required the design and fabrication of only four types of jigs for the installation of the upper brackets because, regardless of the lengths of the different dimensions (A to G), the anchor holes were located according to four variants.

The wind loading calculations will be explained in the following Section in more detail. In order to calculate the loads on the brackets, the wind load pressure was calculated in accordance with AS1170.2 *Structural Design Actions – Wind Actions* (see Appendix P). The angle tension capacity (258 kN) for the 50 mm x 50 mm x 6 mm EA, which was of primary concern, was calculated to be satisfactory for every bracket. The forces acting upon the chemical anchors in the concrete roof were found to be both tensile and shear. However, the greatest forces were calculated to be in tension (see Appendix Q). The tensile forces, when exerted on the anchors under pressure and suction, were identical, yet the shear forces on the bolts were greater under suction. The suction forces were shown principally to exert tension on the anchor bolts away from the louvre side, whereas the pressure forces exerted mainly tension on the anchors closer to the louvre side. When dimension B was extended, then dimension A became smaller and *vice versa*. These dimensional changes were necessitated on site regardless of the calculations since the site locations in some locations contained piping, which was in the vicinity, and this dictated these measurements.

4.6 Pressure and Suction Wind Calculations on Louvre and Brackets

Using the calculations from Appendix P for the forces acting on the louvres and thus against the upper brackets (see Figure 4.65a), the calculations, used for the pressure and suction forces on the louvre system in wind conditions, as specified by AS1170 Part 2:2002 (see Appendices P and Q) must be used. A dimension for B was chosen as an arbitrary value to reflect an average value for the B values in Table 4.2. The total wind pressure exerted upon the chemical anchors in the concrete roof was calculated to be 6.8 kN, acting horizontally on the bolt to the far left (see Appendix Q for complete calculations and vector forces). The moment about this anchor was 2.5 kN·m. The forces acting along the angle on the bolt are the shear force of 3.4 kN and the tensile force of 13.7 kN. Whilst under suction, the tensile force was exerted mainly on the bolt closer to the right, *i.e.*, toward the louvres outside. The shear force on the bolt under suction was 2.2 kN and the tensile force was 12.7 kN.

4.7 Equal Angle to Hold Edges of Main Louvre Sections

As shown in Figures 4.66a and 4.66b for the 6060 T5 unequal angle (UA) and in Figure 4.66c and 4.66d for 6060 T5 EA, the EA and UA were placed at either side of the middle strip, for example, at the edges of the louvres and adjacent to the concrete wall. Both EA and UA were used due to the geometry and practical positioning of the angles against the concrete and louvre. Each angle was riveted using aluminium alloy 5050/7075 rivets to an individual louvre blade and again to the mullion at every alternative louvre span distance. The EA also was secured to the concrete wall adjacent to the louvre sections with *Hilti* hot dip galvanised M10 chemical anchor bolts (see Figures 4.66a-e). Holes 6 mm in diameter were drilled in the horizontal mullions all around the building so that no water could be entrapped. This was taken as an extra precaution since the original design of the mullions did not allow drainage of water from the horizontal mullions. This method actually held the entire louvre section at the edges and tied it into the concrete wall. The calculations of the forces and the results are given in Chapter 7.0 and Appendices P and Q.

4.8 Securing of Entire Louvre Sections on Level 26

Work similar to the preceding was performed, the exception being in the centre of the louvre, where the two main mullions met. Here, an EA was chemically anchored to the concrete roof sill above with two M10 *Hilti* chemical bolts and the angles on either side also were secured to the mullions by riveting and placing M10 chemical anchors into the concrete walls (see Figures 4.66e, 4.67, and 4.68).

Figure 4.67 shows EA chemically anchored to the concrete roof and secured to the louvre on level 26. Figure 4.68 shows concrete drilling to a certain depth as required for chemical anchoring. The EA was chemically anchored to the concrete roof in order to hold the louvre mullion sections in the centre. Figure 4.69 shows a typical arrangement of the BMU, with levels 27-29 above.

Table 4.1 shows a summary of the different brackets positioned at various locations around the building on level 28. The brackets in the table are designated according to the type, location in which they are secured. For example, LB represents lower brackets (either left or right side), LBc represents lower brackets in the centre, and UBc represents upper brackets in the centre. Table 4.1 shows the location of each type of bracket and the quantities of each, as summarised below the table. Figure 4.22 shows an example of typical LB and LBc brackets, Figure 4.64 shows an LBc in more detail, and Figure 4.65c shows an LBc - plate N3, which has the plate (300 mm x 300 mm x 10 mm) welded to EA 50 mm x 50 mm x 6 mm. There also was an upper bracket in the same location, with slightly different positioning of the equal angle. Table 4.1 can be used for future purposes in conjunction with the drawings, should the client or other contractors require replacement of any bracket.

Work similar to the preceding was performed here. The exception was in the centre of the louvre where the two main mullions meet. Here, an angle was chemically anchored to the concrete roof sill above with two M10 *Hilti* chemical bolts and the angles on either side also were secured to the mullions by riveting and placing M10 chemical anchors into the concrete walls (see Figures 4.66e, 4.67, and 4.68).

Figure 4.67 shows structural aluminium EA chemically anchored to the concrete roof and secured to the louvre on level 26. Figure 4.68 shows concrete drilling to a certain depth as required for chemical anchoring. The EA was chemically anchored to the concrete roof in order to hold the louvre mullion sections in the centre. Figure 4.69 shows a typical arrangement of the BMU, with levels 27-29 above.

Table 4.1 summarises the different brackets positioned at various locations around the building on level 28. These brackets are designated according to type and location. For example, LB represents lower brackets (either left or right side), LBc represents lower brackets in the centre, and UBc represents upper brackets in the centre. The total number of each type of bracket is listed below Table 4.1. Figure 4.22 shows an example of typical LB and LBc brackets, Figure 4.64 shows a LBc in more detail, and Figure 4.65c shows a LBC-Plate N3, which has a plate (300 mm x 300 mm x 10 mm) welded to an EA (50 mm x 50 mm x 6 mm). The reference table can be used for future purposes along with the drawings should Westfield or other contractors require replacement of any brackets.

4.9 Maintenance Recommendations

The Managing Director (myself) and Compliance Manager of Perfect Engineering Pty. Ltd. conduct semi-annual inspections each year and provide one report to Westfield early each February (see Appendix O. *Note; see customer feedback from Westfields concerning this project and a feedback form from Qantas also*). Perfect Engineering Pty. Ltd. has continued to consult with the Westfield representatives who are responsible for acknowledging and signing off on these inspections. Perfect Engineering Pty. Ltd. provided an inspection outline, and, in accordance with this, when each inspection has been finalised, the paperwork has been completed and both Perfect Engineering Pty. Ltd. and Westfield have signed the document as a correct and permanent record. The 5 year guarantee to Westfield requires adherence to certain measures in order not to void it in certain aspects:

a) When contractors perform their work, particularly on levels 28 and 29, they must not place stainless steel, steel, or any other material in contact with the louvres. No bolt, rivet, cladding material, or other object can be placed on the louvres, channels, or other structural item. These actions can cause a galvanic reaction and aid corrosion. Westfield has been cautioned of inaction and advised to adhere to these simple measures.

b) The mullion on level 28 on the north side near the east corner was severely corroded but has been treated. Detailed recommendations for maintenance were provided to the client in the report.
c) It was recommended that all of the baffles and the baffle benches that support the baffles should be removed. The corrosion of these baffles and surrounding structure is of concern. At present, Perfect Engineering Pty. Ltd. has removed all of the material in contact with the louvres, which has resulted in the stabilisation of the corrosion rate. However, the continual presence of the baffles may cause further corrosion to the louvres when the corroded metal flakes fall in the mullions and reside there, causing galvanic corrosion. Otherwise, these areas must be washed down more regularly.
d) Damage to the parapet was apparent and a result of contractors' descending the building and hitting the parapet on the way down. The wind is a contributing factor to this and hinders stabilisation of the BMU. Two other recommendations provided to Westfield are as follows:
    - Re-positioning the BMU in such a way as to avoid hitting parapet
    - Submission of SWMSs by contractors in order to ensure that they are equipped with the appropriate knowledge of wind forecast conditions and general safety to themselves but also in order to avoid further damage to the parapet

CHAPTER 5. Estimated Service Life of Structural Strengthening of Louvres on Levels 26-29

5.1 Factorial Method Applied to Rooftop and Façade

The estimated service life of a component (ESLC) can be projected through the use of a factorial calculation that combines the reference service life of a component (RSLC) with a range of factors that describe its materials properties, design considerations, and environmental conditions. In the present study, this approach was based on the coastal marine macro-climate of Bondi Junction, ~2.2 km from the harbour/ocean (see Figure 4.1a for the location of Westfield Tower 2 relative to the ocean). The climatic conditions, including moisture, shelter, prevailing winds, salinity, and pollution, were based on climatic and materials corrosion modelling software (objective) and professional experience (subjective).

As described in Section 1.8 the factorial method is expressed by the following formula:

ESLC = RSLC · Factor A · Factor B · Factor C · Factor D · Factor E · Factor F · Factor G

where:

Factor A = Inherent Performance Level
Factor B = Design Level
Factor C = Work Execution Level
Factor D = Indoor Environment
Factor E = Outdoor Environment
Factor F = Usage Condition
Factor G = Maintenance Level

ISO 15686-1 [59] bases its approach to the determination of the ESLC on the level of expertise of the individuals who are responsible for draughting the Standard. This expertise must cover a wide range of disciplines, including materials, fabrication and construction, structural considerations, and environmental impacts. These influences must be assessed in terms of their influence upon the structure at issue. This document provides guidance for designers on the service life planning of buildings and refers to other parts of the sub-standards of ISO 15686. It incorporates the following summarised points:

a) *Service Life Planning:* This includes the integration of planning into the design process, including client requirements, forecasting service life, design, acceptance, and final documentation.
b) *Design Process:* This involves the preparation of a checklist for the duration of the design stage in order to ensure that the service life will complement the designed service life. This section includes materials selection, site work, future maintenance planning, and a stipulation of neither under- or over-design for the specific purpose.
c) *Forecasting Service Life:* This section deals with allowance of the adjustment of the predicted service life in the design plan, depending upon project-specific requirements. The Standard cautions against the use of speculative or non-expert judgements.
d) *Prediction of Service Life Due to Exposure and Performance:* Materials selection and general problems encountered by designers are outlined in this section.
e) *Estimating Service Life by Use of the Factorial Method:* This deals with a factorial approach using the seven factors mentioned above, based on knowledge of materials and building technology.
f) *Financial and Environmental Costs during a Specific Period of Time:* This covers life cycle costing, which must be addressed prior to commencement of construction, and maintenance specifications, which should include items from planning through to maintenance and disposal.
g) *Obsolescence, Flexibility and Reuse:* This provides a succinct outline of obsolescence, including functional, technological, and economic. This addresses the possibility that future upgrades, as a result of initial lack of design strategies, would be obsolescent in the future due to excessive costs.

In the present work, the following preliminary issues were used to guide the development of the procedure:

a) All of the approaches to the factorial method use the principles set out in ISO 15686-1 [59]; this was done in the present case.
b) ISO 15686-8.2 [61] suggests the use of factors in the range 0.9-1.1 owing to the inherent uncertainty of the method.
c) Taking the preceding concept further, it is possible to focus on certain key factors by setting others at 1, as has been done by Marteinsson [57] and Rider [140].
d) The methodology utilised in the aircraft industry according to ISO 9223, which considers, for instance; the distance from salt water bodies and type of environment (*e.g.*, rural, marine, or industrial) was adopted (see Appendix V4).

Owing to what was hoped to be a high standard of work, the majority of factors were set at 1, indicating the assumption that they were completely under control and thus not relevant. With this in mind, the present work revealed that the most important factor in corrosion resistance was the micro-climate. The recognition of this situation allowed the adaptation of the method of Rider [140], which was based on the following:

a) *Material Quality – Factor A = 1:* Materials characteristics are assumed to be of sound quality owing to certification for all materials and processes.
b) *Design Level – Factor B = 1:* In-depth research and confirmatory consultations with Westfield gave confidence in the overall design according to best practice principles.
c) *Installation Skill Level – Factor C = 1:* Careful selection, training, and monitoring of tradesmen employed gave confidence in the standard of skills.
d) *Indoor Environment – Factor D = 1:* The presence of the open rooftop and louvres indicates that the assumption that enclosed space lacks the driving force for corrosion is questionable; this factor was adapted from the original variable level owing to the observation that the rooftop and louvres remain in pristine condition.
e) *Outdoor Environment – Factor E = Variable:* Although the preceding comments apply, they also must be considered to apply to wind forces. Of course, a freak wind, beyond the range specified in AS 1170.2, is outside of the assumption.
f) *In-Use Condition – Factor F = 1:* The fact of minimal activity on levels 26-29 and specified maintenance procedures lead to the assumption that this of no relevance.
g) *Maintenance Level – Factor G = 1:* The level of work was to a standard such that interventional maintenance is not anticipated to be required for a minimum of 5 years.

Concerning factor E, based on the approaches used by Marteinsson [57] and Rider [140], a set of factors was established. This is given in Table 5.1.

Table 5.1. Factor E values as a function of coverage, shielding, and inclination.

Factor E	Coverage from Above	Shielding from Sides	Inclination (°)
1.0	Total	Total	0-90
1.0	Nil to Partial	Total	0
0.9	Partial	Nil	0
0.8	Total	Nil	0
0.7	Nil to Partial	Partial	0
0.6	Total	Nil to Partial	0
0.5	Partial to Total	Partial to Total	>45
0.4	Partial to Total	Partial to Total	31-45
0.3	Partial to Total	Partial to Total	21-30
0.2	Partial to Total	Partial to Total	11-20
0.1	Partial to Total	Partial to Total	0-10

As explanation, for example, a value of 1.0 is used when the area is completely enclosed and no corrosive materials have access to the area. However, the same value is used when the area is completely walled in with access from above. This arrangement allows salt and other contaminants to enter the area but the enclosing walls prevent their subsequent removal. The lower values are described in terms of the inclination of the floor since this will affect the ability of rain to wash away the contaminants.

Of course, as stated before, there are many variants that can affect these general values. For example, when spliced joints are compared to flat surfaces, the former enable entrapment of contaminants. The same is true of holes or basically any asperities or irregularities in the surfaces. It goes without saying that the potential for galvanic corrosion would have the effect of overriding the E values. That being said, the considered attitude toward the present work is that it is not anticipated to provide the basis for a conclusion, but to provide a starting point for further thought and assessment.

Using the values in Table 5.1 initially and then, subsequently, other assigned factor values, such as due to wind loads, environmental health and safety, a factorial audit was carried in order to ensure that Perfect Engineering Pty. Ltd. could provide semi-documentary reference material to Westfield for the purpose of projecting the longevity of the materials used. That is, the audit would represent another tool for verifying independently the adherence to the specifications of components and compliance with the intended standard of work that was done on the rooftop and façade of Westfield Tower 2.

The results of this audit are given in Table 5.2. The ESLCs calculated in Table 5.2 are the predicted time the first maintenance will be required to ensure the first signs of predicted corrosion are pacified, and the structural integrity of the component is maintained to a guaranteed in-service design strength/corrosion resistance specification.

While the calculations yielded the minimal ESLC, the maximal ESLC was determined by multiplying the minimal ESLC by fixed ratios based on the combination of factors used in the calculation.

Table 5.2. Results of life cycle prediction program based on ISO 15686 (2006) factorial method.

Figure Number	Component	Material	Coating	Minimal ESLC (Years)	Maximal ESLC	Guaranteed ESLC (Years)	Guarantee Satisfied	Comments
4.20	U bracket	HDGS	Zn 80 µm	25	44	15	Yes	Facing west
4.20	M16 to concrete	HDGS	Zn 40 µm	11	28	20	Yes	Protected by cladding
4.21	M12	HDGS	Zn 40 µm	11	28	15	Yes	Facing west
4.21	Connection to mullion	HDGS	Zn 40 µm	14	35	15	Yes	Facing west
4.21	C bracket	HDGS	Zn 80 µm	12	22	15	Yes	Facing west
4.22	Brackets	HDGS	Zn 80 µm	14	25	15	Yes	Facing west
4.22	Attachment	HDGS	Zn 40 µm	10	18	15	Yes	Facing west
4.24b	New PFC	HDGS	Zn 80 µm	31	55	15	Yes	Roof + splice
4.25b	Repaired structural beam	*Emerbond/ Emerclad*	N/A	5	10	5	Yes	Facing west; integrity of coating depends on non-contact and physical damage
4.25c	Equal angle support	HDGS	Zn 80 µm	31	55	20	Yes	Facing west; horizontal surface
4.29b	New nuts and bolts	HDGS	Zn 40 µm	14	35	20	Yes	Holes in plate; potential crevice sites
4.31	Substitution of rounded brackets and tek screws with high-strength welded brackets/bolts	Bracket butt welded and HDGS	Zn 80 µm	31	55	20	Yes	Evidence of failure of original rounded brackets and tek screws in louvre panels in southwest corner
4.31	Bolts	HDGS	Zn 40 µm	14	35	20	Yes	Extra holes in bracket; potential crevice sites
4.34	Bolts	High tensile steel	Cold gal 98.5% Zn primer for manually threaded region only			10	Yes	Extra long bolt, from external to internal, threaded shank section; coated with cold gal
4.34	Structural rivets sleeve	5056 Al	Clear chromate	10	20	15	Yes	Average 15 years
4.34	Combination of rivets and plate	5056 Al + 6061 Al		10	20	15	Yes	Snug fit of rivet-plate connection
4.34	Structural rivets mandrel	7075 Al	Gold chromate	10	20	15	Yes	Mandrel protected from corrosion by 5056 sleeve
4.37/ 4.38a	M8 hexagonal head bolts	High-tensile and HDGS	Zn 40 µm	14	35	20	Yes	Snug fit; HDGS bolt
4.37	New cover strip	6061 T6 Al	Powder coated	10	20	10	Yes	Powder-coated plate
4.37	Structural rivets sleeve	5056 Al	Clear chromate	7	15	15	Yes	Powder coating/plate interface with sleeve - guarantee 10 years
4.37	Combination of rivets and cover plate	5056 Al + 6061 T6 Al	Clear chromate/ powder coated	7	15	15	Yes	Compatibility; only 5056 in contact with 6061 plate if coating is removed
4.37	Structural rivets mandrel	7075 Al	Gold Chromate	10	20		Yes	
4.38a	Bolts through mullions into equal angle	Bolt HDGS/Al 6061 T6 anodised	Bolt Zn 40 µm, mullion anodised	8	16	15	Yes	Horizontal surface/bolt; potential crevice site
4.38b	Equal angle support	6061 T6 Al	Anodised	10	23	15	Yes	
4.38b	M8 dynabolts into concrete	HDGS	Zn 40 µm			15	Yes	

Figure Number	Component	Material	Coating	Minimal ESLC (Years)	Maximal ESLC	Guaranteed ESLC (Years)	Guarantee Satisfied	Comments
4.40	New RHS	HDGS	Zn 80 µm	31	55	20	Yes	Galvanised holes on top plugged
4.41	Putty	Two-mix steel	Zn cold spray			5	Yes	
4.42	Base of old existing RHS columns	*Emerbond/ Emerclad*	As per Parchem warranty			10	Yes	Coating specification guarantees 10 years; depends on installation
4.45	M20 HSL heavy duty anchors	Zn-plated high strength steel	Zn 5 µm	5	6	5	Yes	Plasma-coated zinc
4.46	Two new fabricated beams	HDGS	Zn 80 µm	31	55	20	Yes	Depends on splice joints; potential crevice sites
4.46	Bolts to existing PFCs	HDGS	Zn 40 µm	14	35	7-10	Yes	Zinc on existing PFCs thinning
4.46/ 4.47	Connection plate to concrete block	HDGS	Zn 80 µm	31	55	10	Yes	Depends on integrity of concrete block
4.47	Bolts holding plate	HDGS	Zn 40 µm	14	35	15	Yes	Bolt-plate; potential crevice site
4.47	Bolt in wall holding plate			5	9		Yes	One of the anchors may pass through the mortar between the blocks; adjacent RHS bracket gives support
4.48a,b	New cross-bracing	HDGS	Zn 80 µm	31	55	20	Yes	Minimal crevice points; all connections open to rain
4.48a,b	Bolts and nuts	HDGS	Zn 40 µm	14	35	20	Yes	PFCs (open), unlike RHS, allow contaminant rain washing; bolts benefit
4.48a,b	Old RHS supporting existing PFCs supporting new cross-beams	HDGS	HDGS Zn 40 µm	8	10	5	Yes	Average life remaining of original HDG RHS is ~8-10 years
4.49a	New louvres	6063 T6 Al	Duratec H900	10	20	10	Yes	Depends on ageing due to welding, which in turn may affect corrosion and strength
4.50a	Cross support and brace	HDGS	Zn 80 µm	31	55	15	Yes	Facing west
4.50a	Supporting M18 bolts and nuts	HDGS	Zn 40 µm	14	35	15	Yes	Facing west
4.52	New PFCs and columns	HDGS	Zn 80 µm	31	55	15	Yes	Facing west
4.53	New EA support	HDGS	Zn 80 µm	25	45	20	Yes	Extra-thick EA has extra galvanising
4.53	Supporting bolts and nuts	HDGS	Zn 40 µm	11	28	20	Yes	Facing west
4.54	Refurbished damaged louvres	Al	Powder coated	10	20	15	Yes	Damaged louvre panels re-welded and powder coated
4.55	M8 dynabolts into concrete	HDGS	Zn 40 µm	14	35	20	Yes	Cladding strength depends on wind load and contractors
4.56	Rivets securing parapet and louvres	5056 Al + 6063 Al	Clear chromate; painted			15	Unknown	Average of 15 years; depends on contractors descending in BMU
4.59	Potential damage by others using BMU	BMU/ Cladding	BMU impact upon cladding	10	25	No data	Yes	Users of BMU must observe weather report on winds and submit SWMSs

Figure Number	Component	Material	Coating	Minimal ESLC (Years)	Maximal ESLC	Guaranteed ESLC (Years)	Guarantee Satisfied	Comments
4.60a – 4.60c	Risk assessment abseilers	Drilling angle affects diameter and rivet tightness	5 mm			No data	Yes	Abseilers ensure procedure for drilling and secure tools according to procedures and SWMSs
final years approaching4.62	6-hole special bracket bottom RHS	HDGS	Zn 80 µm + cold gal	11	20	15	Yes	Cold gal added to bolts and strips; powder-coated plates
4.58/ 4.62	Bolts	HDGS coldgal (tapped section only)	Zn 40 µm	6	14	7	Yes	Low due to being tapped on site and sprayed with cold gal
4.63a	U-bracket	HDGS	Zn 80 µm	25	45	15-20	Yes	Depending on location
4.66	EA support	6060 T5 Al		10	20	15	Yes	
4.66-4.68	M10 bolts into concrete	HDGS	Zn 40 µm	11	28	15	Yes	
4.67	Combination M10 HDGS and 6060 T5 Al	Bolt HDGS/60 x 60 EA	Zn 40 µm + powder coating				Yes	Average of 13.5 years
4.67	Combination M10 HDGS and 6060 T5 Al	Bolt HDGS/60 x 60 EA	Zn 40 µm + powder coating	6	11		Yes	Average of 11 years

5.2 Comments Regarding Life Cycle Prediction Program Results

The values in Table 5.2 generally are based upon the ISO 15686 factorial approach and data from product specifications. The results may be used to extrapolate estimated service life data using known variables, such as zinc galvanising thickness and its life according to ISO 9223. The minimal and maximal ESLCs are based on data that are available. However, the guaranteed ELSCs can be seen to be much lower than the minimal ESLCs because other factors affect the former. For example, when two components of different ESLCs are in contact, the performance of the pair of components is determined by the component with the shortest ESLC. Also, the apposition of the two components may be associated with an increased susceptibility to corrosion, so this also must be taken into account, particularly if one component is older than the other. That is, as mentioned before, the components (*viz.*, their ESLCs) cannot be considered in isolation. An example of the factors assigned and references to other factorial values are given in Appendix V4.

Figure 4.25b shows a repaired structural beam. Table 5.2 indicates that the coating was *Emerbond/Emerclad*, which has a guaranteed estimated service life of the component (ESLC) certified by the manufacturer of 5 years for the base coat *Emerbond* and an additional 5 years for the top coat *Emerclad*. The beam was ground back to bare metal before applying the coating in order to remove all existing corrosion deposits and provide a clean substrate in order to ensure longer protection life. To date, there has been no sign of corrosion. However, since the ESLCs are relatively short at 5 years (despite their additivity), it is advisable to implement a maintenance schedule before the 5 year period terminates in case incipient corrosion occurs.

Figure 4.27 shows evidence of the severe conditions that existed in the southwestern section of the building, where the initial failure of the louvres had occurred during the 20 year service period of the building. The radiused brackets and tek screws are likely to have been amongst the first items that gave way under the high wind loads. Figures 4.29b and 4.31, given in Table 5.2, show the replacement components, which are nuts/bolts and brackets that have estimated ESLCs of 14-35 and 31-55 years, respectively, which are in considerable contrast to the original short-lived counterparts. These significant ESLCs derive from the design, which include maximal strength from butt welding (see Figure 4.30), maximal corrosion resistance from hot dip galvanising, and maximal structural connectivity from hot dip galvanised M8 structural bolts of (compared to 6 mm tek screws). Also, the tek screws originally were connected through the 3 mm mullion thickness whereas the M8 bolts completely traverse the mullion for added strength (see appendix Q).

From Table 5.2, Figures 4.37 and 4.38a indicate minimal and maximal ESLCs of 14 and 35 years, respectively, for the bolt, which has two large dome heads (top of photo). However, the bolt was powder coated, thereby adding to its corrosion resistance and probable lifetime. This configuration was chosen so that it would minimise the potential for tearing should there be excessive pull from the brackets on the other side, which in turn were supported on the PFCs. These bolts passed right through the mullion to connect to the brackets mentioned above for Figures 4.29-4.31. This arrangement provided secure attachment between the brackets, PFCs, and louvre system, ensuring minimal movement. Consequently, the lifetimes of these components could be expected to be increased over those of the ESLCs (owing to the reduced effects of the wind load on the louvre system.

Figure 4.42 illustrates the holes' being drilled at the base of the columns in order to expel water and subsequently being dried with an air hose, after which coldgal, *Emerbond*, and *Emerclad* were applied. Table 5.2 indicates that, from the guarantees for *Emerbond* and *Emerclad*, an ESLC is merited. However, the life of this component may be affected by the installers if appropriate measures are not taken in the coating of the holes. These holes were inspected thoroughly and, additionally, cold gal was applied to the edges of the holes. Consequently, the ESLC could be expected to be increased from 10 years. It is implicit that the plugging of the tops of the columns would increase the lifetime owing to the exclusion of water from the interior of the RHS. Conversely, the base plate, being horizontal with inserted bolts, could provide crevice sites that could accumulate deposits, thereby reducing the lifetime. Thus, the potential for this was reduced by providing additional coating to the base plates, especially at the bolt/nut/plate interfaces.

From Table 5.2, Figure 4.45 indicates a minimal ESLC of 5 year for heavy duty M20 anchors that have a 5 μm thickness zinc coating. Despite the relatively short ESLC, the main benefit of these bolts is the fact that their composition is high in alloying elements for the purpose of strength; such properties often also aid in corrosion resistance. This minimal coating thickness appears to have slipped through the QA and so was not picked up during the audit. The fact that this appears to be the case is likely to be due to the following causes:

a) The bolts were delivered by courier.
b) Tradesmen took possession of the bolts and placed them in storage, away from the *Inwards Goods Inspection Station* that Perfect Engineering Pty. Ltd. had established for the receipt of goods and recording all QA details.
c) The absence of traceability documentation was not detected.

Naturally, the greater the coating thickness, the longer is the corrosion protection period, so a zinc coating thickness of only 5 μm was of concern. However, an advantage of having undertaken an ESLC audit is that this situation was revealed and so corrective action has been scheduled to take place before February 2009, at which time a thicker layer of cold gal (see Appendix I for cold gal specification) will be applied to these bolts and any other areas that might be of concern. The corrective action actually is part of QA system, which involves the recording of incidents of concern on a standard form, specification of the relevant details and recommendations, such as:

a) Material description
b) Cause of problem
c) Action to correct problem
d) Action to verify effectiveness of corrective action
e) Action to eliminate problem from future occurrence

It appears that the supplier of the bolt, *Hilti*, does not coat this bolt size to >5 μm of zinc, which should have been known from the product details. That being said, this exercise has highlighted the need for more periodic checks and the requirement for tighter control of deliveries that occur outside the normal QA system.

Overall, while the calculated ESLCs are based on known data, it is desirable to incorporate additional factors not usually considered in conventional factorial methods. A number of these factors came to light during the progress of the present work, including whether or not the components were sheltered and orientation of the building section relative to the direction of seaspray. If a sound mathematical model is to be used to support the factorial method for Westfield Tower 2, then the designer must stipulate that the model will have the capacity to approach validity only if a thorough re-assessment is undertaken. It was only through a final audit that these issues emerged, thereby providing the opportunity to go back and rectify any shortcomings in the entire system, which is almost inevitable in a project of this magnitude.

Ultimately, it is concluded that the main shortcomings of the factorial method are as follows:

a) Approach of the factorial method's being limited to general issues, to the partial exclusion of specific ones.
b) Virtual impossibility of recognising all relevant factors and consequent inability to incorporate them in the audit
c) Difficulty in incorporating aspects associated with factors, such as the influence of welding and resultant microstructure on the corrosion resistance
d) Limited amount of data upon which to base the assignment of values to the known factors
e) Potentially misleading or incorrect data used as the basis for the assignment of values to the known factors
f) Probable absence of data upon which to base the assignment of values to newly introduced factors
g) Subjectivity of the assignment of values to the factors
h) Unrealistically narrow range of factor values used (~1)

Despite these shortcomings, the process still yields potentially useful information. In particular, the ESLCs generally exceed the 5 year guarantee made by Perfect Engineering Pty. Ltd. to Westfield by a comfortable margin.

The examination of the validity of an ESLC audit requires the understanding of a complex range of complementary factors associated with materials and processes. The risk with such an audit is that the designer, an individual conducting a different but related assessment, a person undertaking a feasibility study for prospective clients, or existing owners would be unaware of these complementary factors. Meeting these demands is perhaps unrealistic and so such an audit should involve experts across a range of disciplines, including materials properties and performance, materials processing, structural stability, environmental effects, and so on. It remains to be seen whether this procedure would be adopted widely.

Contents of the Data in Table 5.2

Table 5.2 provides information on:

a) Types of materials and coatings
b) Minimal and maximal estimated service lives
c) Manufacturers' guarantees and prognoses for surpassing them
d) Pertinent comments

Advantages of the Data in Table 5.2

The data in Table 5.2 are useful in that they provide a summary of the majority of the critical components that require attention and are of prime concern in terms of expected life and related safety issues. They also are useful in that they can be used to schedule maintenance, providing a summary of components due for maintenance. The table is a quick guide for referencing the major materials and components of concern on site and it highlights what needs to be replaced and when. Information regarding some aspects of fabrication and processing also are presented should future contractors or the client wish to replace items periodically.

Disadvantages of the Data in Table 5.2

Table 5.2 also has limitations. The information is very brief, which may be insufficient to transmit some key information. It is advisable for an in-depth understanding of the entire system to be had prior to addressing any one component. That is, Table 5.2 presents ESLC data spread over a broad range but consideration of these data in isolation could pose a potential risk if these data are used as the basis to assess a specific lifetime to the exclusion of associated issues.

Another major disadvantage of the data in Table 5.2 is the interpretation of the results. For instance, assessment of the life of components, such as bolts, PFCs, *etc.* may require subjective interpretation. For example, Figure 4.48a shows hot dip galvanised PFC cross beam-brackets being connected to existing PFCs that support the louvre system on level 29. Whilst the results for the nuts and bolts are shown in Table 5.2 as having ESLCs in the range 14-35 years, the values for the old RHS to which these nuts and bolts are attached were much lower at 8-10 years. If the old RHSs provide the principal support to the above beams, then greater weight should be given to the ESLC of the RHS. That is, the values for the cross-beams and bolts are only as good as the weakest link, which is the old RHS columns. The table does not take this into account and so care must be taken when interpreting components that exist in association with others.

Failure of the Factorial Method

The factors assigned to the various materials and coatings fall into a very narrow range of values. This is a very simplified approach to providing a service life for any component. Even though ISO 15686-1 demands an understanding of the materials and their characteristics, it does not incorporate consideration of other more pertinent information, such as the processing of materials. For example, welding involves many variables and factors that would require more than that assumed by the factorial method.

Examples of Failure of the Factorial Approach

In the present project, the factorial approach failed in several areas. One instance is where the fabricator on site decided that he wanted to cut and weld on site without any consultation or approval. The uncertainty associated with the practices of the fabricator could not be incorporated in the relevant factors since the practice might have gone unnoticed and hence neglected.

Improvement of the Factorial Method

The factorial method is likely to experience the most improvement by modification of the treatment of the factors. The availability of more and better empirical evidence, consideration of new types of factors, and an effort to acquire these data by the industry, academia, and the Government would contribute to the potential to identify and assess factors more meaningfully.

Summary

The advantages of the factorial method are:

a) It has provided me with a level of confidence that the projected lifetimes greatly exceed the requirements.
b) The method provides a starting point for presenting the information to future clients in order to give them confidence in the materials and approaches to be used.
c) The method represents additional audit of basic parameters that can assist in the identification of anomalies and oversights.

5.3 Possible Effects of Welding and Ageing on ESLC Life for Newly Fabricated Mullions/Louvres

From the preceding, it is apparent that the factorial method must take into account the variabilities associated with the materials themselves and their processing. Although these factors tend to be recognised generally [141], there do not appear to be any significant studies in these areas. Consequently, the present work discusses some of these factors as they relate to ageing effects of welded aluminum. It is considered that these are essential to consider if a realistic minimal ESLC is to be calculated.

Of all the potential sources which cause corrosion, the manufacturer has direct control of the design and manufacture of the airplane and some limited control in the maintenance practices since a recommended maintenance program accompanies each airplane delivered [71,72].

The manufacturer or merchant may be the original manufacturer of the aluminium or steel. The secondary manufacturer may be the fabricator (workshop or on site).

In the present work, the louvres were welded because the old louvre system was secured to a fly brace with vertical elements joining a single horizontal element for each louvre. This system was unnecessarily complex and subject to corrosion of the rivets and screws, as shown in Figure 4.35. It is important to recall that the welding of tempered aluminium alloys can be expected to lower the strengths by approximately 50% for many alloys. This effect is shown in Table 5.3. While it is possible to repeat heat treat the material to restore the temper, this often is not practical for large pieces, such as the louvres. The effect of welding on the ageing and therefore the overall strength properties of the aluminium will be discussed in detail in Section 7.1.

Table 5.3. Properties of welded aluminium alloys (from Table 3.4).

Component	Grade	Temper	Tensile Strength (MPa)		Welded Tensile Strength (MPa)
			Range	Average	
New Mullion	6351	T6	275-330	302	140
New Louvre	6063	T6	170-245	207	130
Old Mullion	6063	T6*	170-245	207	130
Old Louvre	6060	T5*	110-175	142	90

* Temper unknown (T5 or T6?) for old mullion and louvre.

However, this probably is not critical in this case because it can be seen that the welded strengths of the new mullion (140 MPa) and new louvre (130 MPa) are in the range of that of the unwelded old louvre (average 142 MPa) for 6060 T5 and for the unwelded old mullion (207 MPa) for 6063 T6. As stated in Section 2.1, it is not certain which temper was used with the two alloys for the old mullion and old louvre. Hence, it was considered that, from the strength perspective, an acceptable result would be obtained by the welding of 6351 T6 and 6063 T6.

However, as discussed previously, hardness and strength following welding provide little or no indication of the actual ageing as a result of the variability in microstructures, which have an effect on the corrosion resistance. Also, filler metals play a vital role in the determination of strength of the weld and the corrosion resistance.

5.4 General Observations of Validity of ESLC Life for other Fabricated and Installed Components on Westfield Rooftop

Even from this small sampling of the preceding variables, it is clear that the factorial method is simplistic and subject to some considerable uncertainties. As Marteinsson [57] points out, the method is generic and the concept of *explicit values* for factors is problematic. In his opinion, the most critical issue is the importance of having the required information concerning materials technologies and deterioration such that the designer of the factorial can assign what are intended to be meaningful values.

In the present work, I have organised a factorial audit largely in the hope of being able to assess the viability of determining the following:

a) Whether the materials and methodology of the project were valid
b) Whether the factorial approach offered a suitable means of doing so

At this point, the conclusion is that the results must be viewed as being tentative at best. Although the assignment of factor values represented the biggest challenge to the procedure, indicative data for ESLCs for the entire range of materials used were obtained and these data exceeded the minimal requirement sufficiently such that it is not unreasonable to conclude that the uncertainties in the technique are covered by the effective safety factor represented by the differences between the requirement and the projections. Perhaps the most useful outcomes of this work are that:

a) The factor values require greater attention to be paid to variability (materials and processing), risk, probability, and alteration over time.
b) It has highlighted the need for additional assessments and inspection once the project has been completed.

Assessment of the literature and the present work suggest that auditors of the ISO 15686 (in any of the required sub-standards 15686-1 to 15686-8) factorial method have little choice but to reference against existing data specific to certain materials, processes, conditions, and environments. However, as in many previous types of study, improvements in data and approaches, which start from only general applicability, will lead to the potential to identify and focus on essential variables such that the applicability becomes more specialised, thereby allowing the approach to be directed toward the relevant conditions. This would allow the auditor greater justification in the subjective selection of factor values.

An example of such a consideration is the potential difference between macro- and micro-climatic conditions. At present, the factorial method is able to accommodate only the former with any degree of confidence. When airborne salts are present, the factor values are assigned on the basis of the absence/presence of salt and the degree of accessibility to the structure; these involve macro-climatic considerations. However, retention of the salt in crevices, particularly in the presence of water, is likely to prove to provide a much greater driving force for corrosion; this is a micro-climatic consideration that is not incorporated in the factor values. Even if it were, the value assigned would have to be modified by the degree of rainfall and the potential to wash away salt deposits as well as the potential for wind to blow them away. Further weighting would need to be given to the type and frequency of maintenance, which could result in manual removal of salt. This example makes it clear that a factorial method that incorporates a true indication of all of the relevant factors and their weightings would be likely to become hopelessly burdened with detail. Ironically, this observation is a recommendation for the retention of the general approach.

One of the areas not considered in the factor values is the incline of a roof. This variable is important because the incline is related to both the vertical area exposed to horizontally driven sea spray and the ease of retention of the salt. However, the presence of barrier walls and their locations (north – N, south – S, east – E, west – W) will affect the salt deposition by blocking the transit of the sea spray. Hypothetical examples of the type and amount of information that must be developed for such cases are given in Tables 5.4 to 5.6. Here, the factors affecting corrosion involve:

a) Effect of incline
b) Effect of barrier wall(s)
c) Combined effect of incline and barrier wall(s)

Table 5.4. Corrosion slope factors for steel/aluminium at various inclines without contact with other metals and in open on rooftop levels 28 and 29.

Incline (°)	0	10	20	30	40	50	60	70	80	90
Corrosion Slope Factor	0.30	0.40	0.50	0.60	0.70	0.80	0.90	0.95	1.00	1.00

Table 5.5. Corrosion shelter factors for steel with wind and airborne contaminant exposure from various directions with no rooftop shelter on rooftop levels 28 and 29.

Barrier Side(s)	**N, E, S, W**	**E, S, W**	**E, W**	**E**	**None**
Corrosion Shelter Factor	0.5	0.6	0.7	0.8	0.9

Table 5.6. Corrosion orientation factors for steel multiplied by shelter type with corresponding inclines and with no rooftop and certain walls blockading wind and airborne deposits on rooftop levels 28 and 29.

Barrier Side(s) →	**N, E, S, W**	**E, S, W**	**E, W**	**E**	**None**
Incline (°) ↓	**Corrosion Severity Factor**				
0	0.150	0.180	0.210	0.240	0.270
10	0.200	0.240	0.280	0.320	0.360
20	0.250	0.300	0.350	0.400	0.450
30	0.300	0.360	0.420	0.480	0.540
40	0.350	0.420	0.490	0.560	0.630
50	0.400	0.480	0.560	0.640	0.720
60	0.450	0.540	0.630	0.720	0.810
70	0.475	0.570	0.665	0.760	0.855
80	0.500	0.600	0.700	0.800	0.900
90	0.500	0.600	0.700	0.800	0.900

The values in Tables 5.4 and 5.5 are based on analogies with the work of Marteinsson [20,57] and studies of corrosion and its effects on aircraft and bridges, as outlined previously (see Appendix V4). The main parameters were material, age, location, orientation, vertical barrier, and horizontal shelter. Table 5.6 combines the data in Tables 5.4 and 5.6 by simple multiplication.

The values in Table 5.6 were obtained by multiplying those in Table 5.4 by those in Table 5.5. Figure 5.1 plots the corrosion slope factor against the corrosion severity factor, so called because the multiplication of variables provides a graded rating of the degree of severity of the variable. The data are given in terms of the corrosion shelter factor or the number of walls enclosing the area of interest, assuming no above coverage.

This figure can be useful to designers because it allows a comparison of the conditions that can be designed with corrosion-resistance in mind. For example, if it is desired to build a structure with a moderate lifespan dictated by corrosion, then a severity factor of 0.5 might be selected. In Figure 5.1, this can be identified and a vertical line drawn at that point. Table 5.6 also can be used to identify the intersections with this vertical line, which occur at:

a) 4 Walls – 80°-90°
b) 3 Walls – ~53°
c) 2 Walls – ~42°
d) 1 Wall – ~33°
e) No Walls – ~24°

These outcomes allow the designer to select the number of walls and incline of the floor or foundation so that a moderate severity of corrosion would be predicted for materials subjected to the conditions within that structure.

Concerning the "accuracy" of the outcomes of the factorial method, although Table 5.2 gives minimal and maximal ESLCs of 31 and 55 years, respectively for the PFCs, it is considered that these estimates are exaggerated. This is evidenced by the presence of differential corrosion damage depending on location. The original PFCs on the north side, facing the harbour/ocean, showed a greater degree of corrosion (see Figure 4.23) than elsewhere. As discussed previously, this region on the PFCs collected and retained corrosive debris on the horizontal surface since the PFCs were both open to the outside environment and sheltered from above. Thus, in the absence of salt removal by rain, wind, or maintenance activities, then the resultant salt retention and the potential associated corrosion would enhance the deterioration [142].

Since the galvanising coating used was thick, ISO 9223-1 and AS/NZS 2312-2 indicate an estimated corrosion rate of 4-8 µm per year. This information suggests that a more representative range of ESLCs is 12-17 years.

It is clear that the factorial approach would benefit from the incorporation of worst-case scenarios based on micro-climatic conditions rather than the presently used method that incorporates overall macro-climatic conditions characteristic of the entire building.

Concerning the effects of orientation and barriers, Figures 5.2 to 5.5 show how these effects can vary, despite being treated as constants for the entire building in terms of the macro-climate:

a) *Figure 5.2:* Baffle bench on east side, level 28, under full roof cover, partially exposed to westerly winds; minor corrosion
b) *Figure 5.3:* Baffle bench on east side, level 28, under full roof cover, fully exposed to westerly winds; major corrosion
c) *Figure 5.4:* Baffle bench on north side, level 28, fully covered and enclosed by four walls but with exposure through louvres; slight corrosion
d) *Figure 5.5:* Baffle bench on south side, level 28, fully covered and partially protected by plant and semi-wall; moderate corrosion

It is clear that micro-climatic conditions, such as orientation and the presence of barriers, can dominate the effects of the macro-climate even though the factorial approach treats these micro-climatic variables as constants.

Another example involves the plate distance on the brackets supporting the louvres on the façade, which will be discussed in more detail in Chapter 7. This design actually deviated from the original design and so considerable attention was paid to it. Fortunately, the concrete edge distance that was used did not impair the system since the bolt was positioned away from the edge according to the *Hilti* edge distance specifications, which allowed adequate resultant stress levels (see Appendix R).

The consequences of adherence to one specification that is in conflict with another may require a compromise between design and performance between components.

This will be discussed in more detail subsequently. The important point is that the life cycle prediction program failed to account for this, thereby reinforcing the conclusion that the auditor must be involved at an intimate level of a project so as to be able to deal with such potential conflicts.

Another example is the RHS shown in Figure 4.40, which had ESLCs of 31-55 years. This RHS used two-mix steel putty to seal the steam venting (during galvanising) hole on top. This hole allowed corrosion to take place owing to the retention of water. Since the putty was provided with a 5 year guarantee by the manufacturer, then it is obvious that the RHS to which it was applied should adopt the same ESL. The large difference in these ESLCs draws attention to another potential inconsistency in the factorial method.

In summary, although the factorial method has clear shortcomings, identification of these provides scope to improve the approach. Perhaps the greatest benefit that has come from it is that it has raised awareness of many key issues, which can be placed in more appropriate context, having identified them as being influential in assigning more representative factor values.

CHAPTER 6. Design Service Life Using Matrix Method for Critical Factors

6.1 Design Service Life Using Matrix Method for Critical Factors

During the course of the present work, it became clear that designers would benefit from the development of a practical design tool that could be used to predict the probability of achieving a required design life given a combination of materials, installation parameters, and environment.

It was concluded that such a tool would be useful and could be developed using a variation of the factorial method, where the probability of failure can be calculated by multiplying a series of factor values; each factor being derived through a combination of practical experience and theoretical analysis. The expression takes the simple additive form:

$$P = F_1 \cdot F_2 \cdot F_3 \ldots F_n$$

where:

P = Probability
$F_1 \ldots F_n$ = Factor values

When developed, the expression may be complex since this probability factorial matrix may involve intricate mathematical relationships. However, at present, the principle has been demonstrated in initial applications.

The complete development of such a factorial probability matrix is, in common with the more conventional factorial method, beyond the immediate scope of the present work. However, the factorial matrix has been developed to a level such that it represents a computer-generated interactive program that provides immediate tabular outputs, with examples shown in Tables 6.1 to 6.3.

The information shown in Tables 6.1 to 6.3 is obtained from an operating program that uses a simple factorial expression that has been developed to the point that it now requires only the factorial values to be assigned and the expression to be verified. The values can be seen as changing, depending upon the variables in the red cell boxes.

Table 6.1. Materials compatibility matrix illustrating influence of associated factors with 10 year nominated service life and vertical surface.

Materials compatibility matrix showing probability of achieving nominated service life with a combination of adjacent materials A & B

Primary material ← Click on this cell to select application of material "A"

Attached material ↑ Click on this cell to select application of material "B"

B \ A	Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7	Material 8	Material 9	Material 10
Material 1	102.41%	92.17%	81.93%	71.69%	61.45%	51.21%	Not Suitable	Not Suitable	Not Suitable	Not Suitable
Material 2	92.17%	102.41%	92.17%	81.93%	71.69%	61.45%	51.21%	Not Suitable	Not Suitable	Not Suitable
Material 3	81.93%	92.17%	102.41%	92.17%	81.93%	71.69%	61.45%	51.21%	Not Suitable	Not Suitable
Material 4	71.69%	81.93%	92.17%	102.41%	92.17%	81.93%	71.69%	61.45%	51.21%	Not Suitable
Material 5	61.45%	71.69%	81.93%	92.17%	102.41%	92.17%	81.93%	71.69%	61.45%	51.21%
Material 6	51.21%	61.45%	71.69%	81.93%	92.17%	102.41%	92.17%	81.93%	71.69%	61.45%
Material 7	Not Suitable	51.21%	61.45%	71.69%	81.93%	92.17%	102.41%	92.17%	81.93%	71.69%
Material 8	Not Suitable	Not Suitable	51.21%	61.45%	71.69%	81.93%	92.17%	102.41%	92.17%	81.93%
Material 9	Not Suitable	Not Suitable	Not Suitable	51.21%	61.45%	71.69%	81.93%	92.17%	102.41%	92.17%
Material 10	Not Suitable	Not Suitable	Not Suitable	Not Suitable	51.21%	61.45%	71.69%	81.93%	92.17%	102.41%

Multi dimensional scenarios achieved by selecting various consideration factors below. Click on red cells and select from dropdown box

10 years	Nominated Service Life
Vertical	Orientation of surfaces
Saline	Chemical Exposure
Roof cover & shielded	Weather Protection
Smooth	Surface Roughness
Low Humidity	Humidity
Primary only	Coating
Low	Loading /wind
Equal size	Geometry / Relative size
> 50deg	Temperature range

The matrix consists of horizontal and vertical axes where material combinations can be viewed. The materials are represented as materials 1 to 10, but these names would be identified with actual materials, such as aluminium, steel, anchor bolts, rivets, chemicals, *etc.* The names also could be identified with processes. Additionally, the upper left corner of the matrix highlighted in red shows two further selection dropdown boxes where a mouse click on *Primary material* in horizontal row A or *Attached material* in the vertical column B may be clicked to change the material or the process required.

If material B is selected as the primary or base material and material A is selected as an attachment or, for example, a fixing bolt, then the selection each type of material or application of that material results in a different value's being assigned to a particular factorial element in the expression. To refine the design flexibility options further, there are ten critical environment and application factors listed along the right edge of the matrix, which were selected for applicability on the present project on rooftops and façades.

Table 6.2. Materials compatibility matrix illustrating influence of associated factors with 30 year nominated service life and vertical surface.

Materials compatibility matrix showing probability of achieving nominated service life with a combination of adjacent materials A & B

Fixing bolt — Click on this cell to select application of material "A"

Primary material — Click on this cell to select application of material "B"

B \ A	Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7	Material 8	Material 9	Material 10
Material 1	92.17%	82.95%	73.74%	64.52%	55.30%	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable
Material 2	82.95%	92.17%	82.95%	73.74%	64.52%	55.30%	Not Suitable	Not Suitable	Not Suitable	Not Suitable
Material 3	73.74%	82.95%	92.17%	82.95%	73.74%	64.52%	55.30%	Not Suitable	Not Suitable	Not Suitable
Material 4	64.52%	73.74%	82.95%	92.17%	82.95%	73.74%	64.52%	55.30%	Not Suitable	Not Suitable
Material 5	55.30%	64.52%	73.74%	82.95%	92.17%	82.95%	73.74%	64.52%	55.30%	Not Suitable
Material 6	Not Suitable	55.30%	64.52%	73.74%	82.95%	92.17%	82.95%	73.74%	64.52%	55.30%
Material 7	Not Suitable	Not Suitable	55.30%	64.52%	73.74%	82.95%	92.17%	82.95%	73.74%	64.52%
Material 8	Not Suitable	Not Suitable	Not Suitable	55.30%	64.52%	73.74%	82.95%	92.17%	82.95%	73.74%
Material 9	Not Suitable	Not Suitable	Not Suitable	Not Suitable	55.30%	64.52%	73.74%	82.95%	92.17%	82.95%
Material 10	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	55.30%	64.52%	73.74%	82.95%	92.17%

Multi dimensional scenarios achieved by selecting various consideration factors below. Click on red cells and select from dropdown box

[illegible]	Nominated Service Life
Vertical	Orientation of surfaces
[illegible]	Chemical Exposure
[illegible]	Weather Protection
[illegible]	Surface Roughness
Low Humidity	Humidity
[illegible]	Coating
Low	Loading /wind
[illegible]	Geometry / Relative size
[illegible]	Temperature range

For illustration purposes, these have been assigned descriptors such as *Nominated Service Life*, *Orientation of Surfaces*, *Chemical Exposure*, *etc.* Clicking on each red cell of the matrix adjacent to and left of its descriptor will open another dropdown box, where a selection can be made. For example, by clicking on the cell to the left of the cell with the *Nominated Service Life* descriptor, the user will be presented with a selection of years of 10-20, 30, or >30. Again, each selection made from the ten available parameters results in a different multiplication factor's being applied to the factorial matrix.

The selection of all available materials applications and environment factor allows the simple two-dimensional matrix to achieve a multidimensional capacity since each factor adds a new permutation.

Table 6.3. Materials compatibility matrix illustrating influence of associated factors with 10 year nominated service life and horizontal surface.

Materials compatibility matrix showing probability of achieving nominated service life with a combination of adjacent materials A & B

Fixing bolt — Click on this cell to select application of material "A"

Primary material — Click on this cell to select application of material "B"

B \ A	Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7	Material 8	Material 9	Material 10
Material 1	50.31%	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable
Material 2	Not Suitable	50.31%	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable
Material 3	Not Suitable	Not Suitable	50.31%	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable
Material 4	Not Suitable	Not Suitable	Not Suitable	50.31%	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable
Material 5	Not Suitable	Not Suitable	Not Suitable	Not Suitable	50.31%	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable
Material 6	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	50.31%	Not Suitable	Not Suitable	Not Suitable	Not Suitable
Material 7	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	50.31%	Not Suitable	Not Suitable	Not Suitable
Material 8	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	50.31%	Not Suitable	Not Suitable
Material 9	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	50.31%	Not Suitable
Material 10	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	Not Suitable	50.31%

Multi dimensional scenarios achieved by selecting various consideration factors below. Click on red cells and select from dropdown box

10 years	Nominated Service Life
Horizontal	Orientation of surfaces
Both NaCl & SO2	Chemical Exposure
Roof cover no shield	Weather Protection
Very rough	Surface Roughness
High humidity	Humidity
Attached only	Coating
Low	Loading /wind
Equal size	Geometry / Relative size
> 60deg	Temperature range

Finally, having chosen each materials application, required service lives, and other critical factors, the probability of the design achieving its design life is shown in the cells at the matrix intersects. Where the probability is calculated as being <50%, the cell contains the text *Not Suitable*, thereby providing the designer with a clear indication of the preferred materials combinations.

Further refinement is added in that each material descriptor cell on the horizontal and vertical axes also contains a target bullet point. By clicking on any one of these targets, the user is presented with pop up *Application notes* for that particular material. For example, the notes may include welding or heat treatment advice or precautionary advice regarding the materials limitations for the chosen application.

The matrix also can be a useful tool for architects since clients generally approach architects to provide the initial concept of the design. The initial design stage is crucial in the overall construction process of any engineering structure, and it is well understood that the subsequent general design by structural engineers, *etc.* usually adheres to the initial design, with some modifications to accommodate structural issues. Architects may concentrate on overall aesthetics while structural engineers usually are concerned with the durability of the structure. However, the missing link is materials compatibility and materials integrity, as has been discussed as a major these throughout the present work in regard to other materials, processing, and environment.

For this reason, the matrix may serve as a basis for directing the initial design process to ensure that certain materials only may be used for longevity purposes and, from this stage, the evolution of a selection of suitable structural materials that will be chosen

6.2 Practicality of Matrix Method

As an example of the use of the matrix, it is assumed that the initial design process requires a durability assessment, as is becoming common in many European countries now. For this, the designer must consider all of the various implications of corrosion in detail. The designer is able to use the matrix, which would have the relevant factors downloaded into matrix, from which a selection may be made concerning the probability lifetime of materials combinations that are considered by the client.

The approach underpinning the construction of the matrix with, for example, corrosion factors, is illustrated using the three examples of galvanic corrosion, welding, and anchor bolts. The principal description is given for galvanic corrosion since this phenomenon is well established; more basic illustrations for welding and anchor bolts are provided in order to indicate that the program can be modified through the incorporation of the relevant information.

6.3 Matrix Method Applied to Galvanic Corrosion

The previous discussion indicated that steel can be galvanised with a zinc coating in order to provide the underlying steel with corrosion protection. From Table 6.4, which gives the electrode potentials at ambient temperature (25°C), zinc has an electrode potential of –0.76 V and steel or iron has a value of –0.44 V. This gives a difference of 0.32 V, which is substantial enough to allow current to flow and corrode the zinc since zinc is anodic in comparison to steel. However, if tin is coated on steel, then a different situation arises. Tin has an electrode potential of –0.14 V and that of steel is –0.44 V, giving a difference of 0.32 V, so the potential difference is almost identical. However, in this case, the steel is anodic in comparison to the tin. If the tin coating is damaged and the steel is exposed over a small area, then anodic quality of steel over a small surface compared to that of the cathodic area would result in rapid corrosion. This area effect would be applicable in the case of any coatings on anodic steel. Therefore, the most important factor for protection of the steel in these cases is that the rule of small cathode and large anode always should be implemented and not the reverse.

Table 6.4. Electromotive force series illustrating the electrode potentials of various metals at ambient temperature (25°C) in 1 M solutions.

Anode Half-Cell Reaction	Electrode Potential (V)
$Au \rightarrow Au^{3-} - 3e^-$	+1.50
$2H_2O \rightarrow O_2 - 4H^- - 4e^-$	+1.23
$Pt \rightarrow Pt^{4-} - 4e^-$	+1.20
$Ag \rightarrow Ag^- - e^-$	+0.80
$Fe^{2-} \rightarrow Fe^{3-} - e^-$	+0.77
$4(OH)^- \rightarrow O_2 - 2H_2O - 4e^-$	+0.40
$Cu \rightarrow Cu^{2-} - 2e^-$	+0.34
$H_2 \rightarrow 2H^- - 2e^-$	0.00
$Pb \rightarrow Pb^{2-} - 2e^-$	–0.13
$Sn \rightarrow Sn^{2-} - 2e^-$	–0.14
$Ni \rightarrow Ni^{2-} - 2e^-$	–0.25
$Fe \rightarrow Fe^{2-} - 2e^-$	–0.44
$Cr \rightarrow Cr^{2-} - 2e^-$	–0.74
$Zn \rightarrow Zn^{2-} - 2e^-$	–0.76
$Al \rightarrow Al^{3-} - 3e^-$	–1.66
$Mg \rightarrow Mg^{2-} - 2e^-$	–2.36
$Na \rightarrow Na^- - e^-$	–2.71
$K \rightarrow K^- - e^-$	–2.92
$Li \rightarrow Li^- - e^-$	–2.96

Therefore if an option of coatings is provided to the designer for the protection of steel, then the matrix program will present this information as follows:

a) Selection of Material B is steel and material A is zinc (% of coating relative to steel area should be included).
b) Selection of the coating by clicking on each red cell on the right side of the matrix, which will allow a dropdown box that provides a choice of coating thicknesses.
c) Appearance of pop up *Application notes* for the combined material, coating, and thickness, providing a list of scenarios from which the designer may choose in order to facilitate the design process; for example, in the case of the tin coating above, the application notes would provide a series of outcomes if the tin coating were to be damaged; it also would provide a statement mentioning the implications of the coating's being damaged.

The areal percentages of the anode and cathode for the most common metals can be programmed in order to calculate the severity of corrosion. These calculations are obtained from the values of the electrode potential for each metal. An increment of 10% may be included in addition to the final percentage range of factors so as to stipulate the probability of the design life; these will be shown in cells at the matrix intersects. The text *Not Suitable* is stated clearly as a pop-up when the calculation is at 50%, which then prompts the user to make other selections.

An illustration of a primary material may be galvanised steel, and the fixing bolt is a structural hot dip galvanised bolt as shown in Table 6.1. From the red cells shown on the right side, the user selects a specified lifetime, in this case, 10 years, although the option to choose other lifetimes is available. The next box down allows the user to choose an incline, in this case, vertical. The next box down allows selection of the corrosive compounds NaCl and SO_2, although, in this case, these have not been selected. It can be seen that the boxes below offer additional parameters that can be set. With materials A and B being a hot dip galvanised bolt and the primary material being galvanised steel, respectively, this advantageous combination of materials is assessed to have a 102.41% chance of surviving 10 years without corrosion.

The results are replicated diagonally from the top left corner to the bottom right corner because these diagonal values represent materials combinations with the material in contact with itself. In the present case, both materials in contact are galvanised.

Other combinations of materials are not as effective. The percentages fall in order of increasing distance from zinc in the galvanic series. In fact, the matrix is arranged in the order of the galvanic series, going from highest anode value to the highest cathode value. Also, the two different conditions of galvanic reactions, these being in flowing sea water and at 1 M concentration at ambient temperature, have been assigned separate matrices in order to distinguish between the two conditions.

The matrix also includes facility for interpreting a positive result in the absence of an electrolyte, *i.e.*, when *Chemical exposure* is selected as neither.

Comparing Table 6.1 with Table 6.2, it can be seen that only one parameter was changed, this being a service life increase to 30 years. The reduction in value as a percentage is decreased by 10% (or 8% if 100% is assumed from Table 6.3). This decrease results from the effects of temperature, humidity, local environment, *etc.* over the additional 20 years.

Thirty materials combinations were rejected in Table 6.2 whereas, in Table 6.1, twenty material combinations were rejected. It can be seen that the increase in years has reduced the probability for service with several other materials.

Tables 6.1 and Table 6.3 compare results for a 10 year lifetime, with the only difference being the orientation (vertical and horizontal, respectively). It is notable that this change in orientation significantly differentiates the results. The reasons for this are that horizontal surfaces allow deposits to settle and work their way slowly into the metal, especially in the presence and the accumulation of severely corrosive chemicals, such NaCl and SO_2, and that a sheltering roof exists above the material (horizontal) but no sheltering (vertical) creates one of the worst environments possible. Also, with a roof, no rain enters and hence there is no washing, leaving contaminant free to deposit on the metals.

6.4 Matrix Method Applied to Welding

Another example of the use of this matrix approach is in welding. The same sequence of procedure as above follows, where the multi-dimensional situations are obtained. The materials being welded are selected, followed by choice of weld filler material, nomination of strength values of aluminium alloys with certain tempers, and retained strength after welding. The pop-up application notes detail the extent of the HAZ and how the strength would be affected in the vicinity, with approximate distances provided in millimetres. This would dictate the limit of use of the welded joint in a particular application. Using existing reference data for the HAZ and respective strength values in certain materials being welded, the values can be used as factors in the program, allowing estimation of the probability of successfully welding, for example, 6351 T6 of 3 mm thickness and 6063 T6 of 2 mm thickness. Ideally, the results will favour a better outcome or probability for life prediction when certain variables are more predictable. For instance, welders using MIG and TIG methods vary between one another in that there are inconsistent results in the overall weld owing to various factors, including speed and heat input. Therefore, elimination of the possible variables associated with welding, including provision of data from an automatic welding process, would assist in acquiring the required information.

Anchor bolts are another area of which the user may take advantage using this matrix program. The various factors to be considered are type of anchoring method, type of coating on the bolts, depth of the anchoring, edge distance of the concrete, single or multiple anchor system, various strengths of concrete, and pre-calculated and assumed knowledge of wind load, yielding a maximal calculated load in kN acting upon system and the anchor.

It can be concluded from the preceding discussion that further development of the matrix is likely to yield beneficial outcomes. At the present stage of development, the illustrated matrices and the results mentioned above should not be considered or used for design purposes since the expression and factor assignments for which the resulting probabilities are derived are not verified and are meant to be approximations for illustrative purposes.

Again, it is clear that there is a need for cross-disciplinary expertise in relation to designers, structural engineers, metallurgical engineers, fabricators, site installers, materials suppliers, manufacturers of materials, project managers, quality representatives, and the client (whether in the initial stage of design or during the remedial stage). Therefore, the importance of compliance with all aspects of the overall process is emphasised. Only in this way can it be assumed that the factorial and matrix approaches have meaning and significance. For this reason, Perfect Engineering Pty. Ltd. turned to a third and final audit of the entire system, which involves manual calculations and finite element analysis (FEA) in terms of the structural strength design of the entire system in order to assess the loads acting upon the steel brackets, aluminium brackets, and chemical anchors.

CHAPTER 7. Finite Element Analysis (FEA) Applied to Anchor Design in Modified Rooftop and Façade

7.1 General Comments

Owing to the development of rapid computers and accurate methods for non-linear finite element analysis (FEA), there has been a tremendous increase in the number of types of studies of structures subjected to unusual and accidental actions, such as aircraft accidents, ship-ship collisions, and ships' running aground, and exposure of offshore structures to fires and explosions. Even with today's powerful computers and software, analyses of these events are very complex. Considerable effort therefore has been devoted to the development of simplified methods for rapid design and assessment purposes. The basic concept behind modelling is that information is accumulated so that it may be used to describe the processes simplistically, through interpolation and extrapolation. FEA is a well known technique that incorporates a wide range of data, particularly mechanical, from fields such as materials science, mechanical engineering, and civil engineering.

As the final and critical assessment of the project, FEA (*Strand 7, Release 2.3.7*) for all of the components of the project has been undertaken largely for the purposes of quality control and safety in order to be completely confident that the design and manual stress calculations were correct. Certain sections that were considered to be potential areas of concern were examined more closely, in particular those that were of lower strength and corrosion resistance. FEA as a tool was used in cases when previous audits and factorial assessments had failed to detect non-conformances.

The analysis involved a step-by-step approach to the assessment of the full extent of materials used, from both the mechanical strength and corrosion perspectives, from nuts and bolts through to the main structures. In short, the results for corrosion integrity over the 3 year period since completion of the work indicate the justification for a high level of confidence for extended lifetimes. However, from the mechanical strength perspective, FEA revealed shortcomings in several areas.

For example, the assessment of the 6060 T5 brackets, which supported the louvres on the façade, was intended to examine the integrity of the welding of the brackets. However, upon closer examination of the brackets, not only was the weld integrity in the brackets of interest but the FEA revealed an obvious deviation in the design of the bracket from its original design.

One of the key issues, discussed briefly earlier, involved the brackets that support each louvre section around the building façade (see Figures 4.66a to d). The chemical anchor bolt position in these brackets was designed to give a 50 mm distance from the edge of the concrete. However, this created a conflict with the requirements set forth by *Hilti* (Appendix R). The supplier of these M10 bolts stipulated a minimal edge distance of 90 mm. This change was incorporated during site installation. However, FEA revealed undesirable stress levels in certain locations of the plate, near the drilled hole and on the angle, as will be discussed later.

It is unclear if this adjustment to the design was approved originally by the consulting structural engineer through independent calculations. However, the FEA was not used at the time of incorporating the bracket since there had been no communication follow-up resulting from this change in design. Usually such a change is not allowed to proceed further in the company's QA system unless it has been verified and approved by the QA Manager. Hence, this represented an instance of non-conformance and so was recorded. Upon QA assessment, the following areas of concern were highlighted:

a) The design had deviated from original design.
b) The design change should have been accompanied by a review of certified changes.
c) Once the design had been approved and registered in the system, then relevant Project Manager should have implemented it.
d) If the design had not been approved, a corrective action report should have been raised in order to ensure that reworking of design had been conducted until a satisfactory outcome was obtained.
e) The instructions for the change in design and implementation should have been in line with the guidelines for fabrication, processing, and installation.

When the decision to change the design was made, it was done in the belief that the *Hilti* edge distance criteria took precedence over other considerations. It was not recognised at the time that this might have consequences on the hole near the free end of the plate, away from the concrete edge. Although it was considered at the time to be the correct decision from a structural perspective, this action contravened the requirements of the QA system. The time factor also influenced the decision owing to the tight time constraints placed by Westfield, which conflicted with the requirements of the QA system, which would have required a minimum of at least 2 days before work with these components could have been approved. From Figures 4.66a to d, it can be seen that wind loading would apply two types of force to the louvre system:

a) Pressure force of the plate against the concrete wall, known as *windward force*
b) Pressure force away from the building due to suction, known as *leeward force*

These pressures have been calculated using AS 1170-2 (Appendix P) and they are discussed in Section 7.4. The FEA calculations actually considered the welded section as a single solid unit that is a part of the remaining metal and so does not take into account the weld stress level variations. This modelling therefore would be limited to ascertaining forces acting upon the bracket and not take into account the reduced strength in the welded section. Therefore, the strength and failure predictions based on the FEA could be incorrect.

It is known from the literature that a welded section, and particularly in an aluminium component, has very complex variations introduced in the metal adjacent to the weld [128]. Since the bracket is of 6060 T5 alloy, the HAZ will diminish substantially to some distance the strength and, as a consequence, affect its integrity in many ways. Although the strength reduction was of concern, these alloys offer good resistance to corrosion when welded, as discussed in Chapter 3. The microstructure was altered near the fusion zone and the HAZ, thereby reducing the strength. Further, formation of a variable residual stress field across the weld would have a profound influence on the fatigue life of these welded joints. It is common for most engineers to extrapolate the design rules from steel structures to aluminium [6]. However, the fact is that this practice is inappropriate for aluminium structures since these alloys have a much more complex relationship between the microstructure and the mechanical properties when compared to steel.

It would be instructive to compare the FEA results of the stresses on the assumed HAZ or at least zones in its vicinity with empirical measurement of the stresses in these regions. To this end, there has been at least one study that has assessed the effects of welding on the HAZ using microhardness [143]. Other researchers have used transmission electron microscopy (TEM) and differential scanning calorimetry (DSC) [144,145]. These studies have highlighted the limitations in the interpretation of actual results for the several types of precipitates, which vary in size and cause variations in the strength. One method that has the capacity to probe the precipitate microstructure is small angle X-ray scattering (SAXS) [146]. The reason for this is that the resolution is similar to the X-ray beam size, which allows quantitative assessment of distribution of the mean radius and volume fraction. SAXS has been used to probe the precipitate microstructure in welded joints since the microstructural evolution during the heating can be measured *in situ* and the resulting mechanical properties then were determined via microhardness testing. These data showed that microhardness was not sufficiently accurate and that it was unable to discriminate quantitatively between the microstructural characteristics in welds. These findings allow questioning of the use of these data for FEA.

FEA does not yield the actual stresses in the selected regions of the aluminium alloys; it gives the stresses that act upon the component or the assembly. Determination of the balance of information is the responsibility of the designer, fabricator, or builder to assess referenced data and understand the loads acting upon these regions. The diminished strength level of the HAZ up to a distance 25 mm on both sides of the weld axis (see Section 3.8.11) is taken by most engineers to result in a 25% strength reduction and this is used in the FEA. This is a rather simplistic approach and does not highlight other important parameters affecting the microstructure.

7.2 Case Study of Welded Aluminium Bracket on Louvre System

Fillet welds have a very complex stress distribution [6]. The zones closer to the welds are heated to very high temperatures and tend to expand, although this expansion is constrained by the regions that are further from the weld and so at lower temperatures. Owing to this constraint, upon cooling, residual tensile stresses are established close to the weld and these may reach the yield limit. Equilibrating compressive stresses are formed away from the weld. In welded alloys, the heat input removes some benefits of the original temper and results in a decrease in the elastic limit. The distribution of strength across a profile indicates that the minimal strength is at the welds and that this strength is equal to the elastic limit of the annealed material.

The main section that is riveted to the louvres on the Westfield façade is a 6060 T5 aluminium UA of dimensions 60 mm x 25 mm x 3 mm and ~2200 mm length (see Figure 7.1). The supports that are welded to this section are 6060 T5 aluminium UA of dimensions 100 mm x 50 mm x 6 mm. The shorter side of the unequal angle (50 mm) was shortened to 20 mm in order to accommodate its being welded on the shorter side (25 mm) of the main section.

Figure 7.2 is a schematic of Figure 7.1 and it illustrates the explanation by Mazzolani [6] of the heat distribution adjacent to a typical fillet weld. The schematic shows the bracket welded and incorporating a 5 mm (continuous) deposit fillet weld running along all three sides of the 6 mm thickness UA. It can be seen from Figure 7.2 that the weld is sitting nearly in the corner of the large UA since there is only a 5 mm gap available. The extent of the HAZ is ~25 mm on both sides of the weld [6] and so the section attached to the louvres will transfer some heat to the adjacent side. The other point to note is that the plate brackets (short horizontal bracket plate), as shown in Figure 7.1, indicates a 50 mm distance for the positioning of the bolts. As discussed previously, this hole was moved away from the centre and away from the 60 mm x 25 mm EA that is attached to the louvres so that there is effectively only 20 mm of the plate left on the free plate near the edge.

From the preceding, it is clear that there are many variables to be considered when evaluating a suitable joint strength to be designed. It thus is relevant to mention that the 5 mm continuous fillet weld on the building façade bracket, which runs along all three sides of the 6 mm thick UA, also will be subjected to various forces both parallel and perpendicular to the fillet axis (see Figure 7.1). The continuous 5 mm fillet weld is shown at the top of Figure 7.2 to be progressing in three directions in the 6 mm thick UA section. This is also the case with the underlying 60 mm x 25 mm x 3 mm UA. The central schematic in Figure 7.2 illustrates the likely situation of the half width of the reduced strength zone (b_r) on either side of the central axis extending in all three directions, as shown by the arrows [6]. It is likely that the plate region has been affected. The entire region is termed the *reduced strength zone*. It should be noted that the size of the HAZ typically is twice that of the reduced strength zone.

The centreline of the plate (25 mm centreline across the 50 mm width bracket) region obviously has been affected. There are three fillet welds, where the b_r zone travels in directions opposite to the centre weld deposit. In principle, the entire angle face (100 mm x 50 mm x 6 mm) has had heat travel uniformly over the majority of the angle face. Also, the elastic limit of the bracket has been reduced as a result of the number of times the heat has traversed over its face [79]. The extent of the conventional strength at 0.2% ($f_{0.2}$), the reduced conventional strength at 0.2% ($f^*_{0.2}$), and $b_{r,}$ therefore may be expressed simply as heat generated in the region as a function of time and therefore a function of ageing time. This has not been considered in the FEA calculations and the limitations in the database for this situation recommend further empirical and modelling work to be done in order to facilitate incorporation of these data in the work.

It is not certain to what extent the b_r should be considered to extend along the adjoining leg of the angle that is perpendicular to the fillet welded plate face. It almost certainly would not be to the same extent as that on the welded plate since the heat travels perpendicularly at each weld interval. If it is assumed that the same penetration of the reduced strength zone extends out perpendicularly along the adjoining leg, then this also will extend out to less than 25 mm. The main difficultly is that there are rivets and rivet holes in certain places and these may be affected. This has highlighted that this entire region could be weakened substantially and that there is a possibility that failure may occur in situations of severe wind loading. Single angles rarely are used as compression members principally owing to the unavoidable eccentricities at the connections [94,117]. Twist buckling of open sections, such as angles with relatively thin walls, is inevitable [94,117].

To illustrate the effects of wind load upon the bracket as shown in Figure 7.3, with the bolt chemical anchored in the wall and restrained, Figure 7.4 shows the wind pressure (see Appendix P) exerted against the mullion. The force exerted on the louvre is considered to act along a certain distance on the louvre face and is called a *line force*. The line force is taken as the distance on either side of the secured bracket and along the angle where the stress is highest or buckling is feasible. Since the angle is secured in three positions with brackets, then this buckling distance has been calculated to be ~350 mm on both sides of the middle bracket. The force acting upon the louvre system and hence the plate causes a slight reaction pull-out force of 0.3 kN on the bolt. The pressure force is negligible, so the plate integrity is not compromised.

The calculation for suction, as shown in Figure 7.5a, illustrates the reaction from the concrete on the aluminium plate and it shows the compression on the concrete, as shown in the shaded region. Figure 7.5b shows the effect of suction force on the free end plate. Although the force of the plate against the wall is greater than the pull-out force of the bolt, this force (3.4 kN) is negligible compared to the anchor pull-out strength (16.6 kN). Upon continual loading, this force is likely to impair the bracket. The calculations for these brackets and the FEA will be discussed subsequently.

Considering the reduced strength zone, which is not considered in the FEA, and the twist buckling, which is typical in open sections, these would suggest that the brackets shown in Figures 7.6, 7.9, and 7.10 also may be overstressed in the vicinity of the weld. The actual buckling shown in these drawings and the FEA do not take into account the welded region. Consequently, the real situation may be considerably worse than estimated owing to the microstructural changes that occur during welding.

7.3 Pressure and Suction Forces on Louvre System

Continuing the calculations for both the pressure and suction forces, as discussed for the upper brackets in Figure 4.65a, the calculations of the wind conditions in accordance with AS 1170 Part 2:2002 on the louvre system are given in Appendix P.

It can be seen from the results of the calculations in Appendix Q that the force under suction is greater than that in pressure. The force applied on the chemical anchor acts in reverse or under suction, *i.e.*, pulling away from the building. The shaded region, which is 20 mm long, is under excessive force since the concrete exerts this compressive force against the aluminium plate. Although the above calculation shows a load of 3.4 kN acting on the chemical anchor, it is probable that the 100 mm x 50 mm x 20 mm bracket acts like a lever arm, whereby the full length of the 80 mm bracket (from concrete edge to hole) is lifted and concentrates the load on the bolt, thereby forcing the 20 mm section hard against the concrete. This will be examined in more detail subsequently.

7.4 Assessed Stress Levels

7.4.1 Serviceability

The bracket was satisfactory in terms of serviceability under wind pressure (windward force) and under wind suction (leeward force). Therefore, the bracket may function within an acceptable range.

7.4.2 Strength

Pressure

The 60 mm x 25 mm x 3 mm angle was under pressure, *i.e.,* wind load exerting force and pushing it toward the building. The maximal stress was calculated by FEA to be 122 MPa (see Figure 7.11), which is approximately equivalent to the yield strength of 6060 T5 aluminium alloy.

Suction

The bracket was overstressed under suction and reached a stress level of 146 MPa (see Figure 7.7). The stress distribution adjacent to the bolt hole was compressive and has the wall exerting an equal and opposite reaction to it. The reason the bracket was severely overstressed under suction is that the bolt hole was 20 mm away from the edge of the plate, thus placing stress on the plate in the region where the bolt mates with it when inclined (see Figure 7.8).

Figure 7.6 Illustrates buckling under suction, as viewed from the back of the louvre face. Figure 7.7 illustrates the maximal stress distribution around the bolt region due to suction forces, as viewed from the face of louvres. Figure 7.7 shows the maximal stress distribution against the wall due to suction forces' attempting to lift away the bracket from the wall. As a result, an excessive load is exerted on the bolt on the opposite side, as shown in Figure 7.8. Figure 7.9 indicates buckling due to pressure forces, as seen from the face of the louvres. Figure 7.10 illustrates the general stress stress distribution due to the pressure forces, as seen from the face of the louvres. Figure 7.11 shows the maximal load stress distribution due to the pressure forces, as seen from the face of the louvres, acting in the vicinity of the weld region.

7.4.3 Comparison of Manual Calculations, FEA, and Reality

The results provided by manual calculations (see Appendix S) indicated that there was ~18.7 kPa acting under pressure and ~11.7 kPa under suction. These results were used in the FEA computational program in order to obtain deflection values for the 60 mm x 25 mm x 3 mm UA of 2.4 mm for pressure and 5.8 mm for suction along the entire length. These deflection results have various implications for the louvre mullion joint section, depending on whether it is welded or riveted. The FEA allows the assumption that the louvre system is capable of withstanding this deflection.

The pull-out load acting on the chemical anchor was calculated manually to be 3.4 kN under suction and 0.3 kN under pressure (see Appendix Q). The main reason for this low load under pressure was due primarily to the concrete wall's supporting the bracket, preventing further pressure. However, excessive stress is observed when the system is under suction and this is clear from the geometry of the bracket and the forces acting upon it.

The stress levels provided in these calculations are based on modelled data. Empirical data indicate that the maximal pressure stress is 122 MPa adjacent to the bracket, where it is welded to the angle. However, this does not take into account the precise effects and mechanical properties resulting from the generation of the HAZ. The angle and welded bracket are considered to be a single component according to the FEA calculations. Discussions with numerous engineers over the years lead to the conclusion that many engineers use the 1 inch (25 mm) rule for the HAZ adjacent to the weld and allow a factor of ~25% reduction in strength of the parent metal strength. However, the FEA calculations predict only a range of stresses that act upon the components and do not appreciate or incorporate the true extent to which the HAZ or change in microstructural properties may influence the properties of the alloy, especially at these critical joints. Therefore, it should be emphasised that, in the absence of more specific treatment, conventional FEA assumes that welded aluminium alloys are viewed as continua of consistent properties, unaffected by welding, much the same way that steel more reliably is modelled.

The reason the bracket was over-stressed adjacent to the bolt hole region is that, initially, the design was calculated at 50 mm from the edge of the concrete. However, the decision to move the bolt hole to an edge distance of 80 mm from the concrete edge negated this decision. At the time, it was considered the correct procedure to follow in order to comply with the *Hilti* specifications, which calls for 90 mm. If the bolt had been left in its original position at 50 mm from the concrete edge position, then the worst-case situation would have been a slight reduction in the bolt capability, which will be discussed further in Section 7.4.5.3. Since the entire bracket length is 100 mm, the danger lies in failure of the bracket if and when subjected to severe loading under suction.

The suction and pressure forces that affect the middle bracket can be understood by examining the FEA drawings (Figures 7.6 – 7.11). The bracket under suction involves the louvres' pulling out and away from the building. This will serve to place the bolt in tension. On the other hand, under pressure, the louvre system will be pushed toward the building, and so the bracket will be exerting the force against the concrete wall. Since there is no particular concentrated load on any part of the bracket and the plate is spread uniformly across the wall, the load is minimal. The forces acting under both pressure and suction indicate clearly that the main forces are concentrated about the middle bracket. It appears that buckling is in the same plane for both instances since the bracket is held in position about the bolt. Under pressure, the plate pushes against the wall and, under suction, the plate pulls outward against the bolt and against the wall in the final section of the plate free end. More importantly, the areas under pressure are where the tensile stresses act on the leg of the angle, which is perpendicular to the wall and adjacent to the weld region.

It is expected that the most useful role of FEA is to complement the design of aluminium structures prior to fabrication and installation. Additional aspects to be considered include local buckling, flexural buckling, interaction of local and flexural buckling, and failure in the HAZ. Reliable FEA also requires data from welding heat inputs and the thermal conductivity of aluminium alloys, involving welding speed, current, arc length, travel speed, *etc.*

Welding simulations are required to predict the extent of the HAZ and its effect on various alloy mechanical properties. This would entail obtaining details about the ensuing reduced strength owing to the heating from the weld and the associated microstructural results, which largely determine the precise mechanical properties of the material, as discussed by Askeland [147] (see Appendix V5). Ideally, the stress information generated by FEA would correlate with the complex microstructural phases rather than the strength or hardness properties alone, as discussed and explained previously. The hardness and strength themselves are not adequate indicators for the assessment of the true properties of alloys. Therefore, data input into FEA should be more relevant and suitable for parametric studies so that they can be placed into an optimised algorithm.

Studies have been performed that indicate that the finite element method with a computer model was developed to describe the steady state, two-dimensional heat flow during the welding of thin plates. One study using a grid mesh of variable spacings has focused on incorporating the weld pool configuration, size of the partially melted zone, temperature distribution near the heat source, the heat of fusion, the size and distribution of the heat source, the temperature dependence of thermal properties, the heat conduction in the welding direction and the surface heat loss during welding were considered in order to allow accurate computations. One of the earlier pioneers in this field is Goldmark [148].

7.4.4 Chemical Anchoring and its Effect on Concrete Edge Distance on Bracket

The connection of the bolt to the bracket and the chemical anchor in the wall has a strength of ~16.6 kN, as stipulated by *Hilti* (Appendix R). The manual calculations indicated a load of only 3.4 kN (see Appendix Q) acting on the bolt under the influence of suction forces. There seems to be no problem with the bolt or chemical resin bonding since the bolt itself, the depth to which the bolt was inserted, and the chemical adhesive holding the bolt in place are according to the manufacturer's specification. Also, it has been assumed that no other environmental factors, such as airborne contaminants, will have any detrimental effect on the chemical integrity in general.

Concerning the plate bracket, as mentioned earlier, the 6060 T5 aluminium plate was altered at two main locations, as clearly shown by the FEA results in Figures 7.8 and 7.11. Also, it can be seen that the FEA results indicated high levels of stress in the vicinity of the welded region. The FEA calculations take into account as a general rule of thumb a distance of ~1 inch (25 mm) away from the weld as being the HAZ, which is compensated in the calculations by a multiplication factor of 0.75.

The different effects for optimising the anchor strength and prolong the life and safety of the component are discussed briefly. This following text is included in order to demonstrate that design, which has many variables and facets to it, requires a comprehensive understanding of the effects of all variables. A single wrong assumption and several aspects pertaining to this could go undetected and ultimately cause failure in any one of the three main forms, these being concrete, aluminium bracket, and chemical anchor.

Figures 7.12 to 7.14 show the presence of anchor friction initiated by an applied load that causes the inserted section to expand, keying respectively through tensile load and bonding with an adhesive bond between the anchor rod and synthetic resin adhesive. There are several different methods of anchoring but the present work incorporated an HAS-E-F (HVU) anchor (bonding) as this was the most suitable for the application on site for this project. The focus in this project in regard to the anchors was not on the chemical adhesive bonding but rather on the criticality of the concrete edge distance.

The failure patterns of anchor fastenings to a continually increasing load can be depicted as in Figure 7.15a, which shows the failure modes from static loading. Breakout, anchor pull-away, edge break-out due to the bolt's being positioned at a small edge distance are possible mechanisms. The failure of anchor parts occurs mostly when a single anchor with suitable distance from the edge is subjected to pure tensile load. The weakest point in an anchor fastening determines the cause of failure.

Most concrete structures exhibit cracks. However, attention must be paid to the size of these cracks since, above a specified limit, the anchor is rendered useless. If a substantial crack exists, then the tensile forces acting within that region will not be able to extend beyond the crack region. Therefore, the detail of the concrete was examined *in situ* and the structure was deemed to be fit before manufacturing the brackets and drilling holes for the anchors.

In many traditional professional manuals of the past, there was no consideration of the effects of cracked concrete. In the past, many companies underestimated the fastening of anchors in cracked concrete as there was little information and few tests were performed using loads at different width cracks. An important part of the present work was to calculate the anchors' shear load. If another row of anchors was added, it was assumed that the row closest to the edge took up the entire shear load, as shown in Figure 7.15b. It may be advantageous to add a second row as a safety factor, although this would not be necessary if the brackets are fastened correctly, as shown in the row of load-bearing anchors closer to the concrete edge in Figure 7.15b.

7.4.5 Limiting State Design Method

7.4.5.1 Tensile Resistance

The limiting state design method considers that tensile resistance has three failure modes, these being pull-out failure, concrete failure, and failure of the steel anchor [139]. The schematic below illustrates the required calculations in these instances.

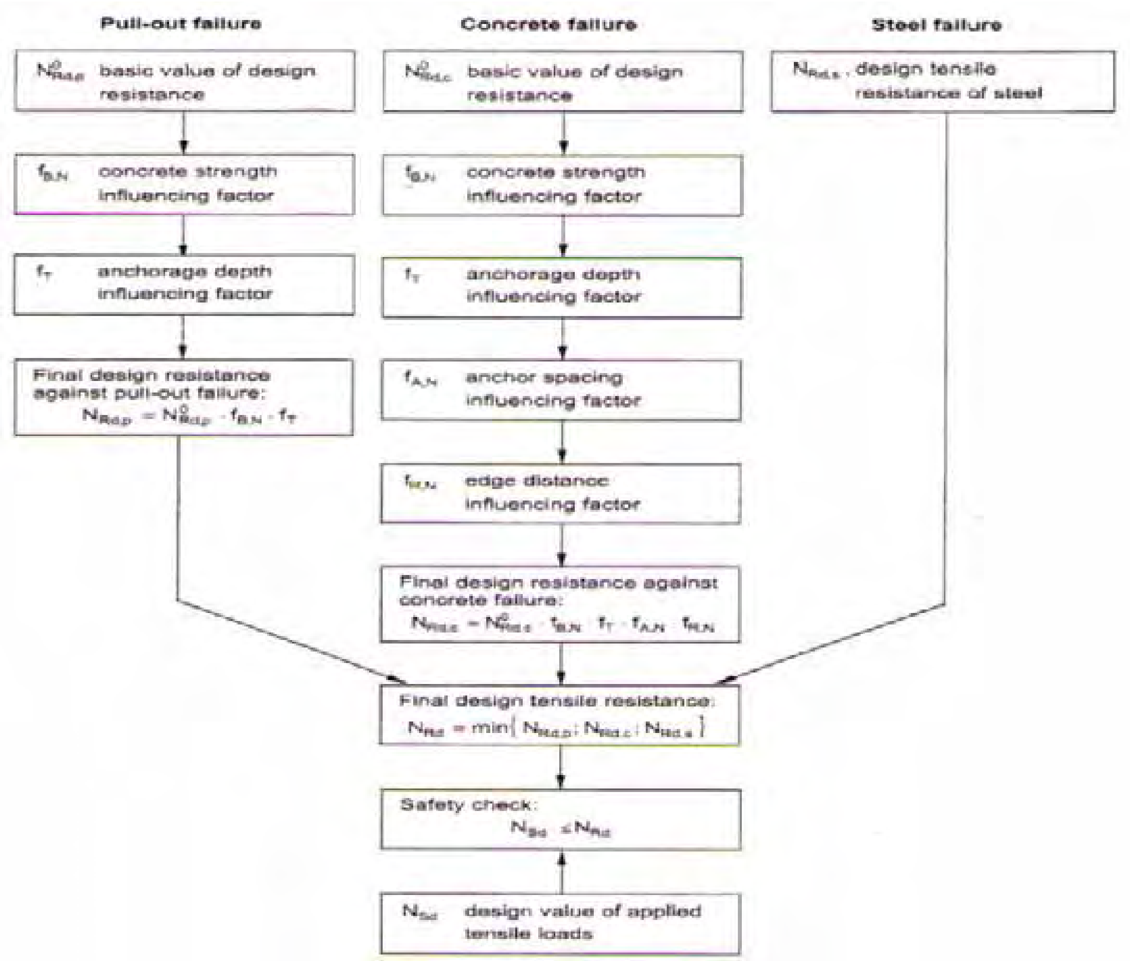
The first schematic below illustrates the calculations required to determine the mode of failure by these three mechanisms (see Appendix R).

7.4.5.2 Shear Resistance

For shear resistance, the limiting state design method considers that there are two failure modes, these being concrete edge failure and shear failure of the steel anchor. The second schematic below illustrates the required calculations in these instances.

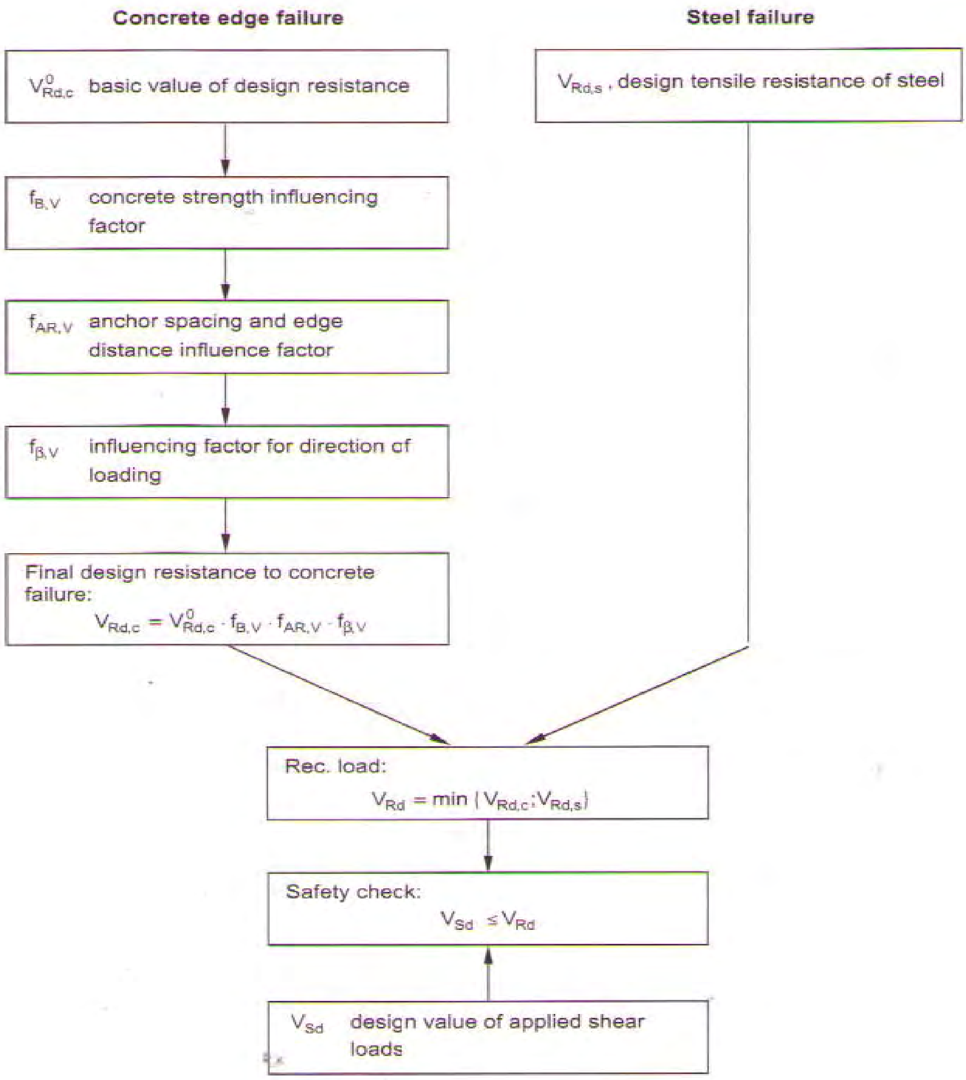
7.4.5.3 Load-Under-Angle Calculation

It is assumed that the single anchor method for force is appropriate for the project [139]. The calculations for a single anchor are given in Appendices R and T. Through load analysis, the maximal force acting on an anchor at an angle can be determined, and this serves as a guide to demonstrate that the anchor is within a safety factor for maximal load analysis. The calculations of forces acting on the anchor show that the maximal load on an anchor is 3.4 kN (using AS 1170.2:2002 conditions). This is acceptable and meets the requirement because the anchor can support a maximal load design resistance of 16.6 kN, as demonstrated in the *Hilti* documentation (see Appendix R). However, there was a problem in that, originally, only the anchor was meant to be in the middle of the steel plate of the bracket, leaving 50 mm from the concrete edge and 50 mm of extra plate remaining on the other side, as shown in Figure 7.16.



Schematic of calculations required to determine mode of failure by pull-out, in concrete, and of steel [139] (see Appendix R).

As shown in Figure 7.16, it was evident that, if the anchor had been placed in the 50 mm position, then the *Hilti* specification would not have been met, which would imply a risk of concrete edge breaking (see Figure 7.15). This requirement is that, for optimal performance, the M10 anchor must be placed 90 mm away from the concrete edge. This is the reason that it was decided to place the anchor away from the edge. However, in fact, it was placed 80 mm away from the concrete edge because the plate



Schematic of calculations required to determine mode of failure for anchor bolts and concrete [139] (see Appendix R).

was not long enough to increase the distance to 90 mm (see Figure 7.17). As a result, the bolt was shifted 80 mm from concrete edge but closer to the plate edge. As the anchor was shifted without making the steel plate longer, this presented another problem, which was that the anchor was closer to edge of the steel plate and it therefore acted as a lever, exerting a large degree of pressure on the plate under suction, as shown in the load analysis section (see Figures 7.8 and 7.17 under suction). A valid solution for this would have been to increase the steel plate length and possibly the thickness.

The interesting aspect of these calculations suggests that, if the bolt were to remain in its original position of 50 mm from the concrete edge, then the actual force on the plate would have been distributed more uniformly and, as a result, the force would not have been concentrated, as shown in the FEA data in Figure 7.8.

In order to test this idea, an original concrete edge distance of 50 mm was assumed and the prognosis for a problem with concrete edge breaking and anchor pull-out was determined. For this calculation, the ultimate limit state design method was. The calculations and tabulations are shown in Appendix U.

From these results, a force of 11.288 kN is required to pull the anchor out from the 50 mm edge distance. This still is above the maximal load of 3.4 kN that acts on the anchor, which was calculated in Appendix Q for the bolt under suction. Therefore, this suggests that there would have been an allowance for the 50 mm concrete edge distance; the shear loading on these anchors in this vicinity would have been minimal since the maximal forces act on the brackets and louvres.

These data indicated that an edge distance of 40 mm would have been unacceptable. This highlights the observation that, even though the *Hilti* specifications stipulate an ideal value, all of the associated parameters must be assessed if even a single parameter is changed. This example illustrates a trade-off in properties between improved concrete edge distance but at the cost of a sacrifice in the integrity of the plate. At times, what may appear to be a simple design alteration may have broader consequences and so every aspect must be examined before a change in design is implemented.

CHAPTER 8. Summary Discussion

8.1. Project Objectives and Engineer's Role in Assuring Optimal Design

The present work outlines some basic principles and ethics of how organisations and engineers must conduct themselves when undertaking important projects such as re-designing or reconstructing high-rise buildings, particularly when public safety is at risk. The aim of this dissertation also was to establish a design approach that would encompass as many facets as possible in an attempt to establish a robust system for the design of new structures and refurbishments on building rooftops and façades with major construction elements consisting of steel and/or aluminium. The focus was to design and construct in a viable manner, to present sound solutions for materials and processes, and to attain safety and longevity in the long term. A focused literature survey was undertaken in order to support the conclusions made about the problems and design recommendations and to avoid or minimise the potential failure of the rooftop and façade structures.

Owing to the buildings' initial poor engineering design on the rooftop, the consequences of this poor design were observed through the unfortunate collapse of the rooftop louvre section in the southwest corner of the building. The extent of corrosion throughout the building rooftop also was observed.

The refurbishment project that was undertaken by Perfect Engineering Pty. Ltd. was conducted with an appropriate level of research by myself, and allowed for the required resources to ensure the achievement of a desired outcome. Subsequent evidence obtained during the 3 years ensuing completion of the project is such that there is no evidence of corrosion at any location that the company refurbished. The façade louvre support and general fabrication and installation on site are deemed to be excellent by all involved parties, including external independent engineers and consultants.

The intention of this project was to re-design the entire rooftop system, including structural steel and aluminium façade and louvres on the building rooftop. The following parameters had to be considered:

a) Childcare facility and general public below
b) High wind area

c) Corrosive environment
d) Budgetary constraints
e) Time constraints
f) Strict work guidelines
g) Necessity of transporting goods using only a goods lift
h) Re-design accommodating lighter materials, maintenance of performance characteristics, and retention of aesthetics
i) Provision of 5 year guarantee

With such a large range of restrictions, many of which were inter-related, the project was very challenging from the perspectives of scheduling and project management.

In light of the demands of this project, it is clear that designers and engineers should be armed with a detailed and workable plan for the achievement of the desired result, especially with rooftops and facades. Engineers are privileged to be able to undertake the work that they do, yet they also have a moral obligation to society as a whole and they must act with duty of care in all instances. Prior to Herbert Hoover's becoming the President of the USA, he was the Engineer-president of the American Institute of Mining Engineers and also of the former Federated American Engineering Societies [67]. In one of his memoirs, Herbert Hoover illustrated the responsibilities and honours of engineering:

It is a great profession. There is the fascination of watching a figment of the imagination emerge through the aid of science to plan on paper. Then it moves to realisation in stone or metal or energy. Then it brings jobs and homes to men. Then it elevates the standards of living and adds to the comfort of life. That is the engineer's high privilege.

The great liability of the engineer compared to men of other professions is that his works are out in the open where all can see them. His acts, step by step, are in hard substance. He cannot bury his mistakes in the grave like the doctors. He cannot argue them into thin air or blame the judge like the lawyers. He cannot be like the architects, cover his failures with trees and vines. He cannot, like the politicians, screen his shortcomings by blaming his opponents and hope that the people will forget. The engineer simply cannot deny that he did it. If his works do not work, he is damned.

Where specific practice is not prescribed in building codes and Standards, then the designer must comply with the legal requirement to engage expert opinion. After all, in any successful building design, a complete plan should be outlined from the onset to include and consider materials science as part of the overall engineering design, especially in the case of any add-ons for the roof or façade. A professional designer's or engineer's role is at the least to comply with the following requirements:

a) An engineer must consult other experts in their fields of expertise. The failure on the rooftop of this high-rise building evidenced that there was lack of expert involvement in the field of material science in the original building design since materials compatibility problems were the primary cause that contributed to this accelerated corrosion.
b) Engineers should begin to identify those components of buildings that will require periodic maintenance in order to maintain integrity over the whole design life of the building.
c) Maintenance recommendations to the building's owners should be prepared so that the affected components comply with the essential maintenance requirements of the Building Code Authority (BCA).
d) Where periodic maintenance is required, the engineer must ensure that safe design principles are used so that the building's maintenance workers of the future are safe and not exposed to risky maintenance practices.

The definition of materials science is quite broad. However, the processes for manufacturing, such as welding, heat treatment, galvanising, and other factors that affect corrosion and other phenomena are aspects that designs must encompass since, in any one of these fields, if the concept is not understood fully, then it would be very difficult to predict the life of any component and therefore the entire structure as a result. As Martin and Caton [70] point out, corrosion in aircraft can be confirmed and realised only by real-time exposure since it is not easily detectable in most instances. In ageing aircraft, corrosion can degrade structures such that fail-safe or load-carrying capability is compromised. For this reason, design for corrosion resistance should be co-ordinated with all other design elements. Strength, fatigue, and damage tolerance may be evaluated and predicted but designers should recognise that corrosion requires an immediate control plan so that the work done is not an *experiment on a social scale involving human subjects* [67].

In general, building structures have certain design codes and rules that have been in some way replicated from known designs of similar buildings throughout history. However, the structure and fabric of the rooftop and façade of a high-rise building is quite a different entity in contrast to the remainder of a building and so they must be treated separately. The design of a rooftop encompasses a myriad of materials that are subjected to the elements of the environment, including wind, rain, sun, and even materials in contact with one another. The task of designing and constructing rooftops and façades in many ways has more repercussions than the design of the building itself, particularly as the greatest risk lies in the possibility of endangering the general public from on high.

Although the results for the project on the rooftop and façade of Westfield Tower 2 was considered to date very good from the perspectives of design, fabrication, and implementation, there are a few areas that could have been improved but that were not evident at the time of installation. The only structure on site that has given rise for concern is the 6060 T5 brackets. However, these have been assessed by FEA with an adequate outcome. Nonetheless, this structure was supplemented with internally positioned bracket supports. The louvres were connected using galvanised steel brackets that were chemically anchored in the concrete hob. If this were not the case, then the situation of 1:500 would be relied upon. Although incidents for the situation of 1:500 generally are rare in buildings, it still is possible that it could happen, so a safety precaution should be put in place. The materials and general processes that were put into practice in this project are appropriate by recognised standards. In most cases, the quality of the project would surpass the requirements stipulated by the building industry. Identification of the key fundamental aspects regarding the approach to design or refurbishment of structural and non-structural ferrous and non-ferrous metals on building rooftops and façades, especially in a corrosive environment due to the proximity of the harbour/ocean, is a challenge in itself.

Several other engineers, particularly in the structural field, were consulted with the view of initiating a cross-disciplinary exchange of technical information. Numerous materials were trialled and tested. In fact, many changes were made along the way, where circumstances or conditions were such that changes and modifications were desirable in order to achieve optimal corrosion resistance and/or strength. The next step was to ensure that the correct teams were engaged to deal with fabrication, installation, safety procedures, quality implementation, auditing, and other areas in order to ensure the efficient running of the program and maintenance of the integrity of the project.

The design included an assessment of the galvanised components since it was clear that deviation from certain criteria in any one of the processes could result in an inferior zinc coating. All steel was supplied with the specified chemical content and audits were performed on the galvanising plant in order to ensure that all of the specifications in the processing were according to the required Standards. Strict monitoring and control of the fabrication, treatment, and installation of these components was maintained at all times. A practical measure for future inspections and maintenance also was put in place for the client to ensure that the structure remains sound for the long term. This also ensures that any signs of corrosion are highlighted in their earliest stages before the problem is established and appropriate action can be taken.

Although the project solutions were sound, improvements and further research still can be made, as has been noted in the present work. This project has allowed identification of many more improvements and innovative designs for the achievement of a gratifying and confident result. Consequently, the purpose of this work was to outline a step-by-step approach to some of the major problems on the building rooftop and façade louvres and how they were solved. The purpose was to direct the designer to go beyond the formulation of basic concepts of mere structural adequacy and to consider some of the alternatives in materials and processes that are available.

This dissertation involves not only research into and application of conventional materials and methods but also includes a design approach for each element that is of importance. The result of this research and application approach stemmed from observations made on the widespread failure of the materials on the rooftop section and these were influenced to a large degree by alternative solutions and unconventional engineering techniques. The work is a compilation of how a designer, structural engineer, or metallurgical engineer might approach any problem of design in general but also when circumstances stipulate stringent measures to be adapted *in situ*.

The main limitations of this project hopefully have been identified and the solutions to these limitations or weaknesses have formed an integral part of this thesis. As a result of these limitations, it is reassuring to know that of all of those that were identified in the project, from its inception to present, were only minor and so it has been possible to go back and remedy these inherent faults at times of choosing.

The main reasons that there were minor problems is a result of the problems encountered during fabrication and general processing, including powder coating, galvanising, *etc.* These have been monitored stringently and any issues that have arisen have been acted upon immediately. Particular consideration was paid to the extent of such problems and their severity/repercussions, which generally have not been addressed yet. To this end, there is a schedule for maintenance and/or repair.

A guiding principle is design should be done in such a way that any structure will be replaceable at any stage and that the design should allow easy inspections and maintenance. Each single connection that was made to strengthen the louvres has been exposed internally so that maintenance and or replacement may be made at any time. For instance, all of the louvres have been secured using bolting from the outside but they also may be undone from the outside. A supplementary manual will be provided to Westfield once the 5 year warranty term is up. This will include further recommendations on inspections at each point and appropriate action to take if deterioration becomes evident at some stage. This also will include all of the component dimensions for re-fabrication.

The engineer must consider seriously his obligation to the precepts of safety and the consequences in terms of human life and structural integrity of failing to fulfil these obligations by ensuring that appropriate designs and procedures are stipulated so that the most favourable outcome is realised. There also is the obvious issue of litigation if engineers neglect their duty. Negligence comes in many forms but one very important form of negligence is due to engineers' not involving other engineers or experts in disciplines outside of their expertise. There are specialists in each field and these specialists are there to be consulted.

Furthermore, the aim of the project was not only to highlight the most suitable materials to be used under the corrosive and windy conditions of the rooftop but also to equip designers and engineers with the appropriate tools to examine corrosion issues by suitable design. These tools include testing, validating, fabricating, coating, materials selection, and so on. Many of the procedures have involved theoretical calculations followed by practical implementation.

The purpose of having a multi-audit stage on a project of this scale indicates how individual audits, techniques, or processes will highlight weaknesses but how, in other areas, they will identify pertinent information relevant to the material's structural integrity. This auditing can take the form of a quality system, a factorial method, use of FEA, or some other method. All of these in some way have contributed to highlighting certain relevant structural deficiencies. Hence, the non-conformances in this project either have been addressed or are on a planned schedule in which the remedial work will take place at the next inspection.

The work done on this building rooftop and façade encompasses all of the best practices, including innovative ideas that may help other designers in the future. In addition to this, this dissertation has highlighted some pertinent information, in particular how future considerations should be taken into account by designers to avoid similar mistakes which has been seen on the Westfield rooftop and louvre façade system in certain areas.

As mentioned previously, the project was very detailed and only some of the design and construction aspects have been mentioned. The main issues have been discussed and some of the key tools of the project involved the following:

a) Researching the existing literature (building, and aerospace materials)
b) Determining the most appropriate material available in terms of shape, size, mechanical properties, and chemical properties
c) Understanding basic difference between steel and aluminium
d) Developing methodologies to design and construct the entire refurbishment project
e) Undertaking planning and project management
f) Ensuring that the correct team provides particular services as required, including designers and engineers so that cross-disciplinary measures are considered.
g) Developing methodologies for fabrication
h) Completing audits and inspections of incoming components and ensuring that factory audits, such as in fabrication and surface coating applications, adhere to relevant Australian Standards
i) Holding inspection audits for every item or material to be used on site
j) Obtaining certifications to accompany each material or process in order to assure conformance
k) Development of a methodology for making jigs

l) Development of a methodology for installation and workmanship for carrying out the work on the various sections of the rooftop and building façade, providing OH&S and quality awareness training, and offering basic education in materials compatibility
m) Ensuring that the project was in compliance with Quality Assurance – ISO 9001:2000 requirements
n) Considering environment effects in regard to each item to be designed, including airborne contaminants and pollution from the macro-environment, although sampling from a microenvironment aspect would have been an ideal means by which to obtain relevant information
o) Assessing wind conditions and loading upon structures and assuming worst-case scenarios

8.2 Materials and Environment

A diverse range of materials, both existing and new, has been discussed. The chemical compositions of metals in connection with other metals are of prime importance. The corrosion rates of different metals in contact depend largely on their differences in electrode potentials. Other factors also play critical roles, including the baffles residing on steel plates above the hobs adjacent to the louvres. These noise attenuators, which have fibreglass inside them, were positioned to impede noise exiting the louvres. However, it is this very material in the baffles that has caused them to corrode. The fibreglass is a medium that traps water and holds it for very long periods since there is no sunlight where most of the baffles are situated. In addition to this, the baffles sit on top of a steel bench-type plate, which has sheet metal extending out to the face of the louvres and covering them. It is in these positions that the majority of the corrosion, such as crevice and pitting, was evident. The removal of this sheet metal has been beneficial because it has allowed the aluminium to be exposed to oxygen, which will suspend the continual degradation. Unfortunately, despite requests to Westfield to remove the baffles entirely, only a few were allowed to be removed.

The geometry and incline of materials plays a major role in corrosion. The horizontal steel bench supporting the baffles collected debris, especially in the absence of overhead roofing. Designs should be such that welds assist contaminants to be washed off during rain periods and not such that they act as crevice points. In these senses, therefore smooth sloped surfaces are superior to rough horizontal ones. An understanding of the effects of corrosion in general will aid the designer in avoiding making erroneous designs in the initial period.

8.3 Rivets

The existing rivets connecting the fly brace to the louvres was comprised of steel mandrel and sleeve. The louvres have been secured by cadmium-plated tek screws through the mullion channels and into the louvre flutes. However, both steel rivets and the tek screws had been corroded severely and detached in several louvre systems, including the southwest section. The heads of the steel rivets that were situated in the sleeves generally were corroded severely and thus no longer able to serve their structural role of supporting the louvres on the façade. The decision to use aluminium alloy 5056 for the sleeve and 7075 for the mandrel was a response to the requirement that both strength and corrosion resistance were paramount.

Calculations revealed that the rivet requirement in the louvre system was only ~0.15 kN of load acting upon each rivet at the most, whether under suction or under pressure from wind load. Therefore, it can be assumed that these rivets (specified by the supplier to withstand at least 2.3 kN for tensile failure and ~3.3 kN for shear failure) were well within the limits of strength and shear.

It was on the basis of the strength and corrosion resistance of the rivets that 10,000 of them were used on the project. These were used primarily on the rooftop and the building face in order to secure the existing louvre profiles to the mullions using 6061 T6 sheet of 2.54 mm thickness. To date there is no sign of corrosion or structural deterioration anywhere in the relevant areas of the building. 6061 is considered ideal from a strength point of view and it was necessary to take advantage of this sheet strength so that there would be no bearing material weakness. This was considered since holes remove material and therefore reduce the material's effective area from a strength perspective and hence weaken the metal.

The load on each rivet, even in the worst case, was 0.15 kN. The bearing yield strength of riveted or bolted connections usually is taken as the stress that produces 1% elongation, based on the hole diameter. Generally, it is recommended to consider the bearing yield stress as ~1.5 times the tensile proof stress of the material if suitable edge distances are maintained. It therefore was decided that it was safe to place the rivets only in positions in which they were required. For example, one rivet was assigned for each louvre and the number of rivets in the structural mullion was staggered in order to ensure that adequate strength of the attachment would ensure security of the plate.

It was considered that 6061 was more suitable than either 6060 or 6063 in terms of corrosion resistance, strength, and compatibility with the existing louvres. The rivet selection required research as well. The rivets need to be compatible with the 6061 of the new louvres and the 6060 of the existing louvres in order to avoid galvanic corrosion. After researching the field, it was clear that general aluminium rivets did not have the required strength or shear properties to support the unusually high wind loads exerted upon the louvre system. A manufacturer in the USA, who produces rivets with 5056 sleeve and 7075 mandrel, often used in aircraft, was identified. The chemical composition of the sleeve was compatible for use on both the aluminium strip and louvre. The grip length, which enables secure rivet attachment, was selected on the basis of the thickness of the plate, louvre, and mullion sections, which were to be riveted to one another. Owing to the limited influence of loading on the rivets, the intent was to optimise both corrosion resistance and strength in the rivets.

8.4 Team Selection Based on Expertise, Safety, and Working on Façade

70% of the project would not have been achievable if new ideas and designs had not been adopted throughout. For example, the use of the Building Maintenance Unit (BMU) was possible at the lowest level of work, level 26. On levels 27-29, owing to the width of the outward protruding and sloping columns, it was not possible to use a BMU. Owing to safety concerns of conventional scaffolding and ladder-type systems, it was decided to use window cleaning abseilers for the levels that the tradesmen in the BMU could not access (levels 27 and 28).

Since drilling and riveting of the louvres on the face of the building was required, the abseilers were trained in drilling and riveting. The client was presented with a worst-case scenario of the fall of a man, if suspended anywhere along the 6 m drop, to the ledge below, which is 1 m wide. A force of at least 276 N was determined to be required (see Appendix J) for the suspended individual to fall over the edge should the rope break. These issues required knowledge of the appropriate Work Cover guidelines for working at heights. The Standards applicable to abseiling are AS/NZS 1891.3 *Fall Arrest Devices*, AS/NZS 1891.4 *Industrial Fall-Arrest Systems and Device: Selection, Use and Maintenance*, AS 4488.2 *Industrial Rope Access Systems*, AS/NZS 4360 *Risk Management*, and Workcover *Guidelines* 4503 and 4512 for portable ladders and the use of fall-arrest systems. Upon having satisfied the criteria for this work, the Compliance Manager set in place the relevant safe work method procedures and risk assessments, which were assessed internally and then provided to the client for approval (see Appendix J).

8.5 Design of Jigs for Abseilers to Drill into Aluminium Mullions

There is considerable previous discussion about the internal brackets and how they secured the louvres, which were on the façade. These were designed, fabricated, and hot dip galvanised to support the louvres internally. These brackets in turn were secured via chemical anchoring in either the concrete roof or the concrete hob on the ground adjacent to the louvre systems. The concrete hob basically was part of the ground floor, which separates level 28 from level 27. However, a connection needed to be made to secure the louvre assembly. The assembly consisted of C-channel mullions, which were considered structural. A great deal of effort was involved in researching what type of connection would be ideal to connect through the mullions.

After extensive research, it was decided that the bolts that were available on the market did not offer a connection that would hold the louvre system from outside to inside. These bolts were capable only, for securing the internal section of the C-channel mullion. Also, the area of holes would be a disadvantage from a structural point of view. On this basis, it was decided to use high tensile M8 bolts and have them threaded along the unthreaded shank section and coated so that the two opposing sides of the mullion could be drilled completely through, with the bolts' being fed through to the internal brackets. The added advantage of and a key consideration in using high-alloy bolts were that high-strength bolts afford the best results in terms of endurance if the surface coating is removed. High-alloy steels have superior fatigue limit life and endurance than standard bolts, especially in corrosive environments.

Another challenge was for hand-access between the concrete hob and the louvre in order to tighten the nuts. In many instances, due to the louvre mullion corner sections' being below the concrete hob, it was difficult even to observe where the bolt would emerge. This is the reason why nuts were welded on the insides of the brackets. This required the design and construction of several jigs to marry up with these nuts on the corresponding brackets. Identification was extremely important since there were different types of brackets (upper, lower, and side). A map was prepared and this designated the various types of brackets and where they belonged. This was crucial since the abseilers could afford to drill only one hole only with no second chances in the 30 mm thick mullion to accommodate the M8 bolt. If the hole were incorrectly located, the whole section would become defunct. Therefore, precision was not only in drilling the holes but also in establish the exact and precise location of the holes.

The bracket design depended primarily on the locations in which they had to be positioned. Jigs were fabricated from 100 mm x 100 mm x 6 mm RHS and these were aligned with the brackets and nuts for pre-drilling into the RHS. The holes in the RHS were drilled later to a diameter of 14 mm and had stainless steel pipe of internal diameter of 10 mm and wall thickness of 2 mm inserted in the holes and welded in position. Stainless steel pipe was selected owing to the fact that the drill bit would not wear out the pipe owing to the lubricating effect, thereby exhibiting both better wear resistance and strength than if mild steel were to be used. Thus, this enabled maintenance of a steady and straight drill throughout the mullion, which was approximately 100 mm wide. A drill bit of 250 mm length was used for the drilling. The advantage of using this method was that the load bearing on the bolt was minimal owing to the alignment, thus ensuring a longer life of the bolt.

8.6 Design Considerations: Wind, Building Shape, and Shelter

It is imperative not only to understand the corrosive environment on a building rooftop but it is equally important to understand the environment as a whole. For example, the wind direction, frequency of wind speeds, and resultant effects in the area are very important parameters in the design stage. The effect of other adjacent buildings and the effects of suction and pressure on the buildings help to determine which side of the building requires more strengthening of one component compared to the same component on another face of the building, or the particular type of design that would be best suited in one location as opposed to another.

On the Westfield rooftop, the greatest wind forces and frequency were primarily from the west and secondly from the south. It was the southwest section of the rooftop that had experienced the initial collapse of the structural roof section. It also was evident that the remaining material was corroded. However, in some parts of the rooftop, there was little or no corrosion, whereas, for the same material but in different locations, the corrosion was very severe. This has been attributed to several factors, but the most important are location and incline of the component.

Shelter is beneficial provided the component is fully enclosed. However, if there is cover above but the sides are open, this actually will subject the material to severe corrosion. The reason for this is that the roof does not allow rain water to enter and cleanse the materials but the windborne contaminants still can enter through the sides.

An incline of the component's face 90° degrees is favourable since deposits cannot settle on the surface. On the other hand, horizontal surfaces can be detrimental since deposits may be retained for protracted periods. This was observed in the original PFCs facing east, where the severest corrosion occurred in the associated bolt hole sections and into the bolts, commencing from the horizontal upper face. In general, there was cover from above but the sides were open owing to the louvres, which face the ocean.

The channels and bolts that were situated externally, *viz.*, on the north, east, south, and west sides under no cover with no obstructing barriers, were in relatively pristine condition. However, this was not the case for the bolts and hole regions of the PFCs in the southwest section. The reason for this is likely to be the inability of the rain and wind to wash away these deposits from the PFCs before corrosion was initiated. Therefore, the southwest section should be considered to require washing on a more frequent basis since corrosion is dependent upon real-time exposure.

The areas with the heaviest accumulations were the crevice joints in the nut/bolt/hole regions. The fact that neither these bolts nor the mating PFCs were hot dip galvanised is a disadvantage. However, the PFCs that were sheltered by the roof in the east and west corners exhibited severe corrosion, especially in the bolt/hole regions (see Figure 4.23). The bolts in the PFCs in the open areas, with exception to southwest section, generally exhibited little corrosion, even though all of the bolts were identical. Thus, it is clear that not only is the surface finish of the components important but it also is of the utmost importance to recognise and understand the wind patterns in a specific location since these carry salt and in turn deposit it in selected areas.

8.7 Alternative Materials and Implications of Properties and Availability

Westfield requested that the metals to be incorporated for strengthening of the louvres on the façade be lightweight and that they be aesthetically acceptable and in harmony with the remainder of the building. The challenge with this was that, for the material to be aesthetically acceptable, it would have to be non-structural in the sense it would require a specific profile and be situated in louvre structural section attached to a wall. Aluminium may be considered non-structural because their alloys have their stress-strain curve derived from tensile testing and so cannot be simplified to perfect elastic-plastic behaviour, as is the case for steels.

The yield stresses or the elastic limits ($f_{0.2}$) are not sufficient to classify the different alloys on the basis of their mechanical properties. These features tend to present problems with deformation, instability, and buckling, especially when the component is in compression. The proof stress in compression may be considered the same as the proof stress in tension. The elongation also must be considered since it is lower than that of steel. The Young's moduli for the alloys are just slightly greater than one third that of steel. In some cases, this is beneficial, as in the case where the structure is loaded under shock because it has greater resilience than a steel section of the same design.

There are many other aspects of the properties of aluminium, including strain hardening due to fabrication and ageing treatments, even during the welding stage. The latter introduces another variable that often is not understood by the average designer. Hence, with ageing, the assumption that the hardness provides an indication of the strength is incorrect. There is no simple relationship between the hardness and tensile strength of aluminium alloys. In fact, it is possible to achieve the same hardnesses in aluminium alloys of different ageing histories because there are two different microstructures. It is understood widely that different microstructures determine materials' wear rates, corrosion lives, tensile and yield strengths, and ductilities and elongation properties. All of these properties vary with the different heating or ageing times, which include welding effects. The stress-strain curves therefore are affected as a result of the above and this is why it is difficult to formulate an accurate structural analysis based on simplified models. That is, the Young's modulus is not constant owing to the various strain hardening effects that result from heat treatment and/or welding.

The way forward on this matter was through the aluminium angles which were selected to connect to the louvre system and the particular choice of angle bracket be connected to the concrete wall. There was no alternative to join but by welding owing to physical constraints imposed by the site.

From a corrosion perspective, this was acceptable since 6060 T5 aluminium alloy was selected. However, from a structural point of view, this would not have been acceptable had it not been for the 1:500 years calculation, which deemed the bracket to be overstressed under severe wind load conditions. This highlights the point that, calculations should be used to identify where the loads and buckling will occur. From this, the welded bracket could be positioned such that these regions would be avoided. These calculations also made it apparent that the bending moment about the welded joint, calculated to be 0.054 N·m, was excessive. This added to the shortcomings of this welded joint. Ideally, consideration should be given to ensuring that welds and therefore the HAZ be placed away from highly stressed joints and areas of greatest bending. The welded joint in these open aluminium sections should ideally have been as close to the centre of gravity of the component as possible. The solution to this problem lay in securing the steel bracket from the inside and connecting to the louvres externally using abseilers.

8.8 Factorial Method in Materials Selection

The latest factorial method studies, *viz.*, ISO 1586-1:2000 were used to compare and determine whether the refurbishment work was appropriate. The assessment identified some processes of installation and mechanical joints as being low on the rankings for the estimated lifetime. This was beneficial in this respect. However, what the study also highlighted was the inherent weakness in the factorial approach. For instance, the method does not take into account the key issues of fabrication of materials, such as welding or even the primary processing of aluminium. For this reason, it would be difficult for the existing factorial approach to achieve widespread acceptance. For this to be truly applicable and credible, the method would require incorporation of every single stage of the material's history. The work also highlighted one of the key absences in the factors used to assign weighting. This was the micro-environment of small spaces rather than the macro-environment, which the method treats as more or less a constant.

Bolts supplied by *Hilti*, a reputable bolt supplier, provided 20 HSL bolts with 5 μm of hot dip galvanising instead of the 40 μm that was observed with the smaller bolts. This could have become a costly exercise. This coating specification was overlooked and was picked up during the factorial assessment since the coating thickness data were required to generate data for the estimated reference service life (ESLC). The bolt, if a thicker coating is not applied, may fail as a result of losing its thin coating within a few years due to pitting corrosion, despite the impressive size of the bolt M20 and the fact that it is made of a high strength alloy.

Designers also must pay attention to the coating thickness as this is related directly to the number of years a material's parent metal will be protected from corrosion. Hot dip galvanising probably is amongst the most robust of all coating treatments, in particular when in the vicinity of the ocean. The 5 µm coating was considered to be inappropriate for this project in the long term. It should be emphasised that contractors should check specifications rigorously prior to purchasing from the supplier. As mentioned earlier, these bolts have been scheduled for maintenance, which will take the form of applying a thicker zinc coating during the next inspection.

Owing to the limitations of the factorial method, a variation of this method in the form of a factorial matrix was developed. The factorial matrix provides guidance in the selection of available materials applications and environmental factors, allowing the simple two-dimensional matrix to achieve a multidimensional capacity. The matrix ideally would identify a choice of materials applications, required service lives, and other critical factors, thereby allowing calculation of the design life.

The matrix also is intended for corrosion factors to be implemented, including *inter alia*, galvanic corrosion, predictability of lifetime in welding, and strengths of anchor bolts. Illustrations for welding and anchor bolts have been provided in Chapter 6 in order to indicate that the program is possible with even a limited amount of information to hand. The user may select a specified lifetime for any item to be designed, and this is dependent on selecting several other variables that will be located in different matrix positions from which to choose.

Also, HAZ calculations may be attempted by using existing reference data and respective strength values in certain materials being welded. The values can be used as factors in the program for the welding of, for example, 6351 T6 of 3 mm thickness and 6063 T6 of 2 mm thickness in order to determine the joint efficiency. It would be recommended to use automatic welding to help eliminate many possible variables associated with manual welding. This would provide the required data be established for a particular material and input into the matrix. The welding of aluminium is a complex procedure and the matrix may be able to summarise the safe and optimal conditions required to deliver concentrated energy to the region to be welded as quickly as possible in order to produce deep and narrow fusion welds.

The varying thicknesses (2 mm and 3 mm) and different material properties (6063 for new louvres and 6351 for new structural mullion channels) attached together for this project must be taken into account since the heat dissipation and thermal conductivity varies between these materials.

The other factor which can be taken into account is the varying effects of the alloys' electrode potentials as a result of the thermal treatment of welding in one section. As a result, galvanic sites may be set up. One form of protection against this type of situation is to apply a durable surface coating on the entire section to eliminate any corrosion as a result of environmental influences. In the case of the new louvre sections that were welded, powder coating was applied for this purpose.

In order to join the louvre material to the mullion material, alloy filler 5356 was used as a response to its adequate strength, feedability, and good welding characteristics with the 6000 series alloys. Even so, an extra step was taken whilst welding the 6351 mullions to the 6063 louvre panels to ensure that any craters that formed were converted to convex orientation in order to minimise the risk of cracking.

During the prototype welding of the louvre system in the workshop, there initially was a trial period of welding. Cracking between the joints was observed for the two materials being joined. Research into this problem revealed that the thinner material (6063 alloy louvres) would have a higher thermal diffusivity since it was relatively thin compared to the 6351 mullion thickness. The solution in overcoming this cracking problem was to weld in a manner so as to create a convex shape instead of the common concave shape that occurs. The reason for this lies in the fact that aluminium cools extremely quickly and it is well documented that these types of craters form tensile stresses on the surrounding material since the weld bead does not have ample time to cool. This prevents the weld bead from flattening out or filling in the crater, eventually forming cracks. Therefore, the initial trial involved continuing to weld at the end of the weld path. Instead of stopping/finishing, the welding continued using a feeding wire whilst also reversing the direction of welding in order to ensure that the usual crater region is re-welded and completely filled. This was done over a distance of ~20 mm and it appeared to produce a sound clean weld, with no visible signs of cracking being evident afterwards.

8.9 Hot Dip Galvanising, Steel Design, and Shelter to Minimise Corrosion

In light of the fact that all goods had to be transported twenty-nine floors using the goods elevator, the attractions of splice sections become apparent. They also have the advantage of being suitable for future dismantling. However, they have the disadvantage when it comes to collecting residue and not being washed off. It is understood from general bridge design that splice joints that have bolts and joints that attract debris facilitate build-up that encourages long-term corrosion.

The steel sections that I designed, have been fabricated and welded off site and then hot dip galvanised, have to date shown no signs of corrosion. However, the areas of concern are the spliced PFCs, which have numerous joints, nuts, bolts, and irregularities, all of which are sitting on a horizontal plane, under cover, and open to one side. Although not obvious now, these irregularities are anticipated by providing sites for potential contaminant accumulation and therefore gradual corrosion unless cleaning maintenance is regularly undertaken on these sections.

The reason that radial brackets were substituted with two plates at right angles with one another and butt welded was because butt welding affords higher strength than radiused brackets, which often crack at the larger radius face, but also because the welded section of the butt welding was at a 45° angle so that no deposits would sit on it and become a site for corrosion, at least out in the open. Further, the amount of silicon in the welded area was stipulated to be equivalent to that of the steel silicon content so that galvanising would be galvanically uniform and not allow premature corrosion. It was ensured that the silicon content of the filler material would not be lower than that of the steel since this would render the whole component vulnerable.

The fact that several PFCs were supplied by the galvaniser with the coating chipped raised concerns. Hence, a further step in the company's QA auditing was added to the inward goods inspection method. Several methods of control were in place to ensure that the galvaniser was galvanising according to the required Standards. The galvaniser was certified to ISO9001:2000 and galvanised in accordance with AS/NZS 4680, so the auditing was made relatively easy due to access to paperwork and relevant batch numbers for the items.

In one instance, my Compliance Manager and myself have inspected the site of the galvanisers and did a complete audit on the service provider's activities. The audit was satisfactory and the entire system seemed to be in order. The audit also included recording the bath temperatures and inspecting the method of dipping. However, during the audit, it was noticed that, when the PFCs were dipped in the galvanising bath, the temperature of the molten zinc dropped somewhat when larger volumes of metal were immersed together. The reason for this was obvious, being due to heat capacity issues associated with the large volume of dipped components. Upon making the observation, the reason for the chipping of the zinc coating on the PFCs became clear. The galvanisers were requested to treat the components in stages where less metal was immersed at one time. It was important for the temperature to be maintained at the correct level. When this procedure was implemented, the galvanising thickness and surface in general obtained the acceptable appearance that galvanised components have. The Project Manager then was instructed to inspect all of the PFCs at the galvanisers prior to leaving the galvanising premises.

The reason why the temperature was important lies in the iron-zinc phase diagram. In this system, there is a partial solid solution of zinc in α-iron. It has been proposed that an intermediate phase ξ forms due to brief immersion or low temperatures [63]. Hence, it may be possible that the coatings on the PFCs were chipping as a result of the formation of this phase.

There was another observation that was visually evident immediately after quenching of some of the PFCs. This was a yellowish/green film. The protective patina on the steel surface, consisting of insoluble zinc oxides, hydroxides and carbonates as a result of the reaction of the galvanised zinc with the atmosphere, generally is stable, and this is what gives the coating its long life [62]. Therefore, it was of concern whether or not this film had interrupted the formation of the beneficial patina. Investigation revealed that the film formed owing to the presence in the quench water of 0.10-0.15 wt% sodium dichromate, which is added by many galvanisers in order to avoid a specific type of corrosion that occurs during wet storage. This solution did not interrupt the natural formation of the patina.

The next step was to audit the steel supplier, also a nationally and internationally reputable supplier and certified to ISO9001:2000. The steel composition for each batch was supplied with a certificate specifying conformation with Australian Standards and included chemical analysis, heat number, mechanical testing, and grain size. This provided confidence in assuring that the steel would conform to the correct galvanising treatments. These were aspects that had to be considered in the design stage but they were not evidenced anywhere on the Westfield site for the original design.

As mentioned above, from a design point of view, such as in the baffles, there should be some outlet for the water that is can become trapped inside. The horizontal steel benches supporting the baffles were corroded severely due to a roof's being positioned above the baffles.

When plates are welded to the ends of a RHS and galvanised, they normally have holes drilled in order to allow venting during galvanising. When erected vertically, these RHSs are used for structural supports to support the entire louvre system. It frequently is overlooked by the designer and fabricator/installer that it is important to stipulate and ensure that the holes are sealed off at the top once galvanising has been completed. The reason for this is due to the entrapment of rain water, which enters the top of the RHS and cannot exit. This is especially detrimental to the structure when in a marine environment. The design must allow for the appropriate sealing of the holes at the top section when erected, especially if the RHS are to be used for structural purposes and outside under no cover. A two-mix steel-type putty was used to seal off the holes in both the newly fabricated and existing RHS columns in order to avoid welding and potentially damaging the galvanising. It is imperative that consideration be given to the galvanised surface because heat treatment or damage to the galvanised layer will establish a weak point for corrosion to be established.

8.10 Selection of Aluminium Brackets for Louvres

Angle 6060 was selected to fit in the profile due to the fact that there was no other shape, size, or structural component that would match the position between the louvres and concrete wall and have the corresponding corrosion resistance and compatibility with the existing façade louvres. The disadvantage with this particular alloy is that the profile or size allows it to be only in the T5 condition. The minimal strength of 6060 T5 is 150 MPa for the tensile strength and 110 MPa for the yield strength.

Therefore, it is clear from the FEA results that the bracket was stressed adjacent to this welded bracket. The FEA did not identify the fact that the bracket was overstressed specifically due to the welding. Incidentally, this is the area where there is greatest stress, and the position of stress indicated by the FEA is alongside the welded bracket. It is known that the welding generates heat across ~25 mm on both sides of the weld in the worst case. So it is safe to assume that the welded bracket was weakened considerably as a result of this. The FEA calculations used the worst wind situation, which is 1:500 years for the annual probability. However, even though it is 1:500, this is not to say that it might happen. Also, in order to ensure that the absolute worst-case scenario was taken into account, all of the calculations assumed that the louvre face is vertical and not at an incline. That is, in these cases, the angle of the louvre profile is of no significance. However, if the angle had been considered, then the wind loading calculations would have given lower stress levels. The calculations used were based on the regional wind speed in the ultimate state. The loads exerted by either suction or pressure indicated that the angle and bracket were stressed in critical regions, which would be potential sites for crack initiation.

The one back-up method for this potentiality was the securing of the brackets internally. For this reason, there is no real cause for concern, but it is essential to understand that certain alloys, such as 6060 T5, cannot be relied upon wholly to be considered in terms of a purely structural perspective.

8.10.1 Consideration of Pressure Forces on Louvres and Connected Brackets

FEA indicated that the stress load upon the angle (shorter width, *i.e.*, perpendicular to the wall) was approximately 122 MPa. This exerted tensile loading directly adjacent to the bracket and in the overlapped and welded regions. The stress distribution extended out over a distance of ~20 mm. There were no other stresses of significance indicated by the FEA in this angle under pressure. This indicates from the basic rules of heat transfer in the welded region that a definite reduction in strength and a high possibility of failure in this region are highly likely with continued loading.

It must be noted that 6060 T5 with reduced strength after welding would be ~90 MPa, which is much less than the 122 MPa force exerted on the angle in this region discussed. The bracket sitting against the concrete would appear to be safe when there are pressure forces acting since the bracket has support behind it and there are no HAZs or other signs of weakening of the bracket along the face of the concrete wall. However, as mentioned, the angle is weakened as a result of the welding. The indicated tensile forces adjacent to the welds, as evidenced by the FEA tensile forces of 122 kN acting perpendicularly and away from the building when the pressure forces are exerted. This is an area that must be monitored.

8.10.2 Consideration of Suction Forces on Connected Brackets

FEA indicates a 146 MPa load acting upon the bracket under suction and adjacent to the bolt hole. The stress is concentrated on the face of the bracket around half of the periphery edge of the bolt hole region and in the position facing the direction upon which the applied load has been exerted upon, *i.e.*, from louvre side. The other single place of notable stress distribution is on the back of the plate that sits flat against the concrete wall. The stress level applied to this region was ~64 MPa. The load is concentrated mainly away from the hole and along the entire width of the bracket. Analysing the entire angle and bracket system, it is evident that the main loads and stresses are applied only about the middle bracket section (the long angle section is situated vertically and perpendicular to the welded bracket) and this was measured to be approximately 700 mm either side of the bracket. It also is evident that the middle section will require extra stiffening. However, it would not be advisable to weld any more brackets in this region since the material already has been weakened substantially previously by the welding of the middle bracket. As mentioned in Section 8.10, these brackets have been further strengthened via galvanised steel internal brackets.

The bolt hole section does not have equal forces acting upon it. The forces act on one side only and this is due to the fulcrum type of load applied on the bracket by the angle, which in turn is influenced by the louvre connection. The load exerted under suction is 146 MPa and, towards the higher side of the material's parent metal, the ultimate tensile strength is 110-150 MPa. The bracket, which is bolted against the wall, has not been affected by heat near the bolt hole region; it is 6 mm thick. However, the continual loading of the bracket under suction may have had a gradual effect on the welded region of the bracket, which also has been evidenced by the 0.054 N·m bending moment calculation about this region too. The strength of the region adjacent to the weld would be ~90 MPa. The possibility of this section's failing before the bolt hole region has not been determined yet and requires some study to determine its likelihood.

The bracket facing the concrete would be under compression and has approximately 60-100 MPa exerted upon it and against the wall, nearer to the edge along the width. Continual loading under pressure would not have any immediate effect on the integrity of the bracket in this location. At worst, this may create crack initiation sites if the loads are continual and they inevitably would lead to failure. Both sites, which are either adjacent to the bolt hole location or the side facing the wall, are potential failure sites. Hence, it is probable that the bracket will fail eventually under continual suction forces, although there is a greater possibility that the bracket itself would fail at the welded regions if there is continual loading. The possibility of failure at the welded joints is greater than failure nearer the bolt hole region. The reason for this is that the strength at the welded joint would be ~90 MPa but the strength of the bracket near the bolt hole would be ~110-150 MPa, but the bracket against the wall is one solid section.

The distribution of stresses near the bolt region can be complex and involve a study of shear and tension, which depend upon the distance of the bolt from the free end plate. This would depend on the direction of the force applied on the bolt/plate hole region. Bolt failure can be ruled out due to its stipulated 16.6 kN capability, but the plate may exhibit oval-shaped plastic deformation about the hole upon excessive loading, or the plate may fail in shear or in tension. The weakest of these will cause the failure mode at the connection. This should be considered as the limiting strength in design. The applied stress about the bolt and hole, shown in Figure 7.7, would be distributed through a range of elastic and elastoplastic phases and a determination would need to be made as to whether shear or tension loads apply. The severity and type of wind load acting on the louvre system will dictate the type of stress and therefore subject the bolt hole to elastic, plastic, or complete failure. The plate thickness and hole distance from the free end all have an influence on the limit for failure and design. The welded bracket has the added possibility of lack of weld fusion between the 6 mm plate and 3 mm angle. Also, thinner materials generally exhibit wider HAZs, which reduce the strength. In either case, fortunately, the loading is limited to the forces acting upon the brackets, which actually are secured internally. Only if the internal brackets were to fail would the above scenario for failure be more than likely than the typical scenario. The progression of failure would be in the following order:

a) Bracket weld joint (122 MPa load position)
b) Bolt hole region (146 MPa load position)
c) Back of plate facing wall by loss of material or wear (60-100 MPa load position)

8.11 Welding of Aluminium Brackets

The brackets that have been welded would at first glance suggest that the areas that are the most likely to be affected by heat transfer would be the entire angle bracket itself. The key variables during welding that may affect the strength and hardness of the HAZ in aluminium will influence the response to forces subjected on the metals, such as wind loads.

Since all welded aluminium has a HAZ adjacent to the welded region, then the metallurgical changes involve recrystallisation of the metal around the weld. This is analogous to ageing. The effect of ageing effectively is dependent upon the alloying elements and/or the degree of mechanical work hardening imposed upon the aluminium. The strength of the aluminium decreases as a result of grain growth. The driving force behind grain growth is heat and this increases with annealing temperature and time.

The HAZ is influenced and increases due to several parameters, including:

a) Increase in heat input
b) Long welds
c) Increase in thermal conductivity
d) Decrease in thickness
e) End of weld
f) Multipass continued welding without cooling
g) Prolonged time

On the other hand, the HAZ decreases as a result of the following:

a) Multipass welding with intermediate cooling
b) Use of heat sink
c) Use of automatic welding machine instead of conventional manual MIG/TIG welding

Any one single aspect of the above may have been affected due to manual welding of the brackets used by the welder. The parameters that may be considered to be fairly constant would be the material's thickness and the thermal conductivity of the aluminium alloy.

8.12 Effect of Chemical Anchor Position on Concrete Edge Distance

The bolt position in the brackets in the wall supporting the louvre on the façade is incorrect. The *Hilti* specification recommends a minimum of 90 mm away from the concrete edge. Consideration of the mechanical properties is necessary:

a) Selection of chemical anchors and drilling techniques
b) Considerations associated with drilling close to edges of concrete façade
c) If reinforcement is present in concrete and in vicinity of drilling, core drilling may be necessary; also, corrosion of the reinforcement would be inevitable if appropriate action is not taken to seal off properly to avoid ingress of corrosive contaminants or electrolytes
d) Strength of concrete, where the higher the concrete strength, the higher the resistance to cracking
e) Type of coating on bolt since corrosion in the concrete will pose an additional detrimental aspect to the concrete, especially if in the vicinity of internal reinforcement bars

All of the above have been considered and discussed in Chapter 7. Through load analysis, it was evident that the maximal force acting on an anchor shows that the anchor is within a safety factor based on maximal load analysis. Calculations of forces acting on the anchor show that the maximal load on an anchor is 3.4 kN, which is well under the *Hilti* anchor specification (Appendix R), which states that it can support a maximal load design resistance of 16.6 kN.

The problem with the re-locating the anchor away from the edge distance to 80 mm, suggests that, originally, the anchor was incorrectly designed to be in the middle of the steel plate. Relocating it created a much worse situation than leaving it in the 50 mm position. From the calculations, it appears that the anchor should have been left where it was and, as an alternative, extend the brackets over the existing ones. Since the nut is easily released, these brackets have sufficient extra material support to ensure the load would be reduced on them. Fortunately, for the initial design, and as described in detail earlier in Chapter 4, it was not necessary to strengthen the brackets due to the fact that the internal brackets are secured from the outside using jigs and long bolts through the louvres, onto the concrete hobs using chemical anchoring. Therefore, there is no need for any modifications or strengthening of the brackets.

8.13 Selection of Louvre Material

Since the majority of the existing louvre profiles (6060) on the Westfield rooftop and façade were re-used due to their structural adequacy and absence of visual corrosion, only the southwest corner was fabricated from new. It is interesting that, in consideration of the long life to date of these louvres under such extreme conditions, they have not been affected by corrosion directly, particularly those in contact with metals than aluminium itself. However, there is evidence of indirect corrosion in light of the corroded steel rivets in these louvres and other metals impinging on the aluminium surface, such as corroded bolts. The reason why the louvres are in such good condition is, besides being of 6060 material which, is suitable for marine environments and being in the anodised condition, these louvre profiles reside at an incline of ~52° and they are completely exposed in the open, with no roof shelter as such. The rain and wind are accessible to these regions and so keep them deposit-free.

At this point, wind considerations became important because a louvre replacement profile had to be selected and the louvres had to be fabricated using a material with specific chemical properties to ensure longevity of the fabricated assembly. It is important to note that a slightly smaller louvre section than the original louvres was selected for use in the southwest section derives from the intention of reducing the surface area, thereby prolonging the life of the louvre system due to the reduced loading conditions. The calculations of the wind pressures and suction in regard to the new louvres, and the old existing refurbished louvres were based on the original profile, which was larger so as to allow for a reasonable safety factor. In order to increase further this safety factor, the properties of 6060 T5 were used in the calculations instead of those of 6063 T6, which was the new louvre material. Further, the calculations took into consideration that the louvre profile was completely flat, sitting vertically at 90°, as opposed to its actual inclination. Thus, the calculations were expected to show a much higher loading factor than would be the case if it had been calculated according to the true condition. Even so, the results were favourable and provided confidence in the design.

6063 T6 of 2 mm thickness was selected for the louvre profiles and 6351 T6 of 3 mm thickness was selected for the mullions. These alloys are in contrast to 6060 for the existing louvres and 6063 for the existing mullions. The mullion channels that were selected were 100 mm x 25 mm x 3 mm. The reason for this choice was that, upon

welding the 6351, the reduced strength properties at worst would still be equal to or greater than the existing old mullions (6060), with a parent metal strength of 110-150 MPa (if the old mullions (6063) were in the T6 condition). Upon welding the 6351 T6 channel onto the new 6063 louvre profile, the reduced strength of the weld in the 6063 T6 louvre profile would be reduced to ~90 MPa. These reductions in strengths for welding were discussed in Chapters 3 and 7 for heat treatable alloys of aluminium.
However, it is the structural column that supports several louvres and is interconnected with other structural members on the rooftop. Therefore, the mullion strength is considered to be imperative.

Even if it is assumed that the HAZ for 6351 T6 had a reduced strength in the worst case of 50% of the parent metal strength (150-165 MPa), this still would be far higher than that of the 6063 parent metal and even the yield strength of the parent metal; it also is nearly double the strength of the welded joint in the 6063 region. The remaining mullion, where it is not welded, would still be in the 300-330 MPa range and would survive under any major wind loading conditions.

The louvre also is thinner (2 mm) than the mullion (3 mm) and, again, this would encourage a wider HAZ in the louvre section. Hence, the louvre section joining the mullion ultimately would be affected and may be considered as the weakest position. If failure is to occur, it is likely to be on the louvre side of the join and may be in the form of a tear.

Strictly speaking, it is the mullion that would have the load bearing upon it, with its cumulative number of joins along its vertical axis. Therefore, these multiple weld sites are a result of joining the individual louvre profiles along the mullion channel. This choice of material and thickness is sound for the reasons mentioned.

The calculations performed for lateral buckling in the mullion sections were based upon the original 100 mm x 30 mm x 3 mm channels comprising two C-channel sections based on 6060 T5 joined/bolted together (see Appendix Q) instead of basing the calculations upon the newly incorporated 6351 T6 aluminium alloy mullions, which would have provided a much higher value than the 9.8 kN calculated. The existing old mullions actually were 6063 and either T5 or T6 (much higher strength than 6060 T5). Also, this does not take into consideration the new channels for the southwest corner using channels or mullions and two C-channels of 6351 T6 of dimensions 100 mm x 25 mm x 3 mm, which are bolted together. The properties of the new mullions (6351 T6), which are of much higher strength than both 6063 and 6060, have not been included in the calculation. Hence, the higher strength values of the mullions were not factored in the calculations, and this allows for a very conservative result.

Although the calculations for the existing old design of the mullions states that the local buckling and plate slenderness are acceptable, the effects of welding on the new louvres would require a different calculation approach as has been done in the present work. In addition, the reduction in channel-mullion size was accompanied by a reduction in bolt size compared to the original channel bolting. This is acceptable because the total height of the column mullions has been fabricated to be half the size of the existing channels on site for the sake of transportation in the goods lift.

To be safe, additional strengthening of the louvre frames was done by constructing structural support for the PFCs and chemical anchoring of the supports to the concrete hob, and EA to the wall as shown in Figures 4.51 to 4.53. The main benefit imparted to these welded mullions/louvres is that they have been powder coated as an extra precaution against corrosion as well as for a suitable aesthetic appearance. This will increase the corrosion resistance immensely, especially in the weakest positions (weld joins), where localised attack may occur if unprotected. The chances of corrosion on the weld join therefore are minimised and longevity is almost assured by this process. Since the welded zone would almost definitely be the weakest zone in the welded aluminium section, it is ideal to have this area specifically coated for as long a period as possible.

Aleo [149] conducted a study that revealed that, in 6351 T6 aluminium alloys, the average measured width of the HAZ based on hardness was 9.9 mm. This was employing a temperature of 230°C. Aleo [149] also found that the measured HAZ under the same conditions but for 6061 T6 was 8.9 mm. His evaluation was compared to that of several other investigators and was consistent with their values. Mazzolani [6] indicated that, in his investigations of heat treatable alloys (including the 6000 series), the average weld strengths in joints are in tension near the weld and in compression away from the weld, as can be seen in Figure 3.35. Aleo [149] also conducted flexural loading on the 6351 T6 welded samples. He concluded that the alloys with the smaller HAZ widths have the greater flexure capacity, and this was consistent with the observations of Malin [129]. He found that the thinnest materials, ranging from 1.6 mm to 3.2 mm, required the greatest heat flux due to the minimal heat input required to produce a minimal weld size, thereby increasing the HAZ. Therefore, it would be reasonable to infer that the HAZ width is greatly influenced by the heat input and, as discussed above, in the case of 2 mm 6063 T6 louvre profiles and the 3 mm 6351 T6 mullion channels, there would be a larger HAZ width in the louvre profile. The thickness of the mullion channel would compensate for the narrowing of the HAZ, whereas the 6063 material profile was only 2 mm. 6351 is able to deflect heat more than the 6063. Aleo [149] concluded that the type of welding also affects the HAZ, and that the semi-automatic welding mode generally narrows the HAZ by 20% whereas, in the automatic welding mode, it is 50% narrower. There also is an increase in the HAZ as the thickness of material decreases. Aleo [149] took only automatic welding into account for his modelling calculations for the HAZ as this is more precise and does not have the inconsistencies of manual MIG and TIG welding by welders.

It would be of considerable importance to determine ways of narrowing the HAZ by using not only thicker materials but also by using various heat sinks, especially when joining two different aluminium alloys of varying thicknesses, such as in the case of the louvre-mullion joint. The joining of two different materials inevitably creates a variation in the HAZ properties and width along the two different materials being welded. These are areas that also require further study but that are not established as yet.

8.14 FEA

FEA analysis could be used before and after fabrication and installation to ensure more favourable results. FEA should involve cross-disciplinary consultation and more rigorous QA to investigate all aspects relating to the construction. The limitations of FEA are that most designers are not familiar with metallurgically induced stresses caused by welding, including the effects of ageing on materials, the consequent extremely complex evolution of precipitates, and the resulting microstructures.

These limitations impose severe limitations on FEA with respect to complex material analyses unless all of the variables and parameters have been identified and included, much as is claimed for the factorial method. This definitely would require a cross-disciplinary approach and use of complex computer modelling. Once developed, this method no doubt would prove to be useful in areas such as the initial design stage of buildings and hence the rooftop structural façade.

Most engineers have a strong structural background but they often are lacking in the field of optimal materials selection and therefore design, as can be seen from the effects of the rooftop of the building. At times, building design calls for aesthetics and light weight. When structural materials are in the marine environments, particularly if the pollution levels are relatively high, then it is imperative to select the most appropriate materials.

Reference was made to the FEA calculations in Chapter 7, which dealt mainly with regions that were deemed to have experienced excessive loads. All of the other components that were designed, fabricated, and installed have satisfied both the manual and FEA calculations. For these, there are no major risks or limitations in the designs that have been incorporated, apart from the structural anchors that will require supplementary coating to compensate for the thin zinc coating.

However the limitations that have been highlighted are exaggerated in that the calculations were performed on the basis of the absolute worst-case scenarios and ultimate state design calculations intentionally allow for conservative calculation results.

In addition to this all of the calculations for the aluminium brackets and louvres have been based either on the lesser strength 6000 series alloys mentioned as yet another layer of safety net. For instance louvre profiles actually were fabricated from 6063 T6 although the calculations were done using data for 6060 T5 instead. Another example is in the calculation for wind loading, which ignored beneficial wind shielding from other buildings, thereby ensuring the severest wind load effects and increasing the safety net to yet another degree.

8.15 Concluding Summary of Project

The present work represents an original contribution to issues of interest to designers and engineers through its distinctive approach to many design considerations, including selection of materials, fabrication, and installation methods. This approach has highlighted many areas that are beyond the scope of a single thesis and so some areas are given relatively brief coverage. As the writing of the present work was concluding, it became apparent that, besides the challenges of designing and searching for ideal methods in physical metallurgy, all of the many facets of materials processing are key components of a larger picture, which possibly could be brought together through the factorial method.

The research undertaken has been able to highlight and focus on some of the positives that have come out of the refurbishment of Westfield Tower 2, Bondi Junction. However, it perhaps is more important to recognise that the research also has uncovered some negatives in terms of materials and their treatment. No project is without fault but the incentive and drive to focus and improve upon these shortcomings is what promotes improved design and engineering practice.

REFERENCES

[1] Web Address: www.experiencefestival.com/a/steel_-_History_of_iron_and_steelmaking/id/607442.

[2] D.J. O'Connor, *Alumina Extraction from Non Bauxitic Materials*, Aluminium Verlag GmbH, Düsseldorf (1988).

[3] H.J. Barnet, *Proceedings 1984 Bauxite Symposium, Society of Mining Engineers of AIMMPE*, Los Angeles, CA, p. 411, (1984).

[4] D. Altenpohl, *Aluminum: Technologies, Applications and Environment*, Aluminium Association Inc., Warrendale, Pennsylvania (1998).

[5] H.M. Flower, *High Performance Materials in Aerospace*, Chapman & Hall London, (1995).

[6] F. Mazzolani, *Aluminium Alloy Structures*, E & FN Spon, London (1995).

[7] M.G. Fontana, *Corrosion Engineering*, McGraw-Hill Book Company, New York, (1986).

[8] P.R. Roberge, *Handbook of Corrosion Engineering*, McGraw Hill Professional, New York, (1999).

[9] G.H. Koch, *Corrosion Costs and Preventive Strategies in the United States*, CC Technologies Laboratories, Inc., Dublin, Ohio (2001).

[10] S. Ganguly, V. Stelmukh, M.E. Fitzpatrick, L. Edwards, "Use of Neutron and Synchrotron X-ray Diffraction for Non-Destructive Evaluation of Weld Residual Stresses in Aluminium Alloys", Journal of Neutron Research, **1**, 225-231, (2004).

[11] I.J. Polmear, *Metallurgy of Light Metals*, Edward Arnold, London, (1995).

[12] G.N. Melhem, S. Bandyopadhyay, P. Krauklis, "The Influence of Artificial Ageing on Abrasive Wear of SiC and Al_2O_3 Particulate Metal Matrix Composites", *MMC – 3, Proceedings of the 3rd Australian Forum on Metal Matrix Composites*, University of New South Wales, (7 December 1992).

[13] G.N. Melhem, P. Krauklis, A.P. Mouritz, S. Bandyopadhyay, "Abrasive Wear of Aged 6061 Al-SiC Composites", *3rd International Conference on Composites Engineering*, New Orleans, USA, (July 1996).

[14] G.N. Melhem, S. Bandyopadhyay, P. Krauklis, "The Influence of Artificial Ageing on Abrasive Wear of SiC and Al_2O_3 Particulate Metal Matrix Composites", *Proceedings Conducted by Institute of Metals and Materials*, Australasia Ltd., Brisbane, Australia, (17 June 1993).

[15] G.N. Melhem , MScEng Thesis, *A Study of Abrasive Wear in SiC and* Al_2O_3 *Particulate Reinforced 6061 Aluminium Metal Matrix Composites*, University of New South Wales, (July 1996).

[16] G.S. Putrich, “USAF Struggles to Replace Aging Aircraft,” Defense News, **22**, 1, (19 February 2007).

[17] R.J. Bucci, C.J. Warren, E.A. Starke Jr., "Need for New Materials in Aging Aircraft Structures", Journal of Aircraft, **37**, 122, (2000).

[18] City of New York, Department of Design and Construction; *High Performance Building Guidelines*, p. 34; (April, 1999).

[19] *United Nations Economic Commission for Europe, Convention on Long-Range Transboundary Air Pollution: An International Co-Operative Programme of Effects on Materials, Including Historic and Cultural Monuments.*

[20] B. Marteinsson*, Assessment of Service Lives in the Design of Buildings – Development of the Factor Method*, KTH’s Research School – HIG Center of Built Environment, Gavle, Sweden, (September 2003).

[21] Web Address: www.corrosion-club.com, M. Tullmin, Canada; Corrosion Club Corrosion Monitoring Information, Corrosion Costs in Industries/Regions, (November 2007).

[22] V.S. Agarwala, "Corrosion Detection and Monitoring - A Review", Paper No. 271, Corrosion 2000, NACE International; IAR Flyer, NRC Institute for Aerospace Research Canada, (2000).

[23] Web Address: www.dsto.defence.gov.au. Defence Science and Technology Organisation (DSTO, Australia).

[24] M. Youson, "Invisible Enemy", Engineering, (September 2003).

[25] Materials World, p. 30 (December 2001).

[26] R. Francis, "Beating Rust on Farm Buildings", (1982), published on www.corrosion.com.au, Australasian Corrosion Association.

[27] Finnish Road Administration, studies conducted in the 1990s, published at www.tieh.fi/winter.htm.

[28] Materials Performance, p. 31 (March 2002).

[29] Web Address: www.corrosioncost.com, Report by CC Technologies Laboratories, Inc. to Federal Highway Administration (FHWA), Office of Infrastructure Research and Development, Report FHWA-RD-01-156; Dublin, Ohio, (September 2001).

[30] BBC news (on-line edition), (7 March 2007).

[31] L.A. Tegtmeier, "U.S. Coast Guard Treads in Deep Water", Overhaul & Maintenance Magazine, Washington D.C., (1 May 2002).
[32] J.P. Broomfield, *Uhlig's Corrosion Handbook*, Chapter 36. Edited by R.W. Revie, John Wiley & Sons, (2000).
[33] L. McLaren, "Bath Time for David", The Globe and Mail, Toronto, ON, (1 October 2002).
[34] New Zealand Archaeology, (11 November 2003). S. Maar CBC radio interview (19 March 2004),
[35] A. Roith, M. Martin, articles published at www.uni-bayreuth.de and www.iza.com.
[36] P. Cavassi and M. Cornago, "The Cost of Corrosion in the Oil and Gas Industry", JPCL, Pittsburgh, PA, p. 30, (May 1999).
[37] M. O'Malley, "Winnipeg's Golden Boy", CBC News Online, Canada, (8 October 2002).
[38] Anon., "Corrosion Costs Eat up DOD Budget" MTTC News, **8** (19 August 2003).
[39] National Institute for Materials Science (Japan).
[40] TACOM, "EMU Coatings Research Institute Continues War Effort Against Corrosion", Eastern Michigan University press release (8 June 2005).
[41] United States General Accounting Office, Report No. GAO-03-753, Washington D.C., (2003).
[42] J. Harris, “Jack Harris Column", Materials World, London, UK (September 2004).
[43] Web Address: www.isa.org, The Instrumentation, Systems, and Automation Society, In-Tech Magazine On-Line, (1 October 1998).
[44] K. McGran, "On the Road to Ruin?", Toronto Star, p. B4, (February 5, 2005).
[45] R. Baboian *et al*., "The Statue of Liberty Restoration", NACE International, Houston, (1990).
[46] IIT Research Institute, Chicago, *Electrolytic Corrosion in DC Powered Transit Systems*, Eight Reports Prepared for the National Cooperative Transit Research and Development Program (NCTRP) Project 48-1, TRB, National Research Council, Washington D.C., (1985-1987).
[47] Web Address: www.empa.ch, Swiss Federal Laboratories for Material Testing and Research, Dübendorf, Switzerland, (1999).
[48] Battelle News Release, (1996).
[49] Akron Chemline, Newsletter of the Akron Section of the American Chemical Society, Washington D.C., (April 1996).

[50] Web Address: www.corrosion-club.com, M. Tullmin, Canada; Corrosion Club Corrosion Monitoring Information, Corrosion Costs in Industries/Regions, Water Infrastructure, link to separate page, (November 2007).

[51] CSIRO news release, Ref. 2001/207, (18 September 2001).

[52] F. Mazzolani, "Inelastic Behaviour of Welded Aluminium Profiles" Costruzioni Metalliche, No.5. ABS (2004), ANSYS (2004); "Guide for Buckling and Ultimate Strength Assessment for Offshore Structures", Release 8.1 Documentation, ANSYS, INC. Code of Practice for Design, (1971).

[53] G.J.C. Frohnsdorff, J.W. Martin, "Towards Prediction of Building Service Life: The Standards Imperative", *7th International Conference on Durability of Building Materials and Components*, (19-23 May 1996), Stockholm, Sweden. Edited by C. Sjostrom. E. & F. N. Spon, New York, p. 1417, (1996).

[54] J. Abbott, "Developing an Effective Service Life Asset Management and Valuation Model", presented at 13th Pacific-Rim Real Estate Society Conference Fremantle, Western Australia, (21-24 January 2007).

[55] *Guideline on Durability in Buildings* S478-1994, Canadian Standards Association (CSA), (1994).

[56] *The English Edition of Planning Guide for Service Life Planning of Buildings*, Architectural Institute of Japan, Tokyo, Japan, (1993).

[57] B. Marteinsson, *Assessment of Service Lives in the Design of Buildings – Development of the Factor Method*, Licentiate Thesis, KTH Research School – HIG Centre for Built Environment, Gavle, Sweden, p. 94 (September 2003).

[58] Technical Committee ISO/TC 59, *Building Construction – Subcommittee SC 14, Design Life*.

[59] ISO (2000) ISO 15686-1:2000 *Building and Constructed Assets – Service Life Planning – Part 1: General Principles*.

[60] ISO (2001) ISO 15686-2:2001 *Building and Constructed Assets – Service Life Planning – Part 2: Service Life Prediction Procedures*.

[61] ISO WD 15686-8.2 *Building and Constructed Assets – Service Life Planning – Part 8: Reference Service Life* (a working document 2002).

[62] *Hot Dip Galvanizing*, Galvanizer Association of Australia, Melbourne, Victoria, (March 1993).

[63] E.V. Proskurkin, N.S. Gorbunov, *Galvanizing, Sherardizing and Other Zinc Diffusion Coatings*, Technicopy Ltd. for Zinc Development Association, London UK, (1980).

[64] Australian Government, *Australian Safety and Compensation Council, Guidance on the Principles of Safe Design for Work*, p. 14 (2006).

[65] Web Address: www.ascc.gov.au, Australian Safety and Compensation Council.

[66] Woolcock Street Investments v CDG Pty. Ltd., HCA 16, Woolcock Street Investments, (2004).

[67 M.W. Martin, R. Schinzinger, *Ethics in Engineering*, McGraw Hill, New York, (1989).

[68] Engineers Australia, *Handbook for Chartered Professional Engineer (CPEng)*, (2004).

[69] "Aircraft Accident Report – Aloha Airlines, Flight 243, Boeing 737-200, N 737 111 near Maui, Hawaii, April 28, 1988," *NTSB/AAR-89103*, National Transportation Safety Board Bureau of Accident Investigation, Washington, D.C., (4 June 1989).

[70] J.A. Marceau, R.G. Caton, "Corrosion Control and Prevention on Aging Commercial Aircraft," *Proceedings of the Tri-Service Conference on Corrosion*, Atlantic City, New Jersey, USA, (17-19 October 1989).

[71] J.A. Marceau, A.A. Adjorlolo, "Commercial Aircraft", in *ASTM, Corrosion Tests and Standards: Application and Interpretation*, American Society for Testing and Materials Society, p. 574, (1995).

[72] D. Banis, J.A. Marceau, M. Mohaghegh, "Design for Corrosion Control," Aero Magazine, **8**, Seattle, Washington, USA, (1999).

[73] M.F. Ashby, D.R.H. Jones, *Engineering Materials 1: An Introduction to Their Properties and Applications*, Pergamon Press, Oxford, UK, (1991).

[74] M.G. Fontana, N.D. Greene, *Corrosion Engineering*, Chapters 2 and 3, McGraw Hill, New York, NY, (1967).

[75] American Society for Metals, *Metals Handbook*, **10**, Materials Park, Ohio, (1975).

[76] *Aerotech 95*, Imeche Seminar Publications, London, UK, (1996).

[77] D. Banis, J.A. Marceau, M. Mohaghegh, "Design for Corrosion Control," Aero Magazine, **8**, Seattle, Washington, USA, (1999).

[78] D. Miller, "Corrosion Control on Aging Aircraft: What is Being Done?"; Materials Performance Magazine, NACE International, Houston, Texas, p. 10, (1990).

[79] C. Hoffman, "20,000-Hour Tune Up", Air & Space Magazine, Washington, D.C., USA, p. 39, (1997).

[80] C. Seher, A.L. Broz, "National Research Program for Non-Destructive Inspection of Aging Aircraft", Materials Evaluation, **49**, 1547, (1991).

[81] P.R. Roberge, *Handbook of Corrosion Engineering*, McGraw Hill Companies, New York, NY (2000).

[82] J.P. Komorowski, S. Krishnakumar, R.W. Gould, *et al.*, “Double Pass Retroreflection for Corrosion Detection in Aircraft Structures”, Materials Evaluation, p. 80 (1996).

[83] J.F. Wildey II, Aging Aircraft, Materials Performance Magazine, NACE International, Houston, Texas, p. 80 (1990).

[84] J.P. Komorowski, N.C. Bellinger, R.W. Gould, *et al.*, “Quantification of Corrosion in Aircraft Structures with Double Pass Retroreflection”, Canadian Aeronautics and Space Journal, p 76, (1996).

[85] F. Saunders, “The Titanic’s Ruin”, Discover Magazine, **22**, New York, NY, USA, (August 2001).

[86] Alcoa Fastening Systems, *HUCK-CLINCH® Process Manual*, (2005).

[87] University of Wisconsin - Stout, Physics Department, *Statics & Strength of Materials* [uw-stout - physics 372-321], Menomonie, WI, USA, (October 2007).

[88] American Society for Metals, *Aluminium Volume. 3: Fabrication and Finishing*, p. 474, Metals Park, OH, USA (1967).

[89] EU, Competitiveness Working Group on E-Construction, Phase II, (2004).

[90] National Institute of Standards and Technology, *Final Report GCR04-867, Cost Analysis of Inadequate Interoperability in the US Capital Facilities Industries*, Gaithersburg, MD, USA, (August 2004).

[91] ACI Materials Journal, *Concrete and Sustainable Development*, September-October, p. 415, Farmington Hills, MI, (1997).

[92] D. Holbrook, “Corrosion Annually Costs $300 Billion”, Battelle Study, Battelle Memorial Institute, Columbus, Ohio, (1 January 1996), Web address www.battelle.org /pr/12corrode.html.

[93] A.G Guy and J.J Hren, *Elements of Physical Metallurgy*, Addison Wesley, Reading, Mass, p. 157, (1965).

[94] L.H. Van Vlack, *Elements of Materials Science and Engineering*, Prentice Hall, p. 534, (1989).

[95] M. Mallon, E. Kolbe, *ORESU-T-79-003*, Oregon State University Sea Grant College Program, Corvallis OR, USA, p. 53, (1979).

[96] S. Dexter, J.P. LaFontaine, “Effect of Natural Marine Biofilms on Galvanic Corrosion”, Corrosion Journal, **54**, 851, (1998).

[97] *Atlas Specialty Metals*, Tech Note No. 7, Altona North, Vic, (May 2006).

[98] L. Yupoj, J.R. Frank, E.J. St.Martin, Corrosion/99 Paper No. 99198, Annwil Conference and Exposition, San Antonio, TX, USA, (April 1999).

[99] International Molybdenum Association, Case Study 03, IMOA ABC 03/03, Brussels, Belgium, (2003).

[100] Research Council on Structural Connection, *Specification for Structural Joints Using ASTM A325 or A490 Bolts*, Chicago, IL, USA (23 June 2003).

[101] P. Albreht, S.K. Coburn, F.M. Wattar, G. Tinklenberg, P. Gallagher*, Guidelines for the Use of Weathering Steel in Bridges*, Transportation Research Board, National Cooperative Highway Research Program, Report 314, (June 1989).

[102] American Iron and Steel Institute, *Interim Guidelines: Evaluation, Repair, Modification and Design of Steel Moment Frames*, Report No. SAC-95-02, CA, USA, (1995).

[103] B. McDad, D. Laffrey, M. Damman, R. Medlock*, Performance of Weathering Steel in TxDOT Bridges*, Texas Department of Transportation, Austin, TX, USA, (May 2000).

[104] Katholieke Universiteit Leuven, Lecture 4A.2: *Factors Governing Protection of Steelwork*, Leuven, Belgium (2008).

[105] *ASM Metals Handbook*, **20**, ASM International, Metal Parks, OH, USA, (1997).

[106] *ASM Metals Handbook*, **2**, ASM International, Metals Park, OH, USA, (1979).

[107] S.H. Avner, *Introduction to Physical Metallurgy*, McGraw-Hill, New York, NY, (1974).

[108] ASM Metals Handbook, **2**,ASM International, Metals Park, OH, USA, (1979).

[109] P.C. Varley, *The Technology of Aluminium and its Alloys*, Newnes International Monographs on Materials Science and Technology, p. 46, (1970).

[110] *ASM Metals Handbook*, Metals Park, OH, USA, p. 1246, (1948).

[111] ASM Metals Handbook, **4**, ASM International, Metals Park, OH, USA, (1981).

[112] V.F. Zackay, *High-Strength Materials*, John Wiley & Sons, New York, NY, p. 53, (1965).

[113] J.E. Hatch, *Aluminium: Properties and Physical Metallurgy*, ASM International, Metals Park, OH, USA, p. 153, (1984).

[114] MatWeb, *Material Property Data*, www.matweb.com, Christiansburg, VA (2008).

[115] I. Dutta, S.M. Allen, J.L. Hafley, “Effect of Reinforcement on the Ageing Response of Cast 6061 Al_2O_3 Particulate Composites”, Metallurgical Transactions A, **22A**, 2553, (1991).

[116] H.J. Rack, R.W. Krenzer, “Thermomechanical Treatment of High Purity 6061 Aluminium”, Metallurgical Transactions A, **8**, 335, (1977).

[117] G. Thomas. Journal of the Institute of Metals, **90**, 57, (1961-1962).

[118] E.A. Brandes, G.B. Brook, *Smithells Light Metals Handbook*, Butterworth-Heinemann, Oxford, UK, (1998).

[119] G. Madhusudhan *et al.*, Defence Metallurgical Research Laboratory, Hyderabad, India, (December 2006).

[120] M.J. Kontoleon *et al.*, "Butt-Welded Aluminium Joints: A Numerical Study of the HAZ Effect on the Ultimate Tension Strength". *Proceedings of the ARW, The Paramount Role of Joints in the Reliable Response of Structures*. Edited by C.C. Baniotopoulos, F. Wald, p. 337, (2000).

[121] P. Rigo, *et al.*, *9th Symposium on Practical Design of Ships and Other Floating Structures (PRADS)*, Luebeck-Travemuende, Germany, (2004).

[122] J.K. Paik, A. Duran, "Ultimate Strength of Aluminium Plates and Stiffened Panels for Marine Applications", Marine Technology, **41**, 108, (2004).

[123] S.F. Pollard, "Boatbuilding with Aluminum", International Marine, (1993).

[124] *Engineers Handbook: Aluminium*, Aluminium Development Council of Australia, Sydney, NSW (1979).

[125] *Aluminium and Aluminium Alloys – Extruded Rod, Bar, Solid and Hollow Shapes*, AS/NZS 1866:1997, Standards Australia, Standards New Zealand, (1997).

[126] *GMAW Welding Guide*, p. 57, Lincoln Electric.

[127] *Aluminium MIG Welding Guide*, p. 9, Lincoln Electric, Milperra, NSW.

[128] H.N. Hill, J.W. Clark, R.J. Brungraber, "Design of Welded Aluminium Structures", Transactions of the American Society of Civil Engineers, **127**, (1962), Part II.

[129] V. Malin, "Study of Metallurgical Phenomena in the HAZ of 6061-T6 Aluminium Welded Joints" Welding Journal, **74**, 305, (September 1995).

[130] W.L. Burch, "The Effects of Weld Speed on Strength of Aluminium Joints", Annual Spring Meeting, St. Louis, MO, (1958).

[131] Canadian Standards Association, *CSA W59.2-M1991*, (1991).

[132] Web address: www.gaa.com.au. Galvanizers Association of Australia, Level 5, 124 Exhibition Street Melbourne, Victoria 3000 Australia; Galvanizers Association of Australia, *Benefits of Galvanizing, Durability and Service Life*, (November 2007).

[133] A. Osawa, J. Ogawa, Zeitschrifte fur Kristallographie, **68**, pp 177-178, (1928).

[134] A. Osawa, J. Ogawa, Scientific Reports of Tokyo University, **18**, pp 165-176, (1929).

[135] C W Stillwell, G L Clark, Industrial Engineering and Chemical Analysis, **2**, (1930).

[136] G.V. Raynor, *Annotated Equilibrium Diagrams, No. 8*, Institute of Metals, London, UK (1951).

[137] Web address: www.galvanising.co.nz. Galvanising (HB) Ltd., 41 Thames St, P.O. Box 1114, Pandora, Napier, NZ; Galvanising Hawks Bay Limited, Technical; (February 2008).

[138] *Huck Magna-Lok Fasteners as per Engineering and Installation Standards*, HWB-865S and HWB-865T, Huck International, Inc. USA.

[139] HILTI, *Fastening Technology Manual*, (2007).

[140] J.R. Rider, *Report on Estimated Service Life (The Factor Method)*, University of New South Wales, Sydney, (2007).

[141] Web address: www.athenasmi.ca, Athena Sustainable Materials Institute, 28 St. John Street, P.O. Box 189, Merrickville, Ontario, Canada K0G 1N0, (April 2006).

[142] *Steel Bridge Design Handbook*, Chapter 23, p. 23, National Steel Bridge Alliance, St. Charles, IL, USA.

[143] B.I. Bjorneklett, O.Grong, O. Myhr, A.O. Kluken, Metallurgical and Materials Transactions A, **30A**, 2667, (1999).

[144] R.Y. Hwang, C.P. Chou, Scripta Materialia., **38,** 215, (1998).

[145] T. Ma, G. den Duden, Materials Science and Engineering A, **A266**,198, (1999).

[146] A. Deschamps, L. David, M. Nicholas, F. Bley, F. Livet, R. Seguela, J.P. Simon, G. Vigier, J.C. Werenskiold: Advances in Engineering Materials, **8**, 579, (2001).

[147] D.R. Askeland, *The Science and Engineering of Materials*. Chapman and Hall, London, (1996).

[148] J.A Goldmark, A. Chakravarti, M.J. Bibby, Metallurgical Transactions of AIME, **15B**, 299, (June 1984).

[149] V. Aleo, Ph.D. Dissertation, *Effect of Welding on the Width of the Heat-Affected Zone of Aluminium Alloys*, University of Windsor, Ontario, Canada, (2004).

SECTION III

A. Figures

Fuselage skin	: 2024–T3, 7075–T6, 7475–T6
Fuselage stringers	: 7075–T6, 7075–T73, 7475–T76, 7150–T77
Fuselage frames/bulkheads	: 2024–T3, 7075–T6, 7050–T6
Wing upper skin	: 7075–T6, 7150–T6, 7055–T77
Wing upper stringers	: 7075–T6, 7150–T6, 7055–T77, 7150–T77
Wing lower skin	: 2024–T3, 7475–T73
Wing lower stringers	: 2024–T3, 7075–T6, 2224–T39
Wing lower panels	: 2024–T3, 7075–T6, 7175–T73
Ribs and spars	: 2024–T3, 7010–T76, 7150–T77
Empennage (tail)	: 2024–73, 7075–T6, 7050–T76

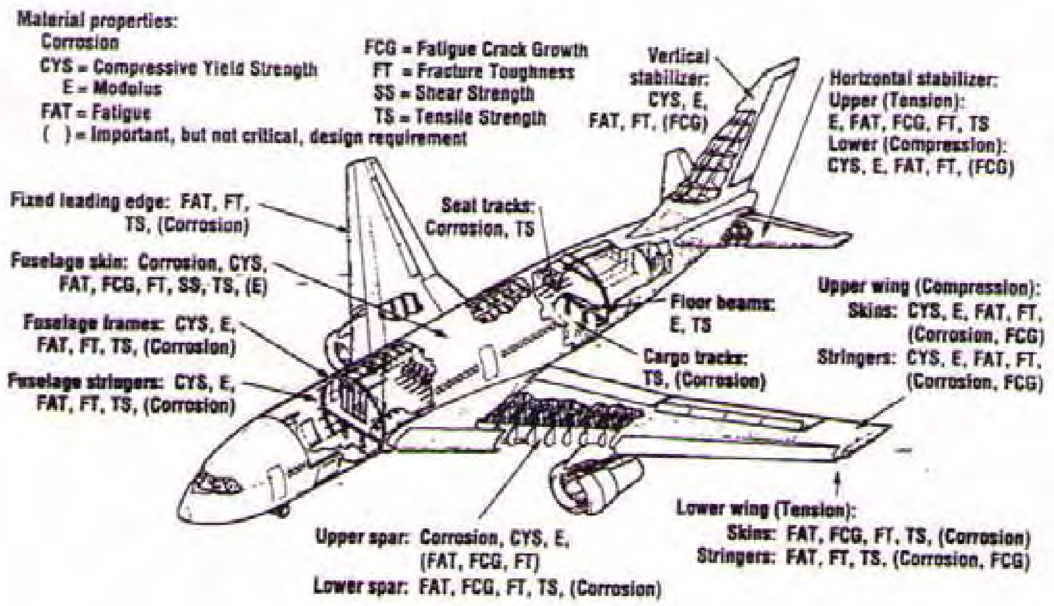


Figure 1.1 Materials selection for structural members of a typical passenger aircraft [11].

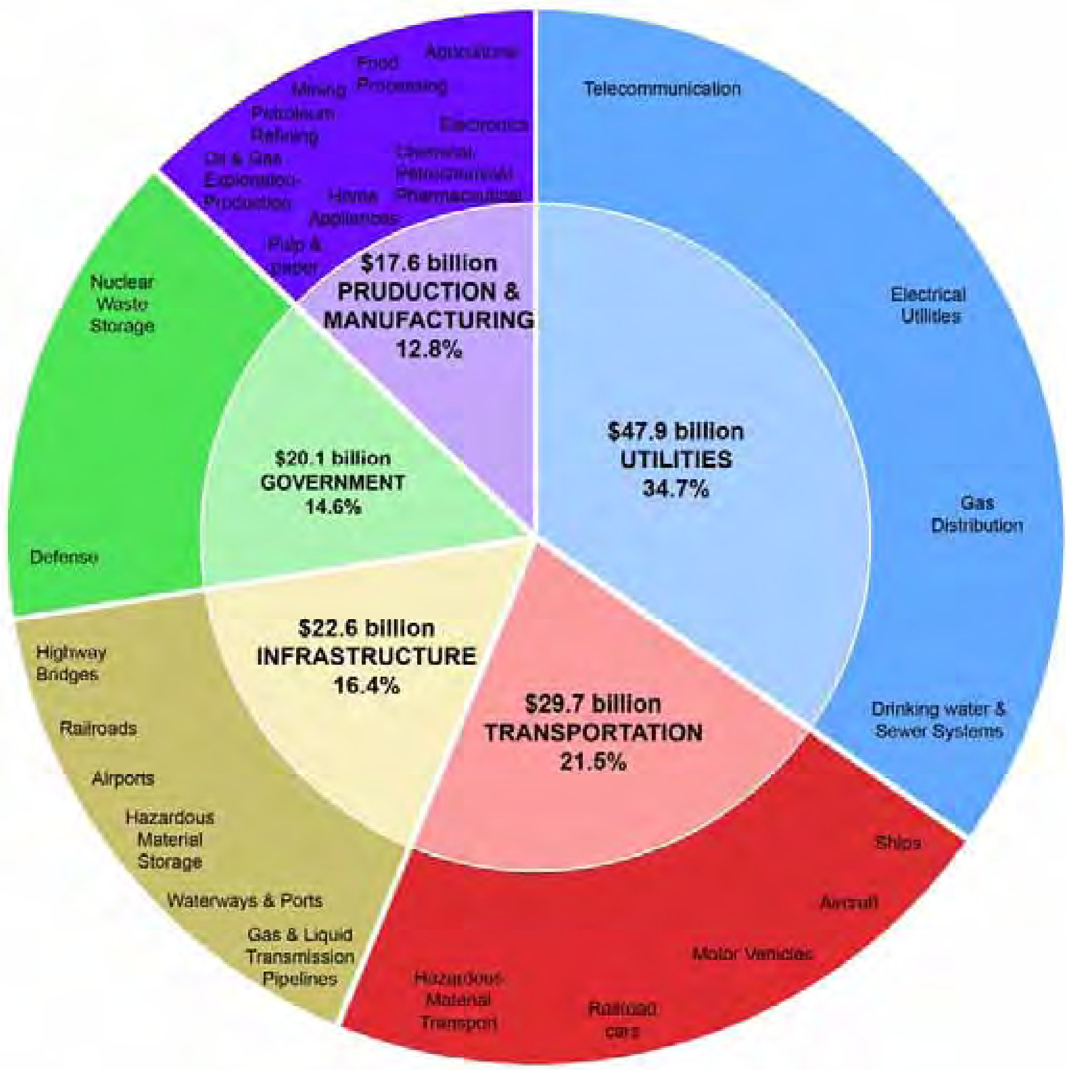


Figure 1.2 Cost of corrosion in various sectors of US economy [29].

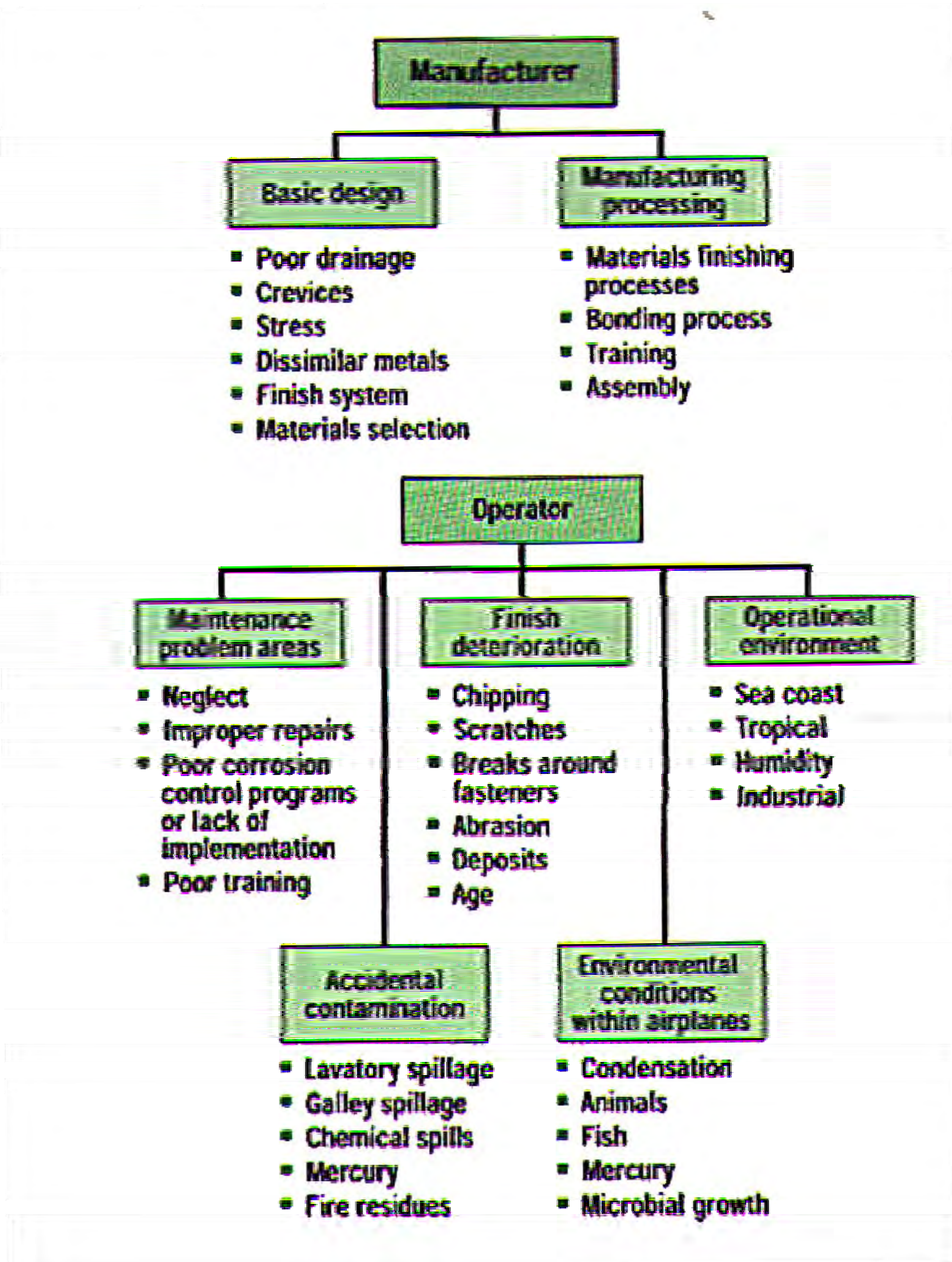


Figure 3.1 Typical causes and sources of corrosion in aircraft [77].

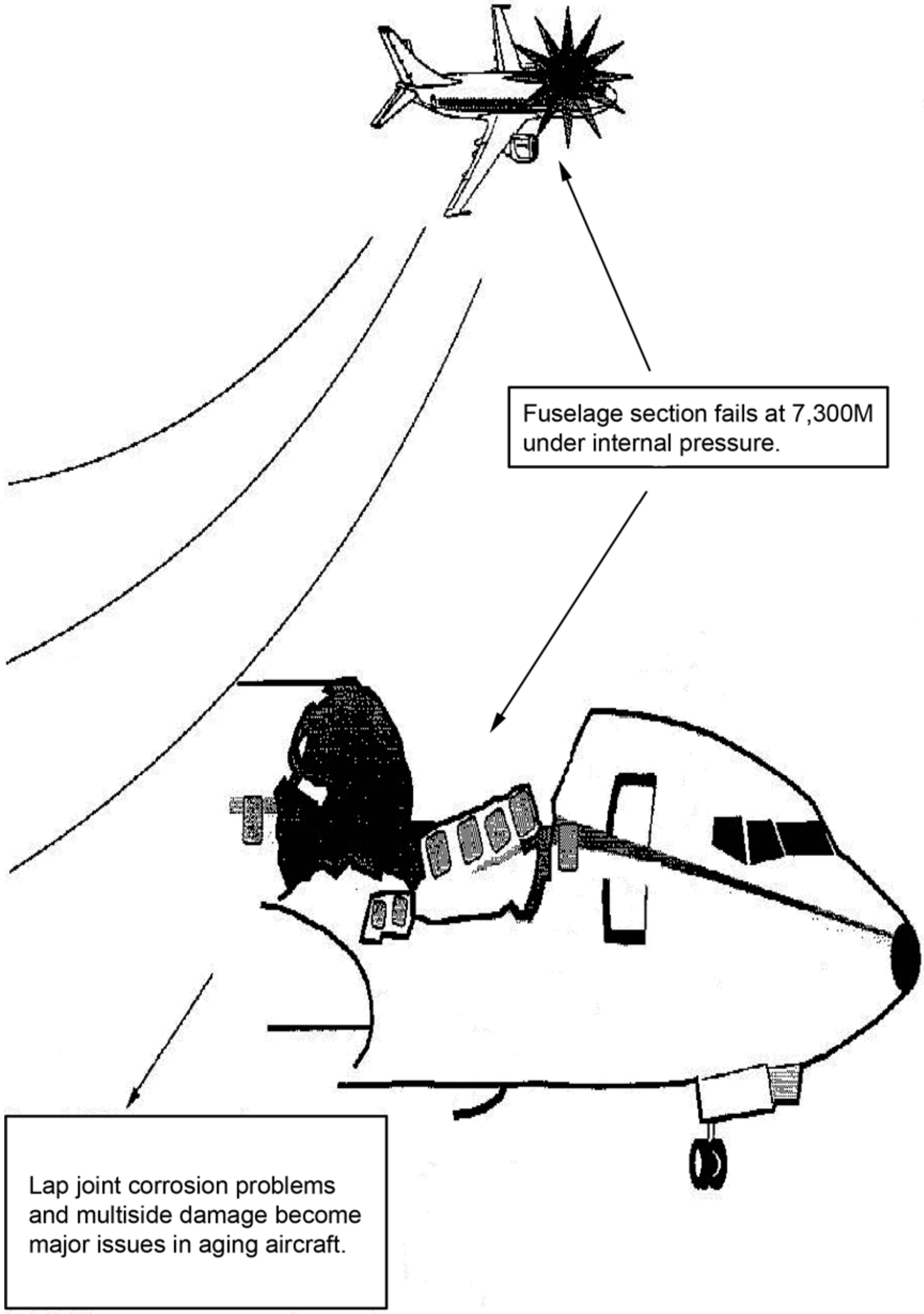


Figure 3.2 Schematic description of the *Aloha* aircraft incident [69,81].

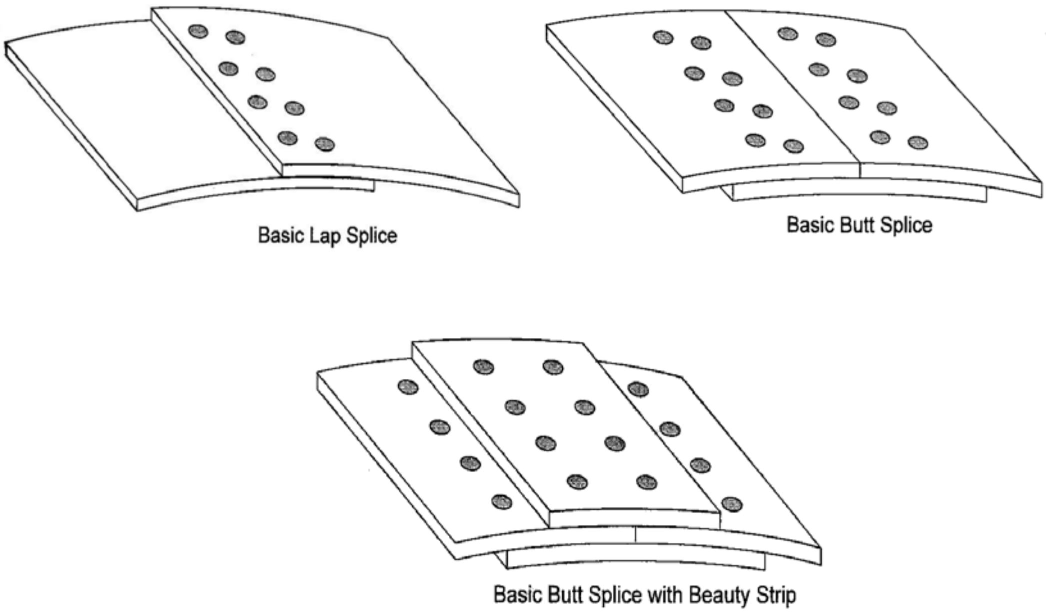


Figure 3.3 Three basic types of lap splices used for construction of aircraft fuselages [81].

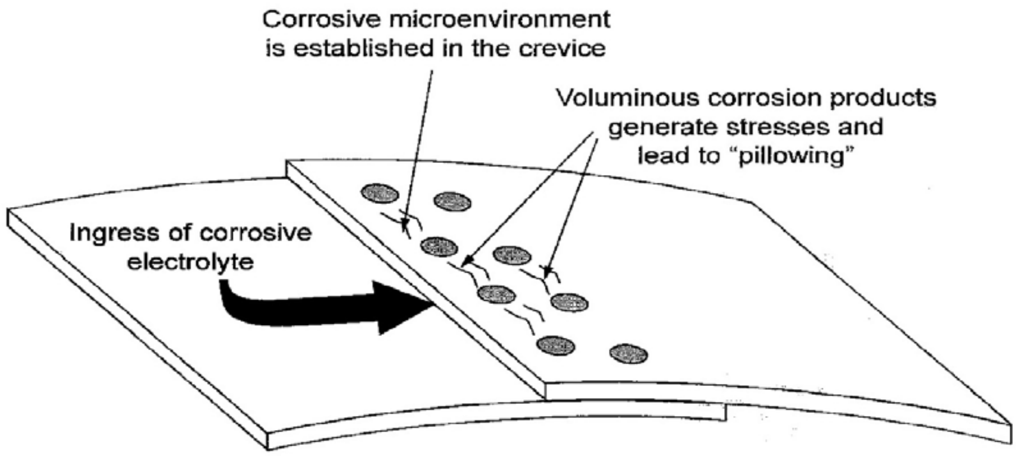


Figure 3.4 Pillowing of lap splices in aircraft [81].

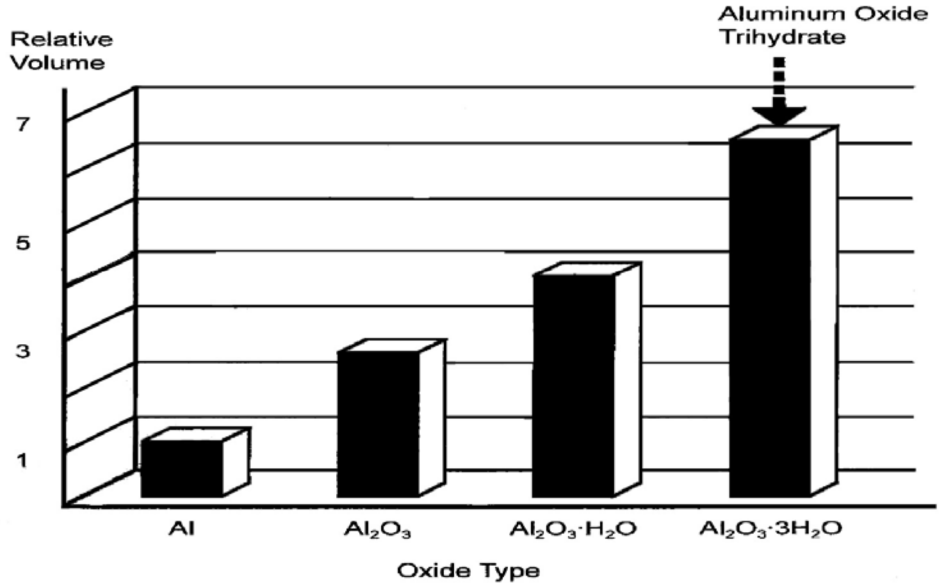


Figure 3.5 Relative volume of aluminium corrosion products [81].

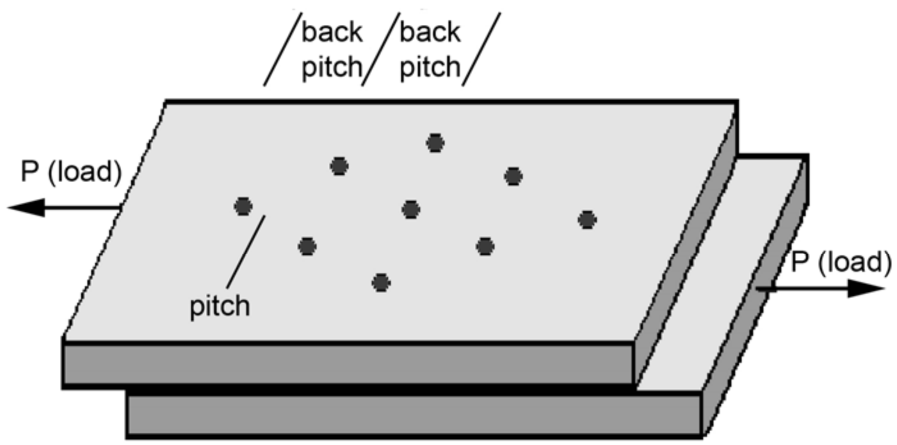


Figure 3.6 Lap joint showing two plates overlapping and rivets or bolts penetrating two plates connecting them together [87].

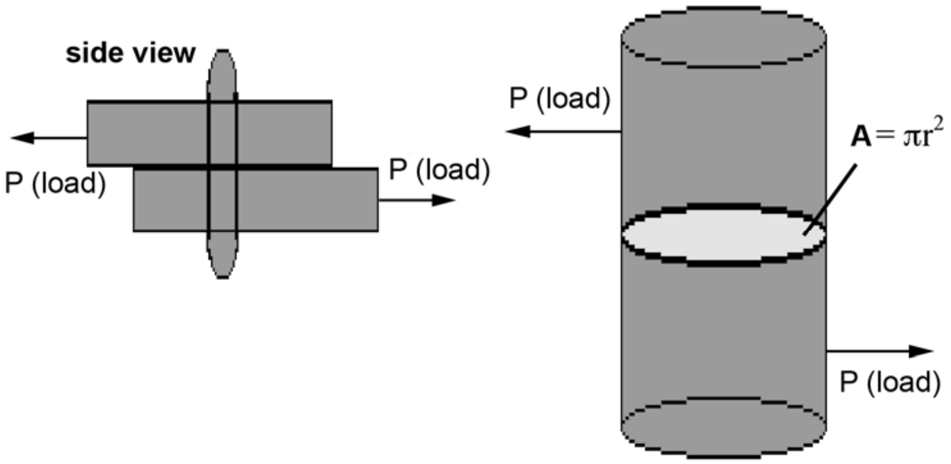


Figure 3.7 Side view of lap joint showing forces applied parallel to area in shear [87].

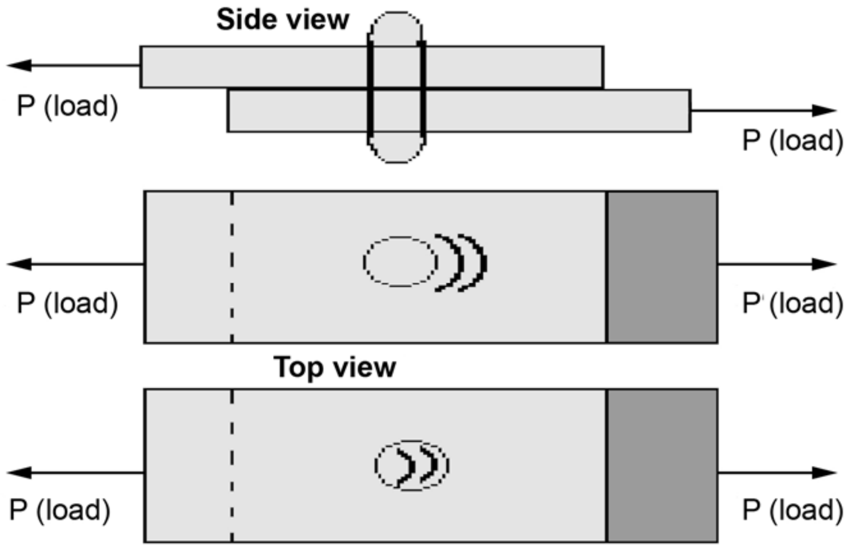


Figure 3.8 Illustration showing top plate being pulled into rivet and exerting compression on rivet [87].

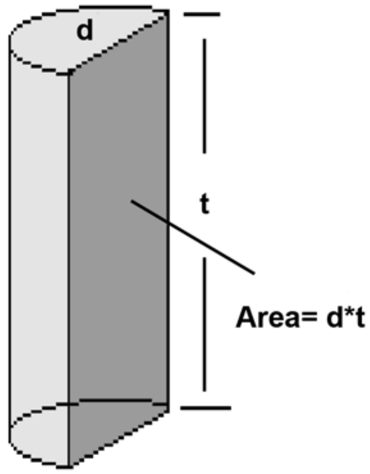


Figure 3.9 Areas of plate and rivet considered in region of compression [87].

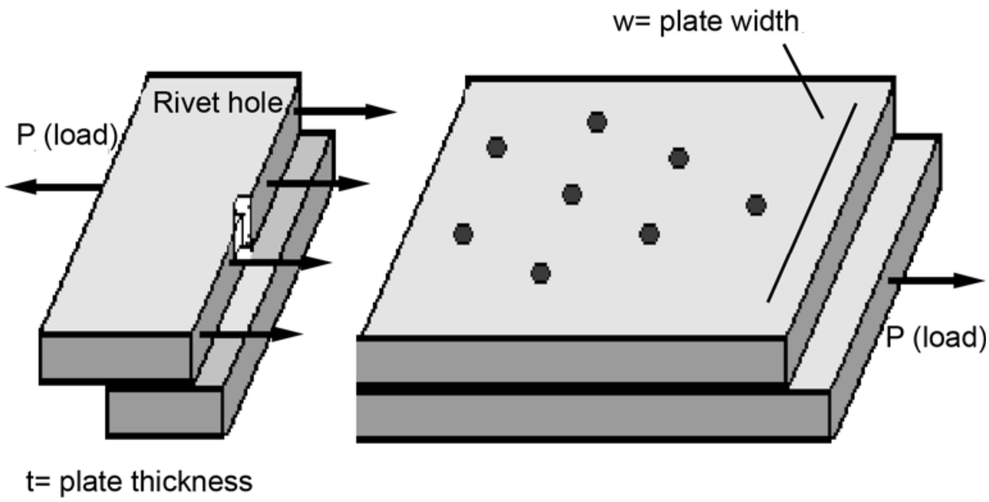


Figure 3.10 Failure under tension of plate occurring where first set of holes is situated [87].

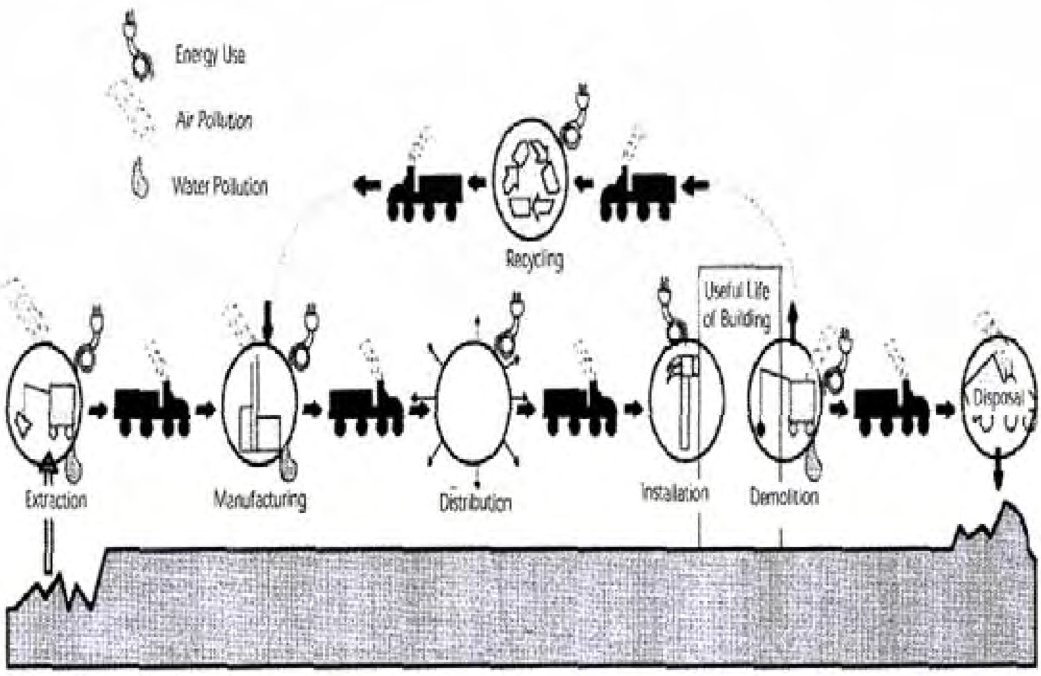


Figure 3.11 Product life cycle assessment [91].

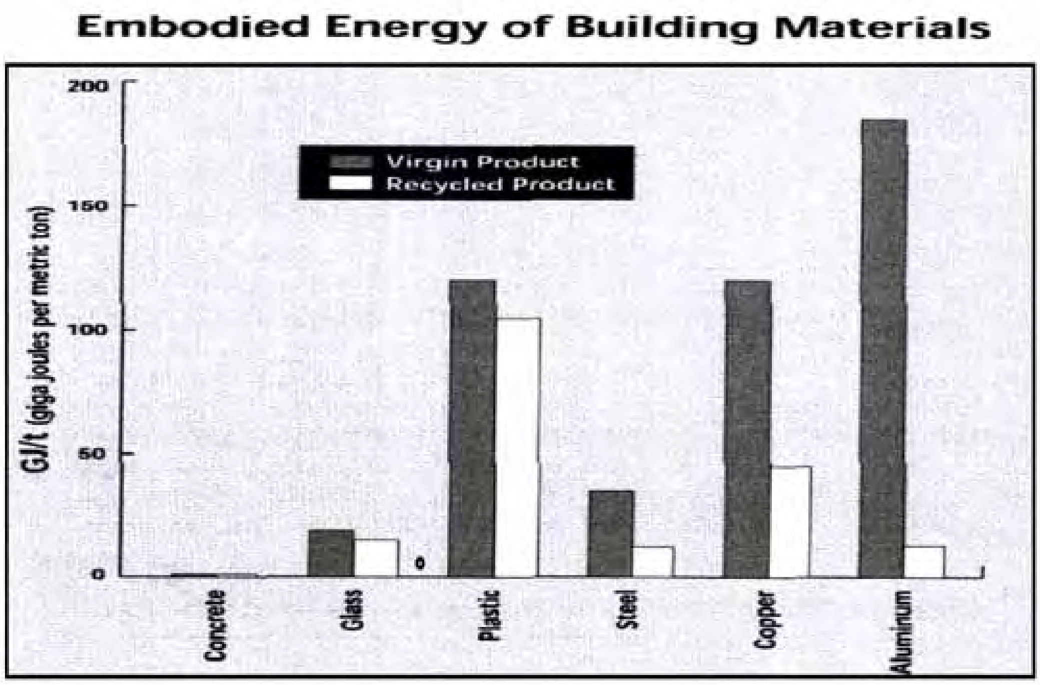


Figure 3.12 Embodied energy of building materials [18].

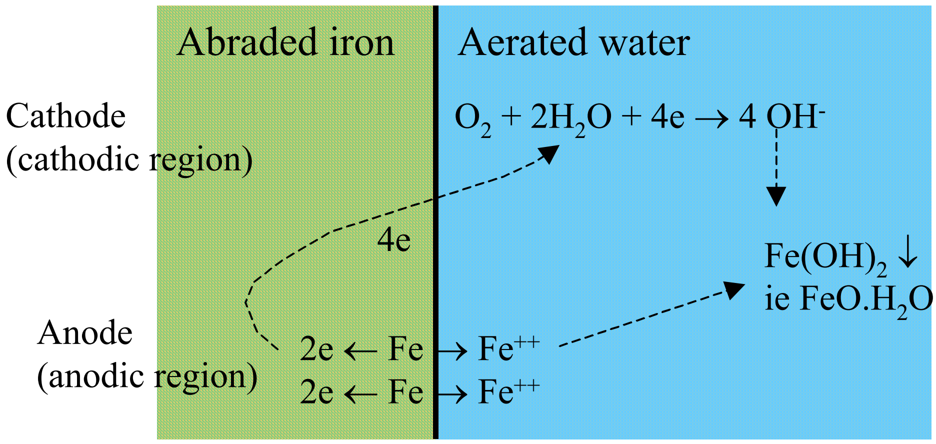


Figure 3.13 Wet corrosion [73].

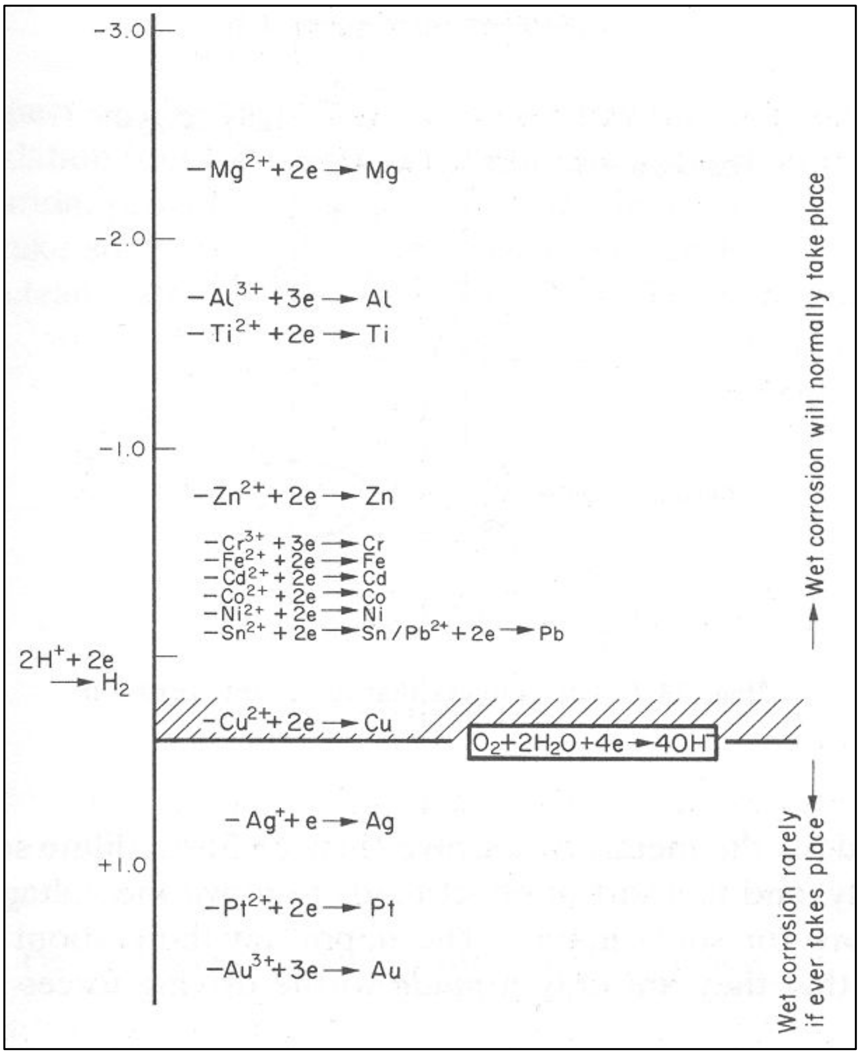


Figure 3.14 Wet corrosion voltages (at 27°C) [73].

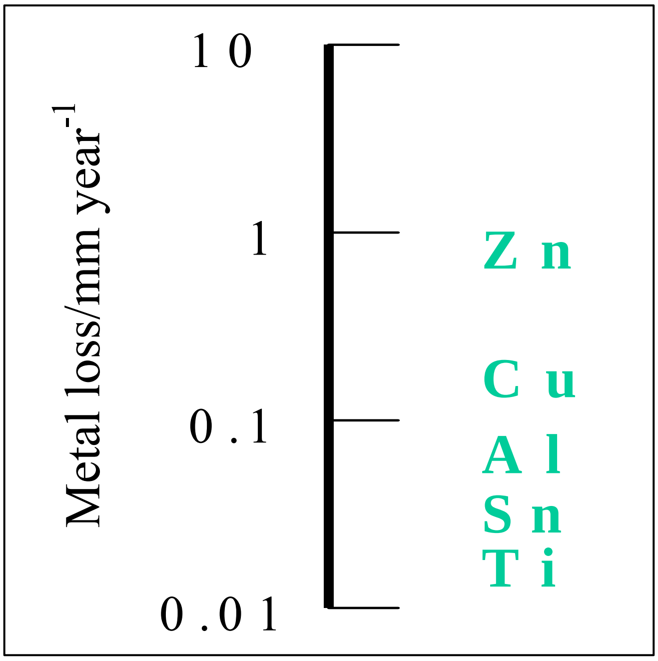


Figure 3.15 Corrosion rates in clean water [73].

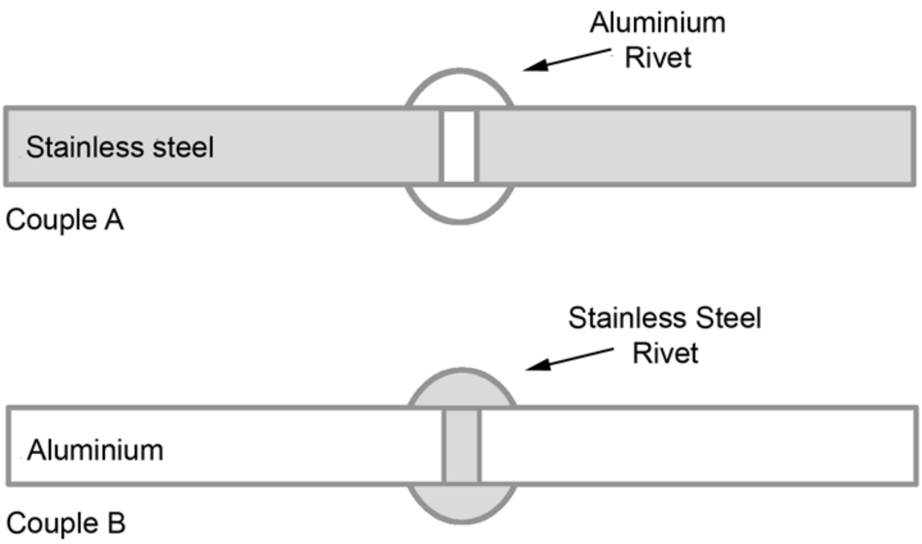


Figure 3.16 Effect of cathode-to-anode (C/A) ratio on galvanic corrosion [96].

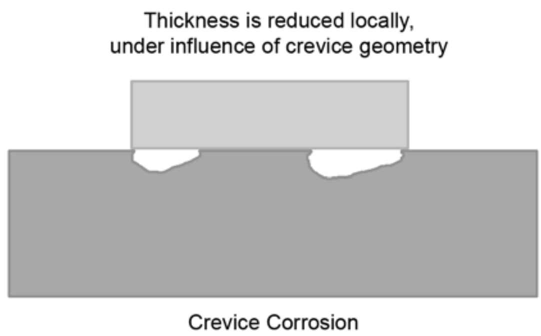


Figure 3.17 Illustration of typical crevice corrosion [73-75].

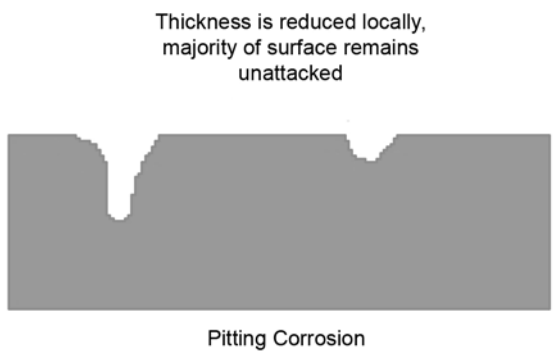


Figure 3.18 Illustration of typical pitting corrosion [73-75].

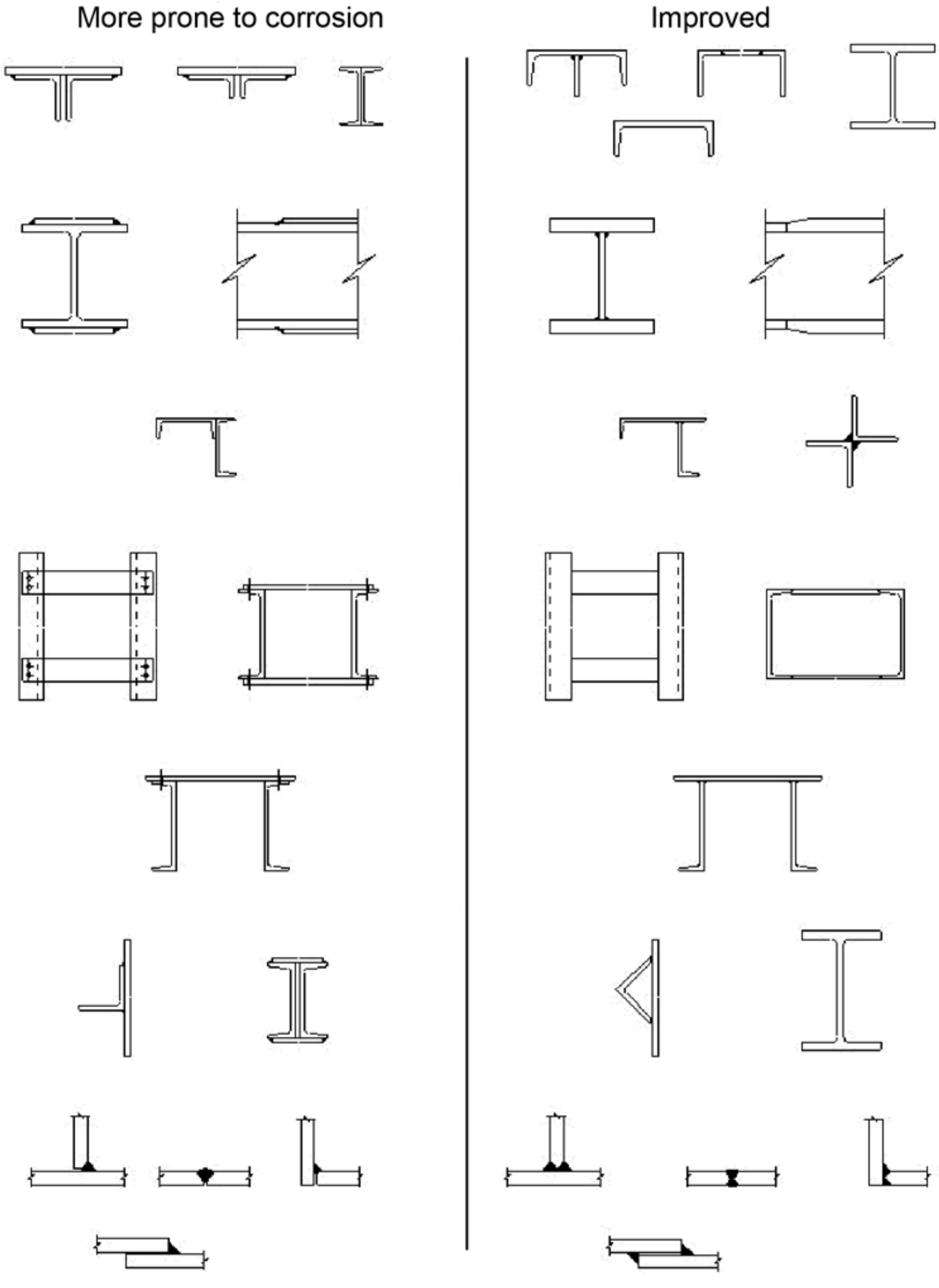


Figure 3.19 Design of parts easily accessible to paint and maintain [98,104].

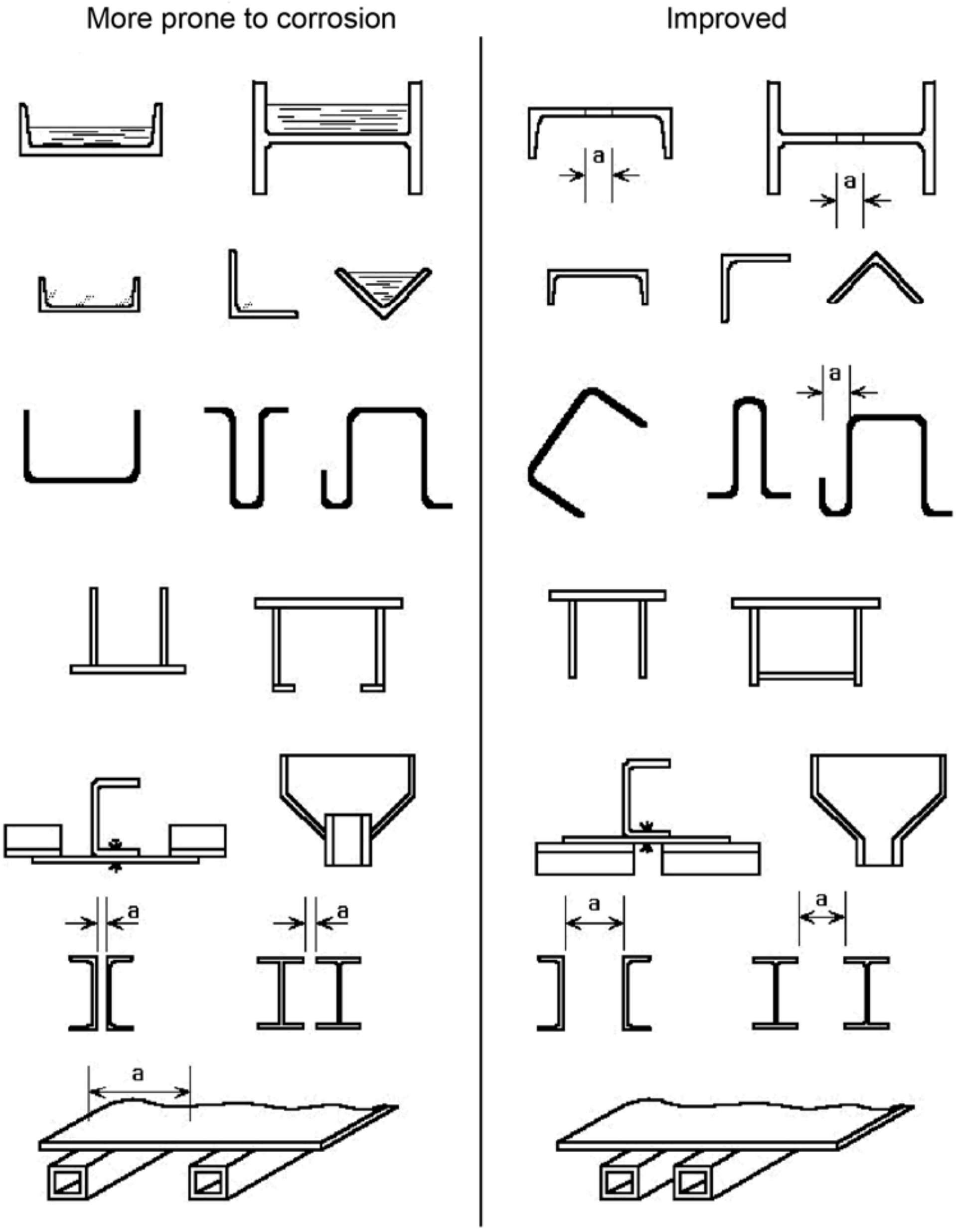


Figure 3.20 Design to avoid formation of humid and dusty zones [98,104].

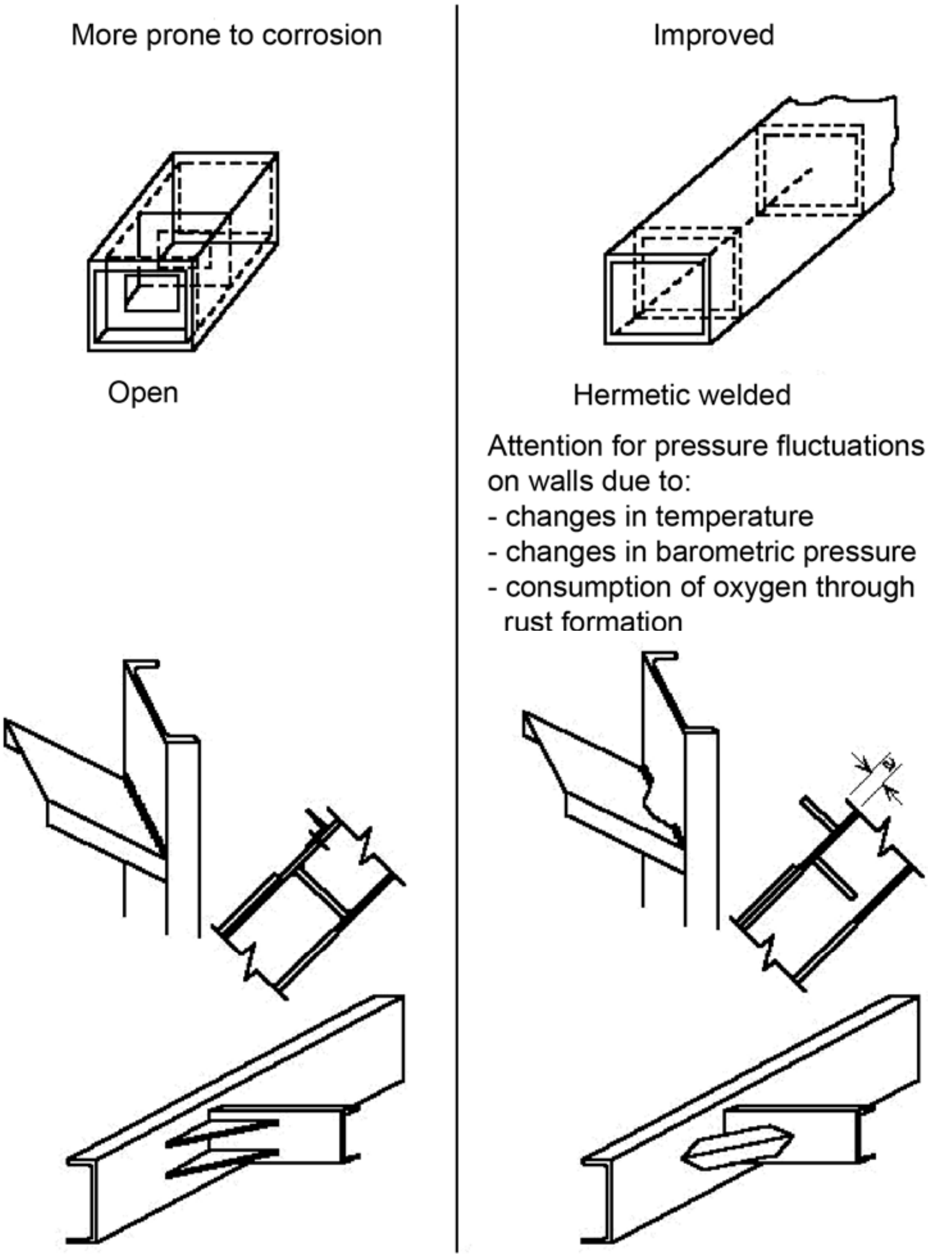


Figure 3.21 Avoidance of entrapment of moisture, dirt, and corrosive elements on or between parts of structures [98,104].

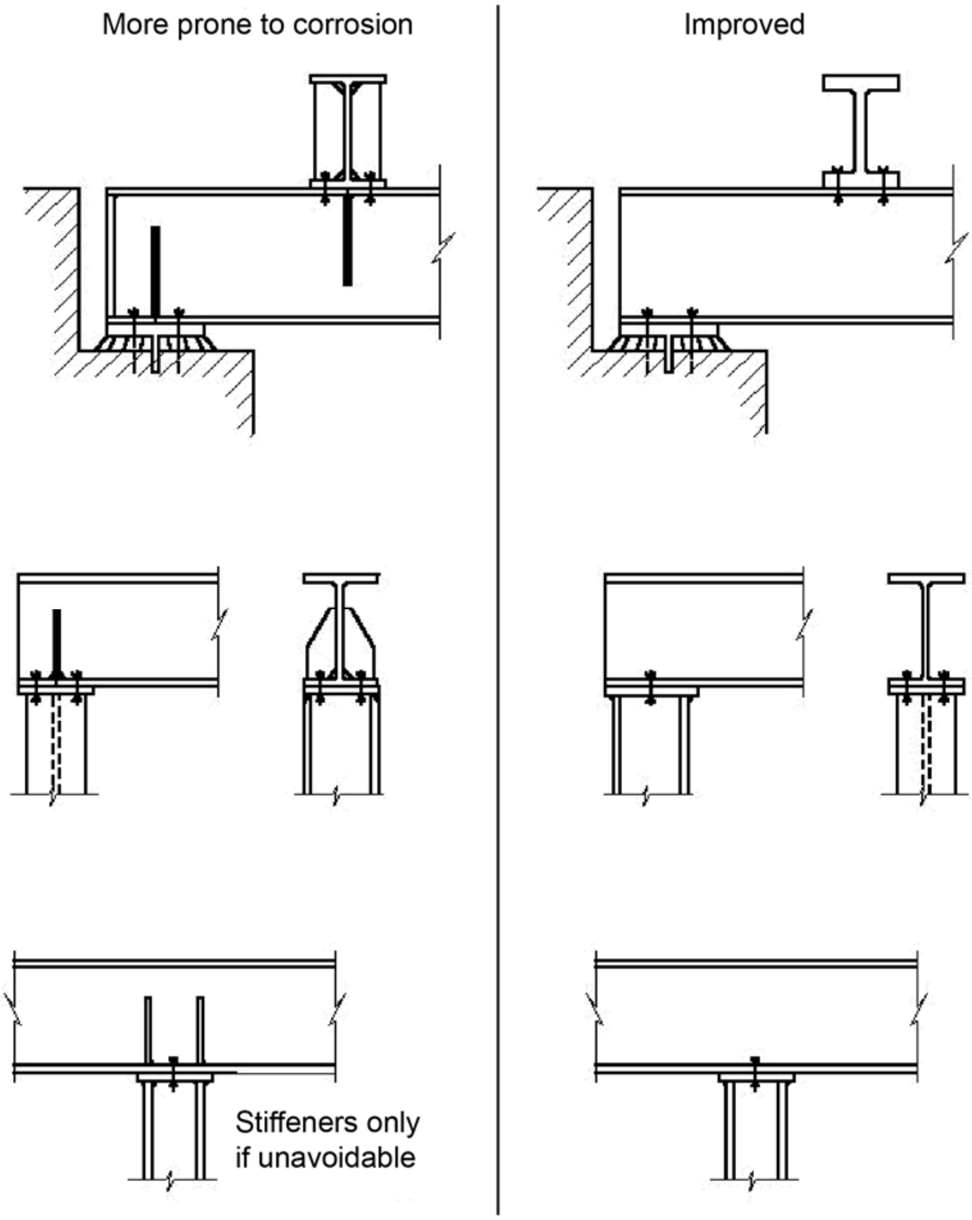


Figure 3.22 Avoidance of stiffeners and entrapment of moisture and dirt in design of steel structures without edges and corners where moisture and dirt collect [98,104].

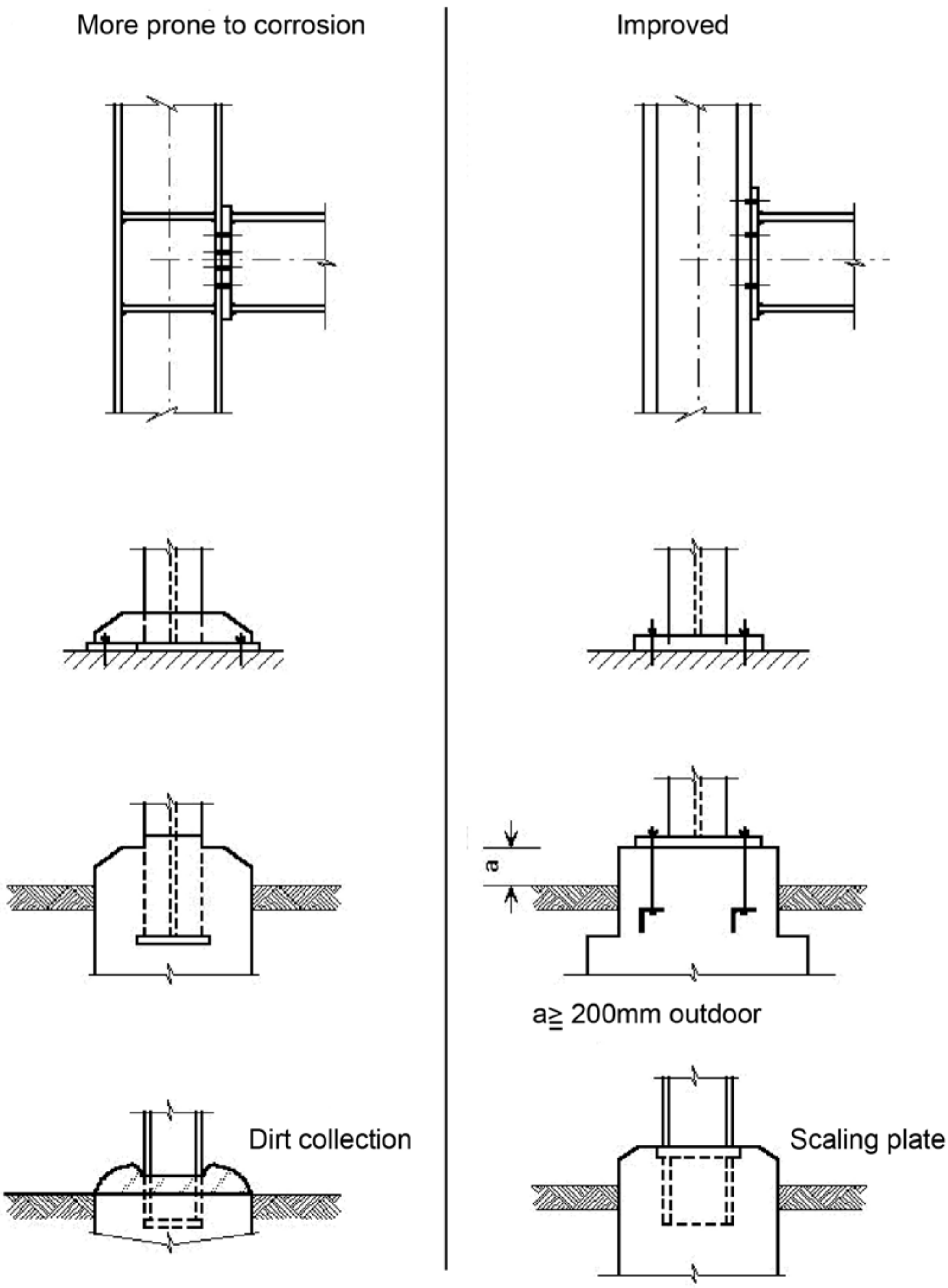


Figure 3.23 Examples of good design of structures [98,104].

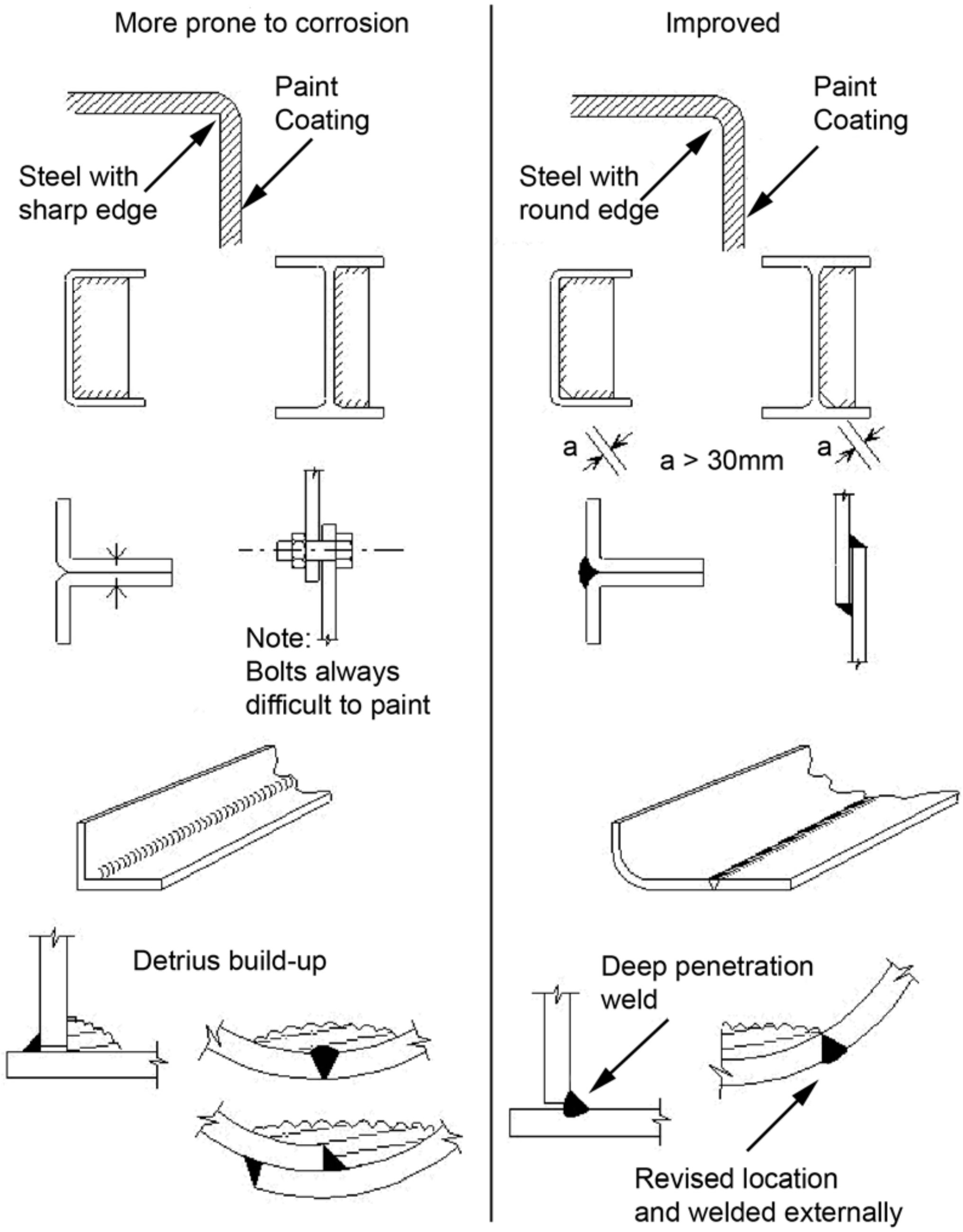


Figure 3.24 Structures with rounded angles to avoid corrosion; edges and corners are corrosion-sensitive points even when protected by coatings [98,104].

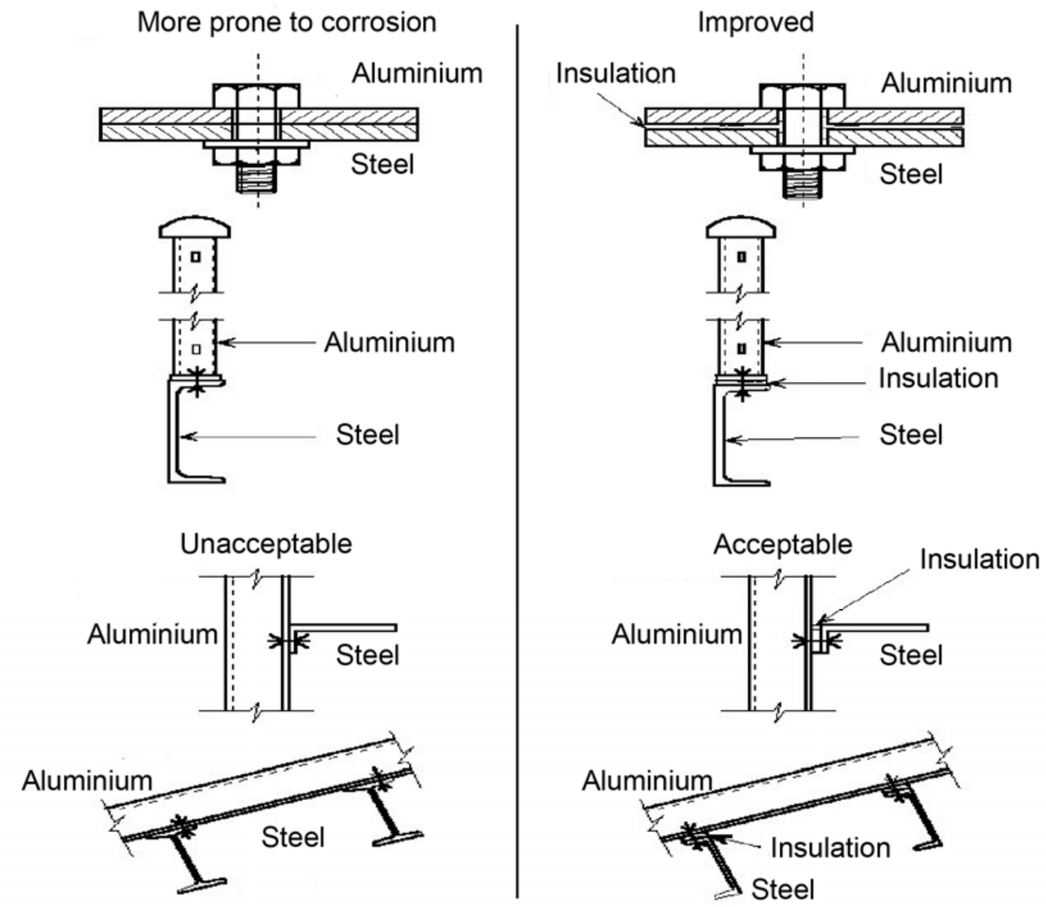


Figure 3.25 Avoidance of contact with other materials using protection by insulating material against galvanic corrosion [98,104].

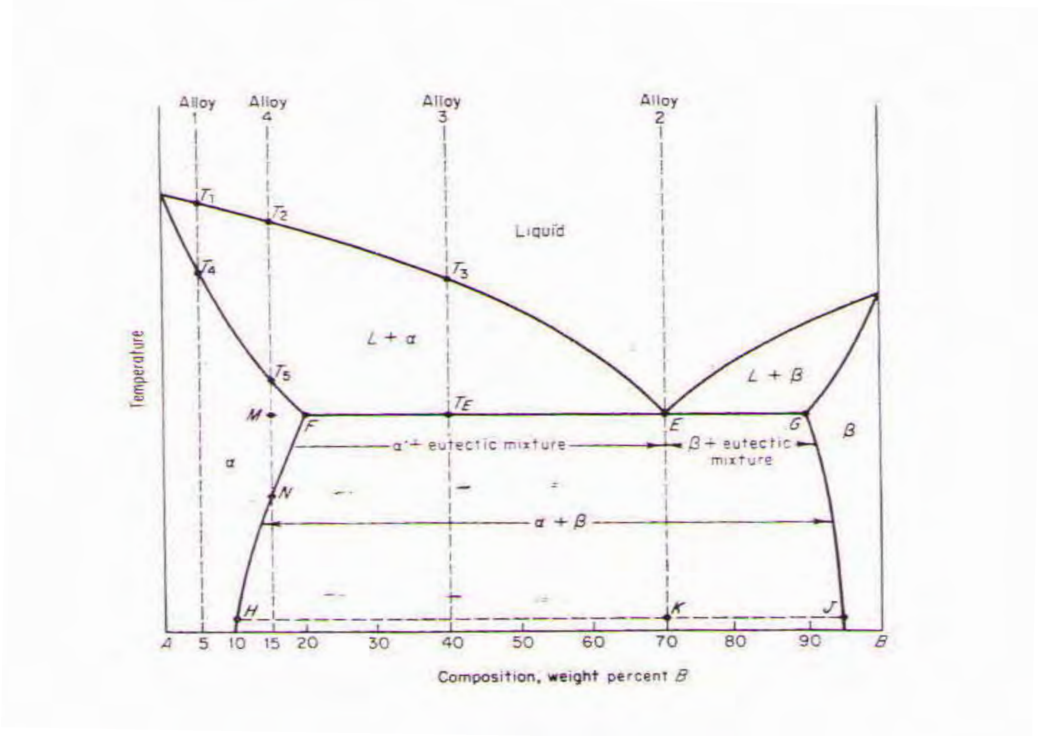


Figure 3.26 Phase diagram showing partial solid solubility [108].

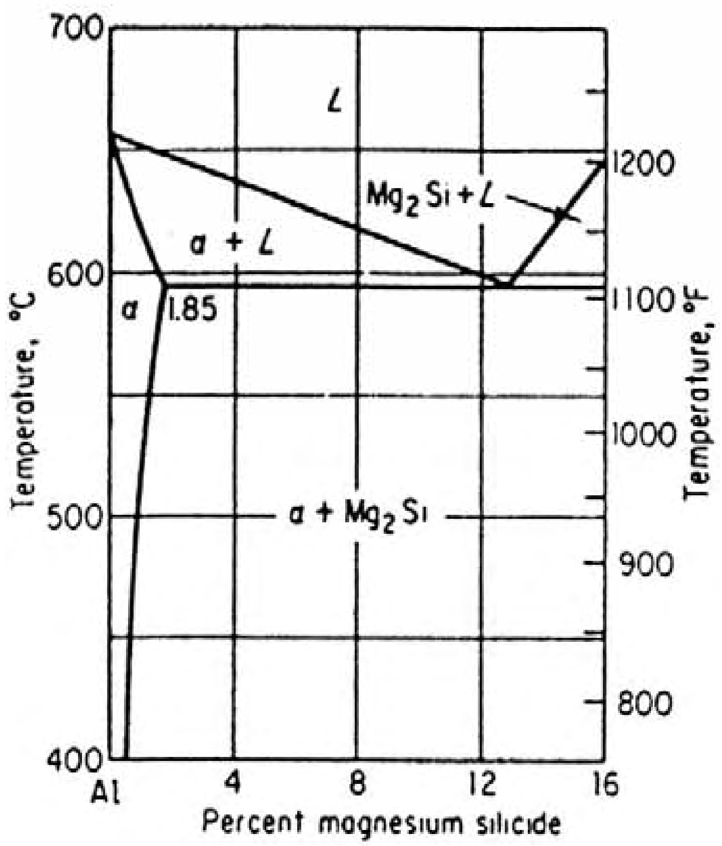


Figure 3.27 Aluminium-rich portion of the Al-Mg-Si system [108].

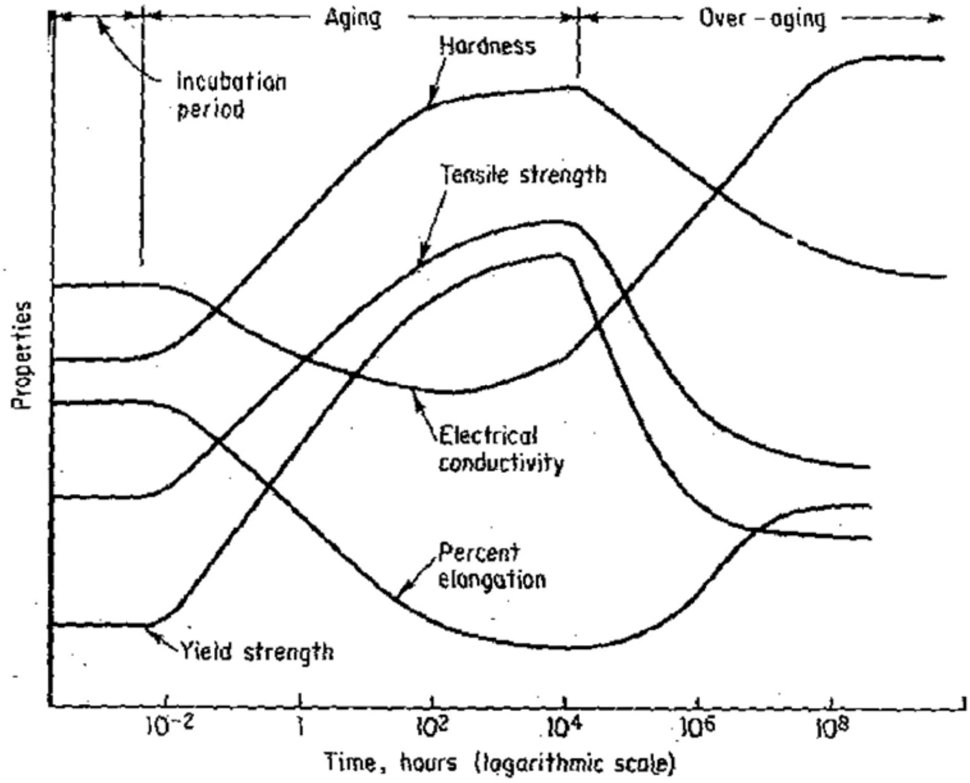


Figure 3.28 Effect of ageing time on properties [107].

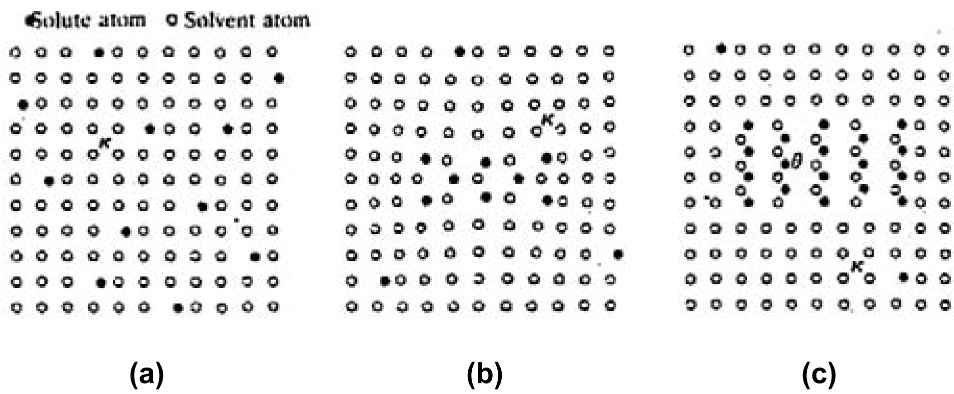


Figure 3.29 Age hardening phenomena in precipitation-hardened alloys [93].

Figure 3.30 Schematic of age-hardening and corrosion [94].

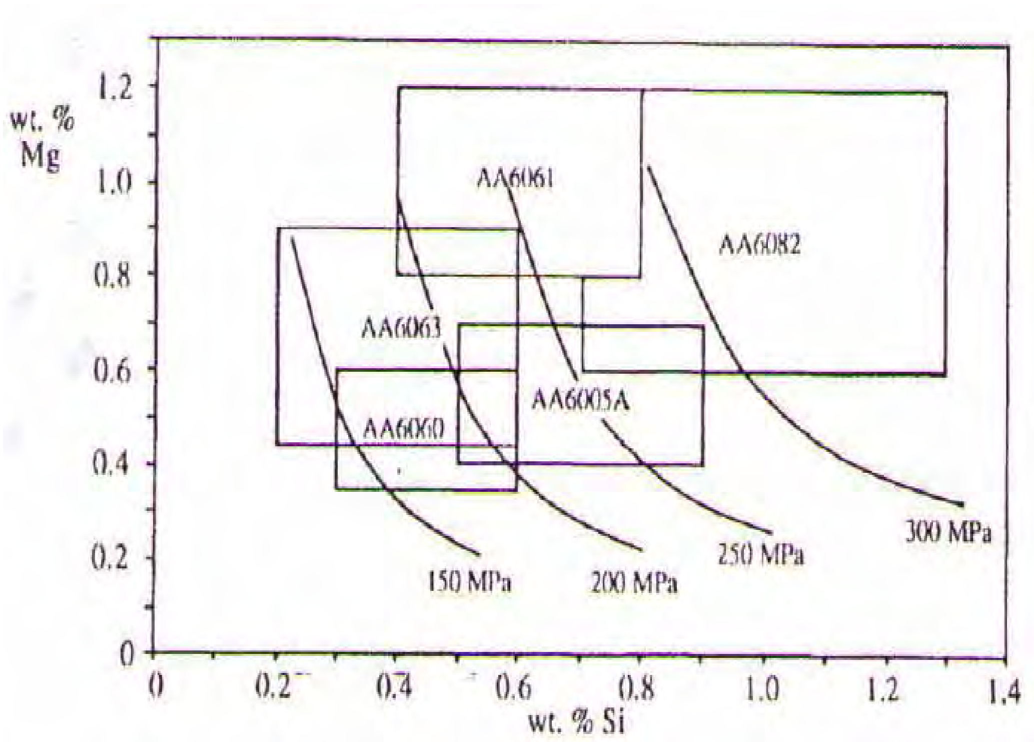


Figure 3.31 Common 6000 aluminium alloys with varying compositional limits in the peak aged condition T6 and corresponding yield strength values [11].

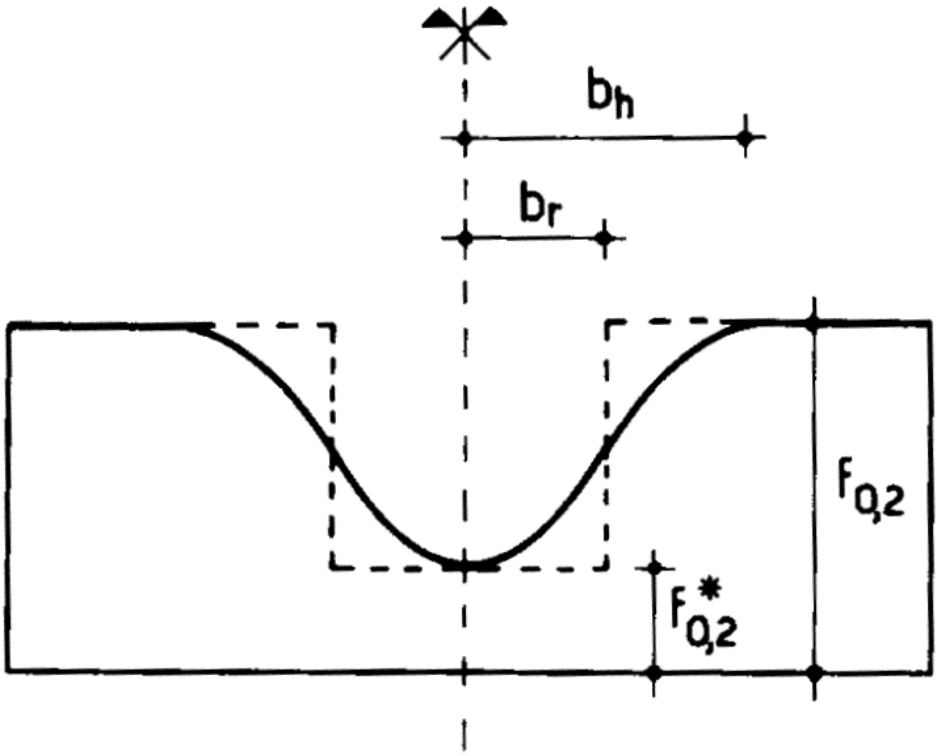


Figure 3.32 Reduced strength zone; $f_{0.2}$ = strength of parent metal; $f^*_{0.2}$ = strength of weld region [6].

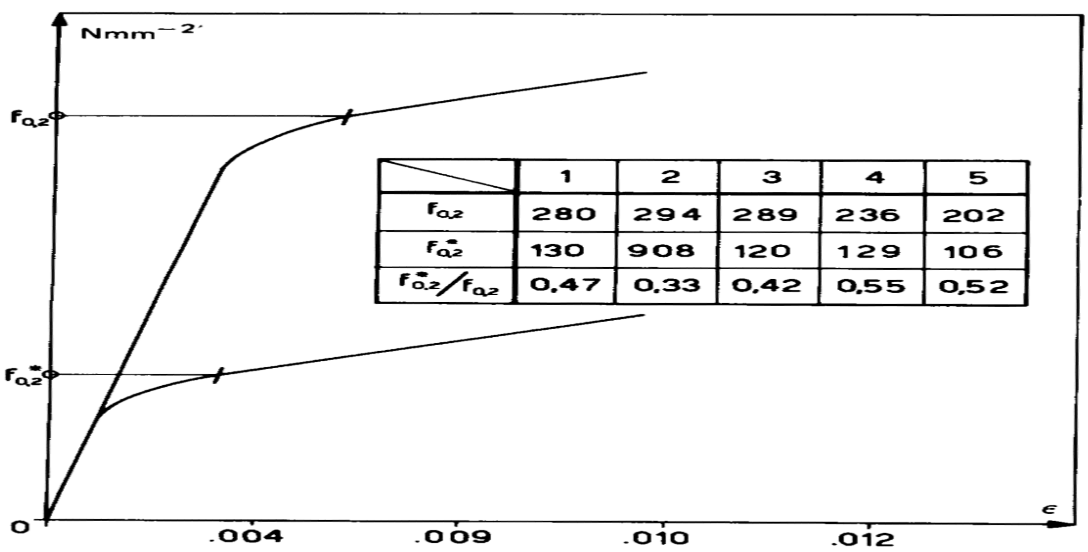


Figure 3.33 Elastic limit of weld compared to elastic limit of parent metal; $f_{0.2}$ = strength of parent metal; $f^*_{0.2}$ = strength of weld region [128].

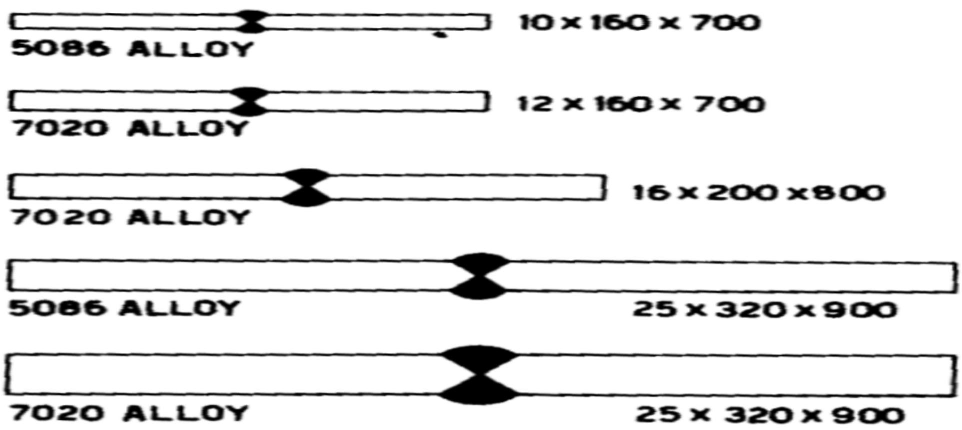


Figure 3.34 5000 and 7000 series showing welded joints [6].

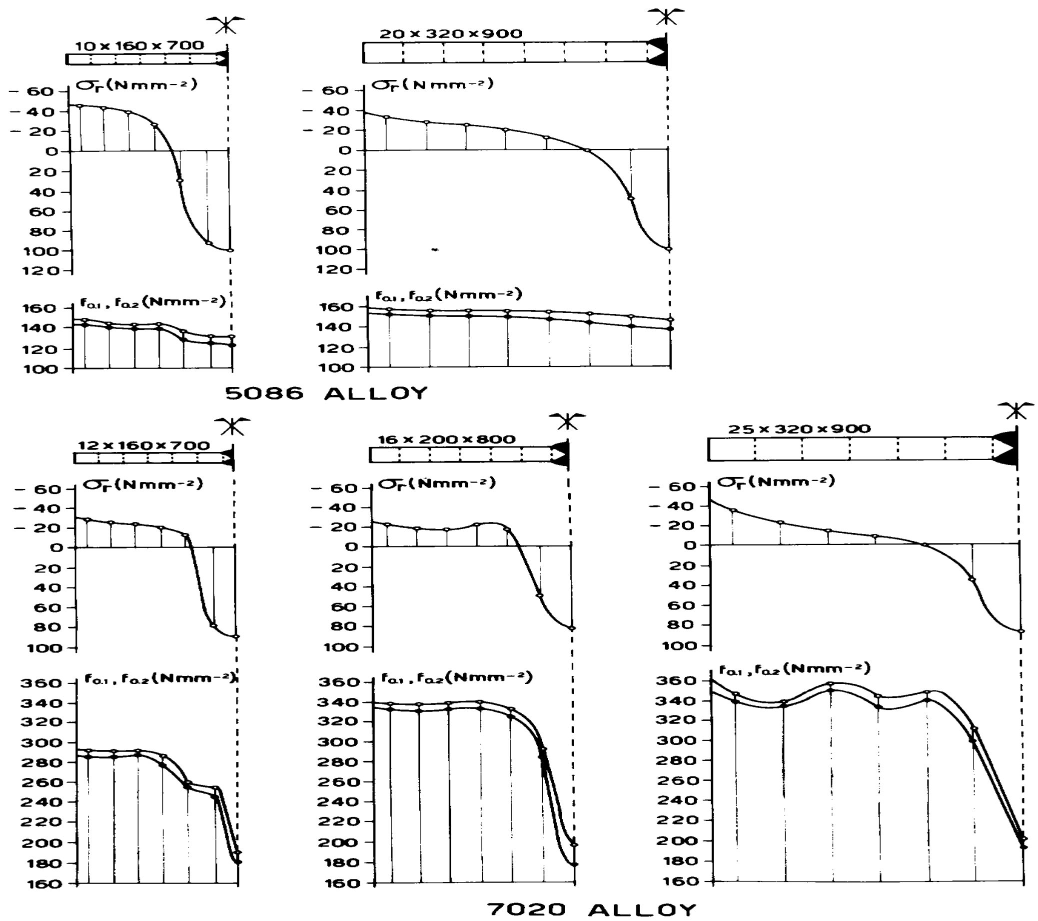


Figure 3.35 Strength comparisons of the welded 5000 and 7000 series alloys at welded joints [6].

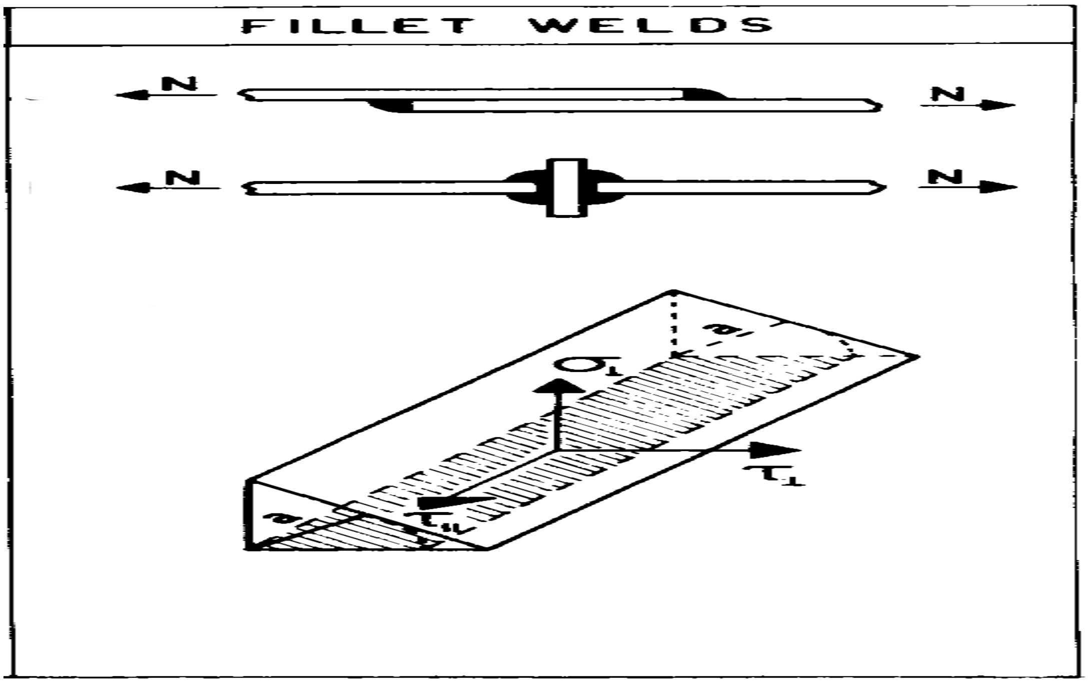


Figure 3.36 Strength of welded joint for fillet welds [6].

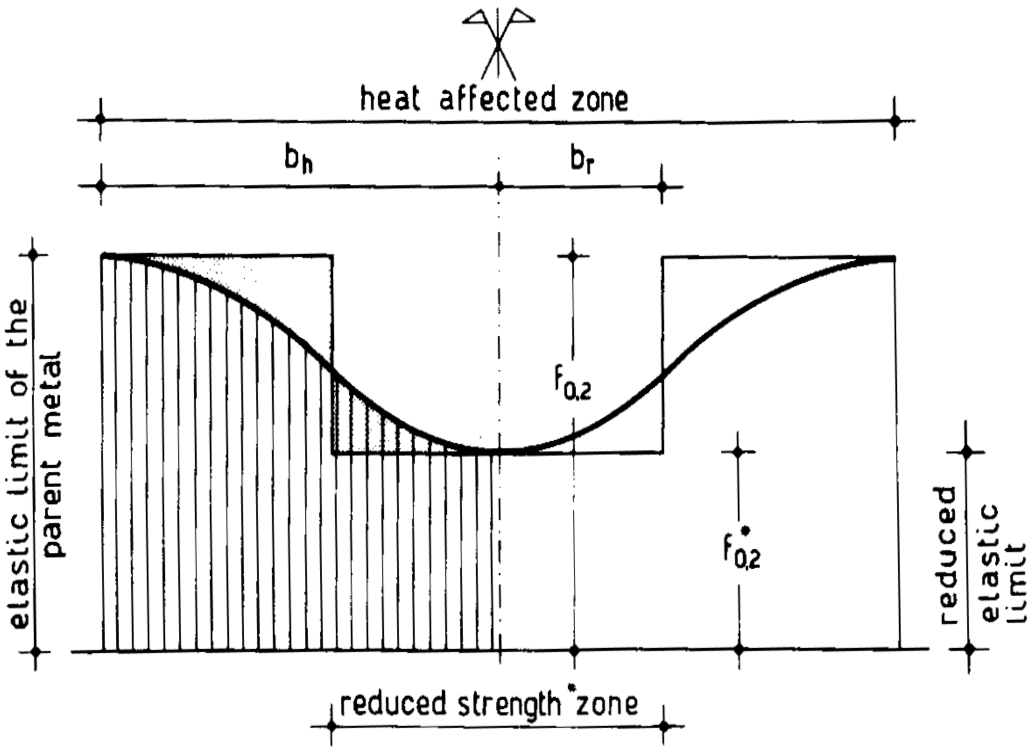


Figure 3.37 Reduced strength zone, characterised by b_r [6].

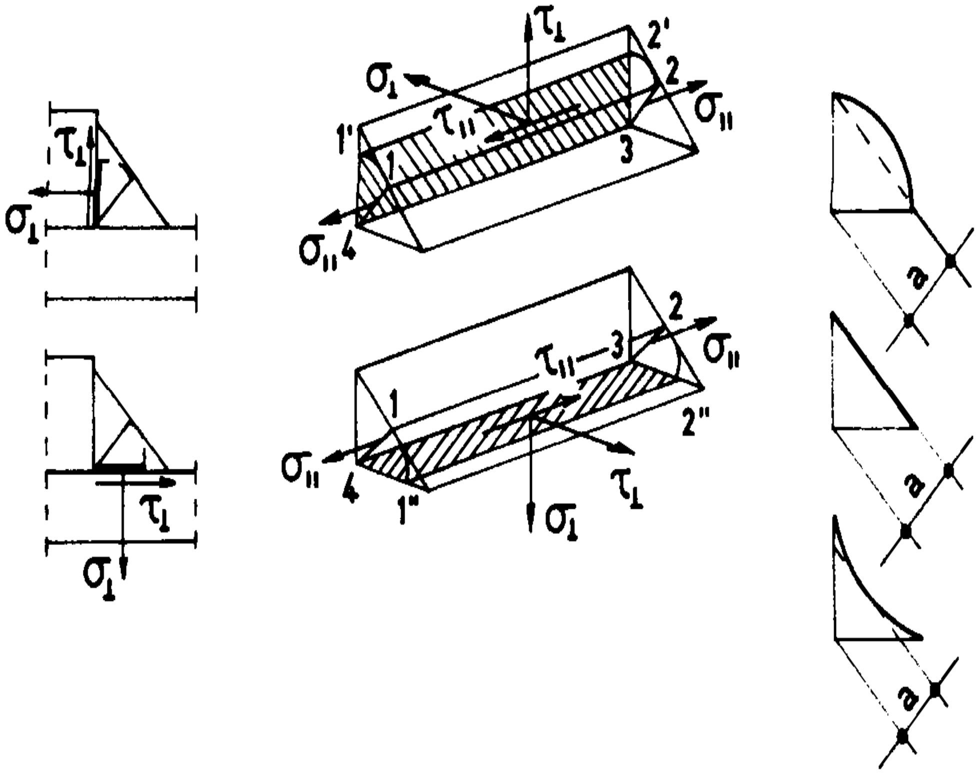


Figure 3.38 Stress fields exerted on fillet in different directions [6].

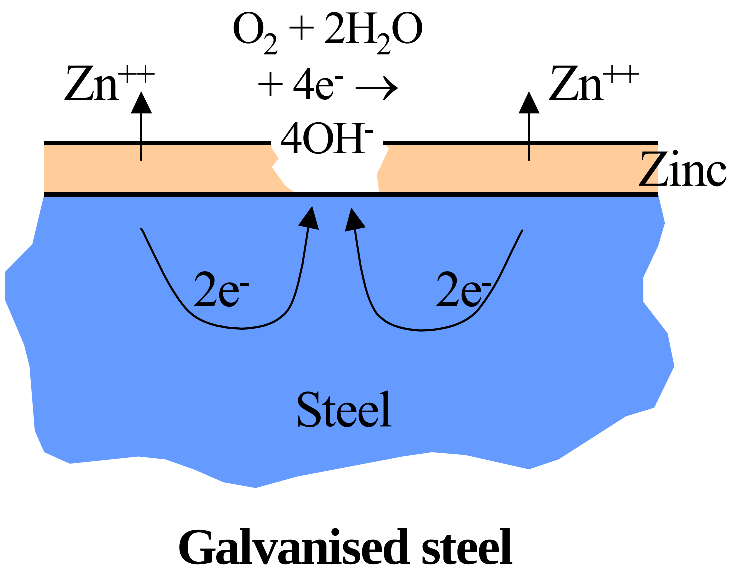


Figure 3.39 Zinc coating corroding in preference to steel on galvanised steel [73].

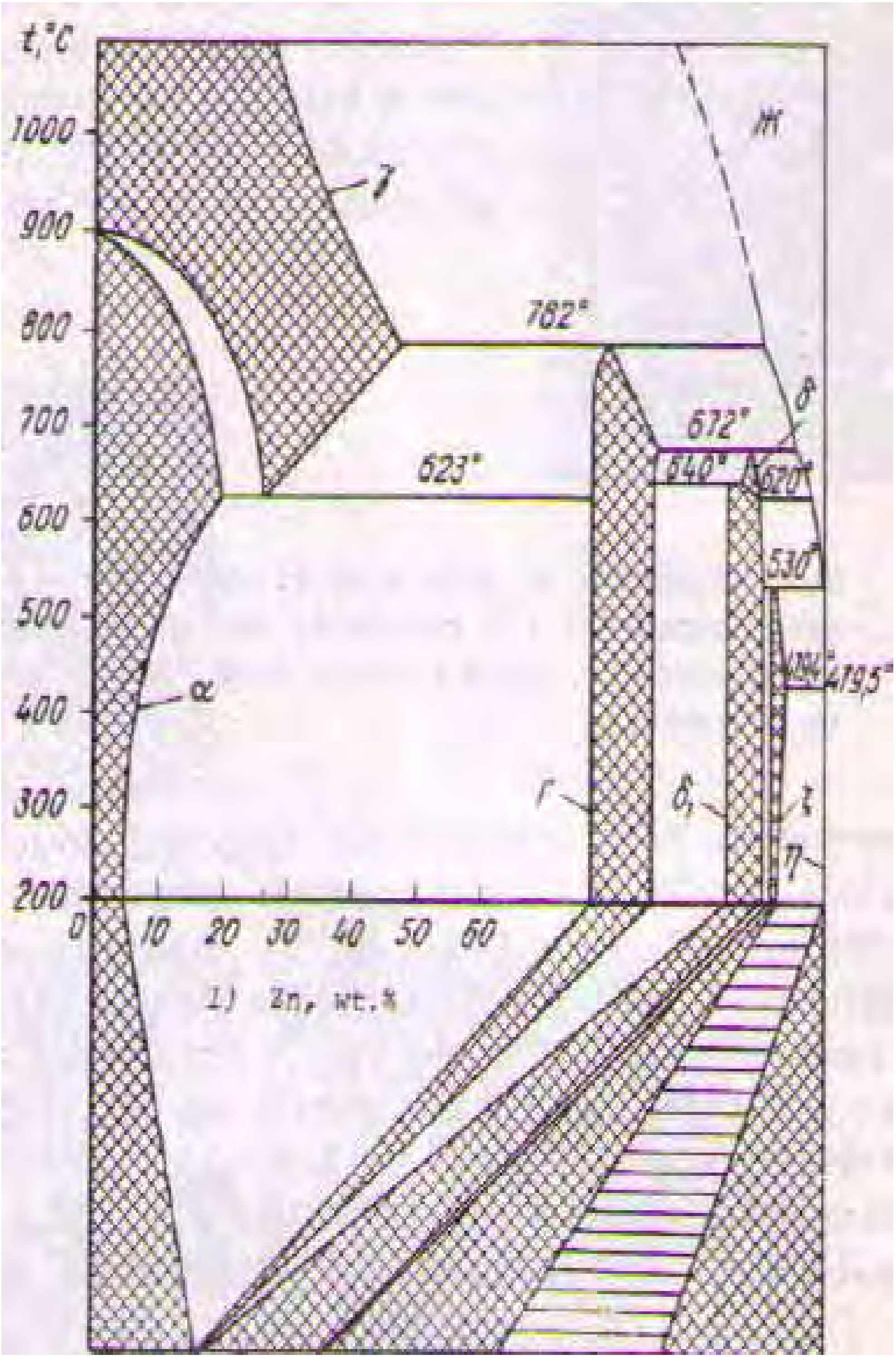


Figure 3.40 Phase diagram of iron-zinc system [136].

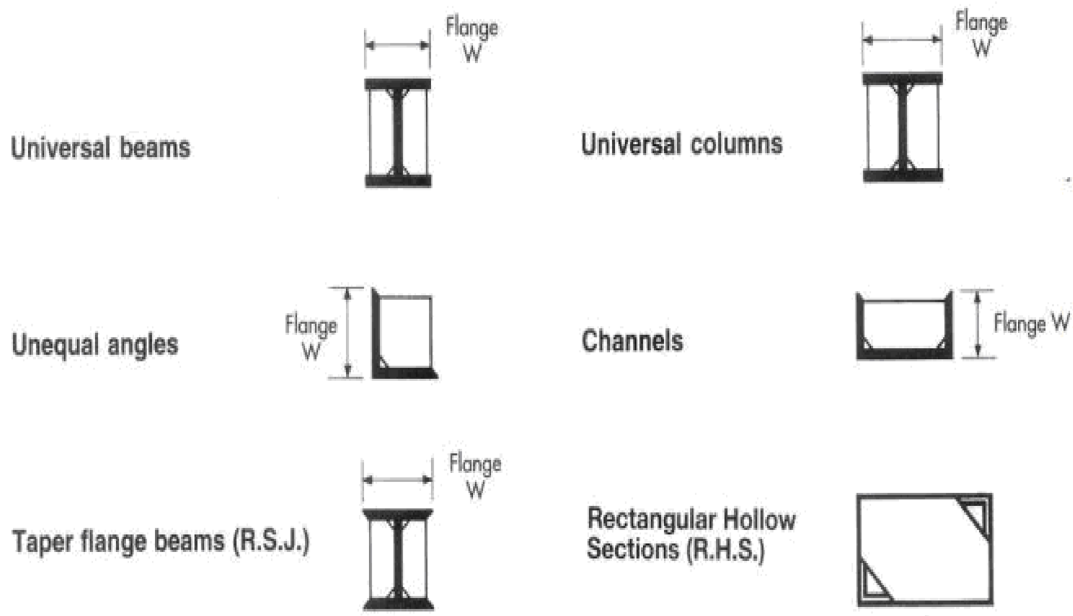


Figure 3.41 Bevel cuts for angles, channels, I Beams, and columns [137].

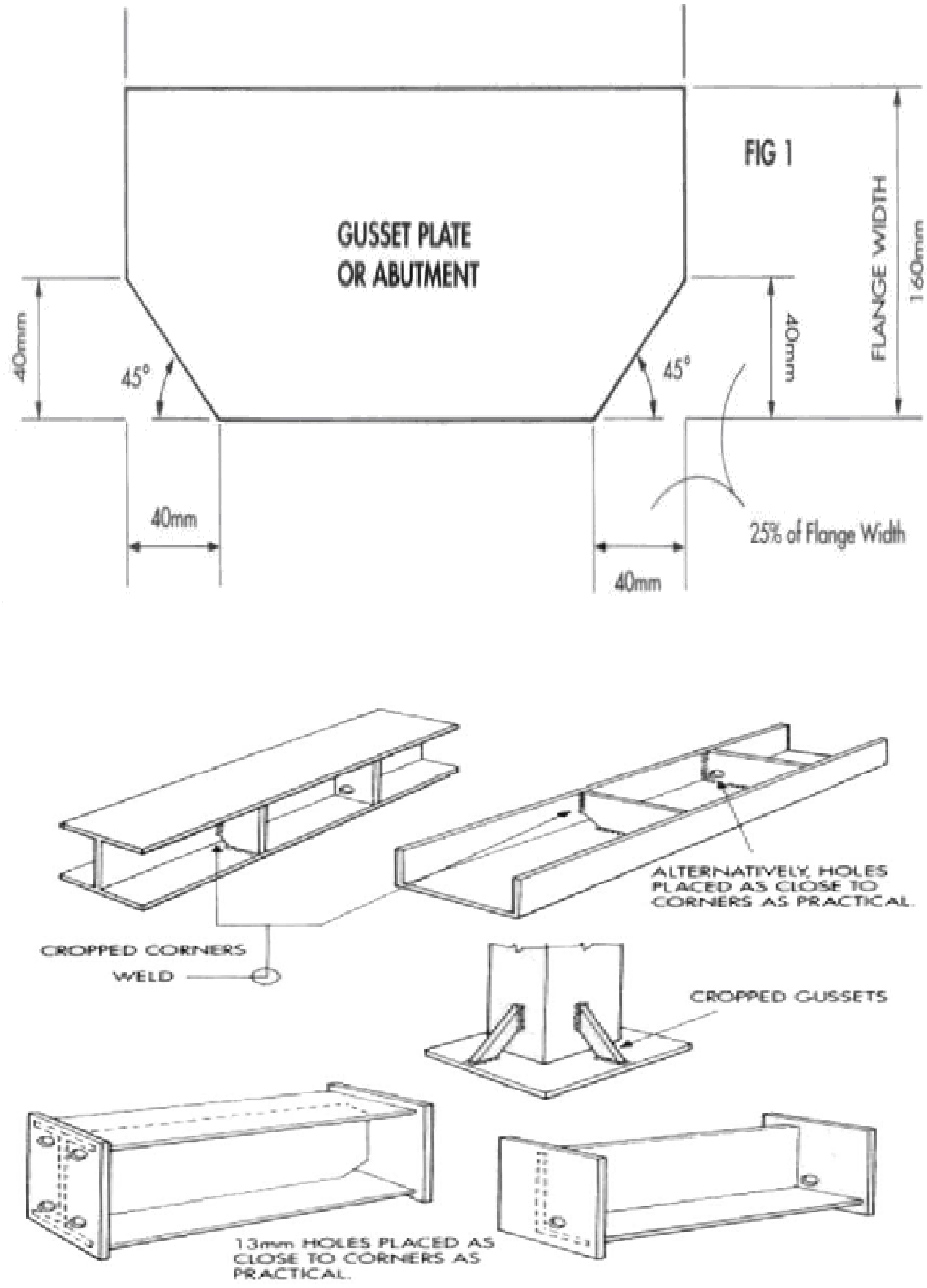


Figure 3.42 Recommended bevel sizes and gusset plates on abutments in channels and beams with both ends bevelled [137].

Figure 4.1a Satellite view Westfield Tower 2, Bondi Junction, in vicinity of Pacific Ocean and Sydney Harbour [Google Earth].

Figure 4.1b Aerial view of Westfield Tower 2 rooftop, childcare facility, and surrounding streets.

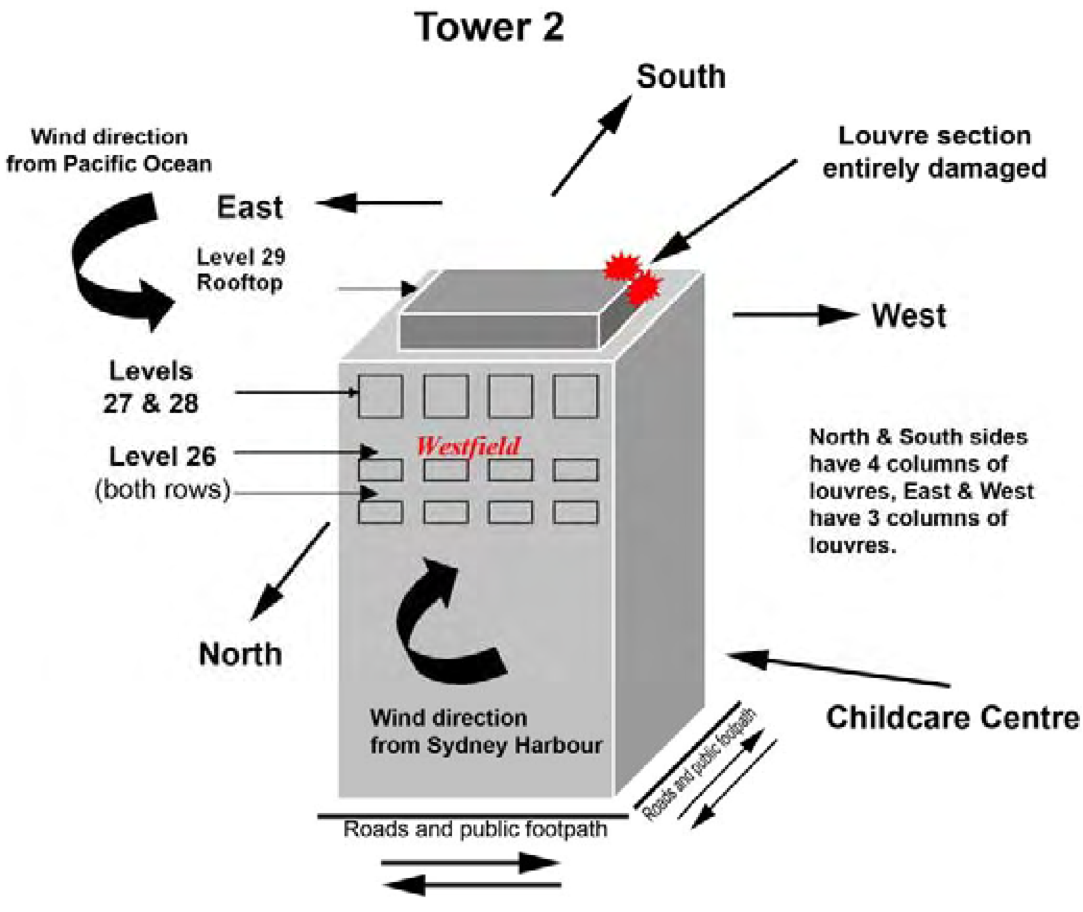


Figure 4.2 Schematic of typical louvre locations on building.

Figure 4.3 Initial assessment of damaged louvres on southwestern section of Tower 2.

Figure 4.4 Louvre panels that have detached from structure above and fallen from level 29 down to level 28 in open section.

Figure 4.5 Typical view of internal appearance of building on level 26.

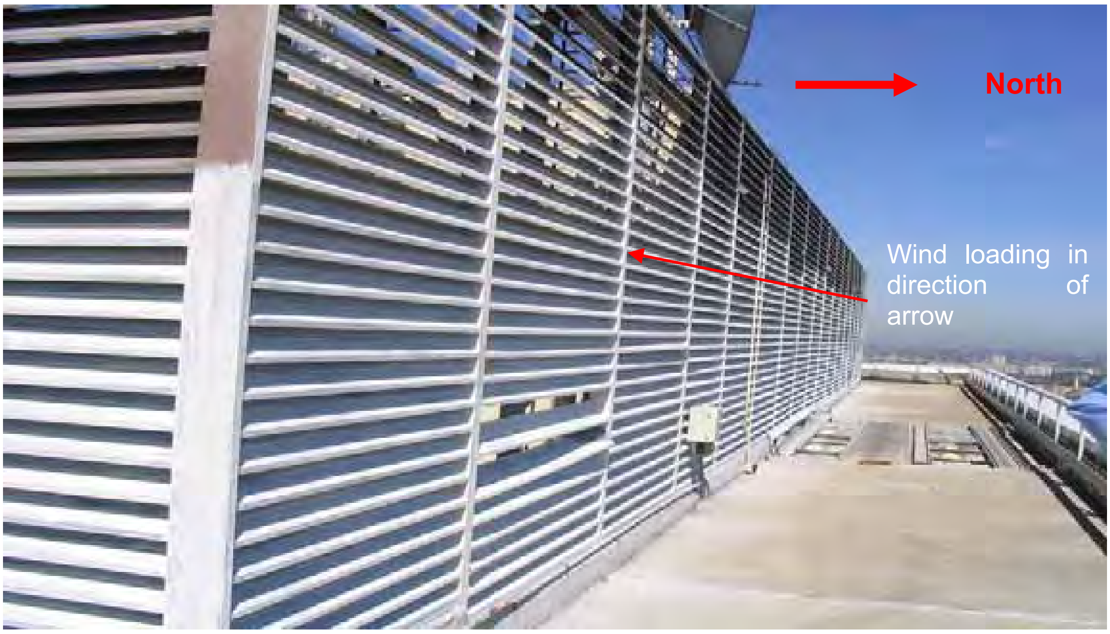


Figure 4.6 Northern face severely and permanently deformed.

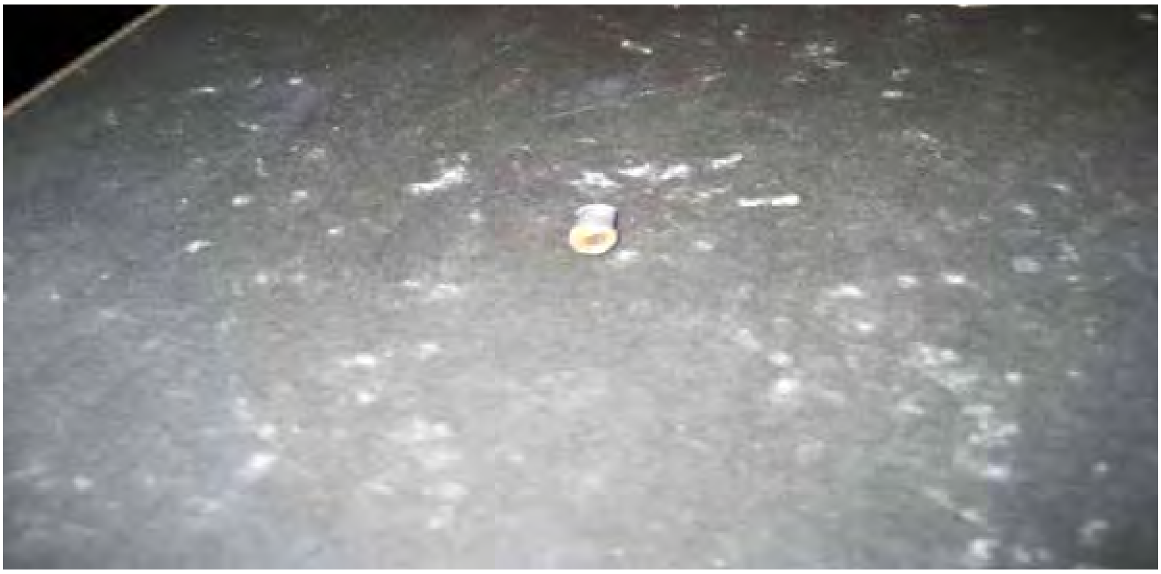
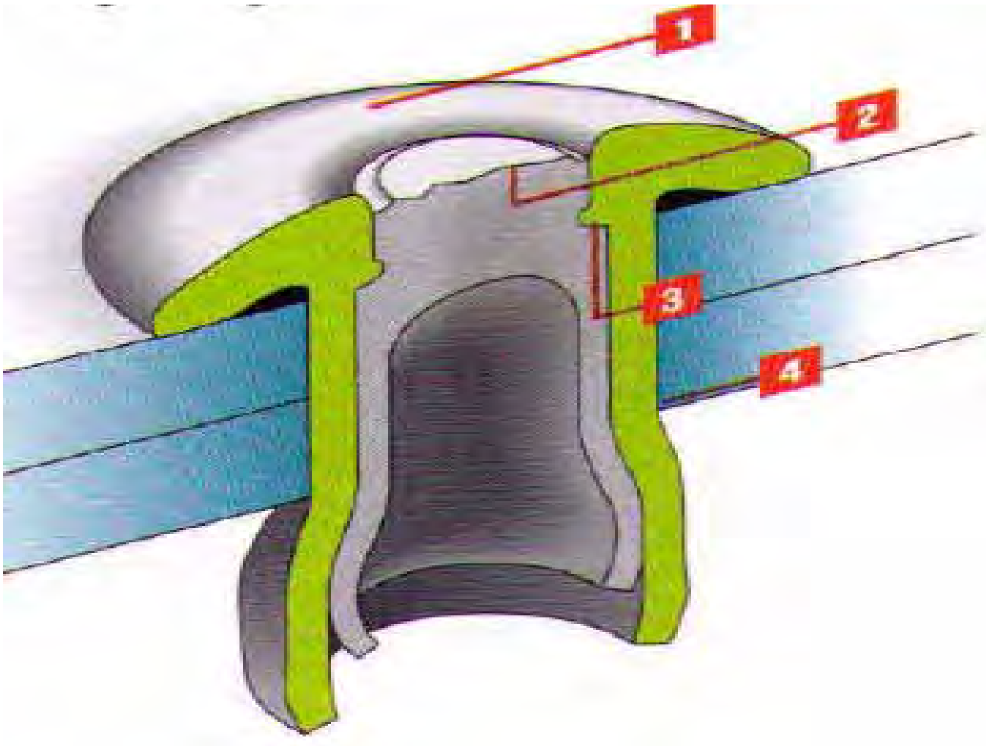


Figure 4.7 Typically corroded mandrels and pins inside aluminium sleeved rivets that were removed from failed louvre panels on southwestern side of building.



Rivets are manufactured by Huck magna Lok – USA [138 and Appendix M].

1 = *Flush installation makes fastener easier to paint and <u>resistant to salt and water,</u>*
2 = *Flush pinbreak eliminates need for grinding/filing,*
3 = *Solid-circle lock ensures maximum strength and <u>resistance to vibration</u> – designed to resist pin pushout,*
4 = *Sleeve expands during installation, tightly filling hole to create a <u>weather-resistant joint.</u>*

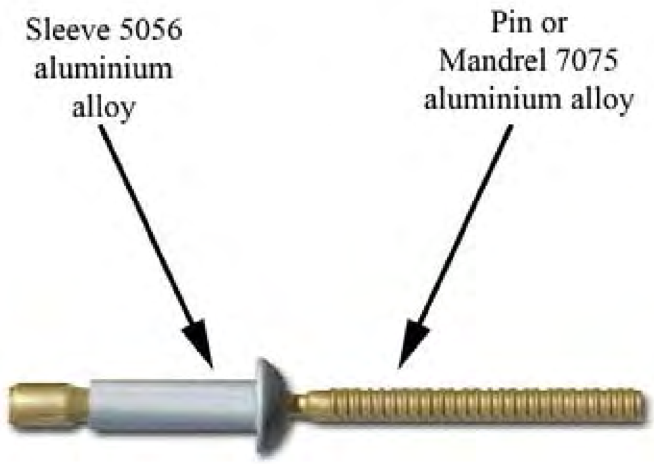


Figure 4.8 New aluminium alloy rivets replacing existing steel rivets [Appendix M].

Figure 4.9 New louvres being manufactured in workshop [Appendix I].

Figure 4.10 Sheet metal beneath the baffles and enveloping aluminium louvre panels, resulting in crevice corrosion on level 28 at corner of northern section closer to southern side.

Figure 4.11 Aluminium panel section showing crevice corrosion and pitting corrosion owing to sheet metal coverage of aluminium.

Figure 4.12 Difficulty in working on louvres at lower section, where steel cradle structure on left hand side is BMU.

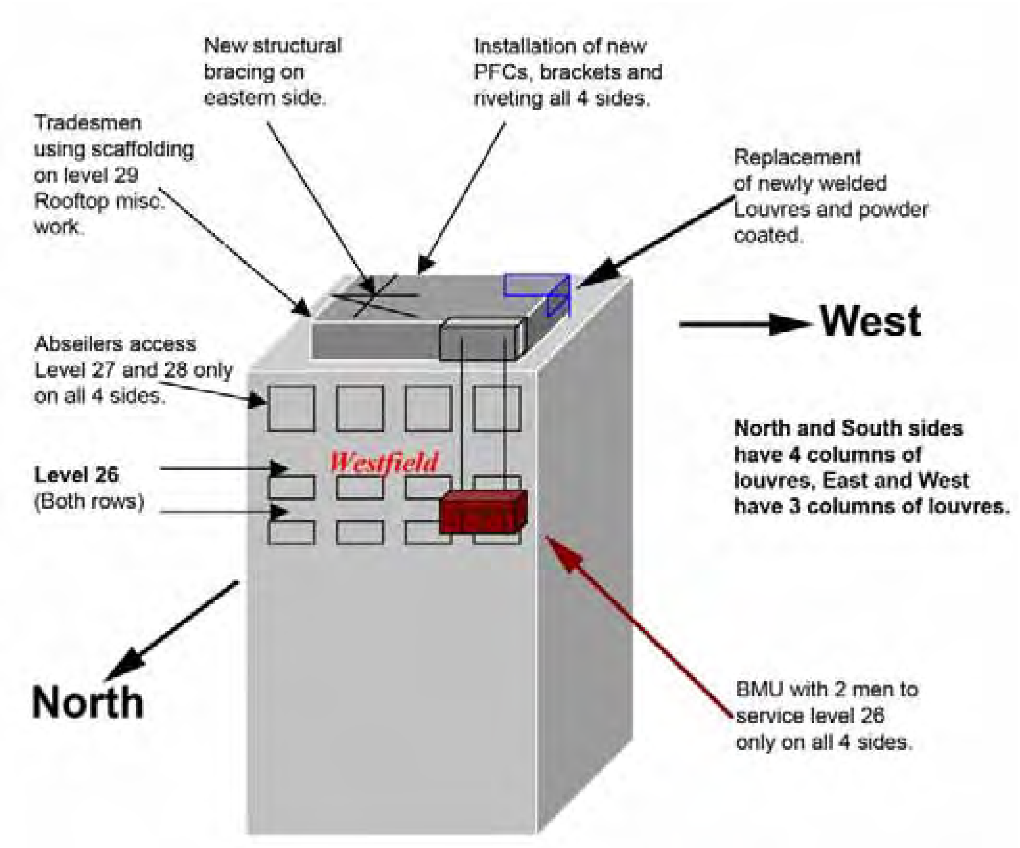


Figure 4.13 Schematic of basic operations during site construction.

Note: North and South sections have 4 rows of louvres on façade, and East and West have only 3 rows. The remaining louvres are on the rooftop

Figure 4.14 Damaged louvre section on southwest corner of roof on level 29.

Figure 4.15 Bolts failed due to corrosion and cyclic loading.

Figure 4.16 Corroded noise attenuators or baffles adjacent to louvres on north, south, and southeast sections of level 28.

Figure 4.17 Steel cladding extending from base of baffles and enveloping face mullion, causing galvanic corrosion.

Figure 4.18 Excessive corrosion in baffles in open area of level 28, caused as result of moisture retained in fibreglass.

Figure 4.19 Preparation and cleaning of mullions adjacent to baffles.

Figure 4.20 Typical U-shaped brackets fabricated and hot dip galvanised for upper sections of louvres on level 28.

Figure 4.21 Typical C-brackets, left-hand side fabricated and hot dip galvanised for lower sections of level 28; additional brackets on right-hand side wall support remainder of mullions.

Figure 4.22 Brackets placed in four locations to provide extra support and replace older brackets.

Figure 4.23 Corroded bolts and corroded PFCs as main structural supports for louvres on level 29; roof and horizontal PFC encourage indefinite corrosion deposits.

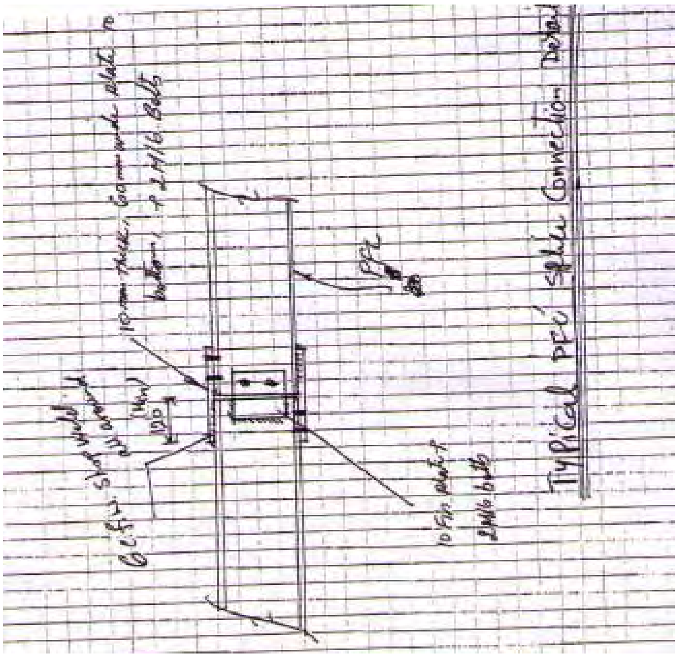


Figure 4.24a Sketch of new PFC to replace the corroded single length span PFC.

Figure 4.24b New hot dip galvanised PFCs designed to be sectioned in two halves to facilitate connection to bracket and louvre and to carry major load.

Figure 4.25a Structural beam holding roof with inadequate support beneath should existing corrosion continue at same rate.

Figure 4.25b Refurbished beam with *Emerbond* and *Emerclad* and new hot dipped galvanised support from below.

Figure 4.25c Hot dipped galvanised structural angle chemset into wall directly beneath beam for additional support.

Figure 4.26 Corroded bolts replaced with new structural galvanised bolts; old brackets held onto PFC using one or two corroded bolts; brackets held to structural mullion with one or two tek screws.

Figure 4.27 Rounded old brackets with cracks at radius.

Figure 4.28 Corroded 6 mm tek screws barely holding structural louvres through rounded brackets; typically one corroded bolt connected to the structural PFC; one of principal reasons for failure of southwest corner.

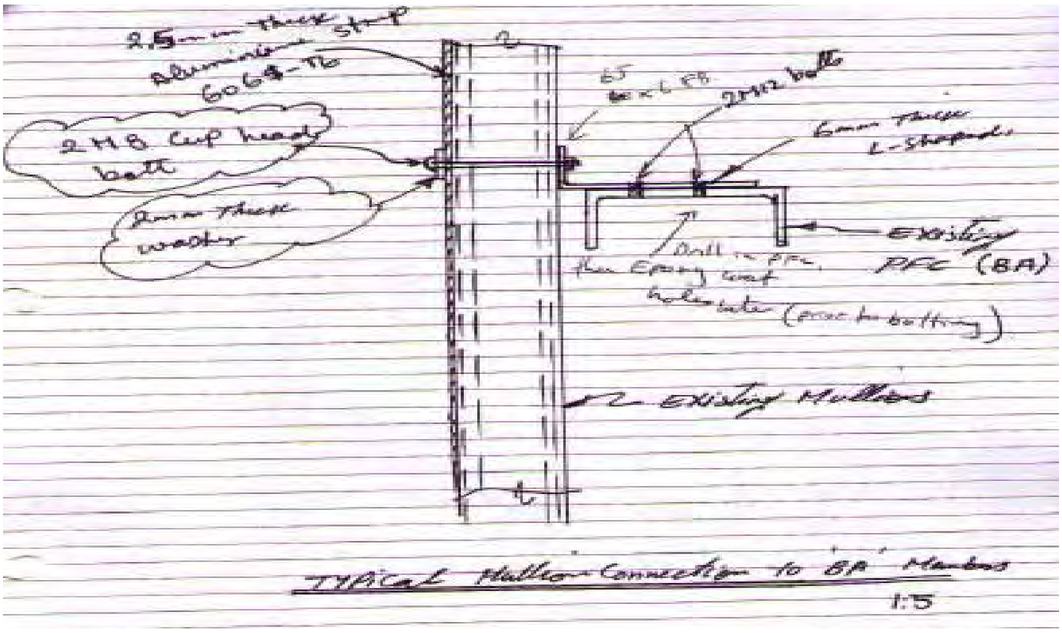


Figure 4.29a Sketch for new bracket proposed as alternative design to existing rounded bracket with tek screws.

Figure 4.29b New hot dip galvanised brackets designed for optimal strength, connected with structural galvanised M8 bolts through mullion and into bracket; structural galvanised M8 bolts connecting bracket to PFC.

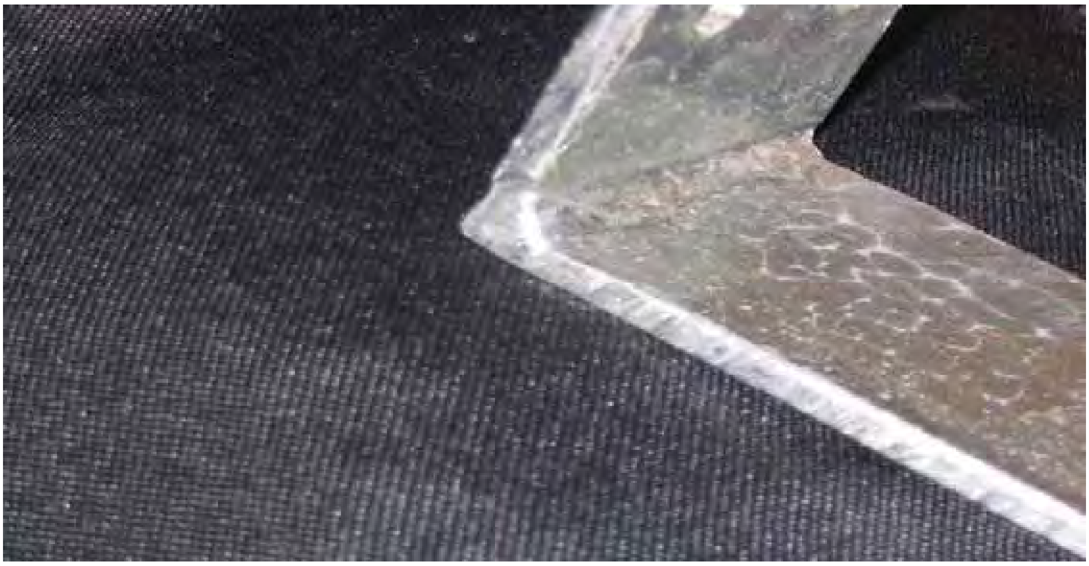


Figure 4.30 Bracket showing typical butt weld joining two plates together to avoid inherent weakness existing in cracked old radiused brackets, which existed at every mullion section throughout.

Figure 4.31 Typical connection for each bolt in each vertical mullion.

Figure 4.32 Chips of galvanised surface removed.

Figure 4.33 One of four typical louvre panels sitting loose due to incorrect and inadequate connection.

Figure 4.34 Louvre panels connected to internal bracket with high tensile M8 bolts.

Figure 4.35 Corroded screws typical of all existing Westfield louvre connections in mullions.

Figure 4.36 6061 T6 aluminium strip used to secure each louvre on site so as to obviate use of existing corroded screws; 6061 alloy strips placed only in centre of louvre system.

Figure 4.37 M8 bolts residing on 2.54 mm 6061 aluminium strip for added strength, connecting through mullion to new PFC.

Figure 4.38a M8 bolts connecting to equal angle on hob on other side.

Figure 4.38b M8 galvanised bolts connecting to existing equal angle with M8 chemically set bolts into equal angle and hob for extra strength against wind uplift or lateral forces.

Figure 4.39 Corroded column on southern face near western section owing to holes' not being plugged on top of columns after galvanising during original fabrication.

Figure 4.40 New hot dip galvanised RHS replacing old corroded column shown in figure 4.39; holes on top for galvanising were sealed with two-mix steel putty.

Figure 4.41 Holes on column left hand side plugged with special two-mix steel putty.

Figure 4.42 Water draining from columns due to drilling at base of each of columns to allow bleeding of excess water.

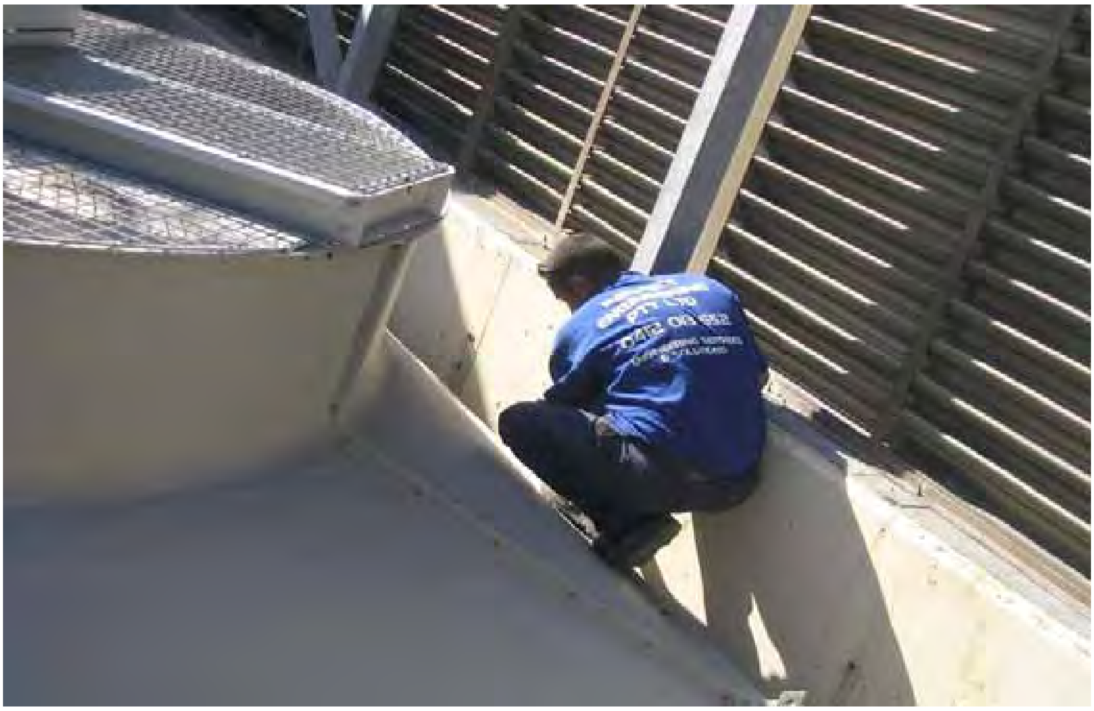


Figure 4.43 Residue build-up in six vertical columns facing south requiring no bleeding as access to holes was open.

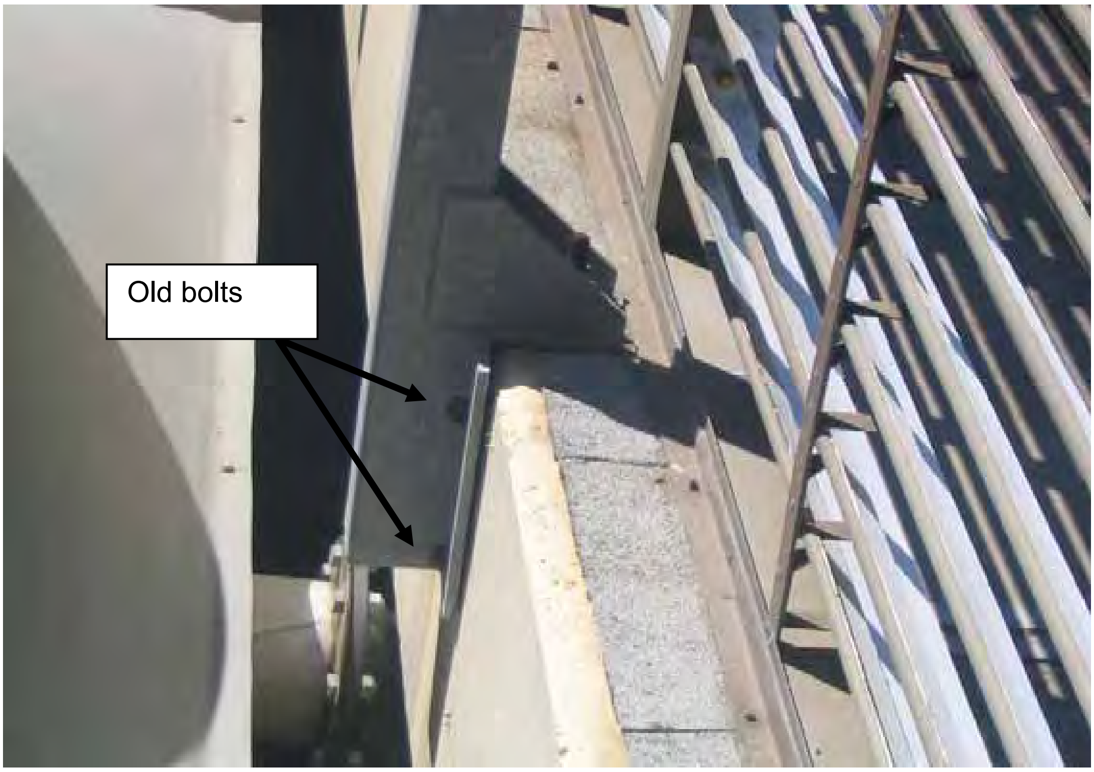


Figure 4.44 Severely corroded bolts barely holding columns supporting vertical base plate.

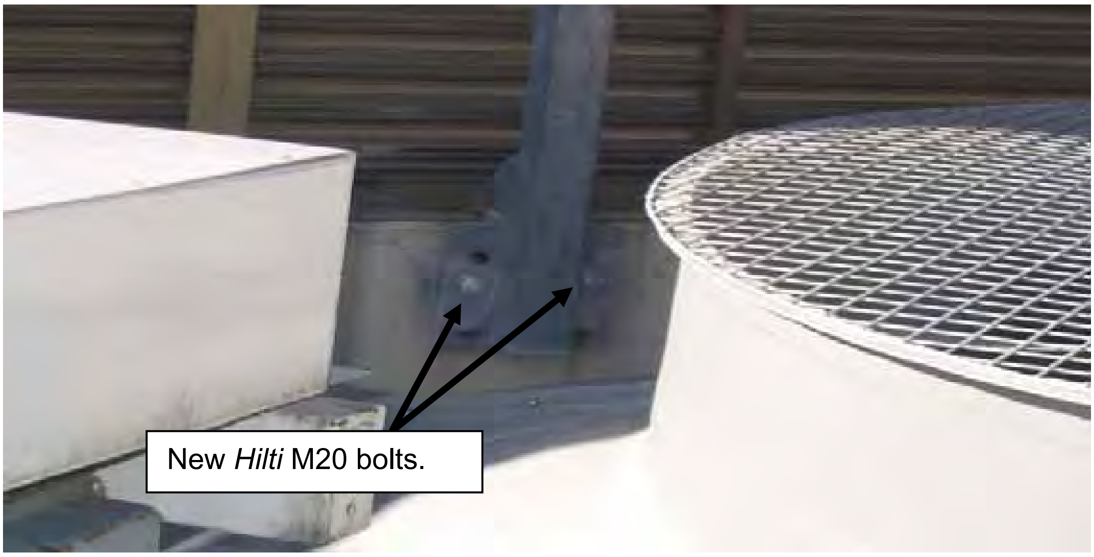


Figure 4.45 Two *Hilti* M20 HSL structural galvanised bolts used to secure base plate to hob and bring plate flush against hob to reduce stress on bolts.

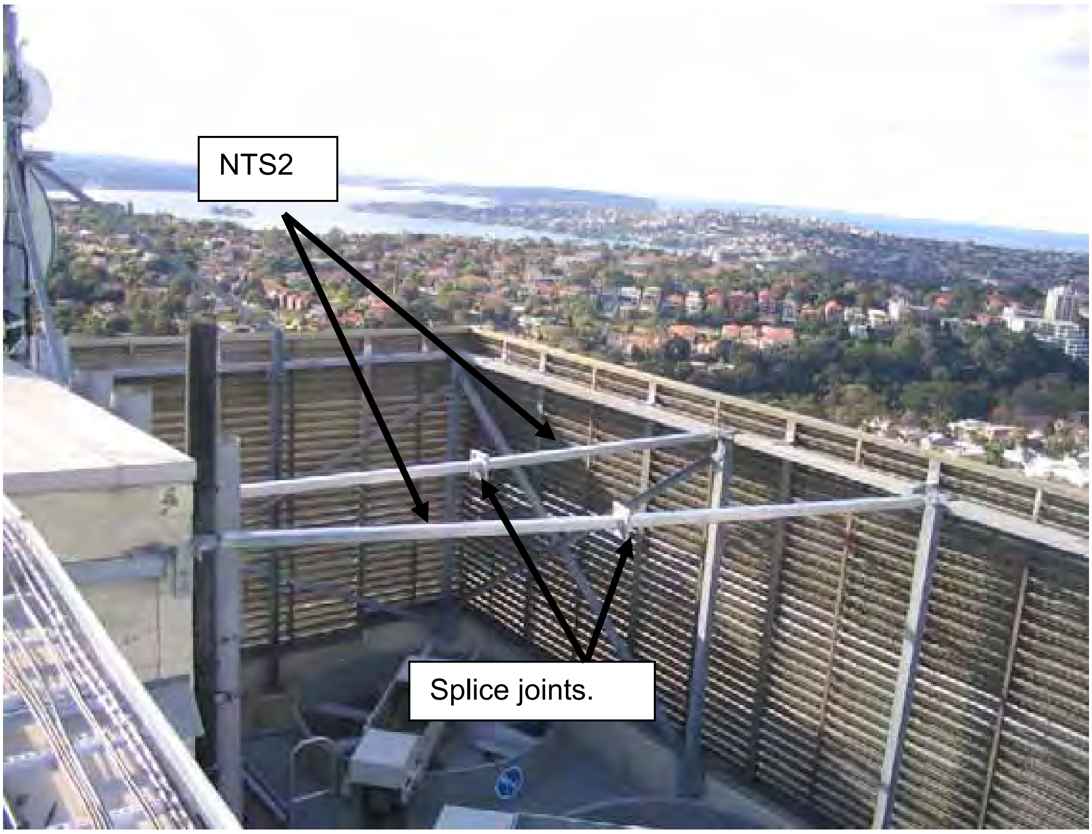


Figure 4.46 Hot dip galvanised cross beams (NTS2) and brackets designed to provide further structural support for eastern section of louvres.

Figure 4.47 Intricate connection of brackets to wall using chemical anchoring.

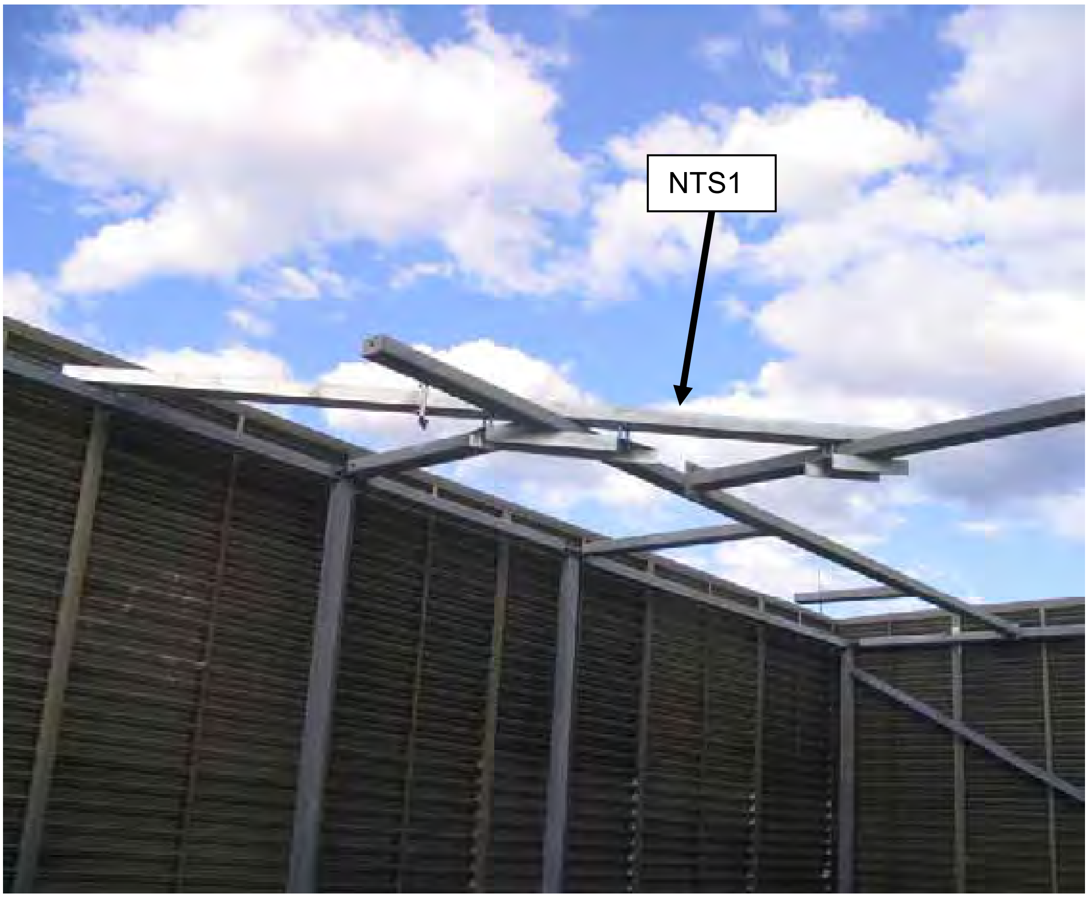


Figure 4.48a Hot dip galvanised cross beams (NTS1) and brackets securing eastern side closer to south.

Figure 4.48b Top view of connection detail of cross beams (NTS1) and brackets using PFCs for additional strength on eastern face.

Figure 4.49a New southwest louvre section; each louvre fully welded to mullion and powder-coated.

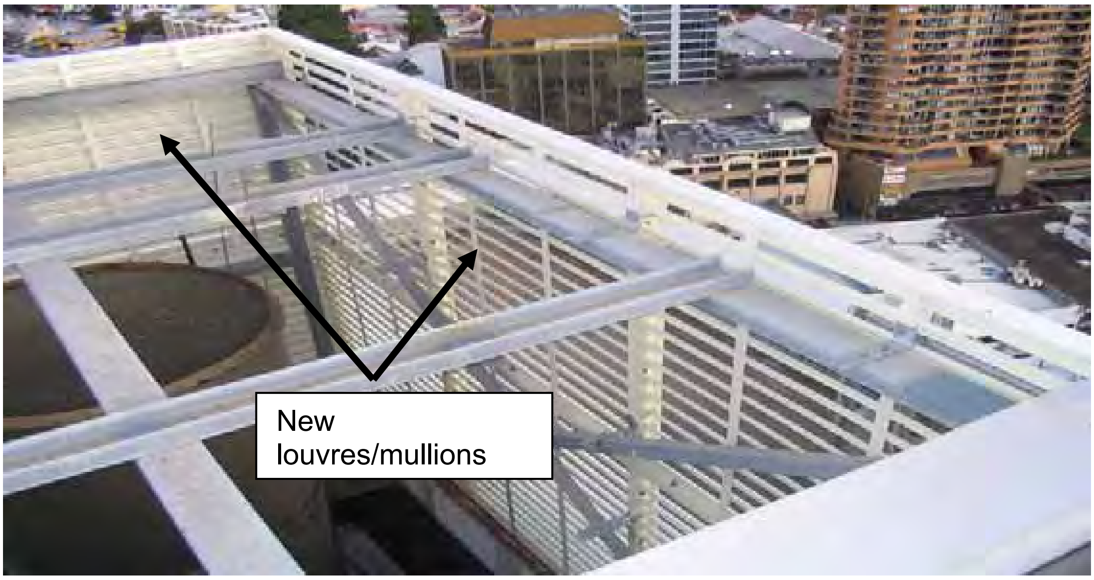


Figure 4.49b Top view of new southwest louvre section, showing details of connections installed at every major structural position.

Figure 4.50a Panel section (with red primer) facing south fabricated fully using existing louvres.

Figure 4.50b Panel section facing south as fabricated using existing louvres.

Figure 4.51 Several additional hot dip galvanised brackets and connections utilised to give further strength to western side.

Figure 4.52 Extra PFCs connected to vertical columns, in turn connected to hob via chemical anchoring.

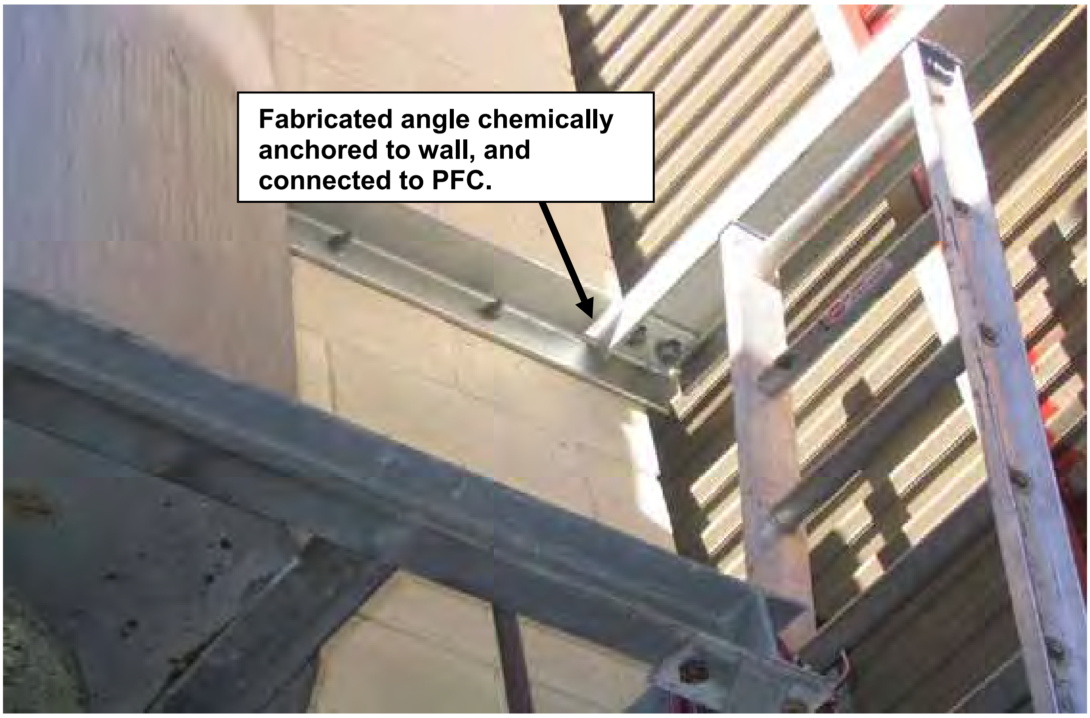


Figure 4.53 PFCs facing south and in southwest corner connected to wall using M18 chemical anchor bolts and structural equal angle; PFCs fabricated as additional support for waist section of new fabricated louvre system in southwest section.

Figure 4.54 New louvre panels fabricated to replace old damaged louvre panels in BMU garage.

Figure 4.55 Typical section of cladding on level 29, showing M8 dynabolts fixed to concrete hob using washers to avoid tearing effect; galvanised bolts placed all around parapet with appropriately sized galvanised washers.

Figure 4.56 Typical cladding separation from mullion sections throughout.

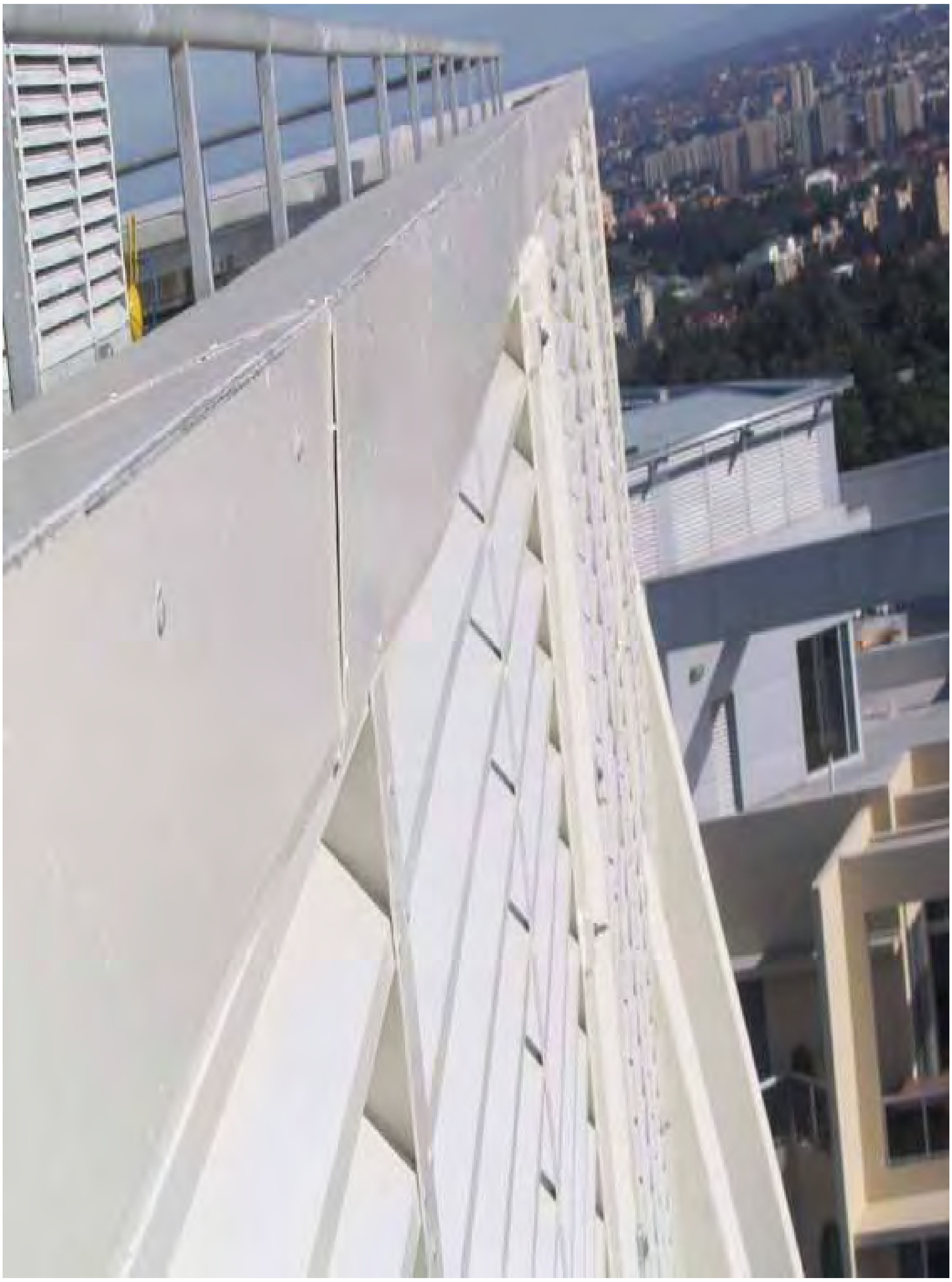


Figure 4.57 Cladding secured over louvres and mullions, riveted to mullion section around parapet; cladding sits over louvre face on façade.

Figure 4.58 Parapet cladding sitting over mullion face of louvres, providing additional connection for louvres; holes drilled in horizontal portion of mullions to allow entrapped water to escape.

Figure 4.59 Potential of BMU to descend posing serious structural problem for integrity and life of cladding.

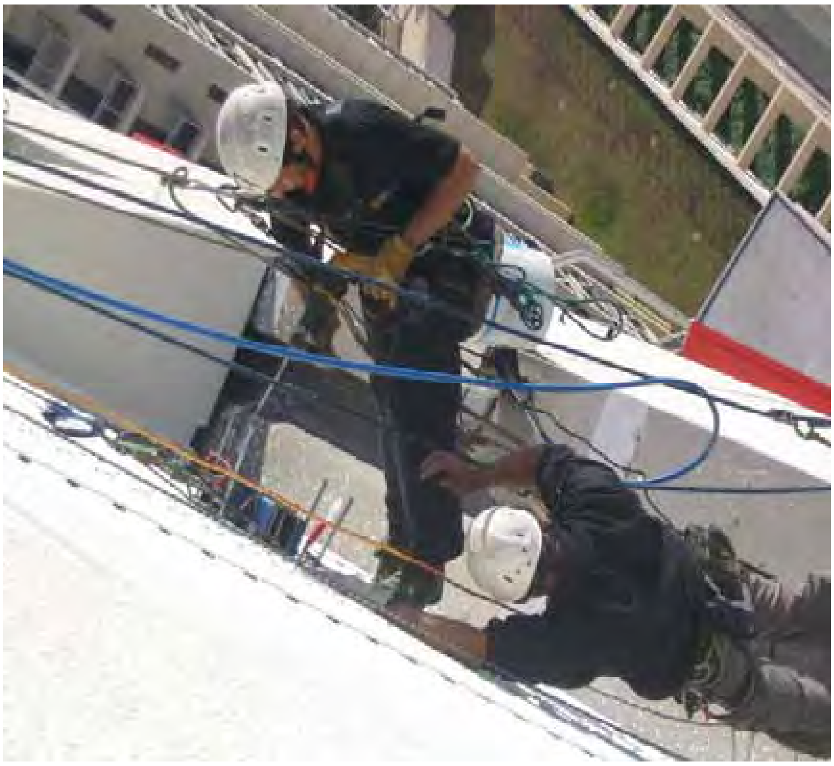


Figure 4.60a Abseilers performing work on louvres due to inability to use BMU to access these levels adequately.

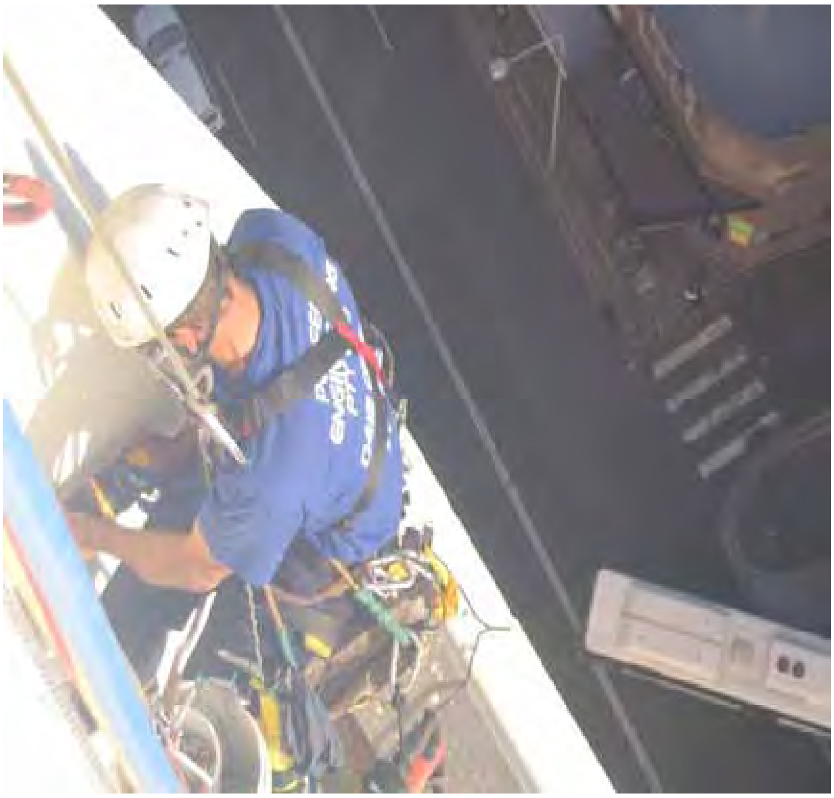


Figure 4.60b Jigs engineered so that abseilers could perform duties with relative ease.

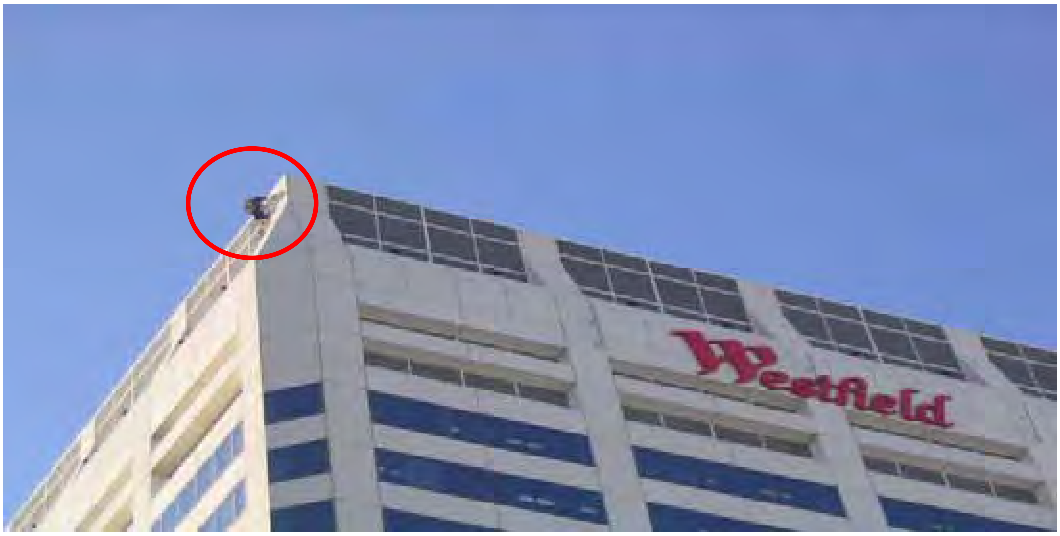


Figure 4.60c Abseilers working on last section of levels 27 and 28.

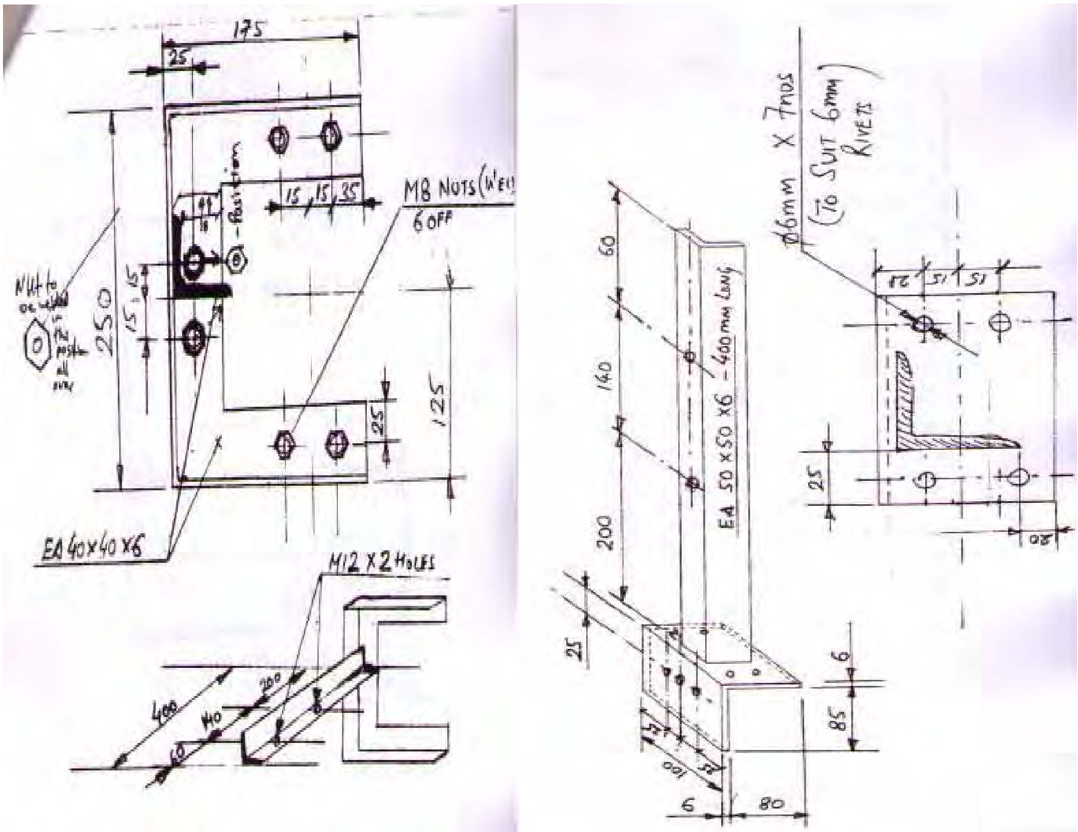
Figure 4.61 Typical section of two main mullions side by side prior to being connected together on level 28.

Figure 4.62 Two mullion sections and louvres connected and held securely in place on level 28.

Figure 4.63a Special jigs engineered to allow marrying up of bolts from outside of mullions to connect through to internally fabricated brackets.

Figure 4.63b Jigs for bolt connection to upper U-brackets in internal of level 28.

Figure 4.63c Jigs for bolt connection to lower C-brackets in internal of level 28.



Note: This drawing shows that riveting with the 5056/7075 aluminium alloy rivets is to be inserted in the 6mm holes (see right hand side). The combined tensile and shear properties of these rivets were calculated and are suitable for this application, since the dimensions of bolts will cause structural damage in the mullions narrow dimensional tolerance.

Figure 4.64a Sketch of actual detailing and measurements for fabrication of a typical lower C-bracket connecting mullion in internal of level 28.

Figure 4.64b Lower C-bracket connecting mullion in internal of level 28 using six bolts; jigs placed on outside for abseilers to drill through mullions and bolt directly through welded nut sitting on face of brackets.

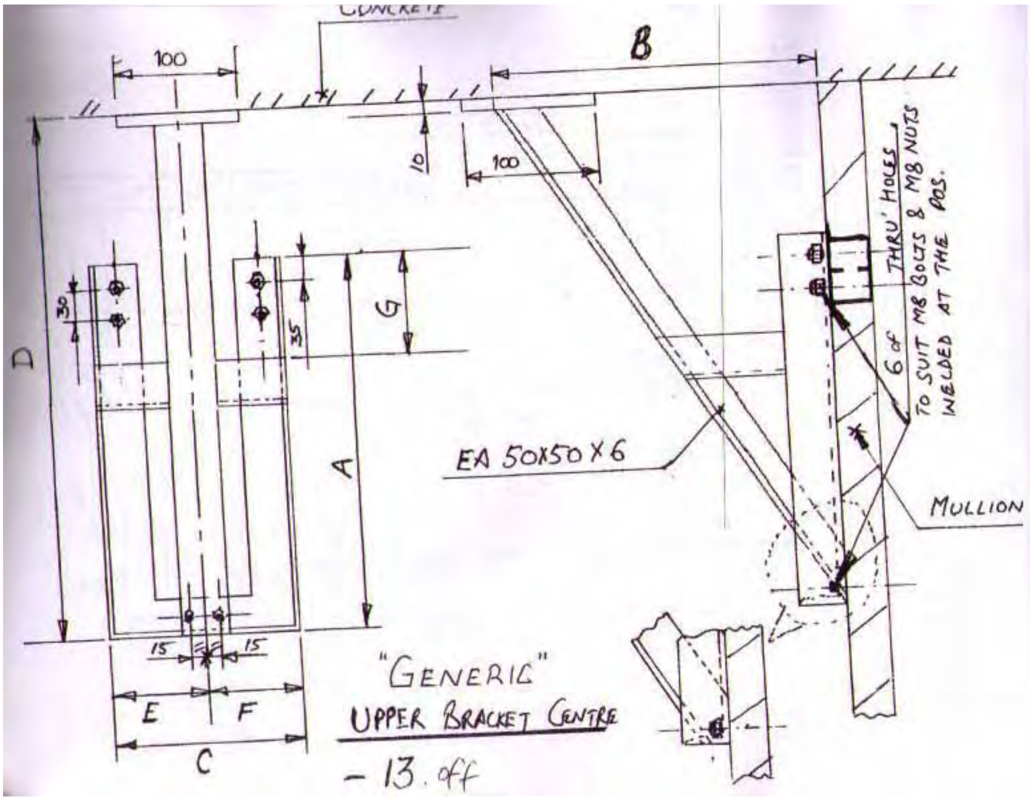


Figure 4.65a Sketch of upper U-bracket connecting mullion from internal of level 28 using six bolts.

Figure 4.65b Upper U-bracket connecting mullion in internal of level 28 using bolts specifically threaded to account for extra length, enabling abseilers to use specially made jigs to drill through mullions and bolt directly through welded nut on brackets.

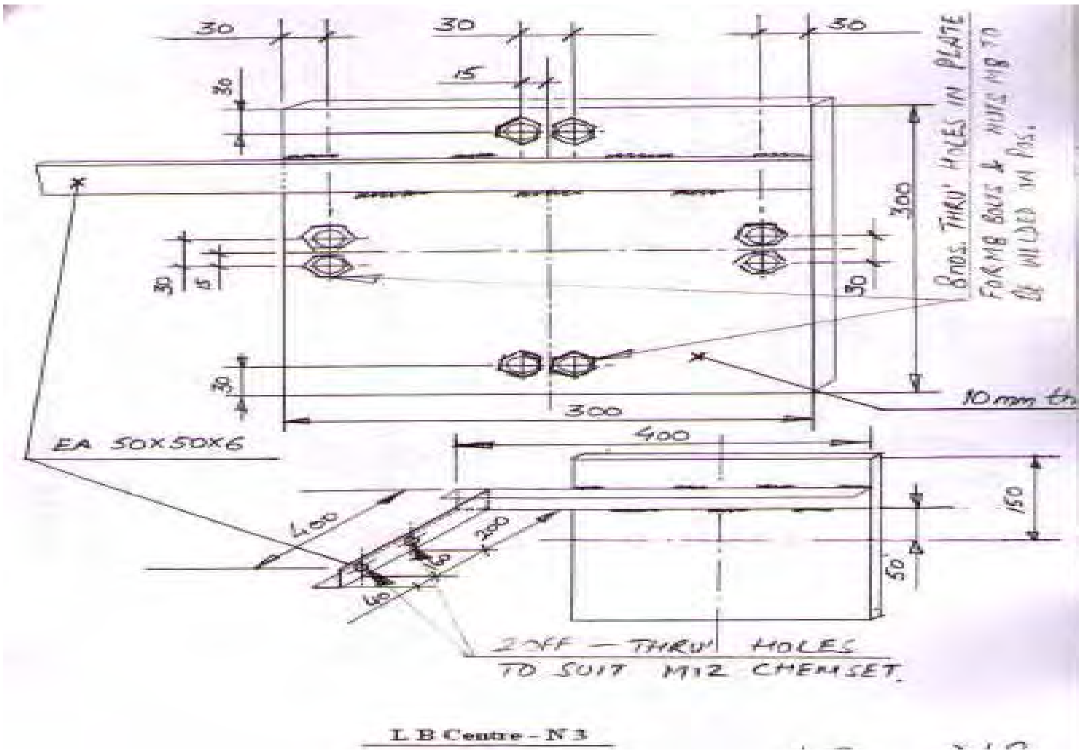


Figure 4.65c Sketch of bracket plate sitting behind concrete hob.

Note: This can not be accessed by hand and is difficult to see inside, attached via eight (8) bolts were required here. Similarly a top bracket was constructed in a similar manner.

Figure 4.65d Detail of plate (for lower bracket) sitting behind hob and awkward to access.

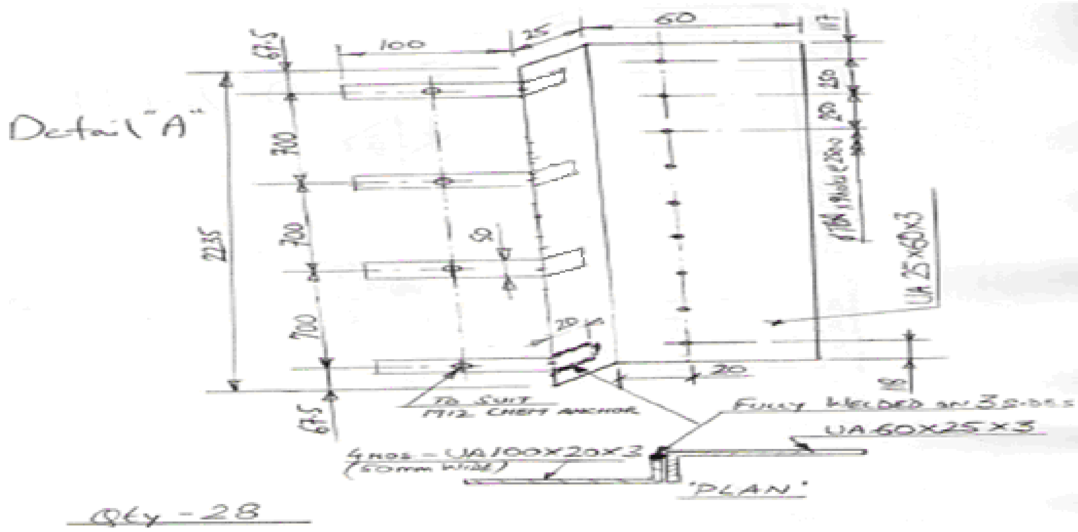


Figure 4.66a Sketch of aluminium unequal angle 60 mm x 25 mm x 3 mm 6060 T5 (top section) riveted to louvres and welded to unequal angle 100 mm x 50 mm x 6 mm 6060 T5 brackets, which were chemically anchored in concrete wall.

Note: The unequal angle shows a series of holes which are required to be riveted into the aluminium louvre panels and mullions.

Figure 4.66b Aluminium unequal angle 60 mm x 25 mm x 3 mm 6060 T5 (top section) riveted to louvres and welded to unequal angle 100 mm x 50 mm x 6mm 6060 T5 brackets, which were chemically anchored in concrete wall.

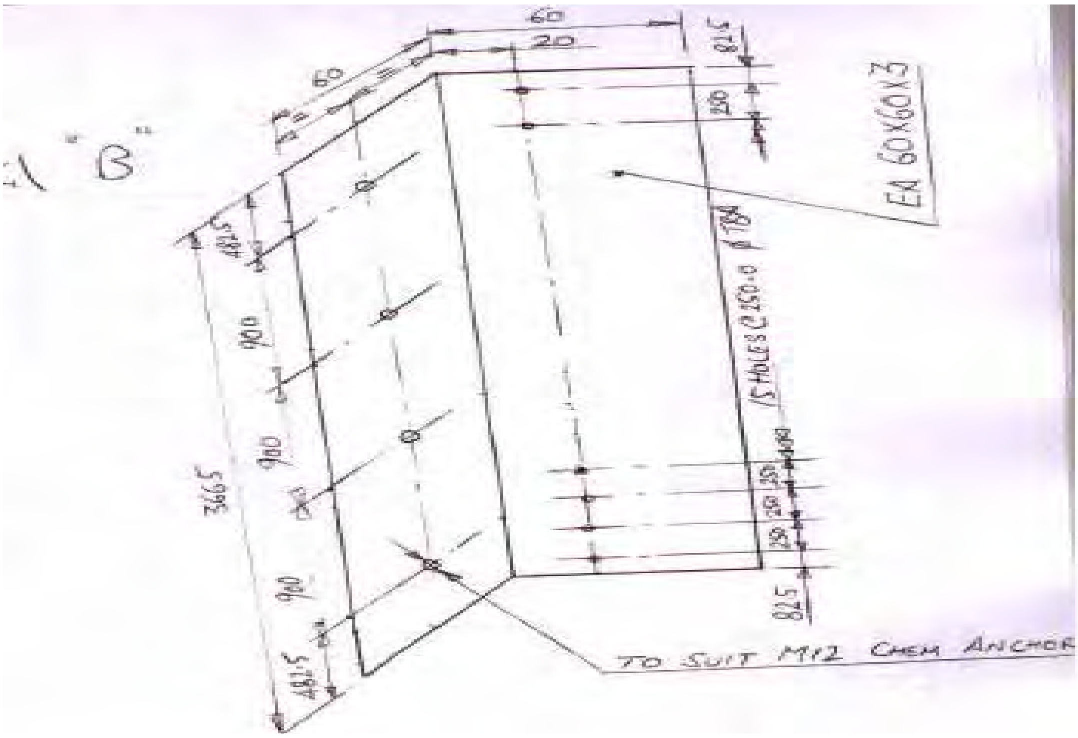


Figure 4.66c Sketch of aluminium equal angle 60 mm x 60 mm x 3 mm 6060 T5 (bottom section) chemically anchored to concrete wall and secured to louvre panels using riveting.

Figure 4.66d Aluminium equal angle 60 mm x 60 mm x 3 mm 6060 T5 (bottom section) chemically anchored to concrete wall and secured to louvre panels using riveting.

Figure 4.66e Aluminium equal angle 60 mm x 60 mm x 3 mm 6060 T5 chemically anchored to concrete wall and secured to louvre as in levels 27 and 28.

Figure 4.67 Aluminium equal angle 60 mm x 60 mm x 3 mm 6060 T5 chemically anchored to concrete roof to hold louvre mullion sections in centre.

Figure 4.68 Typical concrete drilling to secure aluminium equal angles and chemically anchored to concrete on both walls and roof of level 26 anchored to concrete roof to hold louvre mullion sections in centre.

Figure 4.69 BMU situated at level 26 while Perfect Engineering Pty. Ltd. engaged in refurbishment.

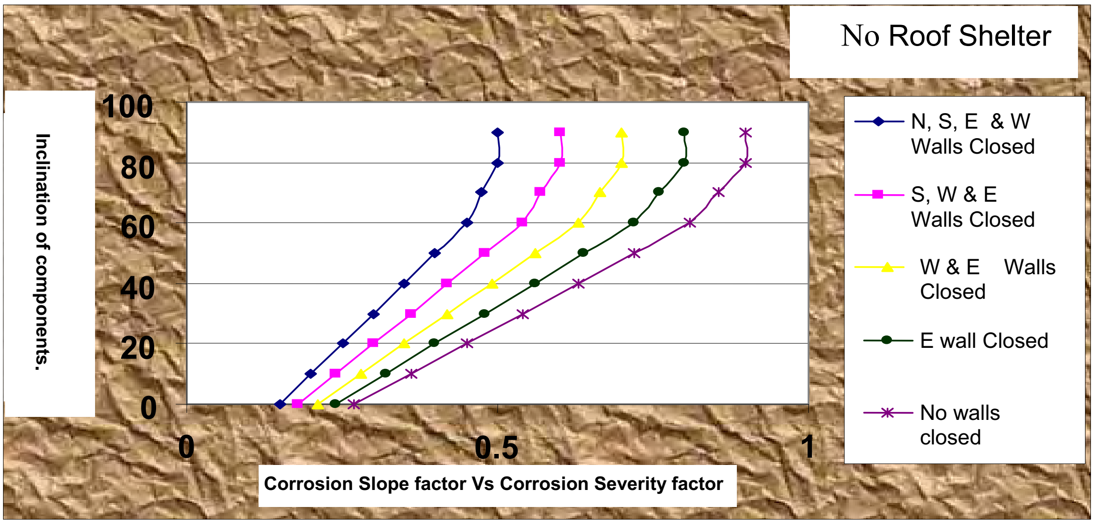


Figure 5.1 Slope as function of resultant factors in Table 5.3; calculated.

Figure 5.2 East (E2); left bracket centre; full cover from roof, exposed to westerly winds.

Figure 5.3 Equivalent to Figure 5.2, 2 m further along.

Figure 5.4 North (N2); level 28, showing condition of both baffles on sides and louvre in centre in nearly acceptable state; fully covered; all sides fully enclosed by concrete walls; only open position from louvres facing outside; resulting in no corrosion.

Figure 5.5 South section; fully under cover; with plant in front; corrosion commencing; westerly wind impinging on plant in front of section and on semi-wall in front of section, protecting it from excess airborne contaminants.

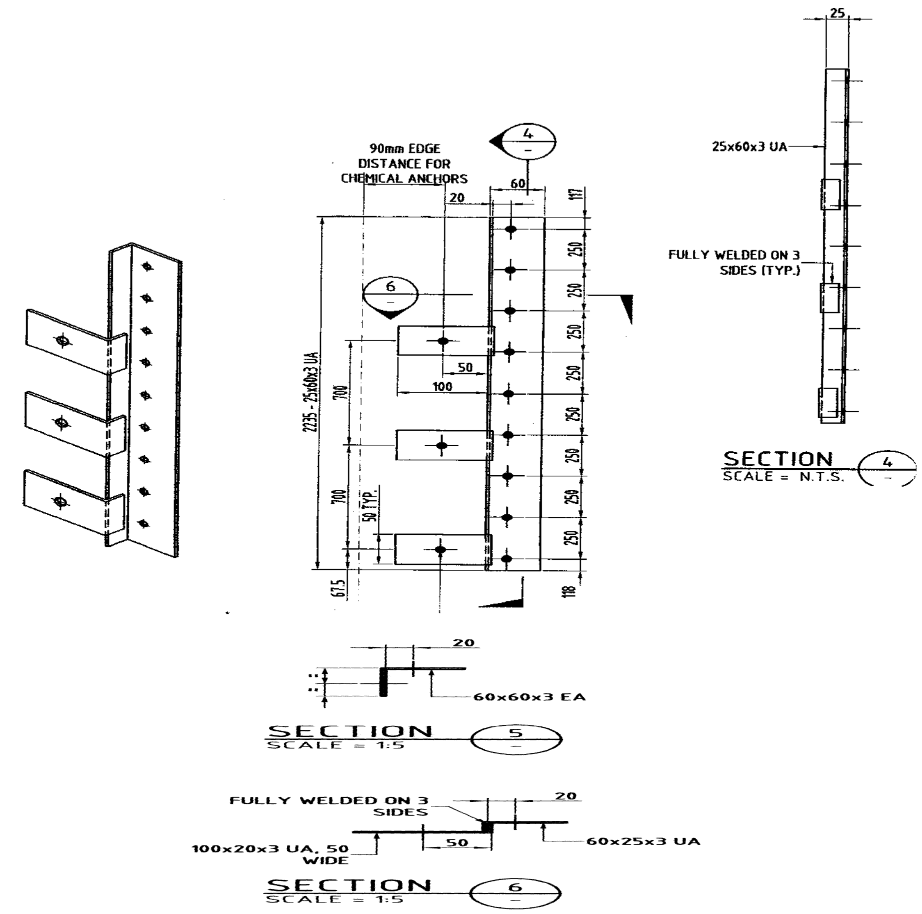


Figure 7.1 Typical bracket connection of 6060 T5 unequal aluminium angle 100 mm x 50 mm x 6 mm welded (5 mm fillet continuous) to 60 mm x 25 mm x 3 mm unequal angle throughout building face.

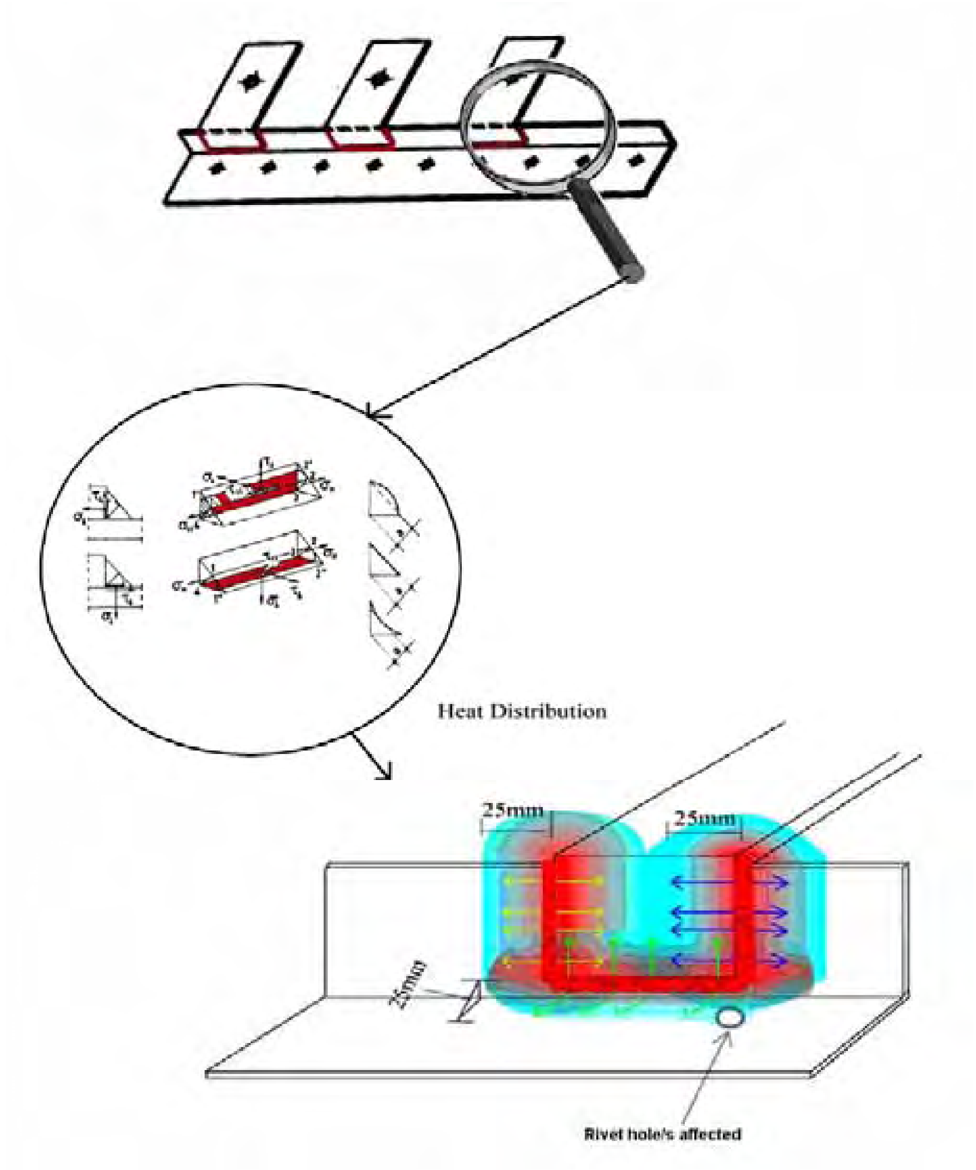


Figure 7.2 5 mm continuous fillet weld running along all three sides of 6 mm thickness unequal angle section and likely extent of b_r in Westfield bracket.

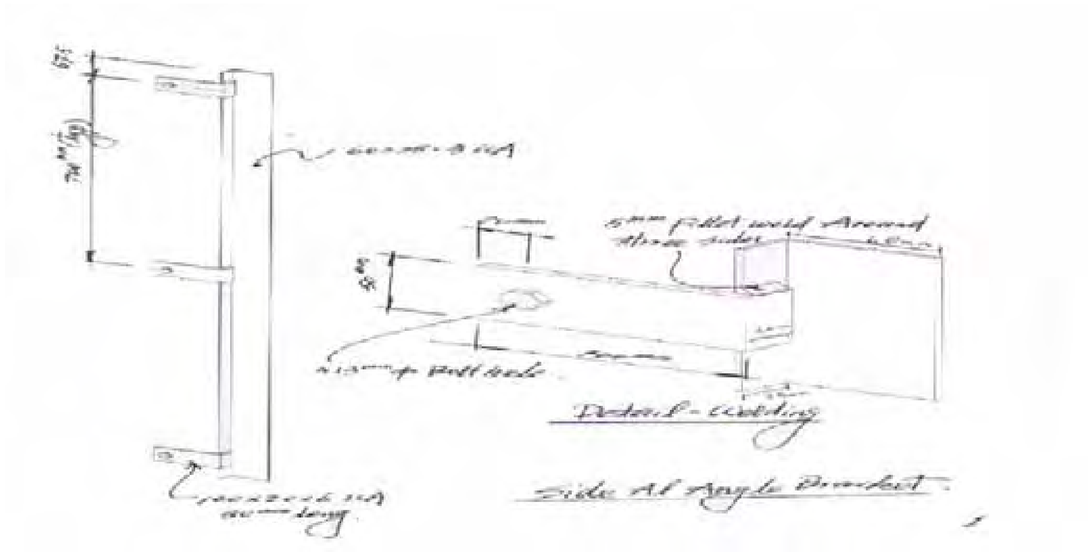


Figure 7.3 Typical angle bracket construction secured to louvre and chemically anchored to building concrete.

PRESSURE:

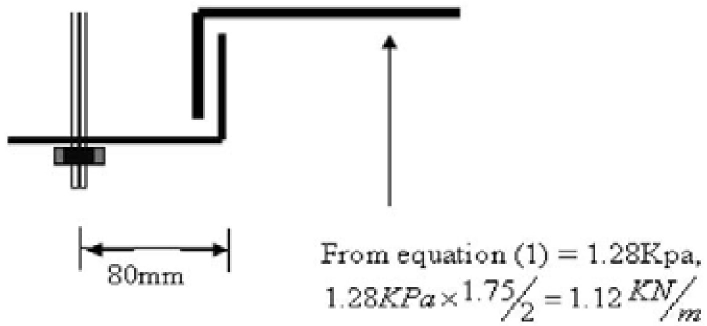


Figure 7.4 Pressure acting against louvre, bracket, and concrete.

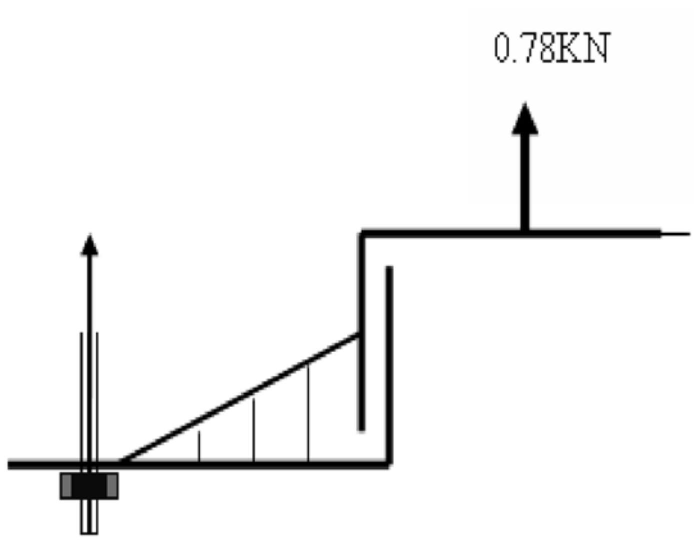


Figure 7.5a Suction acting against louvre and bracket and effect on bolt.

SUCTION:

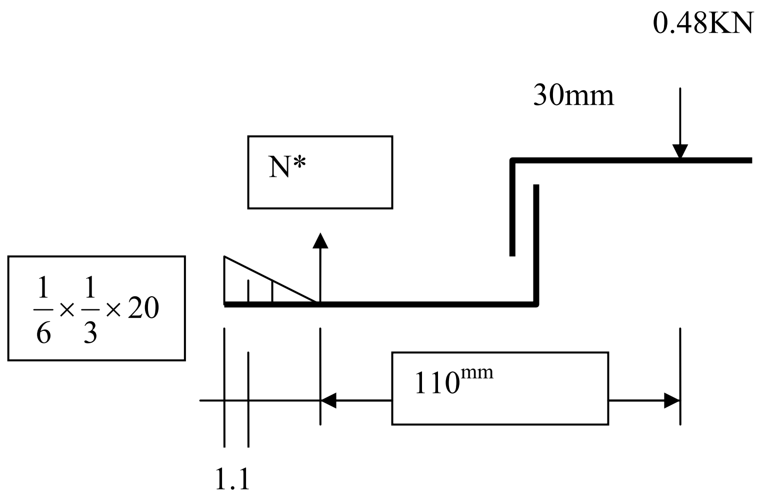


Figure 7.5b Forces acting on bracket under influence of Suction.

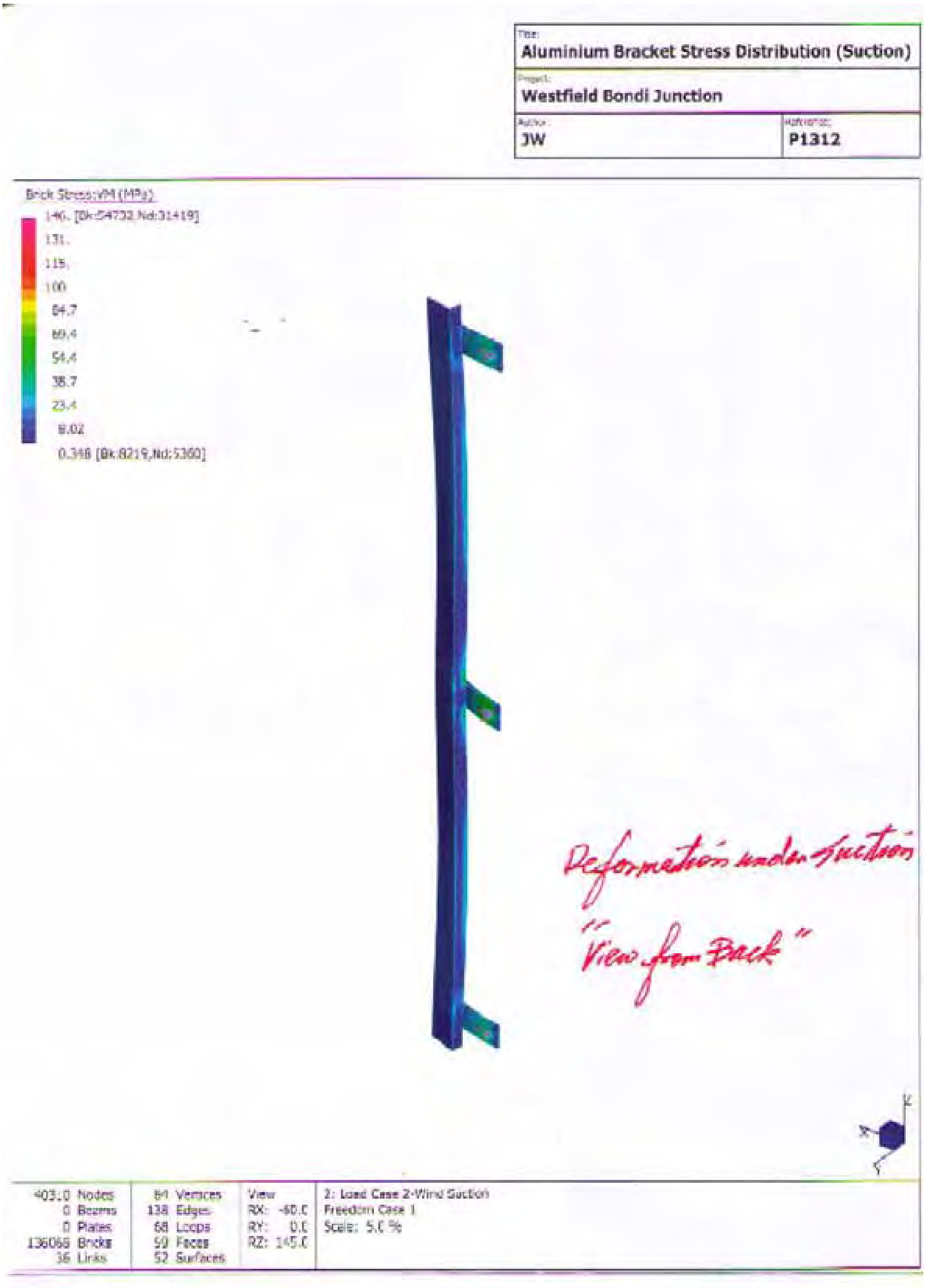


Figure 7.6 FEA illustrating buckling under suction, viewed from back of louvre face.

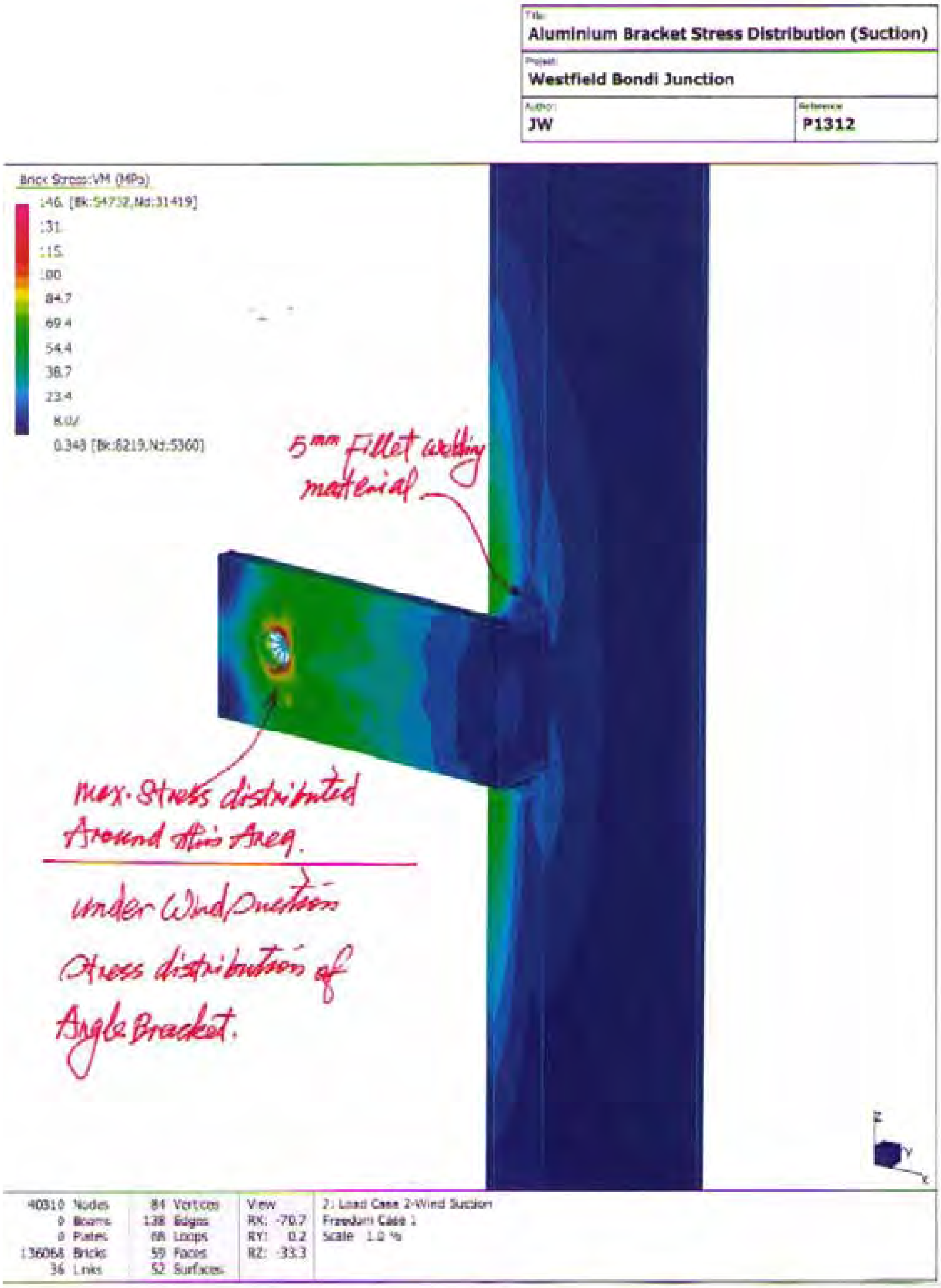


Figure 7.7 FEA illustrating maximal stress distribution around bolt region due to suction forces, viewed from face of louvres.

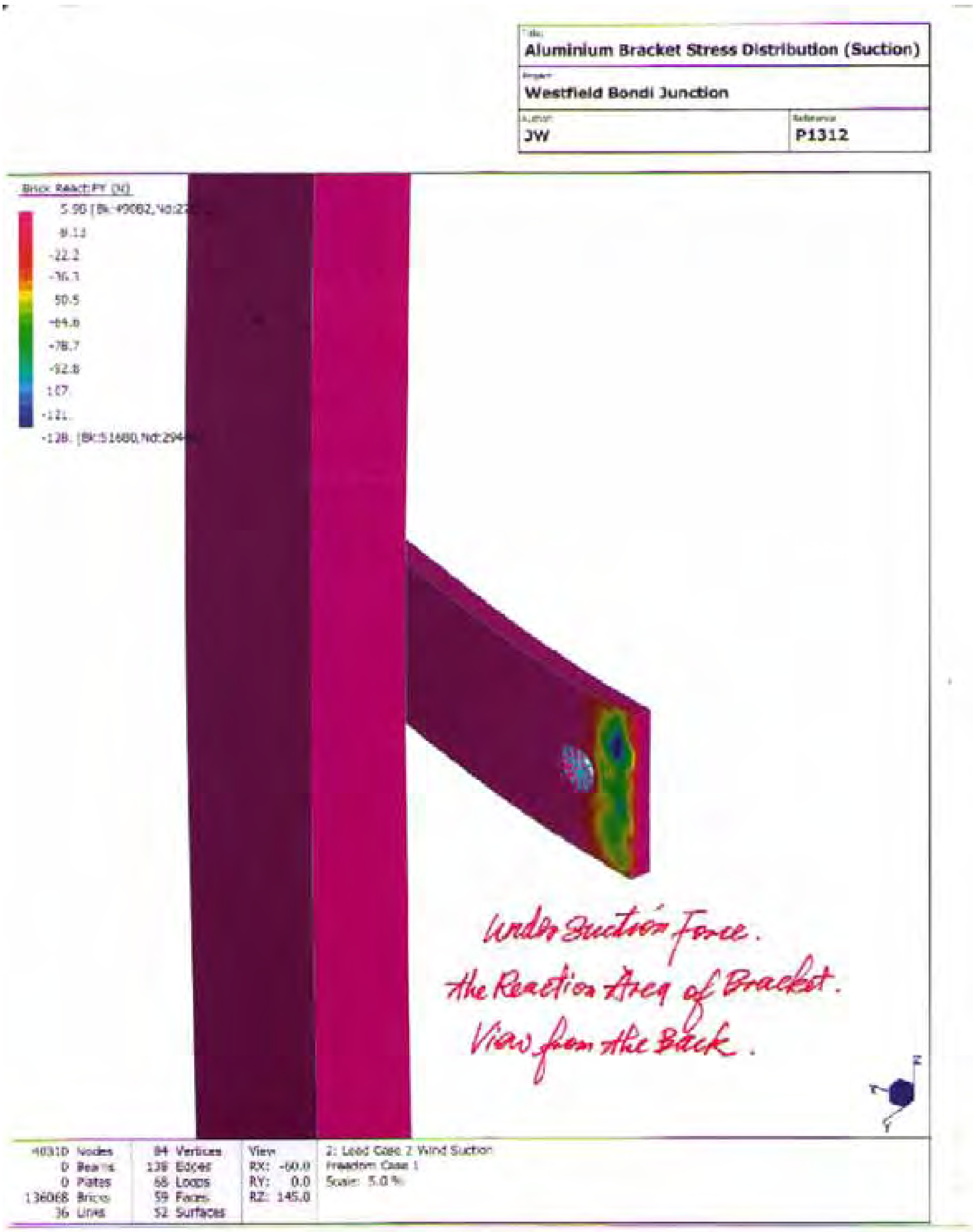


Figure 7.8 FEA illustrating maximal stress distribution against wall due to suction forces' attempting to lift bracket from wall; imposition of resultant excessive load on bolt on opposite side.

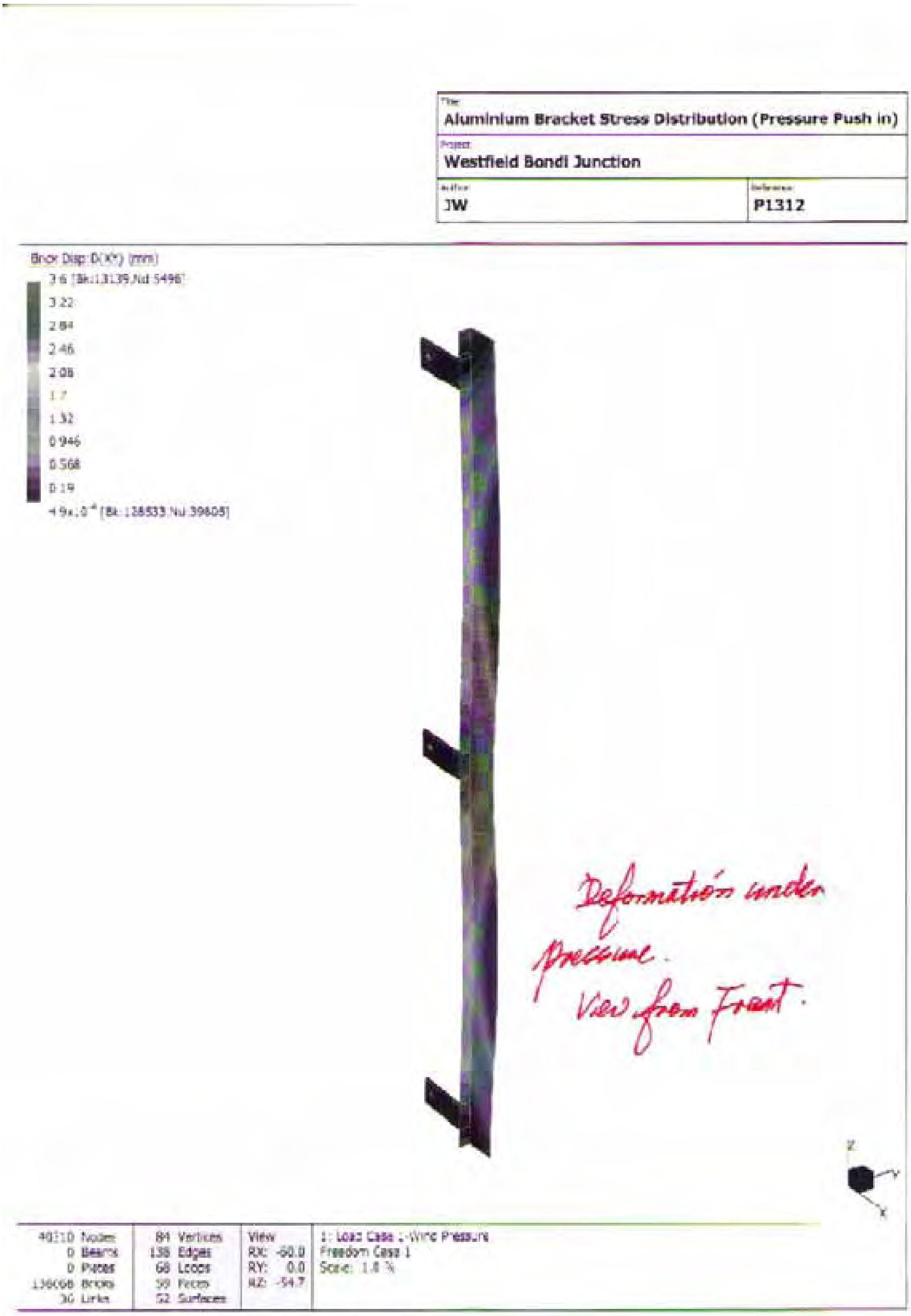


Figure 7.9 FEA illustrating buckling due to pressure forces, viewed from face of louvres.

Figure 7.10 FEA illustrating general stress distribution due to pressure forces, viewed from face of louvres.

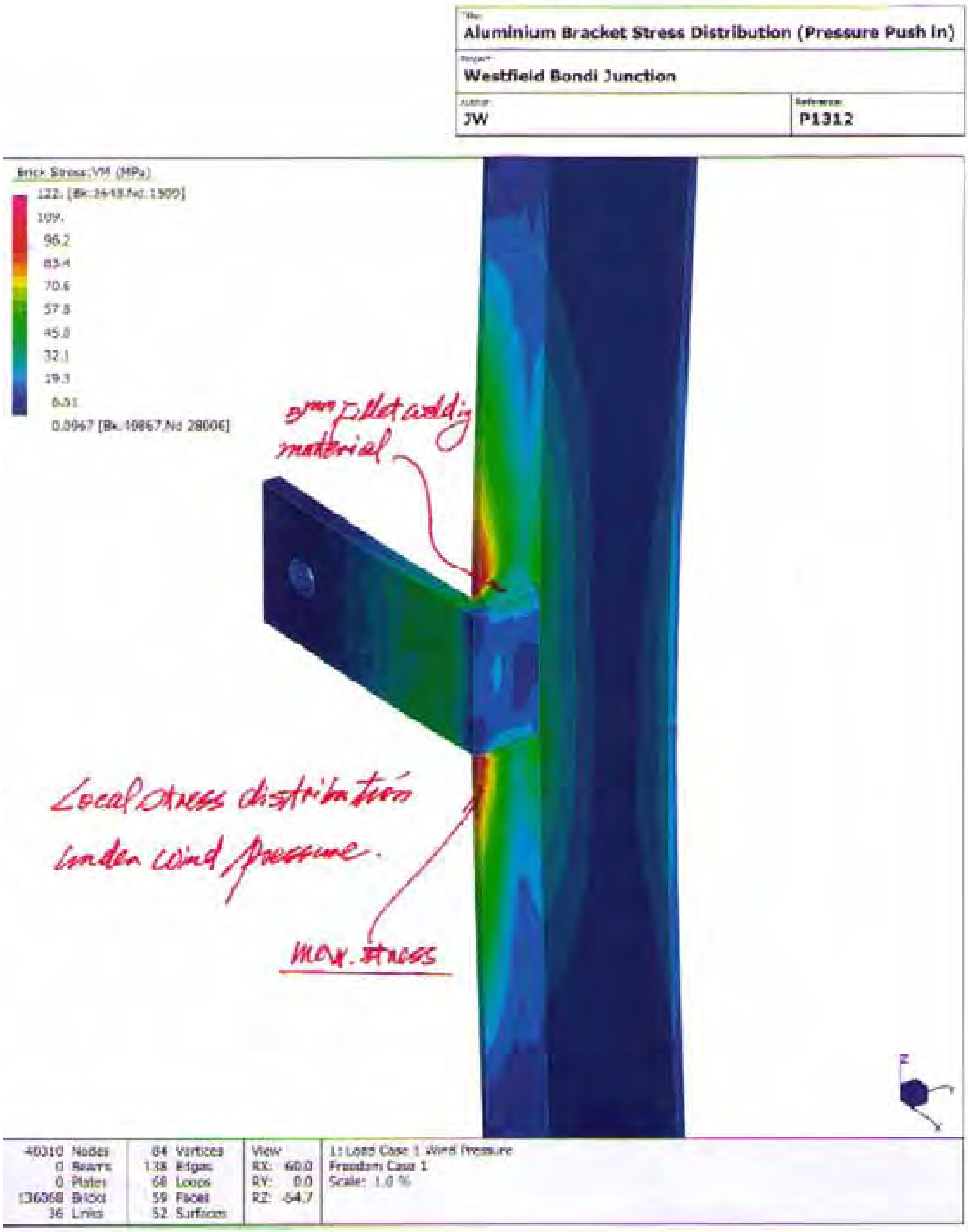
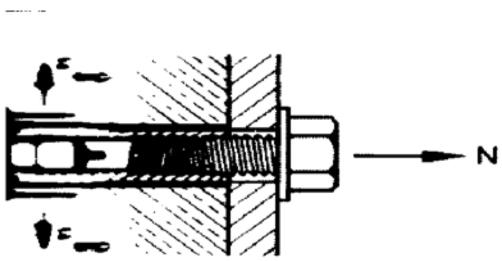
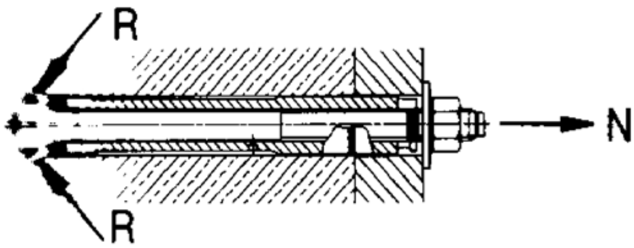


Figure 7.11 FEA illustrating maximal load stress distribution due to pressure forces, viewed from face of louvres, acting in vicinity of weld region.



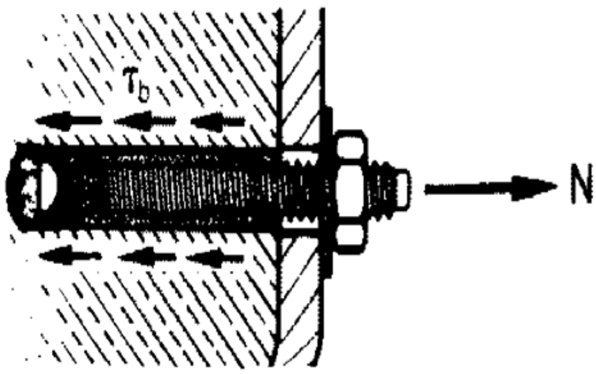
The tensile load, N, is transferred to the base material by friction, R. The expansion force, F_{exp}, is necessary for this to take place. It is produced, for example, by driving in an expansion plug (HKD).

Figure 7.12 Anchor bolt anchor friction [139].



The tensile load, N, is in equilibrium with the supporting forces, R, acting on the base material, such as with the HDA anchor.

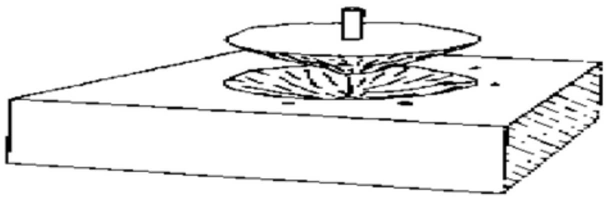
Figure 7.13 Anchor bolt keying [139].



An adhesive bond is produced between the anchor rod and the hole wall by a synthetic resin adhesive, such as with the HVU anchor.

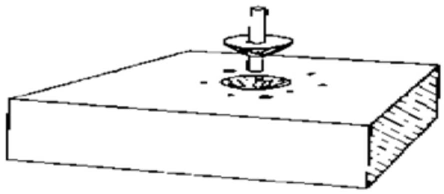
Figure 7.14 Chemical anchor bolt bonding [139].

1. Break out



1

2. Anchor pull away



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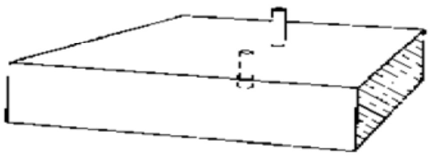

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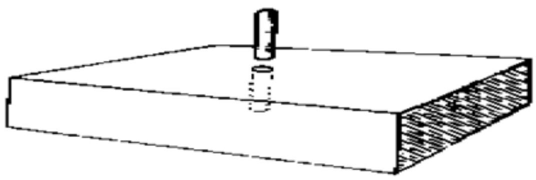
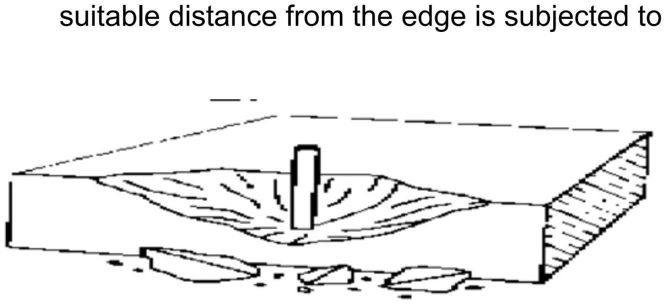


3a

3 and **3a** - Failure of anchor parts occurs mostly when a single anchor with suitable distance from the edge is subjected to pure tensile load.



4

4. Edge break out caused by small edge distance

Figure 7.15a Failure modes by static loading of anchors on concrete [139].

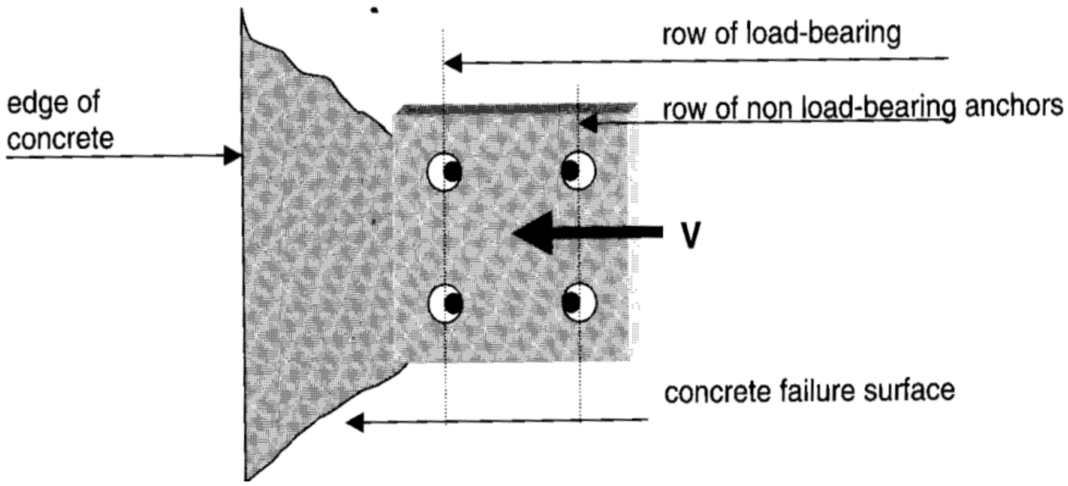


Figure 7.15b Row of load-bearing anchor bolts closer to concrete edge [139].

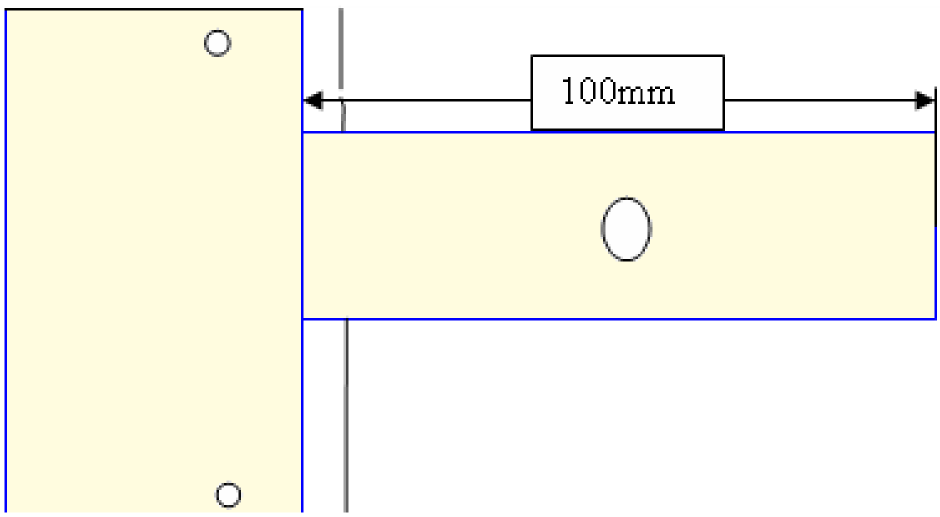


Figure 7.16 Angle plate of 100 mm length and 6 mm thickness originally designed for bolt hole at 50 mm concrete edge distance on Westfield bracket.

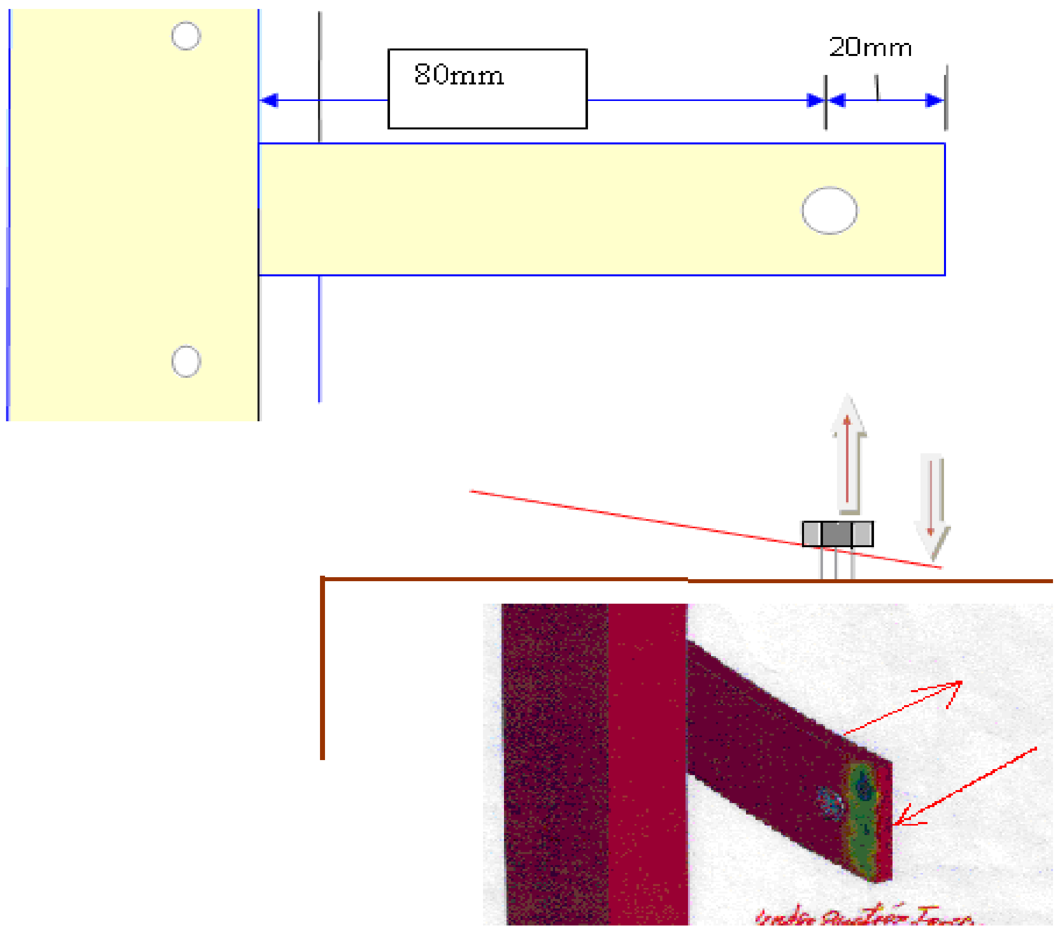


Figure 7.17 Steel plate acting as lever, applying significant pressure on plate closer to hole region on Westfield bracket.

SECTION III

B. Appendices

Appendix A

Author's accreditation as a Chartered Professional Engineer (CPEng) and National Professional Engineer (NPER) from Engineers Australia.

ENGINEERS
AUSTRALIA

This is to certify that

George Nadim Melhem

has been elected

Member

Chartered Professional Engineer

of

ENGINEERS AUSTRALIA

in the

Mechanical College

29 June 2007

Witness our Hands and Seal

National President

Chief Executive

1290572

NATIONAL PROFESSIONAL ENGINEERS REGISTER

Registered Professional Engineer

This is to certify that:

George Nadim Melhem

MIEAust CPEng

has been registered in the following areas of practice from the dates shown

Mechanical (general) 29/06/2007

Chair, National Engineering Registration Board

Registrar, National Engineering Registration Board

Government, community and profession cooperating to maintain national registers in the community interest

For details see - http://www.nerb.org.au

Certificate NOT valid without current membership card that states "National Professional Engineers Register (NPER)" against "REGISTRATION" in the left-hand column.

This certificate is evidence that at the time of assessment the person named on the certificate demonstrated the qualifications and experience to practice competently in the stated area(s) of practice.

When taken in conjunction with a current practice card the certificate also provides evidence of continued practice in the stated area(s) and a commitment to ethical standards and continuing professional development that is satisfactory to the profession.

NPER

NATIONAL PROFESSIONAL ENGINEERS REGISTER

1290572

The National Professional Engineers Register is administered by

The Institution of Engineers, Australia

(This certificate does not imply membership of any of the sponsoring professional bodies)

ENGINEERS AUSTRALIA

Sydney Division

Ref: CID 1290572
29 June 2007

Mr George Nadim Melhem
6 Wolger Road
Ryde NSW 2112

Dear Mr Melhem,

Your application for Chartered Professional Engineer (CPEng) status, College Membership and registration on NPER.

Congratulations on successfully completing the requirements for Chartered Professional Engineer (CPEng) status, Membership of the College of Mechanical (Metallurgical) Engineering and registration on the National Professional Engineers Register in the general area of practice of Mechanical (Metallurgical) Engineering.

It is noted that your Professional Interview was held at the Sydney Division Office of Engineers Australia on 29 June 2007.

You are now a Chartered Member of Engineers Australia in the Professional Engineer Category and, as such, you are entitled to use the postnominals "***MIEAust CPEng***".

A letter confirming your election to Chartered status together with your certificates of membership and NPER registration will be mailed to you shortly.

Please note that you now have an ongoing obligation to maintain and update your expertise by means of Continuing Professional Development (CPD). You should keep careful records of your activities as your CPD may be audited at any time.

Engineers Australia looks forward to your participation in its range of activities.

Yours sincerely,

Roland de Broglio FIEAust CPEng
Manager, Chartered Assessment

George - 29.06.07
An excellent outcome - well done!
You presented well and very professionally, scoring strong in most categories.
With kind regards
Roland

Lvl 3, 8 Thomas Street, Chatswood NSW 2067 or PO Box 1389, Chatsw... ...410 0000
Web Page: www.sydney.engineersaustralia.org.au ...lia.org.au

Ref: Membership Number 1290572
(Please quote in all future correspondence)

ENGINEERS
AUSTRALIA

10 July, 2007

Mr G N Melhem MIEAust CPEng
6 Wolger Road
RYDE NSW 2112

Congratulations on Your Election

Dear Mr Melhem

On behalf of the Council of Engineers Australia may we congratulate you on your election to the grade of Chartered Member, which includes Membership of the Mechanical College in the equivalent grade, effective from 29 June 2007. Membership in this grade entitles you to use the postnominals of MIEAust CPEng.

The Sydney Division Office of Engineers Australia will advise you of the activities and services that are available in your location. For ongoing updates on the range of member benefits, please visit our website at http://www.engineersaustralia.org.au and register as a Member for full access to our online services.

Your application for registration on the National Professional Engineers Register (NPER) has also been approved, effective to 30 June 2008. The general area of practice in which you have been registered is Mechanical Engineering. Any person or organisation seeking to confirm your registration may contact either the local Division Office or Engineers Australia's National Office or search rpsearch on the National Engineering Registration Board's Web site, at http://www.nerb.org.au/. An Information and Record sheet for Continuing Professional Development (CPD) is enclosed to enable you to maintain records of your CPD activities ready for audit.

The National Engineering Registration Board suggests that certificates should be included as a part of documentation provided to authorities in support of engineering certification. Widespread use of these certificates should increase community awareness of NPER and lead to wider recognition that NPER is an important indicator of engineering currency and competence.

Engineering House, 11 National Circuit, Barton, ACT, 2600.
Phone 61 2 6270 6555, Fax 61 2 6273 2354
ENGINEERS AUSTRALIA is the common name of The Institution of Engineers Australia

If you are seeking registration under regulations in a particular State, you may also need to have professional indemnity insurance cover that complies with the requirements stipulated by the responsible Minister.

Your Membership and NPER Certificates are enclosed. Your membership card will be forwarded shortly.

Once again my warmest welcome as a valued member. Engineers Australia looks forward to your support and participation as a member in the range of activities available to members.

Yours sincerely

Rolfe Hartley FIEAust CPEng FEIANZ FIPENZ
National President
Engineers Australia

Mr Mike Marley FIEAust CPEng FAICD
Chair, National Engineering Registration Board

Appendix B

Partnership agreement between Perfect Engineering Pty. Ltd. and Engineers Australia to train engineers in professional development.

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OMC International
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19 July, 2005

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National President

Chief Executive

Appendix C

Author’s relevant publications.

UNIVERSITY OF CAMBRIDGE
DEPARTMENT OF MATERIALS SCIENCE AND METALLURGY
Pembroke Street, Cambridge CB2 3QZ, UK
from Dr I M Hutchings

Telephone: Switchboard 0223 334300
Direct Line 0223 334368
FAX: 0223 334567
Telex: 81240 CAMSPL G
E-mail: imh2@uk.ac.cam.phx

Friday, February 5, 1993

Dr George Melhem
10 Bowden Street
Ryde
NSW 2112

Australia

Dear Dr Melhem

Thank you very much for the paper. I am currently preparing a review of the tribological behaviour of MMCs for a forthcoming conference, and this paper will provide another source. If you could let me have a reference to its place of publication, that would enable me to cite it accurately. I will send you a copy of the review when it is completed.

With many thanks

Yours sincerely

INSTITUTE OF METALS AND MATERIALS AUSTRALASIA LTD
THE MATERIALS SOCIETY OF THE INSTITUTION OF ENGINEERS AUSTRALIA
ACN 004 249 183

Dr G Melhem
School of Materials Science & Engineering
University of NSW
KENSINGTON NSW 2033

Dear Dr Melhem

MATERIALS AND MANUFACTURING IN MINING AND AGRICULTURE

I am pleased to inform you that your paper has been chosen to be part of our conference programme. The technical committee were very interested in the abstract that you submitted and feel that it fits well with the conference theme. The committee would, however, like to stress that when writing your presentation to keep in mind that the audience will be mainly interested in hearing an overview.

Please note that due to the number of papers being presented, all presentations will be **25 minutes in duration followed by 5 minutes for questions.** Please refer to the enclosed Conference Guidelines for further details on writing and presenting your paper.

I have enclosed some copies of the programme for you and your colleagues. We are looking forward to an excellent conference and are pleased that you will be a participant.

Yours sincerely,

Margaret Kirk

Margaret Kirk
Chief Executive Officer

3 March 1993

HEAD OFFICE: Suite 215, 191 Royal Pde PARKVILLE VIC 3052
POSTAL: PO Box 19 PARKVILLE VIC 3052
TELEPHONE (03) 347 2544
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MAR 26 '96 10:11 MAT.SCI.ENG.UNSW 61 2 385-5956 P.1

THE UNIVERSITY OF NEW SOUTH WALES

SCHOOL OF MATERIALS SCIENCE AND ENGINEERING

UNSW **FAX MESSAGE**

Date. 26.3.96 No of Pages- 3

From:

DR SRI BANDYOPADHYAY
School of Materials Science & Engineering
Phone : +61 2 385 4509, Fax : +61 2 385 5956
E-mail: S.Bandyopadhyay@unsw.edu.au

To :

Mr George Melhem
BTR Enginering, Fairfield
Fax : 726 9694

Dear George,

Enclosed is a 2-page abstract of a paper that I plan to present at the 3rd Int Conf on Composites Eng in New Orleans, July 96. PK has prepared this abstract, and he would like, particularly, your comments about the correctness of his assertions.

Please be very quick. Thanks and regards

Dr Band.

SYDNEY 2052 AUSTRALIA
Facsimile: (02) 385 5956
Telephone: (02) 385 4436

ABRASIVE WEAR OF AGED 6061 Al-SiC COMPOSITES

G. Melhem[a], P. Krauklis[b], A.P. Mouritz[c] and S. Bandyopadhyay[b]

[a] BTR Engineering (Australia) Ltd, 77 Seville Road, Fairfield, NSW 2165 AUSTRALIA
[b] School of Materials Science and Engineering, Univ. of NSW, Sydney NSW 2052, AUSTRALIA
[c] Aeronautical and Maritime Research Laboratory, DSTO, PO Box 4331, Melbourne VIC 3001, AUSTRALIA

1. Introduction

There have been many studies on the abrasive wear properties of metal matrix composites[1-4]. However, only a few of these studies have been concerned with the effect of thermal ageing on wear resistance[5-9]. The effect of ageing temperature has been determined by Wang and Rack[8] in 2124 Al-SiC, and by Song *et al.*[9] in 2014 Al-SiC and 6061 Al-SiC composites. In these experiments, it was found that raising the ageing temperature from the under-aged condition to the peak aged condition improved the wear resistance of the composite. The aim of the present work was to determine the effect of ageing time on the hardness and wear resistance of thermally aged 6061 Al-SiC composite.

2. Experimental Materials and Techniques

The abrasive wear characteristics were studied of two metal matrix composites based on the age-hardening aluminium alloy 6061 which had a nominal chemical composition of Al-1.1Mg-0.26Cu. The composites were reinforced with volume fractions of 10 and 20% of 3µm (1200 grit) SiC. Light microscope examination of the microstructures revealed that the particles were reasonably uniformly dispersed throughout the matrix with some tendency toward clustering which was similar in both materials. Unreinforced 6061 aluminium alloy was included in the study as a reference material for comparison purposes.

The materials were heat-treated to the T6 condition, which involved solution treatment at 530 °C for 1 h, quenching in cold water, and then pre-aging at room temperature for 20h. To study the effect of ageing time on the hardness and wear properties, the materials were then artificially aged at 175 °C for 0.5, 4, 8, 20 and 50 h. The specimens were refrigerated at -10 °C to prevent further ageing prior to wear testing and hardness measurement.

After ageing, Vickers microhardness measurements were carried out using a load of 50 g. This created indentations which were approximately 5 times larger than the interparticle spacing, and the hardness values are thus representative of the matrix and reinforcement. The abrasive wear tests were performed on pins 6.35 mm diameter and 30 mm in length, using a pin-on-drum machine according to the method described by Song *et al.*[9]. The tests were performed using 80 µm Al_2O_3 heavy duty cloth with a deadweight load of 66.7 N at a velocity of 4.23×10^{-2} m s^{-1}. The weight loss of each pin was determined to the nearest 0.1 mg from a test run over a path length of 12.84 m. Each pin was tested four times and an average weight loss was taken. The weight loss of a pin of reference material (a quenched and tempered low-alloy steel of hardness HV 265) was also measured between the second and third test runs on each abrasive cloth, and this was used to correct the measured weight losses of the composite material pins to compensate for variability between different abrasive cloths. After wear testing, the surfaces of the wear pins were examined by SEM microscopy.

3. Results and Discussion

Fig. 1 shows the variation of microhardness with ageing time for both composite materials and the 6061 alloy. The materials all exhibit similar ageing characteristics; underaging occurs for times up to 20 h; peak ageing occurs at approximately 20 h, and the overaging occurs at 50 h. The effects of reinforcement volume fraction are also evident in fig. 1. The ageing curves for the three materials are similar in shape, but the general level of the ageing curves increases with increasing volume fraction of SiC reinforcement, with each 10% volume fraction of SiC increasing the hardness by approximately 20 HV points. This pronounced increase in hardness in the presence of SiC particles has been observed previously by other workers and has been attributed[8,10] to the generation of high dislocation densities in the matrix near particles due to differential thermal contraction effects between the SiC reinforcement and Al alloy matrix.

Fig. 2 shows the variation of wear resistance with ageing time for the composite materials and the 6061 alloy. The wear resistance was the reciprocal of the volumetric wear rate (the volume lost per unit distance of sliding in cm^3/cm). The volumetric wear rate was calculated by dividing the average weight loss (g) of each pin by the specific gravity of the material (g/cm^3). Despite some scatter in the wear resistance values, it is evident in fig. 3 that the wear resistance

2

increases with ageing time until the maximum wear resistance is reached for an ageing time of approximately 20 h, and that a reduction in wear resistance occurs with longer ageing times. This trend is parallel with the trend in hardness in figure 1. The decrease in wear resistance is contrary to the effect reported by Wang and Rack[8] that the wear resistance increases in the overaged condition.

Comparison of fig. 2 with fig.1 indicates that the level of the wear resistance curves is not as widely separated between materials as the hardness values, particularly at short ageing times. This suggests that the wear behaviour is governed the matrix properties to a greater extent than hardness.

The typical particle size and interparticle spacing of the SiC in the composite materials were 3 and 5–10 µm respectively The alumina abrasive particle size was larger at 80 µm, and the width of abrasive grooves was typically 20–30 µm. Thus it is likely that many of the small SiC particles are removed relatively easily in larger particles of wear debris.

SEM examination of the worn surfaces showed that the wear mechanisms in the unreinforced 6061 alloy were predominantly microploughing and microcutting. It was observed that the proportion of microcutting increased at the expense of microploughing with increasing ageing time. The same wear mechanisms were also predominant in the case of the composite materials, but it was also observed that significant pull-out of reinforcing particles by the larger abrasive particles occurred. The latter effect appeared occur more frequently in the 20% SiC composite than in the 10% SiC material. Such pull-out of reinforcing particles could be expected to increase the wear rate and thus reduce wear resistance.

4. Conclusions

The abrasive wear resistance and hardness of 6061/SiC composites both increase with ageing time, and reach a maximum value when the composites are in the peak-aged condition. At any particular ageing time, the hardness and wear resistance increase with increasing volume fraction of SiC particle reinforcement. However, the increase in wear resistance associated with SiC reinforcement is less than the corresponding increase in hardness. This is attributed to pull-out of reinforcing particles in the micro-mechanism of wear, which could be expected to increase the wear rate. In the over-aged condition, both hardness and wear resistance decrease below the peak values.

References

[1] A. Banerji, S.V. Prasad, M.K. Surappa, and P.K. Rohatgi. *Wear*, 82 (1982) 141.
[2] M.K. Surappa, S.V. Prasad, and P.K. Rohatgi, *Wear*, 77 (1982) 295.
[3] K. Anand, and Kishore, *Wear*, 85 (1983) 163.
[4] K.H. Zum Gahr, Abrasive wear of two-phase metallic materials with a coarse microstructure, in K.C. Ludema (ed.), *Wear of Materials*, ASME, New York, 1985, p45.
[5] A. Wang and H.J. Rack, *Wear*, 146 (1991) 337.
[6] C.S. Lee and Y.H. Kim, K.S. Han and T. Lim, *J. Mater. Sci.*,27 (1992) 793.
[7] S.J. Lin and K.S. Liu, *Wear*, 121 (1988) 1.
[8] A. Wang and H.J. Rack, The effect of ageing on the abrasion behaviour of SiC$_p$/2124, in *Metal and Ceramic Matrix Composites: Processing, Modelling and Mechanical Behaviour*, The Minerals, Metals and Materials Society, 1990.
[9] W.Q. Song, P.Krauklis, A.P. Mouritz and S. Bandyopadhyay, *Wear*, 185 (1995) 125.
[10] I. Dutta, S.M. Allen and J. Hafley, *Metall. Trans.*, 22A (1991) 2553.

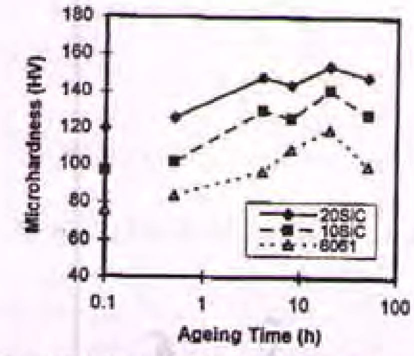

Figure 1. Effect of ageing time at 175 °C on Vickers microhardness.

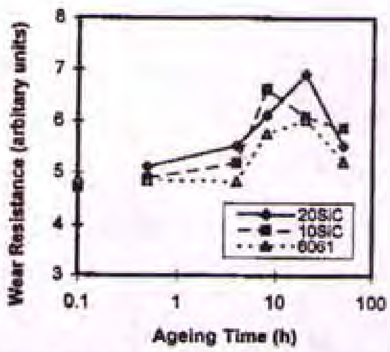

Figure 2. Effect of ageing time at 175 °C on wear resistance. See text for method of calculating wear resistance.

MATERIALS AND MANUFACTURING

IN

MINING AND AGRICULTURE

17 - 18 JUNE 1993
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CONTENTS:

This volume contains twenty-one of the papers presented at the conference '***Materials and Manufacturing in Mining and Agriculture***'. This conference was held in Brisbane, Australia on 17 and 18 June 1993.

Technical Chairperson: Dr Andrej Atrens, The University of Queensland
Conference Convenor : Margaret Kirk, Institute of Metals and Materials Australasia Ltd

THE INFLUENCE OF ARTIFICIAL AGEING ON ABRASIVE WEAR OF SiC and Al_2O_3 PARTICULATE METAL MATRIX COMPOSITES.

G. Melhem, S. Bandyopadhyay and P. Krauklis.

School of Materials Science and Engineering, University of New South Wales, P.O Box 1 Kensington N.S.W. Australia 2033.

Abstract

Abrasive wear behaviour of unreinforced and particulate reinforced 6061 Aluminium alloy metal matrix composites (MMCs) was investigated under high stress two-body abrasion conditions using a pin-on-drum machine surfaced with bonded Al_2O_3 abrasive. The abrasive wear rates were determined in the as-fabricated, solution treated and artificially aged conditions, to determine the effect of variations in matrix hardness. The results indicate that increasing ageing time, up to peak ageing, increases hardness levels and lowers the wear rates of these materials. Reinforced 6061 MMC's appear to have enhanced the ageing kinetics compared with unreinforced 6061 alloy as indicated by higher levels of hardness achieved in the reinforced materials at shorter ageing times. At similar hardness levels, MMCs which were aged for longer periods of time exhibited greater wear resistance than those aged for shorter periods. As a result, the wear rates of composites were seen to be less dependent of hardness and more dependent upon ageing time, i.e. resulting microstructure.

Introduction

Aerospace and automotive applications have provided the main driving force for the development of light alloy Metal Matrix Composites (MMCs) [1]. This is because aluminium MMCs have good combinations of high strength, stiffness and wear resistance compared with the matrix (unreinforced) alloy. Most of the studies on abrasive wear to date have concentrated on the type, volume fraction, size and geometry of the reinforcement with relatively less attention devoted to the effect of matrix microstructure on wear behaviour [2]. To improve understanding of the wear behaviour in MMCs, it would also be useful to identify the role of other parameters such as bulk hardness and microstructure on wear resistance.

A linear relationship has been shown to exist between the wear resistance and bulk hardness for a range of pure metals [3,4]. However, the wear resistance of heat-treated steels is found to be lower than pure metals of the same hardness level [3]. Also, a non-linear relationship is known to exist between hardness and wear resistance when a single steel is heat treated to different levels of hardness [4]. This indicates that microstructure may play an important role in the wear of materials. Moore [5], in his investigation on wear of ferritic steels, proposed that wear resistance is not only related to bulk hardness, but also related to the microstructure.

The effects of ageing on abrasive wear rate (the inverse of wear resistance) have been reported by some investigators to improve the microstructure of the matrix and consequently the wear resistance of the MMCs [6-9]. However, MMCs can become more wear resistant when overaged, compared with the underaged materials of the same hardness [2,6]. Wang and Rack [2] proposed that alloys without reinforcement exhibit similar trends in wear resistance to MMCs in the underaged (UA) and overaged (OA) condition i.e. a decrease in wear rate in the OA condition usually exists. This therefore suggests that the matrix microstructure may influence abrasive wear to a significant extent. However, various reinforcements are reported to enhance the ageing kinetics in MMCs compared with monolithic alloys [2,8,10,11].

In the present investigation the influence of reinforcement and artificial ageing response on wear properties in both unreinforced and reinforced 6061 has been studied.

Materials and experimental procedure

The materials used in this investigation were cylindrical pins (approx. 6 mm x 30 mm long) machined from 19 mm diameter extruded rods of unreinforced and particulate reinforced 6061. The reinforced 6061 consists of 10, 20°/o fine SiC and 10, 20°/o coarse Al_2O_3. More details about the materials are reported elsewhere [12].

MMC - 3

Proceedings of the 3rd Australian Forum

on

METAL MATRIX COMPOSITES

held on Monday, 7 December 1992

at

The School of Materials Science and Engineering
University of New South Wales
Kensington, NSW, 2033, Australia

Organisers:

School of Materials Science and Engineering, UNSW
The Australian Fracture Group (NSW Branch)

Co-sponsors: The Institute of Metals and Materials, Australasia
(The Materials Society of I.E. Aust)

Editors:

Dr. S. Bandyopadhyay
Dr. A.G. Crosky

(ISBN 0 7334 0326 3)

Programme

THE INFLUENCE OF ARTIFICIAL AGEING ON ABRASIVE WEAR OF SiC and Al_2O_3 PARTICULATE METAL MATRIX COMPOSITES.

George Melhem, Sri Bandyopadhyay and Peter Krauklis.

School of Materials Science and Engineering, University of New South Wales, P.O Box 1 Kensington N.S.W. Australia 2033.

Abstract

Abrasive wear behaviour of unreinforced and particulate reinforced 6061 Aluminium alloy metal matrix composites (MMCs) was investigated under two-body abrasion conditions using a pin-on-drum machine. The abrasive wear rates were determined in the as-fabricated, solution treated and artificially aged conditions, to determine the effect of variations in matrix hardness. The results indicate that increasing ageing time, up to peak ageing, increases hardness levels and lowers the wear rates of these materials. Reinforced 6061 MMC appears to have enhanced the ageing kinetics compared with unreinforced 6061 alloy as indicated by higher levels of hardness achieved in the reinforced materials at shorter ageing times. At similar hardness levels, it was observed that all of the MMCs which were aged for longer periods of time exhibited greater wear resistance than those aged for shorter periods. As a result, the wear rates of composites were seen to be less dependent of hardness and more dependent upon ageing time.

Introduction

Aerospace and automotive applications have provided the main driving force for the development of light alloy Metal Matrix Composites (MMCs) [1]. This is because aluminium MMCs have good combinations of high strength, stiffness and wear resistance compared with similar unreinforced alloys. The increase in strength and stiffness is due to the incorporation of ceramic fibres or whiskers [2-5] and improvement in the wear properties is attributed to particle reinforcement [6-9]. Most of the studies on abrasive wear to date have concentrated on the type, volume fraction, size and geometry of the reinforcement with relatively less attention devoted to the effect of matrix microstructure on wear behaviour [10]. To improve understanding of the wear behaviour in MMCs, it would also be useful to identify the role of other parameters such as bulk hardness and microstructure on wear resistance.

A linear relationship has been shown to exist between the wear resistance and bulk hardness for a range of pure metals [11,12]. However, the wear resistance of heat-treated steels is found to be lower than pure metals of the same hardness level [11]. Also, a non-linear relationship is known to exist between hardness and wear resistance when a single steel is heat treated to different levels of hardness [12]. This indicates that microstructure may play an important role in the wear of materials. Moore [13], in his investigation on wear of ferritic steels, proposed that wear resistance is not only related to bulk hardness, but also related to the microstructure.

The effects of ageing on abrasive wear rate (the inverse of wear resistance) have been reported by some investigators to improve the microstructure of the matrix and consequently the wear resistance of the MMCs [14-17]. The best wear resistance has been attained at Peak-hardness for 2124 Aluminium alloy. However, MMCs can become more wear resistant when overaged,

Appendix D

Perfect Engineering Pty. Ltd. ISO 9001:2000 accreditation.

Quality System
Quality Endorsed Company

CERTIFICATE OF REGISTRATION

Perfect Engineering Pty Ltd

ABN 32 106 514 461

6 Wolger Road RYDE NSW 2112 AUSTRALIA

complies with the requirements of

AS/NZS ISO 9001:2000

Quality management systems - Requirements

for the following capability

The registration covers the Quality Management System for the project management and sourcing of fabrication, special purpose machinery, machining and tooling.

Registered by:

SAI Global Certification Services Pty Ltd (ACN 108 716 669) 286 Sussex Street Sydney NSW 2000 Australia with SAI Global Limited ("SAI Global") and subject to the SAI Global Terms and Conditions for Certification. While all due care and skill was exercised in carrying out this assessment, SAI Global accepts responsibility only for proven negligence. This certificate remains the property of SAI Global and must be returned to SAI Global upon its request.

Certificate No.: QEC21503
Issue Date: 11 September 2007
Certified Date: 19 August 2004
Expiry Date: 18 August 2010

Alex Ezrakhovich
General Manager Certification
for and on behalf of
SAI Global Limited

Authorised Local Signatory, SAI Global

SAI GLOBAL · ANAB · SAI Global standards assurance innovation · JAS-ANZ · IAF · IQNet

To verify that this certificate is current please refer to the SAI Global On-Line Certification Register: http://register.sai-global.com

Appendix E

Perfect Engineering Pty. Ltd. NSW Government accreditation for its OH&S management system.

Sydney WATER

13 Jul 2007

Ref letter33h.AK

Mr John Louth
Perfect Engineering P/L
PO Box 856
RYDE
NSW 1680

Dear Mr Louth

Re: Occupational Health & Safety Management System Accreditation.

I am pleased to advise that Perfect Engineering P/L's OHS Management System has been reviewed and accredited by Sydney Water in accordance with the requirements of the NSW Government's OHS Management System Guidelines - 4th edition.

A copy of the review checklist is enclosed.

Should you have any further inquiries in relation to this matter, please contact the undersigned.

Yours sincerely

A. Kelly

Alan Kelly
SWC Registered OHS Auditor
Health & Safety Operations, 7th Floor
ph (02) 9350-5389 fax (02) 9350-6415.
Email agk@sydneywater.com.au

Sydney Water Corporation ABN 49 776 225 038
115 - 123 Bathurst Street Sydney NSW 2000 Australia PO Box 53 Sydney South NSW 1235 Australia
Tel 13 20 92 Fax (02) 9350 4466 DX 14 Sydney www.sydneywater.com.au

Appendix F

Inductively coupled plasma atomic emission spectrometry (ICP-AES) data for original aluminium louvres and mullions.

ETRS

CRITICAL ASSET INTEGRITY SYSTEMS

CHEMICAL ANALYSIS REPORT

REPORT NUMBER: NAM05-0067 C

DATE: 18 March 2005

Perfect Engineering
6 Wolger Road
RYDE NSW 2112

CLIENT CONTACT: George Melhem

ORDER NUMBER: COD

DESCRIPTION: The chemical analysis of two (2) aluminium samples

PERFORMED BY: Atomic Emission Spectroscopy.

RESULTS:

Lowre section — Lowre Al. Strip

Element (wt%)	Coated sample	Uncoated sample
Aluminum	Base	Base
Silicon	0.43	0.46
Iron	0.18	0.19
Copper	0.01	<0.01
Magnesium	0.57	0.52
Manganese	0.05	<0.01
Lead	<0.01	<0.01
Nickel	<0.01	<0.01
Zinc	0.01	<0.01
Titanium	0.03	0.04
Tin	<0.01	<0.01
Chromium	<0.01	<0.01

Notes:
(a) < denotes "less than".
(b) The above mentioned analyses are expressed in weight percent.
(c) The above mentioned analysis was performed at NATA Accredited Laboratory Number 947

COMMENTS: Fits alloys 6063 & 6060

Mullion — Lowre profile

Victor KONSTANTINOFF
Materials Consultant

ETRS Pty Ltd ABN 21 006 353 046
PO Box 6125, Wetherill Park NSW Australia 2164
Tel +61 2 9756 3388
Fax +61 2 9756 3359
An HRL Group Company

Appendix G

Reduced strength zone calculations of welds.

Appendix G

Reduced Strength zone calculation of welds

From Figure 3.37, we have: $f^*_{0.2} b_r = \int_0^{b_h} f(x)dx$

where:

$f_{0.2}$ = Elastic limit of the unaffected base metal

$f^*_{0.2}$ = Elastic limit of the material in the welded region

b_h = Semi-width of the heat affected zone, from which the semi-width of the reduced zone is derived:

and: $$b_r = \left[\int_0^{b_h} f(x)dx\right] / f^*_{0.2} \quad [6]$$

When calculating fillet welded joints subjected to simple tension or compression perpendicular to the axis of the fillet, the effective area is assumed to be: **a . l**. The tensile or compressive force *N* which acts on the joint perpendicularly to the axis of the fillet causes (perpendicular shear or perpendicular stress), with respect to the direction of projection [6].

This is given by: $$\begin{Bmatrix} \tau_\perp \\ \sigma_\perp \end{Bmatrix} = \frac{N}{aL}$$

Design strength of the fillet weld based upon experiments is as follows;

$$f_{d,w} = \eta_w \times lesser\,of \begin{Bmatrix} \sqrt{2(f_{d,red})} \\ \gamma \cdot f_{d,0} \end{Bmatrix}$$

where:

$f_{d,w}$ = Design strength of a fillet weld

η_w = Coefficient of joint; related to quality of joint

$f_{d,red}$ = Strength of base metal in reduced strength zones (side of fillet)

γ = Coefficient that depends on weld metal

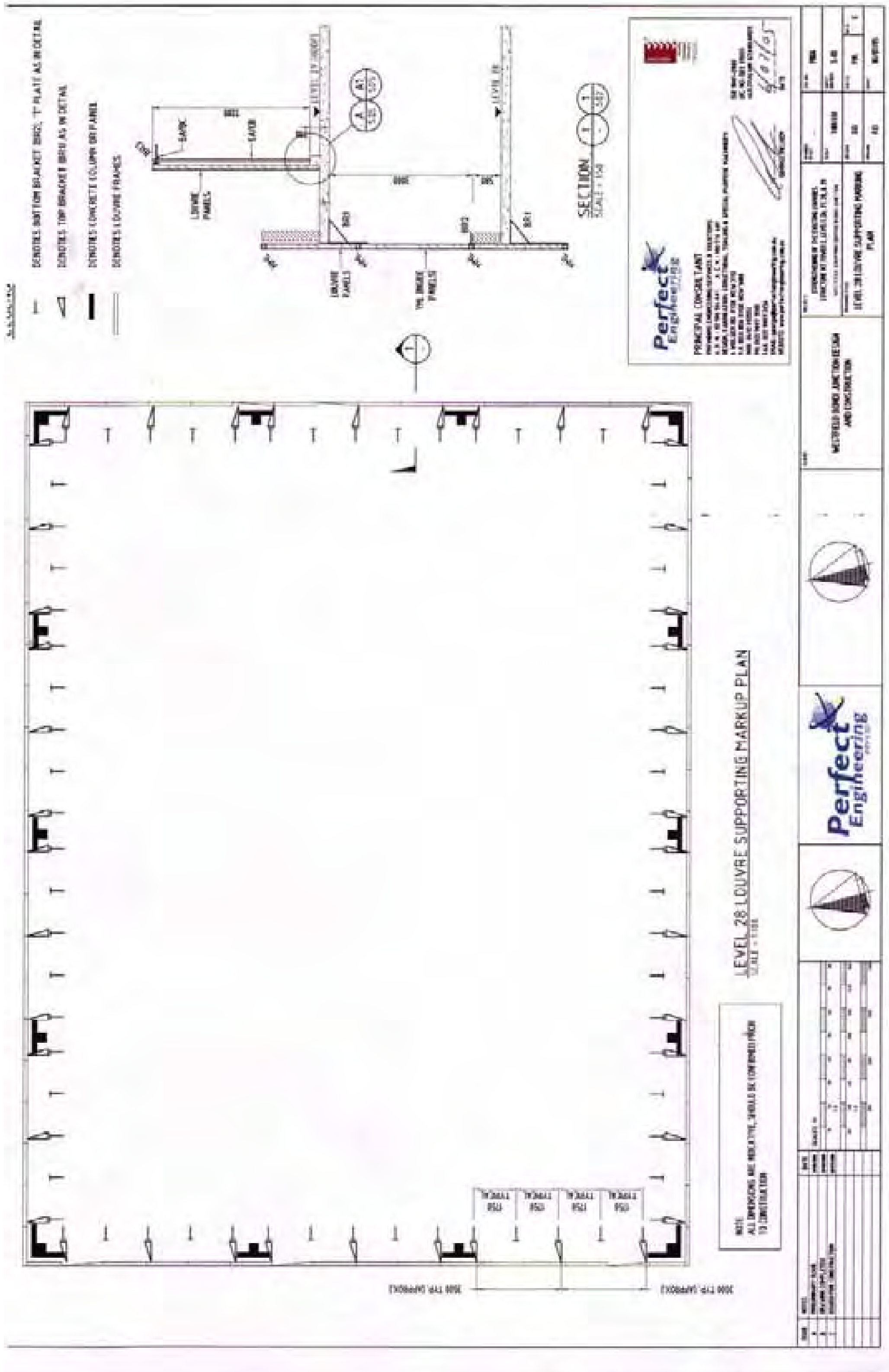
$f_{d,0}$ = Design strength of weld metal

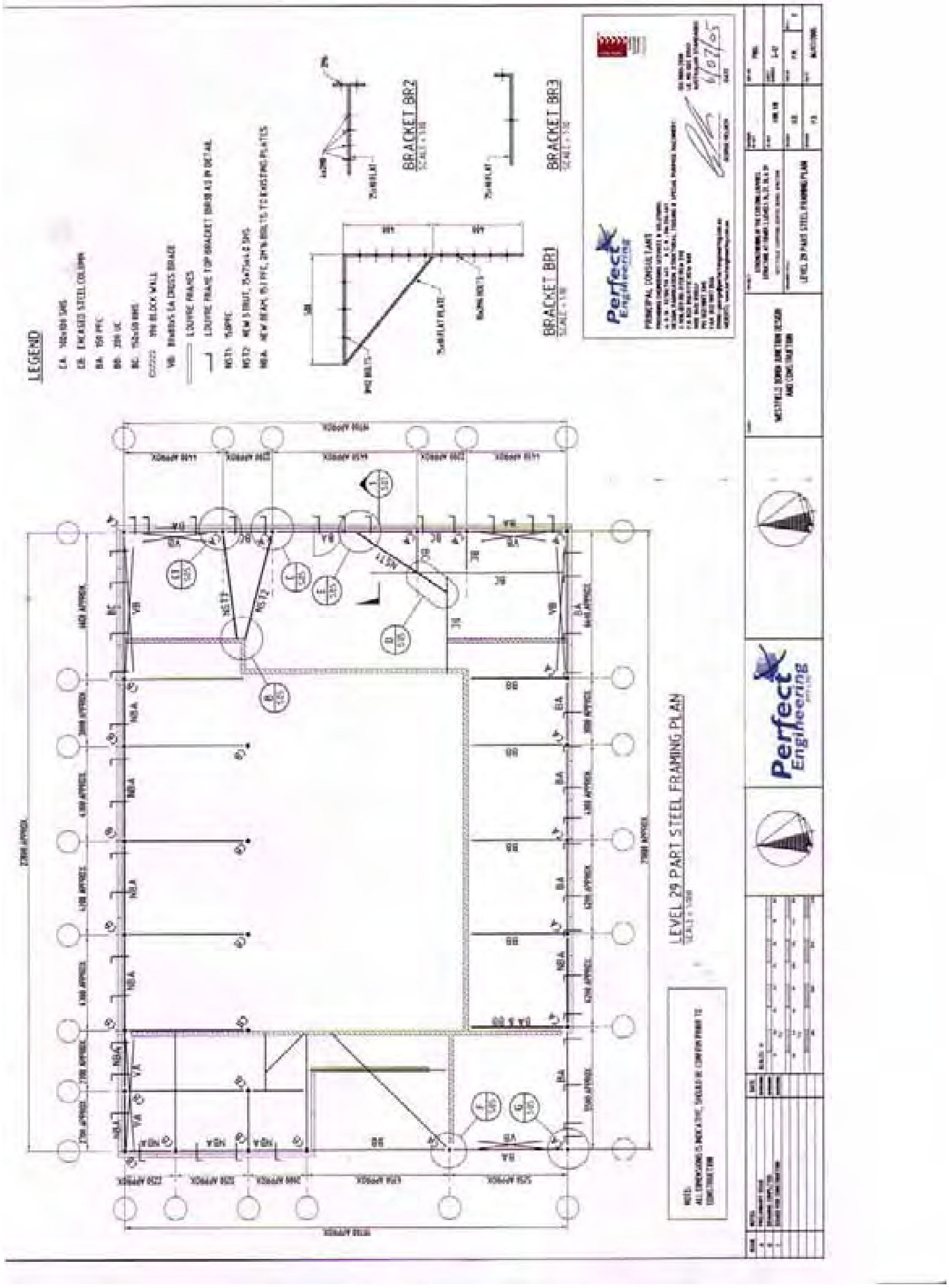
γ is a coefficient that takes into account the complex phenomena related to fillet welds [6]. Some suggested values of γ are as follows:

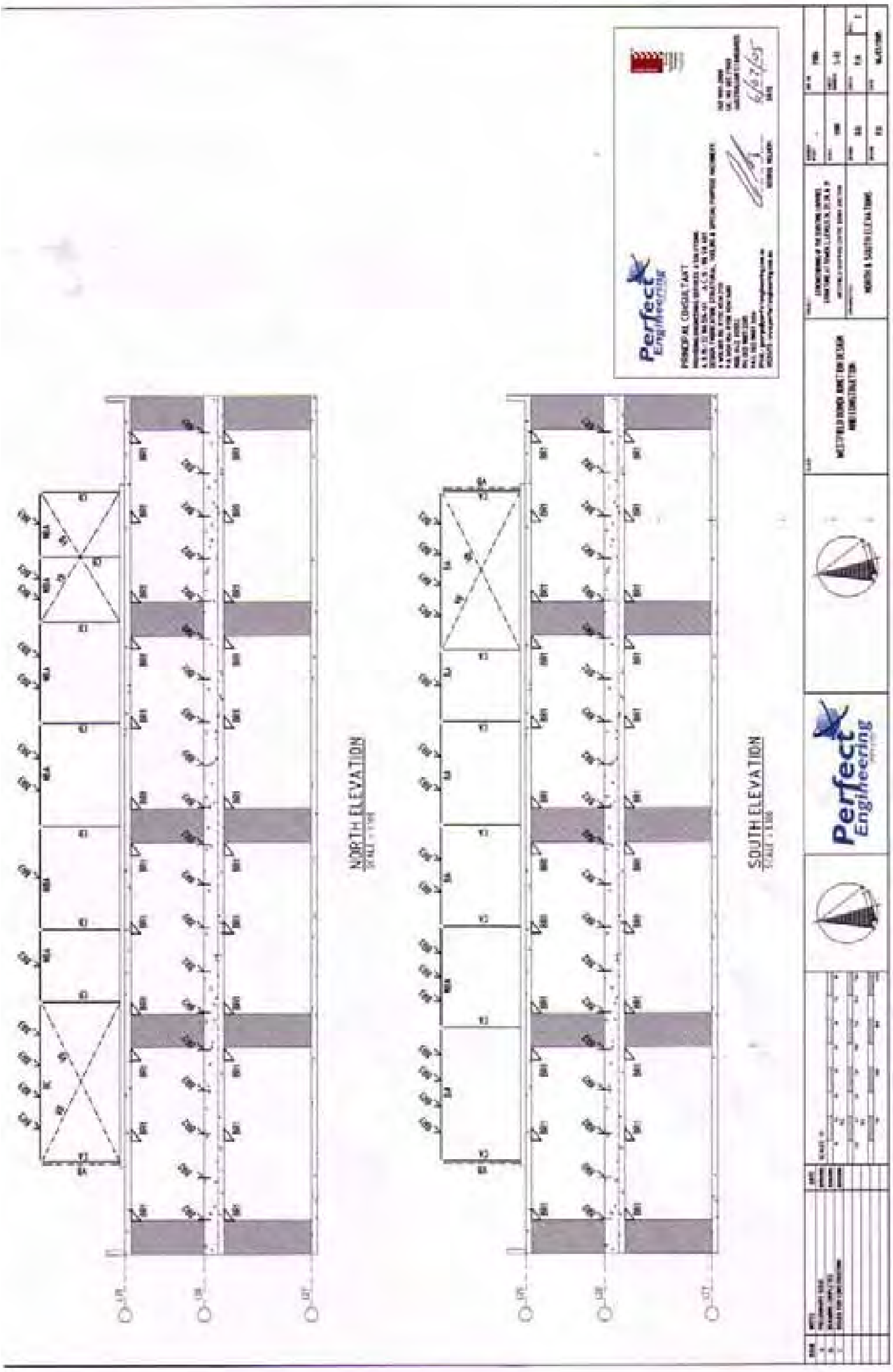
a) AlSi5 = 0.64, **b)** AlMg3Mn =0.75, **c)** AlMg3.5 = 0.75,
d) AlMg4.5Mn = 0.56, and **e)** AlMg5 = 0.56.

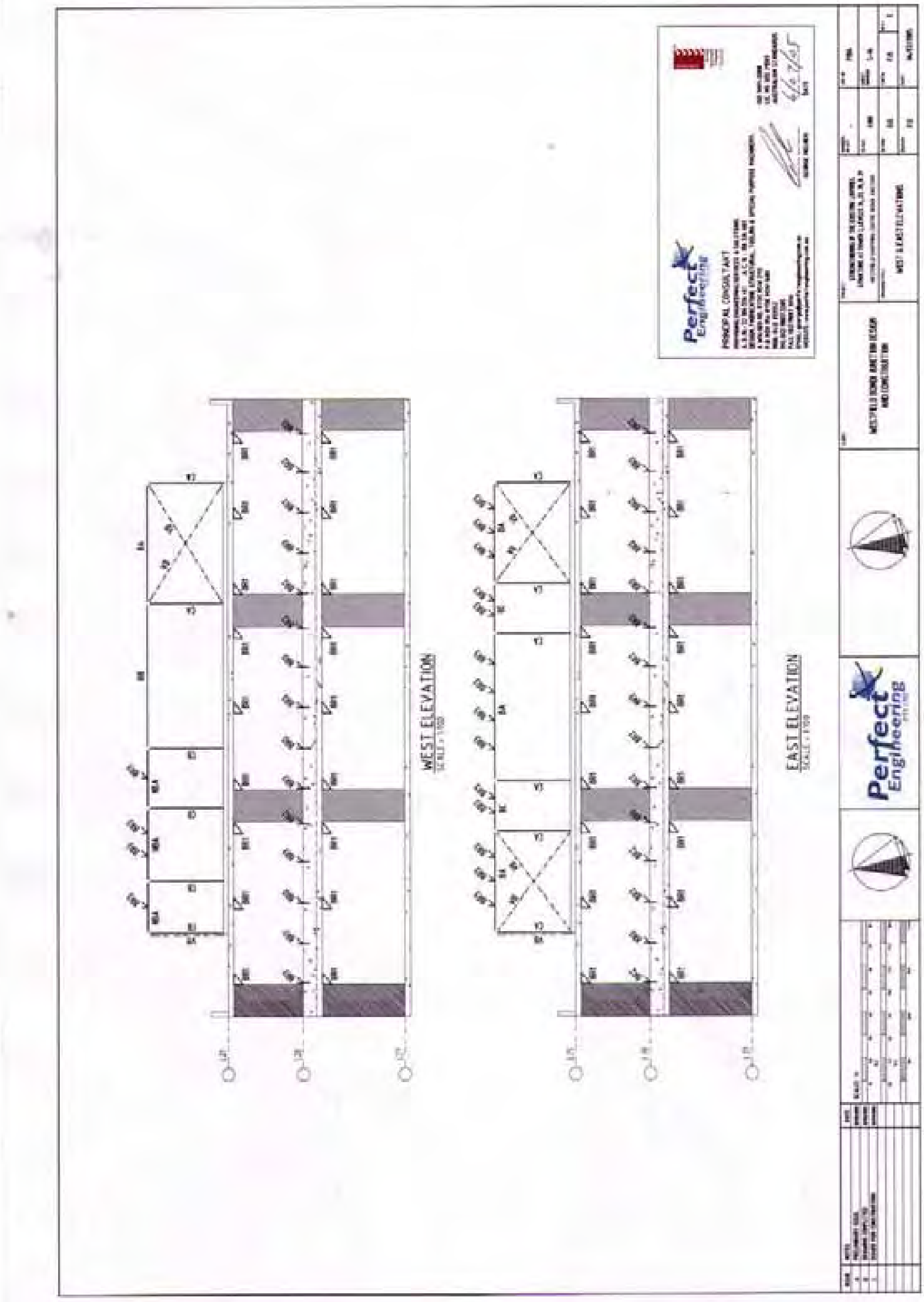
Appendix H

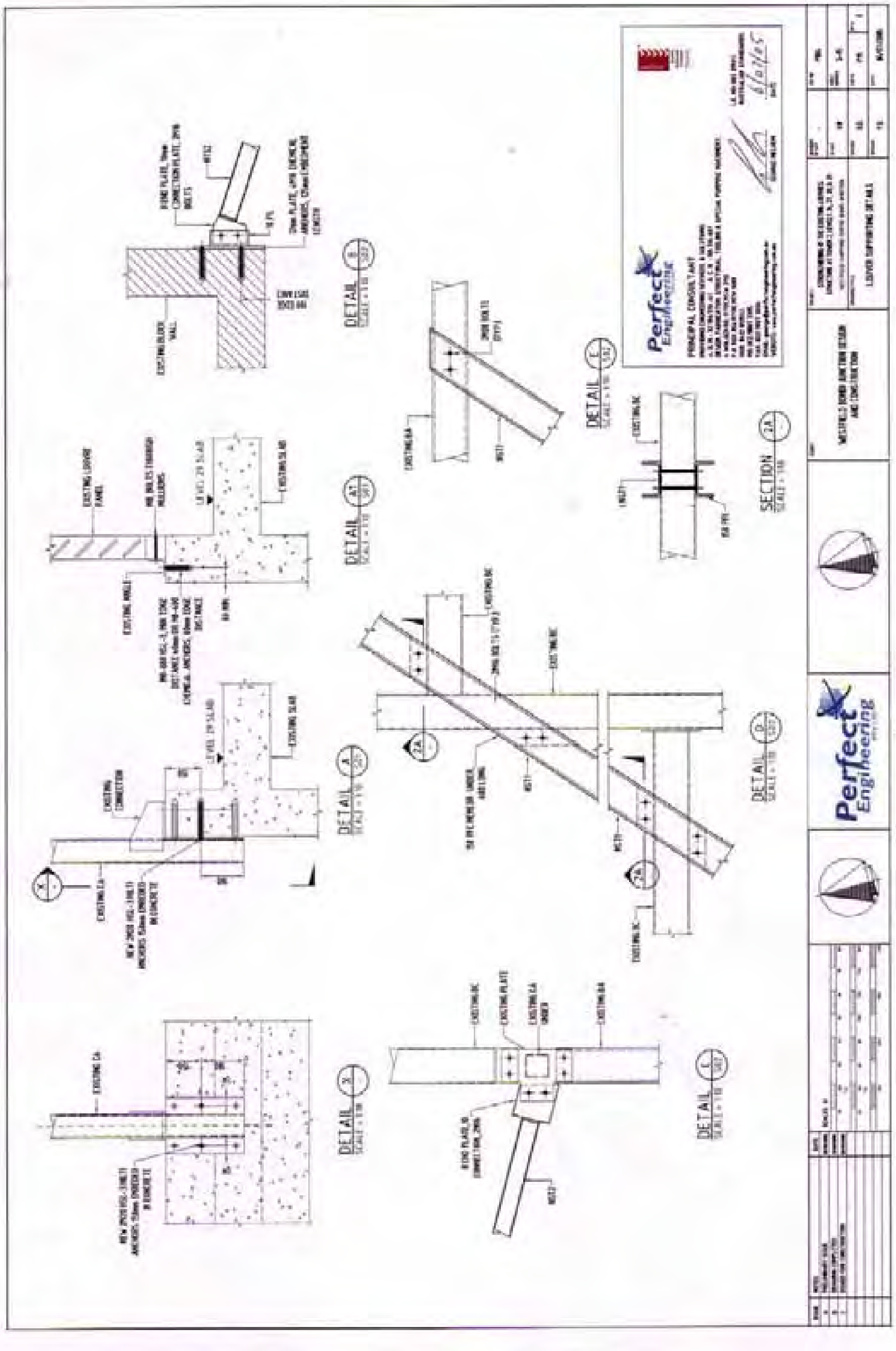
Perfect Engineering Pty. Ltd. workshop drawings for fabrication and site installation.

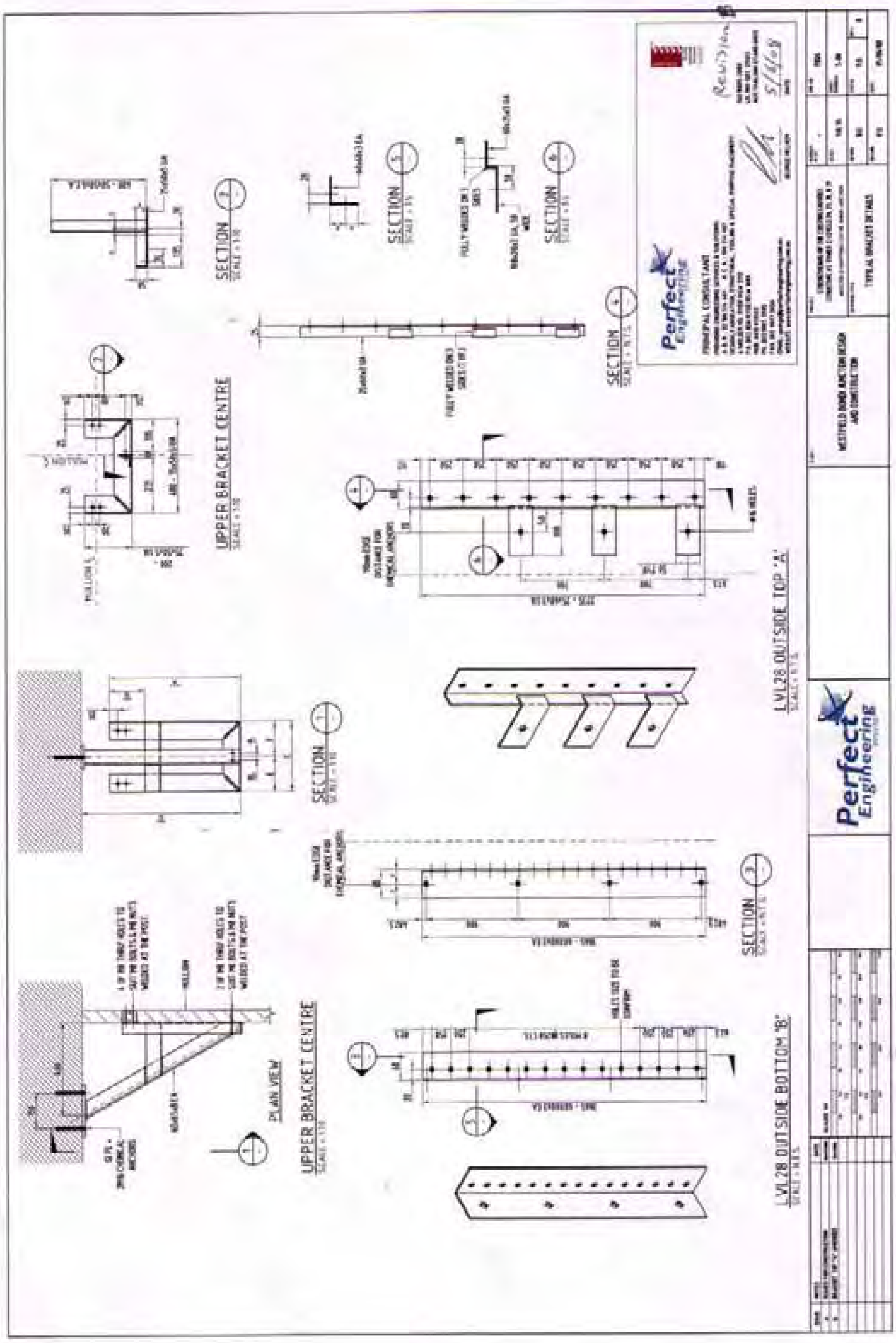

LEVEL 28 LOUVRE SUPPORTING MARKUP PLAN
SECTION
PRINCIPAL CONSULTANT
Perfect Engineering
3500 TYP. (APPROX)
NOTE:
ALL DIMENSIONS ARE INDICATIVE, SHOULD BE CONFIRMED PRIOR TO CONSTRUCTION


LEGEND
LEVEL 29 PART STEEL FRAMING PLAN
BRACKET BR1
BRACKET BR2
BRACKET BR3
Perfect Engineering


NORTH ELEVATION
SOUTH ELEVATION
Perfect Engineering

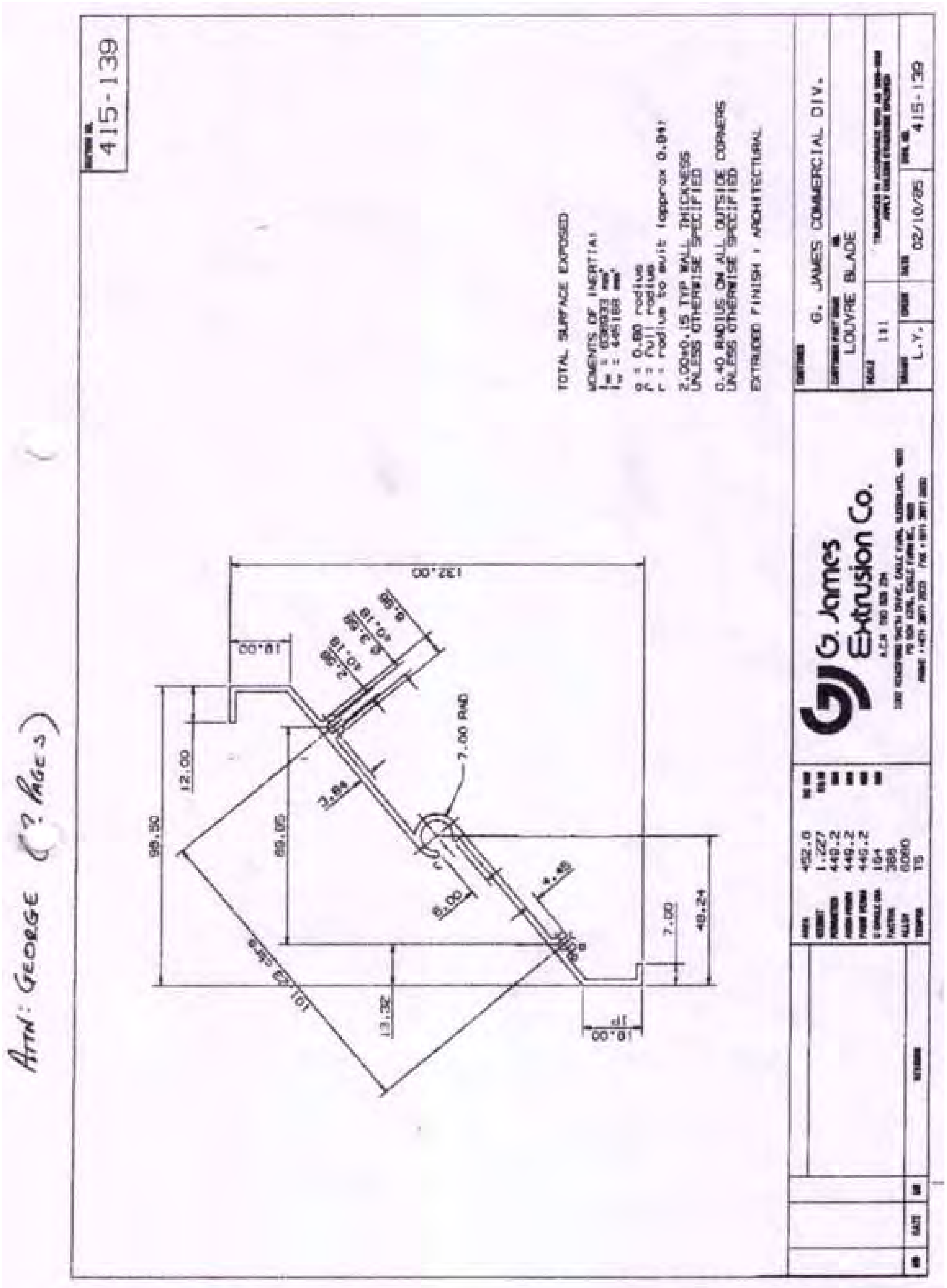

WEST ELEVATION
EAST ELEVATION
Perfect Engineering

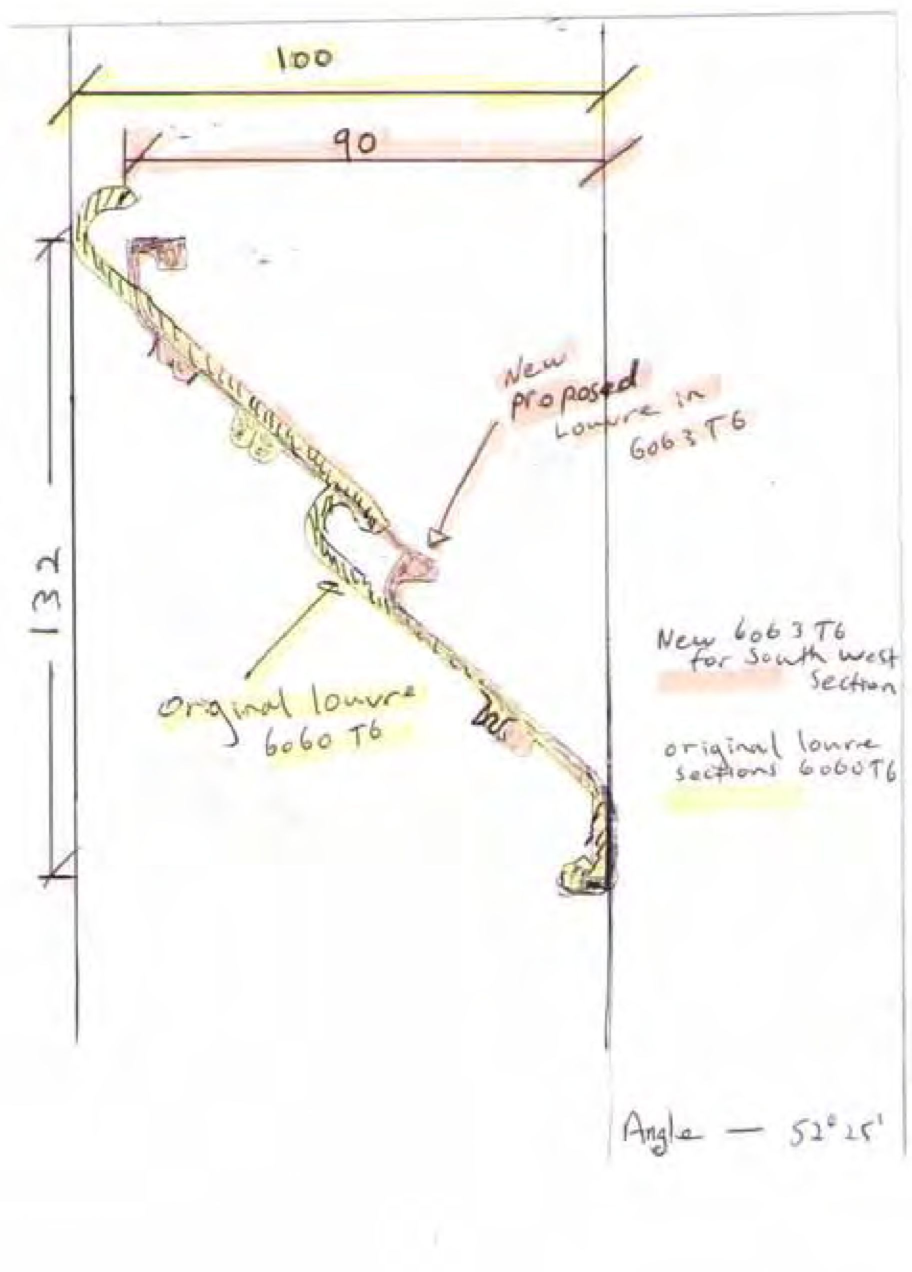

Perfect Engineering
DETAIL
DETAIL
DETAIL
DETAIL
DETAIL
DETAIL
SECTION


UPPER BRACKET CENTRE
PLAN VIEW
SECTION
UPPER BRACKET CENTRE
SECTION
SECTION
SECTION
SECTION
LVL28 OUTSIDE BOTTOM 'B'
LVL28 OUTSIDE TOP 'A'
Perfect Engineering
Perfect Engineering

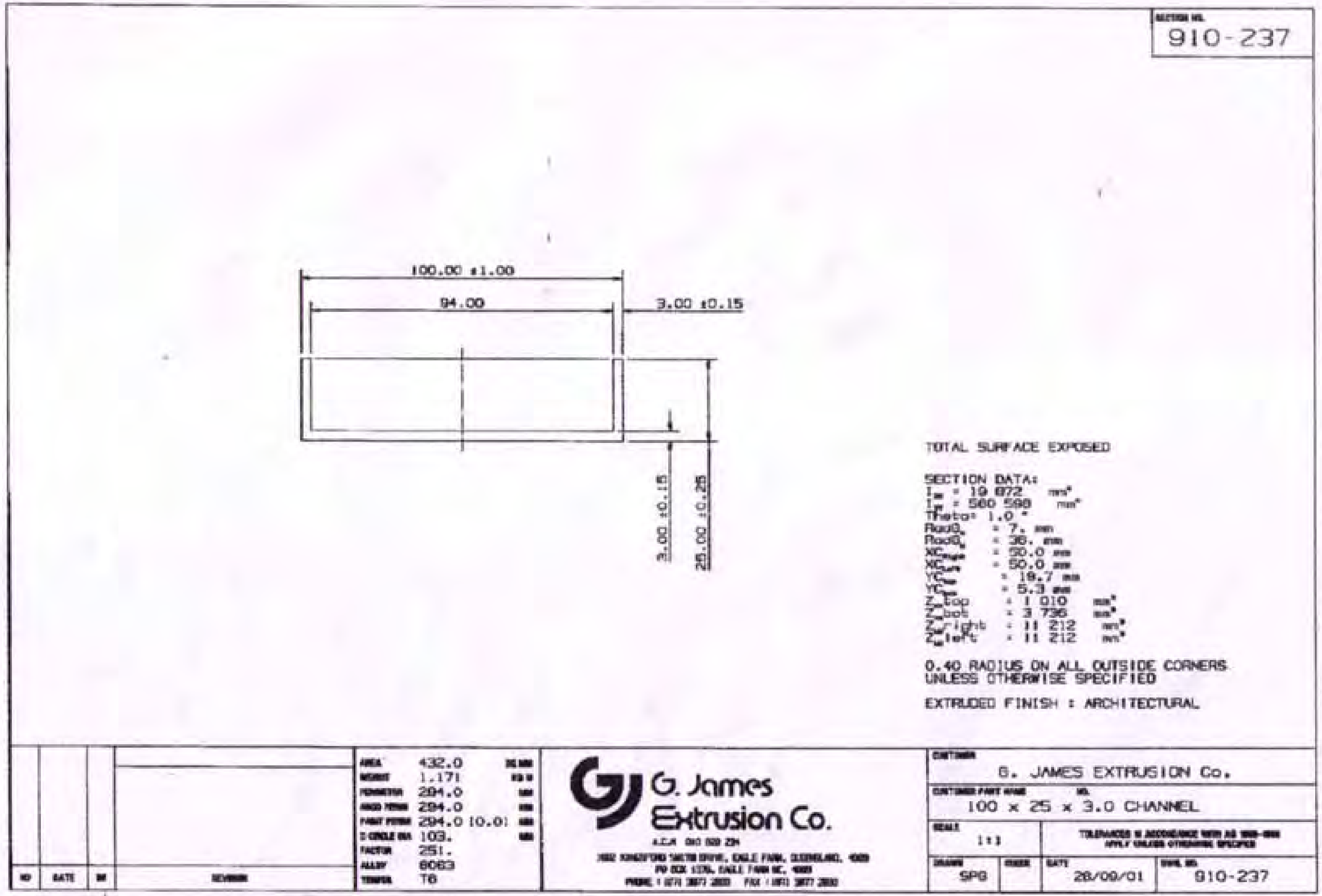
Appendix I

Profile dimensions of old and new louvres.


ATTN: GEORGE (? PAGES)
415-139
7.00 RAD
TOTAL SURFACE EXPOSED
MOMENTS OF INERTIA:
0.80 radius
full radius
radius to suit (approx 0.8)
2.00±0.15 TYP WALL THICKNESS UNLESS OTHERWISE SPECIFIED
0.40 RADIUS ON ALL OUTSIDE CORNERS UNLESS OTHERWISE SPECIFIED
EXTRUDED FINISH : ARCHITECTURAL
G. James Extrusion Co.
G. JAMES COMMERCIAL DIV.
LOUVRE BLADE
1:1
L.Y.
415-139

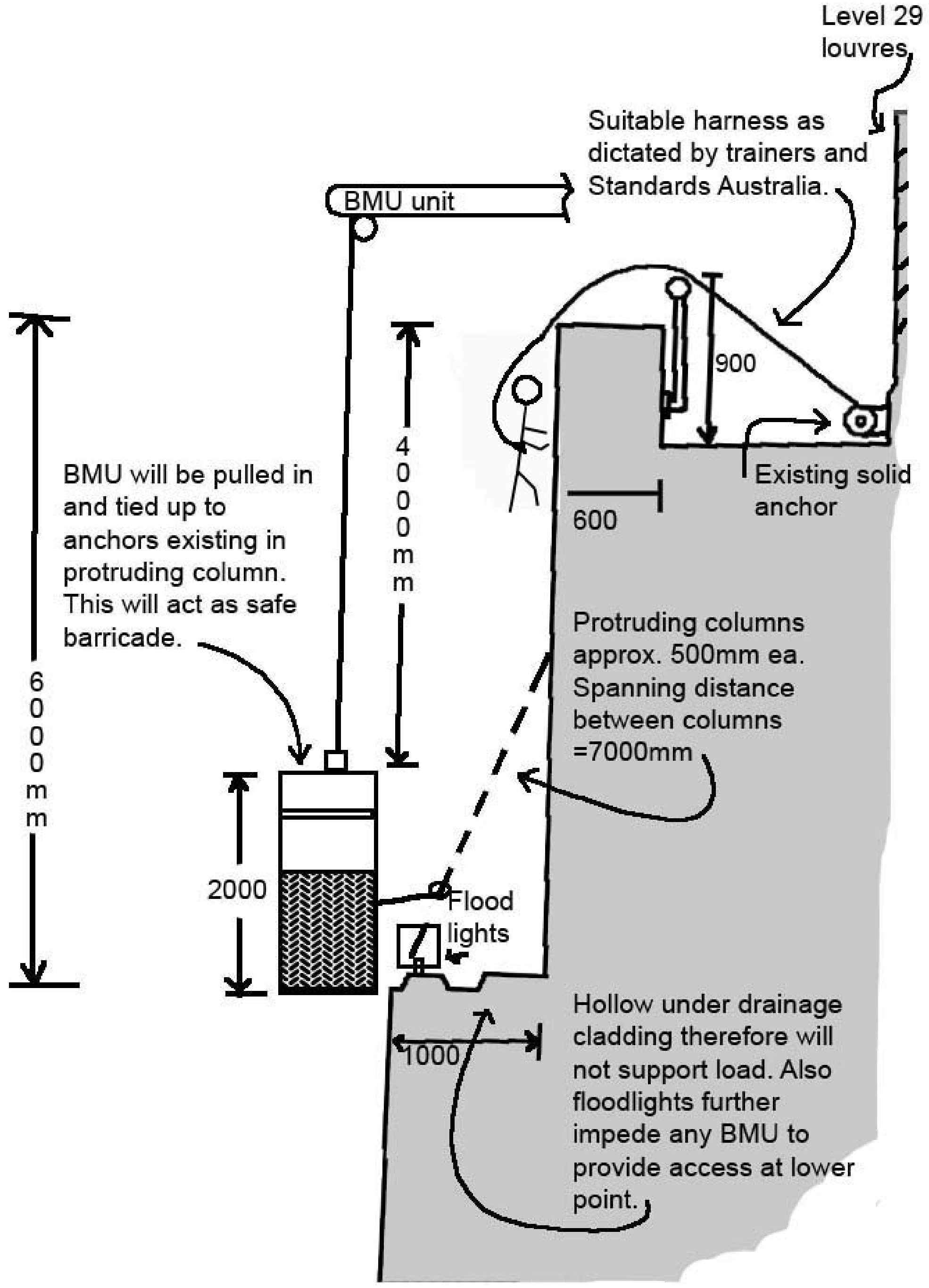


100
90
132
New
proposed
Louvre in
6063 T6
original louvre
6060 T6
New 6063 T6
for South west
Section
original louvre
sections 6060T6
Angle — 52° 25'

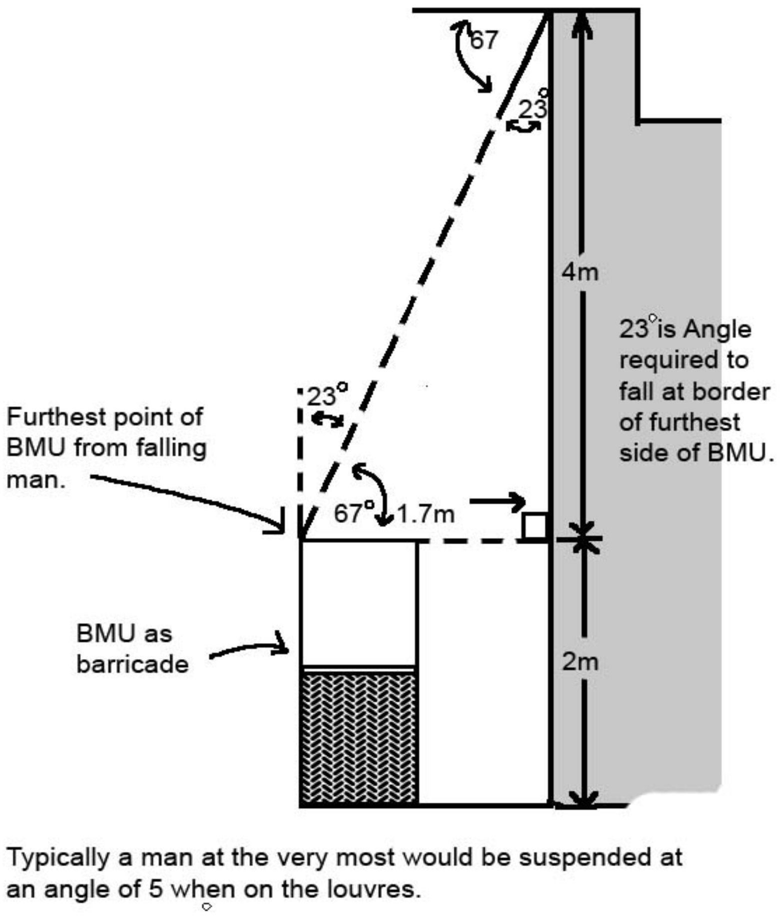

910-237
100.00 ±1.00
94.00
3.00 ±0.15
3.00 ±0.15
25.00 ±0.25
TOTAL SURFACE EXPOSED
SECTION DATA:
Theta: 1.0 °
0.40 RADIUS ON ALL OUTSIDE CORNERS UNLESS OTHERWISE SPECIFIED
EXTRUDED FINISH : ARCHITECTURAL
432.0
1.171
294.0
294.0
294.0 10.01
103.
251.
6063
T6
G. James Extrusion Co.
G. JAMES EXTRUSION Co.
100 x 25 x 3.0 CHANNEL
1:1
SPG
28/09/01
910-237

Appendix J

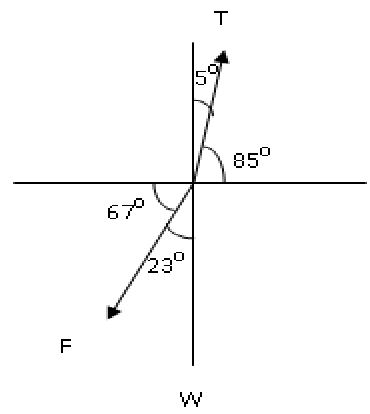
Calculations for abseilers to hang over façade safely and examples of safe work method statements (SWMSs).



Schematic illustration of abseiler and BMU with respect to building facade.



Proposed maximum angle of abseiler suspended.



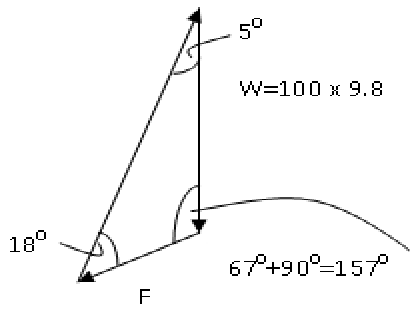
Free body diagram showing;

W = weight of suspended man,
T = Tension in harness from top.
F = Force required to be exerted on abseiler to deliver him at border of BMU, assuming his weight = 100kg

Force required to pull abseiler to outer border of BMU is;

$$\frac{F}{\sin 5^0} = \frac{980}{\sin 18}$$

F = 276.4N

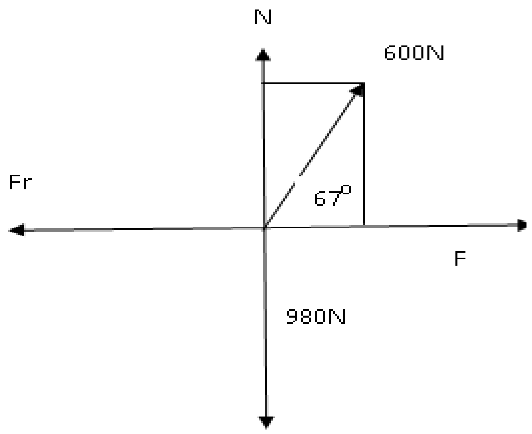


Force required to pull abseiler to outer border of BMU is;

$$\frac{F}{\sin 5^0} = \frac{980}{\sin 18}$$

F = 276.4N

Assume; Rope / harness which t
the border of the BMU has a ten
approx. 100kg, then the coefficient of friction between his shoes and the BMU floor would be;



N = 980 – 600 sin 67^0 = 979N
F = F r= 600 cos 67^0 = 234.4N

$$\mu = \frac{Fr}{N} = \frac{234.4}{979}$$

=0.23

Worst case scenario; If both straps fail (very unlikely), then the probability of the abseiler falling over and past the BMU are remote. A Force of 276.4N is required to pull him over this edge. Thus, abseiling in this instance would be a safe method to work on louvre facade.

Perfect Eng...eering Safe Work Method State ent Form SAF 002

Roof level 29.

SWMS No. SWMS 006 | **Project:** Westfield Louvre Refurbishment - Bondi Junction

Work Task or Process Covered: Fixing aluminium strips to louvres on building roof – outside but away from the building edge – level 29

Risk Assessment Overview Item Reference No. 001/ 006 | **Rev No. and date:** Rev A 05/04/05 | **Revision Comment:**

Principal Contractor: Perfect Engineering Pty Ltd. | **Licence Number:** ISO 9001-2000 QEC 21503

Sub-Contractor if applicable: N/A | **Licence Number:** N/A

SWMS Prepared by: Mr. John Louth / George Melhem | **Signature:**

SWMS Reviewed by: (Supervisor / Proj Manager or MD) George Melhem | **Signature:**

SWMS Consultation Witness: Gagun Singh
(Name of person who has taken part in and can confirm the consultation process) | **Signature:**

Issued to and accepted during induction: George Melhem / Gagun Singh | **Signature:**

Each Hazard is ranked according to the following table: P=Probability, C = Consequence, R = Ranking

		Probability (P)			
Consequence (C)		Very Likely (A)	Likely (B)	Unlikely (C)	Very Unlikely (D)
Kill or cause permanent disability or ill health	(1)	1	1	2	3
Long term illness or serious injury	(2)	1	2	3	4
Medical attention and several days off work	(3)	2	3	4	5
First aid needed	(4)	3	4	5	6

PPE Requirements .... Safety footwear, Safety Eyewear, Safety Gloves

Ref	Job Step / Activity	Identified Hazard & Harm Potential	P	C	R	Control
006/01	Working on mobile scaffold on building roof	• Proximity to edge of building means that any instability of scaffold could cause tipping of workers off the scaffold and a worse case scenario may be that the worker is tipped over the building edge thereby causing death	C	1	2	• Examine the mobile scaffold for defects before use and do not use if there is any doubt about its strength and reliability • The mobile scaffold castors must be locked when scaffold in use • Safe access must be provided • The scaffold height must be less than 3 times its least base dimension • Additional security to be provided by tying the scaffold inner edge down between two BMU anchor points which are located at intervals along on the concrete base of the louvre panels

Ref	Job Step / Activity	Identified Hazard & Harm Potential	P	C	R	Control
006/02	Working on ladders on building roof	• Falling from heights when using ladders and step ladders can cause serious injury or death and as a worse case a worker could fall backwards over the building edge thereby causing	C	1	2	• Ladders must never leaned in a direction towards the edge of the building • Ladder must not be leaned directly against any structure until such structure is checked and found strong enough to take the load • Use the correct ladder for the job. • Use only industrial ladders – do not use domestic ladders. • Examine ladders for defects and damage before use. • Ladders should be adequately supported at the base. • Set the ladder at a slope of 4 in 1 – ladders must be angled one out and four up. • Ladders should extend at least one metre above the access level • Ladders should be firmly secured or tied off or held firmly by another person. • The ties should be attached to the stiles of the ladder and not the rungs. • A ladder should not be walked by the person standing on the ladder. • One person on a ladder at a time with three body limbs on the ladder at all times • Use a static line and harness if carrying out work that requires letting go of the ladder at any time. • Do not climb higher than the third rung from the top of the ladder • Only work on a job within easy arm's reach from the ladder. • Ladders (other than trestle ladders) should not be used to support planks as a work platform. • Metal ladders or wire reinforced ladders must not be used where electrical hazards exist. • Climb and descend facing the ladder maintaining three points of contact with the hands gripping the stiles or each rung. • Do not carry anything in your hands when climbing or descending. • Do not place ladders in vehicle or pedestrian traffic areas. • Long and heavy ladders (greater than 20kg) should be handled by at least two people. • Stepladders should only be used in the fully open position • Wear slip resistant footwear when using ladders. • Clean off footwear and ladder rungs before using the ladder. • A helper at ground level is to hold cladding sheet secure while person at height drills (this ensures the driller does not need to use the spare hand for anything but holding the ladder) • Fit drill bit or change drill bit at ground level

Ref	Job Step / Activity	Identified Hazard & Harm Potential	P	C	R	Control
006/03	Working below another worker who is standing on the mobile scaffold or ladder	• The height of work being carried out at this location is relatively low, and the risk of losing a hard hat over the building edge is considered to be a higher risk than wearing one for protection.	D	4	6	• Exercise caution and do not operate directly below a person on the ladder or mobile scaffold • If a hard hat is chosen for a particular danger then make sure it is gorn with a chin strap
006/04	Generally working with tools and materials on the roof	• Risk of losing an object over the building edge and causing serious injury to the public below	C	1	2	• Never approach the building edge with objects unless they are attached to a secure lanyard • Never carry objects on the roof in windy conditions • Always ensure clothing is secure and wear hats with chin straps if necessary • Never leave loose objects unattended or untied in case a sudden wind causes them to be lifted over the edge • Always clear or secure objects away for the roof area before leaving
006/005	General use of power leads	• Risk of electric shock • Risk of tripping and falling • Risk if fire if lead energised while coiled • Risk of burning and shock if lead is plugged or unplugged while electrical current is flowing	C	1	2	• Always check that lead has a current inspection tag • Never use electrical equipment outside in wet weather • Ensure the electrical supply is fitted earth leakage protection • Visually inspect the lead and make sure there is no damage to cover or plug ends • Always use a restraining device to ensure the lead end and power tool plug cannot be disengaged • Run the lead supported off the ground and above head height in walk areas or use a non-trip protection cover • Never use a power lead unless the whole lead is uncoiled • Always switch off the supply before plugging or unplugging
006/005	Using a hand held power drill	• Risk of shock from faulty tool • Risk of eye injury from flying swarf, chuck keys or broken drill bits • Risk of cuts from contact with drill bit • Risk of cuts and bruising from work piece spinning with bit • Risk of losing balance and falling when drill bit breaks through • Risk of shock or other danger from unintentional contact of drill bit with electrical wiring, gas pipes or critical components	D	1	3	• Always check that the power tool has a current inspection tag • Visually inspect and make sure there is no damage to the tool casing • Always wear eye protection when drilling • Ensure chuck key is removed before drilling • Reduce risk of broken drill bits by maintaining steady pressure and direction • Keep hands away from the drill bit, (two hands on the tool) • Ensure work piece is held firm and get assistance to hold the job if no other means are available • Reduce pressure toward the end of the operation and be prepared for sudden reduction in resistance as the bit break through • Ideally place a sacrificial block behind the exit point so that the drill bit enters this at the end of the operation (not always possible) • Always check drill bit will not damage concealed wiring, gas pipes or other critical components

Ref	Job Step / Activity	Identified Hazard & Harm Potential	P	C	R	Control
006/006	Using a hydraulic pop rivet gun	• Risk of eye injury from flying rivet heads • Risk of limb injury through accidental actuation • Risk of release of hydraulic or mechanical energy causing trapping or bruising	C	2	3	• Always wear safety eye protection when using the equipment • Always ensure the equipment is firmly in place and the rivet placed in the hole before actuating • Never point the rivet gun in any direction except to the floor or at the job face • Observe the manufacturers loading and operating instructions specific for this equipment
006/007	Working outdoors	• Risk of sun exposure, sunburn and skin cancer	B	2	2	• Always wear 30+ sunscreen and suitable clothing when working in the sun

Perfect En[illegible]eering Safe Work Method Stat[illegible]ent Form SAF 002

SWMS No. SWMS 010	**Project:** Westfield Louvre Refurbishment Project – Bondi Junction
Work Task or Process Covered: Replace Steel Channels and bolts on Louvre Structures – All levels excluding building face work	
Risk Assessment Item Reference No. 001/007 — **Rev No. and date:** Rev A 19/04/05	**Revision Comment:**
Principal Contractor: Perfect Engineering	**Licence Number:**
Sub-Contractor if applicable:	**Licence Number:**
SWMS Prepared by: J Louth	**Signature:**
SWMS Reviewed by: (Supervisor / Proj Manager or MD)	**Signature:**
SWMS Consultation Witness: Contribution by John Portelli **(Name of person who has taken part in and can confirm the consultation process)**	**Signature:**
Issued to and accepted during induction: See list on reverse side for additional names	**Signature:**

Sample only

Each Hazard is ranked according to the following table: P=Probability, C = Consequence, R = Ranking

		Probability (P)			
Consequence (C)		Very Likely (A)	Likely (B)	Unlikely (C)	Very Unlikely (D)
Kill or cause permanent disability or ill health	(1)	1	1	2	3
Long term illness or serious injury	(2)	1	2	3	4
Medical attention and several days off work	(3)	2	3	4	5
First aid needed	(4)	3	4	5	6

PPE required: Eye Protection, Safety Gloves, Safety boots

Note: While use of semi skilled labour is acceptable to carry our some of the general duties included in the following SWMS, it is essential that those laboursare supervised by qualified trades peoples and that arc and gas welding equipment be operated **only** by persons with boiler making or welding trade certificates

Ref	Job Step / Activity	Identified Hazard & Harm Potential	P	C	R	Control
010/01	Prepare area, clear area if possible from obstructions and bring all necessary equipment for task	• There are motors, pipes, brackets in areas in some areas where work is to be performed • Risk of tripping and falling injuries	B	3	3	• Make an inspection prior to commencing work and make sure all bolts are properly labeled • Wear safety gloves and boots
010/2	Dismantle channels one at a time - clear and clean rusted cleats and treat with anti-rust agent	• Risk of objects falling on top of workers • Risk of eye damage to workers • Risk of falling from heights	C C C	3 2 1	4 3 2	• Provide bracing if required • Provide block and tackle to lift and dismantle channel • Wear eye and hand protection • Observe working at heights precautions contained in the latest revision of **SWMS 006**

Ref	Job Step / Activity	Identified Hazard & Harm Potential	P	C	R	Control
010/03	Provide and secure louvers Replace all rusted bolts and nuts as per engineer approval	• Risk of louvers falling off building • Risk of bolts falling into machinery • Risk of hitting eye	B C C	1 2 2	1 3 3	• Brace louvers when unsupported, using engineers approved method • Wear gloves and Safety glasses or goggles
010/04	Replace and secure louvers to engineering approval by way of bolts, U-bolts etc.	• Risk of injury from use of drill • Using the wrong equipment can cause injury or damage to materials • Risk of loosing bolt off the building				• Use power drill correctly **(See SWMS 006)** • Make sure at all times there is a static line or scaffold when working on roof outside (See SWMS 006) • Use of correct tools for the job • Never approach edge of building with tools or equipment unless they are secured by lanyards • Provide a catch net or screen if materials are too small to be secured by any other means or where there is a risk of materials being propelled beyond the edge
010/05	Replace post with new galvanized post Provide bracing and welding etc cleat per engineering approval	• Risk of structure collapsing as due to current work or because of existing weakness • Risks associated with arc and gas welding equipment (see following item 010/7 onwards	C B	1 2	2 2	• Harness should be used when working at heights outside at all times • **See precautions following (ref 010/07 onwards)**
010/06	Clean all rust dust and old rust bolts and sweep all rubbish produced by contractor	• Rust could get into workers eyes and get into ventilation ducts • Fumes from paint can cause respiratory problems	B B	2 2	2 2	• Wear eye protection at all times • Wear appropriate dust masks • Use brooms carefully or use vacuum cleaner if necessary to reduce dust.

Ref	Job Step / Activity	Identified Hazard & Harm Potential	P	C	R	Control
010/07	General use of any gas cylinder	• Risk of explosion due to faulty cylinder • Risk of injury due to falling weight or explosive release of energy • Risk of eye injury from released gas projected debris • Risk of pulmonary embolism from gas infusion at skin surface • Risk of injury from incorrectly controlled gas pressure	C C B D C	1 1 2 1 3	2 2 2 3 4	• Ensure the gas cylinder is stamped with a current inspection and test date and visually assess that it is not obviously damaged • Always ensure gas cylinders are restrained in a cradle or chained in position to prevent falling when being stored, transported or used. (A damaged cylinder neck will result in explosion and the cylinder becoming a projectile) • Always direct the nozzle of any gas under pressure, away from eyes, and wear safety eye protection • Never allow gas under pressure to be released directly on the skin's surface (this can cause a gas bubble to be forced into the bloodstream and cause death from embolism) • Always ensure the appropriately rated gas pressure regulating device is fitted and adjusted to the recommended working pressure • Never jam valve
001/08	Special risks associated with oxygen cylinders	• Risk of oxygen/lubricant explosion (when grease or oil is exposed to pure oxygen)	C	1	2	• Never use a lubricant or any other substance on the threads of cylinder valves, regulators or other devices connected to oxygen
001/09	Special risks associated with acetylene cylinders	• Risk of injury due to loss of gas control as a result of liquid acetelyne entering valve mechanism.	C	1	2	• Always keep acetylene cylinders in the vertical upright position
010/10	The gas welding or cutting process	• Risk eye damage due to UV radiation • Risk of Burns • Risk of igniting surrounding materials	B B B	2 3 2	2 3 2	• Always ensure there are no combustible materials within the weld vicinity • Protect any immovable combustibles from the sparks using fire blanket • Do not weld or cut in the vicinity of flammable liquids in any circumstances
001/11	The arcing process	• Risk eye damage due to UV radiation • Risk of Burns • Risk of electric shock due to arcing voltage • Risk of sparks igniting surrounding materials	B B B B	2 2 2 2	2 2 2 2	• Always wear approved welding eye protection, goggles or mask • Always wear spark and burn protection, gloves, apron, spats, safety footwear • Always erect screens to protect passers by, or have anyone in the vicinity wear welding goggles or look away • Never make bodily contact with the electrode or workpiece during the welding operation in case the earth clamp becomes disconnected and your body provides a return path for the current • Always ensure a fire extinguisher is close at hand • Always ensure there are no combustible materials within the weld vicinity • Protect any immovable combustibles from the sparks using fire blanket • Do not weld in the vicinity of flammable liquids in any circumstances

Appendix K

Louvre and mullion certificate for 6351 T6 and louvre profile for 6063 T6 aluminium alloys.

G James Extrusion Co Pty Ltd

PO Box 13176
Eagle Farm BC
Brisbane, Queensland
AUSTRALIA 4009

New Channel - C - Channel Extruded
100 x 25 x 3 (Mullion)

CERTIFICATE OF CONFORMANCE

CUSTOMER:	Sydney – GEORGE MELHEM PERFECT ENGINEERING				
ORDER NO:	133634				
SECTION NO:	910237				
ALLOY & TEMPER:	6351 T6				
LENGTH:	3.600 m				
CARD NO.	LABEL NUMBER	PCS	CARD NO.	LABEL NUMBER	PCS
72072310	4466381	31 PCS			

This product complied to the specification as detailed above.

Quality Manager

12/04/05
Date

QA/T&Mconfcontr

G James Extrusion Co Pty Ltd

PO Box 13176
Eagle Farm BC
Brisbane, Queensland
AUSTRALIA 4009

New Louvre panels - Extruded 2mm

CERTIFICATE OF CONFORMANCE

CUSTOMER:	Sydney – GEORGE MELHEM PERFECT ENGINEERING				
ORDER NO:	133634				
SECTION NO:	415139				
ALLOY & TEMPER:	6063 T6				
LENGTH:	5.500 m				
CARD NO.	LABEL NUMBER	PCS	CARD NO.	LABEL NUMBER	PCS
72072210	4465658	42 PCS			

This product complied to the specification as detailed above.

Quality Manager

12/04/05
Date

QS/18/confconr

Appendix L

Typical powder coating specifications and certificate, cold galvanising data and *Emerbond*/*Emerclad* coating.

AEROCAN PRODUCTS AUSTRALIA
5/21 Power St
St Marys N.S.W. 2760A
ABN 411 072 828 24
PHONE: 02 9673 4488

PRODUCT INFORMATION SHEET

COLD GAL (AEROSOL)

Description:

A one pack zinc rich primer giving protection based on an extremely durable epoxy resin and sacrificial zinc pigment.

Uses: For long term protection of steel surfaces against rust and corrosion. Can be used in the most severe cases of corrosion inducting conditions. Designed for exterior use such as on roofs, handrails, balustrading, gates and wrought iron. Also used for touchup of galvanized and zinc-alum surfaces and touchup after welding.

Properties:
- May be used as a primer and finish coat in one
- May be topcoated if desired
- Matt grey finish
- Aerosol spray
- Zinc Purity 98.5%

Surface Preparation: Surfaces should be free of rust, scale and dirt. Remove rust by grinding, sanding or wire brushing. Treat any remaining rust with Rust Remover. Clean surface with a solvent degreaser.

Application: Apply directly to bare metal. Do not apply over rust converter or any other coating. Apply 2-4 coats to achieve minimu dry-film builds of 785 micrometres when used as a sole coating and 25 micrometres when a topcoat is to be apllied.

Generally topcoating is not required. If colour is required use a topcoat of Quick Dry Enamel.

Drying time:	Touch Dry at 30 minutes
Clean Up:	Mineral Turps
Storage:	Store in a cool dry place.
Safety:	See material safety data sheet

The information contained in this bulletin is presented in good faith based on thorough laboratory and field testing but without warranty. As we have no control over the conditions under which these products are used, it is recommended that all products be tested by the end user to ensure the suitability of the particular application and conditions.

AEROCAN PRODUCTS AUSTRALIA

MATERIAL SAFETY DATA SHEET

1. Identification of Material and Supplier

Product Name	**Cold Gal**		
Other Names	*UN 1950 Class 2.1 Aerosol*		
Recommended Use	A zinc rich primer for steel.		
Supplier Name	**Aerocan Products Australia**	**ABN 411 072 828 24**	
Address	**21 Power Street, St Mary's, NSW 2760, Australia**		
Web Address			
Telephone	**02 9673 4488**	**Facsimile**	**02 9673 4220**
Emergency Telephone	**02 9673 4488**	**Technical Support**	**02 9673 4488**

2. Hazards Identification

Hazard Classification This product is hazardous according to the criteria of the NOHSC. Listed as a Schedule 5 Poison according to the SUSDP. Listed on the AICS. Classed as UN 1950 Aerosol Class 2.1 according to the ADG Code.

Risk Phrases Xn R 20 Harmful by inhalation, R 36/37/38 Irritating to the eyes, respiratory system and the skin, S 48 Risk of serious damage to health by prolonged exposure R 66 Repeated exposures may cause skin dryness and cracking, R 67 Vapours may cause drowsiness and dizziness.

Safety Phrases S 2 Keep out of the reach of children, S14 Keep away from oxidisers, S 23 Do not breathe vapours, S 24/25 Avoid contact with the skin or eyes, S 26 In case of contact with eyes, rinse immediately with plenty of water and seek medical advice, S 28 After contact with skin, wash immediately with plenty of soap-suds, S 33 Take precautionary measures against static discharges, S 35 This material and its container must be disposed of in a safe way. S 61 Avoid release to the environment.

3. Composition/Information on Ingredients

Chemical Identity	Proportion	CAS No
Zinc Powder	> 60 %	7440-66-6
Xylene	10 - 30 %	1330-20-7
Dimethyl Ether	10 - 30 %	115-10-6
Aromatic Petroleum Solvent 100	< 10 %	64747-95-6
	< 10 %	
Ingredients determined to be non-hazardous or below cut-off concentrations	to 100 %	n.d.

9. Physical and Chemical Properties

Appearance:	Grey liquid droplets and aerosols	**Odour:**	Typical hydrocarbon solvent
Freezing/Melting Point:	– 141.5° (Dimethylether)	**Boiling Point:**	– 24.8 °C (Dimethylether)
Density:	1.8 - 1.9	**Vapour Pressure:**	4450 mm Hg (Dimethylether)
Solubility in water :	Insoluble	**Volatiles Percent**	> 60 %
Flash Point:	–41°C (Dimethylether)	**Flammability Limits:**	3.45 to 26.70 % vol/air (Dimethylether)
Auto Ignition Point:	350°C (Dimethylether)		
Other Properties:	Incompatible with oxidising substances.		

10. Stability and Reactivity

Under normal circumstances of use this product is stable. Keep away from oxidisers.

11. Toxicological Information

No product relevant data.

12. Ecological Consideration

Potential to bioaccumulate or biomagnify is low. Solvents in this product are biodegradable with half lives of 2 to 7 days in aerobic systems. Is slower in anaerobic systems. Not persistent.

13. Disposal Considerations

Disposal must be in accordance with local regulations for hazardous industrial wastes (Aerosol or paint related waste)

14. Transport Information

Transport as UN No 1950 Aerosol Class 2.1 in accordance with the ADG Code & Regulations the IMDG Code or the IATA DG Regulations as appropriate to mode of transport.

Appropriate EPG 2 D 1 or Guide 49 SAA/SNZ HB [illegible]

15. Regulatory Information

Label as a Schedule 5 Poison in accordance with the SUSDP: the word "WARNING" on the first line of the label in bold sans serif capital letters not less than 5mm tall. On the second line immediately below the word "warning" the phrase "KEEP OUT OF REACH OF CHILDREN" in bold san serif capitals not less than 2.5 mm tall. Under the trade name the phrase "Contains Liquid Hydrocarbons 10 % - 30 %" must appear. Label in accordance with the "National Code of Practice for the Labelling of Workplace Substances" [NOHSC: 2012(1994)] with the Risk and Safety Phrases displayed on page 1 of this MSDS. Label as a Dangerous Goods substance in accordance with the ADG Code with Class 2.1 Diamond, UN 1950 and the shipping name: Aerosols.

16. Other Information

Date Prepared/Amended: 21/09/2005 [illegible] of Material Safety Data Sheets 2nd Edition [illegible] Sheets 2nd Edition NOHSC: 2011 (2003)

Data Sources used: in the preparation of this MSDS include: "*Chempendium*" and "*Cheminfo*" published in CD format by CCOHS Canada 2003 - 4."*TOMES*" a CD database published by Micromedex, USA, "*Hazardous Properties of Industrial Materials*" Van Nostrand Rheinhold NY, USA . "*List of Designated Hazardous Substances*" NOHSC 10005:1999, "*National Exposure Standards*" NOHSC 1003:1995 . **Abbreviations used:** n.d = not determined, n.a = not applicable, n.all =not allocated, n.est = not established, SUSDP = Standard for the Uniform Scheduling of Drugs and Poisons, ADG = Australian Dangerous Goods (Code), IATA = International Air Transport Association, (Dangerous Goods Regulations), IMDG = International Maritime Dangerous Goods (Code)

Disclaimer

No representative of Aerocan Products Australia or any other person has authority to add to, or alter in any way, any MSDS or the information supplied thereon. Any alterations render this MSDS invalid. The information contained herein is believed by Aerocan Products Australia and SSC Pty Ltd to be accurate at the issue date shown and in accordance with information available to us. Persons dealing with the products referred to in this MSDS do so at their own risk since their actions are beyond our control. Aerocan Products Australia and SSC Pty Ltd accepts no liability whatsoever for damage or injury arising from the use of the information contained in this document

7. The Applicator agrees that:

   7.1 The Applicator has no authority to make any representations or statements in relation to the Products on Dulux's behalf.

   7.2 The Applicator will not give any warranty, condition or guarantee or make representation to the owner of the Building ("Building Owner") other than to give the same warranties as are set out in this Performance Warranty

   7.3 The Applicator shall indemnify Dulux against all claims, costs, damages and losses, whether direct or consequential, as a result of a breach by the Applicator of clauses 7.1 and/or 7.2 .

8 All notices given under or pursuant to this agreement shall be in writing and sent by registered mail, postage paid, return receipt requested to:

Marketing Manager
Dulux Coatings
51 Winterton Road, Clayton, Victoria, 3168
Australia

9 The law of Australia is the governing law of this Performance Warranty and the Conditions of Sale in Schedule B.

Schedule A

Name of Applicator	AAF – Davis Road NSW
Registration Number	2503
Project Name	Westfield Shopping Centre Bondi
Project Location ("the Building")	Oxford Street, BONDI JUNCTION NSW
Stage of project completed	Louvers – Level 26,27,28,29
Architect / Specifier	Perfect Engineering Pty Ltd
Builder	Perfect Engineering Pty Ltd
Fabricator	Perfect Engineering Pty Ltd
Powder Name	Duratec® – Chalk USA (Duratec® is a registered trademark of Orica Australia Pty Ltd)
Powder Code	900 – 73713
Batch number	E/E 48057

Signed .... (Applicator)
Date 30/6/05

Signed .... (Dulux)
Date 24/06/2005

Dulux

DURATEC® PERFORMANCE WARRANTY

Orica Australia Pty. Ltd., A.C.N. 004 117 828, A.B.N. 99 004 117 828, trading as Dulux Powder Coatings, 51 Winterton Road, Clayton, Victoria, 3168 Australia ("Dulux") being the manufacturer or distributor of the Duratec® products listed in Schedule A ("the Product"), warrants to the Applicator listed in Schedule A ("the Applicator"), subject to the provisions set out below, that the Products will perform in the manner and for the times set out below when properly applied to chemically cleaned and pretreated aluminium of a type suitable for exterior use ("Metal")

PERFORMANCE WARRANTY PROVISIONS

1. Subject to the provisions of any law (statute or otherwise) rendering any exclusion or limitation of liability in this Performance Warranty unlawful and of no effect and to any conditions, warranties, guarantees or rights which are mandatorily implied into the sale of goods or provision of services, the only condition, warranty, guarantee or right given by Dulux in relation to the Product is as set out in this Performance Warranty. The Applicator agrees that this Performance Warranty replaces condition 2 of Dulux's Standard Conditions of Sale (attached in Schedule B). Otherwise, the Standard Conditions of Sale are to be read together with this Performance Warranty. This Performance Warranty shall prevail in the case of any inconsistency between the provisions of this Performance Warranty and the provisions of Dulux's Standard Conditions of Sale. This Performance Warranty shall be null and void to the extent that there is non-compliance with any of its terms.

2. Dulux warrants that the product when applied to the metal and baked in accordance with this Performance Warranty and the Applicator's Manual, will not, under normal atmospheric conditions:

   2.1 Peel, crack or flake for a period of 10 years from the date the Product is applied to the Metal.

   2.2 Chalk in excess of a numerical rating of 6 within 10 years from the date the Product is applied to the Metal when measured in accordance with the procedures specified in AS1580 method 481.1.

   2.3 Fade or change in colour so as to give delta E (Hunter) laboratory reading greater than 5 units from the original colour within 10 years from the date the Product is applied to the Metal. Colour measurements shall be made on clean surfaces free of oil, grease, dirt, chalk oxidised film or other contaminants and using the procedure described in ASTM D-2244-85.

   It is understood that chalk, fade or colour changes may not be uniform if the surfaces are not equally exposed to the sun and the elements.

3. The warranties in clause 2 are subject to the following further provisions:

   3.1 The Product must be applied to pretreated new Metal under Manufacturing conditions, coating weights of chromate conversion coating to Dulux approved specification and applied as described in the Duratec® Applicator's Manual.

   3.2 The pretreatment must meet ASTM D1730 Type B, method 5 of method 7. Processing must conform with AS3715 for coating weights of 200 - 500mg/m^2. Colour of coating light yellow or light green is a guide to effectiveness of pretreatment deposition.

   3.3 The warranties will apply only to the Building and the Product batches which Dulux has specifically and in writing designated to the Applicator as being covered by this Performance Warranty.

   3.4 This warranty shall apply only to Metal which is coated with the Products by an Applicator registered with Dulux.

   3.5 Systematic building maintenance programme meeting AAMA 610.1 1979 must be instituted to periodically at least once every 3 months clean the surface of accumulation of concentrated deposits and pollutants.

   3.6 The warranties will apply only to the Product which the Applicator applies within 12 months from the date Dulux delivers the Product to the Applicator.

3.7 The Applicator must complete all tests as detailed in the Duratec® Applicator's Manual and retain test reports and 3 pieces of production coated Metal extrusions or sheets or sections or parts coated with the Product per shift. Each sample coated with the Product must be fully representative of the beginning, middle and end of the production for the nominated building and must be identified by a Dulux batch number and a date of coating. It is incumbent on the Applicator to forward only coated Metal that meets the test methods described in AS3715/BS6496/ Duratec® Applicator's Manual.

3.8 The Applicator will maintain throughout the relevant warranty period, adequate records to provide identification of the batch number of all Products in the field and where each batch of product was applied to Metal in the building. The Applicator agrees that Dulux shall be permitted to inspect such records. In the event of a claim under this Performance Warranty, the Applicator shall provide Dulux with evidence that the Products were manufactured by Dulux and applied by the Applicator to this Metal.

4. Subject only to any overriding law (statutory or otherwise) to the contrary, Dulux shall not be liable for any representation or statement made by or on behalf of Dulux whether made prior to or after the giving of this Performance Warranty. Dulux's liability will be solely derived from the terms of this Performance Warranty.

5. In the event of a claim under this Performance Warranty:

5.1 Claims must be made to Dulux in writing by the Applicator within 30 days after the Applicator is informed of the defective coating.

5.2 Dulux must be given reasonable opportunity to inspect the coated Metal claimed to be defective.

5.3 The Applicator must send to Dulux a copy of all production and quality records describing the application of the Product, demonstrating that the production conditions and quality control checks as described in the Duratec ® Applicator's Manual were followed and the dates on which the product was applied.

5.4 The warranties shall not apply if the failure is caused by a failure resulting from abnormal external influences including but not limited to bi-metallic corrosion; mechanical abrasion; falling objects; damage during transportation, installation and storage; explosion; fire; riots; acts of war; terrorism; radiation; harmful chemicals or fumes; temperatures in excess of 110°C; water chemicals and foreign substances and excessive salt atmospheres or deposits or failure from post formed or post fabrication processes or any other circumstances beyond Dulux's reasonable control.

5.5 For a valid claim to be made under this Performance Warranty, the Applicator shall establish to Dulux's satisfaction that 5% or more of the total coated area to which the Product has been applied failed to meet the performance criteria referred to in clause 4, as a result of an error or defect in the formulation or manufacture of the Product.

6 If it is determined that the failure is covered by the warranties:

a) Orica's liability shall be limited to the actual cost of repairing, ie. replacing or recoating, the defectively coated Metal or replacing the Product at Dulux's election, which shall constitute Dulux's sole liability and the Applicator's sole remedy (whether at law or in equity or otherwise and including for negligence). In no event shall Dulux be liable for any further direct, incidental, special, or consequential damages.

b) The cost of repair or replacement shall be determined by Dulux using contractors, materials and practices selected by Dulux. Dulux will determine, at its reasonable discretion, the most appropriate materials and practices for remedying the failure.

c) Where Dulux elects to repair the defectively coated Metal, the Applicator will upon request by Dulux obtain and submit to Dulux two or more competitive bids for remedying the failures in the manner required by Dulux. Dulux reserves the right to reject such bids and may obtain additional bids itself.

d) Upon acceptance by Dulux of any such bids, Dulux may authorise the Applicator in writing to proceed with the required corrective work and the manner in which it is to be performed. Upon receipt of satisfactory proof of its expenses and a full and complete written release from the Applicator of any and all further claims against Dulux under this Performance Warranty arising from such failure, Dulux will pay the Applicator's authorised costs of labour and materials, in accordance with sub-clause b).

e) This Performance Warranty shall extend to any repaired coated Metal for the remainder of the Warranty period applicable to the Metal originally coated.

Schedule B - Conditions of Sale

Unless otherwise agreed to in writing by Dulux, the following provisions apply to the sale of the Products to the Applicator:

1. Customer's Statutory Rights

The exclusions and limitations contained in this Schedule B are subject to any overriding law to the contrary, the application of which may not be excluded or limited.

2. Advice

Subject to clause 1 of this Schedule B and to the provisions of the Performance Warranty, any advice, recommendation, information, assistance or service provided by Dulux in relation to the Products or its use or application is given in good faith and is believed by Dulux to be appropriate and reliable. However, advice, recommendations, information, assistance or service provided by Dulux in relation to the Products is provided without liability or responsibility on the part of Dulux.

3. Property

a The risk in the Products purchased shall pass to the Applicator upon delivery to the Applicator or his agent or to a carrier commissioned by the Applicator.

b Property in each unit of the Products purchased shall pass to the Applicator when full payment has been received (each unit being considered as a whole) by Dulux, resale by the Applicator, consumption of the Products (otherwise than by repacking) by the Applicator or the mixing of the Products with other goods, whichever occurs first.

c Dulux may (without prejudice to any of its other rights) without previous notice retake and resume possession of all goods which remain the property of Dulux and by its servants and agents may enter upon the Applicator's premises or any other place where goods may be for that purpose upon the occurrence of one of the following events:

i. Where the Applicator is a corporation, the Applicator commences to be wound up or is placed under statutory or like management or a receiver or administrator is appointed or an encumbrancer takes possession of its undertakings or property or any part thereof; or

ii. Where the Applicator is a natural person, the Applicator becomes insolvent or bankrupt or commits an act of bankruptcy or make an assignment for the benefit of a creditor; or

iii. The Applicator fails to pay the whole or any part of the purchase prior or transport or other charges for any unit of the Product supplied when due and payable.

4. Force Majeure

Deliveries may be totally or partially suspended by Dulux during any period in which Dulux may be prevented or hindered from delivering by Orica's normal means of supply or delivery by normal route through any circumstances outside its reasonable control, including but not limited to strikes, lockouts, raw material shortages, accident or breakdowns of plant or machinery. Should Dulux due to short supply of any material, ingredient or finished stock be unable to supply, it may as its sole and unfettered discretion make available a proportion of available supply to the Applicator and will not be regarded as a breach of contract for so doing.

5. Future Dealing

The provisions of this Schedule B, the Performance Warranty and Dulux's General Conditions of Sale shall prevail over any items set out in the Applicator's documentation and shall apply, until further notice is given to the contrary by Dulux, to all supplies of the Products to the Applicator.

FC

Warranty

Parchem Construction Products Pty Ltd
5 + 5 Years Materials Warranty

Subject to the Warranty Conditions printed on the back of this document and any Specific Exemption listed below, Parchem Construction Products Pty Ltd (ABN 80 069 961 968) hereby warrants that the company's products listed below, supplied to the project described on this document, will conform with the technical data as contained in the current Technical Data Sheet/s (TDS) for the specified warranty period from the completion date on this warranty.

Warranty No	1832	
Project Name	Westfields Bondi Junction	
Project Address	Oxford Street Bondi Junction NSW 2022	
Project Owner		
Products Used	Emer-Bond Emer-Clad Satin Light Grey	20m²
Application Details	New aluminium beams under carpark decks (not trafficable)	
Customer Name	Perfect Engineering	
Customer Address	6 Wolger Road RYDE NSW 2112	
Customer Contact	George Melhem	
Completion Date	April 2005	
Special Conditions / Exclusions		

Signed on behalf of PARCHEM CONSTRUCTION PRODUCTS PTY LTD

[signature] .... 4th July 2005

PARCHEM CONSTRUCTION PRODUCTS PTY LTD
TERMS AND CONDITIONS

1. The Product shall be applied strictly in accordance with the instructions contained in the Tdedata sheet/s and with any other instructions that the Company may provide. This warranty does not in any way cover the application of the Product and relates solely to the Product as supplied by the Company.

2. The Company supplies the Product as principal and no other person has the authority to give any further warranty on behalf of the Company.

3. In the event that it is proved to the satisfaction of the Company that all or part of the Product does not perform in accordance with this warranty then the Company shall at its option either:

    i) Supply without charge replacement Product to the purchaser.

    OR

    ii) Pay to the purchaser the original purchase cost of such Product, or its equivalent;

    In either case the value of product supplied, or the sum of money refunded shall not exceed the value of the original purchase and shall be reduced by a percentage equal to the expired warranty period divided by the full warranty period.

4. This warranty shall only apply if the Company has been given notice in writing within seven days of any defect or failure of the Product first becoming apparent and the Company has been given full opportunity to inspect the Product.

5. This warranty becomes valid only when the Company or its agent has been paid in full for all Product used and the Company been advised of the quantity and batch number/s (where applicable) of all Product used.

6. The Company shall not be liable for any consequential loss or damage whatsoever arising from or in connection with the Product.

7. The Company shall not be liable for any costs of scaffolding or other access equipment necessary to reach works, costs of exposing the works or reinstatement of any building finishes following any rectification works.

    This warranty is in lieu of all other warranties and/or conditions whether expressed or implied and all other obligations on the part of Parchem Construction Products other than warranties or conditions which arise by operation of law and are not capable of being negated or modified by agreement.

Appendix M

Aluminium alloy rivet specifications [138].

ALCOA

Alcoa Fastening Systems

14 Viewtech Place.
Rowville Vic 3178

Quality Endorsed Company

CERTIFICATE OF CONFORMANCE

PART #	WORK ORDER #	INVOICE #
MGLP-B6-E X 3000	141781 16	SLI 43388
MGLP-B6-E X 3000	131744 16	SLI 43388
MGLP-B6-E X 1000 (BAG)	131744 16	SLI 43388

This is to attest that Alcoa Fastening Systems Pty Ltd will warranty the above items as conforming to our published specifications with regard to mechanical properties and dimensional tolerances.

Signed:

Previous Screen

LockRite

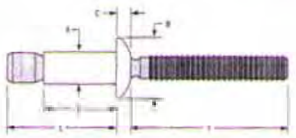
Tooling Options

Table of Contents

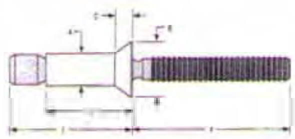
Magna-Lok™ LockRite™

Magna-Lok® LockRite™

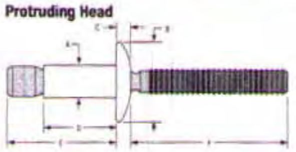
Strong, consistent and reliable. Employing a unique solid-circle lock, the Magna-Lok® fastener creates an internal lock during installation that virtually eliminates pin pushout.



Protruding Head



100° Countersunk Head



Truss Head

Dimensional Data—Protruding Head

Dia. (No.)	Steel	Aluminum	Stainless	Grip Range	Hole Size	A	B	C	D	E	F
3/16 (6)	MGLP-R6-4*	MGLP-B6-4*	MGLP-U6-4	.062 - .270	.191 - .201	.188	.385	.085	.415	.675	1.00
	MGLP-R6-7*	MGLP-B6-7*	MGLP-U6-7	.214 - .437	.191 - .201	.188	.385	.085	.572	.825	1.00
	MGLP-R6-E*	MGLP-B6-E*		.062 - .437	.191 - .201	.188	.385	.085	.572	.950	1.00
1/4 (8)	MGLP-R8-6*	MGLP-B8-6*	MGLP-U8-6	.080 - .375	.261 - .272	.253	.525	.117	.560	.970	1.00
	MGLP-R8-10*	MGLP-B8-10*	MGLP-U8-10	.350 - .625	.261 - .272	.253	.525	.117	.810	1.220	1.00
	MGLP-R8-E*	MGLP-B8-E*		.080 - .625	.261 - .272	.253	.525	.117	.810	1.405	1.00
3/8 (12)	MGLP-R12-12	MGLP-B12-12		.120 - .560	.392 - .408	.386	.787	.175	.840	1.650	1.545

Dimensional Data—Truss Head

Dia. (No.)	Steel	Aluminum	Grip Range	Hole Size	A	B	C	D	E	F
3/16 (6)	MGLT-R6-4	MGLT-B6-4	.062 - .270	.191 - .201	.187	.500	.085	.415	.675	1.00
	MGLT-R6-7	MGLT-B6-7	.214 - .437	.191 - .201	.187	.500	.085	.572	.825	1.00
	MGLT-R6-E	MGLT-B6-E	.062 - .437	.191 - .201	.187	.500	.085	.572	.950	1.00
1/4 (8)	MGLT-R8-6	MGLT-B8-6	.080 - .375	.261 - .272	.253	.588	.117	.560	.970	1.00
	MGLT-R8-10	MGLT-B8-10	.350 - .625	.261 - .272	.253	.588	.117	.810	1.220	1.00
	MGLT-R8-E	MGLT-B8-E	.080 - .625	.261 - .272	.253	.588	.117	.810	1.405	1.00

Dimensional Data—100° Countersunk Head

Dia. (No.)	Steel	Aluminum	Stainless	Grip Range	Hole Size	A	B	C	D	E	F
3/16 (6)	MGL100-R6-6	MGL100-B6-6	MGL100-U6-6	.125 - .331	.191 - .201	.188	.345	.070	.486	.762	1.00
	MGL100-R6-9	MGL100-B6-9	MGL100-U6-9	.305 - .500	.191 - .201	.188	.345	.070	.653	.929	1.00
1/4 (8)	MGL100-R8-8	MGL100-B8-8	MGL100-U8-8	.160 - .475	.261 - .272	.257	.405	.079	.660	1.059	1.00
	MGL100-R8-12	MGL100-B8-12	MGL100-U8-12	.415 - .725	.261 - .272	.257	.405	.079	.910	1.309	1.00

Huck Fasteners

Previous Screen

LockRite

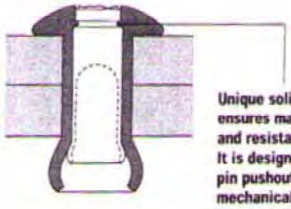
Tooling Options

Table of Contents

Magna-Lok™ LockRite™

Typical Installed Values in Nominal Grip (lbs.)

		Aluminum	Steel	Stainless Steel
3/16	Shear	600	1300	1300
	Tensile	500	1200	950
	Pin Retention	50	150	100
1/4	Shear	1300	2500	2350
	Tensile	890	2200	1800
	Pin Retention	100	300	200
3/8	Shear	2950	5600	NA
	Tensile	1900	4000	NA
	Pin Retention	250	650	NA



Unique solid-circle lock ensures maximum strength and resistance to vibration. It is designed to eliminate pin pushout. It forms a mechanical lock, permanently locking the pin and sleeve together.

Material and Finish

Material	Sleeve	Pin	Sleeve Finish	Pin Finish
Steel	Low Carbon Steel	Medium Carbon Steel	Zinc Plated Clear Chromate	Zinc Plated Gold Chromate
Aluminum	5056	7075	Clear Chromate	Gold Chromate
Stainless	302	305/304	Passivated	Dry Lubricated

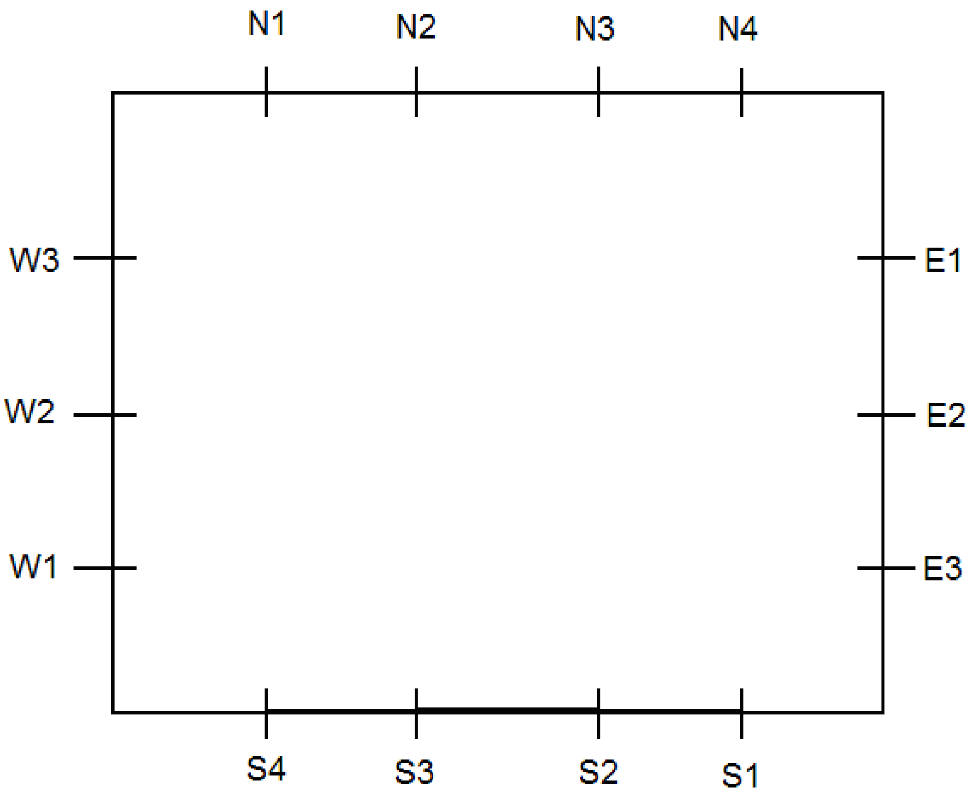
Installation Tooling

Dia.	Installation Tool	Nose Assembly	Type	Use
3/16	229	99-3300 99-3316-68	Pneudraulic	Maintenance
	230	99-3300 99-3316-68	Pneudraulic	Maintenance & Repair
	2025	99-3300	Pneudraulic	Maintenance & Repair
	202	99-3303 99-3316-68	Pneudraulic	Prod. or Maint. & Repair
	2015	125154 (Insert, included with tool)	Pneudraulic	Prod. or Maint. & Repair
	212	99-3300 99-3303 99-3316-68	Pneudraulic	Production
	AK180-I	120982	Pneudraulic	Maintenance & Repair
	2480	99-3300 99-3303 99-3316-68	Hydraulic	Production
1/4	229	99-3301 99-3316-68	Pneudraulic	Maintenance
	230	99-3301 99-3316-68	Pneudraulic	Maintenance & Repair
	2025	99-3301	Pneudraulic	Maintenance & Repair
	202	99-3301 99-3316-68	Pneudraulic	Prod. or Maint. & Repair
	212	99-3301 99-3305 99-3316-68	Pneudraulic	Production
	AK180-I	202142	Pneudraulic	Maintenance & Repair
	2480	99-3301 99-3305 99-3316-68	Hydraulic	Production
3/8	246	99-3318	Pneudraulic	Production
	2580	99-3318	Hydraulic	Production

Huck Fasteners

Appendix N

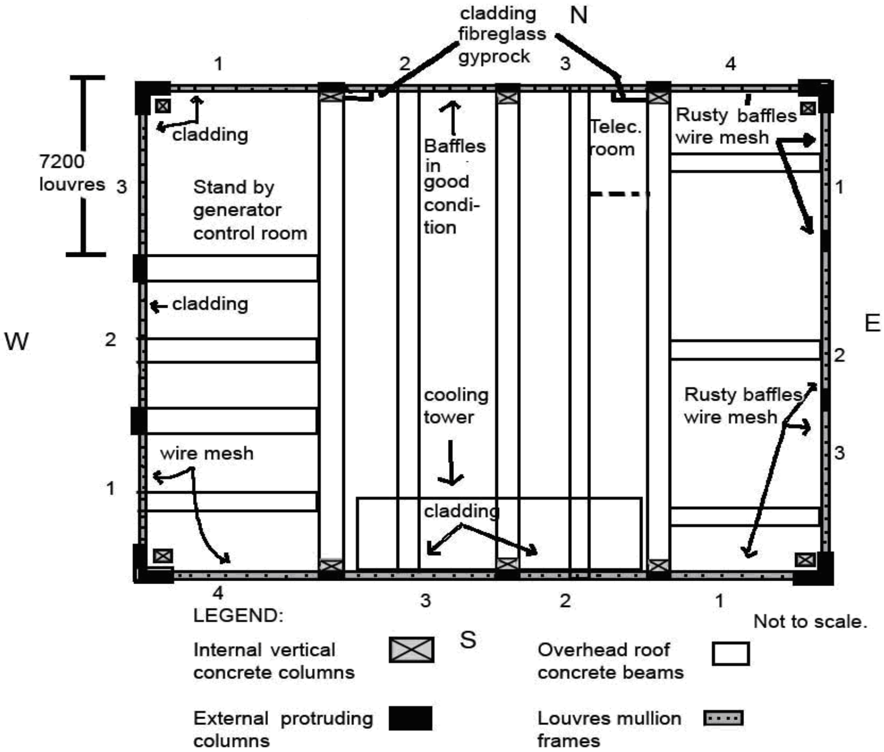
Initial site sketch drawings of requirements to prepare workshop drawings and calculations.



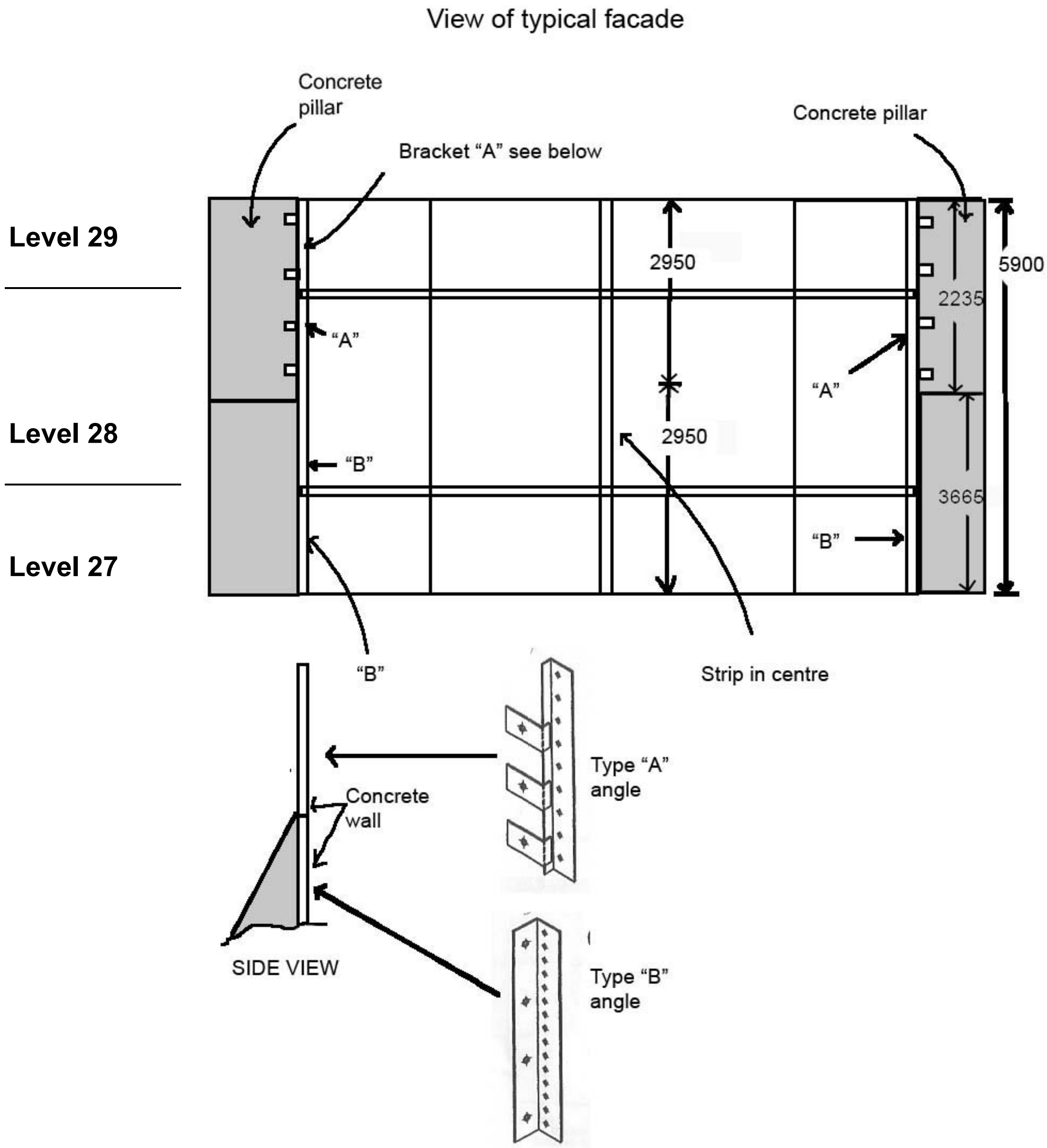
Plan view designating louvre/bracket positions for level 28.

N1 – N3, W2, W3, S2, S3, all fully enclosed – only louvre side open to outside.

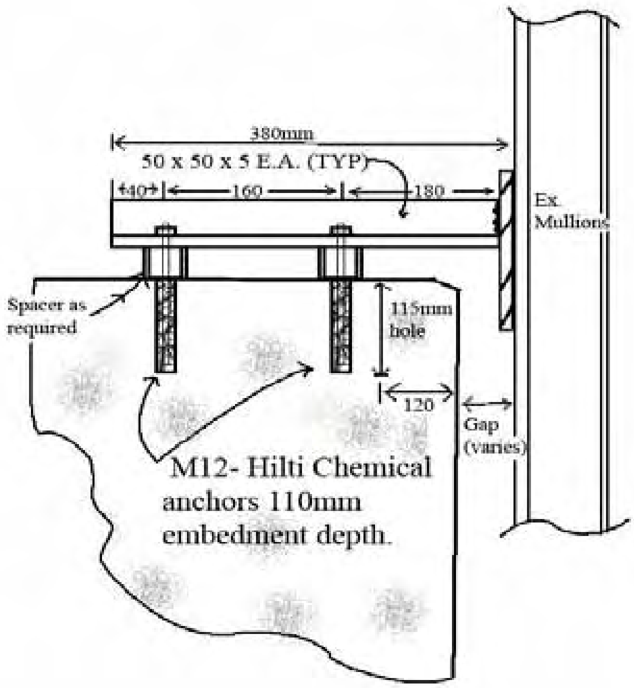
W1, S4, S1, E1, E2, E3, N4 All open roof and some barriers.



Level 28 Plan View



View of typical façade for levels 27, 28 and 29



Typical supplementary bracket supporting louvre from inside, to support external aluminium brackets.

Appendix O

Westfield annual maintenance report and customer feedback.

Westfield - Bondi Junction

Annual Inspection Records

for

Tower 2 Louvre Systems
Levels 29, 28, 27 and 26

Issued by Perfect Engineering Pty Ltd

Annual Inspection Reports

Index and Record of Issue

Year and Report No.	Page Reference	Date Completed	Issued Signature	Accepted Signature
2006 Report 1	1 to 3	23/02/2006	[illegible]	[illegible]
2007 Report 2	4 to 6	30/08/2007	[illegible]	[illegible]
2008 Report 3	7 to 9	22/02/2008	[illegible]	[illegible] 2/4/08
2009 Report 4	10 to 12			
2010 Report 5	13 to 15			

Comments Section

General

Building face inspection was carried out using the BMU. Bolted connections were assessed visually for signs of mechanical displacement or corrosion. All connections were found to be in order, the corrosion protective coating was intact and there were no tell tale traces of corrosion in the vicinity of any bolts.

Louvres were visually inspected for signs of displacement, and the aluminium cover strips were checked for signs of displacement or rivet corrosion. All louvres were found to be in order, the aluminium cover strips were sound, and there were no signs of corrosion activity at the rivet points.

Internal building inspection was carried out to assess the condition of replaced members, the bolted connections and specifically those areas which are subject to the worst corrosion environment. In all cases the structural members were discovered to be sound, and there was no evidence of corrosion activity.

Defect Comments if Applicable

No defects requiring comment this inspection.

Inspection carried out by: George Melhem, Gagan Singh, John Louth (Perfect Engineering Pty Ltd)

Report Confirmed Correct and Approved for Issue: 1/3/06

Report Accepted by Westfield: 9/3/06

Comments Section

General

Building face inspection was carried out visually for signs of mechanical displacement or corrosion. All connections were found to be in order, the corrosion protective coating was in tact and there were no tell tale traces of corrosion in the vicinity of any bolts.

Louvres were visually inspected for signs of displacement, and the aluminium cover strips were checked for signs of displacement or rivet corrosion. All louvers were found to be in order, the aluminium cover strips were sound, and there were no signs of corrosion activity at the rivet points.

Internal building inspection was carried out to assess the condition of replaced members, the bolted connections and specifically those areas which are subject to the worst corrosion environment. In all cases the structural members were discovered to be sound, and there was no evidence of corrosion activity.

Defect Comments if Applicable

Note:1*

Although no defects were detected, it was noted that the level 29 louvres have been sprayed with a light paint coating at some time following Perfect Engineering's completion of the works. This additional coating has not adhered well to the powder coated original finish and appears to be peeling away. While it does not appear at this stage to be detrimental to the original powder coated finish, this peeling paint detracts slightly from the finish left by Perfect Engineering.

Inspection carried out by: George Melhem and John Louth (Perfect Engineering)

Report Confirmed Correct and Approved for Issue: [signature] 3rd Sept. 2007

Report Accepted by Westfield: [signature] 17/9/07

Comments Section

General

The inspection team was accompanied by Professor C Sorrell of the University of NSW Faculty of Engineering, Material Science and during the visit Professor Sorrell noted the depth of design work that had been undertaken and he made comment on the effectiveness of the installed system that is showing no sign of corrosion except two very small surface discolorations on the tips of two bolt shanks where there may have been some surface abrasion that has been affected by a build up of bird droppings. These are considered very minor and not in a position that is near the load bearing part of the bolt or nut. Perfect Engineering will clean and apply a repair coat of cold gal at the next inspection visit.

The inspection team also noticed large areas of salt deposits in several locations and we draw Westfield's attention to the matter. While these salt deposits have not had any apparent impact as yet on the works installed by Perfect Engineering we consider it necessary for routine maintenance and cleaning to be carried out periodically to ensure maximum life of the installation particularly those components of the original structure that Perfect Engineering did not install.

These areas were generally on the inside of the Eastern side of the building in areas that maybe more subject to weather blowing in and wet conditions in the area of evaporation system equipment and tanks.

The bird dropping also pose a threat to longevity since these are rich in corrosive chemicals.

If Westfield requires any assistance to carry out maintenance work, we would be pleased to discuss the opportunity.

Defect Comments If Applicable

No significant reportable defects.

Please note maintenance recommendations included above in the General Comments section.

Levels 26 involved a building face visual inspection for signs of mechanical displacement or corrosion. All connections were found to be in order, the corrosion protective coating was in tact and there were no tell tale traces of corrosion in the vicinity of any bolts.

Louvres were visually inspected for signs of displacement, and the aluminium cover strips were checked for signs of displacement or rivet corrosion. All louvers were found to be in order, the aluminium cover strips were sound, and there were no signs of corrosion activity at the rivet points.

Inspection carried out by: George Melhem and John Louth. Professor Sorrel accompanied Perfect Engineering Pty Ltd for the annual inspection in Feb 2008.

Report Confirmed Correct and Approved for Issue: [signature] 2/4/08

Report Accepted by Westfield: [signature] 2/4/08

Annual Warranty Inspection Report. Report No. 3 - 2008

Actual date of inspection: February 22, 2008

Item Description	Mechanically Sound	Corrosion free	Comment Reference
North Side Level 29 cover strips and louvre sections	Yes	Yes	N/A
North Side Level 29 louvre support structure	Yes	Yes	N/A
North Side Building Face Level 28 Bolted Connections	Yes	Yes	N/A
North Side Building Face Level 28 cover strips and louvre sections	Yes	Yes	N/A
North Side Level 28 Internal Louvre Support Structure	Yes	Yes	N/A
North Side Building Face Level 27 Bolted Connections	Yes	Yes	N/A
North Side Building Face Level 27 cover strips and louvre sections	Yes	Yes	N/A
North Side Level 27 Internal Louvre Support Structure	Yes	Yes	N/A
North Side Building Face Level 26 Bolted Connections	Yes	Yes	N/A
North Side Building Face Level 26 cover strips and louvre sections	Yes	Yes	N/A
North Side Level 26 Internal Louvre Support Structure	Yes	Yes	N/A
South Side Level 29 cover strips and louvre sections	Yes	Yes	N/A
South Side Level 29 louvre support structure	Yes	Yes	N/A
South Side Building Face Level 28 Bolted Connections	Yes	Yes	N/A
South Side Building Face Level 28 cover strips and louvre sections	Yes	Yes	N/A
South Side Level 28 Internal Louvre Support Structure	Yes	Yes	N/A
South Side Building Face Level 27 Bolted Connections	Yes	Yes	N/A
South Side Building Face Level 27 cover strips and louvre sections	Yes	Yes	N/A
South Side Level 27 Internal Louvre Support Structure	Yes	Yes	N/A
South Side Building Face Level 26 Bolted Connections	Yes	Yes	N/A
South Side Building Face Level 26 cover strips and louvre sections	Yes	Yes	N/A
South Side Level 26 Internal Louvre Support Structure	Yes	Yes	N/A

Client: [signature] 2/4/08

Item Description	Mechanically Sound	Corrosion free	Defect Comment Ref No.
East Side Level 29 cover strips and louvre sections	Yes	Yes	N/A
East Side Level 29 louvre support structure	Yes	Yes	N/A
East Side Building Face Level 28 Bolted Connections	Yes	Yes	N/A
East Side Building Face Level 28 cover strips and louvre sections	Yes	Yes	N/A
East Side Level 28 Internal Louvre Support Structure	Yes	Yes	N/A
East Side Building Face Level 27 Bolted Connections	Yes	Yes	N/A
East Side Building Face Level 27 cover strips and louvre sections	Yes	Yes	N/A
East Side Level 27 Internal Louvre Support Structure	Yes	Yes	N/A
East Side Building Face Level 26 Bolted Connections	Yes	Yes	N/A
East Side Building Face Level 26 cover strips and louvre sections	Yes	Yes	N/A
East Side Level 26 Internal Louvre Support Structure	Yes	Yes	N/A
West Side Level 29 cover strips and louvre sections	Yes	Yes	N/A
West Side Level 29 louvre support structure	Yes	Yes	N/A
West Side Building Face Level 28 Bolted Connections	Yes	Yes	N/A
West Side Building Face Level 28 cover strips and louvre sections	Yes	Yes	N/A
West Side Level 28 Internal Louvre Support Structure	Yes	Yes	N/A
West Side Building Face Level 27 Bolted Connections	Yes	Yes	N/A
West Side Building Face Level 27 cover strips and louvre sections	Yes	Yes	N/A
West Side Level 27 Internal Louvre Support Structure	Yes	Yes	N/A
West Side Building Face Level 26 Bolted Connections	Yes	Yes	N/A
West Side Building Face Level 26 cover strips and louvre sections	Yes	Yes	N/A
West Side Level 26 Internal Louvre Support Structure	Yes	Yes	N/A

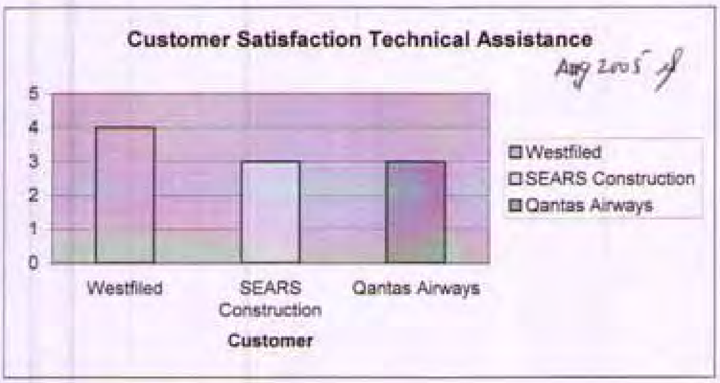
8

Client: [signature]

Satisfaction Technical Assistance *Aug 2005*			
Customer no.	Organization	Location	Level
Cust-01	Westfiled	Sydney	4
Cust-02	SEARS Construction	Sydney	3
Cust-03	Qantas Airways	Sydney	3

Legend

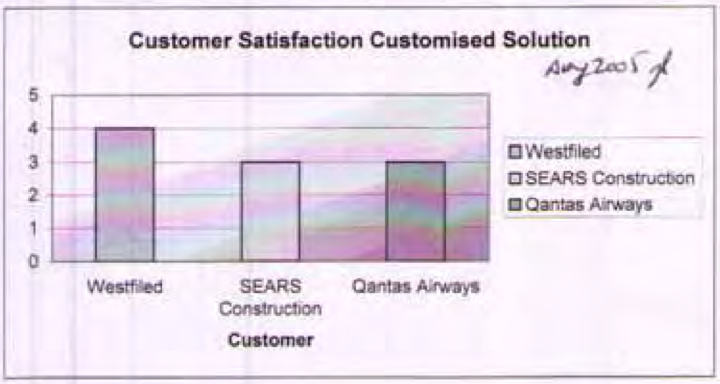
Unsatisfied	1
Fairly Satisfied	2
Satisfied	3
Very Satisfied	4



Satisfaction Customised Solution Aug 2005			
Customer no.	Organization	Location	Level
Cust-01	Westfiled	Sydney	4
Cust-02	SEARS Construction	Sydney	3
Cust-03	Qantas Airways	Sydney	3

Legend

Unsatisfied	1
Fairly Satisfied	2
Satisfied	3
Very Satisfied	4



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Satisfaction Total Solution Aug 2005			
Customer no.	Organization	Location	Level
Cust-01	Westfiled	Sydney	4
Cust-02	SEARS Construction	Sydney	4
Cust-03	Qantas Airways	Sydney	3

Legend

Unsatisfied	1
Fairly Satisfied	2
Satisfied	3
Very Satisfied	4

6

Satisfaction Product Quality Aug 2005			
Customer no.	Organization	Location	Level
Cust-01	Westfiled	Sydney	4
Cust-02	SEARS Construction	Sydney	4
Cust-03	Qantas Airways	Sydney	4

Legend

Unsatisfied	**1**
Fairly Satisfied	**2**
Satisfied	**3**
Very Satisfied	**4**

3

PERFECT ENGINEERING PTY LTD

CUSTOMER FEEDBACK FORM

Dear Sir/Madam,

It is our endeavour to continually improve our capabilities and services to make them more effective, reliable and customer friendly. We will highly appreciate and value your feedback and perception on how well our capability and services meet your needs and expectations.

The information provided in this form is confidential.

Kindly fill this form, and return to Perfect Engineering by Fax, Email, Mail or in person:

PERFECT ENGINEERING PTY LTD
Postal Address: P.O Box 856, Ryde NSW 1680
Head Office : 6 Wolger Rd, Ryde, NSW, 2112

Mobile: 0412 013 552

National:
Ph: (02) 9807 3305
Fax: (02) 9807 2656

International:
Ph: (61) 2 9807 3305
Fax: (61) 2 9807 2656

Email: george@perfectengineering.com.au
Website: www.perfectengineering.com.au

We appreciate your cooperation.

George Melhem

Managing Director

PERFECT ENGINEERING PTY LTD

Personal Details:

☑ Mr ☐ Ms ☐ Miss ☐ Mrs

Full Name: CARLO LOGIUDICE

Company Details:

Organisation: WESTFIELD

Address: TOWER 2, LEVEL 12, 500 OXFORD ST.

City: BONDI JUNCTION

State/Prov: NSW **Zip/Postcode** 2022

Country: AUSTRALIA

Phone: 02 9947 8000 **Fax:** 02 9947 8122

Email:

PERFECT ENGINEERING PTY LTD

Please Answer The Following Questions:

Q1) Will you recommend Perfect Engineering to Others ?

☑ Yes ☐ No

Q2) What are the three most important reasons to continue to do business with Perfect Engineering?

☑ **Product Quality**

☑ **On-Time Delivery**

☐ **Service Responsiveness**

☑ **Total Solution**

☐ **Customised Solutions**

☐ **Competitive Pricing**

☐ **Technical Assistance**

Q3) Rate your satification level for each of the following categories?

	Unsatisfied 1	Fairly Satisfied 2	Satisfied 3	Very Satisfied 4
Product Quality	☐	☐	☐	☑
On-Time Delivery	☐	☐	☐	☑
Service Reponsiveness	☐	☐	☐	☑
Total Solution	☐	☐	☐	☑
Customised Solutions	☐	☐	☐	☑
Competitive Pricing	☐	☐	☐	☑
Technical Assistance	☐	☐	☐	☑

PERFECT ENGINEERING PTY LTD

Q4) How do you feel Perfect Engineering's overall performance compares to its competitors?

☐ Same ☑ Better ☐ Worse

Q5) What suggestions for improvement would you recommend to increase the value you receive as a customer?

PERFECT ENGINEERING HAS MET ALL OUR EXPECTATIONS.
HEATFIELD IS VERY SATISFIED WITH THE PERFORMANCE OF PERFECT ENGINEERING.

Thank You, For Your Cooperation.

D015-3.04 Rev. 01

Perfect Engineering
PTY LTD

CUSTOMER PRODUCT QUESTIONNAIRE

NOTE:

This is only a verbal questionnaire.

Company: WESTFIELD

Date: AUG. 2005

Contact Person: CARLO LOGIUDICE

Project No. 023-1-1

1- Was the project delivered on- time?

Yes ☑ No ☐

2- Were you satisfied with the quality of the job supplied?

Yes ☑ No ☐

3- As a valued customer how can we improve our quality of services to suit your needs?

PERFECT ENGINEERING HAS MET ALL OUR EXPECTATIONS

4- Any comments you have for Perfect Engineering?

WESTFIELD IS VERY SATISFIED WITH THE PERFORMANCE AND PROFESSIONALISM OF PERFECT ENGINEERING

Draft

PERFECT ENGINEERING PTY LTD

CUSTOMER FEEDBACK FORM

Dear Sir/Madam,

It is our endeavour to continually improve our capabilities and services to make them more effective, reliable and customer friendly. We will highly appreciate and value your feedback and perception on how well our capability and services meet your needs and expectations.

The information provided in this form is confidential.

Kindly fill this form, and return to Perfect Engineering by Fax, Email, Mail or in person:

PERFECT ENGINEERING PTY LTD
Postal Address: P.O Box 856, Ryde NSW 1680
Head Office : 6 Wolger Rd, Ryde, NSW, 2112

Mobile: 0412 013 552

National:	International:
Ph: (02) 9807 3305	Ph: (61) 2 9807 3305
Fax: (02) 9807 2656	Fax: (61) 2 9807 2656

Email: george@perfectengineering.com.au
Website: www.perfectengineering.com.au

We appreciate your cooperation.

George Melhem

Managing Director

PERFECT ENGINEERING PTY LTD

Personal Details:

☑ Mr ☐ Ms ☐ Miss ☐ Mrs

Full Name: ADRIAN CALMER

Company Details:

Organisation: QANTAS

Address: QANTAS JET BASE BUILDING M

City: MASCOT

State/Prov: NSW **Zip/Postcode** 2020

Country: AUSTRALIA

Phone: 02 9691 9202 **Fax:** 02 9691 7801

Email:

D015-3.04 Rev 01

PERFECT ENGINEERING PTY LTD

Please Answer The Following Questions:

Q1) Will you recommend Perfect Engineering to Others ?

☑ Yes ☐ No

Q2) What are the three most important reasons to continue to do business with Perfect Engineering?

☑ **Product Quality**

☑ **On-Time Delivery**

☐ **Service Responsiveness**

☑ **Total Solution**

☐ **Customised Solutions**

☐ **Competitive Pricing**

☐ **Technical Assistance**

Q3) Rate your satification level for each of the following categories?

	Unsatisfied 1	Fairly Satisfied 2	Satisfied 3	Very Satisfied 4
Product Quality				✓
On-Time Delivery				✓
Service Reponsiveness			✓	
Total Solution				✓
Customised Solutions			✓	
Competitive Pricing				✓
Technical Assistance			✓	

PERFECT ENGINEERING PTY LTD

Q4) How do you feel Perfect Engineering's overall performance compares to its competitors?

☑ Same ☐ Better ☐ Worse

Q5) What suggestions for improvement would you recommend to increase the value you receive as a customer?

QANTAS HAS ESTABLISHED A GOOD COOPERATION WITH PERFECT ENGINEERING.
WE ARE SATISFIED WITH THE WORK DONE BY PE.
KEEP UP THE GOOD WORK.

Thank You, For Your Cooperation.

Perfect Engineering PTY LTD

CUSTOMER PRODUCT QUESTIONNAIRE

NOTE:

This is only a verbal questionnaire.

Company: QANTAS

Date: NOVEMBER 2005

Contact Person: ADRIAN RAUMER

Project No. CIP-1-09

1- Was the project delivered on- time?

Yes ☑ No ☐

2- Were you satisfied with the quality of the job supplied?

Yes ☑ No ☐

3- As a valued customer how can we improve our quality of services to suit your needs?

QANTAS HAS ESTABLISHED A GOOD COOPERATION WITH PERFECT ENGINEERING. QANTAS IS SATISFIED WITH THE WORK DONE BY PE.

4- Any comments you have for Perfect Engineering?

KEEP UP THE GOOD WORK.

Draft

Appendix P

Calculations for pressure and suction wind forces in accordance with AS1170 Part 2:2002 and acronyms for calculations of aluminium to AS/NZS 1664:1997 and steel to AS4100:1998.

Note 1   AS/NZS 1170.2 (2002) Structural Design Actions – Part 2: Wind Actions, Standards Australia

Note2:   Acronyms also apply for Appendices P, S, T, and U.

Other references relevant to this Appendix are:

AS 1170.2 (1989) Minimum Design Loads on Structures, Part 2: Wind Loads, Standards Australia

BCA (2002) Building Code of Australia , Volume 1, Part B

Appendix P

Acronyms for calculations in Steel and Aluminium for appendices P,S,T & U

Reference for steel Acronyms; AS 4100 – 1998

A_n = Net area of a cross section; or sum of net areas of the flanges and the gross area of the web.

A_g = Gross area of a cross section

bw = Web depth

E = Young's modulus of elasticity, 200 x 10^3 MPa

F^* = Total design load on a member between supports

I = Second moment of inertia of a cross-section

Ix = I about the cross-section major principal x-axis

Iy = I about the cross-section major principal y-axis

J = Torsion constant for a cross-section

Kt = Twist restraint effective length factor; or correction factor for distribution of forces in a tension member.

Kl = Load height effective length factor

Kr = Effective length factor for restraint against lateral rotation; or effective length factor for a restraining member; or reduction factor for the length of a bolted or welded lap splice connection.

Kf = Form factor for members subject to axial compression

Lc = Distance between adjacent column centres

lb = Length between points of effective bracing or restraint

Le = Effective length of a compression member; or effective length of a laterally unrestrained member.

M^* = Design bending moment

M_s = Nominal section moment capacity

M_{sx} = M_s about principal x-axis

N^* = Design axial force, tensile or compressive.

N_s = Nominal section capacity of a compression member; or nominal section capacity for axial load.

N_c = Nominal member capacity in compression.

N_t = Nominal section capacity in tension.

ry = Radius of gyration about minor principal y-axis

R^* = Design bearing force; or design reaction.

tw = Thickness of web

UDL = Uniformly distributed load

V^* = Design shear force

V_f = Nominal shear capacity of a bolt or pin – strength limit state

α = Angle between x- and h- axes for an angle section.

α_b = Compression member section constant.

α_c = Compression member slenderness reduction factor .

α_m = Moment modification factor for bending.

α_s = Slenderness reduction factor; inverse of the slope of the S-N curve for fatigue.

M_{bx} = M_b about the major principal x-axis.

λ = Slenderness ratio; or elastic buckling load factor.

λ_n = Modified compression member slenderness

Φ = Capacity factor.

Reference for Aluminium acronyms; AS/NZS 1664:1997

b/t = Width to thickness ratio of a rectangular element of a cross-section

B, D, C = Buckling formula constants, with the following subscripts:
C – Compression in columns, p – compression in flat plates

E = Compressive modulus of elasticity.

F_L = Limit state stress

Fcy = Compressive yield strength

Fsy = Shear yield strength

Ix = Moment of inertia of a beam about axis perpendicular to web.

Iy = Moment of inertia of a beam about axis parallel to web.

q = Uniform design load

rx, ry = Radii of gyration of the cross-section about the centroidal principal axes.

S_1 ,S_2 = Slenderness limits (with superscripts * for columns).

Φ = Capacity factor (strength reduction factor) – depending on the application, this notation has different subscripts.

General Engineering terminology

T^* = Tension force

ΦNs = Section capacity in compression

ΦNc = Member capacity in compression

ΦNt = Member capacity in tension.

4.6/s = Snug tight bolt and nut.

S = Plastic section modulus

q_z = Basic wind pressure

Calculations for Pressure and Suction wind force in accordance with AS1170 Part 2 – 2002.

Calculations for louvre system and roof for Westfields building Bondi Junction.

Wind actions are in accordance with "wind code" (AS 1170 Part 2- 2002).

a) Importance Level = 2 (based on BCA)
b) Design Life = 50 years (based on BCA)
c) Annual Probability of Exceedance = 1:500 years for ultimate state
d) Years for Serviceability State = 1:20 years
e) Australian Region for Wind Load Calculations = A2

According to the map of wind regions of AS1170.2-2002, this translates to the following regional wind speeds:
V_{Ru}= 45 m·sec^{-1} (Wind velocity at its highest)
V_{Rs} 37 m·sec^{-1} (serviceability state)

The building height at a particular location must be considered in terms of the following equations:

$$V_{Des} = M_z^{cat} \cdot M_d \cdot M_s \cdot M_t \cdot V_{Ru}$$

where:

V_{Des}	=	Design Wind Velocity	=	
H	=	Building Height	=	100 m
M_z^{cat}	=	Modification Factor for Height Category	=	1.16 for terrain category 3
M_d	=	Directional Wind Factor	=	1.0
M_s	=	Wind Shielding Factor	=	1.0
M_t	=	Regional Topographical Factor	=	1.0
V_{Ru}	=		=	45 $m \cdot sec^{-1}$
V_{Rs}	=		=	37 $m \cdot sec^{-1}$ (serviceability state)

Height (H) = 100 m

$M_z$cat = 1.16 (for Terrain category = 3) (Modification factor for height category AS1170.2)

Note: $M_z$cat is dependant upon height and location.

Md = 1.0 (Ignore directional wind effect conservatively)

Ms x Mt = 1.0 (Shielding effect is taken as 1 to be the worst case due to no adjacent buildings)

Note: Mt is the topographical factor for the region.

(Where $V_{Ru} = 45 \, m/s$) (Assuming wind velocity is at its highest) $= 52 \, m/s$

Basic Wind Pressure

= 0.0006 x V_{Des}^2 = 1.6 kPa (This basic wind pressure is assumed for both suction and pressure)

Ultimate Wind Pressure on Windward Force:

(refer to AS1170.2 for building shape factor)

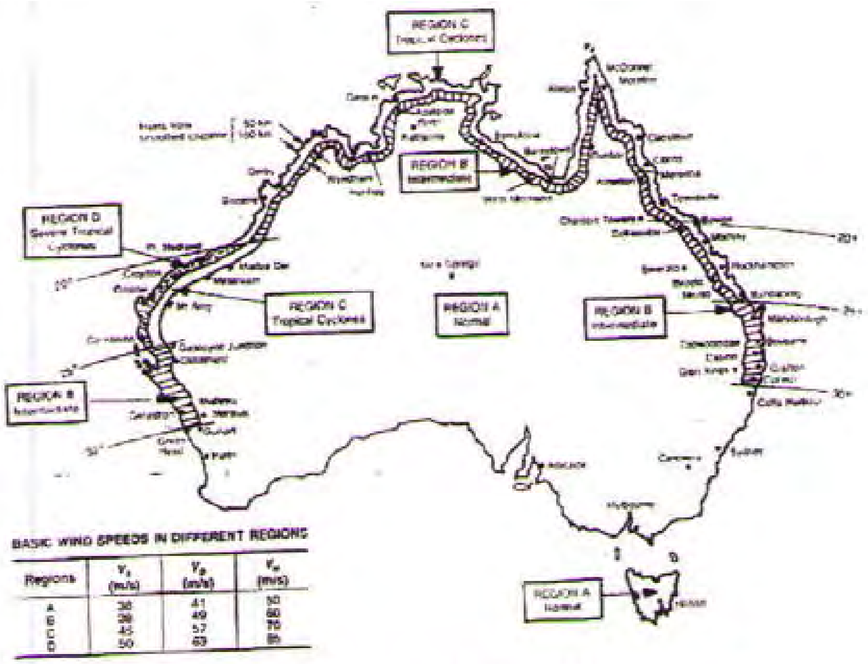
0.8 x 1.6 = 1.28 kPa (1)

(0.8 is taken as the factor for wind pressure in this region as per AS 1170.2)

Ultimate Wind Suction

0.5 x 1.6 = 0.8 kPa (2)

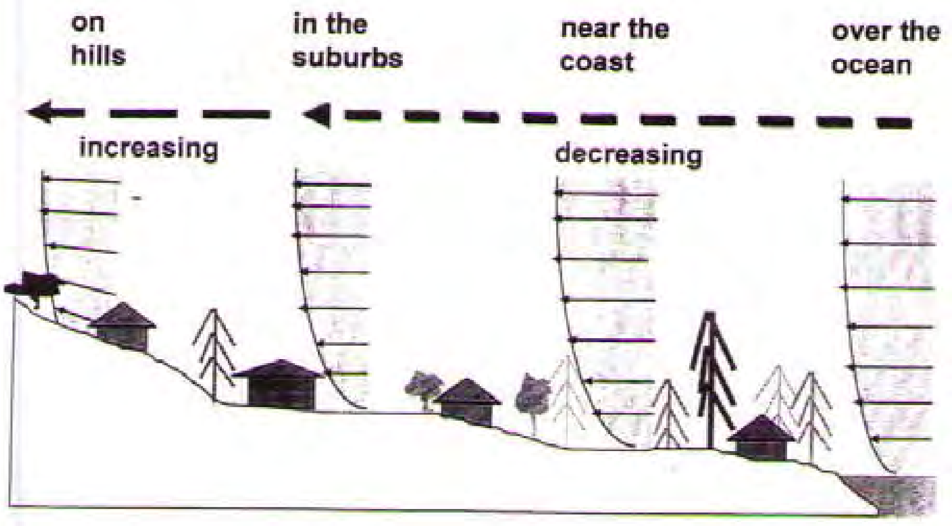
(0.5 is taken as the factor for wind suction in this region as per AS1170.2)



Wind regions of Australia (AS1170.2-1989)

Australian tropical cyclone category scale.

Category	Maximum Wind Gust (km h^{-1})	Potential Damage
1	<125	Minor
2	125-170	Moderate
3	170-225	Major
4	225-280	devastating
5	>280	Extreme



Schematic of SEA model terrain and topography influences.

6.3 Output wind speed (Vref)

For each district, the SEACATd model calculates a reference maximum wind speed (Vref), which represents the maximum 3 second gust wind speed for standard exposure and applicable to +10 m above ground level experienced at the nominal location of the district during the passage of a tropical cyclone. Vref is then factored up or down to apply to those proportions of houses that are shielded, on slope, two storey etc.

Three second gust wind speeds ranging from 47 m/s to 74 m/s, with their annual probability of exceedance for cyclonic region C as defined in AS/NZS 1170.2:2002, are shown in Table 6.1. Based on this defined annual probability of exceedance level, the probabilities of the tabled wind speeds being exceeded once in 10 years and once in 50 years have been calculated.

Table 6.1: Probability of exceedance

Probability of wind speed (Vref) being exceeded			
Vref (m/s)	Annual probability of exceedance	Probability of exceedance in 10 years	Probability of exceedance in 50 years
47	1:20 (5 %)	40 %	92 %
55	1:50 (2 %)	18 %	64 %
59	1:100 (1 %)	10 %	40 %
69	1:500 (0.2 %)	2 %	10 %
74	1:1000 (0.1 %)	1 %	5 %

The Australian Building Codes Board sets the societal risk for the ultimate limit state strength of a structure, in the Building Code of Australia (2002). From Table 6.2, the design level for housing (Importance level 2) is to be a minimum annual probability of exceedance of 1:500.

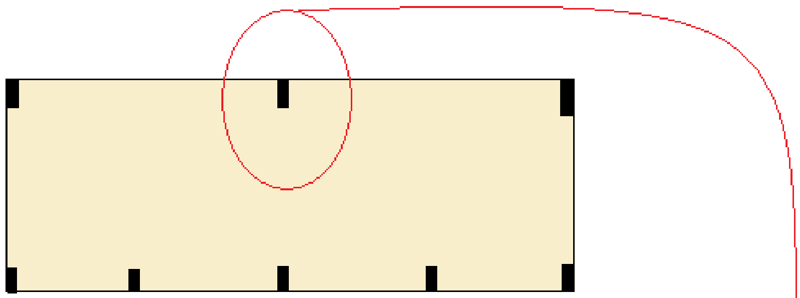
The wind speed at ultimate limit state is the design level that the structure is meant to withstand and still protect its occupants. It is interesting to note that the Vref wind speed for a 1:500 probability is 69 m/s. This is in the range of gust wind speeds for a Category 4 cyclone. Cyclone Tracy was classed as a Category 4 cyclone.

Table 6.2: Table B1.2a and B1.2b from Building Code of Australia (2002)

Importance levels of Buildings and Structures		Annual Probability of Exceedance
Level	Building Type	Cyclonic Regions
1	Buildings or structures representing a low degree of hazard to life and other property in the case of failure.	1:200
2	Buildings or structures not included in Importance levels 1, 3 and 4.	1:500
3	Buildings or structures that are designed to contain a large number of people.	1:1000
4	Buildings or structures that are essential to post disaster recovery or associated with hazardous facilities.	1:2000

Appendix Q

Calculations for brackets and louvres.

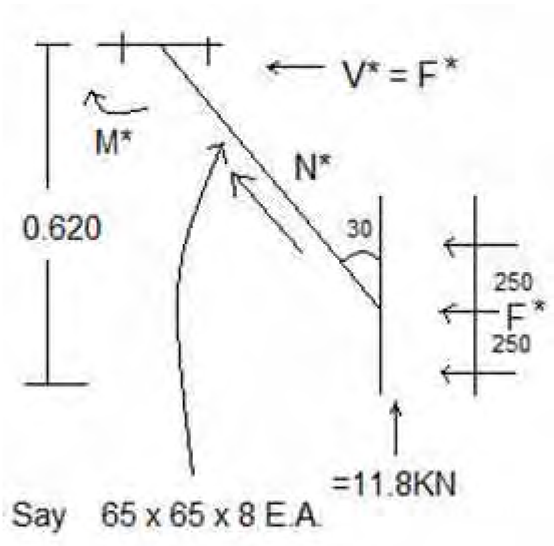


Maximum tributary area = 1.5 x 3.5
= 5.3m^2

Wind Pressure: F*= 5.3 x 1.28 = 6.8KN

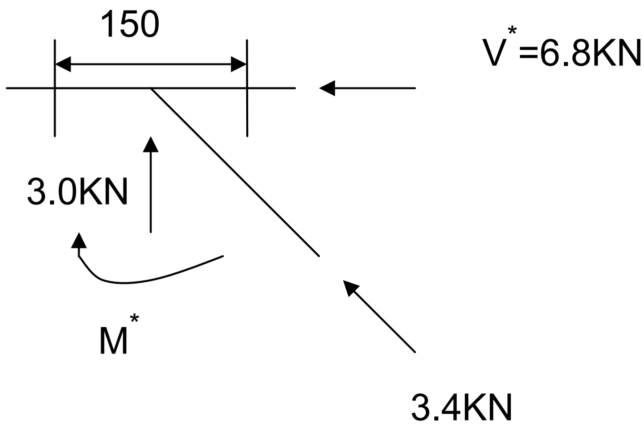
Wind Suction: F*= 5.3 x 0.8 = 4.24KN

1/ Under Pressure;



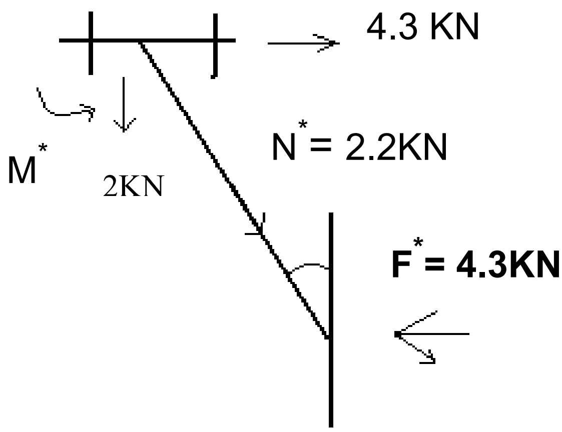
V^* = 6.8KN
M^* = 6.8 x (0.62 – 0.25) = 2.5KN.m
N^* = 6.8 x sin 30 = 3.4KN
ΦMs = 0.9 x 14.6 x 10^3 x 300MPa
= 3.9KN **Acceptable!**
ΦNs = 0.9 x 957 x 1.0 x 300
= 258KN **Acceptable!**

Top Connection:



Force on Bolt:
Tension: $T^* = (2.5/0.15) - 3.0 =$ **13.7KN**
Shear: $V^* = 6.8/2 =$ **3.4KN**

<u>2/ Under Suction;</u>

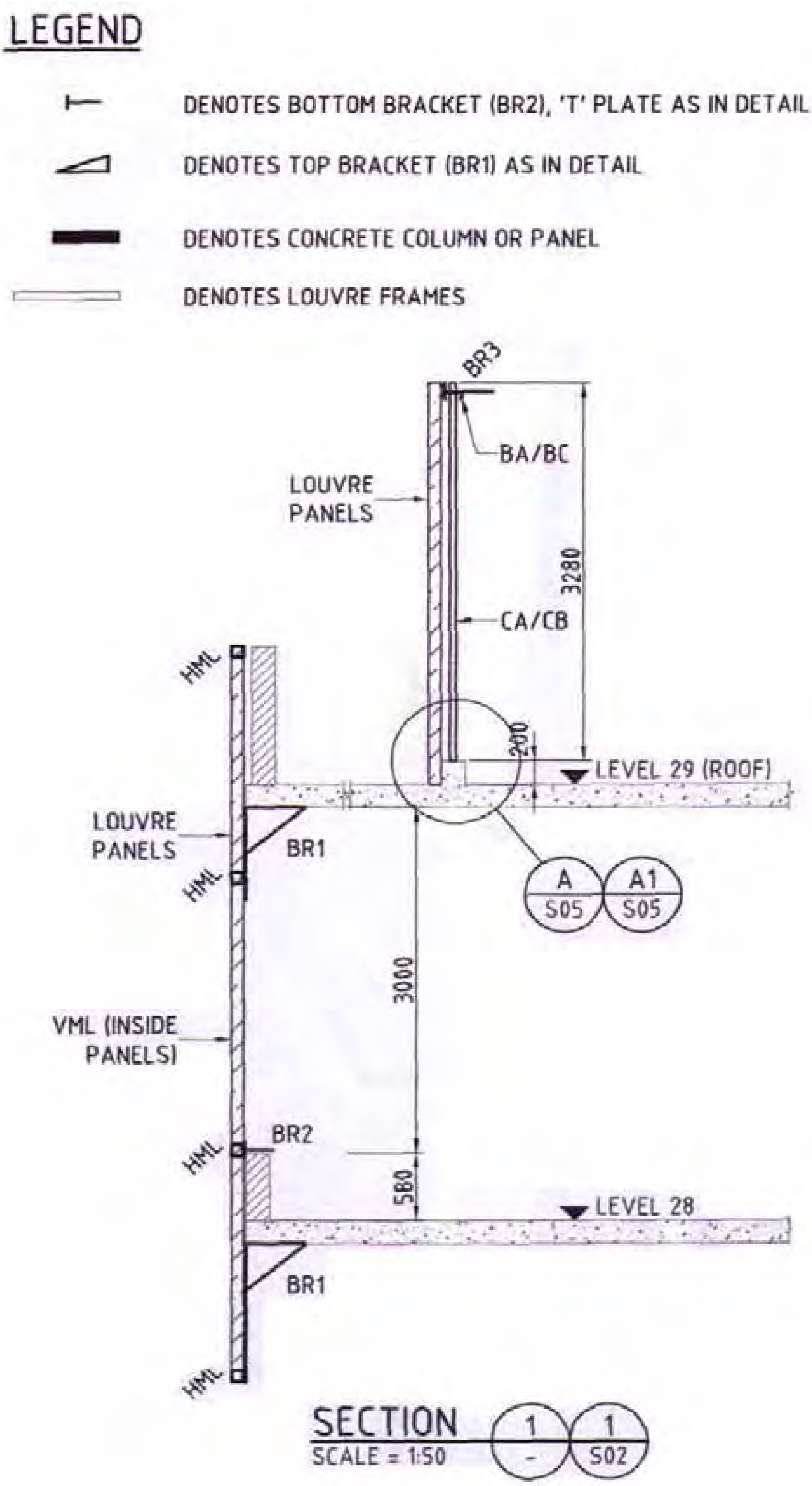


$M^* = 4.3 \times (0.62 - 0.25) = 1.6$KN.m
$V^* =$ **4.3KN**

Angle Tension Capacity Acceptable!

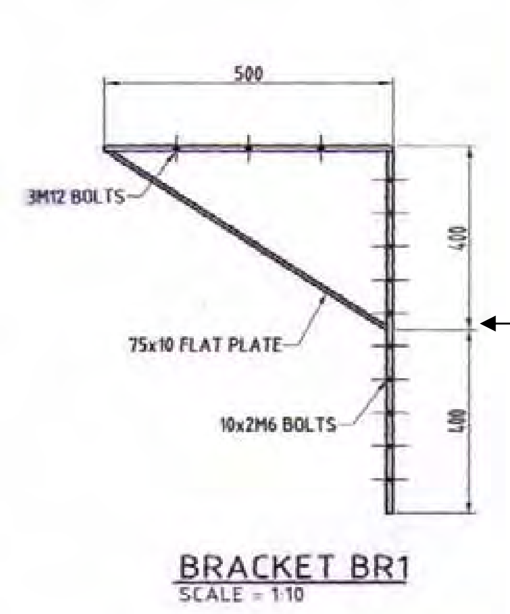
Force on Bolt:

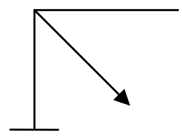
$V^* = 4.3/2 =$ **2.2KN**
$T^* = (1.6/0.15) + 2 =$ **12.7KN**



Cross section view of façade louvres on levels 27, 28 and 29. Refer to Appendix H for full details of building.

Bracket: BR1





F^*= 6.8KN

α

N^*

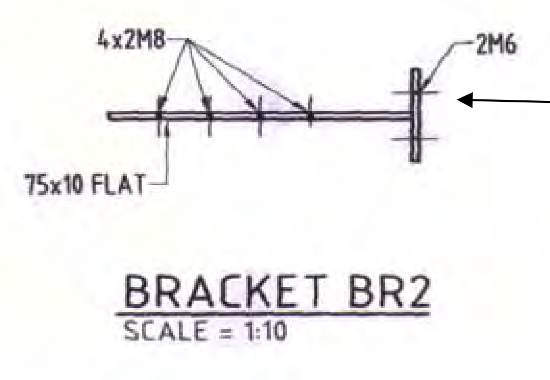
N^*cos α = 6.8KN
N^* = 8.7KN
Plate: Ag = 750 mm^2
ΦNs = 0.9 x 750 x 250MPa = 168KN
Iy = 1/12 x 75 x 10^3= 6250
Φy = 2.9mm

$\lambda_n = 640 / 2.9 = 220$

α_b = 0.5 α_c = 0.142
so, **ΦNc** = 168 x 0.142 = **23.9KN > N^*= 8.7KN Acceptable!**

Bracket: BR2

Tributary Area = 3.5/2 x 1.5 = 2.6m^2
1/ Under pressure
F^*= 2.6 x 1.28 = 3.3KN



F^*/2

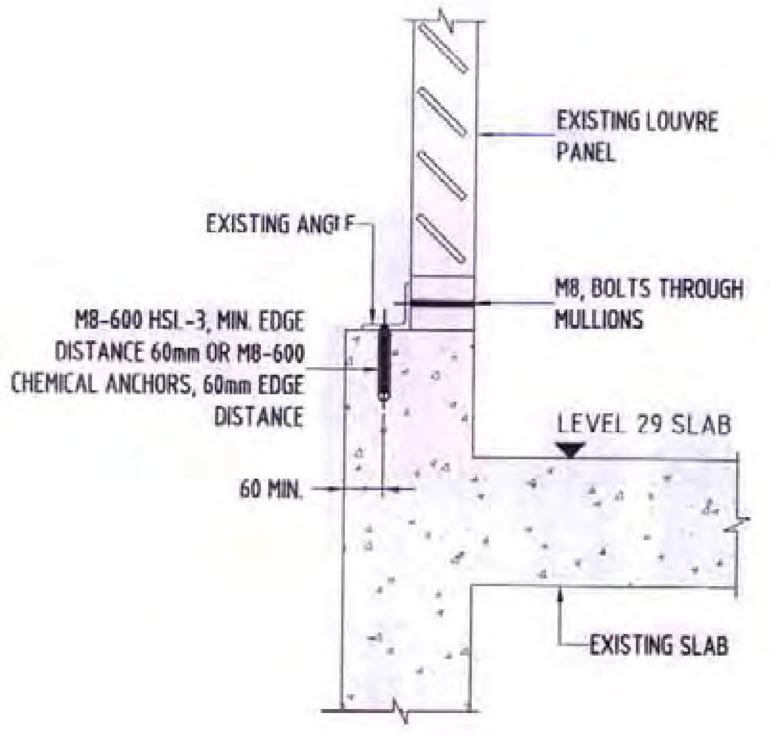
$$M^* = \frac{F^*}{2} \times \left(\frac{2}{3} \times 100mm \right) = 0.11KN.m$$

ΦM^*s = 0.9 x ¼ x 75 x 10^2 x 250MPa
= 0.42 > M^*= 0.11KN.m **Acceptable!**
Compression Acceptable on 75 x 10 plate.
Shear on each bolt = 3.3/4=0.83KN

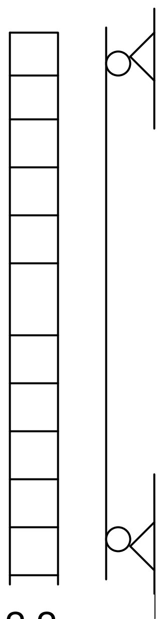
2/ Under suction

F^* = 0.8 x 2.6 = 2.1KN
Capacity Acceptable!

= 2.1/0.626 = 3mm (6mm Fillet weld) **Acceptable!**



Mullion/louvre panel on level 29 on rooftop.



Due to wind pressure

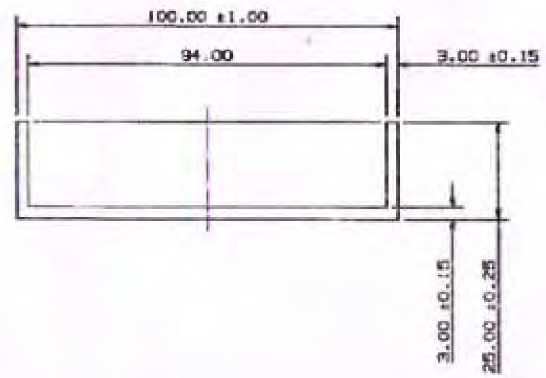
UDL = 1.75 x 1.28
(2.2KN)

M^* = 2.48KN.m

V^* = 5.6KN

Note: This calculation does not apply to the new fabricated louvre in the southwestern section, and is based on the existing design which has been refurbished, and secured at top and bottom only. New louvre in southwest section will have less buckling as a result of the extra PFCs and brackets installed about the waist line as an extra.

SECTION NO. 910-237



TOTAL SURFACE EXPOSED

SECTION DATA:
I_{xx} = 19 872 mm^4
I_{yy} = 580 598 mm^4
Theta= 1.0 °
$RadG_x$ = 7. mm
$RadG_y$ = 36. mm
XC_{max} = 50.0 mm
XC_{min} = 50.0 mm
YC_{max} = 19.7 mm
YC_{min} = 5.3 mm
Z_x top = 1 010 mm^3
Z_x bot = 3 736 mm^3
Z_y right = 11 212 mm^3
Z_y left = 11 212 mm^3

0.40 RADIUS ON ALL OUTSIDE CORNERS
UNLESS OTHERWISE SPECIFIED

EXTRUDED FINISH : ARCHITECTURAL

AREA	432.0	SQ MM
WEIGHT	1.171	KG M
PERIMETER	284.0	MM
	284.0	MM
	284.0 [0.0]	MM
C-CIRCLE DIA	103.	MM
FACTOR	251.	
ALLOY	6063	
TEMPER	T6	

NO	DATE	BY	REVISION

G. James Extrusion Co.

CUSTOMER: G. JAMES EXTRUSION Co.

CUSTOMER PART NAME: 100 x 25 x 3.0 CHANNEL

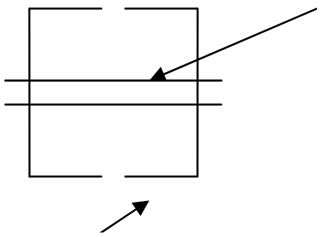
SCALE: 1:1

DRAWN: SPG

DATE: 28/09/01

DWG NO: 910-237

Section: Alloy **6060-T5 (Note:** *alloy for new louvre in Southwest section is actually **6351 T6**. **6060 T5** used for conservative calculation only*). Section Data is based on G James Drawing **910-237**.



100 x 30 x 3 Channel · 2 off, connected via bolt.

$Ix = 1.26 \times 10^6\ mm^4$

$Iy = 0.566 \times 10^6$

$Ag = 924mm^2$ $J = 1.19 \times 10^6 mm^4$

Buckling Constant:

Bp=134.28 Bc= 119

Cp= 94 Cc= 95

Dp= 0.60 Dc= 0.49

Lateral Buckling

Slenderness Ratio: LbSc **/ [**0.5 x $(IYJ)^{0.5}$**]** = 1852
Limits $S_1 = 12$ $S_2 = 3854$

Lateral Buckling; $\Phi F_L = \Phi_b$ [Bc -1.6Dc x **[**LbSc **/ [**0.5 x √ $(IYJ)^{0.5}$**]**
= 73MPa

Local Bucking 1/ Plate slenderness (flange)

= 60/3
= 20

$\Phi F_L = \Phi_b [B_p\text{-}1.6Dp \times (b/t)] = 98$ MPa

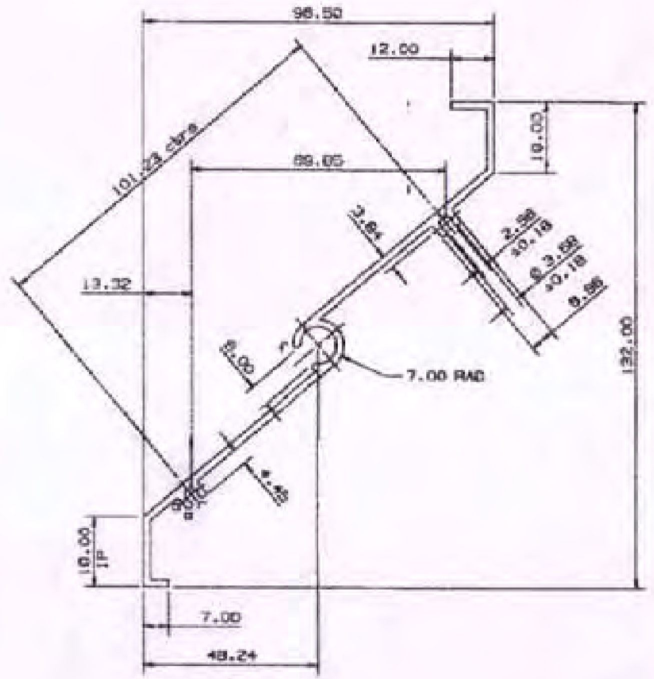
Local Buckling 2/ Plate slenderness (web)

160/3 = 53.3
$\Phi F_L = 1.3\phi yFcy$ =136MPa
$\Phi F_L =$ 73Mpa (*lateral Buckling critical*)

Under wind load M^*_{max}=2.48 kN.m Φ_{max}=9.8MPa **Acceptable!**

ATTN: GEORGE (? PAGES)

415-139



TOTAL SURFACE EXPOSED

MOMENTS OF INERTIA:
Iu = 638833 mm⁴
Iw = 445188 mm⁴

a = 0.80 radius
ř = full radius
r = radius to suit (approx 0.8)

2.00±0.15 TYP WALL THICKNESS UNLESS OTHERWISE SPECIFIED

0.40 RADIUS ON ALL OUTSIDE CORNERS UNLESS OTHERWISE SPECIFIED

EXTRUDED FINISH : ARCHITECTURAL

AREA	452.6
WEIGHT	1.227
PERIMETER	448.2
	446.2
	446.2
C CIRCLE DIA	164
FACTOR	366
ALLOY	6060
TEMPER	T5

G. James Extrusion Co.

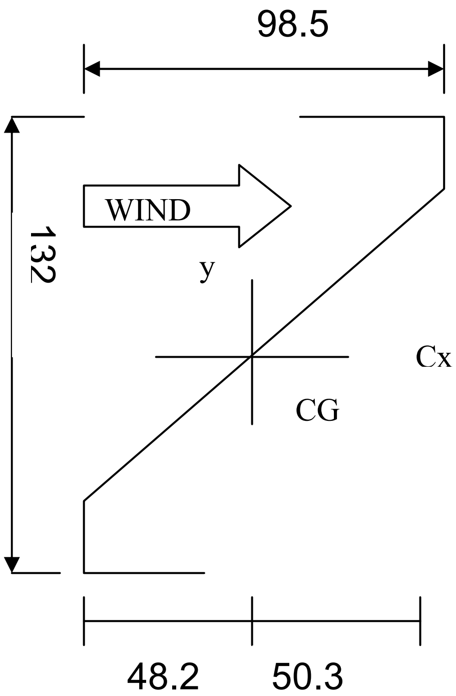
G. JAMES COMMERCIAL DIV.

LOUVRE BLADE

1:1

L.Y. 02/10/85 415-139

At Louvre ; **Alloy 6060-T5**. Section Data is based on G James Drawing **415-319**.
Note: *Although **6060 T5** material was incorporated for the calculations in the new louvre profiles for the Southwest section, the actual material is **6063 T6**. This calculation has been intentional to assume a conservation result and base it on an approximately 15% reduction in strength.*



Area = 453mm^2

Ixx = 0.64 x 10^6 mm^2
Iyy = 0.45 x 10^6 mm^4

Zx = (0.64 x 10^6) / (132/2) = 9.7 x 10^3 mm^2
Zy = (0.45 x 10^6) / (50.3) =8.9 x 10^{3}mm^3

Radius of Gyration:
rx = 37mm
ry = 31.5mm

Torsion Constant:
J= 1/3(130 +19 x 2+ 7 +12) x 2^3
= 500

Ultimate wind* = 1.28 kPa / (pressure)
Line load = 1.28 x 0.132 = 0.17kN/m
Service Wind* = 0.85 kPa
Line Load = <u>0.11 kN/m</u>

Max deflection under service load

$$\delta_{\max} = \frac{5}{385} \times \frac{0.11 \times 1750^4}{70 \times 10^3 \times 0.45 \times 10^6} = 0.43\ mm$$

<u>Serviceability acceptable</u> eg span/4100

Design M* = 0.125 x 0.17 x 1.75^2 = 0.065 KN.m
R* = ½ x 0.17x1.75 = 0.15KN
2 rivets are acceptable
Assume, flat plate supported on two sides
bw = 160mm
tw = 2mm
bw / tw = 80

Local Buckling

Slenderness limits:

$$S_1 = \frac{B_P - \phi y \times Fcy \;/\phi b}{k_1 \times bp \;/1.6Dp} = 12$$

$$S_2 = \frac{k_1 Bp}{1.6Dp} = 12 = 50$$

Buckling Constants for alloy 6060 T5

Bp= 134.3
Cp= 93.6
Dp= 0.60

bw / tw > S_2

Therefore $\phi F\angle = K2\sqrt{Bp \times E} \Big/ 1.6(bw/tw) = 46MPa$

σ max under ultimate wind load

= 0.065 x 10^6/8.9 x 10^3 = 7.3 MPa < 46 MPa
Strength Acceptable!

There is no chance of flexural lateral buckling as bending is around weak axis.

Top level new struting members

V_{DES} = 52 m/s
Basic Wind pressure= 1.6 kPa
Loading Cpn = 1.3
qz = 1.3 x 1.6 = **2.1 kPa**

*for pressure and suction

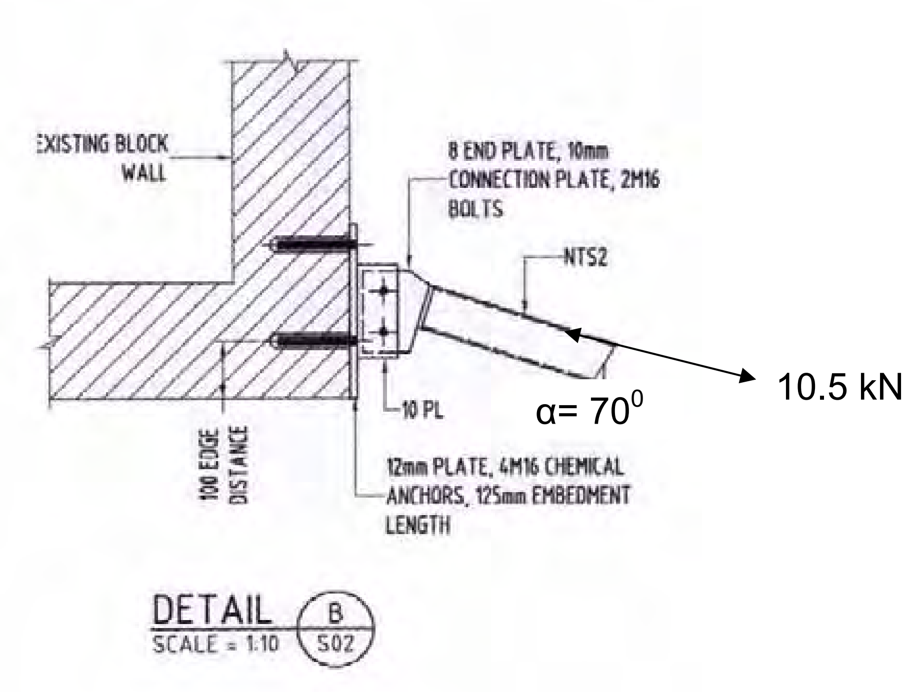
NST2

Tributary Area= 3.3 x 1.5= 5m^2
F^*= 5.0 x 2.1 = **10.5 kN**

NST2 = 75 x 75 x 4.0 Square Hollow Section (Grade C350)
Length = 4800mm
Compression = ΦNs = 340 kN
capacity = ΦNc = 64 kN > F^* **Acceptable!**

Tension
capacity = ΦN_T = 340 kN **Acceptable!**

Connecting plate: NTS2



Say V^* on each bolt= 10.5/2= 5.3 kN
For M16 4.6/s Bolt
ΦV_f = 28.6KN > V^* **Acceptable!**
Required 6mm Fillet weld.
(10.5KN) / (0.835KN/mm) = 12mm

More than required, hence acceptable!
***Forces applied on chemical anchors:**

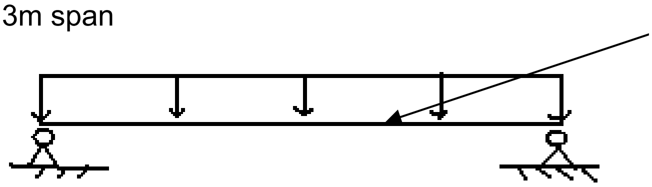
Shear $V^* = 10.5 \times \cos 72^0 / 4 = 0.8$ kN

Tension $T^* = 10.5 \times \sin 72^0 / 4 = 2.5$ kN

NBA – 150PFC

(New beam all along the Eastern face (See appendix A).

4.3m span



= 3.2 x 2/3 = 2.1 kN/m
(service)

Max deflection at mid span.

δ_{max}= 5/384 x ((2.1 x 4300^4) / (200 x 10^3 x 8.3 x 10^6)) = 5.6mm
(Horizontally)

Eg = span / 760 **Acceptable for serviceability**!

Ultimate: M^*= 1/8 x 3.2 x 4.3^2 = 7.4 kN.m
Segment: Lay = 4300mm

Effective length Le= Lay x Kt Kl Kr = 4300
Slenderness Ratio = ∟ay/ ry = 180

α_m = 1.13 (for uniformly distributed load)
α_s = 0.46
$\alpha_s\alpha_m$ = 0.52

ΦMsx = 0.9 x 300MPa x Zex =37 kN.m
ΦMbx = ΦMsx . α_s . α_m = 37 x 0.52 = 11 kN.m
> M^*= 7.4

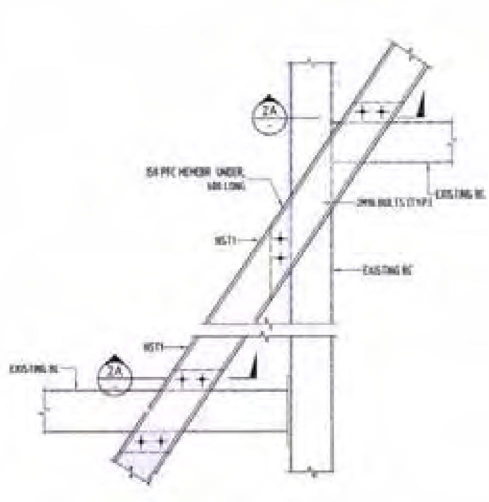
Ultimate strength acceptable!

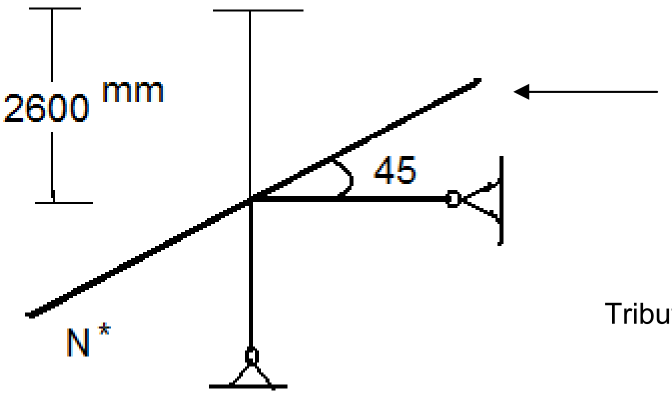
Support reaction R^*= ½ x 3.2 x 4.3
= 6.9 kN
Say 2M16 4.6/s Bolts for the connection.

Bolt capacity ΦV_f= 28.6 x 2 = 57 kN (total) > R^*=6.9
[*thread included in the shear plane*]

Bolt and weld at connection acceptable!

NST1 Span 4.5m for Compression





F* = 5.0 x 2.1 kPa
= 10.5 kN

Tributary Area = 3.2 x 1.5
= 5m^2

Axial Force:

$N^* = F^* / \cos 45^0$
= 14.8 kN

Buckling Length = 4.5m

Modified slenderness ratio: $\lambda_{ny} = \frac{Le}{r}\sqrt{Kr} \times \sqrt{\frac{fsy}{250}}$

= 213

Buckling Constant:

α_b= 0.5
α_c= 0.15

Section Capacity; ΦNs = 0.9 x fsy x An x Kf = 648 kN
Member Capacity; ΦNc = α_C x ΦNs = 98 kN
>14.8 kN = N^*

Ultimate Compression strength Acceptable!

Use 2M20 4.6/s Bolts
Shear capacity ΦV_f = 44.6KN (*thread included*) **Acceptable!**

Flexural Capacity: (*Conservatively ignore the splice section*)

M^*= 2.6 x 10.5= 27.3 kN.m

Section: ΦM_{sx}=37 kN.m

Lay = 3500^{mm}

α_m = 1.75
α_s = 0.46

Member: $\Phi M_{bx} = \Phi M_{sx} \times \alpha_{m} \times \alpha_s$
= 37 x 1.75 x 0.46 = 29 kN.m > M^*=27

Ultimate flexural strength is acceptable!

Appendix R

Tables and calculations for *Hilti* chemical anchors.

Hilti AG. International data

Basic loading data (for a single anchor): HVU capsule with HAS-E, HAS-E-F

All data on this page applies to

- concrete: See table below.
- correct setting (See setting operations page 49)
- no edge distance and spacing influence
- steel failure: steel grade 5.8 for M8 – M24 sizes and steel grade 8.8 for M27 – M39

CONC	non-cracked concrete

Characteristic resistance, R_k [kN]: concrete ≡ C20/25

Anchor size	M8	M10	M12	M16	M20	M24	M27	M30	M33	M36	M39
Tensile, N_{Rk}	16.4	26.1	38.1	72.2	112.7	162.0	182.4	228.0	440.9	494.0	503.2
Shear, V_{Rk}	9.9	16.8	22.9	43.2	67.5	97.0	206.0	249.1	310.5	364.4	436.3

Following values according to the

Concrete Capacity Method

Design resistance, R_d [kN]: concrete, $f_{ck,cube}$ = 25 N/mm^2

Anchor size	M8	M10	M12	M16	M20	M24	M27	M30	M33	M36	M39
Tensile, N_{Rd}	12.3	16.6	23.8	34.7	62.9	90.6	110.9	145.6	171.0	203.3	232.9
Shear, V_{Rd}	7.9	12.6	18.3	34.6	54.0	77.8	164.0	199.3	248.4	291.5	350.6

Table 1

Features:	
	- foil capsule vs. glass
	- flexible for inserting into crooked / irregular holes
	- pre-setting / through-setting
	- specials lengths available on request
	- test reports: fire, dynamic (fatigue, shock, seismic), water tightness
Material:	
HVU:	- urethane methacrylate resin – styrene free, hardener, quartz sand or corundum, foil tube
HAS-E:	- grade 5.8 and 8.8, ISO 898 T1, zinc plated to min. 5 microns
HAS-E-F:	- grade 5.8 + 8.8, ISO898 T1, hot dipped galvanised to min 40 microns
HAS-ER:	- stainless steel; A4-70; 1.4401, 1.4404, 1.4571
HAS-HCR:	- stainless steel; A4-70; 1.4529 (High corrosion resistant)

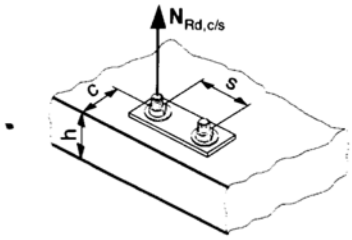
HVU

ULTIMATE LIMIT STATE DESIGN METHOD

(Detailed design method - Hilti CC)

(The Hilti CC method is a simplified version of ETAG Annex C.)

Caution: In view of the high loads transferable with HVU, it must be verified by the user that the load acting on the concrete structure, including the loads introduced by the anchor fastening, do not cause failure, e.g. cracking, of the concrete structure.



TENSION

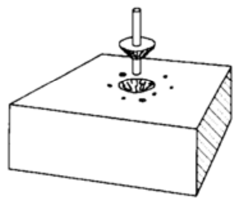
The design tensile resistance of a single anchor is the lower of

$N_{Rd,c}$: concrete cone/pull-out resistance

$N_{Rd,s}$: steel resistance

$N_{Rd,c}$: Concrete cone/pull-out resistance

$$N_{Rd,c} = N^{o}_{Rd,c} \cdot f_{B,N} \cdot f_{T} \cdot f_{A,N} \cdot f_{R,N}$$



$N^{0}_{Rd,c}$: Concrete cone/pull-out design resistance

- Concrete compressive strength, $f'_{c,cyl}$ = 20 MPa

Anchor size	M8	M10	M12	M16	M20	M24	M30	M36
$N^{0}_{Rd,c}$ [1] [kN]	12.4	16.6	23.8	34.7	62.9	90.6	145.6	203.3
h_{nom} [mm] Nominal anchorage depth	80	90	110	125	170	210	270	330

1) The design tensile resistance is calculated from the characteristic tensile resistance, $N^{o}_{Rk,c}$, by $N^{o}_{Rd,c} = N^{o}_{Rk,c}/\gamma_{mc,N}$, where the partial safety, $\gamma_{mc,N}$, factor is 1.8.

$f_{B,N}$: Influence of concrete strength

Cylinder compressive strength, $f'_{c,cyl}$ [MPa]	$f_{B,N}$
20	**1.0**
25	**1.05**
32	**1.15**
40	**1.25**
50	**1.35**

Limits:
20 MPa $\leq f'_{c,cyl} \leq$ 50 MPa

f_T : Influence of anchorage depth

$$f_T = \frac{h_{act}}{h_{nom}}$$

Limits to actual anchorage depth h_{act}: $h_{nom} \leq h_{act} \leq 2.0\ h_{nom}$

$f_{A,N}$: Influence of anchor spacing

Anchor spacing, s [mm]	Anchor size							
	M8	M10	M12	M16	M20	M24	M30	M36
40	0.63							
45	0.64	0.63						
50	0.66	0.64						
55	0.67	0.65	0.63					
60	0.69	0.67	0.64					
65	0.70	0.68	0.65	0.63				
70	0.72	0.69	0.66	0.64				
80	0.75	0.72	0.68	0.66				
90	0.78	0.75	0.70	0.68	0.63			
100	0.81	0.78	0.73	0.70	0.65			
120	0.88	0.83	0.77	0.74	0.68	0.64		
140	0.94	0.89	0.82	0.78	0.71	0.67	0.63	
160	1.00	0.94	0.86	0.82	0.74	0.69	0.65	
180		1.00	0.91	0.86	0.76	0.71	0.67	0.64
200			0.95	0.90	0.79	0.74	0.69	0.65
220			1.00	0.94	0.82	0.76	0.70	0.67
250				1.00	0.87	0.80	0.73	0.69
280					0.91	0.83	0.76	0.71
310					0.96	0.87	0.79	0.73
340					1.00	0.90	0.81	0.76
390						0.96	0.86	0.80
420						1.00	0.89	0.82
450							0.92	0.84
480							0.94	0.86
540							1.00	0.91
600								0.95
660								1.00
720								

Note: For multiple anchor fixings, the anchor capacity is influenced by neighbouring anchors. As a result, the individual anchor spacing influence factor $f_{A,N}$, for the adjacent anchors are multiplied by each other to determine the total reduction factor.
(See page 44 and worked example page 159).

$$f_{A,N} = 0.5 + \frac{s}{4h_{nom}}$$

Limits: $s_{min} \leq s \leq s_{cr,N}$
$s_{min} = 0.5 \cdot h_{nom}$
$s_{cr,N} = 2.0 \cdot h_{nom}$

$f_{R,N}$: Influence of edge distance

Edge distance, c [mm]	Anchor size							
	M8	M10	M12	M16	M20	M24	M30	M36
40	0.64							
45	0.69	0.64						
50	0.73	0.68						
55	0.78	0.72	0.64					
60	0.82	0.76	0.67					
65	0.87	0.80	0.71	0.65				
70	0.91	0.84	0.74	0.68				
80	1.00	0.92	0.80	0.74				
90		1.00	0.87	0.80	0.66			
100			0.93	0.86	0.70			
110			1.00	0.91	0.75	0.66		
120				0.97	0.79	0.69		
140				1.00	0.87	0.76	0.65	
160					0.96	0.83	0.71	
180					1.00	0.90	0.76	0.67
210						1.00	0.84	0.74
240							0.92	0.80
270							1.00	0.87
300								0.93
330								1.00
360								

Note: If an anchor is influenced by more than 1 concrete edge, the individual edge distance influence factor $f_{R,N}$, for each edge are multiplied by each other to determine the total reduction factor.
(See page 44 and worked example page 159).

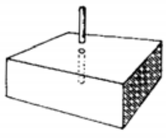
$$f_{R,N} = 0.28 + 0.72\frac{c}{h_{nom}}$$

Limits: $c_{min} \leq c \leq c_{cr,N}$
$c_{min} = 0.5 \cdot h_{nom}$
$c_{cr,N} = 1.0 \cdot h_{nom}$

Note: If more than 3 edges are smaller than $c_{cr,N}$, consult your Hilti technical advisory service.

$N_{Rd.s}$ [1)] : Steel design tensile resistance

Anchor size	M8	M10	M12	M16	M20	M24	M30	M36
HAS-E/E-F grade 5.8[2)][kN]	10,9	17,4	25,4	48,1	75,1	108,1	*173,0*	*253,1*
HAS-E/E-F grade 8.8[2)][kN]	*17,5*	*27,9*	*40,7*	*78,9*	*120,1*	*172,9*	276,8	404,9
HAS-E-R,HAS-HCR[2)3)][kN]	12,3	19,6	28,6	54,0	84,3	121,0	*108,1*	*158,2*



1) The design tensile resistance is calculated from the characteristic tensile resistance, $N_{Rk,s}$, using $N_{Rd,s} = A_s * f_{uk} / \gamma_{Ms,N}$, where the partial safety factor, $\gamma_{Ms,N}$, for grade 5.8 and 8.8 is 1.5; 1.87 for grades A4-70 and HCR of the M8 to M24 sizes and 2.4 for grades A4-70and HCR in the sizes M30 – M36.

2) Data given in *italics* applies to non-standard rods.

3) Note: The values for the nominal tensile steel strength, f_{uk}, for grade A4 change for the M30 to M36 sizes from 700 MPa to 500 MPa and the yield strength, f_{yk}, changes for the M30 to M36 sizes from 450 MPa to 250 MPa. The partial safety factor, $\gamma_{Ms,N}$, changes with the steel strengths as stated in note 1) above.

N_{Rd} : Limit state tensile capacity

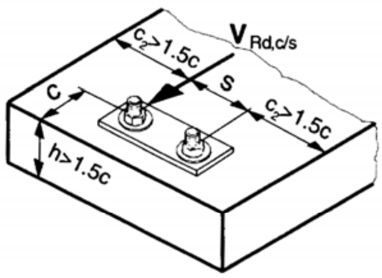
N_{Rd} = lower of $N_{Rd,c}$ and $N_{Rd,s}$

Check **$N_{Rd} \geq N^*$**

ULTIMATE LIMIT STATE DESIGN METHOD

(Detailed design method – Hilti CC)

(The Hilti CC method is a simplified version of ETAG Annex C.)



Note: If the conditions for h and c_2 are not met, consult your Hilti technical advisory service.

SHEAR

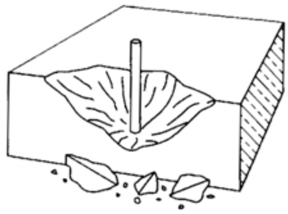
The design shear resistance of a single anchor is the lower of

- $V_{Rd,c}$: concrete edge resistance
- $V_{Rd,s}$: steel resistance

$V_{Rd,c}$: Concrete edge design resistance

The lowest concrete edge resistance must be calculated. All near edges must be checked, (not only the edge in the direction of shear). The direction of shear is accounted for by the factor $f_{\beta,V}$.

$$V_{Rd,c} = V^0_{Rd,c} \cdot f_{B,V} \cdot f_{AR,V} \cdot f_{\beta,V}$$



$V_{Rd,c}$: Concrete edge design resistance

- Concrete compressive strength, $f'_{c,cyl}$ = 20 MPa
- at a minimum edge distance c_{min}

Anchor size		M8	M10	M12	M16	M20	M24	M30	M36
$V^o_{Rd,c}$ 1)	[kN]	2.6	3.4	5.0	6.7	12.4	18.5	30.2	44.3
c_{min} min. edge distance	[mm]	40	45	55	65	85	105	135	165

1) The design shear resistance is calculated from the characteristic shear resistance, $V^o_{Rk,c}$, using $V^o_{Rd,c} = V^o_{Rk,c}/\gamma_{Mc,V}$, where the partial safety factor, $\gamma_{Mc,V}$, is 1.8.

***available, subject to lead time. Please contact your local Hilti Engineer.**

$f_{B,V}$: Influence of concrete strength

Cylinder compressive strength, $f'_{c,cyl}$ [MPa]	$f_{B,V}$
20	1.0
25	1.10
32	1.26
40	1.41
50	1.55

Limits:
20 MPa ≤ $f'_{c,cyl}$ ≤ 50MPa

$f_{AR,V}$: Formulae for edge distance and spacing influence

Formula for single-anchor fastening influenced only by edge

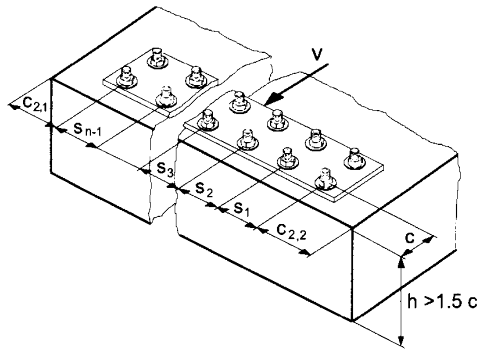
$$f_{AR,V} = \frac{c}{c_{min}}\sqrt{\frac{c}{c_{min}}}$$

Formula for two-anchor fastening (edge plus 1 spacing) only valid for s < 3c

$$f_{AR,V} = \frac{3c+s}{6c_{min}}\sqrt{\frac{c}{c_{min}}}$$

General formula for n-anchor fastening (edge plus n-1 spacing) only valid where s_1 to s_{n-1} are all < 3c and c2 > 1.5c

$$f_{AR,V} = \frac{3c+s_1+s_2+\ldots+s_{n-1}}{3nc_{min}} \cdot \sqrt{\frac{c}{c_{min}}}$$



Note: It is assumed that only the row of anchors closest to the free concrete edge carries the centric shear load.

n = number of anchors in a row closest to the free concrete edge

$f_{AR,V}$: Influence of edge distance and spacing

$f_{AR,V}$	c/c_{min} → 1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0
Single anchor with edge influence,	1.00	1.31	1.66	2.02	2.41	2.83	3.26	3.72	4.19	4.69	5.20	5.72	6.27	6.83	7.41	8.00
s/c_{min} ↓ 1.0	0.67	0.84	1.03	1.22	1.43	1.65	1.88	2.12	2.36	2.62	2.89	3.16	3.44	3.73	4.03	4.33
1.5	0.75	0.93	1.12	1.33	1.54	1.77	2.00	2.25	2.50	2.76	3.03	3.31	3.60	3.89	4.19	4.50
2.0	0.83	1.02	1.22	1.43	1.65	1.89	2.13	2.38	2.63	2.90	3.18	3.46	3.75	4.05	4.35	4.67
2.5	0.92	1.11	1.32	1.54	1.77	2.00	2.25	2.50	2.77	3.04	3.32	3.61	3.90	4.21	4.52	4.83
3.0	1.00	1.20	1.42	1.64	1.88	2.12	2.37	2.63	2.90	3.18	3.46	3.76	4.06	4.36	4.68	5.00
3.5		1.30	1.52	1.75	1.99	2.24	2.50	2.76	3.04	3.32	3.61	3.91	4.21	4.52	4.84	5.17
4.0			1.62	1.86	2.10	2.36	2.62	2.89	3.17	3.46	3.75	4.05	4.36	4.68	5.00	5.33
4.5				1.96	2.21	2.47	2.74	3.02	3.31	3.60	3.90	4.20	4.52	4.84	5.17	5.50
5.0					2.33	2.59	2.87	3.15	3.44	3.74	4.04	4.35	4.67	5.00	5.33	5.67
5.5						2.71	2.99	3.28	3.57	3.88	4.19	4.50	4.82	5.15	5.49	5.83
6.0						2.83	3.11	3.41	3.71	4.02	4.33	4.65	4.98	5.31	5.65	6.00
6.5							3.24	3.54	3.84	4.16	4.47	4.80	5.13	5.47	5.82	6.17
7.0								3.67	3.98	4.29	4.62	4.95	5.29	5.63	5.98	6.33
7.5									4.11	4.43	4.76	5.10	5.44	5.79	6.14	6.50
8.0										4.57	4.91	5.25	5.59	5.95	6.30	6.67
8.5											5.05	5.40	5.75	6.10	6.47	6.83
9.0											5.20	5.55	5.90	6.26	6.63	7.00
9.5												5.69	6.05	6.42	6.79	7.17
10.0													6.21	6.58	6.95	7.33
10.5														6.74	7.12	7.50
11.0															7.28	7.67
11.5																7.83
12.0																8.00

**These results are for a two-anchor fastening.
For fastenings with more than two anchors, use the general formulae for n anchors.**

$f_{\beta,V}$: Influence of shear loading direction

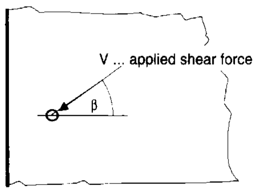
Angle, β [°]	$f_{\beta,V}$
0 to 55	1
60	1.1
70	1.2
80	1.5
90 to 180	2

Formulae:

$f_{\beta,V} = 1$ for $0° \le \beta \le 55°$

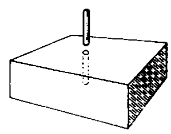
$f_{\beta,V} = \dfrac{1}{\cos\beta + 0.5\sin\beta}$ for $55° < \beta \le 90°$

$f_{\beta,V} = 2$ for $90° < \beta \le 180°$



$V_{Rd,s}$ [1] : Steel design shear resistance

Anchor size	M8	M10	M12	M16	M20	M24	M30	M36
HAS-E/E-F grade 5.8[2] [kN]	7.9	12.6	18.3	34.6	54.0	77.8	*124.6*	*182.2*
HAS-E/E-F grade 8.8[2] [kN]	*12.6*	*20.1*	*29.3*	*55.3*	*86.4*	*124.4*	199.3	291.5
HAS-E-R, HAS-HCR[2) 3)] [kN]	8.8	14.1	20.5	38.8	60.6	87.2	*77.9*	*113.9*



1) The design shear resistance is calculated using $V_{Rd,s}$= (0.6 A_s f_{uk})/$\gamma_{Ms,V}$. The values for the stressed cross-section, A_s, and the nominal tensile strength of steel, f_{uk}, are given in the table "Anchor mechanical properties and geometry". The partial safety factor, $\gamma_{Ms,V}$, is 1.25 for grades 5.8 and 8.8; 1.56 for grade sA4-70 and HCR in the sizes M8 to M24, and 2.0 for grade A4-70 in the sizes M30 to M36.

2) Data given in *italics* applies to non-standard rods.

3) Note: The values for the nominal tensile strength of steel, f_{uk}, for grade A4-70 change for the M27 to M39 sizes from 700 MPa to 500 MPa and the yield strength, f_{yk}, changes for the M30 to M36 sizes from 450MPa to 250MPa. The partial safety factor, $\gamma_{Ms,V}$, changes the steel strengths as stated in note 1) above.

V_{Rd} : Limit state shear capacity

V_{Rd} = lower of $V_{Rd,c}$ and $V_{Rd,s}$

Check **$V_{Rd} \ge V^*$**

Appendix S

Effect of pressure and suction wind forces on serviceability of façade louvre brackets and bolts in accordance with AS1170 Part 2:2002.

Effect of Pressure and Suction wind force on serviceability of façade louvre bracket and bolt in accordance with AS1170 Part 2 – 2002

Calculations for louvre system and roof for Westfields building Bondi Junction.

Ultimate Wind Pressure on Windward Force

(Refer to 1170.2 for building shape factor)

0.8 x 1.6 = 1.28 kPa (1) as calculated in appendix P

(0.8 is taken as the factor for wind pressure)

(Due to the permeability of louvre, the internal suction is ignored)

(1.28x1.75/2)/ 0.06m = **18.7 kPa** is exerted on the 60 x 25 angle face.

This is the line force acting upon the angle.

(*Note: 0.06 m is the face width of the angle and 1.75 m is the louvre half width*).

Ultimate Wind Suction

0.5 x 1.6 = 0.8 kPa (2) as calculated in appendix P

(0.5 is taken as the factor for wind suction)

(0.8x1.75/2) / 0.06 **= 11.7 kPa**

is exerted on the angle face which now suggests that the angle is now in tension. A typical angle bracket is shown in **Figure 7.6,** and the construction is secured to louvre and chemical anchored to building concrete.

Loading Ratio of Ultimate Serviceability

$(37/45)^2 = 0.67$

Combined Displacement (maximum) for 1:20 years return period

(**SUCTION**) = 0.67 x 8.6mm = 5.8mm = Span/120

(**PRESSURE**) = 0.67 x 3.6mm = 2.4mm = Span/290

Note: 8.6 mm and 3.6 mm are deflection results from FEA computation.

5.8 mm and 2.4 mm are the deflection in the total length of the 60 mm x 25 mm x 3 mm unequal angle.

Angle + Concrete

Bolt Strength: (mid Bracket Connection)

Pressure

Pressure exerted against the louvre is shown in **Figure 7.9 & 7.11** on the bracket and concrete. The bolt position and forces acting on the bracket is shown schematically.

F* = 1.12 x 0.7 m = 0.78 kN/m

(0.7 m is taken as the total distance either side of the centre bolt-bracket)

Bolt M10 *Hilti* chemical anchor.

M = F x d

Then moment about the two lapped regions is:

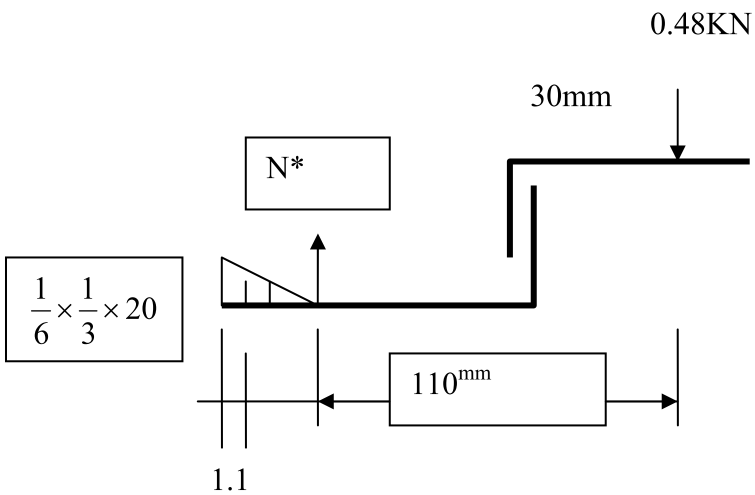
N* = Pullout force

N* x 80 = 0.78 x 30 (30 mm being the half distance of the 60 mm angle face)

N* = 0.3 kN, therefore the pullout force on the bolt is minimal.

Since the force is acting under pressure, then that bracket anchored into the wall is preventing any further pressure. The concrete wall is actually supporting this minimal load. An illustration of suction acting against louvre, the bracket and the forces on the bolt as shown below.

Suction:



Forces acting on bracket under influence of Suction.

From equation (2), the Suction force is 0.8 KN,

Therefore, 0.8 x 1.75/2 = 0.7 kN/m

Again taking the distance in the vertical section of the angle as 0.7 m, *i.e.*, 350 mm either side of the middle bracket vertically, we have;

0.7 kN/m x 0.7 m = 0.49 kN

The bending moment is as follows:

M*= 0.49 x 0.11= 0.054 Nm. Thus, N* x (20-20x1/6x1/3) = 0.49x(110+20-20x1/6x1/3)

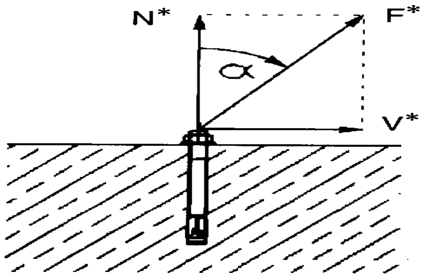
N*=3.4 kN (Applied on chemical anchor)

Appendix T

Load-under-angle calculations for anchor bolts securing brackets on façade.

Load-Under-Angle Calculation for anchor bolt securing brackets on façade

$F^*(\alpha) \leq F_{Rd}(\alpha)$, Where $F^*(\alpha)$ = Design action at angle, $F_{Rd}(\alpha)$ = Final design force.



$F^* = [(N^{*2}) + (V^{*2})]^{0.5}$

$\alpha = \arctan V^*/N^*$

Where:

N^* = Tensile component

V^* = Shear component

Combined loads: (NOTE: refer to diagrams in Hilti [139] handbook to use in formulas)

Anchor stability – Method (1)

$$\left(\frac{N^*}{N_{Rd}}\right)^{\alpha} + \left(\frac{V^*}{V_{Rd}}\right)^{\alpha} \leq 1$$

N* + V* ……………(1) **See parabolic curve below.**

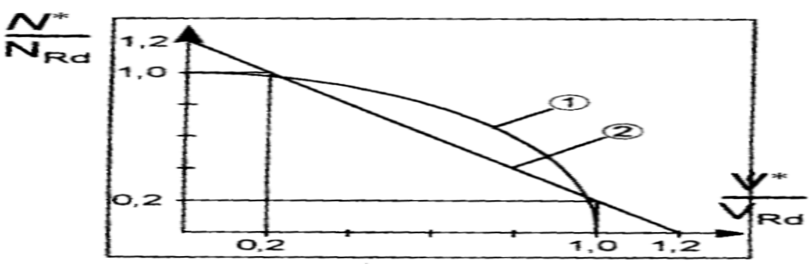
$\alpha = 2.0$ If N_{Rd} and V_{rd} are governed by steel failure

$\alpha = 1.5$ For all other failure modes

Anchor stability – Method (2)

$$\left(\frac{N^*}{N_{Rd}}\right)^{\alpha} + \left(\frac{V^*}{V_{Rd}}\right)^{\alpha} \leq 1.2$$

…………..(2) **See straight line linear relationship below.**



Anchor stability method diagram [139].

Working loads:

To convert limit state capacity to working loads

$$N_{rec} = \frac{N_{Rd}}{1.4} \qquad V_{rec} = \frac{V_{Rd}}{1.4}$$

Appendix U

Calculations for ultimate limit state design method incorporating the 50 mm edge for anchor on façade.

$N_{Rd,c}$ = Concrete cone/pullout resistance

$f_{B,N}$ = Concrete strength as a factor

f_T = Influence of anchor depth as a factor

$f_{A,N}$ = Influence of anchor spacing

$f_{R,N}$ = Influence of edge distance

Hence, $N_{Rd,c} = N^0_{Rd,c} \times f_{B,N} \times f_T \times f_{A,N} \times f_{R,N}$. [139]

$N^0_{Rd,c}$ = 16.6 KN as per data for M10 anchor bolt,

$f_{B,N}$ = 1.0 @ (at 20 MPa concrete strength)

Note: *I have deliberately assumed the concrete strength to be at its weakest i.e.,* ***20 MPa.*** *In fact the concrete strength is rated at* ***32 MPa*** *Minimum for the Westfield building. This allows for a conservative calculation.*

$f_{B,N}$ = 1.0 (Assuming 20Mpa for concrete. Higher concrete strength increases the factor value further)

f_T = 1.0 (90/90 =1 from table assuming that we have inserted the anchor to correct depth of 180mm)

$f_{A,N}$ = 1.0 (data for anchor spacing is N/A since we are only using single anchor)

$f_{R,N}$ = 0.28 + 0.72 (50/90) (50 mm is the edge distance, 90 mm is the recommended edge distance,

$f_{R,N}$ = 0.68

Hence, $N_{Rd,c}$ = 16.6 x 1.0 x 1.0 x 1.0 x 0.68 = **11.288 kN**

If we are to repeat the above for an edge distance of 80 mm, we would have:

$N_{Rd,c}$ = 16.6 x 1.0 x 1.0 x 1.0 x 0.92 = **15.272 kN**

Appendix V1

Typical extruded aluminium angles with moment and gyration data.

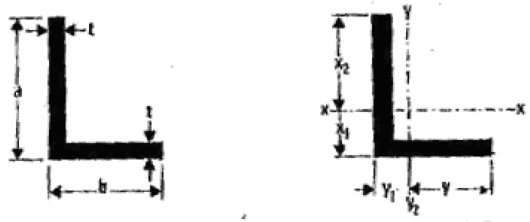


Table 4.1: Angles – Architectural

Size	Thick-ness	Mass per Metre	Area	Distance of neutral axis from extreme fibres				Second moment of Area		Radius of Gyration		Moduli of Section			
a x b	t			x_1	x_2	y_1	y_2	I_x	I_y	r_x	r_y	Z_{x_1}	Z_{x_2}	Z_{y_1}	Z_{y_2}
mm	mm	kg/m	mm^2	mm	mm	mm	mm	mm^4	mm^4	mm	mm	mm^3	mm^3	mm^3	mm^3
12 x 10	3	0.164	57.00	4.34	7.66	3.34	6.66	716	444	3.55	2.79	165	94	133	67
12 x 12	1.6	0.097	35.84	3.59	8.41	3.59	8.41	475	475	3.64	3.64	132	56	132	56
12 x 12	2.5	0.145	53.75	3.90	8.10	3.90	8.10	672	672	3.53	3.53	172	83	172	83
12 x 12	3	0.170	63.00	4.07	7.93	4.07	7.93	765	765	3.48	3.48	188	96	188	96
20 x 12	1.6	0.131	48.64	6.85	13.15	2.85	9.15	1997	551	6.41	3.37	291	152	193	60
20 x 12	2.5	0.199	73.75	7.18	12.82	3.18	8.82	2912	784	6.28	3.26	405	227	247	89
20 x 12	3	0.235	87.00	7.36	12.64	3.36	8.64	3366	898	6.22	3.21	457	266	267	104
25 x 12	1.6	0.153	56.64	9.06	15.94	2.56	9.44	3695	581	8.08	3.20	408	232	227	62
25 x 12	3	0.275	102.0	9.59	15.41	3.09	8.91	6329	953	7.88	3.06	660	411	309	107
32 x 12	1.6	0.183	67.84	12.27	19.73	2.27	9.73	6502	613	9.79	3.01	530	330	270	63
32 x 12	3	0.332	123.0	12.82	19.18	2.82	9.18	12642	1013	10.14	2.87	986	659	360	110
40 x 12	1.6	0.218	80.64	16.04	23.96	2.04	9.96	8072	639	10.00	2.82	503	337	314	64
40 x 12	3	0.397	147.0	16.60	23.40	2.60	9.40	23564	1066	12.66	2.69	1419	1007	410	113
50 x 12	1.6	0.261	96.64	20.83	29.17	1.83	10.17	24738	663	16.00	2.62	1187	848	362	65
50 x 12	3	0.478	177.0	21.42	28.58	2.42	9.58	43908	1119	15.75	2.51	2050	1536	463	117
16 x 16	1.6	0.131	48.64	4.59	11.41	4.59	11.41	4180	4180	9.27	9.27	911	366	911	366
16 x 16	3	0.235	87.00	5.09	10.91	5.09	10.91	1963	1963	4.75	4.75	386	180	386	180
25 x 16	1.6	0.170	63.04	8.22	16.78	3.72	12.28	4089	1342	8.05	4.61	497	244	360	109
25 x 16	2.5	0.260	96.25	8.56	16.44	4.06	11.94	6047	1948	7.93	4.50	707	368	480	163
25 x 16	3	0.308	114.0	8.74	16.26	4.24	11.76	7038	2247	7.86	4.44	805	433	530	191
20 x 20	1.6	0.166	61.44	5.59	14.41	5.59	14.41	2371	2371	6.21	6.21	424	165	424	165
20 x 20	3	0.300	111.0	6.10	13.90	6.10	13.90	4029	4029	6.03	6.03	661	290	661	290
25 x 20	1.6	0.187	69.44	7.54	17.46	5.04	14.96	4411	2535	7.97	6.04	585	253	503	169
25 x 20	2.5	0.287	106.3	7.87	17.13	5.37	14.63	6535	3722	7.84	5.92	831	381	693	264
25 x 20	3	0.340	126.0	8.05	16.95	5.55	14.45	7617	4320	7.78	5.86	946	449	779	299

Table 4.1: Angles Architectural (continued)

Size a x b mm	Thickness t mm	Mass per Metre kg/m	Area mm^2	Distance of neutral axis from extreme fibres x_1 mm	x_2 mm	y_1 mm	y_2 mm	Second moment of Area I_x mm^4	I_y mm^4	Radius of Gyration r_x mm	r_y mm	Moduli of Section Z_{x_1} mm^3	Z_{x_2} mm^3	Z_{y_1} mm^3	Z_{y_2} mm^3
32 x 20	1.6	0.218	80.64	10.45	21.55	4.45	15.55	8694	2711	10.38	5.80	832	403	609	174
32 x 20	2.5	0.334	123.8	10.78	21.22	4.78	15.22	13004	3987	10.25	5.68	1206	613	833	262
32 x 20	3	0.397	147.0	10.97	21.03	4.97	15.03	15224	4631	10.18	5.61	1388	724	932	308
40 x 20	1.6	0.252	93.44	13.95	26.05	3.95	16.05	15972	2860	13.07	5.53	1145	613	724	178
40 x 20	3	0.462	171.0	14.48	25.52	4.48	15.52	28289	4898	12.86	5.35	1953	1109	1093	316
50 x 20	1.6	0.295	109.4	18.49	31.51	3.49	16.51	29276	3000	16.36	5.24	1583	929	860	182
50 x 20	3	0.543	201.0	19.04	30.96	4.04	15.96	52309	5147	16.13	5.06	2748	1689	1275	322
70 x 20	1.6	0.382	141.4	27.88	42.12	2.88	17.12	73010	3186	22.72	4.75	2619	1733	1106	186
70 x 20	3	0.705	261.0	28.45	41.55	3.45	16.55	131840	5489	22.48	4.59	4633	3173	1589	332
80 x 20	3	0.786	291.0	33.25	46.75	3.25	16.75	190376	5614	25.58	4.39	5725	4072	1726	335
25 x 25	1.6	0.209	77.44	6.84	18.16	6.84	18.16	4739	4739	7.82	7.82	693	261	693	261
25 x 25	2.5	0.321	118.8	7.17	17.83	7.17	17.83	7032	7032	7.69	7.69	981	394	981	394
25 x 25	3	0.381	141.0	7.35	17.65	7.35	17.65	8204	8204	7.63	7.63	1116	465	1116	465
25 x 25	4	0.497	184.0	7.71	17.29	7.71	17.29	10352	10352	7.50	7.50	1343	599	1343	599
25 x 25	6	0.713	264.0	8.40	16.60	8.40	16.60	13999	13999	7.28	7.28	1667	843	1667	843
32 x 25	3	0.437	162.0	10.09	21.91	6.59	18.41	16463	8844	10.08	7.39	1631	752	1341	480
40 x 25	1.6	0.274	101.4	12.91	27.09	5.41	19.59	17248	5412	13.04	7.30	1336	637	1000	276
40 x 25	3	0.502	186.0	13.44	26.56	5.94	19.06	30625	9406	12.83	7.11	2280	1153	1585	493
40 x 25	4	0.659	244.0	13.80	26.20	6.30	18.70	39294	11908	12.69	6.99	2847	1500	1889	637
50 x 25	1.6	0.317	117.4	17.29	32.71	4.79	20.21	31611	5710	16.41	6.97	1829	966	1193	282
50 x 25	3	0.583	216.0	17.82	32.18	5.32	19.68	56614	9937	16.19	6.78	3177	1759	1868	505
60 x 25	3	0.664	246.0	22.35	37.65	4.85	20.15	93271	10342	19.47	6.48	4172	2478	2131	513
32 x 32	3	0.494	183.0	9.11	22.89	9.11	22.89	17851	17851	9.88	9.88	1960	780	1960	780
32 x 32	4	0.648	240.0	9.47	22.53	9.47	22.53	22778	22778	9.74	9.74	2406	1011	2406	1011
32 x 32	6	0.940	348.0	10.17	21.83	10.17	21.83	31401	31401	9.50	9.50	3087	1439	3087	1439
40 x 32	1.6	0.304	112.6	11.71	28.29	7.71	24.29	18732	10835	12.90	9.81	1600	662	1405	446
40 x 32	3	0.559	207.0	12.23	27.77	8.23	23.77	33325	19097	12.69	9.61	2726	1200	2322	803
40 x 40	1.6	0.339	125.4	10.60	29.40	10.60	29.40	20102	20102	12.66	12.66	1897	684	1897	684
40 x 40	3	0.624	231.0	11.11	28.89	11.11	28.89	35820	35820	12.45	12.45	3224	1240	3224	1240
40 x 40	4	0.821	304.0	11.47	28.53	11.47	28.53	46079	46079	12.31	12.31	4016	1615	4016	1615
40 x 40	6	1.199	444.0	12.19	27.81	12.19	27.81	64482	64482	12.05	12.05	5290	2319	5290	2319

Appendix V2

Aluminium alloy properties.

Table 3.7: **Minimum Mechanical Properties for Wrought Aluminium Alloys**

Alloy and Temper	Product	Thickness range mm	Tension (MPa) F_{tu}	Tension (MPa) F_{ty}	Compression (MPa) F_{cy}	Shear (MPa) F_{vu}	Shear (MPa) F_{vy}	Bearing (MPa) F_{pu}	Bearing (MPa) F_{py}	Compressive Modulus of Elasticity E
1100–H12	Sheet, plate	Up to 50	96	75	69	62	45	193	124	69 637
–H14	Sheet, plate	Up to 25	110	96	99	69	55	221	145	69 637
1200–H12	Sheet, plate, d awn tube	Up to 50	96	75	69	62	45	193	124	69 637
–H14	S eet, plate, drawn tube	Up to 25	110	96	90	69	55	221	145	69 637
2014–T6	Extrusions	Up to 10	432	386	379	241	214	786	586	75 153
3003–H12	Sheet, plate	Up to 50	117	82	69	76	48	234	131	69 637
–H14	Sheet, plate	Up to 25	137	117	97	83	69	276	172	69 637
–H16	Sheet	Up to 4	165	145	124	97	83	317	214	69 637
–H18	Sheet	Up to 3.25	186	165	138	103	96	338	234	69 637
Alclad 3004–H32	Sheet	Up to 6	186	137	117	110	83	372	234	69 637
–H34	Sheet	Up to 6	213	165	145	124	97	428	262	69 637
–H36	Sheet	Up to 4	234	186	165	131	110	469	296	69 637
–H38	Sheet	Up to 3.25	255	207	193	145	117	483	303	69 637
3203–H14	Sheet, plate	Up to 12	139	117	97	83	69	276	172	69 637
–H16	Sheet	Up to 4	162	138	117	97	83	303	206	69 637
5005–H12	Sheet	Up to 6	124	96	90	76	55	234	152	69 637
–H14	Sheet	Up to 6	144	117	103	83	69	276	172	69 637
–H16	Sheet	Up to 4	165	138	124	96	83	331	206	69 637
–H32	Sheet	Up to 6	117	83	76	76	48	234	138	69 637
–H34	Sheet	Up to 6	137	103	98	83	59	276	167	69 637
–H36	Sheet	Up to 4	158	124	110	90	76	317	200	69 637
50[illegible]A–H32	Sheet	Up to 6	151	110	96	96	82	303	186	69 637
–H34	Sheet	Up to 6	172	137	124	103	83	345	221	69 637
5052–H32	Sheet, plate	Up to 50	213	158	145	131	90	414	269	70 327
–H34	Sheet, plate	Up to 25	234	179	165	138	103	448	303	70 327
–H36	Sheet	Up to 4	255	199	179	152	117	483	317	70 327
–H38	Sheet	Up to 3.25	268	220	207	152	124	510	338	70 327
–H391	Sheet	Up to 2	290	241	227	159	138	524	358	70 327
5083–H111	Extrusions	Up to 126	275	165	145	159	97	538	262	71 705
–H321	Plate	Over 5 to 40	303	213	179	179	124	579	365	71 705
–H321	Plate	Over 40 to 75	282	199	165	165	117	538	338	71 705
–H323	Sheet	Up to 6	310	234	221	179	138	607	400	71 705
–H343	Sheet	Up to 6	344	268	255	200	159	655	455	71 705
5086–H112	Sheet	Over 4.8 to 6	248	124	117	152	69	496	214	71 705
–H112	Plate	Over 6 to 25	241	110	110	145	62	483	193	71 705
–H112	Plate	Over 25 to 50	241	96	–	–	–	–	–	71 705
–H34	Sheet, plate	Up to 25	303	234	221	179	138	579	400	71 705
5251–H34	Sheet, plate	Up to 25	231	179	159	131	103	434	303	70 327
5454–H34	Sheet, plate	Up to 25	268	199	186	159	117	510	338	71 705
6061–T6	Sheet, plate	Up to 25	289	241	241	186	138	607	400	69 637
–T6	Extrusions	All	262	241	241	165	138	552	386	69 637
–T6	Drawn tube	Up to 12	293	241	241	186	138	607	386	69 637
6063–T5	Extrusions	Up to 12	151	110	110	90	62	317	179	69 637
–T6	Extrusions	Up to 25	206	172	172	131	97	434	276	69 637
–T83	Drawn tube	All	275	248	248	165	138	579	393	69 637
6351–T5	Extrusions	All	262	241	241	165	138	552	386	69 637
–T6	Extrusions	Up to 150	293	255	255	172	145	607	421	69 637

Table 3.8: Minimum Mechanical Properties for Welded Aluminium Alloys[1]

Alloy and Temper	Product	Thickness range mm	Tension (MPa) F_{tuw}	Tension (MPa) F_{tyw} [2]	Compression (MPa) F_{cyw} [2]	Shear (MPa) F_{vuw}	Shear (MPa) F_{vyw}	Bearing (MPa) F_{puw}	Bearing (MPa) F_{pyw}
1100–H12	All	All	75	31	31	55	17	158	55
–H14	All	All	75	31	31	55	17	158	55
1200–H12	All	All	75	31	31	55	17	158	55
–H14	All	All	75	31	31	55	17	158	55
3003–H12	All	All	96	48	48	68	27	206	82
–H14	All	All	96	48	48	68	27	206	82
–H16	All	All	96	48	48	68	27	206	82
–H18	All	All	96	48	48	68	27	206	82
3203–H16	All	All	96	48	48	68	27	206	82
–H18	All	All	96	48	48	68	27	206	82
Alclad 3004–H32	All	All	144	75	75	89	44	303	131
–H34	All	All	144	75	75	89	44	303	131
–H36	All	All	144	75	75	89	44	303	131
–H38	All	All	144	75	75	89	44	303	131
5005–H12	All	All	103	48	48	62	27	193	68
–H14	All	All	103	48	48	62	27	193	68
–H16	All	All	103	48	48	62	27	193	68
–H32	All	All	103	48	48	62	27	193	68
–H34	All	All	103	48	48	62	27	193	68
–H36	All	All	103	48	48	62	27	193	68
5050A–H32	All	All	124	55	55	82	31	248	82
–H34	All	All	124	55	55	82	31	248	82
5052–H32	All	All	172	89	89	110	51	344	131
–H34	All	All	172	89	89	110	51	344	131
–H36	All	All	172	89	89	110	51	344	131
–H38	All	All	172	89	89	110	51	344	131
–H391	All	All	172	89	89	110	51	344	131
5083–H111	Extrusions	All	268	144	137	158	82	537	220
–H321	Plate	Up to 40	275	165	165	165	96	551	248
–H321	Plate	Over 40 to 75	268	159	159	165	90	538	234
–H323	Sheet	Up to 6	275	165	165	165	96	551	248
–H343	Sheet	Up to 6	275	165	165	165	96	551	248
5086–H112	Sheet	Over 4.8 to 6	241	117	117	144	65	482	193
–H112	Plate	Over 6 to 25	241	110	110	144	62	482	193
–H112	Plate	Over 25 to 50	241	96	96	144	55	482	193
–H32	Sheet, plate	All	241	131	131	144	75	482	193
–H34	Sheet, plate	All	241	131	131	144	75	482	193
5251–H32	Sheet, plate	All	170	89	89	110	51	344	131
–H34	Sheet, plate	All	170	89	89	110	51	344	131
–H36	Sheet, plate	All	170	89	89	110	51	344	131
5454–H34	Sheet, plate	All	213	110	110	131	65	427	165
6061–T6[3]	Extrusions & drawn tube	All	165	137	137	103	82	344	206
6063–T5	Extrusions & drawn tube	All	117	75	75	75	44	234	151
–T6	Extrusions & drawn tube	All	117	75	75	75	44	234	151
–T83	Extrusions & drawn tube	All	117	75	75	75	44	234	151
6351–T5	Extrusions	All	165	137	137	103	82	344	206
–T6[3]	Extrusions	All	165	137	137	103	82	344	206

Footnotes

[1]Filler wires used are those recommended in Table 1.

[2]0.2 percent offset in 250 mm gauge length across a butt weld.

[3]Values when welded with 5183, 5356, or 5556 alloy filler wire.

Engineers Handbook Aluminium

Design Data

First Edition, February 1979.

THE ALUMINIUM DEVELOPMENT COUNCIL OF AUSTRALIA (LIMITED)
99 Elizabeth Street, Sydney, N.S.W. 2000, Australia. Telephone: 233 8933

ADC and SAA Standards for Aluminium

Aluminium and Aluminium Alloys

The chemical, mechanical and physical properties of Aluminium and aluminium alloys are specified in various standards issued by the Aluminium Development Council of Australia and the Standards Association of Australia. These two organisations work in association to ensure accuracy and consistency of their standards.

The principal Standards are:

Aluminium Development Council of Australia:

Aluminium Standards and Data for Wrought Products
Aluminium Standards and Data for Cast Products

These two documents describe the aluminium and aluminium alloy materials produced in Australia and include data concerning chemical composition, mechanical and physical properties, standard sizes, tolerances on wrought product dimensions, general fabrication characteristics etc.

Standards Association of Australia:

AS 1734	Wrought Aluminium and Aluminium Alloy Flat Sheet, Coiled Sheet and Plate for General Engineering Purposes.
AS 1865	Wrought Aluminium and Aluminium Alloy Drawn Wire, Rod, Bar and Strip for General Engineering Purposes.
AS 1866	Wrought Aluminium and Aluminium Alloy Extruded Rod, Bar, Solid and Hollow Shapes for General Engineering Purposes.
AS 1867	Wrought Aluminium and Aluminium Alloy Drawn Tubes for General Engineering Purposes.
AS 1874	Aluminium Ingots and Aluminium Alloy Ingots and Castings.

Using Aluminium

There are two principal Australian Standards concerning the structural use of aluminium.

AS 1664	Aluminium Structures Code
AS 1665	Aluminium Welding Code

The first of these two documents prescribe the maximum permissible stresses and general design requirements for the use of aluminium alloys in structures. It is complemented by the second document concerning the fusion welding of aluminium structures (other than those constructed in accordance with AS 1200 – Boiler Code).

Aluminium Products

The following are the principal Australian Standards concerning products made from aluminium and aluminium alloys. Other Standards may be located by reference to the Standards Association of Australia and its publications.

AS 1588	Filler Rods for Welding
AS 1231	Anodic Oxidation Coatings on Aluminium for Architectural Applications
AS 1799	Small Boats Code
AS 1956	Anodic Oxidation Coatings on Aluminium
AS 1562	Design and Installation of Self-Supporting Metal Roofing without Transverse Laps
AS 1210	Unfired Pressure Vessel Code
AS 1796	Welding Certification Code
AS 2047) AS 2048)	Aluminium Windows
AS 1135	Non-Ferrous Pressure Piping Code
AS 2016	Road Tank Vehicles for Flammable Liquids
AS H51	Wrought Aluminium and Aluminium Alloy Wire - for Rivets
AS H52	Wrought Aluminium and Aluminium Alloy Wire - welding wire

Table 3.12: Typical Tensile Properties at Various Temperatures[1] — Wrought Alloys (continued)

Alloy and Temper	Temp. C	Tensile Strength (MPa) Ultimate	Yield[2]	Elongation in 50 mm Percentage
5086–0	−195	379	131	46
	− 80	269	117	35
	− 30	262	117	32
	25	262	117	30
	100	262	117	36
	150	200	110	50
	205	152	103	60
	260	117	76	80
	315	76	52	110
	370	41	29	130
6351–T5	−195	407	324	17
	− 80	352	303	10
	− 30	331	296	11
	25	310	283	11
	100	283	269	12
	150	172	152	18
	205	66	48	35
6351–T6	−195	434	365	14
	− 80	372	331	10
	− 30	352	324	10
	25	331	310	11
	100	296	290	12
	150	186	165	18
6061–T6	−195	414	324	22
	− 80	338	290	18
	− 30	324	283	17
	25	310	276	17
	100	290	262	18
	150	234	214	20
	205	131	103	28
	260	52	34	60
	315	32	19	85
	370	21	12	95
6262–T9	−195	510	462	14
	− 80	427	400	10
	− 30	414	386	10
	25	400	379	10
	100	365	359	10
	150	262	255	14
	205	103	90	34
	260	59	41	48
	315	32	19	85
	370	21	12	95
6063–T1	−195	234	110	44
	− 80	179	103	36
	− 30	165	97	34
	25	152	90	33
	100	152	97	18
	150	145	103	20
	205	62	45	40
	260	31	24	75
	315	22	17	80
	370	16	14	105

Appendix V3

Typical properties of wrought aluminium alloys at various temperatures.

Table 3.12: Typical Properties at Various Temperatures[1] — Wrought Alloys (continued)

Alloy and Temper	Temp. C	Tensile Strength (MPa) Ultimate	Tensile Strength (MPa) Yield[2]	Elongation in 50 mm Percentage
6063–T5	−195	255	165	28
	− 80	200	152	24
	− 30	193	152	23
	25	186	145	22
	100	165	138	18
	150	138	124	20
	205	62	45	40
	260	31	24	75
	315	22	17	80
	370	16	14	105
6063–T6	−195	324	248	24
	− 80	262	228	20
	− 30	248	221	19
	25	241	214	18
	100	214	193	15
	150	145	138	20
	205	62	45	40
	260	31	24	75
	315	23	17	80
	370	16	14	105

Footnotes

[1]These data are based on a limited amount of testing and represent the lowest strength during 10,000 hours of exposure at testing temperature under no load; stress applied at 34.5 MPa/minute to yield strength and then at strain rate of 0.05 mm/minute to failure. Under some conditions of temperature and time, the application of heat will adversely affect certain other properties of some alloys.

[2]Offset equals 0.2 percent.

V4

Resistance of aluminium to various chemicals and factors assigned according to various variables on Westfield rooftop, with corrosivity factors applied.

Table 5.2: Corrosion Resistance

Resistance of Aluminium to Various Chemicals

A = Excellent resistance (corrosion so slight as to be harmless)

B = Good resistance (satisfactory service expected)

C = Fair resistance (satisfactory service only under specific conditions; aluminium not recommended without additional data).

D = Poor resistance (Satisfactory for temporary service only; aluminium should not be used without test experiment).

Relative Corrosion Resistance of Aluminium

Alloy	Non-Industrial Atmosphere	Industrial Atmosphere	Marine Atmosphere or Sea Water Service
1100, 1200	A	B	B
3003, 3203	A	B	B
3004	A	B	B
5005	A	A	A
5050A	A	A	A
5052, 5251	A	A	A
5083, 5086	A	A	A[1]
6061–T4, –T6	A	B	B
6351–T5, –T6	A	B	B
6063–T5, –T6	A	B	B
2024–T3	B	C	D
2014–T6	B	C	D

Footnote

[1]In annealed or strain-hardened tempers that have proved resistant to exfoliation corrosion.

Table 5.3: Aluminium in Contact with Specific Chemicals

The following guide list indicates in a very general way the resistance of commercially pure aluminium to attack by chemicals and other common substances arranged in alphabetical order. Because the chemical behaviour of aluminium is dependent upon conditions of service, environment, the actual composition of the metal, etc., aluminium suppliers should always be consulted in cases of doubt.

***CAUTION: Under certain conditions some Halogenated Hydrocarbons may produce a rapid rate of corrosion of aluminium or a violent reaction. The service conditions to ensure safety should be recognized or established before aluminium is used with any such compounds.**

Compound	Rating	Compound	Rating
Acetaldehyde	A	Alcohols, Higher	A
Acetanilide	A	Aluminium Chloride	C
Acetic Acid, Dilute	C	Aluminium Formate	A
Acetic Acid, Glacial	A	Aluminium Nitrate (no free nitric acid)	A
Acetic Anhydride	A	Aluminium Sulfate	B
Acetone	A	Ammonia (dry)	A
Acetylene (dry)	A	Ammonium Acid Fluoride	D
Acrylonitrile (dry)	A	Ammonium Aluminium Sulfate	B
Acrylonitrile (wet)	B	Ammonium Bicarbonate	A
Albumen	A	Ammonium Bromide	C
Alcohol, Methyl	A	Ammonium Carbonate	B
Alcohol, Ethyl	A		

Factors assigned according to various variables on Westfield rooftop:

SO2	0.95	Chemical	factor3
NaCl	0.9		
Both NaCl & SO2	0.8		
Neither	1		
Horizontal	0.85	Shedding	factor2
Vertical	1		
Angled to shed	0.95		
Angled to trap	0.75		
High humidity	0.95	Humidity	factor4
Low Humidity	1		
10 years	1	Years	factor1
20 years	0.95		
30 years	0.9		
Greater than 30 years	0.85		
Roof cover no shield	0.85	Weather Protection	factor 5
Roof cover & shielded	1		
No roof but shielded	0.9		
No protection	0.95		
Very rough	0.85	Roughness	factor 6
Medium	0.9		
Smooth	0.95		
Polished	1		
Both Surfaces	1.20	Coating	factor7
Primary only	1.1		
Attached only	1.1		
High	0.9	Wind	factor8
Medium	0.95		
Low	1		
Equal size	1	Geometry	factor9
Primary >50%	0.96		
Primary >80%	0.94		
Primary >90%	0.92		
<20deg	1	Temperature Range	factor10
20 - 50deg	0.99		
> 50deg	0.98		
Primary material	1	Material Use	
Attached material	2		
Fixing bolt	3		
Fixing rivet	4		

ISO 9223 Corrosion Rates after One Year of Exposure Predicted for Different Corrosivity Classes: [81]

Corrosion category	Steel, $g/m^2 \cdot year$	Copper, $g/m^2 \cdot year$	Aluminum, $g/m^2 \cdot year$	Zinc, $g/m^2 \cdot year$
C_1	≤10	≤0.9	Negligible	≤0.7
C_2	11–200	0.9–5	≤0.6	0.7–5
C_3	201–400	5–12	0.6–2	5–15
C_4	401–650	12–25	2–5	15–30
C_5	651–1500	25–50	5–10	30–60

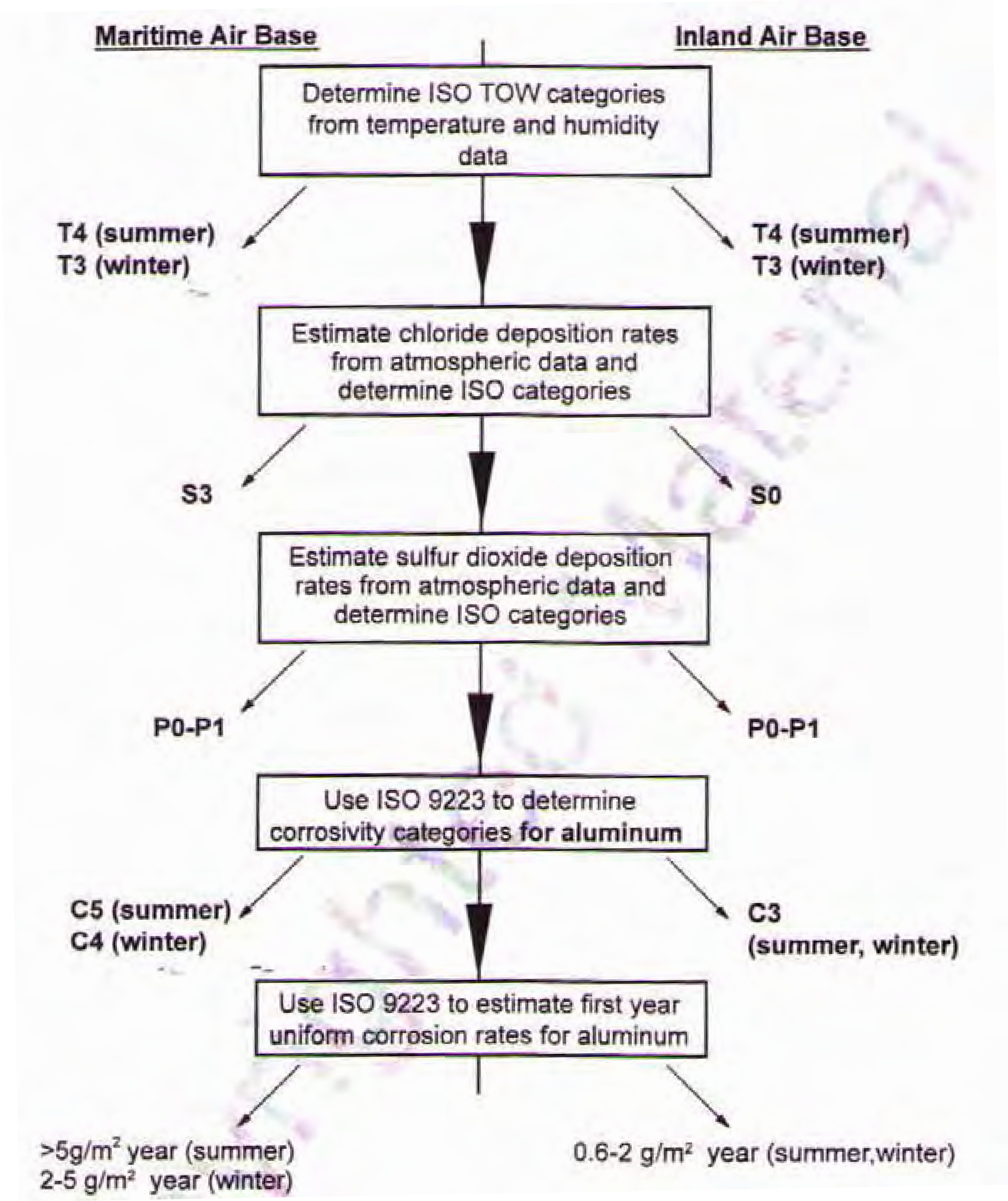
ISO 9223 Classification of Sulphur Dioxide and Chloride "Pollution" Levels: [81]

Sulfur dioxide category	Sulfur dioxide deposition rate, $mg/m^2 \cdot day$	Chloride category	Chloride deposition rate, $mg/m^2 \cdot day$
P_0	≤10	S_0	≤3
P_1	11–35	S_1	4–60
P_2	36–80	S_2	61–300
P_3	81–200	S_3	301–1500

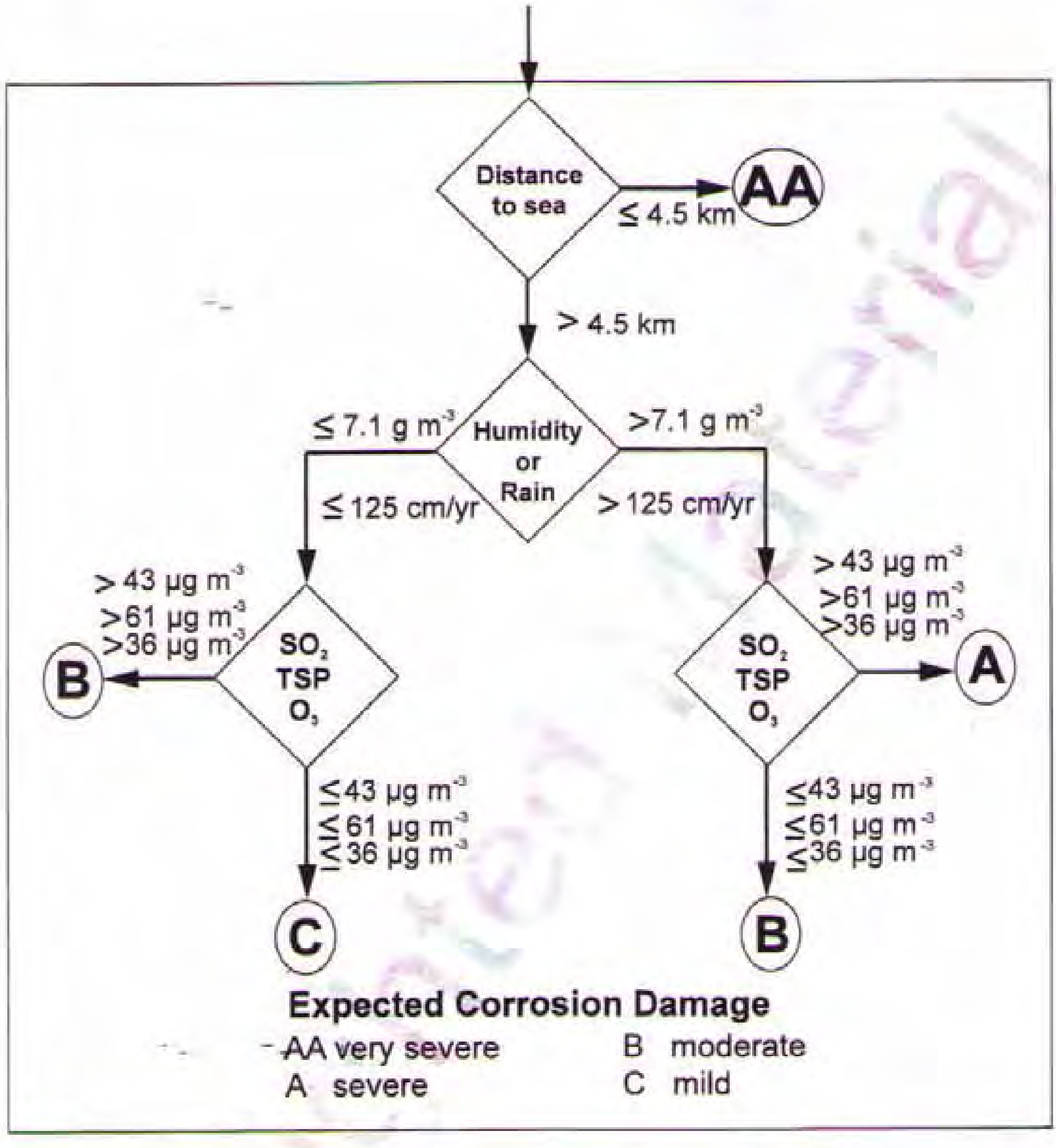
ISO 9223 Corrosivity Categories of Atmosphere: [81]

TOW	Cl^-	SO_2	Steel	Cu and Zn	Al
T_1	S_0 or S_1	P_1	1	1	1
		P_2	1	1	1
		P_3	1–2	1	1
	S_2	P_1	1	1	2
		P_2	1	1	2
		P_3	1–2	1–2	2–3
	S_3	P_1	1–2	1	2
		P_2	1–2	1–2	2–3
		P_3	2	2	3
T_2	S_0 or S_1	P_1	1	1	1
		P_2	1–2	1–2	1–2
		P_3	2	2	3–4
	S_2	P_1	2	1–2	2–3
		P_2	2–3	2	3–4
		P_3	3	3	4
	S_3	P_1	3–4	3	4
		P_2	3–4	3	4
		P_3	4	3–4	4
T_3	S_0 or S_1	P_1	2–3	3	3
		P_2	3–4	3	3
		P_3	4	3	3–4
	S_2	P_1	3–4	3	3–4
		P_2	3–4	3–4	4
		P_3	4–5	3–4	4–5
	S_3	P_1	4	3–4	4
		P_2	4–5	4	4–5
		P_3	5	4	5
T_4	S_0 or S_1	P_1	3	3	3
		P_2	4	3–4	3–4
		P_3	5	4–5	4–5
	S_2	P_1	4	4	3–4
		P_2	4	4	4
		P_3	5	5	5
	S_3	P_1	5	5	5
		P_2	5	5	5
		P_3	5	5	5
T_5	S_0 or S_1	P_1	3–4	3–4	4
		P_2	4–5	4–5	4–5
		P_3	5	5	5
	S_2	P_1	5	5	5
		P_2	5	5	5
		P_3	5	5	5
	S_3	P_1	5	5	5
		P_2	5	5	5
		P_3	5	5	5

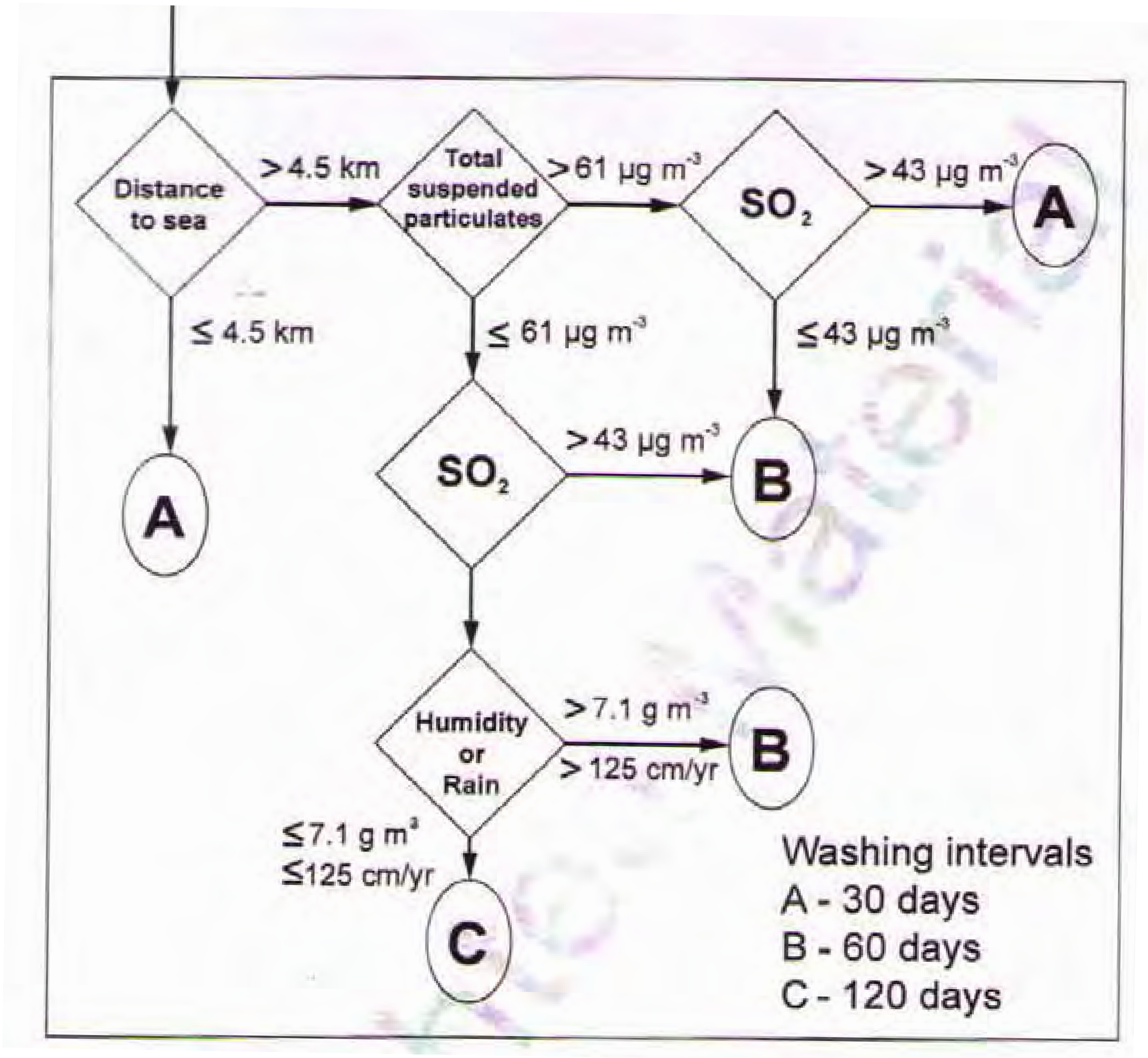
Use of ISO 9223 in aircraft to determine corrosivity rates due to various environmental factors: [81]



Corrosive damage algorithm as a result of distance to salt and water: [81]



Aircraft maintenance and washing schedule: [81]



Assigning factors at Westfields roof top based on the below values – Corrosive rates for carbon steel at various locations: [81]

Location	Environment (macro)	Section loss (μm) 1 yr	Section loss (μm) 2 yr
Phoenix, AZ	rural	6.6	9.2
Vancouver, B.C.	rural-marine	17.3	26.7
Detroit, MI	industrial	23	28.9
Potter County, PA	rural	21.8	41.1
State College, PA	rural	25.1	45.9
Durham, NH	rural	35.4	54.7
Middletown, OH	semi-industrial	36.2	57.6
Pittsburgh, PA	industrial	42.8	61.3
Bethleham, PA	industrial	55.1	75.3
Newark, NJ	industrial	72.4	102
Bayonne, NJ	industrial	127	155
East Chicago, IN	industrial	111	169
Cape Kennedy, FL *0.8 km from coast*	marine	41.1	173
Brazos River, TX	industrial-marine	107	187
Cape Kennedy, FL *54 m from coast, 18 m elevation*	marine	61.3	263
Kure Beach, NC *240 m from the coast*	marine	85.1	292
Cape Kennedy, FL *54 m from coast, 9 m elevation*	marine	70.8	330
Daytona beach, FL	marine	209	592
Cape Kennedy, FL *54 m from coast, ground level*	marine	191	884
Point Reyes, CA	marine	315	1004
Kure Beach, NC *24 m from the coast*	marine	712	1070
Cape Kennedy, FL *beach*	marine	1057	

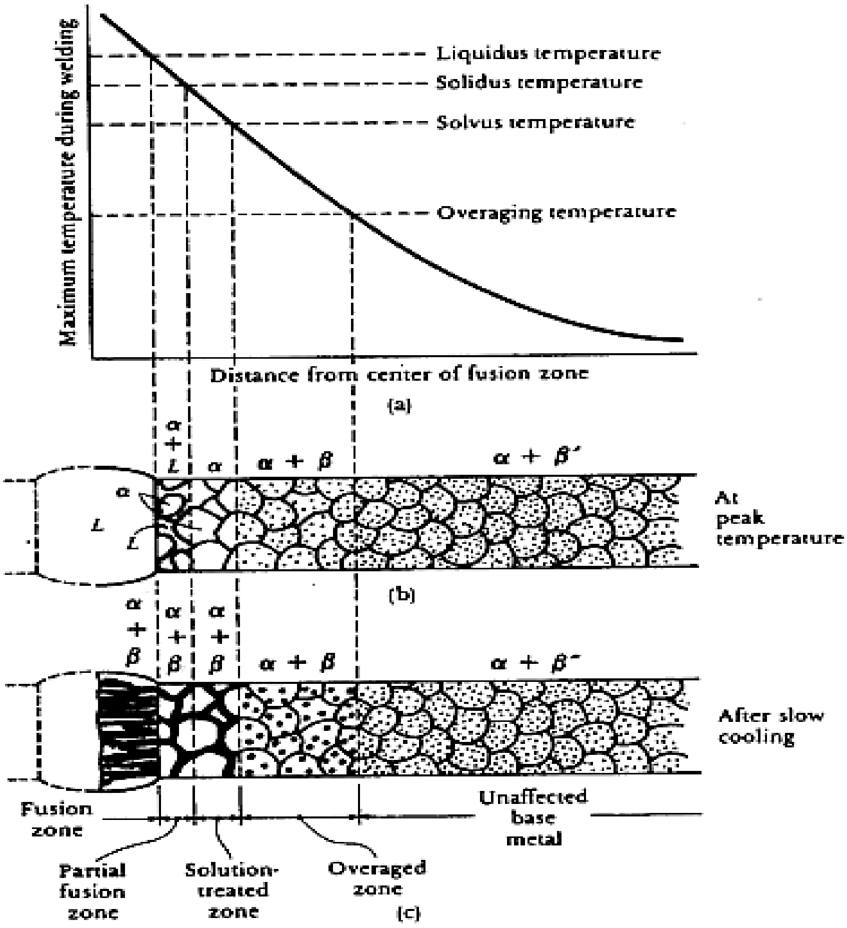
Appendix V5

Maximal re-heating times for heat treatable aluminium alloys and maximum temperature during welding versus distance from centre of fusion zone for heat treatable aluminium alloys.

table may be used as a guide during reheating for hot-forming. Under these conditions of time and temperature, the losses in strength as a result of reheating generally will not exceed about 5 per cent. It should be understood that these are maximum accumulated times of reheating and that, in most cases, equal formability will be obtained with shorter periods of heating.

Table 6.2: Maximum reheating Times for the Forming of Heat-Treatable Alloys at Various Temperatures

Temperature °C	2014-T6	6061-T6 and 6063-T6
260	No	No
230	To Temp.	5 min.
220	To Temp.	15 min.
205	5 - 15 min.	30 min.
190	30 - 60 min.	1 - 2 hr.
175	2 - 4 hr.	8 - 10 hr.
160	8 - 10 hr.	50 - 100 hr.
150	20 - 50 hr.	100 - 200 hr.



Maximum temperature during welding Versus Distance from centre of fusion zone for heat treatable aluminium alloys [147].

Appendix V6

Aluminium filler alloys for general purpose welding (MIG and TIG).

Table 7.3: Aluminium Filler Alloys for General Purpose Welding (MIG and TIG)

Base Metal Welded to Base Metal	1100 1200 3003	3004 Alclad/ 3004	5005 5050A	5052 5251	5083 5086	5454 5154A	6061 6063 6351	7005
1100 1200 3003 3203	1100[1] 1200[1] 60[5]	4043[2] 68[5]	4043[2] 68[5]	4043[2] 68[5]	5356[1] 78[5]	4043[2] 68[5]	4043 68[5]	5356[2] 78[5]
3004 Alclad/3004	— —	4043[2] 68[5]	4043[2] 68[5]	5356[1,2] 78[5]	5356[2] 78[5]	5356[2] 78[5]	4043[3] 68[5]	5356[2] 78[5]
5005 5050A	— —	— —	4043[2,4] 68[5]	4043[2] 68[5]	5356[2] 78[5]	5356[2] 78[5]	4043[3] 68[5]	5356[2] 78[5]
5052 5251	— —	— —	— —	5356[3] 78[5]	5356[2] 78[5]	5356[3] 78[5]	5356[1,2] 78[5]	5356[2] 78[5]
5083 5086	— —	— —	— —	— —	5356[2] 78[5]	5356[2] 78[5]	5356[2] 78[5]	5356[2] 78[5]
5454 5154A	— —	— —	— —	— —	— —	5356[2,3] 78[5]	5356[1,3] 78[5]	5356[2] 78[5]
6061 6063 6351	— — —	— — —	— — —	— — —	— — —	— — —	4043[3] 68[5]	5356[2] 78[5]
7005	—	—	—	—	—	—	—	5356[2]

Footnotes

1 4043 may be used for some applications.
2 5556 may be used.
3 5154A, 5356 and 5556 may be used. In some cases they provide:-
   (a) improved colour match after anodizing treatment
   (b) highest weld ductility
   (c) higher weld strength
   (d) improved stress corrosion resistance
4 Filler metal with the same analysis as the base metal is sometimes used.
5 Filler metals in accordance with AS 1588—TIG only.

Adhesive Bonding

Adhesive bonding processes are particularly suitable to aluminium, because of the minimum need for surface preparation. For new aluminium, preparation entails a simple degrease operation and for maximum bond effectiveness, some measure of surface abrasion dependent upon type of adhesive being used. 'Contact' adhesives generally require no abrasion, whilst epoxy type bonds subject to some amount of 'peel' loading are improved by the provision of a coarse abraded surface. When aluminium extrusions are to be adhesively bonded, it is often practicable to incorporate a serrated surface in the extrusion design.

Manufacturers and suppliers of adhesive materials provide specific data upon the use and application of their products and it is important to follow their instructions concisely to achieve best results.

Solvents commonly used for degreasing aluminium surfaces include:

White Spirit
Trichlorethylene

Appendix V7

Welded aluminium properties and recovery of strength upon ageing.

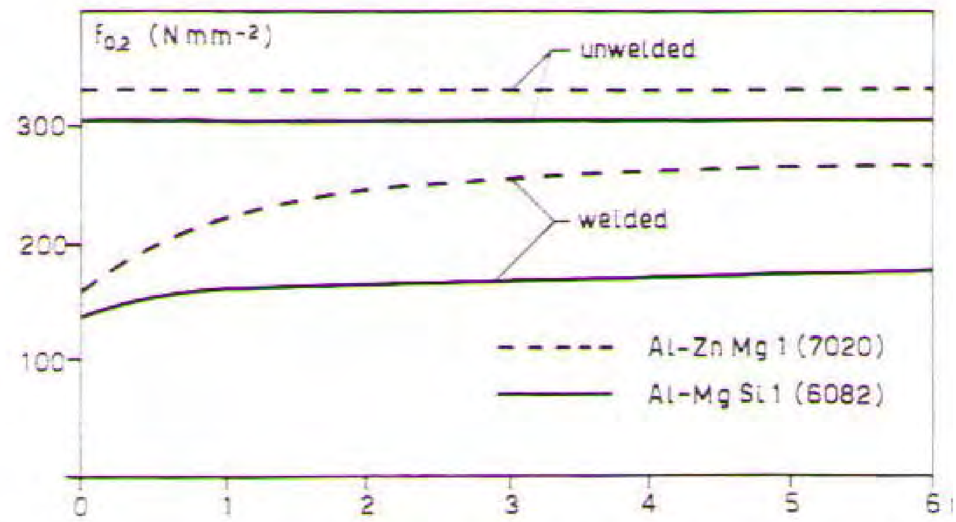


Fig. 4.6 Wrought alloys for welded structures

Series	Chemical composition	International designation
1000	Al99.0	1200
	Al99.5	1050A
5000	AlMg2.5	5052
	AlMg2.7Mn	5054
	AlMg3.5	—
	AlMg4.4	5086
	AlMg4.5	5083
6000	AlMgSi	6060
	AlSi1MgMn	6082
	AlMg1SiCu	6061
7000	AlZn4.5Mg	7020

Fig. [illegible] Metal combinations for TIG and MIG welding

Parent metal	Filler metal
5052	5554 5654
5454	5356*
5086 5083	5356
6060 6082 6061	5356† 4043‡
7020	5356

* Suitable for metallurgical reasons.

† Recommended for strength reasons, when no thermal treatment after welding.

‡ Recommended for strength reasons, when an appropriate thermal treatment follows welding.

ECCS recommendations for welding metal combinations

Parent metal	7020	6082 6061	6060	5083	5454
7020	5356 4043 5183				
6082 6061	5356 4043 5183	5356 4043 5183			
6060	5356 4043	5356 4043	5356 4043 5754		
5083	5356 5183	5356 5183	5356	5356 5183	
5454	5356 5754 5183	5356 5183	5356 5754	5356 5754 5183	5356 5754 5183