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Cohesive zone modeling and calibration for mode I tearing of large ductile plates

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A B S T R A C T

This paper focuses on extensive ductile crack growth by modeling a mode I fracture experiment. Solution of this problem, requires structural scale plate/shell finite which cannot resolve the details of the fracture process. Thus, a cohesive zone model, which accounts for the dependence of the cohesive tearing energy on the crack advance is employed. The steady-state cohesive energy is informed by the detailed analysis of necking localization and shear failure, performed with the Gurson model. The structural scale model reveals the partition of the tearing energy into the cohesive energy and the additional plastic dissipation occurring outside the cohesive zone.

1. Introduction

The governing mechanism of ductile fracture in metals is nucleation, growth and coalescence of micro-voids. In stretching of bars or plates of most ductile structural alloys, there is no appreciable porosity in the material until necking localization sets in producing enhanced local stress triaxiality. The increase in tri-axial stress accelerates the void growth and, eventually, causes localization in a shear band and coalescence into a crack [5,13]. The plastic strains inside the neck can reach high levels (on the order of ~100% measured by the grain width reduction [6]) which are usually much larger than strains outside the neck. To accurately capture neck development and progressive damage development within the neck, a detailed numerical analysis is necessary with micromechanically motivated constitutive models, such as the Gurson model [8] and its subsequent modifications [10,20,21], the Perzyna model [7,14], or the Rousselier model [16]. While these micromechanical approaches can reproduce the details of the deformation and plastic dissipation in the fracture process zone, including details such as the cup-cone fracture mode, they require very small element sizes, on the order of void spacing, as emphasized by Xue et al. [32]. This level of resolution is computationally expensive and only feasible for small scale geometries such as coupon test samples. The fact that it is not feasible to use micro-mechanically based constitutive models is a significant handicap for engineers attempting to quantify the response of large-scale structures such as ships, aircraft, and automobiles to extreme loading conditions leading to component-level fracture and failure. Generally, large structures must be analyzed using plate/shell elements with characteristic in-plane lengths larger than the plate thickness.

The present study is specifically concerned with modeling mode I ductile tearing of large sheet metal components such as those found on a ship, an automobile or an aircraft. The large scale of the problem requires large plate/shell finite elements

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Nomenclature

A_0	initial undeformed cross-sectional area of a tensile coupon
d	overall elongation of the detailed neck model simulated using shear modified Gurson model
D	void spacing in the dominant void population
E	elastic modulus
F	applied force for the detailed neck model simulated using shear modified Gurson model
K	elastic stress intensity factor
$K_R(\Delta a)$	crack growth resistance in small scale yielding under monotonic load
K_{IC}	plane strain mode I toughness – stress based
K_C	plane stress toughness
L	initial specimen length of a tensile coupon
N	Considere condition strain at the necking onset; material power law hardening exponent
P	applied force in large scale fracture model
R_P	plastic zone size
t	plate thickness
T	nominal cohesive traction
T_{max}	maximum cohesive traction
$\widehat{T}$	peak cohesive traction
α	steady-state crack growth coefficient for cohesive energy/area
β	plane strain toughness coefficient
Γ	cohesive energy = work/area required to separate the plate after the onset of necking
Γ_{I}	work/area dissipated in necking
Γ_{II}	work/area dissipated in shear localization
Γ_{IC}	plane strain mode I toughness – energy based
$\Gamma_{steady\text{-}state}$	steady state energy/area
$\Gamma_{SSY}(\Delta a)$	crack growth resistance in small-scale yielding
δ	cohesive separation within the neck region
δ_1, δ_2	cohesive traction–separation shape parameters
δ_{max}	maximum separation across the neck
Δ	crosshead displacement in large scale plate model
Δa	crack advance in small scale yielding
Δx	distance ahead of the pre-crack
ε	strain
ε_{log}	logarithmic strain
ε_0	strain at yield
ν	Poisson's ratio
σ	true stress
σ_M	true stress governing flow of the damage-free base material (matrix material) in the Gurson model
σ_U	ultimate stress
σ_y	yield stress

with a minimum in-plane dimension limited by plate thickness. In this paper, crack growth resistance is modeled starting from initiation from a pre-crack through extensive propagation. Standard shell elements cannot capture the details of necking localization and subsequent micro-mechanical damage and fracture. The complicated behavior beyond the onset of necking leading to failure can be addressed in several ways. In this paper, a cohesive zone is used to represent the sequence of failure processes. Similar efforts for both ductile and brittle materials have been undertaken by other authors [2,4,9,17,31]. Simonsen and Törnqvist [18] employed a critical plastic strain criterion to advance the crack tip, demonstrating how the critical strain must depend on element size when calibrated against experiment. In each approach, the sequence of failure processes is subsumed within either the cohesive zone or the calibrated critical strain. Another approach [24–28,30] employs special shell elements allowing for damage and softening in a phenomenological way to generate the effective non-linear response of the structural components. A recent study by the present authors [29] compared the use of these special elements in plate tearing simulations with an approach based on a cohesive zone. Similar efforts have been recently undertaken by other authors [1,18,19].

The present approach, which is directed to tearing of plates under large scale plastic yielding conditions, has parallels with an early simulation of mode I crack growth under small scale yielding plane strain conditions by Tvergaard and Hutchinson [22]. Those authors embedded a cohesive zone imbued with a peak strength and cohesive energy within a finite element representation of the surrounding elastic–plastic field. Crack growth resistance was computed under monotonically

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