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Rate-dependent elastic and elasto-plastic cohesive zone models for dynamic crack propagation

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ABSTRACT

To overcome deficiencies with existing approaches a new cohesive zone model is introduced and trialled in this paper. The focus is on *rate-dependent* cohesive zone models which have appeared in the recent literature but can be shown to suffer unrealistic behaviour. Different combinations of material response are examined with rate effects appearing either in the bulk material or localised to the cohesive zone or in both. A benefit of using a cohesive-zone approach is the ability to capture plasticity and rate effects locally. Introduced is a categorisation of bulk-material responses and cohesive zone models with particular prominence to the role of rate and plasticity. The shape of the traction separation curve is shown to have an effect and captured in this paper with application of a trapezoidal cohesive zone model. Rate dependency for the cohesive zone model is introduced in terms of a rate-dependent dashpot models applied either in parallel and/or in series. Traditionally, two possible methods are adopted to incorporate rate dependency, which are either via a temporal critical stress or a temporal critical separation. Applied singularly, tests reveal unrealistic crack behaviour at high loading rates. The new rate-dependent cohesive model introduced here couples the temporal responses of critical stress and critical displacement and is shown to provide for a stable realistic solution to dynamic fracture. Dynamic trials are performed on a cracked specimen to demonstrate the capability of the new approach.

1. Introduction

Monotonic and fatigue crack growth can be modelled by using a method called the Cohesive Zone Model (CZM), which has become the focus of the research in the area of fracture mechanics because of its ability to overcome limitations of other methods founded on linear elastic fracture mechanics (LEFM). The initial concept of the CZM was introduced by Dugdale (1960) and Barenblatt (1962). They considered the fracture process zone as a small area ahead of the crack tip, where the normal stress perpendicular to the crack direction of travel is constant and equal to the yield stress according to Dugdale but decreases with deformation and vanishes at separation according to Barenblatt.

The CZM is founded on a traction separation law (TSL) and according to this law, material damage starts when traction reaches a critical value called the critical cohesive stress σ_c. The crack propagates when the displacement jump between the cracked-material surfaces reaches a critical value δ_c at which point the cohesive stress becomes zero and all the cohesive energy Γ_o is dissipated. The CZM gained greater acceptance when Hillerborg et al. (1976) analysed numerically, crack-growth in a brittle material using a bilinear cohesive zone model (BCZM) together with the finite element method (FEM). This was followed by Needleman (1987), who introduced the polynomial CZM and subsequently, the exponential CZM (Needleman, 1990). Scheider (2001) introduced the partly constant CZM, which is similar to Needleman's polynomial model but with a flat region in the middle. The trapezoidal cohesive zone model (TCZM), which is of particular interest in this work, was introduced by Tvergaard and Hutchinson (1992). A bode of contention in the literature is the importance of the shape of the traction separation curve underpinning the cohesive zone approach. Some authors claim that the shape hardly influences fracture simulation results (Tvergaard and Hutchinson, 1992; Needleman, 1990; Siegmund and Needleman, 1997; Alfano et al., 2004), whilst other investigations demonstrate that the shape does indeed matter (Alfano et al., 2004; Falk et al., 2001; Zhang et al., 2003). This issue is revisited in this paper by contrasting the trapezoidal cohesive zone model (TCZM) with the bilinear cohesive zone model (BCZM). It is demonstrated that under the constraint of invariant toughness the shape of the traction-separation curve does indeed have an effect.

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List of symbols

Γ_o	critical cohesive energy
Γ_{rate}	rate-dependent cohesive energy
σ_c	critical cohesive stress
δ_c	critical separation
δ_o	instantaneous applied displacement
δ_1	shape parameter for the linear and trapezoidal model respectively
δ_2	second shape parameter of the trapezoidal model
δ^p	plastic separation
δ^e	elastic separation
δ_f	final separation at fracture
δ^{coh}	separation in the cohesive element
$\dot{\delta}$	separation rate
$\dot{\delta}^D$	separation rate at the dashpot
σ	cohesive stress
σ_Y	yield stress
ϑ	Poisson's ratio
σ^D	stress at the dashpot
E	elastic modulus
E^p	plastic modulus
C_R	Rayleigh surface wave speed
G_c	total dissipated energy per unit area
G^p	dissipated plastic energy in the cohesive zone per unit area
$G^{p_{rate}}$	rate-dependent plastic dissipated energy in the cohesive zone per unit area
ε^{coh}	strain at the cohesive zone
ε^e	elastic strain
W^e	elastic strain energy per unit area
W^Γ	dissipated energy per unit area due to the fracture process
W^p	dissipated energy per unit area due to plastic deformation in the bulk material
W^d	total work done per unit area by the external load
W^D	dissipated energy per unit area in the dashpot
η	material viscosity
B	parameter representing the rate dependency of the cohesive material
B_1	parameter representing the rate dependency of the cohesive material
σ_c^{rate}	rate-dependent critical stress
δ_c^{rate}	rate-dependent critical separation
δ_{max}	the separation at the onset of unloading
σ_{max}	the stress at the onset of unloading
σ_{limit}	upper limit on the rate-dependent critical stress
$W_{limit}^{\Gamma_{rate}}$	upper limit on the rate-dependent fracture energy

Abbreviation

CZ	cohesive zone
CE	cohesive element
CZM	cohesive zone model
BCZM	bilinear cohesive zone model
TCZM	trapezoidal cohesive zone model
LEFM	linear cohesive zone model
TSL	traction separation law
QS-B	quasi-static simulation using the rate-independent bilinear model
QS-T	quasi-static simulation using the rate-independent trapezoidal model
DYN-σ_c^{rate}-B	dynamic simulation using the stress rate-dependent bilinear model
DYN-σ_c^{rate}-T	dynamic simulation using the stress rate-dependent trapezoidal model
DYN-δ_c^{rate}-B	dynamic simulation using the separation rate-dependent bilinear model
DYN-Γ_c^{rate}-B	dynamic simulation using the new rate-dependent bilinear model
DYN-Γ_c^{rate}-T	dynamic simulation using the new rate-dependent trapezoidal model

It is well documented that the CZM in its standard (rate-independent) forms provide an effective approach for the numerical analysis of the failure for a range of materials. This is essentially because of the insensitivity of the crack and certain bulk materials to strain rate and crack velocity. This is not true for all materials however and rate sensitivity can manifest itself in a crack at rate facing greater resistance from the surrounding material along with other effects such as crack branching. The standard CZM has been found to overestimate crack speeds in the case of dynamic fracture (Valoroso et al., 2014). The predicted crack speed can reach the Rayleigh surface wave speed C_R of the material yet experimentally the maximum crack growth speed is significantly lower than C_R even for very brittle materials (Ravi-Chandar, 1998). To achieve a better representation of the physics it is necessary to incorporate rate dependency either in the CZM or the bulk material or possibly both. The literature contains examples of research with rate-dependent behaviour in the bulk material combined with a rate-independent traction separation law under monotonically applied loading. Ortiz and Pandolfi (1999) for example used this approach and demonstrated good agreement with the experimental data and argued that through this approach the CZM captures the rate dependency of the failure process. Similarly, Song et al. (2006) and Zhou et al. (2004) successfully applied the approach to asphalt concrete and reinforced aluminium, respectively. Zhou et al. (2005) pointed out however that the success of the study of Ortiz and Pandolfi (1999) was limited to ductile materials and was successful because of the intrinsic timescale associated with ductility. The approach failed to reproduce existing experimental crack propagation data of pre-strained brittle Polymethyl methacrylate (PMMA). Costanzo and Walton (1998) asserted that the rate-independent CZM is unable to represent the experimental results from the literature, regardless of the type of the traction-separation law and the fracture criterion used. A similar conclusion was reached by Langer and Lobkovsky (1998) and again Costanzo and Walton (1997). The use of a rate-dependent CZM is therefore recommended (Zhou et al., 2005; Costanzo and Walton, 1998; Langer and Lobkovsky, 1998; Costanzo and Walton, 1997), where the cohesive traction σ is related not just to the crack separation δ, but also to separation rate $\dot{\delta}$, i.e.$\sigma = f(\delta, \dot{\delta})$; a relationship first pioneered by Glennie (1971). Glennie concluded that the reason behind the observed reduction in crack speed with increase in strain rate is an increase in stress levels in the vicinity of the crack tip. Further developments to Glennie's work has been done by Freund and Lee (1990), Costanzo and Walton (1998),(1997) and Xu et al. (1991). A negative feature of these approaches however is unrealistically large values for the stress in the cohesive zone and associated crack arrest. A related but alternative approach is adopted by Valoroso et al. (2014) and Zhou et al. (2005) who employed a CZM with critical traction independent of rate but involving temporal changes in fracture energy along with critical separation. It is demonstrated in this paper however that this approach can lead to unrealistic separation values and crack tearing ahead of the crack tip.

The model proposed in this paper is designed to overcome these identified limitations since it is apparent from the literature that presently no optimum CZM exists that can simulate