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A novel rate-dependent cohesive-zone model combining damage and visco-elasticity

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ABSTRACT

This paper presents a novel rate-dependent cohesive-zone model combining damage and visco-elasticity and based on two fundamental assumptions. Firstly we postulate the existence of an intrinsic (i.e. rate-independent) fracture energy. Secondly, within a thermodynamically consistent damage-mechanics framework we assume that the evolution of the damage variable is related to the current free energy and to the intrinsic fracture energy. The underlying idea is that the energy of the bonds at the micro-level is rate-independent and that the rate-dependence of the overall dissipated energy during crack propagation is a natural by-product of the visco-elastic dissipation lumped on the zero-thickness interface. Quite good agreement within an expected range of loading rates was obtained between numerical and experimental results for a DCB specimen with steel arms bonded through a rubber interface. This is despite the fact that for this application the model has been kept as simple as possible using a quadratic elastic energy and linear visco-elasticity with one relaxation time only. Therefore, the presented results support the fundamental principles behind the proposed approach and indicate that the model has the potential to be refined into a highly accurate tool of analysis based on sound physical arguments.

1. Introduction

Cohesive zone models stem from the seminal work by Barenblatt [1] and have often being coupled with interface elements for the purpose of modelling crack propagation along interfaces. The first application in the context of finite-element methods is due to Hilleborg et al. [2]. The key idea of cohesive-zone modelling is to introduce a finite length process zone at the crack tip, opposed to the classical Griffith's approach where all the dissipation occurs at a singularity at the crack tip. A cohesive-zone model is characterized by a "traction-discontinuity jump" relationship, playing a role analogue to a material constitutive law for a continuum material. This relationship also provides, in the case of infinitesimal elastic deformations, the link to linear elastic fracture mechanics as its integral equals the critical energy release rate. To allow the presence on the interface of a discontinuity jump, in the sequel denoted as δ, the kinematics of the problem has to be enriched relaxing the regularity requirements on the displacement field $\mathbf{u}(\mathbf{x})$, not requiring that $\mathbf{u}(\mathbf{x}) \in \mathbf{C}^0$. It is easy to see, at least heuristically, that the cohesive-zone approach converges to Griffith's crack model as the process zone length tends to zero (a claim that has been rigorously proved by Giacomini [3]).

The rate dependence of the mechanical response leading to crack initiation and/or growth can not be neglected for a wide class of engineering applications. The complexity of the problem and the presence of numerous competing factors is evident from the fact the fracture thoughness may not show a monotonic trend with respect to crack speed, even when the latter is small enough not to consider intertial effects. Furthermore, even when such trend is monotonic, fracture toughness can increase with crack speed for some materials and decrease for others [4–6]. The importance of the problem has justified numerous experimental investigations. For example, results for a DCB test on a rubber modified epoxy show a decrease in fracture thoughness with increasing rate of applied displacement [7], whilst for a DCB made of Al 6061-T6 adherends and polyethylene as the adhesive the opposite trend has been reported [8].

Ancillary issues such as the possible sudden transition in some cases from stable to unstable propagation, also known as "stick-slip" behaviour, have been suggested to depend on the rate dependence of the fracture mechanism in the process zone [9–11].

In general, the overall rate dependence can arise as a consequence of the rate dependence of the bulk material's behaviour, of the interface response itself, or of both. A number of cohesive zone models and modelling strategies have been presented covering these different assumptions.

Among the first group we will refer to Van Der Bosch et al. [12], who analyzed peel testing of PET. They were able to capture the rate sensitivity of the test results by only modelling the rate

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dependence of the bulk material. A similar approach is followed in a study by Nguyen and Govindjee [13], who studied the propagation of a crack in an infinitely long strip of visco-elastic material. To demonstrate how the total fracture energy dissipated during crack propagation increases with the crack speed they use a cohesive-zone model with an intrinsic fracture energy so that the rate-dependence originates from the bulk material only. As examples of the second approach a reference is made to Xu et al. [8,14] who similarly constructed a rate-dependent model by adding the contributions from a rate-independent and a rate-dependent element, the latter given by a Maxwell element. This quite satisfactorily replicates a class of experimental results but suffers from some inconsistencies in the formulation such as the fact that the traction discontinuosly goes to zero after reaching a threshold displacement given by a critical separation. Corigliano and Ricci [15] also focus on the rate-dependence of the interface to model a DCB carbon fibre-Poly-Ether-Imide (PEI) specimen. The interface deterioration is reproduced using two alternative phenomenological approaches, one of them based on softening plasticity and a second one in which a rate-dependent damage evolution law is adopted. Another example of this type of approach is the model proposed by Allen and Searcy [16], in which the interface element is conceived through an homogenization procedure conducted at the micromechanical scale.

Finally, Liechti and Wu [17] introduced rate-dependent behaviour in both the bulk material and the interface, motivating their decision by observing significant differences in crack surface depending on test speed, which convinced them of the necessity of modelling the viscous losses at the interface. They also assumed the interface strength could be assimilated to a non-linear elastic response summed to a viscous contribution, given by a non-newtonian dashpot. Damage evolution is implicit in their formulation as the elastic response is given by a bilinear elastic traction-separation law. Furthermore, the authors suggest that the use of a non-newtonian dashpot could possibly reproduce the rate-dependent nature of void formation. The model proposed by Landis et al. [18] follows the same approach of introducing the rate-dependence in both the bulk and the interface. They are able to investigate the competing effects and present an explanation for the possible non-monotonic relationship between crack speed and toughness. The rate dependence of the cohesive zone is taken to obey a functional form similar to the elasto-viscoplastic formulation used to model the bulk material.

To the authors' knowledge a rigorous discussion on the merit and fallacies of each of the above mentioned general approaches has not been tackled. It is evident that the dissipation occurring in the real material has to be accounted for in any realistic modelling attempt, so the problem eventually condenses to whether it is possible to neglect the dissipation occurring at the interface, capturing the overall behaviour by simply focusing on the bulk material (as for example attempted with analytical tools by Xu et al. [19] and Persson and Brener [20]). In our opinion the answer is negative. In the cohesive-zone approach the zero-thickness interface is assigned a mechanical behaviour which indeed originates from the interaction of the crack with a process zone which is possibly very thin, yet of finite thickness. This region of finite measure is "lumped" into a line (or a surface in 3D) and hence it seems to be necessary to account for its own time-dependence. It is interesting to compare this observation with the experimental work of Hauch and Marder [21]. They observed how the increase in fracture energy with crack speed was matched by the development of a microstructure of branching transversal cracks whose length and density was increasing too. They also noted though that below a certain speed the fracture energy was still not constant in spite of the lack of any observable transversal crack pattern. Upon dissection of the specimens it was found out that the additional dissipation was likely to be connected with some "subsurface activity", in their terminology. We postulate that these occurences can only be accounted for by introducing the rate-dependence at the interface level. Also it is worth noting that this approach has a very significant advantage for the practising engineer. In many structures elastic materials are bonded using polymers, and the analysis could avoid modelling the polymeric layer altogether, under certain restrictions, replacing it with interface elements.

As for the use of plasticity, it might be deemed not physically justified as it can hardly be evoked to explain that tractions decrease to zero at incipient fracture. It is possibly an effective numeric tool to reproduce softening but, as crack formation and/or propagation ultimately involves breaking bonds at the molecular or atomic scale, it seems to be better described by damage mechanics from the physical point of view.

In this paper we aim to capture the rate dependence within the process zone of the interface itself regardless of the behaviour of the surrounding material, and we strive to do so resorting to first principles. It is clear that assumptions are necessary to model such a complex phenomenon as fracture, yet our aim is to develop a general, physically well based cohesive model, without resorting to any phenomenological law other than basic physical and engineering understanding.

As a cornestone of our modelling approach we recognize the existence of an intrinsic, i.e. rate-independent, fracture energy. This is related to an elastic energy threshold needed to break bonds at the micro or possibly the atomistic scale [22]. We then use a damage-mechanics approach and introduce a suitably defined damage variable whose evolution is related to the difference between the energy threshold and the elastic energy. The rate-dependence of the overall dissipated energy during crack propagation is a natural by-product of the visco-elastic dissipation lumped on the zero-thickness interface. We postulate that a reasonable characterization of the interface rate-dependence can be achieved by assuming that the interfaces behaves, in a suitably defined way, as its constituent material considered as a continuum. We then present the cohesive model formulation in the general framework of thermodynamics.

To validate the concept we (i) specialise our formulation to the case of a rubber interface, (ii) make the simplest possible assumption by assuming a quadratic form for the elastic energy and by choosing a linear viscoelastic law with exponential kernel and one relaxation time only and (iii) present a comparative analysis of numerical and experimental results.

The structure of the paper is as follows. In Section 2, starting from fundamental physical principles we derive a thermodynamically consistent formulation of our proposed interface model and obtain the governing equations. The algorithmic implementation is described in Section 3. Numerical results are then compared with experimental findings in Section 4. Conclusions are finally drawn in Section 5 together with a discussion on some of the opened perspectives.

2. Formulation of the interface model

We postulate that the interface response can be described by resorting to the free energy potential of the material considered as a continuum. The functional dependence of the free energy upon its arguments is kept the same as in the continuum case while the variables themselves are suitably adapted. This is a result of the dimension reduction implied by the use of a cohesive-zone model, whereby a thin layer is modelled as a surface in 3D and a two dimensional slender region is shrunk into a line in 2D. Accordingly, displacement discontinuity jumps at the interface replace continuum strains as new deformation measures. Progressive degrada-