CRITERIA FOR MATRIX FAILURE IN CONTINUOUS FRP-COMPOSITES - A LITERATURE STUDY. PART II: DELAMINATION

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ABSTRACT

Some examinations and criteria of the interior delamination (interlaminar cracking) are reviewed. Also, aspects related to the experimental determination of fracture mechanics parameters are discussed. A critical survey of these criteria showed that due to heterogenity of composite material, statistical variability of the mechanical properties and environmental effects, gross simplifications in the crack growth characterization of these materials must be made. In order to improve the understanding of the matrix failure, the physical basis of the phenomenon concerning the constrained cracking behaviour should be strengthened, at least, by the knowledge of the residual stresses in the microstructure and the initial crack size in the application of the fracture mechanics theory.

INTRODUCTION

The use of composites in load bearing structures is primarily motivated by the low weigth-to-stiffness and weigth-to-strength ratios. In the design phase the stiffness characteristics of a composite can be determined fairly accurately by rigorous micromechanical methods. However, despite the extensive research work on the field of composite materials, a comprehensive failure criterion for the composites has not yet been introduced. There are serious doubts that a general failure criterion could actually be achieved.

The matrix failure has received considerable attention in literature. Several micromechanical models that consider the initiation of matrix failure and/or the stiffness loss due to damage are established. As a contribution to this field, we reviewed in the first part of this paper some of the most important papers of the initiation of matrix cracking failure in order to give the reader guidelines for further study (Isometsä, Lahtinen (1995)). There we also compared some failure criteria for matrix cracking to analyse the unidirectional tensile test of cross-ply laminates. In this part of our paper we first review some examinations and criteria of the interior delamination (interlaminar cracking). After this we discuss aspects related to the experimental determination of fracture mechanics parameters.

DELAMINATION FAILURE OF FIBER REINFORCED COMPOSITES

There are four primary failure modes in FRP (Fiber Reinforced Plastics) composites. These modes are matrix cracking, fiber/matrix debonding, fiber breaking, and delamination. The initiation of damage is dominated by the matrix cracking in the off-axis plies. These cracks run parallel to fiber directions and are usually spanning the width of the specimen (Flaggs and Kural (1982), Wang (1984)). Subsequent damage consists of delamination initiated from these secondary cracks and leads to highly localized damage with fiber failures and finally to fracture (Talreja (1987)).

One important phenomenon associated to matrix cracking is that the crack initiation strain depends on ply thickness (Parvizi et al. (1978), Flaggs and Kural (1982)). This phenomenon is known as constrained cracking. Flaggs (1985) found that the crack initiation strain for $[0_2/90]_s$ graphite/epoxy laminate was 2.48 times that would have been expected from a unidirectional transverse tensile test. This led the researchers to conclude that the laminate strength is not a lamina property, and that the matrix cracking is governed by fracture mechanics criteria.

The matrix cracking is one of the reasons why the delamination is usually occuring between the layers of different fiber angle. However, the matrix cracks are not the only source of delamination. In common, delamination is caused by interlaminar stresses, which are, for example, due to mismatch in engineering properties, discontinuities in structure, and high deformation gradients (Garg (1988)). The mismatch in engineering properties involves changes in Poisson's ratio and in elastic and shear moduli from one layer to another. Examples of discontinuities in structures are free edges, holes, ply termination, joints, and layers with different fiber angle. In addition, impact loading causes typically high deformation gradients and high through the thickness stresses under the contact area.

The constrained cracking phenomenon is also observed in the delamination of laminates. Brewer and Lagace (1988) investigated laminates analytically and experimentally. In the figure 1 the initiation stresses of the delamination for $[\pm 15_n/0_n]$-laminate is presented as a function of ply thickness. The figure suggests that the interlaminar strength may also depend on lamination configuration. In this case, it is possible that the initiation of the delamination is connected to the initiation of matrix cracking, which is delayed when the ply thickness is small. However, a similar behaviour is observed with laminates subjected to impact loading (e.g., Choi, Downs, Chang (1991)), where the number of matrix cracks occuring with delamination vary a lot, and where the delamination does not necessarily initiate from the tips of matrix cracks.

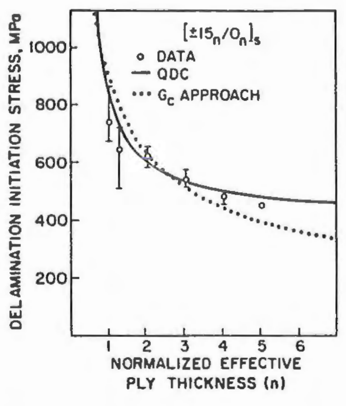

Figure 1. The initiation stress of the delamination for $[\pm 15_n/0_n]_s$-laminates (Brewer and Lagace (1988)).

FAILURE CRITERIA FOR DELAMINATION

Like the matrix cracking also delamination can be predicted by criteria that are based on the strength of materials approach or on the fracture mechanics approach. A stress criterion is easy to apply, especially, in the absence of an initial failure. In the fracture mechanics approach the actual problem is the prediction of the initial failure.

The delamination prediction requires that the stresses normal to the plane of the laminate are known. That is why, both approaches must be preceded by a precise stress analysis, where also interlaminar stresses are determined. In the literature there are some very special types of failure criteria involved with the delamination, which contain a large number of formerly unknown parameters that are artificially connected to physical quantities. These criteria are often used with examinations, which contain inaccurate stress analysis, and they try to compensate the shortages of the analysis with parameters that fit the predictions to the experimental tests. However, the use of the fitting parameters solve the problem only apparently and leave the real problem without explanation. That is why, these criteria are not reviewed here.

As in the matrix cracking, the strength of a laminate against delamination seems to be a function of the geometry and the material properties. However, the influence of the layer thicknesses on the initiation of delamination is still unknown.

Failure criteria based on linear fracture mechanics

The fracture mechanics theory is simply an energy criterion enclosed by a theory of the stress field around a crack tip, which helps the understanding of the material behaviour in the presence of a crack. The utilization of fracture mechanics needs always a good stress analysis, and the crack growth depends on the stress level in its surrounding and on the inherent ability of the material to withstand the load.

The formation of matrix cracks is often considered as a sudden event because of the lack of experimental crack propagation data, whereas the delamination is clearly progressive in nature. Usually, a criterion for the initiation of a delamination crack is used. However, as the crack has begun to propagate, the resistance of the material against crack growth is different compared with the initiation event. Therefore, the fracture toughness or the strain energy release rate values for all the fracture modes in the initiation (K_{init}, G_{init}), in the steady state propagation ($K_{s/s\ prop}$, $G_{s/s\ prop}$), and in the arrest (K_{arr}, G_{arr}) of the crack are needed in order to be able to predict the final condition of the structure.

The fracture criterion itself for a single fracture mode is not a problem in the fracture mechanics approach. The definition of the failure can be carried out simply by comparing calculated and measured fracture toughness or strain energy release rate values with each other. The actual problem in this approach has been in the difficulty to find the computational values for fracture parameters. In the literature the strain energy release rate has usually been calculated by the finite element method. However, it is not self-evident that the obtained results are satisfactory. Problems arise from the nonhomogenity of the material. It is very difficult to take into account the influence of the fibre-matrix interaction in computational models. In addition, the material has very often resin- and fibre-rich regions which can act as stress raisers. In the delamination, the fibre orientation and the presence of two dissimilar anisotropic materials around the crack also increase the complexity of the solutions.

Solution for an interface crack

An interface crack problem contains a delamination crack between two dissimilar material layers. Williams (1959) was the first one to study the problem where the two dissimilar materials have isotropic material properties. He demonstrated that the stresses around the crack possess singularities of the types $r^{-1/2 \pm i\gamma}$, where r is the radial distance from the crack tip and γ is a bimaterial constant. Due to the presence of this kind of singularities, the stresses exhibit violent oscillation in the immediate vicinity of the crack tip as long as the materials are different. Later, it was shown that the oscillatory behaviour of the stresses is also present for anisotropic interface cracks.

Due to the oscillation of the stresses, different fracture modes are coupled together. That is why, the delamination crack always induces opening, shearing, and tearing mode fracture simultaneously for a single mode loading. The interface crack between two isotropic or anisotropic materials have been an intense subject of research. Earlier, it was found (Rice (1988), Wu (1990)) that due to the oscillatory behaviour the strain energy release rates of the different fracture modes may not exist, although, the total strain energy release rate is well defined.

Hwu and Hu (1992) were the first ones to solve the delamination crack problem explicitly. They also managed to separate the total strain energy release rate into three different modes. The result is unified for isotropic, orthotropic, and anisotropic bimaterials, and it is consistent with the classical definition for a crack in homogeneous media. In addition, a simple quadratic relation is obtained between the separate strain energy release rates and the stress intensity factors, and the relation is further reduced for orthotropic bimaterials.

Hwu and Hu found that as $\Delta a/a$ approaches zero, G_I , G_{II} and G_{III} exhibit oscillatory behaviour and have no converged solution. However, there exists a range of $\Delta a/a$ ($10^{-5} < \Delta a/a < 10^{-1}$) where G_I , G_{II} and G_{III} remain relatively constant. That is, if a finite crack extension Δa is chosen from this region for the calculation of the strain energy release rates, unambiguous values for G_i can be obtained.

They also showed that the stress intensity factors depend on the ply orientation of upper and lower plies and that the opening, shearing, and tearing modes are coupled together. However, the coupling was noticed to be insignificant between the different modes, and it remains always under 5% of the main fracture mode. Hence, the classical stress intensity factor is still dominating the mixed mode condition induced by the interface.

Solution for delamination crack originating from transverse cracking

Kim et al. (1991) have considered the problem of delamination crack that is originating from transverse cracking in cross-ply composite laminates under extensional load. In their paper two types of cross-ply laminates are considered, namely, [0/90/0]- and [90/0/90]-laminates. In the beginning of their study it is assumed that numerous transverse cracks will occur in the 90°-ply with an approximately uniform spacing along the length of the laminate. As the extensional load further increases the matrix cracks develop into delamination cracks along the interface of 0°- and 90°-plies.

In the calculations the transverse cracks are uniformly arranged and a model containing a representative unit cell (fig. 2) is solved under the assumption of plane strain elasticity. Based upon Stroh formalism for anisotropic elastic materials and upon the method of eigenfunction expansion, the stress distribution of the unit cell is examined. The structure of the solution, in the form of a series expansion, is determined from the eigenvalue equation resulting from appropriate near-field conditions. To complete the solution, use is made of a boundary collocation technigue in conjunction with the eigenfunction series that includes a large number of terms, enough to represent the elastic state throughout the appropriate domain concerned.

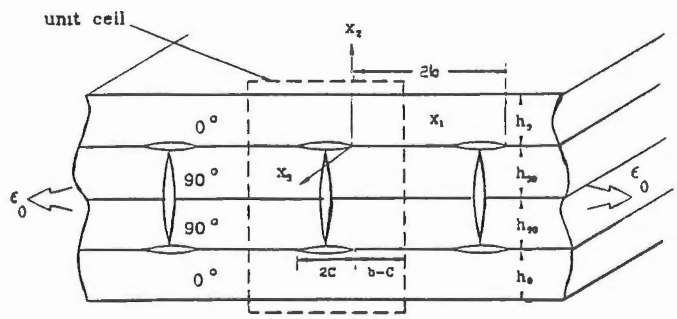

Figure 2. Delamination cracks originating from transverse cracking (Kim, Kim, Im (1991)).

As mentioned the solution is completed with a numerical method. The accuracy of the solution is confirmed through a comparison with another numerical method, namely, the finite element method. In this case a special hybric crack element is needed, because the crack is propagating along the interface of two different materials. The results of the two numerical methods for the stress intensity factors K_I and K_{II} agree very well, the relative difference is less than 2%.

In their paper Kim et al. present typical stress distributions for the structures involved. According to the results for the cracks in the 90°-ply of $[0/90]_s$-laminate the normal stress of the crack tip is compressive, and the shear mode is responsible for delamination growth. It is also noticed for the cracks in the 90°-ply of $[90/0]_s$-laminate that the interlaminar shear stress component is greater than the tensile normal stress component. That is why, the modes I and II are coupled for an opened delamination crack.

As a function of the length of delamination the strain energy release rate curve first increases quite strongly and after the maximum it decreases gradually. Therefore, after the critical G_c is exceeded, the delamination will grow in unstable manner. The crack grows under a fixed loading until the strain energy release rate decreases to the arrest toughness G_a. Thus, there exists an inherently built-in crack arrest mechanism for the present delamination cracks. The critical crack length is dependent on the relative crack spacing as well as on the relative ply thickness of the 90°-ply. As the thickness of the 90°-ply increases relative to the 0°-ply, the strain energy release rate notably increases, and, therefore, the crack growth after the onset of the delamination crack will be more unstable.

Mixed mode criterion

As it was previously mentioned, the edge delamination is not concerned here. That permit us to exclude the tearing mode, which has only a small effect on the local delamination. Of course, the tearing mode exists due to the coupling of the modes when the crack is located between two dissimilar materials. However, it is assumed that the coupling is insignificant

(Hwu and Hu (1992)). That leaves us two different modes, and, therefore, the fracture may be an opening, shearing, or mixed mode fracture.

The mixed mode delamination growth is not observed to follow a single propagation law. That is why, various fracture criteria have been suggested. Very often a total strain energy release rate $G_T = G_I + G_{II}$ has been used, and the fracture occurs when G_T reaches a critical value G_c. This criterion is very simple, but it is suitable only if the values of the critical strain energy release rates for the modes I and II are nearly equal to each other. This holds, for example, for some tough epoxy resins where the G_T was found to dominate the fracture (Johnson and Mangalgiri (1987)). However, most of the graphite/epoxy composites have $G_{IC} << G_{IIC}$, and, hence, the fracture is dominated by the opening mode.

A more appropriate delamination growth criterion is

$$\left(\frac{G_I}{G_{IC}}\right)^m + \left(\frac{G_{II}}{G_{IIC}}\right)^n = 1 \quad , \tag{1}$$

where the exponents m and n have different values for different materials (Garg (1988)). For example, values like m = n = 1, m = n = 2, and m = 3/2, n = 1 have been suggested. A criterion suggested by Hashemi et al. (1990) has the form

$$\left(\frac{G_I}{G_{Ic}}-1\right)\left(\frac{G_{II}}{G_{IIc}}-1\right) - I_i\left(\frac{G_I}{G_{Ic}}\right)\left(\frac{G_{II}}{G_{IIc}}\right) = 0 \quad , \tag{2}$$

where I_i is an interaction parameter. For $I_i = 0$ the two modes are completely independent of each other, while for $I_i = 1$ the expression reduces to the equation (1) with m = n = 1. The strength of the interaction can be varied changing the value of I_i between zero and one.

In the literature there exists many suggestions for mixed mode criterion. However, the criteria presented above are the most commonly used. Although, these expressions are useful in curve-fitting with the experimental data, they have a lack of physical basis.

Variational approach

As discussed earlier Hashin analysed a cracked cross-ply laminate by a variational approach. This analysis was extended by Nairn et al. who used the same approach for delamination growth induced by matrix cracks (Nairn and Hu (1992)). In his study the existing microcrack span the cross section of the 90°-plies and then expands to a delamination crack between dissimilar laminae. The model is for $[(S)/90_n]_s$-laminate, where (S) is any orthotropic sublaminate. The problem is similar to the one solved by Kim et al. (1991), while the unit cell used in the model is the structure between two transverse cracks (fig. 2). The loading of the laminate is a uniform and uniaxial tension in the direction transverse to fibers of 90_n-ply.

The solution has again only one assumption, and it concerns the stresses. Namely, the tensile stresses are independent on thickness direction. This assumption actually removes the stress concentration from the crack tip, and, in that way, the solution loses information. However, the assumption makes it possible to find a simple and admissible stress state that satisfies all boundary conditions.

The admissible stress state provides an approximation for the total strain energy, which is used to calculate the strain energy release rate for self-similar, through-the-width delamination growth of the representative element. Also, the effect of thermal expansion is taken into account in calculation of the strain energy release rate.

The final equations of the strain energy release rates for the delamination and the matrix cracking are very similar compared with each other. Once a microcrack has been formed, the question is whether the next damage mode will be another microcrack or delamination induced by the existing microcrack. Nairn and Hu (1992) sought the answer by examining the strain energy released by the damage modes. They assumed that the critical strain energy release rates for the microcracking and the delamination are equivalent. According to their results the microcracking is the preferred mode of failure. However, there exists a critical crack density after which the delamination will begin depending on the material and on the geometrical properties of the laminate. Once the delaminations initiate, the microcracking will cease and the delamination will continue to grow.

Failure criteria based on strength of materials

The strength based failure criteria are quite seldom used in delamination analysis. This is mainly due to required knowledge of the through-the-thickness stresses. Wu and Springer (1988) have tested a few quadratic point failure criteria, for example, Tsai-Wu and Hoffman criteria, and the results show that these criteria are not very suitable for the prediction of the delamination. All two dimensional versions of these criteria were unsatisfactory, and only the three dimensional Tsai-Wu criterion succeeded reasonably. The results clearly point out the importance of the determination of the through-the-thickness stresses in the analysis of the delamination. In spite of the results, the 3D Tsai-Wu criterion is not commonly used because of the difficulties arising from the required biaxial experimental tests.

Garg (1988) considered that strength based criteria predict the failure initiation well, if the failure is caused and dominated by the through-the-thickness normal stress component. The most common strength based failure criterion used in the literature (e.g. Jen et al. (1993)) is the criterion

$$\left(\frac{\sigma_{33}}{Z_i}\right)^2 + \left(\frac{\sigma_{13}}{S_i}\right)^2 + \left(\frac{\sigma_{23}}{S_i}\right)^2 = 1 \quad . \tag{3}$$

In this criterion only the interlaminar stresses are taken into account. Here, the normal stress component contains tensile stress, but in some versions of this criterion also the possible normal compressive stress is included. The criterion is suitable for the prediction of the initial failure, and it has been perceived accurate when Z_i and S_i are the in situ strengths of the laminate. It is clear that the influence of the layer thickness cannot be explained by this criterion.

In the failure propagation the strength approach is unsatisfactory because of the stress singularity developing into the crack tip. A similar situation will occur in the edge delamination. Due to the ambiguous stresses at the crack tip, average stress components are commonly calculated and used in the strength criterion (eqn 3). The average stresses are

$$\sigma_{ij} = \frac{1}{x_{avg}} \int_0^{x_{avg}} \sigma_{ij} \, dx \quad , \tag{4}$$

where x is a distance from some reference point and x_{avg} an averaging dimension, which must be determined experimentally. The accuracy reached by using the average stresses in the strength criterion is good, but x_{avg} is again a new parameter that must be fitted to the experimental data.

EXPERIMENTAL METHODS FOR STRAIN ENERGY RELEASE RATE

In order to use a fracture criterion based on the strain energy release rate method, it is necessary to measure the crack opening resistance, which is characteristic to the material and structure. The resistance for both the matrix cracking and the delamination cracking is measured in the same way, although the formation of the cracks might be different. In the composite laminates the formation of the cracks is often a mixed mode and non-self-similar fracture process. Usually, both the tension and the shear stresses are present. At the delamination front the interlaminar tensile stresses give rise to a mode I component, and the interlaminar shear stresses give rise to a mode II component. To characterize the laminates, it is necessary to devise testing methods to produce the various modes and, hence, determine G_{IC} and G_{IIC}, but also G_{IC}/G_{IIC} under the mixed mode loading.

Various testing methods for the different fracture modes have been developed. The double cantilever beam testing method (DCB, fig. 3) for the mode I is a widely accepted method (Garg (1988)). The mode II has two alternatives. The first one is the end notched flexure method (ENF, fig. 3) (Garg (1988)), which has the same specimen as the DCB but it is loaded as in three point flexure test. The second one is called the end loaded split test (ELS, fig. 3) (Hashemi et al. (1990)). The ELS-specimen is again similar to DCB-specimen, but it is clamped at one end and loaded as a cantilever beam by a point load at the other end of the specimen pressing the crack faces against each other. The ELS specimen can also be used for mixed-mode testing. Then, the loading direction is opposite compared to the pure mode II testing.

In order to find the value for the strain energy release rate of the tested specimen, it is necessary to know the value of the load, the specimen opening, and the crack length during the crack growth. If the crack initiation is an unstable phenomenon, the data collection can present problems. Therefore, it is reasonable to reduce the data needed by using the help of simple beam theory. However, the strain energy release rate equations for different testing methods, which are derived by the beam theory, suffer from simplifications and, hence, some corrections should be made. In the DCB test the influence of large displacements and the stiffening of the beam due to presence of end supports are usually corrected by simple factors (Hashemi et al. (1990)). In addition, the response of the DCB specimen may be corrected by other factors that depend on the material properties and on the geometry used in the tests (Keary et al. (1985)).

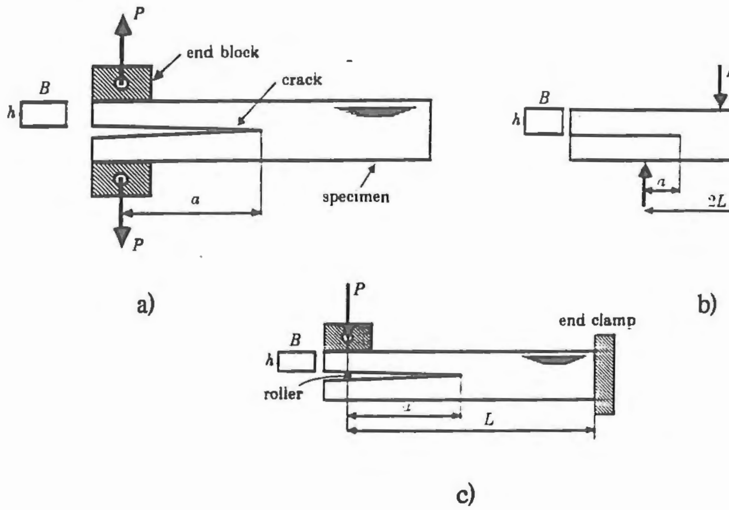

Figure 3. Testing specimens used for determination of strain energy release rates. a) Double cantilever beam method (DCB), b) end notched flexure method (ENF), and end loaded split method (ELS).

The corrections needed with the ENF tests are caused by interlaminar shear deformation and friction between the crack surfaces (Carlsson et al. (1986)). However, the ENF specimen is only a little affected by large displacements, end rotation, and end block effects, which need to be corrected in the ELS tests (Hashemi et al. (1990)). The friction effects are eliminated in the ELS specimen by a small diameter roller.

In spite of the efforts addressed to improve the accuracy and the consistency of the results, very large experimental scatter do exist for the values of the critical strain energy release rates in the literature. For example, the reported mean values of G_{IC} for T300/5208 composite vary between 80 and 100 J/m^2 (Garg (1988), Jones et al. (1988)), which is actually quite a good result. The situation with the measurements of the mode II is much worse. For the graphite epoxy composite just mentioned the ENF test results vary from 600 to 1150 J/m^2.

The reasons for the scattering of the experimental results are not precisely known. However, some partial explanations can be named. For example, interpreting the values of the G_{IC} from DCB specimens, attention should be given to the surface morphology of the delamination area, since extensive fibre bridging and intraply cracking can influence the value of the strain energy release rate obtained. In that case, a higher value for G_{IC} would be obtained than in a test where the delamination was entirely confined within the matrix-rich region and the plane of initial delamination. Further, different processes in manufacture produce varying material properties and initial defects in the specimens. In addition, one part of the variation of the results is the very ordinary scatter of the parameters that belong to the experimental methods in common. As a result, the stresses to initiate and propagate the delamination cracks, and also the matrix cracks, for the same material and the same layup configuration can be quite different from one laboratory to another.

As noticed, one problem connected to the experimental tests of the strain energy release rate is the accuracy reached. However, there is another problem which might be even more severe. Namely, the consistency between measured and predicted values. We have already learned that the formation of matrix transverse cracks of the brittle materials is a sudden event. Also, no initial flaws have been observed. It is believed that a very low stress level causes a lot of fiber debondings and other microflaws in the material, and the matrix crack will form when the microflaws combine as the load further increases. In this light, it is questionable to compare the measured strain energy realease rates with the predicted ones in the matrix cracking, when the formation of the cracks differs so much from each other. Furthermore, it has been noticed that in the tests the crack growth does not necessarily follow the initial plane of the crack, which causes changes to the values of the measured data. This should indicate that the material resistance for the crack growth is different when the propagation takes place through a resin-rich layer in one plane or through fiber-matrix interfaces in a zigzag-manner, as it is with the matrix cracking. In fact, Lucas (1992) showed that the fracture toughness increased nearly by a factor of 2 as the angle between the crack direction and the fiber orientation varied from 0° to 90°. The reason for the difference of measured values was the bifurcation, deflection, and twisting of the crack tip when the propagation direction was transverse to the fiber direction.

In the delamination cracking the influence of fiber orientation and crack propagation angle should also be taken into account. This can be proved simply by impact tests, in which delamination shape between layers is affected by fiber angles of adjacent layers and is very often named peanut shape. In addition, in the experimental tests it is meant to avoid the intraply cracking, because it again changes the values of the strain energy release rate. This is very acceptable guideline. However, when a laminate is, for example, tension loaded, there will always appear a great number of intraply cracks before the delamination begins to form from the crack tips. Again, there is an inconsistency between the measured and the predicted strain energy release rates. Therefore, caution should be exercised in applying the energy criterion to predict the behaviour of propagating cracks in real composite structures.

DISCUSSION

The composites are heterogeneous and they exhibit complex modes of failure, which cause that the ideas borrowed from classical fracture mechanics, developed mostly for the metals, does not necessary hold for composites. The key assumption in the LEFM is that there exists three independent values of G_{ic} (i = I,II,III), which are material properties. According to the theory these values have to be geometrically invariant quantities, and the crack has to grow in a self-similar manner (Sierakowski and Chaturvedi (1986)). This means that the measured critical values for strain energy release rate should correlate to structures of different shapes and sizes. Also, the crack should retain its shape and propagation direction as the load increases. However, many experiments have shown that both the invariance and the selfsimilarity requirements do not hold well for the composite materials. Sierakowski and Chaturvedi (1986) concluded that the linear fracture mechanics cannot be accepted in general for fiber reinforced composites.

In matrix cracking the constraint effect is obvious (Isometsä, Lahtinen (1995)), but when the crack plane is turned in its position (i.e. in the 90°-ply) parallel to the plane of laminate (i.e. a matrix crack becomes a delamination crack) the constraint effect suddenly seems to disappear. If the transverse tensile strength of a unidirectional laminate is inaccurate in cross-ply laminates for matrix cracking, could it be accurate for delamination? In the delamination problems the attention is mostly concentrated on the mixed mode criterion and on the finite element modelling, while the possible variation of the stress or the strength is forgotten.

The delamination criteria suffer from the same problems as the criteria for the matrix cracking. Namely, the structure and the loading used in the analysis are very simple. In spite of the simplicity of the models, the mathematical expressions tend to become very complex, which particularly reduces the applicability of the criteria. The accuracy of the criteria is often ensured by fitting the results with the experimental results, especially when the mixed mode effects are clearly present. Here, it should be emphasized that both in the matrix cracking and in the delamination also the large scatter in the values of the measured strain energy release rates increases the uncertainty of the analysis.

Another topic that needs more attention is the magnitude of the residual stresses induced by the manufacturing process. Although we accept the use of "homogeneous" material properties in the macrostate analysis, the lack of knowledge of precise stress state in the composite might lead to erroneous results.

The residual stresses appear during the manufacturing because of the volume change of the matrix phase. During the curing process the residual stresses are solely due to the chemical reaction and not due to the temperature difference. The volume of the matrix decreases, because the formation of chemical bonds, and this volumetric shrinkage for a typical epoxy resin is about 5%. In addition, as the curing temperature is usually near 200 °C and the application temperature of composites is near the room temperature, the residual stresses caused by the temperature change are also important.

Some authors suggest that the generation of residual stresses due to curing process is exactly analogous to those generated by the temperature drop, or even that the cure residual stresses are not important. These arguments, however, have not been proven. In the beginning of the curing process the matrix is in rubbery state, and as the chemical bonds begin to occur, the hardening starts. This means that the volume shrinkage and the hardening happen simultaneously. When the matrix is partly in uncured state and partly in cured state, the chemical volume shrinkage cannot necessarily be assumed to relax completely. For example, in thick laminates there may appear too strong evolution of heat because of the exothermic cure reaction. This causes varying temperature field and, therefore, a varying speed of curing in the laminate. It may happen that fully cured layers constrain regions of the laminate, where the matrix is still in uncured state. A similar situation occurs in the micromechanical level, where the resin shrinkage is constrained by the reinforcement phase. Also, in the case of volume shrinkage caused by the temperature drop, the volume change is constrained by layers with different ply angle and the reinforcement phase. However, this time the matrix should be in fully cured state, and the possible relaxation of the residual stresses should be extremely small compared to the case of the chemical volume shrinkage.

Usually, only residual stresses due to the temperature drop have been considered in the macromechanical analysis of matrix failure. However, the understanding of the effects of the chemical shrinkage could strengthen a lot the physical basis of the problem. In this light, one basic problem in the matrix based failures is the micromechanical behaviour of the material.

There is a general acceptance that a great deal of concern should be taken to develop reliable micromechanical tools to study the failure characteristics of a composite material. However, unlike the problem of physical property definition, the concept of RVE in the failure analysis is more laborious to use. In property analysis the implication of the microfields is considered in the relations between the averages, but the same concept cannot be applied in the problem of failure analysis where the microfields in the unknown microstructure determine directly the damage evolution. However, the analysis of the matrix failure of the composites suffers so huge difficulties that every attempt to bring insight to this problem should be welcomed but also critically examined.

CONCLUSIONS

The problem of matrix failure concerning delamination has been examined. Also, aspects related to the experimental determination of the strain energy release rate have been discussed. A critical survey over the literature regarded to the delamination failure shows that the criteria reviewed suffer from the same problems as the criteria for the matrix cracking. Namely, they are applicable only to very limited types of specimen geometry, material configurations, environmental conditions, and loading types. Here, the so-called in situ strength problem have not been examined very much, but the attention is mostly directed to the mixed mode criterion. The authors feel that the analysis of matrix failure and the experimental tests crave the knowledge of the residual stresses in the microstructure and the initial crack size in the application of the fracture mechanics theory. Also, the theory of the fracture mechanic may need modifications when applied to the composites.

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