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Stress State Dependent Cohesive Zone Model for Thin Walled Structures

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Abstract: A new stress-state dependent cohesive zone model for thin walled structures is proposed. The model incorporates the stress-state explicitly within the traction-separation law using basic elasticity-plasticity equations combined with a model parameter. The numerical implementation of the model is able to reproduce ductile fracture observed in a pre-cracked C(T) specimen as well as a notched plate specimen of the same material.

Introduction

To ensure the structural integrity of thin-walled structures, a ductile fracture model must incorporate two characteristic features of their failure. It must be able to simulate significant stable crack extension prior to final failure, but more importantly should be sensitive to the significant differences in the stress state of precracked or initially uncracked sheets [1]. In the cohesive zone framework, the stress-state dependence of the fracture process under plane strain has been the subject of investigations during the last decade. Using porous plasticity damage mechanics on unit cells, triaxiality dependent traction-separation laws (TSLs) have been developed and successfully applied to various geometries [2, 3]. However, the corresponding analysis cannot be done using void growth models as they have difficulties in dealing with low triaxiality of thin-walled structures. More recently, a stress-state dependent model which incorporates triaxiality explicitly has been proposed [4]. The model for plane strain mode I ductile fracture is formulated by using basic elastic-plastic constitutive equations combined with two new stress-state independent model parameters. Extending the methodology to plane stress conditions, the present work develops a new stress-state dependent cohesive model for thin-walled structures. Cohesive elements based on the proposed model are applied to reproduce experimental data on fracture of notched as well as precracked thin sheets of Aluminium Al 5083. In contrast to models with constant parameters, the proposed model is able to closely reproduce the experimentally observed macroscopic behaviour for both the notched as well as precracked sheet specimens.

Formulation of the model in plane stress

The scope of the proposed model is prediction of mode-I plane stress fracture in ductile metals described by elastic modulus, E, yield stress, σ_y and power-law strain hardening exponent, n. For a state of stress with fixed bi-axiality ratio, $\alpha = \sigma_{11}/\sigma_{22}$, under conditions of plane stress, the triaxiality developed can be calculated from elastic constitutive relations to be:

$$H = \frac{\sigma_{mean}}{\sigma_{mises}} = \frac{1+\alpha}{3\sqrt{\alpha^2-\alpha+1}}. \tag{1}$$

Fig. 1 shows that the triaxiality parameter increases with increasing bi-axiality ratio up to $\alpha \approx 0.6$, beyond which it tends to saturate to the maximum possible value of 2/3. Compared

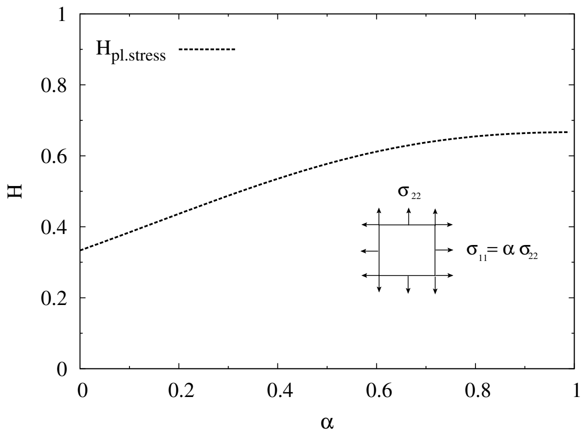

Figure 1: The dependence of triaxiality parameter, H, on a fixed applied bi-axiality ratio, α, under conditions of plane stress.

to plane strain triaxiality, the plane stress parameter does not exhibit singular behaviour for α tending to unity. For the cohesive layer of initial thickness, D, traction separation behaviour up to attainment of peak stress, σ_{max}, can be established using elastic constitutive relations and deformation plasticity theory, while the softening behaviour can be characterised by an appropriate smooth curve such as the exponential one used in the present work. Taking $\hat{\delta}_n = \delta/D$ as the separation of the bounding surfaces of the process zone normalized by the initial thickness of the process layer, the TSL with three distinct regions of constitutive behaviour is proposed to be

$$T_n = \begin{cases} \dfrac{2E}{2-\alpha}\hat{\delta}_n & 0 < \hat{\delta}_n \le \hat{\delta}_{n1}, \\ \dfrac{\sigma_y}{\sqrt{\alpha^2-\alpha+1}}\left(\dfrac{2E}{\sigma_y}\dfrac{\sqrt{\alpha^2-\alpha+1}}{2-\alpha}\hat{\delta}_n\right)^n & \hat{\delta}_{n1} \le \hat{\delta}_n \le \hat{\delta}_{n2}, \\ \sigma_{max}\exp\left[-0.02\left(\dfrac{\hat{\delta}_n-\hat{\delta}_{n2}}{\hat{\delta}_{n2}}\right)^2\right] & \hat{\delta}_{n2} \le \hat{\delta}_n \le 10\hat{\delta}_{n2}, \end{cases} \tag{2}$$

where,

$$\hat{\delta}_{n1} = \frac{2-\alpha}{2E}\frac{\sigma_y}{\sqrt{\alpha^2-\alpha+1}}, \qquad \hat{\delta}_{n2} = \frac{2-\alpha}{2}\frac{Ce^{-1.5H_o}}{\sqrt{\alpha^2-\alpha+1}} + \hat{\delta}_{n1}. \tag{3}$$

The factor 0.02 in the argument of the exponential function controls the slope of the softening curve, therefore it can be considered as a model parameter. A higher value of the factor will result in rapid drop of traction beyond its maximum value. Here H_o is 0.5, an average value chosen to represent the equivalent plastic strain failure locus for lower triaxilities encountered in plane stress.

$$\sigma_{max} = T_n|_{\hat{\delta}_n=\hat{\delta}_{n2}} = \frac{\sigma_y}{\sqrt{\alpha^2-\alpha+1}}\left[\frac{E}{\sigma_y}Ce^{-1.5H_o}+1\right]^n. \tag{4}$$

Results and discussion

The proposed stress-state dependent cohesive zone framework for thin-walled structures is used in predictions of the fracture behaviour behavior of a power law hardening aluminum alloy AL 5083. The effect of tri-axiality and the model parameter, C, on the traction separation law is

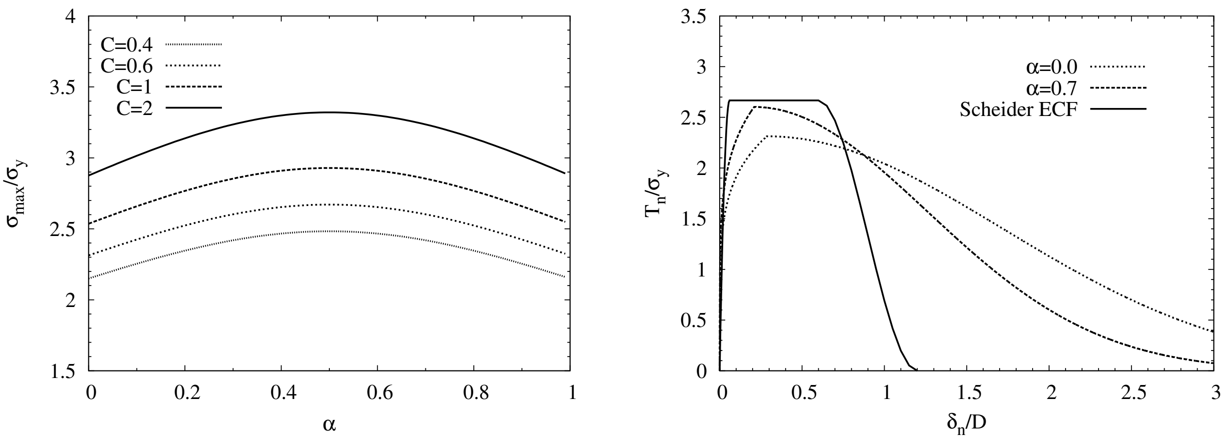

Figure 2: Comparison of model parameters at different levels of triaxiality. (a) Effect of C and bi-axiality ratio on peak stress; (b) Comparison of TSL used in [6] for the same material with TSL shapes at different bi-axiality ratios for $C = 0.6$.

discussed. The model is implemented and validated by comparison with experimental results on specimens with as well as without an initial flaw.
Fig. 2(a) shows the effect of parameter C on the peak stress, Eq. (4), developed in the traction separation law. As the bi-axiality of the applied stress state increases, the peak stress increases up to $\alpha \approx 0.5$, further increase in bi-axiality ratio results in lowering of peak stress. The effect of C is to elevate the peak stress levels for the entire range of bi-axiality. The cohesive layer thickness, D, affects the total energy dissipated through crack extension, the so-called cohesive energy, Γ_0, which is calculated by

$$\Gamma_0 = \int_0^{10\hat{\delta}_{n2}} T_n D d\hat{\delta}_n. \tag{5}$$

Since the fracture resistance, especially the crack initiation, is mainly influenced by Γ_0, D must be treated as additional model parameter. Fig. 2(b) shows the effect of bi-axiality on the TSL curve. For $\alpha = 0.7$ the corresponding higher tri-axiality of the stress state while inhibits plastic deformation, it promotes void nucleation, growth and coalescence. While the peak stress developed in the proposed model compares well with the predictions of Scheider and Brocks [6], the shape of the TSL curve is different. However, it must be noted that only a constant shape of the TSL was used in the previous publication, and therefore any comparison must be interpreted with caution. For validation of the model, experimental results on Al 5083 alloy performed at GKSS [5] were used. To test the efficacy of the proposed model in prediction of ductile fracture under varying conditions of triaxiality, data from two different types of specimens are presented, namely a flat notched bar with notch radius $R = 2$ mm, and a C(T) specimen with a width of 50 mm. The thickness of the plate was 3 mm for both types of specimens. The structures lead to tri-axialities between 0.35 and 0.55 for the notched bar and well above 0.6 for the C(T) specimen. For the parameters $C = 0.6$, and intial cohesive layer thickness $D = 0.02$ mm, comparisons between the experimental data and numerical results are shown for both specimens in Fig. 3. The tension test till failure of notched bar is presented in Fig. 3(a) by force-elongation and force-necking curves. Both curves are well reproduced by the model.

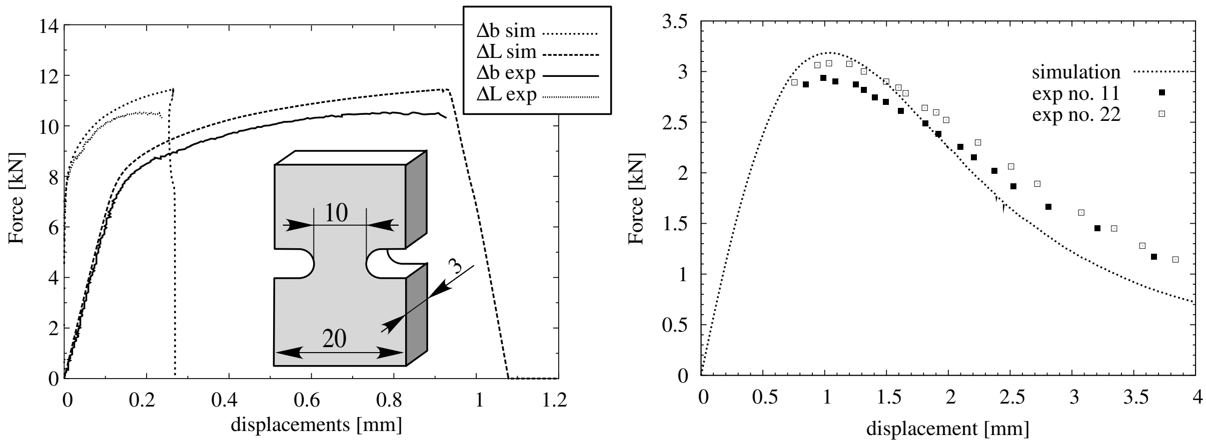

Figure 3: Comparison of fracture data at different triaxiality: (a) Notched bar (b) C(T) specimen.

Conclusions

In prediction of ductile fracture of thin-walled structures, finding cohesive parameters which can cover a wide range of conditions requires a model that is sensitive to changes in stress-state. Earlier investigations used other models (e.g. void growth models) to introduce a constraint dependent model, which increases the number of parameters and thus the complexity of the model. The present work proposes a new approach, in which the tri-axiality is incorporated within the traction separation law in a natural manner; the two model parameters C and D are stress-state independent and can be considered as a material properties. The effectiveness of model was shown at two specimens with different constraint conditions, namely a notched metal sheet and a precracked C(T) specimen. It was demonstrated in [6] that both specimens cannot be simulated with one set of parameters, if a traction-separation law with a fixed shape is used. With the new approach the failure of both specimens was simulated with good accuracy.

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