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Transverse crack formation in unidirectional composites by linking of fibre/matrix debond cracks

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ABSTRACT

Plausible mechanisms of transverse crack formation in unidirectional (UD) composites under applied tension normal to fibres are investigated numerically using a finite element model. Two initial scenarios are considered: Scenario 1 where a pre-existing single fibre/matrix debond crack kinks out into the matrix and induces fibre/matrix debonding at neighbouring fibres, and Scenario 2 where multiple pre-existing debond cracks link up by the debond growth and crack kink-out process. The 2-D finite element model consists of a circular region of matrix with a central fibre surrounded by six fibres in a hexagonal pattern. The region is embedded in a homogenized UD composite of rectangular outer boundary. Energy release rates (ERRs) of interface cracks and kinked-out cracks are calculated under applied tension normal to fibres. Results show that Scenario 2 is more likely to lead to formation of a transverse crack than Scenario 1. These results provide understanding of the roles of fibre clustering and fibre volume fraction on transverse crack formation in composites.

1. Introduction

Cracking within the plies of a composite laminate, often referred to as matrix cracking or transverse cracking, is invariably the first failure mechanism to occur on loading of the laminate. Although by itself this failure mechanism may not affect the performance of the laminate significantly, it can lead to other failures, e.g. delamination and fibre breakage, which can have detrimental effects on the load bearing capability of the laminate. Therefore, understanding what governs the initiation and evolution of cracking within the plies is of great interest. The early studies of this mechanism, (e.g. [1–3]), were focused on explaining the observed multiplication of the matrix cracks by simple one-dimensional models. More rigorous mechanics treatments of the evolution of the crack number density and its effects on laminate stiffness reduction were developed later (see [4] for a comprehensive review). Common to all such analyses is the assumption of homogenized plies in which cracks appear according to a strength or a fracture toughness based criterion, and then multiply under increased loading when the local stresses between the cracks satisfy that criterion.

In recent years, the process of matrix crack formation within the plies has been examined in more detail by considering the local stress fields in the matrix between the fibres. Among the earliest works in this direction were studies of the effect of tri-axiality in the local stress field on cavitation in the matrix polymer [5]. Further studies of this phenomenon led to a dilatation energy density criterion for brittle cracking in the matrix [6] and its predictions agreed well with experimental data [7]. Since the favourable locations for satisfaction of the criterion are points in the matrix close to the fibre surfaces, it is reasonably assumed that the matrix failure leads to debond cracks at the fibre/matrix interfaces. Other assumed criteria for the debond crack initiation resort to fibre/matrix interface properties such as strength or fracture toughness based on finite fracture mechanics [8], or a combination of these via a cohesive zone model for single-fibre debonding [9] or multiple-fibre debonding [10]. The interface properties in a cohesive zone model cannot be found independently and must be inferred or calibrated. It is worth noting that the inferred interface properties depend on the stress state on the fibre/matrix interface at incipient failure. A comprehensive review of various methods to infer the interfacial strength has been given in [11].

Experimental observations [12,13] suggest that the individual fibre/matrix debond cracks connect through the matrix to form transverse cracks. The images obtained in these studies do not provide sufficient details of the mechanisms by which the debond cracks connect. Since in situ observations are difficult to make other than perhaps for model composites, numerous studies have attempted to understand the governing conditions underlying the mechanisms involved by analysis.

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Before understanding the kinking out of the debond crack from the fibre/matrix interface, one must analyse the growth of the debond crack on the fibre surface. For this, a single-fibre composite has been considered in an analytical study [14] and in numerous numerical studies (e.g. [15–20]). The kinking out of a debond crack has also been studied in a single-fibre model [21]. Recognizing the importance of the presence of neighbouring fibres on the debonding and crack kinking process, later studies considered a two-fibre model [22] and found that presence of a nearby fibre accelerates the initiation of debond crack growth in the central fibre only when it is aligned with the external loading direction, and for the rest of the positions, it inhibits the debond crack growth in the central fibre. An experimental and numerical study [23] of a model composite indicated the effect of the presence of multiple fibres and their distribution on the transverse crack formation process. Various numerical simulation studies have been reported [24–26] that considered the effect of nonuniform fibre distribution on the transverse crack formation. None of these studies, however, explicitly analysed the debond crack linking mechanism in the transverse crack formation process.

Clearly, the linking of the fibre/matrix debond cracks must play a key role in the transverse crack formation process. Without understanding this role, the effects of fibre volume fraction and fibre clustering in nonuniform fibre distribution on the composite transverse strength cannot be explained. To understand the debond crack linking process, the conditions governing the kinking out of a debond crack must be clarified. The local stress field responsible for the kinking process is affected by the stress perturbations induced by the fibres surrounding the debond crack. Since single-fibre or two-fibre models are inadequate to provide the local stress field with sufficient accuracy, a model with multiple-fibre representation was adopted in a previous study [27]. In that work, the effect of inter-fibre spacing on the growth of a debond crack was studied by placing the debonded fibre at the centre in a hexagonal fibre configuration. Using the same model, the effect of thermal cooldown on the debond crack growth was also studied [28]. In the current work, we focus on the debonding and subsequent kinkout process in two scenarios. Scenario 1, where the central fibre is debonded and its kink-out induces debonding of a neighbouring fibre, and Scenario 2, where multiple fibres are already debonded, and the linking occurs by their kink-out into the matrix. The growth conditions for the debond cracks and their kinking are studied by calculating the energy release rates (ERRs).

2. Scenario I: one pre-existing fibre/matrix debond

This scenario is studied by the finite element (FE) model shown in Fig. 1a, which was also used in another study [27]. Due to the symmetry, only half of the region is shown. As seen in the figure, the central fibre is debonded on one side with the centre of the arc-shaped debond crack lying on the horizontal tensile load axis. The debonded fibre is surrounded by six fibres placed in a hexagonal pattern. The circular region of seven-fibre assembly is embedded in a homogenized composite of rectangular outer boundary. The homogenized composite in a FE model is of importance as Pupurs and Varna [29] found that ignoring it would lead to significant errors in ERR calculation of the debond crack under longitudinal tension. The distance between the surfaces of the central fibre and the neighbouring fibres, denoted *ID*, is varied in order to study the effects of inter-fibre spacing. The fibre radius $r_f = 4$ µm and the radius RMO of circular matrix region (Fig. 1a) are chosen such that the fibre volume fraction V_f within this region equals the global fibre volume fraction of the composite. The half-height and the width of the model are chosen as H = 20 × RMO and W = 40 × RMO, respectively, beyond which the calculated ERR of the debond crack is taken not to be affected by the size of the model.

As shown in Fig. 1a, the x-displacement is applied uniformly to the right edge (x = W) of the model, while it is constrained on the left edge, to induce the strain $\varepsilon_x = 0.5\%$. 2-D quadratic plane strain elements (PLANE 183) were adopted in the FE model and in addition to that, contact elements were generated on the debond surface in ANSYS. For the FE models adopted in the present paper, each one has 200,000–260,000 elements generated. The ERR is calculated by the virtual crack closure technique (VCCT) using the ANSYS FE software [30]. It has been well documented that for an interface crack between two dissimilar materials (here: a debond crack), Mode I and Mode II components of the ERR are not well defined [31–34]. Therefore, the calculated ERR modes here depend on the size of the near tip element. Fig. 1b shows the typical mesh near debond tip adopted in the current study where uniform quadrilateral elements were generated ahead of and behind the debond tip. The size of the near-tip element is $r_f \cdot d\theta$, where $d\theta = 0.5°$. It has been shown in [27] that the obtained ERR results based on this element size agree very well with those calculated by the boundary element method in [22] for a single glass-fibre composite.

The material used in the present study consists of carbon fibres in an epoxy matrix with $V_f = 0.6$. The elastic material properties for each constituent are displayed in Table 1. The transverse properties of the carbon fibre were estimated based on [35–37]. In order to generate a preferred failure initiation site in the composite, two different values of the inter-fibre spacing were chosen as: IDn (ID/r_f) = 0.15 and IDn = 0.35 (as a reference, the inter-fibre spacing in a uniform hexagonally packed UD composite of $V_f = 0.6$ is IDn ≈ 0.48). Both these values represent local cluster of fibres with significant interaction between fibres.

This scenario is investigated first under purely mechanical loading, followed by a discussion of the thermal stress effects.

2.1. Debond crack growth

The results for the two cases of *IDn* = 0.15 and 0.35 under pure mechanical loading at $\varepsilon_x = 0.5\%$ are shown in Fig. 2. As displayed in Fig. 2, all ERRs of the debond crack are lower at closer inter-fibre spacing as a result of constraint effect of neighbouring fibres (see details in [27]). For both cases, the debond growth is in mixed-mode. Both mode I ERR component (G_I) and mode II ERR component (G_{II}) increase first and then decrease with increasing debond angle θ, and the same trend results for total ERR G_T ($G_T = G_I + G_{II}$). When debond crack grows to an angle θ ≈ 70°, a finite contact zone (≈1°) is detected between two debond surfaces and G_I diminishes while G_{II} remains high. This angle is of interest with regard to the kinking of the debond crack, as suggested by the experimental observations [38] of debonding on the free surface and numerical computations [21] for a single-fibre composite. Based on these studies, it appears reasonable to assume that even though the mode II ERR is high beyond θ ≈ 70°, the debond growth on the fibre surface is governed by the mode I ERR and would therefore cease at this angle.

The relative radial displacement, i.e., radial separation, of the two debond surfaces, is shown in Fig. 3 for different debond arc angles θ at *IDn* = 0.15. As seen in the figure, for larger angles ($\theta > 30°$), the radial surface separation towards the debond crack tip decreases, indicating a closing action. At $\theta = 70°$, the debond surfaces come clearly into contact and beyond this angle the contact zone increases with increasing debond angle. These results also support the ERR based inference, stated above, that beyond $\theta \approx 70°$ the debond crack is not likely to grow.

2.2. Debond crack kinking

Fig. 4 illustrates the FE model used to investigate debond crack kinking. According to the analysis of cracks between dissimilar materials [39], an interface crack tends to kink out into the more compliant material, which in this case is the matrix, assuming sufficient resistance to crack growth in the interface exists. Accordingly, we will calculate ERRs for both the kinked crack and the debond crack as the driving forces for kinking versus growth in the interface. The geometry of the