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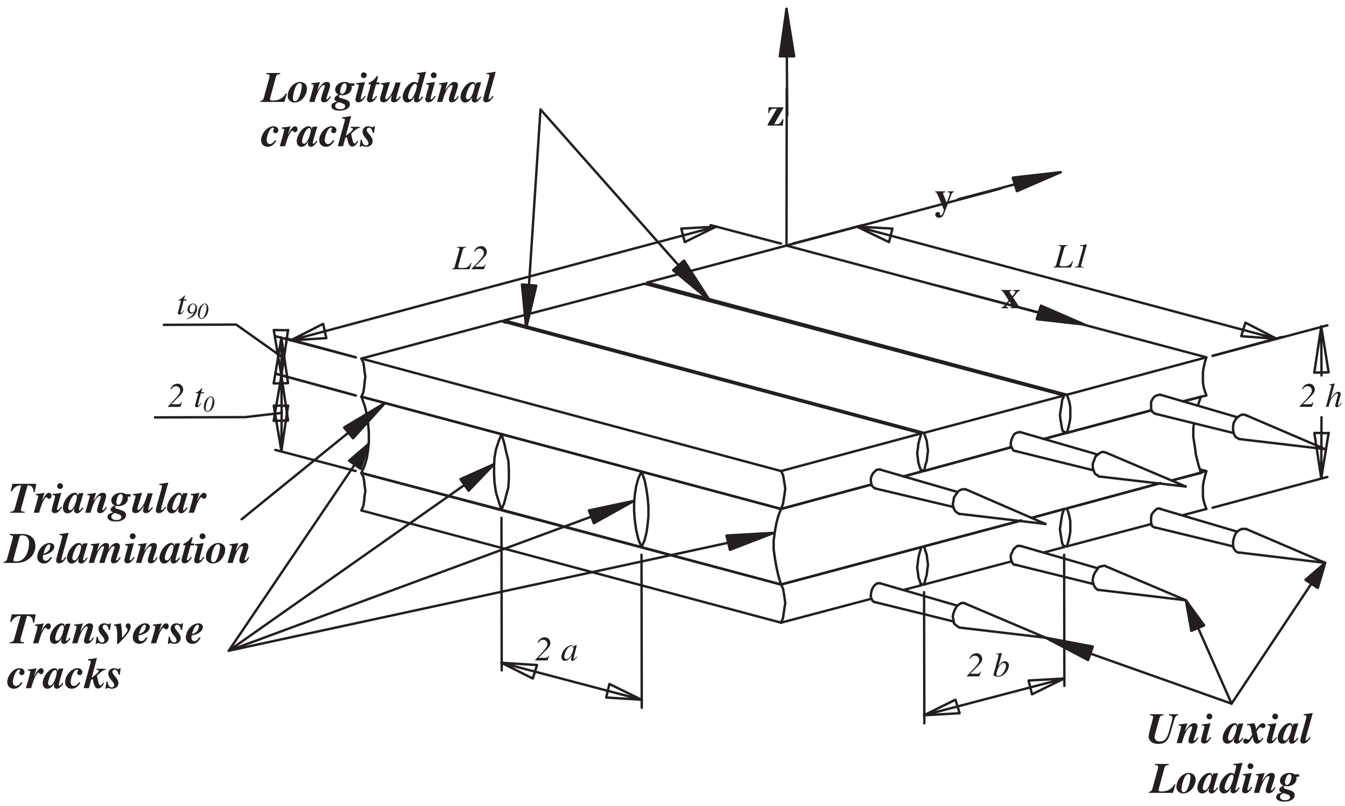

MECHANICAL ENGINEERING | RESEARCH ARTICLE

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Matrix cracking and delamination evolution in composite cross-ply laminates

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Abstract: This study followed numerous simulations of the stress field distribution in damaged composite cross-ply laminates, which were subjected to uni-axial loading. These results led us to elaborate an energy criterion. The related criterion, a linear fracture-based approach, was used to predict and describe the initiation of the different damage mechanisms. Transverse crack damage was generally the first observed damage. The second type of damage was longitudinal cracking and/or delamination. The stress field distribution in the damaged cross-ply laminates was analysed through an approach that used several hypotheses to simplify the damage state. The initiation of transverse cracking and delamination mechanisms was predicted. The proposed results concern the evolution of the strain energy release rate associated to the evolution of transverse cracking and delamination. As in several studies in the literature, to quantify the evolution of the damage mechanisms in the present approach, the laminate is supposed to be pre-damaged.

Subjects: Engineering & Technology, Science, Technology

Keywords: composite laminates, failure criterion, matrix cracking, delamination

1. Introduction

Composite materials are increasingly used in many structural components such as aerospace, aeronautics, automobile and sport, thanks to their height strength-to-weight ratio. It is, therefore, necessary to predict whether these structures will be able to resist under all applied stresses. A damage criterion was elaborated to evaluate the damage evolution in composite structures.

ABOUT THE AUTHOR

The activities of the laboratory are focused in most cases on "audible" acoustics, but in recent years, the laboratory also initiated research into new topics—in the field of vibrations and ultrasounds in materials. Studies concern the *spread of waves* in fluids (in repose or in flow) and in the solid (porous, granular or composite materials, vibrating structures) as well as on the *mechanisms of coupling*. Their objective is to understand physical phenomena by favouring the development of *analytical models* and of *experimental studies* linked to necessary *numerical simulation*. Researchers operate in one of three teams specialized on complementary themes: Materials; Transducers; and Vibrations, Guided Acoustics and Flow.

PUBLIC INTEREST STATEMENT

The objective of the present study is to understand the physical phenomenon of damage mode evolution in composite laminates. We propose the development of an *analytical model* with *numerical simulation*. Composite materials are used in many structural applications: aerospace, aeronautics, automobile, sport, etc. This is due to their height strength to weight ratio. It is, therefore, necessary to predict whether these structures will be able to resist all of the applied stresses. So, a damage criterion was developed to evaluate the damage evolution in composite structures. We can estimate the sequence of initiation of the different types of damage (transverse cracking, delamination and longitudinal cracking) that depend on the main parameters: material constituent, stacking sequence and loading history.

The proposed criterion is an energy-based approach. The choice of this type of criterion has been achieved after numerous studies of the stress field distribution in damaged laminates. In composite cross-ply laminates subjected to monotonic or fatigue tensile loading, the first observed damage is generally transverse cracking. This damage occurs in the central layer of the cross-ply laminate $[0_m, 90_n]_s$. This damage consists of matrix breaking between fibres in the plies perpendicular to the principal loading direction. For transverse cracking, we can experimentally observe two characteristic stages: the initiation of the damage called "first ply failure" and the limiting state when no more transverse crack can be initiated, named "characteristic damage state". The nature of the second damage mode depends on the following parameters: the laminate geometry, thicknesses of 0° or 90° layers, the nature of the fibre/matrix constituents, the loading history and the manufacturing cycle. The second damage mode, caused by high interlaminar stress levels at the interface of the layers, can be longitudinal cracking or delamination. Longitudinal cracking is similar to transverse cracking, but this damage causes matrix cracking between fibres in the layers parallel to the loading direction. Delamination is debonding between layers with different orientations. Composite structures damaged by incipient delamination or longitudinal cracking must be repaired. Experimentally, for example, in Wang and Crossman (1980), the initiation and growth of delamination were observed in a thick composite laminate. Ply separation is caused by the increase of interlaminar normal and shearing stresses. In thin composite cross-ply laminates, the damage mode succession is different. In Jamison, Schulte, Reifsnider, and Stinchcomb (1984), the second damage mode, which follows transverse cracking, is a longitudinal cracking. In this case, local delamination appears between 0° and 90° layers very late. In every case with the evolution of all the damage states, all the different damage modes cause fibre breaking in the 0° layers. All fibre breaks entail "splitting" which appears just before the ultimate failure of the composite laminate. The main objective of this work is to study the initiation and evolution of transverse crack and delamination damage.

For modelling the strain/stress relationship during damage growth, many analytical and numerical approaches have been proposed. Some models can describe the initiation of the first damage mode, transverse cracking. They mainly rely on some stress field distribution and a relationship between loading and crack density is usually proposed. The simplest model, called the "shear lag analyses", for example, (Steif, 1984), usually involves elementary assumptions regarding the displacement and stress distributions. Other models such as variational approaches use the principle of minimum complementary energy (Hashin, 1985; Vasil'ev & Duchenco, 1970). Other studies are based on finite element method (Herakovich, Aboudi, Lee, & Strauss, 1988; Rebière, 1992). Some models are based on phenomenological approaches (Allix, Ladevèze, & Le Dantec, 1990), self -consistent analyses (Adali & Makins, 1992) or approaches relying on specific aspects of the cracks (Kaw & Besterfield, 1992). As explained previously, the longitudinal cracking damage is similar to transverse cracking damage, but arises in the layers where fibres are parallel to the main loading direction, but longitudinal cracks are not always continuous (Rebière, 1992). In some laminates, longitudinal cracking does not occur before the end of life of the structure. In other laminates, longitudinal cracks can appear before the ultimate failure of the laminate. For these reasons, the investigation of longitudinal cracking is often ignored by many models in the literature. In the present work, relying on experimental observations, we suppose that the longitudinal cracks are continuous and that they span the whole length of the studied specimen.

For the study of delaminated damage, a delaminated surface with a triangular shape at the crossing of longitudinal and transverse cracks was used. The initiation of the interface debonding between orthogonal plies is estimated with the study of the evolution of the size of the triangular delamination in the *x* and *y* directions. A similar method was used by Nairn (1989).

In the literature, several approaches have been proposed to investigate the evolution of the different types of damage in composite cross-ply laminates and several kinds of criteria have been proposed (Farrokhabadi, Hosseini-Toudeshky, & Mohammadi, 2011; Rebière, Maâtallah, & Gamby, 2001), among them maximum stress-based approaches. Other kinds of criteria (Akshantala & Talreja, 2000; Barbero & Cortes, 2010; Mc Cartney, 2005; Moure, Sanchez-Saez, Barbero, & Barbero, 2014;

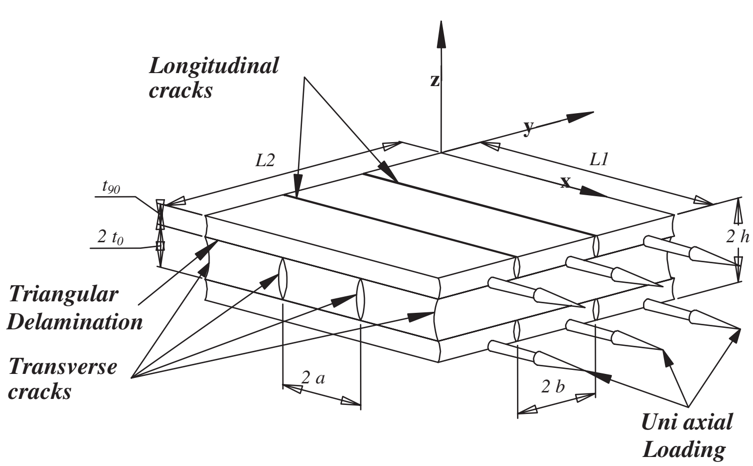
Nairn, 1989; Rebière & Gamby, 2004; Yokozeki, Aoki, & Ishikawa, 2005) rely on the energy release rates associated with each type of damage. Our interest in damage mechanism evolution and succession lead us to bring out the respective contributions of the transverse or longitudinal damage mechanism development which can be found in the strain energy release rate (Rebière & Gamby, 2004). The present study is restricted to damage growth in cross-ply laminates. Here, we again use the decomposition of the strain energy of the whole laminate. This analysis relies upon some estimates of the role of each strain energy component in the initiation and propagation of a given damage mechanism, such as transverse cracking, longitudinal cracking or delamiantion.

2. Model

The studied laminate is the specimen confined to a $[0_m, 90_n]_s$, composite cross-ply laminate as represented in Figure 1. The parameter used to describe the laminate architecture is the constraining parameter λ coefficient ($\lambda = t_0/t_{90}$ where t_0 is the 0° ply thickness and t_{90} is the 90° ply thickness). With the proposed approach by hypothesis, transverse and longitudinal cracks are taken continuously. The energy model used for evaluating the strain energy release rate gives good results for small stiffness laminates. However, although the proposed approach is successful for thin laminates, for thicker and more rigid laminates, the method gives approximate good results. Based on linear elastic fracture mechanics, the estimated values of the strain energy release rates are computed in a pre-damaged laminate, a method used in several damage models in the literature. Thus, there are already pre-existing transverse and longitudinal cracks. Then, the progression of transverse cracking damage is described in the following way. We consider a laminate with a periodic array of transverse cracks in the inner 90° layer. Damage initiation occurs when the spacing between two consecutive cracks is very large (*infinite*). In Rebière (1992), the strain energy release rates associated with two related problems are compared: a single transverse crack across the specimen width and two consecutive transverse cracks which span the whole width of the laminate. The equivalence of the two problems was assessed. For studying longitudinal cracking with the continuous crack hypothesis, a similar method can be used. The laminate is supposed to be "pre-cracked". The problem at hand is thus to compute the strain energy release rate for a laminate which is supposed to be previously damaged by transverse and longitudinal cracks, see Figure 1 for the whole cross-ply laminate.

The accepted assumptions for the crack geometries in the two types of layers of the laminate are as follows. The crack surfaces are supposed to have a rectangular plane geometry. Each crack extends over the whole thickness and the whole width of the 90° damaged ply. Similar assumptions are made for the longitudinal cracks in the two 0° layers. With these assumptions, it is sufficient to study only the "unit damaged cell". This "unit damaged cell" thus lies between two consecutive transverse and longitudinal cracks. In Rebière et al. (2001), the summary of the method is exposed to estimate the stress field distribution in the cracked laminate. The proposed analytical model is

Figure 1. Laminate damaged by transverse cracks, longitudinal cracks and triangular delamination.



based on a variational approach relying on the proper choice of a statically admissible stress field (Rebière et al., 2001). In the damaged laminate, the stress field in the two layers has the following form:

$$\sigma_{ij}^{T(k)} = \sigma_{ij}^{0(k)} + \sigma_{ij}^{P(k)} \tag{1}$$

In the undamaged laminate loaded in the x direction, the layers experience a uniform plane stress state $\sigma_{ij}^{0(k)}$ obtained by the laminate plate theory (where k is the ply index, $k = 0°, 90°$). The orthogonal cracks induce stress perturbations in the 0° and 90° layers which are denoted $\sigma_{ij}^{T(k)}$. In the present approach, for the sake of simplicity, thermal stresses are not taken into account.

3. Strain energy release rate

As explained previously, the laminate is supposed to be damaged by "pre-existing" transverse and longitudinal cracks. The size of the unit damaged cell depends on the transverse and longitudinal damage levels in the two types of layers, 90° and 0° layers. The strain energy release rate G associated with the initiation and development of intra-ply cracking for a given stress state is defined by the following expression:

$$G = \frac{d}{dA}\tilde{U}(\sigma, A) \quad \text{with} \quad \tilde{U}_d = N.M.U_{\text{cel}} \tag{2}$$

where $\tilde{U}_d$ is the strain energy of the whole laminate and A is the cracked area. Let L_1 denote the laminate length in the x direction and L_2 its width in the y direction. The strain energy in the damaged unit cell is denoted by U_{cel}. $N (N = L_1/2\bar{a}t_{90})$ is the number of transverse cracks and M $(M = L_2/2\bar{b}t_{90})$ is the number of longitudinal cracks. Dimensionless quantities are defined by, $\bar{a} = a/t_{90}$, $\bar{b} = b/t_{90}$. The crack area is $A = L_1 L_2 (1/\bar{a} + \lambda/\bar{b})$.

The strain energy release rates associated with transverse and longitudinal cracking are denoted G_{FT} and G_{FL}, respectively. The transverse (*resp. longitudinal*) cracking growth is characterized by the increase of the transverse (*resp. longitudinal*) crack surface initiated in the 90° (*resp.* 0°) layers. All details are given in Akshantala and Talreja (2000). Then:

$$G_{\text{FT}} = \frac{d\tilde{U}_d}{dA} = \frac{d\tilde{U}_d}{d\bar{a}}\frac{d\bar{a}}{dA} \quad G_{\text{FL}} = \frac{d\tilde{U}_d}{dA} = \frac{d\tilde{U}_d}{d\bar{b}}\frac{d\bar{b}}{dA} \tag{3}$$

The strain energy release rates associated with delamination is G_{del}, we get:

$$G_{\text{del}} = \frac{d\tilde{U}_d}{d\bar{d}_l}\frac{d\bar{d}_l}{dA_d} \tag{4}$$

For the analysis of the delamination evolution, only isosceles triangular geometries of the debonded area are studied. Using the present approach, the respective contribution of each damaged layer to the whole strain energy release rate can be estimated. In some models in the literature, when significant hypotheses are used to model the stress field distribution, the strain energy is only attributable to the normal stress in the damaged layer, so only the initiation of transverse cracks can be estimated with this unsophisticated type of model.

4. Results

All the numerical simulations are carried out for a prescribed uni-axial loading of 150 MPa. The T300/914 graphite/epoxy material system is studied in the following numerical computations. The proposed results show the variation of the G_{FT} and G_{del} strain energy release rates. The strain energy release rate is plotted against transverse crack density (cm^{-1}) and delaminated length for the carbon epoxy composite laminates $[0_2, 90_2]_s$. Using the above result, one can study the evolution of the strain energy release rates G_{FT} or G_{del} associated with the multiplication of transverse cracks and the evolution of the triangular delaminated surface (Table 1).

Table 1. Mechanical properties and ply thickness of T300/914 graphite epoxy system and glass epoxy system

	Graphite epoxy system	Glass epoxy system
E_{LT} (GPa)	140	41.7
$E_{TT'}$ (GPa)	10	13
G_{LT} (GPa)	5.7	3.4
$G_{TT'}$ (GPa)	3.6	4.58
ν_{LT}	.31	.3
$\nu_{TT'}$	.58	.42
Ply thickness (mm)	.125	.203

In Figure 2, the results of the variation of the strain energy release rate give an idea of the influence of a pre-existing damage on the evolution of the transverse cracking and delamination damage. This result highlights the risk of the presence of a pre-existing local delamination on the transverse crack damage. At the initiation of the transverse damage, if the triangular delaminated damage is about .2 (*d*/*a*), this delaminated surface creates at the initiation of the transverse cracks a very important increase of G_{FT}. This physically corresponds to an early onset of transverse cracks in the case of laminates containing pre-existing local delamination. In the case of a large delaminated

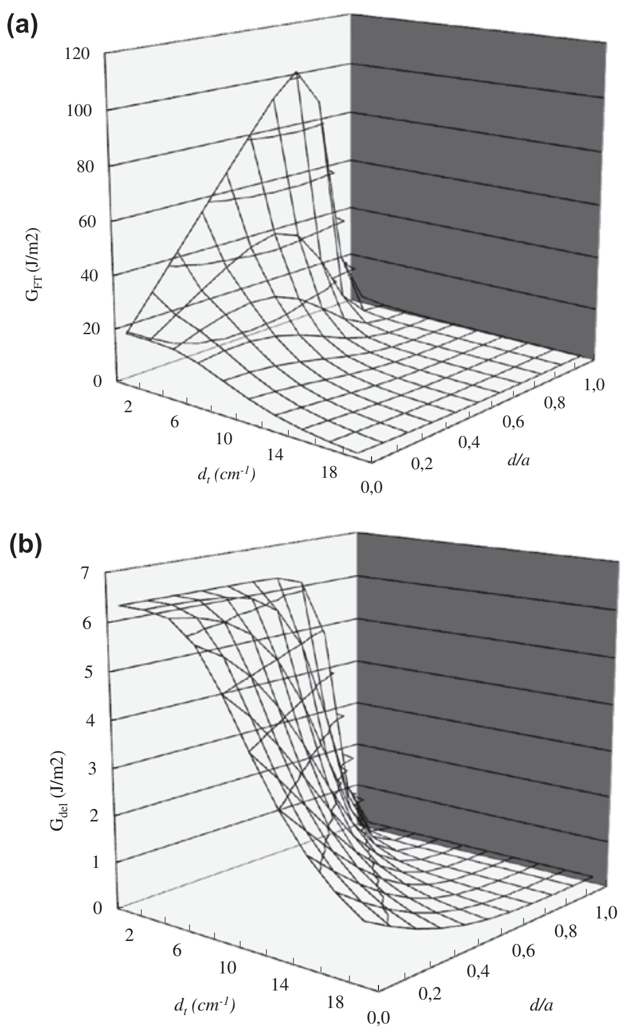


Figure 2. Strain energy release rates vs. transverse crack density and delaminated length for a graphite epoxy laminates: $[0_2, 90_2]_s$ (a) G_{FT} and (b) G_{del}.

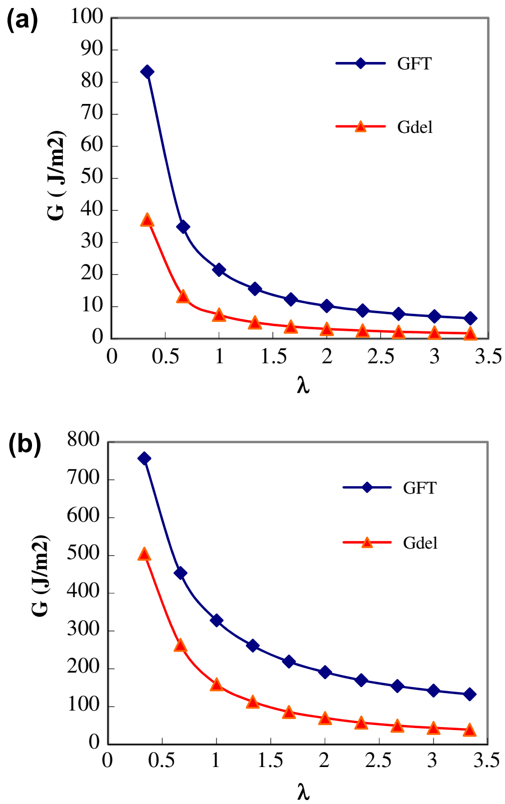


Figure 3. Strain energy release rates G_{FT} and G_{del} vs. constraining parameter λ (a) graphite/epoxy system and (b) glass/epoxy system.

area ($d/a > .7$), the strain energy release rate associated to the initiation of transverse crack tends to decrease. It is so difficult to see the initiation of transverse cracks in this case. At this stage of the delamination damage (*very large delaminated surface*), the transfer of all the stress between the two types of layers is not achieved and the central 90° layer is practically not loaded. During the multiplication of the transverse cracks, the influence of pre-existing local delaminations on the strain energy release rate G_{FT} is not always the same. From transverse crack density value of .6, the presence of local delamination causes decrease of the strain energy associated to transverse crack damage. So it becomes difficult to initiate new transverse cracks. The strain energy associated to delamination damage G_{del} decreases with the transverse crack damage growth. This allows us to say that the multiplication of transverse cracks stops the development of local delamination. This result is in the same direction with experimental results of Wang and Crossman (1980).

In Figure 3, the variation of the initiation of the strain energy release rate is exposed as a function of the constraining parameter λ. The variation of the strain energy release rate is similar for the two presented materials. For other materials, not presented in the article, the only difference lies in the numerical values of the strain energy release rates. With the present results, we can note that it will be easier to cause damage in a glass epoxy laminate than in a carbon epoxy laminate.

5. Conclusion

The curves displayed confirm that transverse cracking first occurs in the 90° layers. The results of the numerical simulations are in good agreement with experimental data and confirm that when there are incipient delaminations in a laminate resulting from the laminate manufacturing, the evolution of matrix cracking damage will quickly become very dangerous.

In this approach, the laminate is supposed to be "pre-damaged" by transverse, longitudinal cracks and delamination to investigate the initiation and development of transverse cracking and delamination. It is shown that, for properly describing the damage process, a refined computation of all the normal stresses and the inclusion of some shear stress components are necessary. Two material systems studied are proposed; for other materials, similar variations of the strain energy release rate are obtained with different numerical values.

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