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Publication details:
Australasian Structural (ASEC2008) Engineering Conference
pp. 18.1-18.8
9781877040702 (ISBN)

Event details:
2008 Australasian Structural Engineering Conference (ASEC 2008)
Melbourne, Australia

Publication Date:
2008

DOI:
https://doi.org/10.26190/unsworks/348

An Artificial Neural Network Approach to Elastic-Creep Life Assessment

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Abstract

This paper describes a new multiaxial model for predicting creep lives of structures. The model hypothesises that the creep damage is proportional to the creep internal energy density absorbed by the material. The authors argue that the model is the most appropriate for characterizing gross creep damage from a macroscopic point of view because it takes into accounts both the multiaxial internal deformation and loading**.** The verification and application of the model are demonstrated by applying it to various notched bars for which the experimental data are available. The results show that the proposed model is capable of predicting creep lives of the structures conservatively.

1. Introduction

There are many engineering structures that operate at sufficiently high temperatures to be subjected to creep damage. The basic creep deformation and failure mechanism have been previously outlined by many researchers (see for example Milne et al, 2003). The microstructural damages highlight the fact that failure is generally by cavity nucleation and growth; dislocation creep is the main mechanism with microstructural features such as sub-grain formation and growth, new phase formation, such as the *Z* phase, coarsening and leading to the dissolution of the MX phase. This leads to the removal of pinning precipitates which can allow local heterogeneous sub-grain growth, weakening due to this growth and also to the dissolution of the MX. These features lead to the earlier formation of tertiary creep and reduced life.

From macroscopic point of view, there are several creep damage models, which include the Robinson's life fraction rule (Robinson, 1952), strain fraction rule (Milne et al, 2003), continuum damage model (Kachanov, 1958 and Rabotnov, 1969) and Omega parameter (Prager, 2000). The limitations of the above-mentioned models have been discussed in Zarrabi and Ng, 2006 and for the sake of brevity they are not described here. It is suffice to state that the above-listed models are either too complex for pragmatic applications and/or the required material data are not readily available and/or they do not result in conservative life predictions for at least some cases. Zarrabi and Ng, 2006 have proposed a creep damage model based on total internal energy density and tertiary creep behaviour. This paper modifies this model and combines it with the artificial neural network.

2. An artificial neural network model for predicting creep life

Although the extension of proposed model to the cases where there is elastic-creep-plastic deformation is straightforward, this paper concentrates on elastic-creep damages. However, note that provided an engineering structure is designed correctly, any plastic deformation is limited to the stress concentration regions and should be relatively small. Also, it is assumed that: (i) the creep damage induced in the material is proportion to the creep internal energy density input to the material and (ii) for the purpose of determining the creep life, the actual (multi-axial) creep damage in the structure may be converted into a hypothetical uniaxial case in such a way that the creep life of the structure is equivalent to creep life of the uniaxial component. The later assumption is similar to the concept of equivalent stress for the purpose of predicting the onset of plastic deformation and yielding. The proposed model then follows the following procedure.

The first step is to compute the creep internal energy density (W_c) as a function of time (t)for the structure. If analytical solutions are not available, this can be achieved using a numerical method such as the finite element method (FEM):

$$W_c = f_c(t) \tag{1}$$

Having computed numerical values of W_c for various time points, instead of usual curve-fitting approach, this paper will use ANN to obtain f_c in equation (1). When data are assumed to fit a mathematical distribution, we are adding information that helps us to model the available data. This, however, may be misleading if we have chosen the wrong distribution. An ANN consists of a training stage and a prediction stage. ANN models the data that are presented to it during the training stage without assuming a particular distribution. After the network is trained it is used to predict W_c using t.

ANN has a parallel processing architecture that is composed of many non-linear computational elements (neurons). It is naturally suited to tackle complex and non-linear problems. The elements or neurons in ANN are arranged in patterns reminiscent of biological brain cells. The present investigation uses a back propagation, feed forward ANN with input, hidden, and output layers (Zarrabi, 2006). In operation, ANN learns a predefined set of input-output example pairs by using a two-phase propagate-adapt cycle. As mentioned before, the development of ANN consists of two stages, viz., a learning and a prediction stages. During the learning stage, first, the inputs are supplied to the input layer where they are acted upon by input transfer functions, weights and biases at each neuron; then they propagate through hidden and output layers. At hidden and output layers the variables are acted upon by the corresponding transform functions, weights, and biases. Biases are normally set to unity for all three layers. At the output layer, the variables are combined to produce an output. This output is then compared with the desired output (Computed W_c from FEM) and an error signal (ER) is computed. ER is then minimized with respects to weights and the process is iterated until ER is less than a desired value. The final weights are used in the predication stage to compute the desired output variable. Before the training of the network both input and output variables (V) are normalized within the range 0–1 using:

$$V_n = \frac{2V - V_{\max} - V_{\min}}{V_{\max} - V_{\min}} \tag{2}$$

where V_n is the normalized value of the variable V, $V_{\max}$ is the maximum value of the variable and $V_{\min}$ is the minimum value of the variable.

Having determined W_c as a function of time, to calculate creep life, the expression for the uniaxial creep internal energy density (W_u) is also needed. This expression depends on the creep constitutive equation, e.g., for Norton power law:

$$W_u = B\,\sigma^{(n+1)}\,t_{ru} \tag{3}$$

Where σ is stress, B is the Norton stress coefficient, n is the creep stress index and t_{ru} is the uniaxial rupture time. Note that the uniaxial relationship between σ and t_{ru} in equation (3) is also known from the uniaxial rupture data so that:

$$\sigma = f(t_{ru}) \tag{4}$$

Combining equations (3) and (4) results in:

$$W = B\,[\,f(t_{ru})]^{(n+1)}\; t_{ru} \tag{5}$$

Noting the above equations the model is outlined in Figure 1.

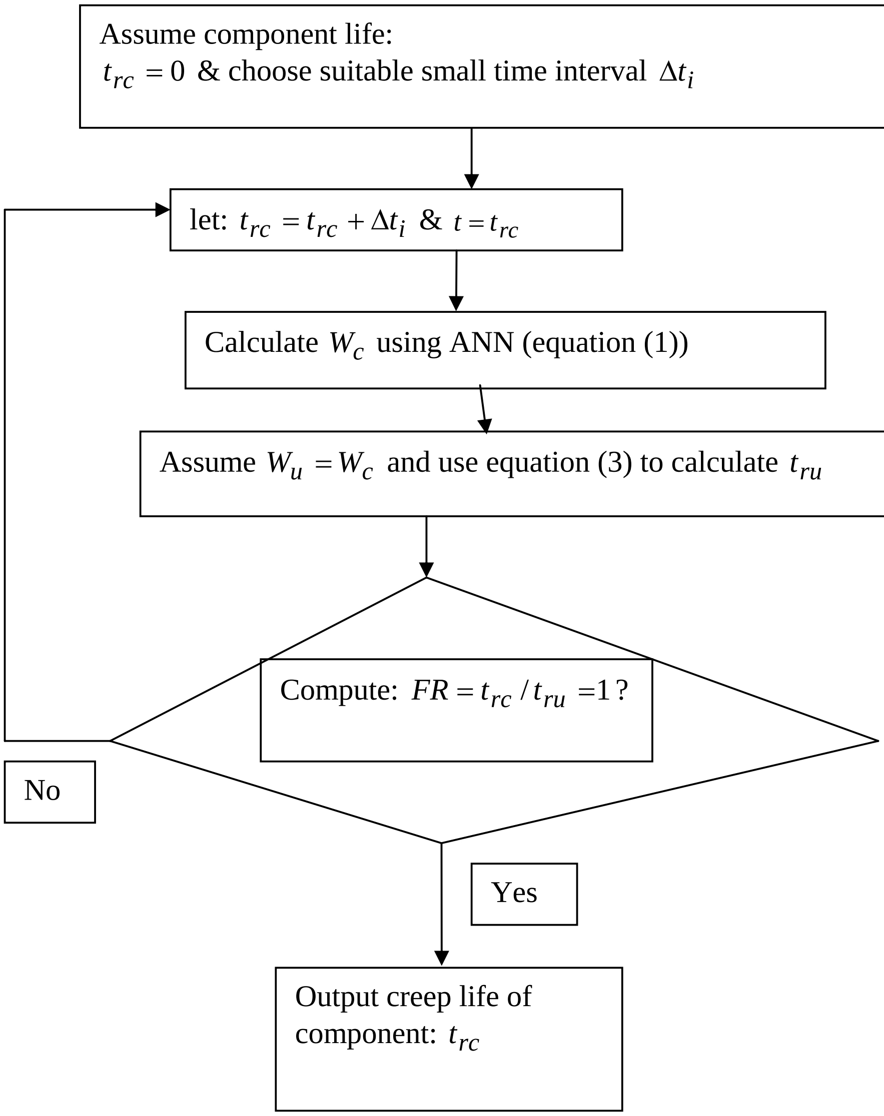

Figure 1 – Algorithm of creep life prediction

3. Validation of the model

Ideally to validate the model presented in Section 2, one should compare the predictions from the proposed model with those obtained experimentally for various structures made of various materials and subject to various temperatures and multiaxial stress fields. However, high temperature creep experiments on anything other than the uniaxial tensile specimens are costly, time-consuming and often contaminated with scatter. One relatively convenient way of introducing a state of multiaxial stress into otherwise uniaxial tensile specimens is to subject circumferentially notched solid bars to a constant tensile force applied in the axial direction of the bar. In this way, various stress states can be simulated by changing the circumferential notch profile. Kwon et al, 2004 have carried out creep testing using notched bars all made of 2.25%Cr1%Mo steel tested at 550°C. The bars were: (1) Bridgman notched bar with the notch acuity $a/r = 1.5$ where r was the notched root radius and a was the radius of the cross-section at the notch root , see Figure 2, (2) modified Bridgman I notched bar with $a/r = 5.0$, (3) modified Bridgman II notched bar with $a/r = 0.7$ and (4) modified British Standard notched bar with $a/r = 9.0$. Note also that for all bars: $R = 4.38\ mm$ and $L = 12.5 mm$ (Figure 2).

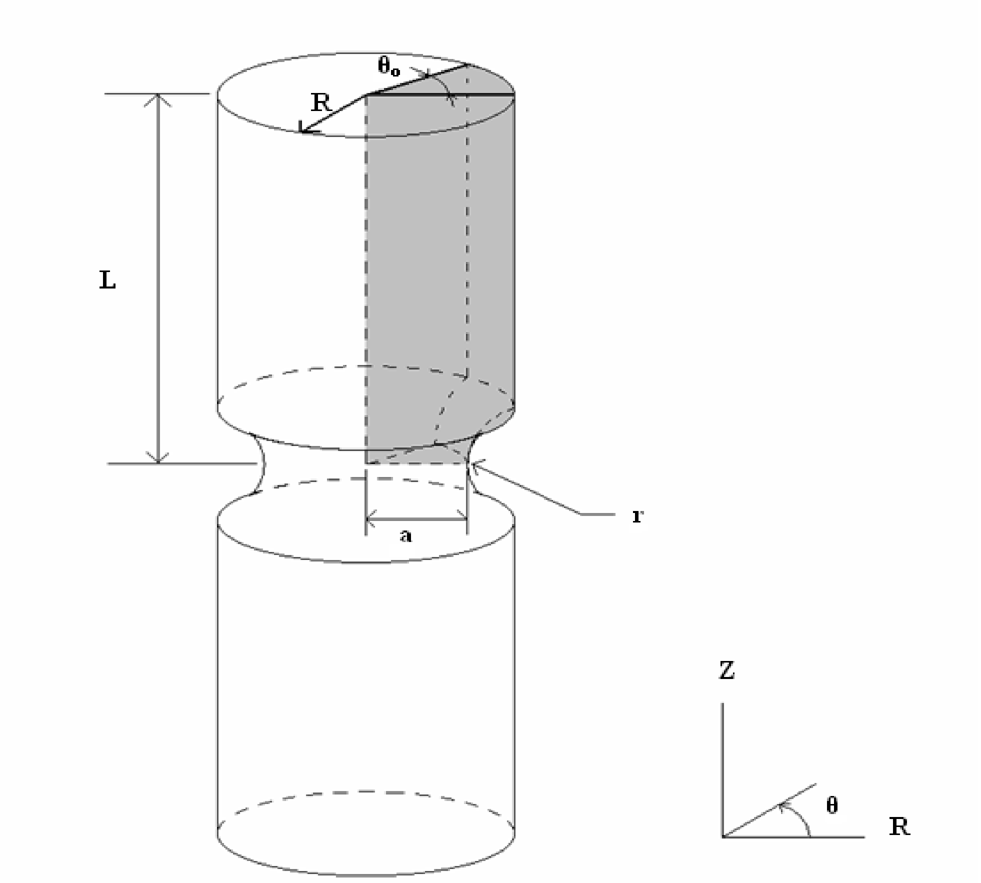

Figure 2 – Bridgman notched bar

To obtain the creep internal energy density at the notch root, finite element analysis was employed using MSC/NASTRAN, 2006 because of its availability to the authors. The material properties used in an analysis were: the modulus of elasticity at the test temperature of $0.157x10^6\ MPa$, $n = 9.0$ and $B = 6.408 \times 10^{-14}$ where these values when used in equations (3) and (5) resulted in time in hours and stress in MPa. The uniaxial rupture data at 550 deg C described by:

$$\sigma = [\frac{t_{ru}}{2.1830 \times 10^{20}}]^{-1/7.9} \qquad (6)$$

where t_{ru} was in hours and σ was in MPa. The axial traction load applied to each bar in each finite element analysis matched those used experimentally by Kwon et al, 2004. Because there are no axisymmetric elements for creep analysis brick element were used for the present analysis. To this end, a section of the bar subtended by $\theta_0 = 3.924^\circ$ was modelled and a typical mesh is shown in Figure 3. Note that because of symmetry only half of the length of the bar was modelled. A typical mesh was consisted of about 1,600 brick elements.

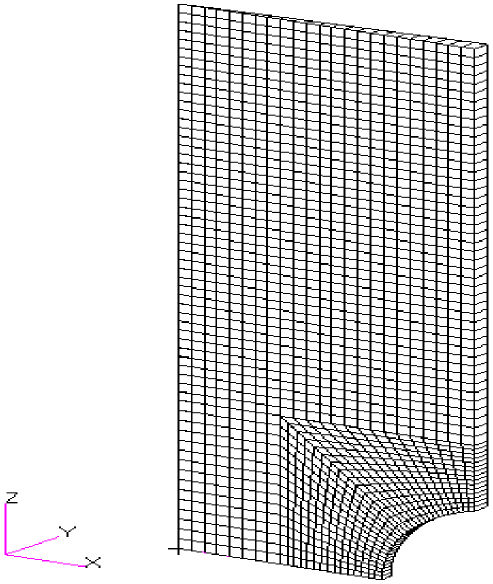

Figure 3 – Finite element mesh for Bridgman notched bar

The computed creep internal energy density as a function of radius at the notch root section for the Bridgman notched bar for various time points are shown in Figure 4. As it might be expected the highest internal energy densities occurred at the notch root. Similar results were obtained for other bars.

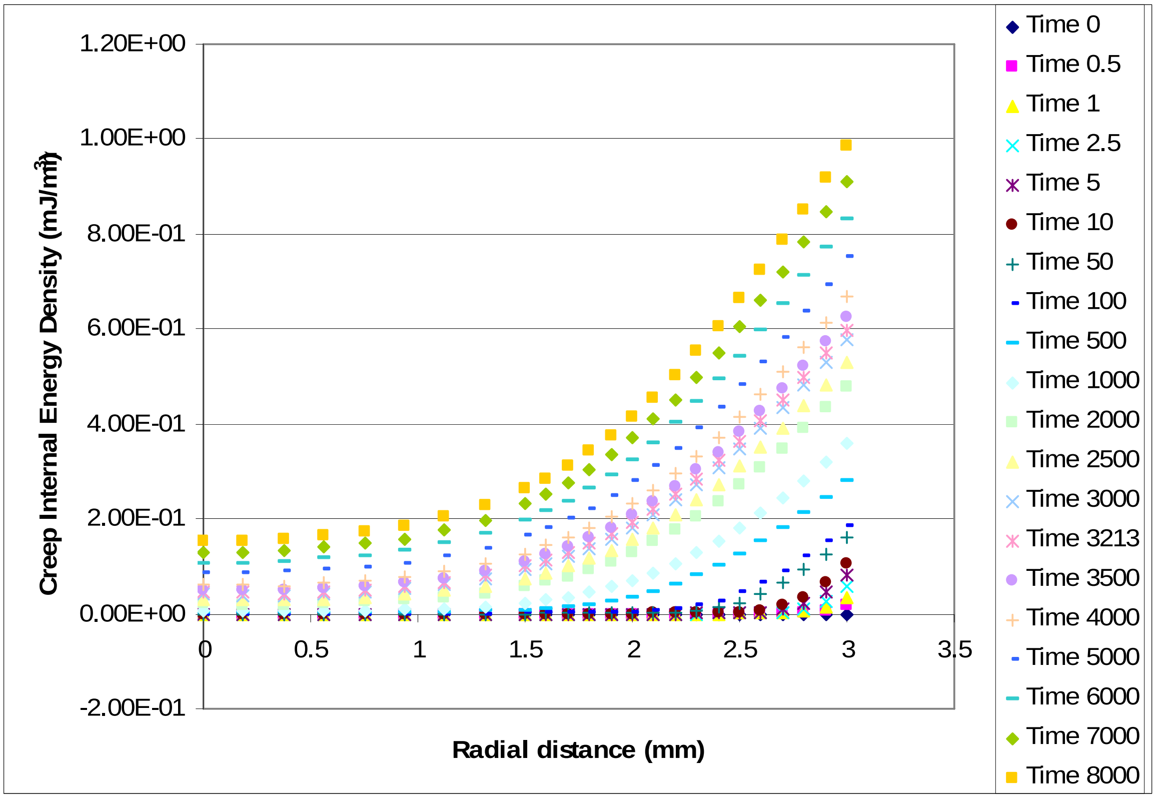

Figure 4 – Creep internal energy density versus radial distance at the notched section for various time points for Bridgman notched bar

Using the computed creep internal energy densities and the model described in Section 2, life of each bar was computed and listed in Table 1. Table 1 includes the experimental lives obtained by Kwon et al, 2004.

Table 1 – Comparison of computed and experimental lives for various notched bars

Bar	Experimental Life (Hours)	Computed Life (Hours)	r/a
Modified British Standard	865	172	9.0
Modified Bridgman I	1,190	367	5.0
Bridgman	3,213	1,850	1.5
Modified Bridgman II	4,439	4,120	0.7

The results listed in Table 1 show that the proposed model can conservatively predict the creep lives of the bars. However, as acuity (r/a) decreases, i.e., as the damage is concentrated more at the notch root, the computed and experimental lives become closer. This might be expected because, in order to be conservative, the model deliberately assumes that the damage is concentrated at the notch root, which is the case for small acuity values. Whereas in reality and as the acuity increases the creep damage redistributes from the notch root and spreads to its surrounding area as time progresses resulting higher lives.

4. Conclusions

A new model for predicting creep lives of structure was presented. The model assumes the creep damage is proportional to the creep internal energy density at most critically loaded region in the material. By applying the model to various notched bars for which experimental lives available, it was shown that the model can conservatively predicts the creep lives of the bars.

The model has several advantages when compared with other continuum creep damage models. The model is based on the exhaustion of the total internal energy in the highly stressed/strained zone in the material and therefore it is a true multiaxial model taking into account the contributions from all the stress/strain components. This is a measure of total deformation as well as internal loading in the component and therefore it should be the most appropriate for characterising gross creep damage. In practical terms, the model does not require quantities such as rupture stress, the damage parameter and some material parameters that are cumbersome and costly to determine and/or employ in practice. Therefore, it should be more practical and should result in more accurate predictions for the creep life of components. In addition, the proposed model is relatively simple to employ and can be used in conjunction with any commercial finite element code with creep analysis capabilities

5. References

Kachanov L M, Izv Akad Nauk, SSSR, Ser Fiz, 1958,.Vol 8, pp 26-31.

Kwon O, Thomas C W and Knowles D. Multiaxial stress rupture behaviour and stress-state sensitivity of creep damage distribution in Durhete 1055 and 2.25Cr1Mo steel. Int J of Pressure Vessels and Piping; 81: 6: 2004; June; p. 535-542.

Rabotnov Y N, Proc XII IUTAM Congress, Stamford, CN, eds: Hetenyi & Vincent, 1969, p 137, Springer.

Milne I, Ritchie R O and Karihaloo B. Comprehensive Structural Integrity. Volume 5. Creep and high –temperature failure. Volume Editor: Saxena A, Elsevier Pergamon, London, UK, 2003.

MSC/NASTRAN, Handbook for Non linear Analysis. 2006, The MacNeal Schwendler Corporation, Los Angeles, California, USA

Prager M. The omega method – an engineering approach to life assessment. Trans of ASME, J of Press Vessel Tech, 2000, Vol 122 No 3, pp 273-280.

Robinson E L, Trans Am Soc Mech Eng, 1952, 4:777.

Zarrabi K and Ng L. A novel and simple approach for predicting creep life based on tertiary creep behaviour. the ASME PVP 2006 / ICPVT-11 Conference (CD-ROM), Paper No: PVP2006-ICPVT11-93035, July 23-27, 2006, Vancouver, Canada. This paper was selected and scheduled for publication in the Nov 2008 edition of the ASME Journal of Pressure Vessels Technology.

Zarrabi K. Estimating the plane-strain fracture toughness under mode I from the uniaxial tensile data. Proceedings of the Structural Integrity & Failure conference, CD-ROM, Sydney, Australia, 27 – 29 September 2006, ISBN: 1 876855 26 6.