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Abstract

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It has been previously found that bolted joints loaded in bearing exhibit rate sensitivity whereas bolts loaded in pull-through experience very little sensitivity, for nearly identical joint configurations. The primary focus of this paper was to use explicit finite element simulation of pull-through failure to shed light on discrepancies between experimentally observed rate sensitivity for seemingly similar tests. The paper uses the stacked-shell modelling approach to efficiently model the interaction of delamination and ply failure under the complex dynamic load state.

The results of the simulation indicated that the properties of the interface susceptible to loading rate sensitivity, Mode I and II strain energy release rates (SERR), did not have a great effect on the overall joint response; despite the prevalence of delamination during the failure process. A weak relationship between Mode II SERR and joint response was discovered which was consistent with experimental observations.

Keywords

Carbon Fibre Composites; Bolted Joints; Explicit Finite Element Analysis; Stacked-Shell Modelling; Dynamic Joint Failure; Pull-Through

1 Introduction

Pull-through failure of bolted joints in composite structures is an often overlooked failure mechanism. Bolted joints in composite laminates experience pull-through failure at loads 2-3 times lower than bearing failure for similar joint configurations [1, 2]. Critically, some load cases which impose prying loads across the joint can lead to very high loads normal to the joint plane, exacerbating pull-through failure [3]. Recently it has been identified that pull-through failure also plays an important role in the ultimate bearing load and energy absorption of bolted joints, especially under dynamic conditions [3-6]. Energy absorption and ultimate strength are of critical importance to determining the behaviour of aircraft structures during impact and crash conditions, so pull-through behaviour must be well understood.

Many of the published studies of dynamic failure of bolted joints in composites [3-9] offer conflicting findings. Ger, Kawata and Itabashi [8] found that joint stiffness increased with loading rate, and total energy absorption dropped sharply. Contrastingly, Li, Mines and Birch [9] found that joint stiffness was unchanged with increased loading rate, yet energy absorption increased somewhat. Additionally, each failure mode exhibits a different response to increased loading rate; for example, pull-through failure exhibits little [4] to no [3, 6] rate sensitivity, but bearing failure is quite rate-sensitive under some conditions [3-6], even though both failure modes are matrix dominated.

The fundamental issue is that joint failure mechanisms (net tension, bearing, pull-through, etc.) are complex emergent phenomena which are not monotonically related to the underlying constituent failure mechanisms and rate sensitivities. Intricate interactions exist between the rate sensitivity of the composite constituents (fibre, resin), the laminate parameters (thickness, stacking), the joint parameters (bolt type, diameter, friction, geometry, pre-torque) and the test conditions. The complexities are such that no parameter can be satisfactorily decoupled from the others to study it independently in an experimental setting.

Simulation has a critical role to play in extending our understanding of dynamic bolted joint failure in composite structures. Parametric investigations are extremely useful to probe the sensitivity of joints to variation in intrinsic material parameters as a result of strain rate effects. Furthermore, simulation of joint failure can provide insight into failure mechanisms which are occurring in dynamically-loaded bolted joints which cannot be observed experimentally; high-rate tests are necessarily destructive and intermediate states of damage cannot be observed. This is of the utmost importance for joints which experience a change in failure mode at increased loading rate [3-6].

This paper uses the stacked-shell modelling approach to investigate potential loading rate effects in pull-through failure of bolted carbon fibre composite joints. The models presented shed light on the damage onset and propagation within a pull-through loaded joint. More importantly, insights into the relationship between joint configuration and rate sensitivity are presented which clarify some of the inconsistent experimental results reported in the literature.

2 Summary of Experimental Results

This paper will numerically study pull-through failure of countersunk fastened joints in composite laminates, with a specific focus on high-rate dynamic failure. The failure mechanisms have been experimentally investigated by several authors both quasi-statically [1, 10-14] and dynamically [3, 4, 6, 7].

An ASTM standard exists for pull-through testing of composite bolted joints, ASTM D7332 [15], which is relatively new and post-dates much of the important research in this area. Although the specifics vary, a general pull-through test schematic is shown in Figure 1. A bolt is assembled into a composite plate which is supported around the boundaries, either in a simply supported or clamped condition. A load is applied to the bolt which forces the head of the bolt to pull through the laminate.

In most cases little damage to the composite plate is observed on the side initially adjacent to the bolt head (entry face) whilst significant damage is observed on the reverse face (exit face). There are two general forms of load-deflection response observed in the literature, based predominantly on the relative ratio between specimen thickness and unsupported area, shown in Figure 2. Specimens with low thickness and a large unsupported area around the bolt failed in a bending dominated fashion characterised by: an initial linear elastic region, onset of tensile fibre breakage on the "exit" face of the specimen, progressive fibre breakage and delamination growth, and finally catastrophic bending failure of the delaminated "sublaminates" within the specimen. These specimens are analogous to an axisymmetric 3-point bend test.

Specimens with high thickness relative to the supported area follow a similar progression, but initial damage is not in the fibres; rather a rapid period of delamination growth is experienced, which drops the stiffness of the specimen and hence the load carried. After this period of delamination growth the failure progresses in a similar fashion. These specimens are analogous to an axisymmetric short beam shear test.

High-rate pull-through tests have been shown to have low rate sensitivity up to a loading rate of 10 m/s. In the most extreme test conducted by Pearce et al. [4], shown in Figure 3, there is some suggestion that the high-rate test experiences a higher maximum load. This must be viewed with caution as oscillation of testing equipment can induce noise in the force response of these high rate tests that is difficult to filter from true data [5, 6]. There is also the possibility that catastrophic failure initiates slightly earlier in the high-rate tests. Again, this needs to be treated cautiously as the crosshead displacement is not a very accurate measure of the true position of the bolt relative to the laminate [6]. The possibility of early catastrophic failure (and hence reduced energy absorption) will be investigated with a numerical parameter study later in this paper.

The test configuration for comparison in this paper is taken from Pearce et al. [3, 4]. The bolt is a Hi-Lok™ HL523 100° head countersunk fastener. The shank diameter was ¼" (6.35mm). The bolt was assembled according to manufacturer guidelines into a laminate made from T300/Cycom970 plain weave fabric with a $[(45/0)_4]_s$ layup having a nominal thickness of 3.52mm. The total specimen size was 65x65mm and the specimen was simply supported on a steel plate with a ∅55mm hole.

3 Modelling Procedure

3.1 Stacked-Shell Modelling

In this work, the stacked-shell modelling approach described in detail in [16] was utilised to model the bolted joint. The techniques used here replicate the approach used in [16] unless expressly discussed below.

The stacked-shell methodology represents a composite laminate as a set of discrete 2D "sublaminates". The sublaminates can include any number of plies, or fraction of a ply if desired. The sublaminates are "glued" together using tying elements between adjacent layers. The sublaminates are given typical in-plane composite properties, while a cohesive zone delamination model (CZDM) is applied to the tie links between sublaminates to represent delamination and through-thickness failure modes. Greve and Pickett [17] have shown that the stacked-shell approach is elastically nearly identical to other laminate modelling approaches, while Pearce et al. [16] showed that a stacked-shell approach captures complex failure mechanisms, such as bolt bearing, well. A schematic view of the stacked-shell modelling approach is shown in Figure 4.

Stacked-shell modelling is a compromise between simplified shell models and high detail finite element (FE) modelling using a completely solid representation of the material. The benefit of the approach is most evident when using explicit FE solvers, where large efficiency gains can be made with minimal reduction in the fidelity of the results. This paper does not attempt to make a strong claim regarding the value of stacked-shell modelling; that has been done elsewhere [16, 18-20]. Rather, this paper attempts to investigate the limitations of the already validated methodology and also to use it to gain insight into the failure processes that occur during bolt pull-through failure.

3.2 Pull-through Model

The pull-through model used for the analyses which follow is shown in Figure 5. The model was solved using PAM-CRASH™ [21], a commercially available software package widely used for crash simulation of vehicles. This model was assembled from four independent sub-parts: the bolt, bushing, laminate (stacked sublaminates) and strike plate. All parts were modelled with a structured mesh. The model utilised two symmetry planes to improve computational efficiency. The symmetry approximation was justified because damage evolution in the specimen was generally symmetric, and the laminate is identical under reflection in planes normal to the 0° and 90° directions. Generalised penalty-based contact was used to transfer loads between different parts of the model.

The bolt, bushing and loading plate were meshed using regular 8-node hexagonal elements with selective reduced integration formulation. Selective reduced integration mitigated hour-glassing problems and improved the consistency of the contact pressures in the model. The loading plate was defined as a rigid body, with one degree-of-freedom (DOF) in the loading direction. The plate was given a constant velocity throughout the simulation. The constant velocity chosen was 5 m/s as this velocity gave the best computational efficiency whilst still maintaining negligible inertial effects. Any rate sensitivity in the model was captured by the material models.

The composite laminate was modelled as a stack of laminated shell elements joined by cohesive zone delamination interfaces. The laminates were organised according to the geometry of the laminate, hole and the locations of expected delamination damage. A number of different shell-interface arrangements were tested, but the best balance between accuracy and computational efficiency was found with a five-shell (four-interface) arrangement. The arrangement of the sublaminates relative to the ply stack and the countersunk bolt hole is given in [16]. The size of the regular mesh on the laminate varied with radial position but at the edge of the hole the average element edge length was 0.4mm.

The model was displacement-controlled. The lower face of the bushing was held fixed, while the tail of the bolt was moved by a small preload displacement (0.1mm) and then held fixed to represent the preload. The loading plate was offset from the laminate slightly, such that the loading plate struck the laminate at the same time that the preload was completed. The displacement conditions as a function of time are shown diagrammatically in Figure 6. Crosshead load was measured from the reaction force imposed by the bolt and bushing boundary conditions. Crosshead displacement was considered to be the same as the loading plate displacement.

3.3 Material Parameters

The bolt was given the properties of Ti-6Al-4V, which is the aerospace grade titanium alloy used for Hi-Lok fasteners. The alloy was considered elastic-plastic with a linear hardening slope. The bushing was given the properties of mild steel, which was considered elastic since the loads involved were well below yield. The properties for the two materials are given in Table 1.

The composite ply material model used was a bi-phase fabric formulation (PAM-CRASH, Material 132, Ply Type 6), with the fabric ply properties given in Table 2. The explanation for and derivation of these properties are given in the solver manuals [22, 23] and in [16].

The interface properties are given in Table 3 (see [16] for derivations). Note that G_{Ic} and G_{IIc} represent the Mode I and Mode II strain energy release rates for delamination. There is significant disagreement in the literature as to the effect that loading rates and crack speeds have on the energy absorbed by delamination. Some authors suggest that strain energy release rate (SERR) decreases with increased loading rate [24, 25], some suggest SERR increases with loading rate [26, 27] whereas others found no change [28]. It has been suggested that SERR variation may be responsible for at least part of the rate sensitivity of bolted joints [3] and hence will be the focus of a numerical parameter study. If suggested trends in SERR align with observed trends in failure load and failure mode, then it is possible that a correlation exists. Conversely, if variation of SERR leads to results which are not observed experimentally, then this can be ruled out as a physically significant effect.

4 Results and Discussion

4.1 Baseline Results

The load-displacement response of the model under the prescribed displacement loading is shown in Figure 7. The progress of the internal damage development is shown diagrammatically above the graph in subfigures (a)-(d). The damage progression follows the same course as for the experiment: (a) radial tensile fibre damage in the outermost ±45° ply progressively penetrating through the ply stack in the thickness direction; (b) lobe delamination growth initiating first near the mid-plane of the specimen around the cracks; (c) progression of the delamination until the delaminated areas merge; (d) rapid delamination growth and catastrophic bending failure of the now unsupported sublaminates.

4.2 Effect of Cohesive Parameters

The in-plane loads imposed on the laminate during a pull-through test are predominantly tensile (low shear and compression). Any in-plane components of the stress-tensor are carried principally by the fibres; hence rate sensitivity of these failure modes is likely to be low [29]. The through-thickness loads, however, are only carried by the matrix phase and are consequently susceptible to rate-sensitivity under the right conditions.

A parametric study was conducted to investigate the effect of the interface strain energy release rate (SERR) on the load-displacement response of the model. The Mode I and II SERRs were varied above and below the default value, and the results are shown in Figure 8.

It was found that the model was insensitive to the Mode I SERR (Figure 8a) and mildly sensitive to the Mode II SERR (Figure 8b). In the latter case, the maximum load carrying capacity of the joint remained almost unchanged. The only measurable effect of increasing G_{IIc} was to retard the growth of delamination, and hence delay the onset of catastrophic bending failure of the unsupported sublaminates. There was also a resulting minor increase in energy absorption with increased Mode II SERR.

4.3 Addressing Limitations of the Interface Model and Possible Improvements

Hou et al. [30] have shown that even small compressive stresses have a large restraining influence on the growth of delamination. The Hou model penalises compressive normal loading heavily, and even completely inhibits delamination if the compressive normal load exceeds a certain critical cut-off. In the vicinity of the bolt in the pull-through test apparatus there is a *compressive cone*: a region which experiences compressive through-thickness stresses due to the introduction of load from the bolt and also any pre-tightening that may occur before the test. The size and shape of the compressive region varies as load is applied to the specimen, but an example is shown in Figure 9.

The stacked-shell modelling approach implemented in PAM-CRASH depends on the application of a CZDM to the interface ties between the sublaminates. The CZDM model built into PAM-CRASH is described in detail in [16]. One limitation of the CZDM is that it does not account for the retarding effect that through-thickness compression may have on the growth of shear delamination.

To simulate the effect identified by Hou et al., extra interfaces were added within the compressive cone that the bolt pretension provided. The size of this region was found by running a preload analysis on the default model, and selecting the links that had compressive loads of greater than 20% of the maximum compressive load. The extra links are shown in Figure 10. These extra links had twice the strength for a given opening or sliding displacement, effectively tripling the strength of the interface near the bolt. This was considered reasonable, as the normal loads were generally significantly above those where delamination was forbidden according to the Hou model. The additional links significantly improved the correlation between the experimental failure mode and the simulation, which will be shown in the next section.

4.4 Experimental Correlation

A comparison between measured and simulated load-deflection response is given in Figure 11. It is clear that the initial failure load and failure progression are captured extremely well. Divergence between the experimental and simulation results occurs once delamination growth begins to increase significantly, although the form of the curve is still very similar. The addition of the extra links to the region underneath the bolt head improves the prediction considerably in this region. The displacement scale on the abscissa of Figure 11 does need to be treated with some care, as the experimental displacements were measured at the crosshead of the testing machine, whereas the simulation results were measured directly from the model. A recent study by Heimbs et al. [6] raises doubts about the reliability of the crosshead displacement scale for dynamic testing.

Comparisons of the observed external and internal damage and the simulated (extra links) results are shown in Figure 12 and Figure 13 respectively. The damage state at the end of the test is captured extremely well using the stacked-shell model. Note that the model has not been allowed to relax in Figure 13b, so additional elastic deformation is displayed.

5 Discussion and Conclusions

The correlation between experimental and simulated results shows that the stacked-shell modelling approach provides a powerful (and efficient) modelling tool for investigating pull-through failure of bolted joints in composite structures. Along with the paper by Pearce et al. [16] which studied bearing failure, a strong case can be made for the methodology. In [16], some limitations with the methodology were identified. In the present case, the limitation is primarily due to the specific implementation in PAM-CRASH. Additional modelling assumptions needed to be made in order to capture the beneficial effect of through-thickness compression. A minor modification to the cohesive zone delamination model would improve predictions significantly.

The primary focus of this paper was to use simulation of pull-through failure to shed light on experimentally observed loading-rate effects, or rather a lack of strongly observed effects. Many authors have observed rate sensitivity when studying bearing failure [3-6, 9], yet studies to date have only shown very minor [4] or no [3, 6] rate sensitivity for pull-through failure. It has been previously suggested [3] that high crack growth rates lead to a reduction of SERR for delamination, which in turn explains the observed changes in bearing behaviour. This statement is seemingly contradictory, as both bearing and pull-through failure modes are heavily matrix dependent, and only the bearing mode experiences strong rate sensitivity.

This paper investigated the phenomenon by conducting a parametric study involving the Mode I and II strain energy release rates for delamination cracking in the model. Contrary to intuitive experience, it was shown that although delamination plays a major role in pull-through failure, modifications to the SERRs made little difference to the measured force-displacement curve. More importantly, the weak correlation between G_{IIc} and the model output which was observed (shown in Figure 8b) is consistent with the experimental data in Figure 3. An example of two load-displacement curves (shown in Figure 14) illustrates the possible rate sensitivity.

Regardless of the existence of rate-sensitivity in pull-through failure, the assertion by Pearce et al. [3] that SERR plays a role in rate sensitivity of bolted composite joints during bearing remains consistent with the findings of this paper. Although this paper does not find strong evidence to support the previous assertion by Pearce et al. [3], it does indicate that further investigations into this correlation are not unfounded.

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Figure Captions

Figure 1: Pull-through test configuration

Figure 2: Typical load-deflection response of published pull-through test results

Figure 3: High-rate pull-through test data [3, 4]. (For interpretation of the legend colours the reader is referred to the web version of this article)

Figure 4: Stacked-shell approach showing (a) laminate cross-section, (b) laminate exploded into sublaminates, (c) shell model of sublaminates and (d) stacked-shells with cohesive zone delamination model

Figure 5: Stacked-shell model of pull-through test

Figure 6: Displacement-controlled boundary conditions to apply load to model

Figure 7: Load-displacement response for pull-through model showing: (a)-(d) damage progression and (inset) model state

Figure 8: Interface parameter study showing the effect of: (a) G_{Ic}; and (b) G_{IIc}. Units J/mm^2. (For interpretation of the legend colours the reader is referred to the web version of this article)

Figure 9: Region of compressive stress under countersunk fastener

Figure 10: Additional links added under bolt head

Figure 11: Load-displacement comparison between simulation and experiment. (For interpretation of the legend colours the reader is referred to the web version of this article)

Figure 12: Comparison of splitting and delamination of the specimen exit face for extra links model

Figure 13: Comparison of internal delamination damage at the mid-plane of the specimen showing: (a) CT reconstructed delamination; and (b) numerical prediction for extra links model

Figure 14: A comparison of two example load-displacement curves (For interpretation of the legend colours the reader is referred to the web version of this article)

Tables

Table 1: Isotropic metallic material properties

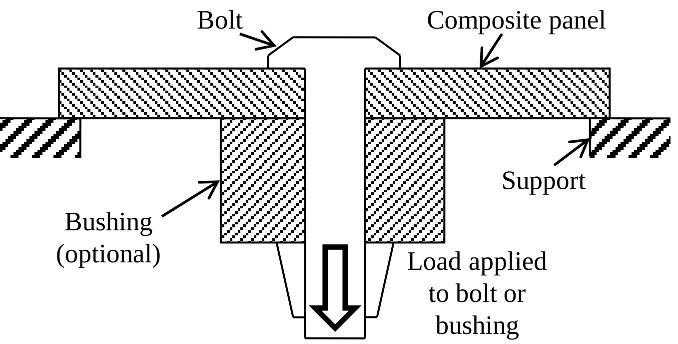
Alloy	Young's modulus E (GPa)	Poisson's ratio ν	Shear yield stress τ_y (MPa)	Tangent modulus E_t (GPa)
Ti-6Al-4V	115	0.33	900	10
Mild steel	210	0.33	-	-

Table 2: Composite fabric ply properties

	E_{11} [= E_{22}] (GPa)	E_{33} (GPa)	G_{12} (GPa)	G_{23} [= G_{31}] (GPa)	ν_{12}	ν_{23} [= ν_{13}]	ε_i	ε_l	ε_u	d_l	d_u
Tension	55.8	5.56	3.65	3.65	0.06	0.38	0.0071	0.0085	0.0106	0.05	0.80
Compression	55.8	5.56	3.65	3.65	0.06	0.38	0.0025	0.0030	0.0106	0.05	0.55

Table 3: Interface properties (* denotes baseline value for parametric study)

E (GPa)	G (GPa)	G_{I0} (kJ/m^2)	G_{II0} (kJ/m^2)	G_{Ic} (kJ/m^2)	G_{IIc} (kJ/m^2)
5.56	3.65	0.078	1.506	0.68*	3.25*


Bolt
Composite panel
Support
Bushing
(optional)
Load applied
to bolt or
bushing

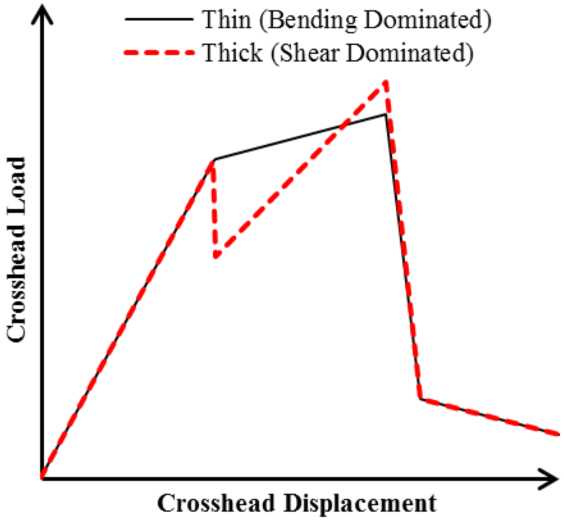
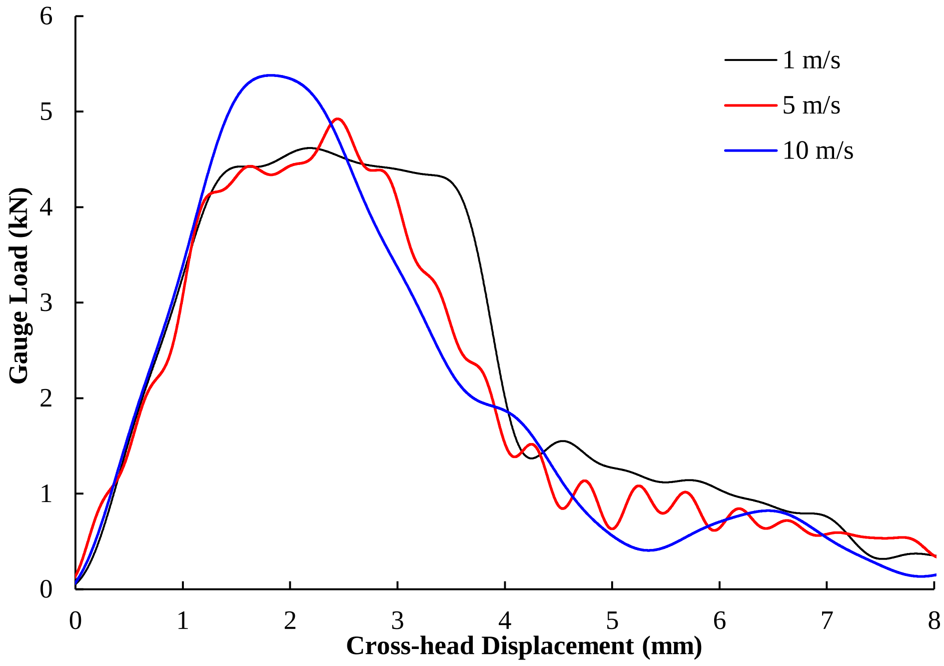
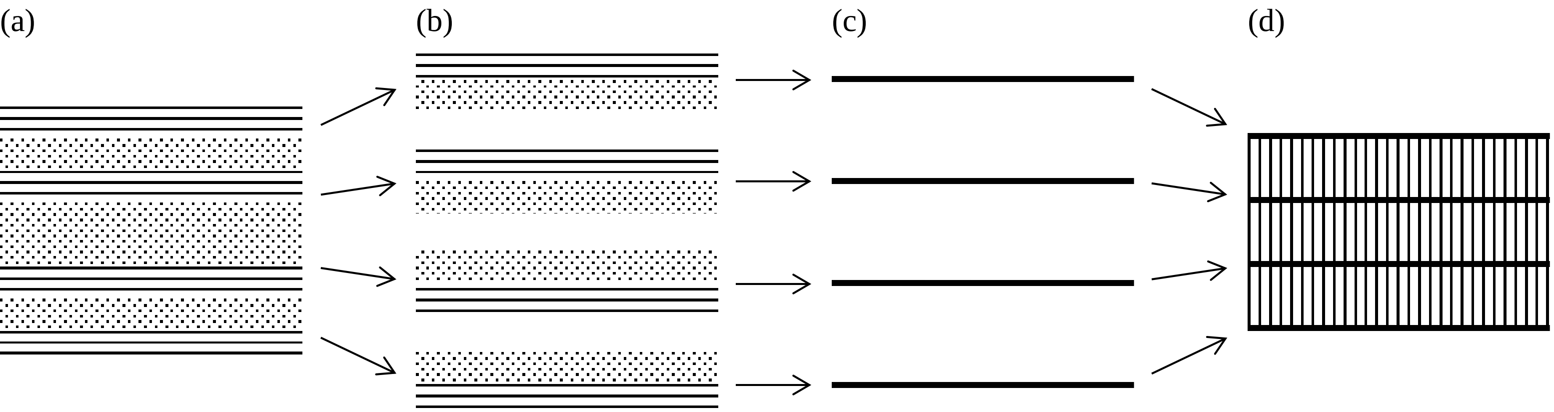

Thin (Bending Dominated)
Thick (Shear Dominated)
Crosshead Load
Crosshead Displacement

Figure 2

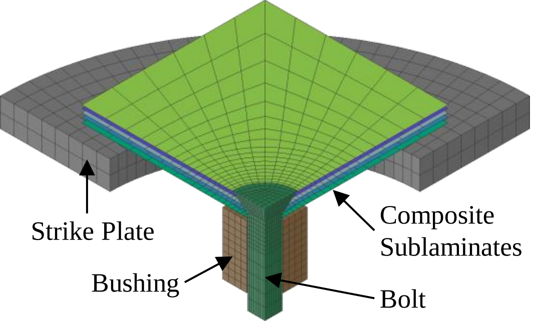


Gauge Load (kN)
Cross-head Displacement (mm)
1 m/s
5 m/s
10 m/s
0
1
2
3
4
5
6
0
1
2
3
4
5
6
7
8

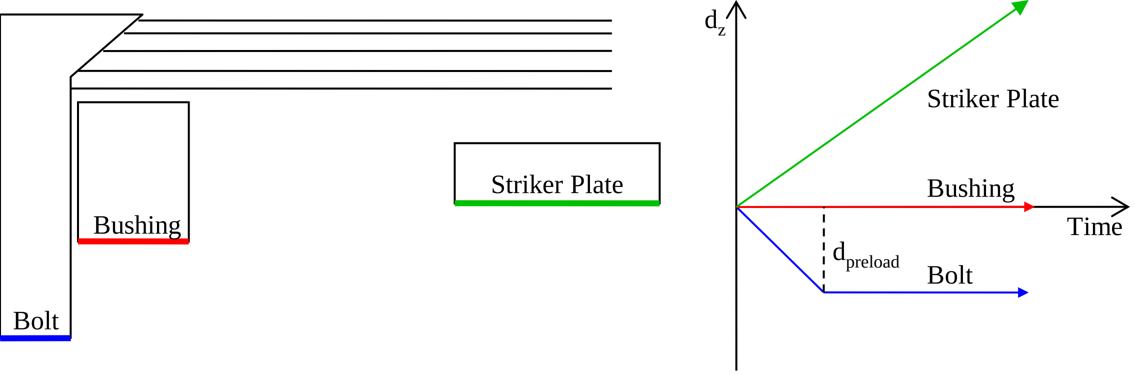
Figure

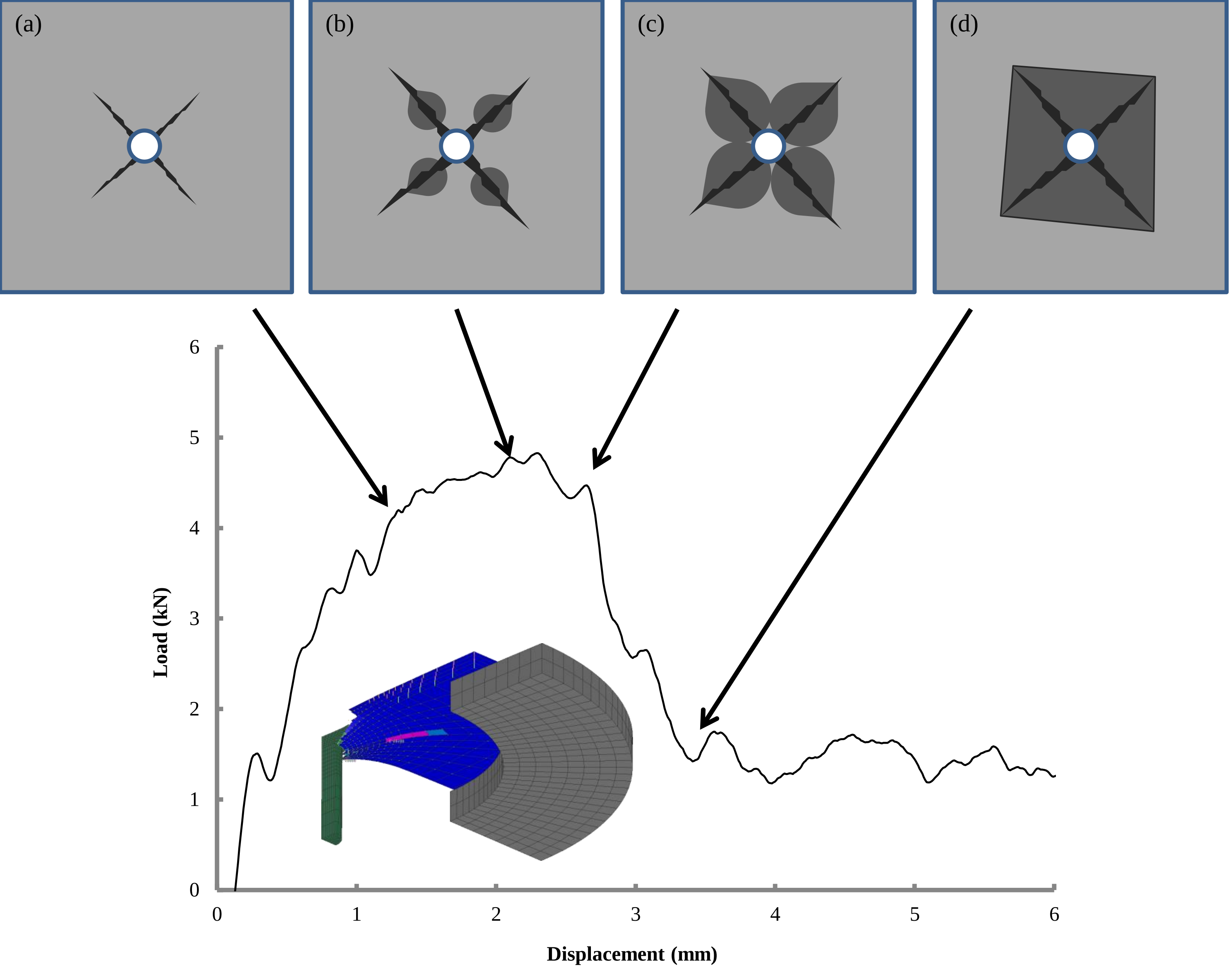


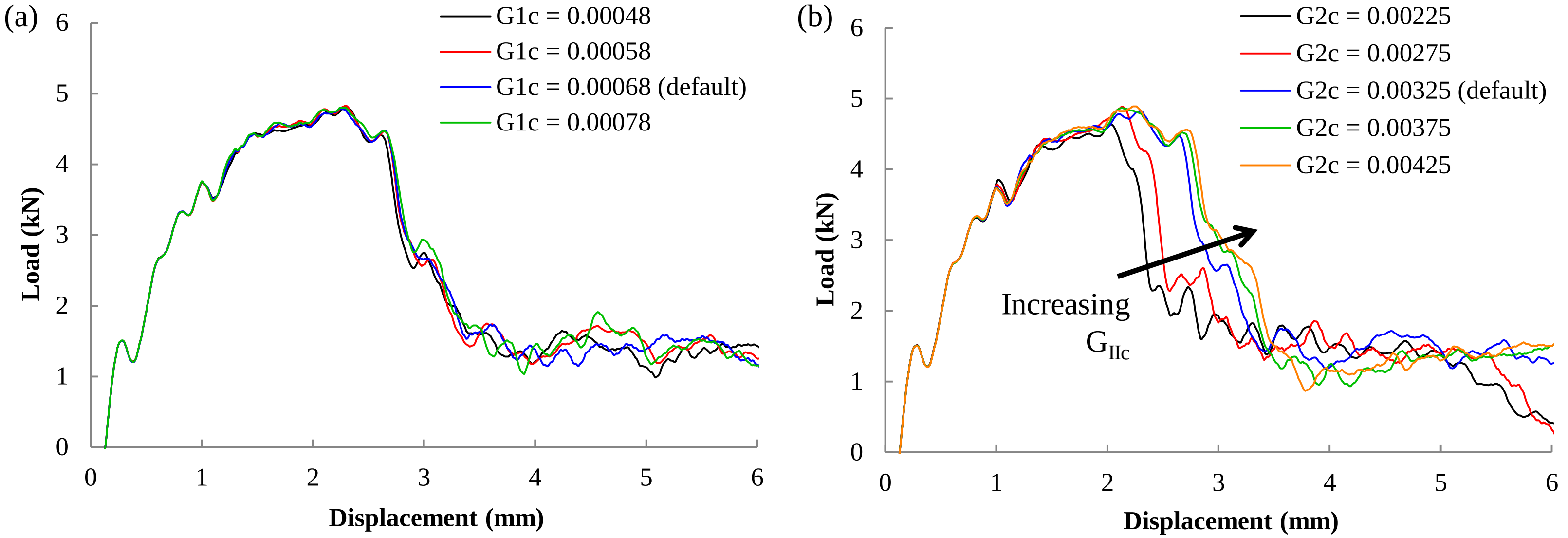
Figure

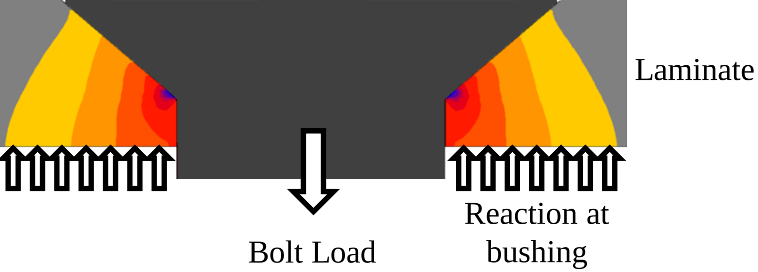


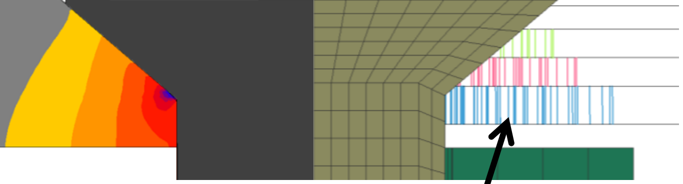
Figure


Bushing
Bolt
Striker Plate
d_z
Striker Plate
Bushing
Time
$d_{preload}$
Bolt

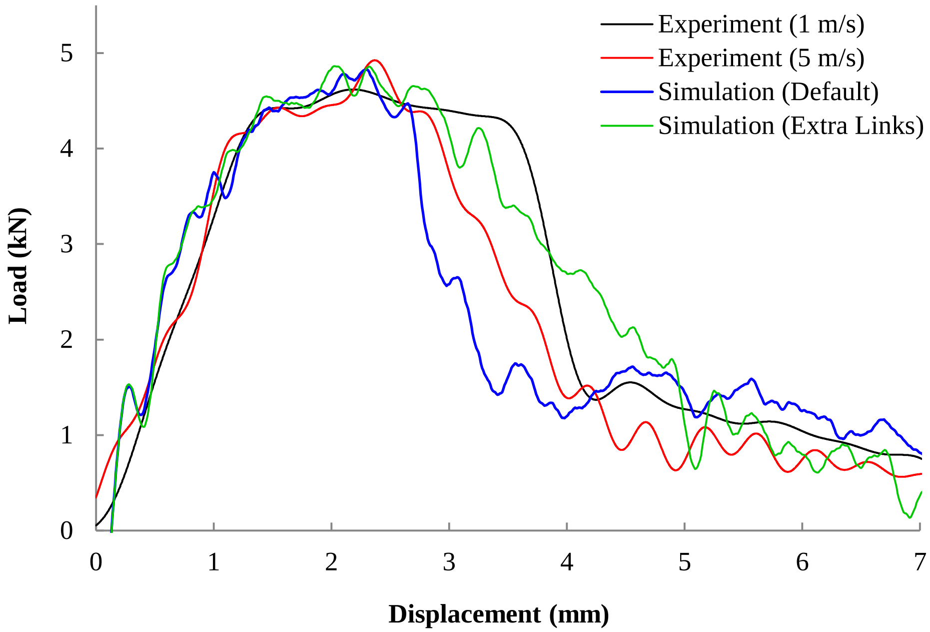

(a)
(b)
(c)
(d)
Load (kN)
Displacement (mm)
0
1
2
3
4
5
6
0
1
2
3
4
5
6


(a)
G1c = 0.00048
G1c = 0.00058
G1c = 0.00068 (default)
G1c = 0.00078
Load (kN)
Displacement (mm)
(b)
G2c = 0.00225
G2c = 0.00275
G2c = 0.00325 (default)
G2c = 0.00375
G2c = 0.00425
Increasing G_{IIc}
Load (kN)
Displacement (mm)


Laminate
Reaction at bushing
Bolt Load



Additional links added to retard delamination under bolt head


Experiment (1 m/s)
Experiment (5 m/s)
Simulation (Default)
Simulation (Extra Links)
Load (kN)
0
1
2
3
4
5
0
1
2
3
4
5
6
7
Displacement (mm)

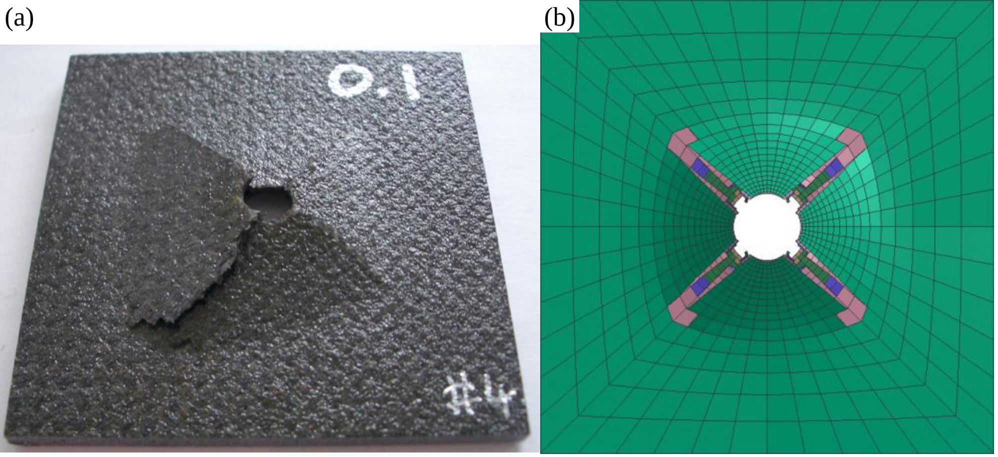
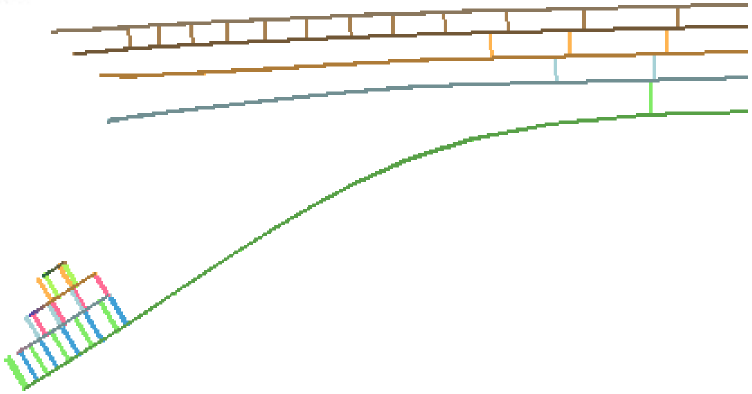
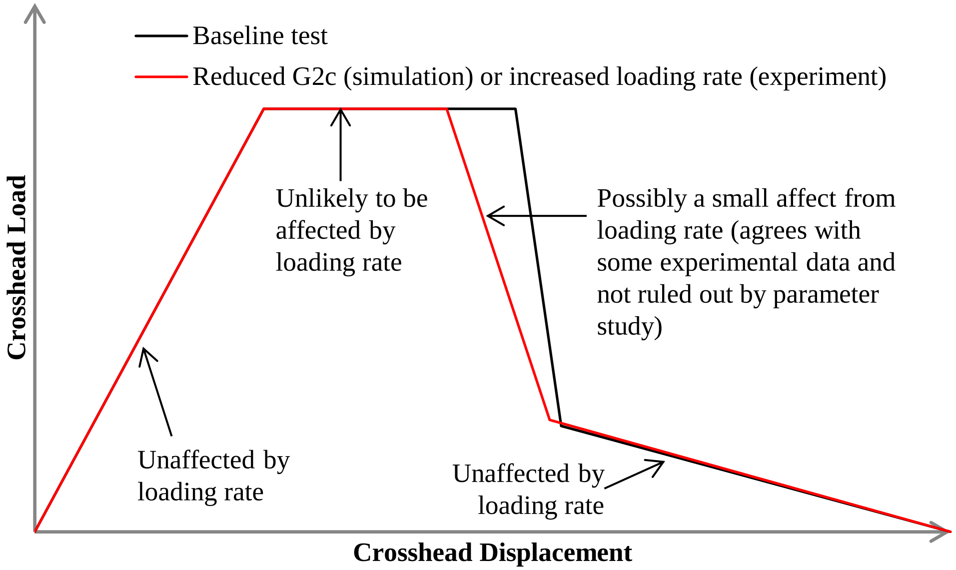


Figure 12

(a)

(b)




Baseline test
Reduced G2c (simulation) or increased loading rate (experiment)
Unlikely to be affected by loading rate
Possibly a small affect from loading rate (agrees with some experimental data and not ruled out by parameter study)
Unaffected by loading rate
Unaffected by loading rate
Crosshead Load
Crosshead Displacement