MICROMECHANICAL VIEW OF FAILURE OF THE MATRIX IN COMPRESSION IN FIBROUS COMPOSITE MATERIALS.

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ABSTRACT

The present paper attempts to elucidate whether the assumption that the failure of the matrix in compression is governed by the stress vector associated to the plane of failure is a physically based assumption for fibrous composite materials. To this end a micromechanical study is conducted considering, based on failure observations, that the mechanism of failure is produced by a crack running between the fibre and the matrix. The numerical analysis is performed using the Boundary Element Method and allowing contact between the debonded surfaces of fibre and matrix. Different loads are applied transversally to the plane of failure to check its influence in the energy release rate, which is the fracture parameter evaluated. The influence of the friction coefficient in the contact surfaces is also taken into consideration in the study carried out. The results obtained prove that the stress perpendicular to the macromechanical plane of failure plays an important role in the micromechanism of failure of the composite.

INTRODUCTION

Fibrous composite materials have traditionally been regarded as designed to work in the direction of the fibres. In impact problems, however, the main mechanism of failure is that associated to the failure of the matrix in compression. The existing proposals to predict this failure are variations of original proposals, Hashin and Rotem [1], which basically estimate that the failure at one plane of the composite is governed by the components of the stress vector associated to this plane, a quadratic interaction between the components additionally being proposed.

Hashin [2] extended this idea to the three-dimensional case, though finding difficulties in determining the plane of failure. Kroll and Hufenbach [3] among others, have taken up the idea, determining the plane of failure and proposing some modifications to the original interaction between the stresses, in order to take into account experimental results that do not agree with the predictions of the original expression. Sun et al [4], in the context of a two-dimensional case, presented a similar modification to the original expression of the criterion. These modifications involve material parameters which are not able to be measured in a direct form. A more detailed discussion on original Hashin and derived proposals can be found in París [5].

The objective of this paper is to elucidate whether or not the main hypothesis of failure prediction of the matrix in compression (i.e.: the failure at a plane is governed by the components of the stress vector associated to such a plane) is a physically based assumption. To this end a micromechanical analysis based on a boundary elements model will be carried out. The micromechanical model is described in the next section, the results and discussion being presented later on.

THE MICROMECHANICAL BOUNDARY ELEMENT MODEL

To be able to elucidate the stresses, and their interaction, involved in a mechanism of failure, the model to be developed has to consider the actual mechanism of failure of the material in question. In this case (failure of the matrix in compression), it is considered, based on observations of damaged specimens, that the damage starts at micromechanical level by a crack running circumferentially between the fibres and the matrix. After these cracks have grown to a certain extension, they interact with each other, giving rise to a macro-failure of the composite. The first step described, the growth of the crack along the interphase between the fibre and the matrix, is the mechanism considered in this study. It is thought that this is the most significant period of damage in an actual composite.

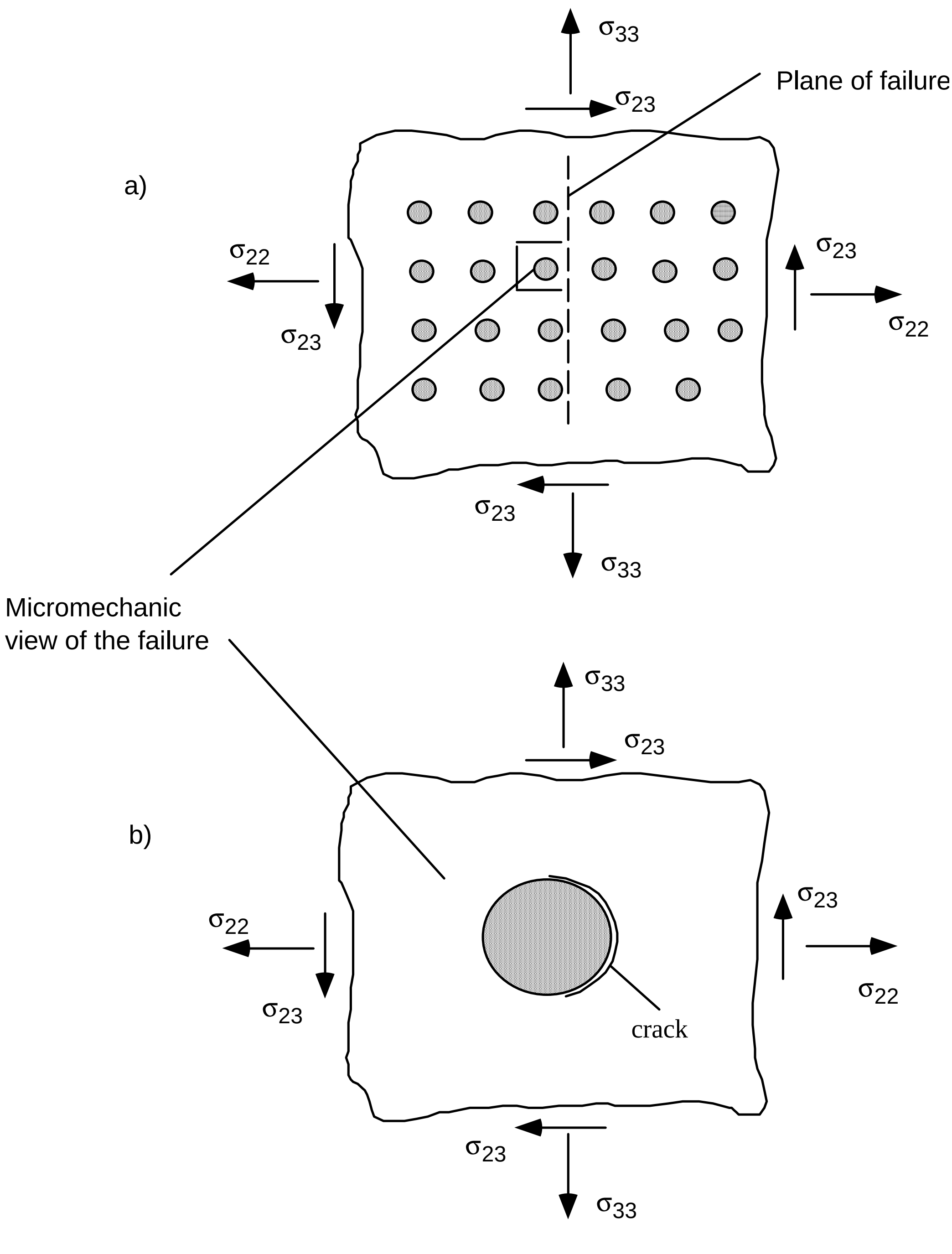

Figure 1: Micromechanical implications of associating the failure at a plane to the stresses associated to such a plane.

Figure 1 represents the former explanations graphically. In Figure 1a the failure at a plane in an idealized configuration of a fibrous composite is presented, a failure along a vertical plane in this case being assumed. This failure at micromechanical level involves, as the most plausible mechanism of failure, the presence of a crack running between the fibre and the matrix as is indicated in Figure 1b.

Initially a transversal section of an isolated fibre embedded in a matrix with an existing partial debonding between the fibre and the matrix in a plane strain state under remote stresses is going to be studied. The geometry and features of the model are shown in Figure 2. This geometry, as deduced from Figure 1, would lead, in an actual composite when the damage is extensive, to a macro-failure along the vertical plane.

The numerical analysis is going to be performed with the Boundary Element Method, París and Cañas [6]. Details of the modelization performed for this case can be found in París et al [7]. The model permits the development of a contact zone (θ_d-θ_s in Figure 2) between the debonded surfaces of the fibre and the matrix to be taken into consideration. The two boundaries corresponding to the interface are modeled with circular elements, those at both sides of the crack tip having discontinuous interpolation to facilitate the modelization of the possible singularities that will appear depending on the presence of contact zone along the debonded surfaces.

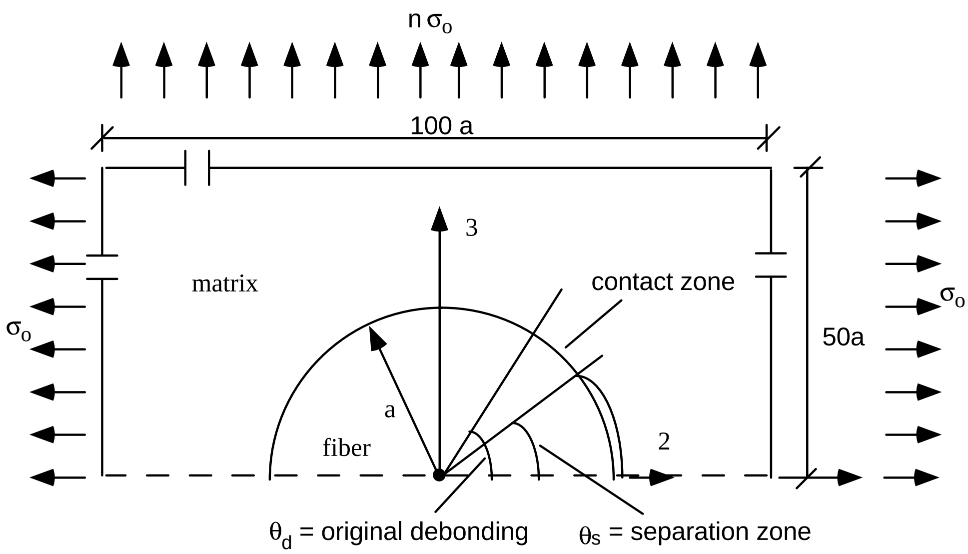

Figure 2: Single fibre configuration with damage modeled by an interface crack between fibre and matrix.

To characterize the problem from the Fracture Mechanic point of view, the energy release rate will be used. The expression employed, in the crack closure technique, when the crack propagates from a certain angle α to $\alpha + \delta$ ($\delta \ll \alpha$), is:

$$G_{\delta}^{arc}(\alpha) = \frac{1}{2\delta} \int_{\alpha}^{\alpha+\delta} \left\{ (\sigma_{rr})_{\alpha} (u_r)_{\alpha+\delta} + (\sigma_{r\theta})_{\alpha} (u_{\theta})_{\alpha+\delta} \right\} d\theta \tag{1}$$

where σ_{rr} and $\sigma_{r\theta}$ represent respectively radial and shear stresses along the interface and u_r and u_θ their associated displacements. The two modes of fracture, I (associated to σ_{rr}) and II (associated to $\sigma_{r\theta}$) are obviously considered in this expression. The presence of contact zone between the debonded faces of matrix and fibre will nevertheless alter the character of the mode of fracture. When the numerical model does not detect a contact zone (which happens, for instance. for a remote tension stress for small debonding angles, smaller than 30 degrees, París et al [7]), both stresses σ_{rr} and $\sigma_{r\theta}$ are singular and the crack is working in a mixed mode. When a contact zone is detected, only $\sigma_{r\theta}$ reaches a singular value, the crack working in a pure shear mode. The singular character of the contact pressure along the contact zone at the crack tip does not play any role in the fracture procedure.

The values of the energy release rate will be normalized by means of:

$$\overline{G}(\theta_d) = G(\theta_d, \sigma_o) \frac{G^m}{a\,\sigma_o^2} \tag{2}$$

where G^m is the shear modulus of the matrix.

RESULTS AND DISCUSSION

The results have been obtained for a graphite-epoxy system having the following properties:
ν^f = Poisson coefficient of the fibre = 0.22
ν^m = Poisson coefficient of the matrix= 0.33
G^f = Shear modulus of the fibre = 29 10^9 Pa
G^m = Shear modulus of the matrix = 1.05 10^9 Pa
a = radius of the fibre = 8.5 10^{-6} m.

Figure 3, as a preliminary result, shows the evolution of the normalized energy release rate as a function of the initial debonding for the two simple situations of having a remote tension, or compression, oriented perpendicularly to the defect (when it is small). The smallest defect modeled is sixty degrees, thirty degrees in the symmetric part solved. The results shown in Figure 3 correspond, when a contact zone is detected, to the frictionless case.

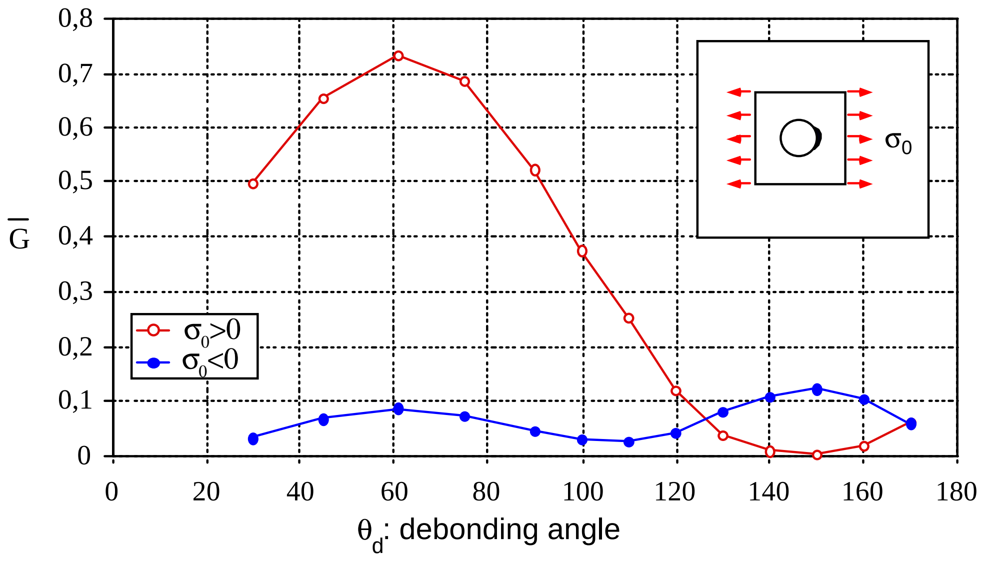

Figure 3: Normalized energy release rate versus the debonding angle for uniaxial load.

With reference to the tension case represented in Figure 3, it can be observed that it has a maximum at around 60 degrees (in the symmetric part solved) when a contact zone of macromechanical meaning appears. The generation of this contact zone is motivated by the change in the relative orientation of the crack tip with respect to the load when the length of the crack is being increased, París et al [7]. The form of the curve for this case suggests an unstable crack growth up to the angle of maximum value of the energy release rate, followed by stable crack growth for greater angles. Considering the area under the curve as an indication of the energy of the system which can be released, it is clear that the major part is associated to values of the debonding smaller than 90 degrees. In an actual composite, in accordance with the experimental evidence, a link of the crack with other cracks of other surrounding fibres is expected for values smaller than 90 degrees. Thus, a mechanism of greater release of energy (kinking) than the growth along the interface could take place.

With reference now to the compression case represented in Figure 3, the differences in the shape of the curve with respect to the tension case are apparent. The explanation for this comes from the interaction between the two modes of failure. Mode I is only significant in the neighbourhood of 90 degrees (where it has its maximum) of debonding. Mode II presents two peaks at around 45 and 135 degrees, values of debondings which have associated orientations of the crack tip that correspond to orientations at which the nominal values of the shear stress in a body under uniaxial compression reach a maximum. The addition of the contribution of modes I and II thus gives rise to the shape of the curve observed in Figure 2. To reach the second period of unstable crack growth will obviously depend on the appearance of a different mode of failure basically involving the matrix, as was previously mentioned. In any case, the lower level of values of G for the case of compression in relation to the case of tension is significant.

Once the model has been checked and the results understood, the biaxial cases of load, of interest in this paper, can be studied. The load applied in horizontal direction, perpendicular to the original small cracks and perpendicular to the assumed macro plane of failure, is always going to be assumed in compression. In the transversal direction, tension (Figure 4) and compression (Figure 5) are going to be applied respectively.

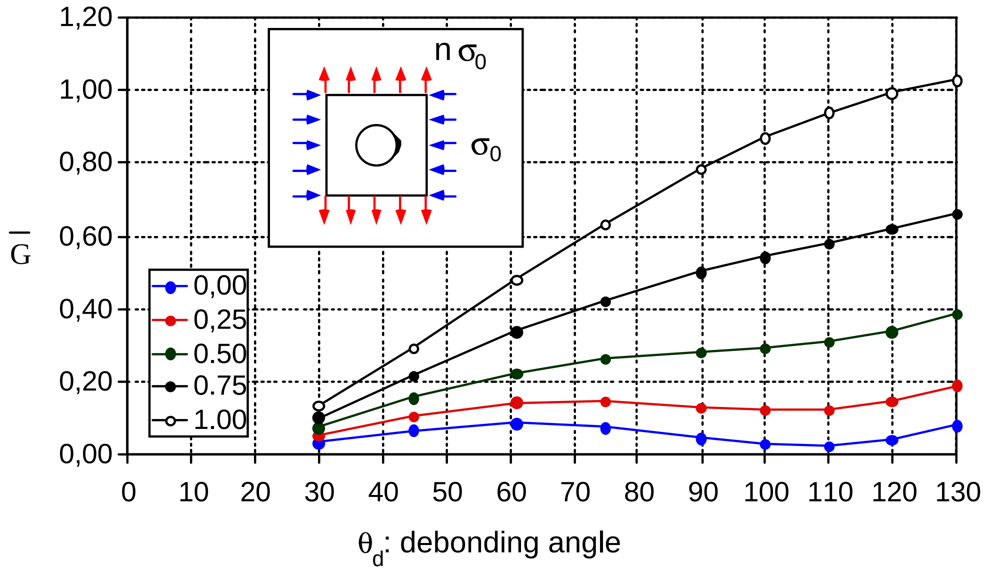

Figure 4: Normalized energy release rate versus the debonding angle for compression-tension.

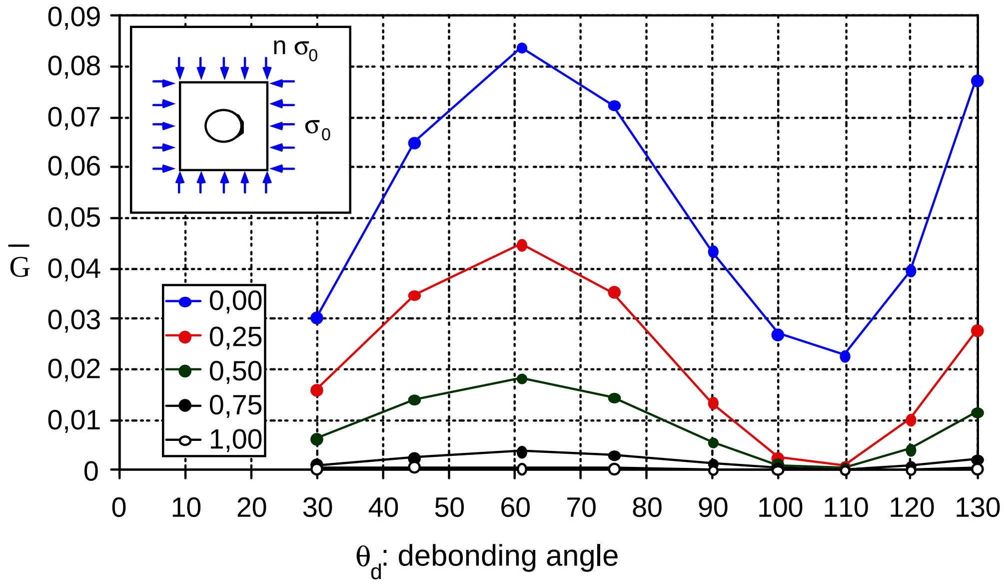

Figure 5: Normalized energy release rate versus the debonding angle for compression-compression.

The objective of this paper is clearly reached by an inspection of Figures 4 and 5. The aim is to elucidate the role of macro components of the nominal stress state in the failure in compression of a plane parallel to the fibres of composite. The plane of failure is, in the model developed, assumed to be the vertical plane. The assumption of quadratic interaction of the components of the stress vector for the failure of the plane (e.g.: Hashin and Rotem [1]) would have led, in accordance with Figures 1 and 2 to the expression:

$$\left(\frac{\sigma_2}{Y_C}\right)^2 + \left(\frac{\sigma_{23}}{S_T}\right)^2 = 1 \qquad (3)$$

where:

σ_2 is the nominal stress in the lamina in the direction transversal to the fibres and transversal to the assumed plane of failure.

σ_{23} is the nominal shear stress in the plane of the lamina.

Y_C is the strength in the direction transversal to the fibres in compression.

S_T is the transversal shear strength.

In the problem analyzed the shear stress σ_{23} has been omitted for simplicity, due to the fact that the sole interest of this analysis is to elucidate the role of out of plane stresses in the failure. Figures 4 and 5 clearly illustrate the important role of stress σ_3 (taken as $n\sigma_o$ in Figure 2, σ_o being the nominal stress in direction 2) in the energy release rate and consenquently in the prediction of failure in compression in the composite. Going to extreme situations, the curves illustrate the difference, maintaining a nominal stress $\sigma_2=\sigma_o$ perpendicularly to the assumed plane of failure, between applying a tension or a compression of absolute value σ_o parallel to the plane of failure. Whereas in the first case, $\sigma_3 = \sigma_o$ (n=1 in Figure 4), the value of the energy release rate increases enormously, in the second case, $\sigma_3 =- \sigma_o$ (n=1 in Figure 5), there is almost no liberation of energy, the apparent strength of the material thus increasing significantly. This fact had been noticed via experiments and was incorporated by Hashin [2] in his second failure criterion proposal.

Some factors that might affect the conclusions obtained are now going to be studied. The first is the size of the cell. The former study has been carried out assuming an isolated fibre in a matrix, whereas in an actual composite the matrix is surrounded by fibres. A first approximation to the actual situation is to reduce the size of the cell. Figures 6 and 7 represent the values of the normalized energy release rate for a length of the side of the cell of only 2.5a, for the cases compression-tension and compression-compression respectively.

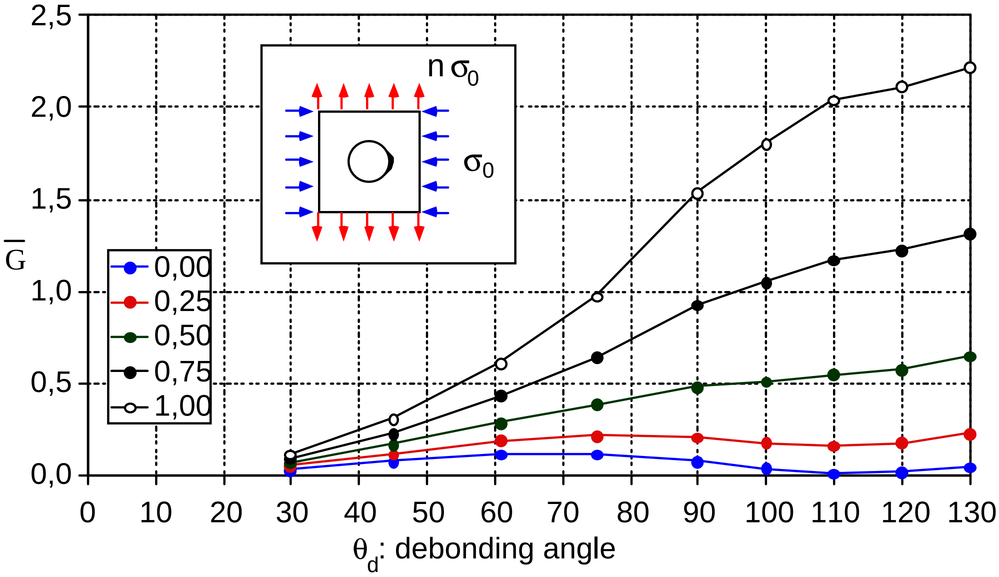

Figure 6: Normalized energy release rate versus the debonding angle for compression-tension. Effect of the cell size.

Independently of the variations noticed in the values of the normalized energy release rate with respect to the case of infinite cell, it is clearly observed that although the numerical values have changed, the tendency with respect to the factor under consideration, the influence of σ_3, in the energy release rate (i.e.: in the failure of the material) is of the same nature as in the case of infinite cell previously studied.

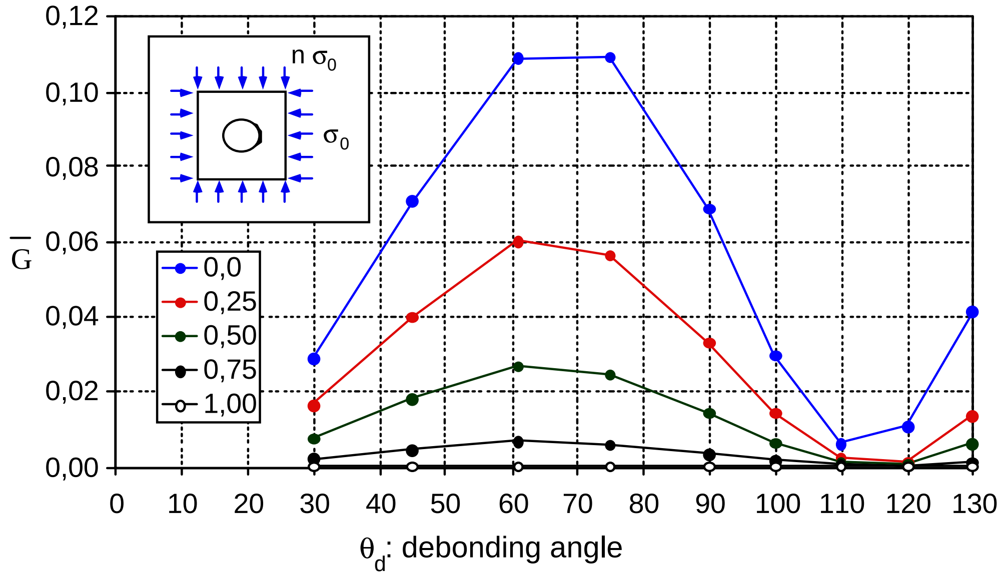

Figure 7: Normalized energy release rate versus the debonding angle for compression-compression. Effect of the cell size.

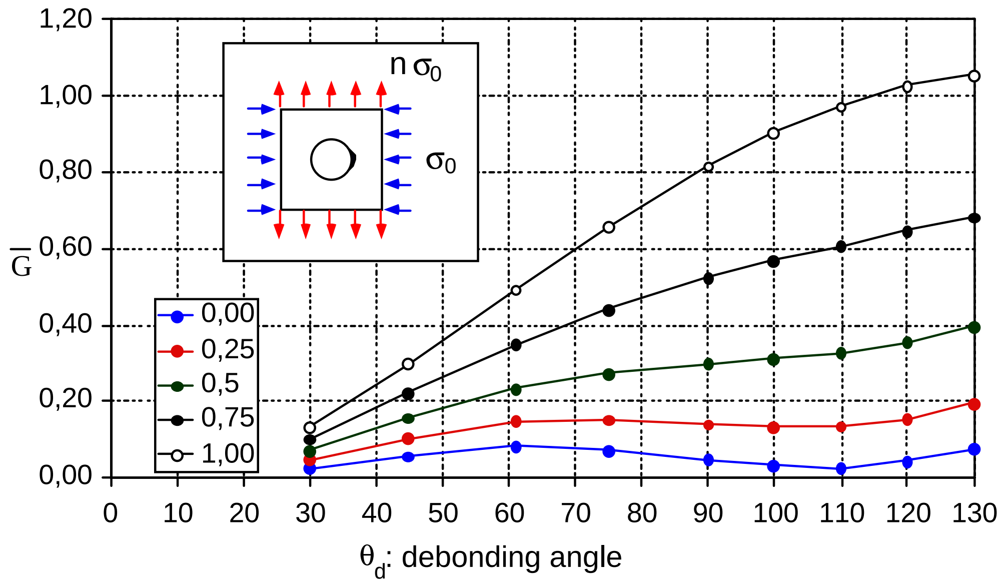

Figure 8: Normalized energy release rate versus the debonding angle for compression-tension. Effect of the friction, μ=0.1.

Another hypothesis that can be revised is the frictionless character of the contact between the fibre and the matrix in the debonded zone. The calculations have been repeated for a value of the friction coeffient of μ=0.1.

It can again be observed that the values change but the tendency is unaltered: σ_3 plays an important role in the failure of the material at a plane parallel to direction 3.

CONCLUSIONS

The numerical study carried out has proved that it is not correct to assume that the failure of a composite in compression at a plane is governed only by the components of the stress vector associated to this plane. It has been shown, by means of a micromechanical analysis, that the stress parallel to the assumed plane of failure plays an important role, in any case discardable, in the energy release rate of a crack running between the fibre and the matrix, which has been considered the actual mechanism of failure of a fibrous composite by compression of the matrix.

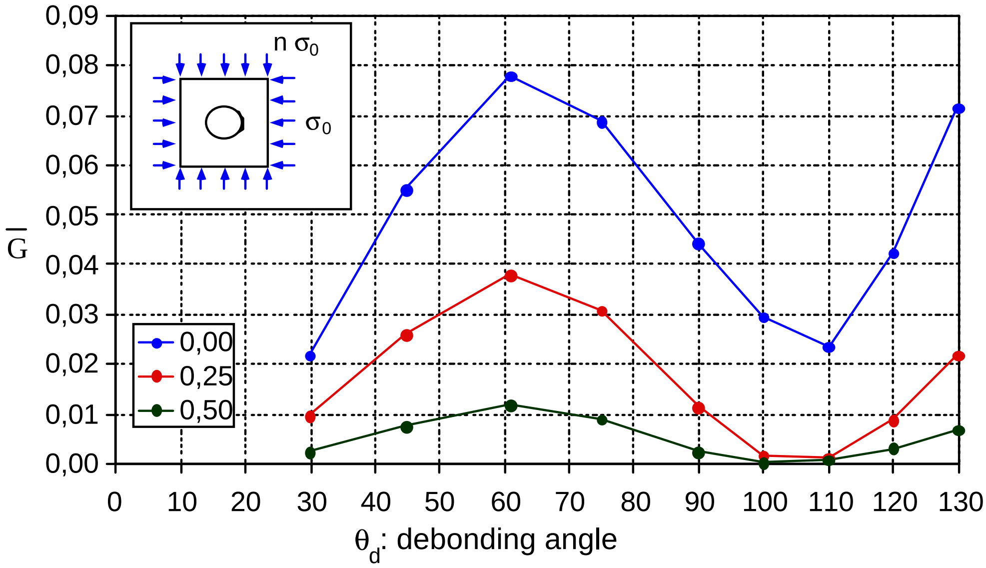

Figure 9: Normalized energy release rate versus the debonding angle for compression-compression. Effect of the friction, μ=0.1.

The results obtained give a physical explanation of the well known fact that the strength of a composite in compression transversal to the fibres increases significantly when there is an iso compression in the plane perpendicular to the fibres.

What again can be learnt from this study is that when considering a certain material as homogeneous, which is a common hypothesis for many studies of materials as continuum bodies, one can not forget, proposing failure criteria, the internal structure of the material. Thus, a hypothesis such as the one discussed here (the failure at a plane is only governed by the components of the stress vector associated to this plane), can be acceptable for certain materials but not for materials having the internal structure of fibrous composites

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