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Cohesive traction-separation relations for plate tearing under mixed mode loading

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ABSTRACT

The present study investigates a sequence of failure events related to steady-state tearing of large-scale ductile plates by employing the micro-mechanics based Gurson-Tvergaard-Needleman (GTN) model. The fracture process in front of an advancing crack is approximated by a series of 2D plane strain finite element models to facilitate a comprehensive study of mixed mode fracture behavior as well as a parameter study of the cohesive energy and tractions involved in the process. The results from the conducted GTN model simulations are used to define cohesive zone models suitable for plate tearing simulations at large scale. It is found that mixed mode loading conditions can have a significant effect on the cohesive energy as well as relative displacement (in reference to pure mode I loading), while peak traction is practically unaffected. Specifically, increasing mode II contribution leads to monotonic increase of the cohesive energy. In contrast, the effect of mode III is more complicated as it leads to reduction of the mixed mode cohesive energy (in reference to pure mode I loading) at low to medium levels of mode mixity ratios (0–0.3). However, increasing mode III contribution beyond the mode mixity ratio of 0.3, reverses this trend with cohesive energy potentially exceeding the pure mode I level when at mode mixity ratio of 0.6 or higher. This behavior cannot be captured by the interactive cohesive zone models that rely on a simple rotational sweep of mode I traction-separation relation. Depending on the shear mode contribution, i.e., mode II or mode III, these models can lead to overly conservative (mode II) or unconservative (mode III) prediction of the crack growth resistance.

1. Introduction

The main focus of the present work is on determination of the cohesive zone model parameters that can be used to approximate the complex ductile fracture process evolving in large-scale plate tearing under mixed mode loading conditions. When the tearing crack in a large-scale plate has advanced several plate thicknesses, under monotonic loading, and the failure process ahead of the crack tip has reached a steady-state propagation, the energy dissipation proceeds through a sequence of events which includes: i) local thinning that takes place some distance ahead of the crack tip; ii) shear localization that subsequently develops on a smaller scale inside the thinning region closer to the tip, and; iii) final separation that advances the crack (see also discussion in Nielsen and Gundlach, 2017; Nielsen and Hutchinson, 2017). This complex plate tearing process is driven by the mechanism of void nucleation and growth to coalescence and it can be captured by the micro-mechanics based Gurson-Tvergaard-Needleman material model in a full 3D framework (Felter and Nielsen, 2017). To accurately represent the complexity of the plate tearing process, a through-thickness resolution that scales with the dominant void spacing (e.g. $\sim 100\ \mu m$) is required (see also Xue et al., 2010; Nielsen and Hutchinson, 2012). Such resolution is presently only possible for coupon specimens and small components. Thus, engineers rely heavily on the phenomenological alternatives, such as cohesive zone models embedded in shell elements, to ensure computation times that are short enough for industrial applications (see also discussion in Li and Siegmund, 2002; Woelke et al., 2017).

When modeling failure in thin-walled structures using shell elements, one needs to consider constraints related to the plane stress condition, which is an inherent assumption in shell mechanics. Maintaining a plane stress state within a shell element requires that its in-plane dimensions are larger than the thickness. Since the height of the localized neck is on the order of sheet thickness, only a single element can be used to represent necking and failure. This is, of course, not sufficient to capture the detailed geometry of local thinning. To address this deficiency, cohesive zone models can be employed to represent the effects that cannot be captured by large shell elements. In this case, the cohesive zone must take over as soon as through-thickness localization

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starts and describe the remaining part of the fracture process. Tvergaard and Hutchinson (1992) studied the relation between ductile crack propagation and the cohesive zone parameters that govern the fracture process. An interesting conclusion in their work is that in plane strain, it is the peak traction and the cohesive energy that primarily control the tearing response, whereas the shape of the traction-separation relation is of minor importance. In a later work, Nielsen and Hutchinson (2012) made an attempt to design a cohesive traction-separation relation for extensive crack propagation in tough ductile plates where the tearing energy and the peak traction were direct outcomes of the underlying micro-mechanics. Here, by considering a cross-section of the plate with the normal along the crack growth direction, modeled in 2D plane strain, a detailed micro-mechanical study of the slant failure was performed using the shear extended GTN modeling framework (Gurson, 1977; Tvergaard, 1990; Nahshon and Hutchinson, 2008). In this approach, the cohesive zone takes over once the peak traction of the plate cross-section has been reached and both the localization process and final failure were treated in a rigorous, but phenomenological, manner. Thus, the cohesive zone model reflects the actual micro-mechanics that lead to crack propagation once the fracture process has settled into a steady-state (Scheider and Brocks, 2006). Despite only treating mode I loading, the traction-separation relation proposed by Nielsen and Hutchinson (2012) has been successfully applied by Woelke et al. (2013, 2015) to investigate large-scale plate tearing. By adopting the micro-mechanics based traction-separation relation, a near perfect match to experimentally measured load-deflection curves was obtained for the macroscopic structural response. As an aside, Woelke et al. (2015) concluded that for plane stress conditions, the shape of the traction-separation relation is also important for accurate prediction of crack growth resistance. However, these considerations were limited to pure mode I loading, whereas real life structures often encounter mixed mode loading. A common practice in modeling mixed mode loading with cohesive zone relies on essentially a rotational sweep of the normal mode I traction-separation relation, $T(\delta_n)$, into the tangential separation (between fracture surfaces) space such that the traction curves become $T(\delta_{t1})$ and $T(\delta_{t2})$ in pure mode II or pure mode III, respectively (see Eq. (1)). The work of separation is thus traditionally assumed to be unchanged between modes (Li and Siegmund, 2002) and mode mixity is calculated as

$$\Gamma_0 = \int_0^{\lambda_0} T(\lambda)d\lambda, \text{ with } \lambda = \sqrt{\left(\frac{\delta_n}{\delta}\right)^2 + \left(\frac{\delta_{t1}}{\delta}\right)^2 + \left(\frac{\delta_{t2}}{\delta}\right)^2} \tag{1}$$

Here, Γ_0 is the work of separation (equal for all modes), δ_n is the normal separation, δ_{t1} and δ_{t2} are the tangential separations of the fracture surfaces related to mode II and mode III separation, respectively. The present study will show that this approach does not represent reality in ductile plate tearing under mixed mode loading. It will be demonstrated that after peak traction is reached, the work of separation depends on mode mixity. The goal of the current study is twofold: i) to highlight the effects of mode mixity on the overall cohesive energy as well as other parameters defining the traction-separation relation, and; ii) to develop a new mixed mode traction-separation relation that readily fits into the framework of combining plane stress shell elements with cohesive zone modeling without sacrificing the accuracy for mixed mode loading. Details of the traction-separation relations will be developed through micro-mechanics modeling, which in turn will form the basis for guidelines on how parameterized traction-separation relations can be constructed without compromising accuracy. The employed modeling framework has been adopted from Nielsen and Hutchinson (2012), but with modifications to take out-of-plane actions into account.

The paper outlines the constitutive relations and finite element model in Section 2. The problem formulation is described in Section 3, after which the cohesive zone model is defined in Section 4 by identifying key parameters to be extracted from the micro-mechanics based numerical simulations. Results are given in Section 5 with focus on improving accuracy within the field of cohesive zone modeling of large-scale plate tearing. Conclusions are listed in Section 6.

2. Model: constitutive relations and finite element formulation

2.1. Material description

The undamaged (matrix) material in this study is assumed to follow a true stress-logarithmic strain power hardening relation described as:

$$\varepsilon = \begin{cases} \frac{\sigma_M}{E} & , \text{for } \sigma_M < \sigma_y \\ \frac{\sigma_y}{E}\left(\frac{\sigma_M}{\sigma_y}\right)^{1/N} & , \text{for } \sigma_M \geq \sigma_y \end{cases}$$

where σ_y is the initial yield stress, E is the Young's modulus, and N is the hardening exponent. To account for the softening effect of the damage that evolves during severe plastic straining, the material is assumed to be governed by void growth to coalescence and to follow the flow rule for a porous ductile GTN material (Gurson, 1977) with the yield surface modified by Tvergaard (1981).

$$\Phi = \frac{\sigma_e^2}{\sigma_M^2} + 2q_1 f^* \cosh\left(\frac{q_2}{2}\frac{\sigma_k^k}{\sigma_M}\right) - (1 + (q_1 f^*)^2) = 0.$$

Here, $\sigma_e = \sqrt{3s_{ij}s^{ij}/2}$ is the effective macroscopic Mises stress, with $s^{ij} = \sigma^{ij} - G^{ij}G_{kl}\sigma^{kl}/3$ being the stress deviator where G_{ij} and G^{ij} are the co- and contravariant component of the metric tensor, respectively, associated with the deformed geometry. The microscopic stress in the matrix material is denoted σ_M, whereas q_1 and q_2 are fitting parameters introduced by Tvergaard (1981), and f^* is a function of the porosity that takes void coalescence into account. Tvergaard and Needleman (1984) suggested the following phenomenological model to accelerate the damage increase once micro-voids link up in the coalescence process:

$$f^* = \begin{cases} f & , \text{for } f \leq f_C \\ f_C + \frac{\bar{f}_U - f_C}{f_F - f_C}(f - f_C) & , \text{for } f > f_C \end{cases}$$

where f is the accumulated damage (or porosity), f_C and f_F are the critical and final porosity, respectively. The ultimate damage, $\bar{f}_U$, is defined as $1/q_1$.

The development of damage in the material is partly controlled by void growth and partly a shear contribution, such that the total rate of damage reads:

$$\dot{f} = \dot{f}_{growth} + \dot{f}_{shear}$$

where a damage contribution from nucleating voids is omitted for clarity of results in the present study. Void growth follows from plastic incompressibility and can be expressed as:

$$\dot{f}_{growth} = (1 - f)G^{ij}\dot{\eta}_{ij}^p$$

where $\dot{\eta}_{ij}^p$ is the increment of the plastic strain tensor. It is known, however, that evolution of the damage predicted by the GTN model stops if the stress triaxiality goes to zero, e.g. for a pure shear loading case. In order to investigate the effect of shear damage, the shear extension introduced by Nahshon and Hutchinson (2008) will be considered as part of the analysis. The governing equation for the shear contribution to total damage is:

$$\dot{f}_{shear} = k_\omega f \omega(\sigma) \frac{s^{ij}\dot{\eta}_{ij}^p}{\sigma_e} \tag{2}$$

where $\omega(\sigma) = 1 - (27J_3/(2\sigma_e^3))^2$. Here, J_3 is the third invariant of Cauchy stress deviator and k_ω is the amplification factor for the shear contribution, which typically lies in the range of [0; 3] (see also Tvergaard and Nielsen, 2010). It is worth mentioning that the Nahshon-Hutchinson extension is purely phenomenological and it is, therefore, only