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A multi-scale based cohesive zone model for the analysis of thickness scaling effect in fiber bridging

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ABSTRACT

A cohesive zone model (CZM) is proposed to assess the thickness scaling effect associated with fiber bridging during fracture. The CZM was developed through a multi-scale simulation approach and utilizes an embedded cell model of the Double Cantilever Beam (DCB) that explicitly accounts for the bridging bundles on the fracture plane. In particular, micromechanical simulations of failure were carried out, for varying arms thickness, in order to determine the homogenized fracture behavior. To model the observed scaling effect, the conventional cohesive law, formulated as an opening-stress relation, is enriched with information on the crack opening angle. Continuum finite element simulations indicated that the proposed CZM was able to mimic very well the essential features observed in the experiments, *e.g.* raising R-curve behavior and thickness scaling effect on the energy dissipated at steady state.

1. Introduction

Several engineering and biological materials undergo deformation and damage, which occur at multiple scales and contribute towards increasing the amount of energy dissipated during crack growth. The peculiar behavior is associated with the mutual competition between *intrinsic* and *extrinsic* damage mechanisms operating *ahead* and *behind* the crack tip [1]. The intrinsic damage mechanisms are related to the inherent fracture resistance of a material, *e.g.* large plastic zones in metal alloys act against crack initiation and propagation [2]. However, extrinsic mechanisms originate in the crack wake and can be represented by several processes, *e.g.* crack bridging by collagen fibrils in human bones [3], un-cracked ligaments in dehydrated dentin [4–6], or fiber bridging in composite materials [7–10] and wood [11].

Figure 1 illustrates some extrinsic damage mechanisms that have been observed experimentally in the wake of a propagating crack. Such damage leads to the formation of large bridging zones, spanning from the micro- to the millimeter scale, that hinder the release of elastic energy and exert a *shielding effect*, which decreases the stress level at the crack tip. As a consequence, an increase in the applied energy release rate (ERR) is required in order to extend the crack further, giving rise to the so-called R-curve behavior observed in several experimental works [12,13]. Since these extrinsic damage mechanisms significantly affect the macroscale response, it follows that failure analysis of biological and advanced materials requires linking deformation and damage events at the lower scale with the effective behavior at the macroscale.

Despite the significant progress that has been made towards the theoretical understanding of the influence of microscopic processes on fracture, the development of predictive models is still a challenging task. A natural way to pursue this goal is to incorporate the description of the relevant failure mechanisms of fracture process in conventional finite element models (FEM). The cohesive zone model (CZM) lends itself to this difficult task and has already been successfully employed to simulate failure of several quasi-brittle materials, including metals, polymers or biological materials [14–17]. By using the CZM, the fracture process is captured by a cohesive law that describes the evolution of the tractions, $\tilde{t}$, across the crack surfaces as a function of the crack opening displacement, *i.e.* $\tilde{t} = f(\delta)$.

The crucial aspect in this approach is selecting the cohesive law [18], which is often assumed to be a material property. Considerable attention has been recently paid to the determination of cohesive laws for materials that develop large scale bridging (LSB),

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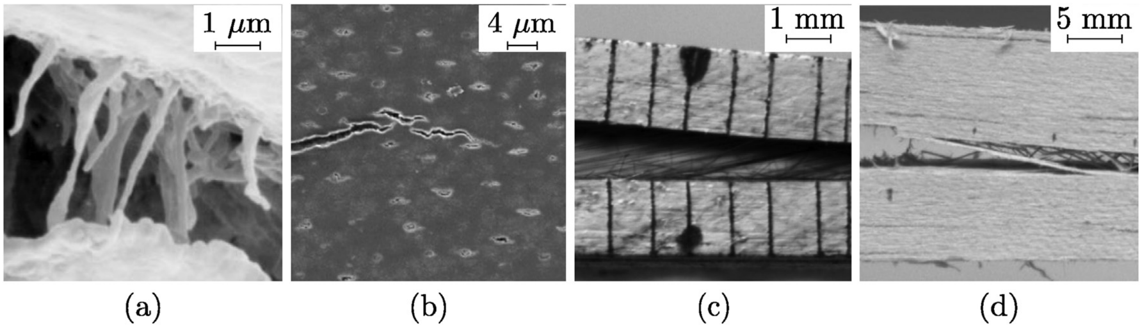

Fig. 1. Examples of damage mechanisms involving large scale bridging in biological and engineering materials. (a) Crack bridging by collagen fibrils in human bones [3]; (b) formation of localized un-cracked ligaments in dehydrated dentin [4]; crack bridging in (c) fiber reinforced polymer matrix composite materials [10] and (d) balsa wood [11].

especially long fiber reinforced polymers, where the length of the bridging zone is comparable with the specimen's linear dimensions [8,17,19]. From this standpoint, the experimental determination of cohesive models through stable tensile tests presents several shortcomings [20]. Therefore, alternative methods have been proposed based on optimizing the shape of the cohesive law to reproduce the experimental behavior [21], by identifying the parameters from the R-curves [22], through the derivative of the J-integral [23] or inverse identification [9,19].

A common feature among the existing models employed to capture fiber bridging is that only one length scale is involved. In other words, the cohesive laws are treated as a material property independent of the size of the system. However, as already mentioned earlier, the R-curves of these materials are affected by fiber bridging, which, in turn, depends on the specimen's geometry. Therefore the identified cohesive models cannot be regarded as a material property [24,25]. Moreover, the cohesive model is very often used as a phenomenological approach, though it has been shown that its shape has an effect on the crack propagation analysis [26]. It follows that, in order to obtain realistic results, the appropriate shape must be used.

Analytical models have been proposed to obtain cohesive laws accounting for fiber bridging [27–30]. However, these simplified models are not able to capture some of the experimentally observed features like the thickness effect. Given the complexity of the damage mechanisms leading to failure, alternative schemes are provided by the so-called *bottom-up* simulation approaches, which use fundamental mechanics and physics to link the microscale to the macroscopic aspects of deformation and fracture [31–33]. A bottom-up approach is employed in this work to obtain a new cohesive model that is able to capture the thickness scaling effect observed during failure of long fiber reinforced polymer matrix composites. The macro- and micro-scales were linked using an embedded cell model of the Double Cantilever Beam (DCB) which relies on the explicit representation of the bridging bundles. The model consisted of an embedded region (or core) containing the bundles, that is connected to an outer region, *i.e.* the DCB arms, through which far field loads were applied.

Micromechanical simulations were carried out for various specimen thickness and allowed to reproduce, with remarkable accuracy, the creation and failure of bridging bundles. The results showed excellent qualitative agreement with recent experimental results [34], and captured the fiber bridging development and the size-effect in the energy dissipated during fracture. In addition, the bridging traction distribution could be accessed. This last is difficult to extract from actual experiments and represents an invaluable information in the development of accurate cohesive models [35]. Since the results suggested that the interplay between the curvature of the arms and the development of bridging gives rise to the thickness scaling effect, such information has been extracted from the finite element simulations and employed to construct a new cohesive model. The proposed cohesive constitutive relationship was obtained by combining the crack opening displacement (COD), the crack opening angle (COA) and the tractions extracted from the micromechanical simulations. Continuum finite element analyses, based on the use of interface elements embedding the cohesive model, demonstrated the effectiveness of the method in capturing the thickness scaling effect and highlighted the crucial contribution of bridging to the high toughness of advanced materials. The paper is organized as follows. First, the embedded cell model is presented, and the thickness dependence of fiber bridging is demonstrated. Next, a new cohesive model which accounts for the thickness scaling effect is proposed. Finally, interface elements based on the aforementioned cohesive model are implemented in the finite element framework. In turn, comparisons are made with the results of micromechanical simulations to illustrate the effectiveness of the present approach.

2. Computational micromechanics of fiber bridging

2.1. Embedded cell approach

Following the strategy outlined in Ref. [36], virtual tests were herein carried out using a three dimensional embedded cell model of the DCB specimen. A schematic of the DCB is shown in Fig. 2 (a). The sample is symmetric with respect to the *xz* plane and the arms are made-up of unidirectional carbon fiber/epoxy laminate, with reinforcing fibers oriented along the *x*-direction. Stainless steel loading blocks were included to mimic the boundary conditions recommended by the ASTM D5528 Standard [37].

The corresponding embedded cell model is shown in Fig. 2(b). Owing to the symmetry across the *xy* plane, only half of the specimen was considered in the simulations. The model consisted mainly of two parts, *i.e.* a local heterogeneous embedded region (or core), represented by a discrete arrangement of fibers, and an embedding outer region represented by the DCB arms and the loading blocks. The outer region transfers the applied far field peel loads to the core.

The 3D finite element models were generated using ABAQUS [38]. The DCB arms and the loading blocks were discretized using 8-noded linear brick elements. The constitutive behavior of the DCB arms was assumed to be linear, elastic and anisotropic and the elastic properties, that were extracted from literature data [19], are reported in Table 1. The stainless steel blocks were represented with elastic and isotropic solid material whose elastic properties are also given in Table 1. A perfect interface (*i.e.* no damage) was assumed between the loading blocks and the composite material.

The bridging bundles were represented by 2-noded linear