FAILURE OF COMPOSITES UNDER TRANSVERSE LOADING - A FRACTURE MECHANICAL APPROACH

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Abstract

The failure of fiber reinforced composites under transverse loading is investigated on a representative volume element. The volume element is composed of a twelve fiber hexagonal array. The debonding of the central fiber is studied under transverse shear as well as under transverse compressive loading by calculating the mode I and mode II part of the energy release rate. The initiation of failure is assumed to take place at the location of maximum tensile or maximum shear stresses, respectively. In order to determine the failure initiation point, the stress field in the interface before crack initiation is calculated.

1 Introduction

As well known, the failure of laminates usually starts in plies with strong loading transverse to the fibers. The inter fiber failure is due to the stress concentrations between the neighbouring fibers which become more and more dominant with growing fiber content. The main portion of deformation arises in the small matrix regions between the fibers since the deformation of the fibers is very low compared to the matrix. These stress concentrations cause interface failure because the interface usually is weaker than the matrix itself. Accordingly, the strength of the fiber-matrix interface is an essential factor limiting the transverse strength of fiber reinforced composites. The interfacial bond strength, mainly focused on the strength under dominating axial shear stresses, is studied by many researchers e.g. by pull-out, push-out and fragmentation tests [1-3]. The interface strength under transverse tension as well as under combined shear and tension is studied e.g. by Tandon et al [4], Ogihara et al [5] and by the author [6].

2 Failure criteria for composites

Most common failure criteria for fiber reinforced composites are more or less based on stress interaction functions which are only partly related to the failure mechanisms. In addition to the purely mathematical criteria, e.g. the Tsai-Wu criterion [7], criteria related to the failure plane were developed by Puck [8] and Cuntze [9,10]. Even though the latter are less phenomenological than the Tsai-Wu type criteria, they are based on a macroscopical view of the failure process, regarding the composite as a homogenised material. Accordingly, they do not take into account microscopical failure processes such as fiber debonding and inter fiber crack growth. The limits of the existing failure criteria and their experimental verification are shown in the "World wide failure exercise" by Hinton et al [11]. Beside stress based failure criteria also criteria based on the energy release rate are common. A comparison of these types of criteria is given by Leguillon [12].

3 Failure of fiber-matrix interface under transverse loading

Before developing a failure criterion based on the actual failure mechanisms for fiber reinforced composite under transverse loading it is necessary to get a better understanding of the failure process on a microscopical scale. The first step is to study the debonding of fibers under transverse loading. To do so the debonding of single fibers was investigated by Paris [13,14], Correa and coworkers [15] by simulating the propagation of an interface crack. They calculated the mode I and mode II energy release rate of interface cracks in 2D single fiber model composites using the boundary element method. Their studies cover uniaxial and biaxial loading as well. Since the stress field around the fibers strongly depends on the distance to the neighbouring fibers, i.e. on the fiber volume fraction, further studies on multifiber composites were performed. The debonding of a fiber in the center of the model under transverse tensile loading was studied using the finite element method by calculating the mode I and mode II energy release rate for an interface crack propagating in circumferential direction [16]. As expected, the fiber volume fraction has a great influence on the course of the energy release rate as a result of the change of the stress field by the neighbouring fibers. While at low fiber volume contents the mode II part of the energy release rate is governing the fracture process, the mode I part becomes dominating at high fiber volume fractions.

4 Model composite

In the present paper interfacial failure under transverse shear loading as well as compressive loading are studied. The analyses are restricted to plane stress conditions, this is, no stresses in axial direction are taken into account. The debonding of a fiber within a composite material possessing a hexagonal fiber arrangement material is investigated. In order to ensure conditions existing in a vast composite material, a twelve fiber model is used. The respective fiber is surrounded by a full hexagonal cell which itself is surrounded by the half of the ten next neighbouring fibers (fig. 1). On the edges of the rectangular model symmetric or periodic boundary conditions are prescribed, depending on the load case. One has to keep in mind that due to the boundary conditions the debonding of the single fiber under investigation means that in the real composite material a large number of fibers would debond simultaneously. The model chosen ensures that the influence of the other - virtual -simultaneously debonding fibers is negligible.

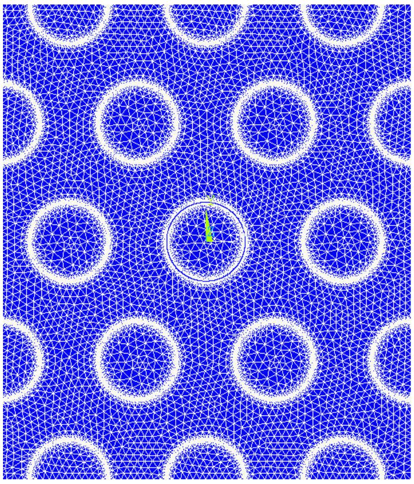

Figure 1. FEM mesh, 30% fiber volume fraction.

When studying debonding in terms simulating the propagation of an interface crack first the location where the failure will start has to be identified. To locate the point of failure initiation a failure criterion must be applied. Different concurring strategies exist to define the initiation of a crack, i.e. strength or toughness based ones [12]. In the present study strength criteria are used to determine the onset of interfacial failure. The simplest strength criterion is the maximum stress criterion, this is, failure starts at the point where one of the stress components becomes maximal, i.e. either the radial tensile stresses or the shear stresses.

Since the crack faces may come into contact during crack propagation contact elements are arranged at the interface on the fiber and the matrix side. Interfacial friction is not taken into account. During crack propagation the prescribed displacement remains unchanged, the crack propagation accordingly is analysed under "fixed grips" conditions. The elements used are plane stresses 8-node quadrilateral elements. In order to get comparable results for different fiber volume fractions the mesh in the vicinity of the interface is chosen identical for either fiber volume fraction. Two rows of almost quadratic elements are arranged on either side of the interface (4 rows in total), each corresponding to a 1° crack increment. In the interface, the adjacent fiber and matrix elements posses individual nodes which are glued together until they are separated when the crack is forming.

The composite material used for the analyses consists of glass fibers embedded in epoxy resin wit a fiber volume content of 30% (Table 1). Linear elastic material behaviour is presumed as well as small deformations.

Material	E-Modulus [MPa]	Poisson ratio
fiber	72000	0.21
matrix	2800	0.35

Table 1. Elastic constants of glass fiber and epoxy matrix

5 Failure of fiber-matrix interface under transverse shear loading

In case of shear loading, the geometrical symmetry plane (x-y plane) is a plane of anti-symmetry concerning deformation and stresses, since shear is an anti-symmetric load case. Periodic displacement boundary conditions are prescribed on every edge (fig. 2).

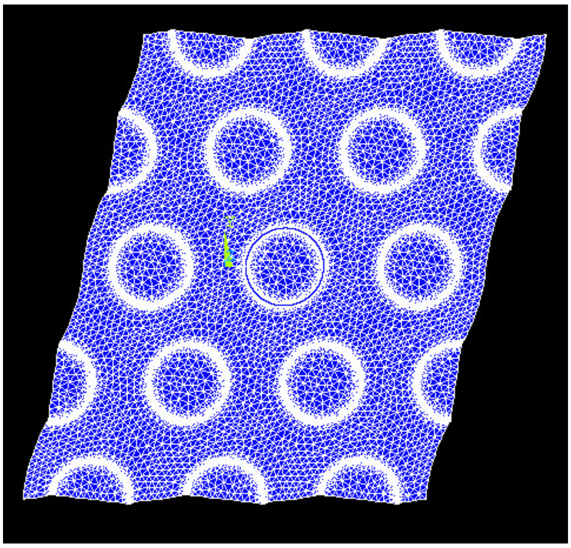

Figure 2. Deformed element mesh under shear loading, 30% fiber volume fraction.

The failure initiation is assumed to occur due to tensile stresses. This is, a simple maximum tensile stress criterion is applied and no interaction with the shear stresses is taken into account. The interfacial stresses for a fiber volume fraction of 30% are given in fig. 3, corresponding to the coordinate system used for the interfacial stresses as shown in fig. 4a . The angle φ is counting counter clockwise from the x-axis. The radial stresses σ_n vanish at 0° because this corresponds to the plane of anti-symmetry. The radial tensile stresses reach a maximum an angle of 53° where the interfacial failure is supposed to start. The tangential stresses σ_t are almost vanishing at this point.

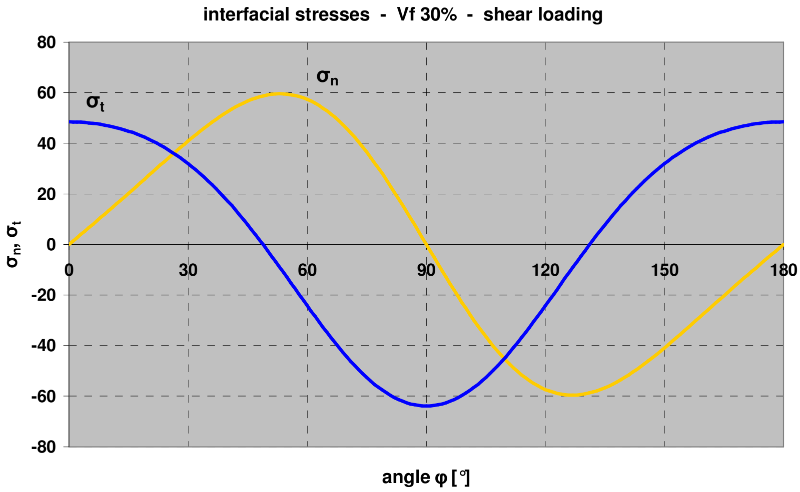

Figure 3. Radial stresses σ_n and tangential stresses σ_t in the interface of the central fiber before crack initiation, transverse shear loading.

From the point of initiation the crack propagates in circumferentially both directions, i.e. clockwise and counter clockwise (fig. 4b). The crack angle is denoted by α .

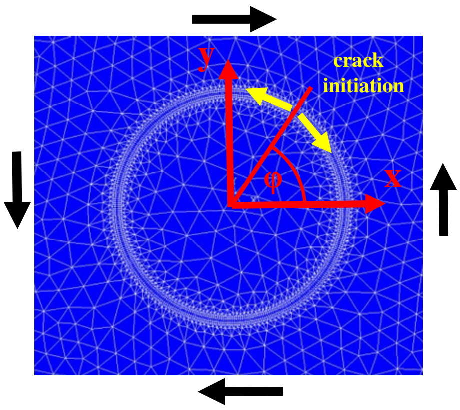

Figure 4a. Single fiber: crack initiation, angle φ.

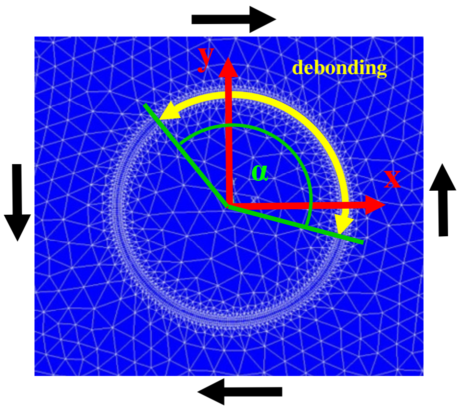

Figure 4b. Single fiber: debonding, crack angle α.

The energy release rate for the interface crack is shown in fig. 5. In the first phase the mode I energy release rate is dominating the crack propagation. This is not surprising since the crack starts in the region with the highest radial stresses. Accordingly the crack is opening. At a crack angle of 30° the mode I part reaches its maximum. Since the crack closes around 90° meaning that the faces come into contact, the radial stresses become compressive and the mode I part vanishes. Beyond an angle of 30° the mode II part becomes dominating and reaches a maximum at an angle of 110°. The mode II part decreases and almost vanishes at a crack angle of 260°. At this stage the debonding usually comes to an end because in a real composite the interface crack comes to a stop at low energy release rate and declines into the matrix, propagating to a neighbouring fiber before the anew increase of the energy release rate. This is, the curves beyond the minimum of the energy release rate have no practical meaning.

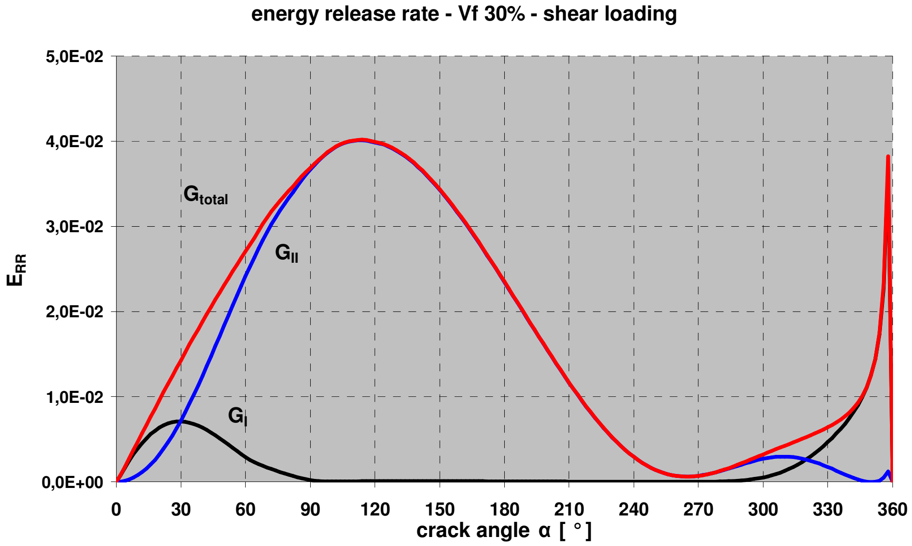

Figure 5. Mode I and mode II energy release rate of interface crack at central fiber, transverse shear loading.

For a thorough interpretation of these results with respect to the failure taking place in real composite the definition of a failure criterion for interfacial failure is necessary, which is not part of this paper. However, even without defining a failure criterion, some basic findings can be stated. From the beginning of the crack up to an angle of 30° both parts of the energy release rate are increasing. This is, the crack propagation is unstable. When the mode I part begins to decrease the mode II part strongly increases. Accordingly, even if the influence of the mode I part on the critical energy release rate of the interface is higher than that of the mode II part, which is valid for most polymer-fiber interfaces, it is likely that the crack will propagate unstably a lot further. Before giving any detailed statement about these questions, further experimental research concerning the mixed mode adhesive strength between fibers and polymer matrices is needed [4-6] .

6 Failure of fiber-matrix interface under transverse compressive loading

In case of compressive loading the whole interface is under compressive radial stresses. Accordingly debonding will be initiated by shear stresses. In contrast to the maximum tensile stress criterion applied in case of external shear loading a maximum shear stress criterion is applied in case of external compressive loading. The shear strength of many polymers and their interface to fibers is significantly higher than their tensile strength. For this study the shear strength is assumed to be three times the tensile strength. The maximum shear stresses arise 37°, accordingly the crack is assumed to start at this point (fig. 6).

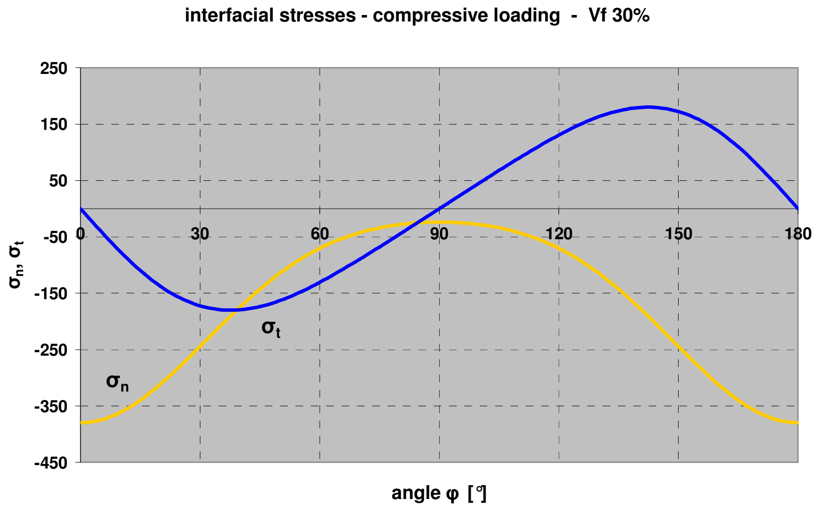

Figure 6. Radial stresses σ_n and tangential stresses σ_t in the interface of the central fiber before crack initiation, transverse compressive loading.

The mode II energy release rate is dominating the first phase of crack propagation (fig. 7). The maximum arises at a crack angle of 45°. Due to the crack propagation the stress field around the debonding fiber undergoes extensive changes. At a crack angle of about 30° the radial stresses in the interface become tensile resulting in an opening of the crack and, in turn, a mode I energy release rate develops. The maximum of the mode I part arises at a crack angle of 100°. After almost vanishing, although at different locations, the mode I as well as the mode II part increase again and reach a second maximum. Due to the fact that the external loading in case of compression is higher compared to the case of external shear loading and, in addition, a different failure criterion is applied, the absolute energy release rate is significantly higher for the compression load case.

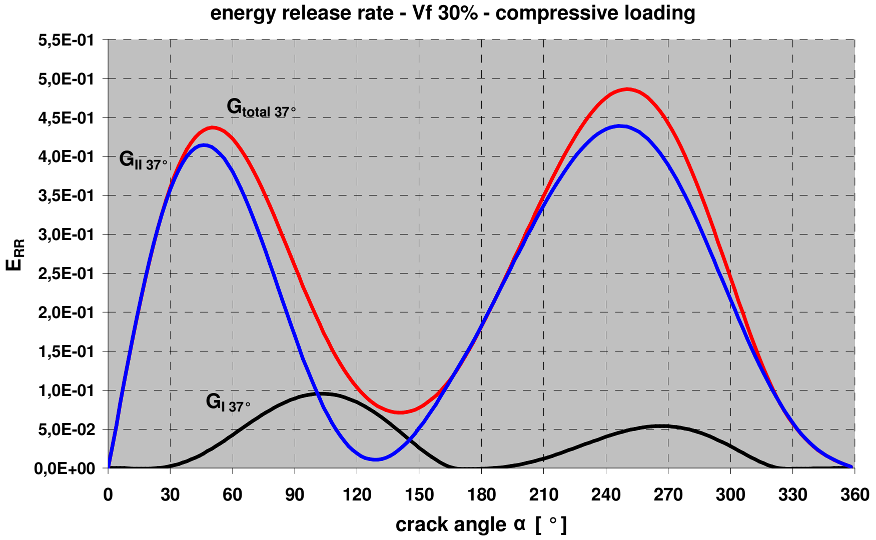

Figure 7. Mode I and mode II energy release rate of interface crack at central fiber, transverse compressive loading.

Conclusions

The studies show that debonding process of a fiber within a composite material under transverse loading varies strongly with the kind of loading. Common to all studied load cases is the strong increase of the total energy release directly after crack initiation. This indicates an unstable propagation of the crack. The mode II part is dominating a large part of the debonding process in case of a fiber volume fraction of 30%. The ratio of the mode I and the mode II part strongly varies during crack propagation.

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