



Debonding at the fibre–matrix interface under remote transverse tension. One debond or two symmetric debonds?



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ABSTRACT

The controversy about the symmetry of the debond onset at the fibre–matrix interface in single-fibre specimens under transverse tension is studied here applying the coupled stress and energy criterion of the finite fracture mechanics. This criterion enables to compare the two different post-failure configurations found in the literature studying this problem: an asymmetric configuration with a single debond and a symmetric one with two debonds. The coupled criterion applied here predicts that an asymmetric post-failure configuration is originated by a lower critical remote tension than the symmetric one, the difference being above 10% in some cases. Thus, the asymmetric debond onset is the preferred solution to the initially symmetric problem, which agrees with the experimental evidences found in the literature. This result is a consequence of the shielding effect between the two debonds in the symmetric solution. Numerical results are obtained for two common composites, glass/epoxy and carbon/epoxy, and three virtual bimetals corresponding to the extreme values of the Dundurs elastic parameters. The stress–strain curves predicted for the two post-failure configurations are also compared. Eventually, simplified models using springs and breakable elements, which capture the essence of the problem studied and explain the energetic origin of the loss of symmetry, are introduced.

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1. Introduction

Structural applications of composites have recently increased dramatically in industries where light-weight is a key aspect of design. Moreover, composites are now often applied in structurally relevant parts, e.g., in primary structures in aerospace applications. Thus, a substantial improvement of the existing failure criteria for composites is highly demanded by the industry.

In particular, the failure criteria still do not predict satisfactorily failures of unidirectional laminae under transverse loads (with loads perpendicular to the fibre-axis), as was highlighted in a series of coordinated studies (known as the world-wide failure exercises) currently underway (Hinton et al., 2004; Hinton and Kaddour, 2013). A reason for this is that the current failure criteria are still not sufficiently physically based from the microscopic point of view.

The so-called *matrix failure* or *inter-fibre failure* is one of the most complex failure mechanisms in these laminae due to its strong dependence on the microstructure. At micromechanical level, the stages of the initiation of this failure are well known (Hull and Clyne, 1996; París et al., 2007): (i) failure is initiated as microdebonds at the fibre–matrix interfaces, (ii) subsequently these microdebonds grow along the interface and (iii) kink out the interface towards the matrix, where (iv) coalescence of several microcracks generates a macrocrack which may cause the failure of the lamina.

A simplified model given by a single long fibre surrounded by an infinite matrix is often used as a reasonable first approximation to study some failure mechanisms at the micromechanical level in fibre-reinforced composites, at least for dilute packing. Additionally, a few experimental studies of debond onset and growth in single fibre or inclusion specimens subjected to transverse loads have been presented by Zhang et al. (1997), Gamstedt and Sjögren (1999), Contreras (2000), and Martyniuk et al. (2013).

In the case of *matrix failure* under remote transverse tension, the single fibre model leads to a plane strain problem of a circular

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inclusion embedded in an infinite matrix. The stress solution of such a problem for perfect and linear-elastic inclusion-matrix-interface, respectively, was deduced by Goodier (1933) and Gao (1995). Assuming the open model of interface cracks at perfect interfaces, analytic solutions for stresses, displacements and energy release rate (ERR) were obtained by England (1966) and Toya (1974) in the presence of a debond at the inclusion–matrix interface. Although, assuming a more realistic contact model of interface cracks at perfect interfaces, no analytic solution is available for the present problem, accurate numerical solutions were presented in París et al. (1996) and Mantić et al. (2006).

Debond growing along the fibre–matrix interface and kinking out, both originated by transverse loading, have been intensively analysed in many works, see e.g. París et al. (2007), Hasebe and Yamamoto (2014), and also He and Hutchinson (1989) for a general theory of interface crack kinking. However the initiation of the debond has not called so much attention. After some pioneering articles (Xu and Needleman, 1993; Levy, 1994, 1995), a few works studied the debond onset at the fibre–matrix interface under transverse uniaxial loading by using different interface laws, e.g., Legarthy (2004), Carpinteri et al. (2005), Han et al. (2006), Kushch et al. (2011) and Távara et al. (2011). This idea has also been applied to related problems, e.g., Tvergaard (2006) studied the effect of the triaxiality on the debond growth when the composite is mainly loaded along the fibre direction.

Several of these works agree on some relevant results such as a size effect on the critical load, see García et al. (2014) for a recent comparison study. However, there is a disagreement on a key issue of the *post-failure configuration* (or *post debond-onset configuration*). For instance, some works (Carpinteri et al., 2005; Kushch et al., 2011) predict a symmetric debond onset whereas others (Levy and Hardikar, 1999; Han et al., 2006; Távara et al., 2011) predict breaking the symmetry of the original configuration due to the onset of a single debond. The loss of symmetry from perfectly symmetric initial conditions has also been predicted in other problems of fracture mechanics. For instance, the problem of a long strip containing a transverse crack symmetrically situated with respect to the strip edges (Bažant and Cedolin, 1991). The authors show that the asymmetric crack growth is preferential even if the initial state is perfectly symmetric. Some examples of loss of symmetry can also be found in Bigoni (2012). A model with (asymmetric) imperfections at the interface was studied in Legarthy (2004) by assuming a non-uniform interface strength leading also to an asymmetric failure.

The present work aims to analyse these two post-failure configurations observed in previous studies, an asymmetric debond and two symmetric debonds, by means of the coupled criterion of the finite fracture mechanics (FFM). The objective is to assess which of them is to be expected to appear in experiments and clarify why. It is assumed that the lower critical remote tension is predicted for the preferential post-failure configuration. The initial state, previous to the crack onset, is assumed to be perfectly symmetric in geometry, material properties and loading. Thus, the results obtained should be understood as a qualitative tendency in more realistic cases with initial asymmetries due to the natural randomness of the problem conditions. The natural presence of small defects or other sources of asymmetry would slightly modify the quantitative results, but no consequence is expected on the qualitative results about the failure symmetry. Actually, the objective of this work is not only to provide predictions about the failure in the present particular problem but also to give a conceptual answer, which can be applied to many other problems.

The coupled stress and energy criterion was proposed by Leguillon (2002) in the context of crack initiation, see also Cornetti et al. (2006), and has been applied in a semianalytical manner by

Mantić (2009), Mantić and García (2012) and Carraro and Quaresimin (2014) to the present problem assuming a single debond, the configuration usually observed in composites damaged under transverse loads (Hull and Clyne, 1996; Zhang et al., 1997; Gamstedt and Sjögren, 1999). In addition, it has been applied successfully to predict crack onset in related problems by Quesada et al. (2009) and Camanho et al. (2012). This criterion is based on the assumption that the crack or debond onset occurs if two criteria are fulfilled simultaneously: a stress condition on the stresses along the future crack path, and an energetic condition based of the first law of thermodynamics for the energetic balance between the states before and after the crack onset, corresponding to an asymmetric debond and two symmetric debonds, in order to compare the predicted critical remote tension for each of them.

The plane strain problem under study is shown in Fig. 1. In the initial state, a single fibre is perfectly bonded to an infinite matrix. The matrix is loaded by a uniaxial remote tension σ^∞ in the x -direction. For *a priori* two different critical values of σ^∞ , one or two debonds appear as showed in Fig. 1. As both initial state and post-failure configurations are symmetric with respect to the x -axis, only the upper-half ($y \geq 0$) of the geometry is considered. Hence, the polar angle θ and also other angles are defined as ≥ 0 . Glass/epoxy composite is taken as a reference bimaterial in the present work, see Table 1 for its linear elastic properties, although, a summary of key results is also shown for carbon/epoxy composite (Table 2) and for a few virtual materials with extreme values of the main parameters governing the problem.

First, stress and energy criteria are studied and applied separately in Sections 2 and 3, respectively. Both criteria are applied in a parallel manner for the two post-failure configurations. The combination of both criteria is described in Section 4. Finally, the results about the loss of symmetry are discussed in Section 5 for several bimaterials, and a novel representation of crack onset by the stress–strain curves predicted for the two post-failure configurations is introduced and interpreted.

2. Stress criterion

A stress criterion is usually invoked for brittle or quasi-brittle materials when no pre-existing damage exists. In the framework of the FFM, the stress criterion defines a condition on stresses along the assumed future crack surface in the elastic state prior to the crack onset. Several stress criteria have been used for this purpose. While the tensile criterion requires that normal tractions at all the points along the future crack surface exceed a critical value (Leguillon, 2002; Mantić, 2009), the mixed stress criterion (García and Leguillon, 2012; García et al., 2014; Carraro and Quaresimin, 2014) takes into account the influence of shear tractions as well. On the other hand, a weaker condition was proposed by Cornetti et al. (2006) assuming that only the mean value of normal tractions along the future crack extension has to exceed the critical value, see also Camanho et al. (2012).

The tensile criterion is used in the present study for the sake of simplicity. Assuming a critical value $\sigma_c > 0$ for normal tractions $\sigma(\theta)$ along the interface before the debond onset, the condition for the onset given by this criterion can be expressed as,

$$\sigma(\theta) \geq \sigma_c, \quad \forall \theta \in [0, \Delta\theta], \quad (1)$$

where θ is the polar angle, see Fig. 1, and $\Delta\theta$ is the debond semiangle immediately after the onset. Analytical expression of the normal tractions σ along the fibre–matrix interface in the undamaged state can be extracted from the classical solution by Goodier (1933), cf. Mantić (2009),

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