INITIATION OF MATRIX CRACKING AND DELAMINATION IN A COMPOSITE LAMINATE

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Abstract
This study follows the stress field analysis in a damaged laminate. The results of the stress distribution lead us to elaborate an energy criterion. This criterion is based on the computation of the partial strain energy release rate associated with all the damage types. The related criterion, linear fracture based approach, can predict and describe the initiation of the different damage mechanisms. Transverse cracking damage is generally the first observed damage. The second type of damage will be longitudinal cracking or delamination. The damage mechanism is study with this approach.

Keywords: Composite laminate, Matrix cracking, delamination, failure criterion, strain energy release rate

1 – Introduction:
During the last decades, composite laminates are extensively used in many structural applications thanks to their high strength to weight ratio, their durability still needs to be carefully assessed. So, it is desirable to be able to rely on a suitable damage-growth criterion. Experimentally, in composite cross-ply laminate subjected to monotonic or fatigue tensile loading that the damage mechanisms sequence is as follows. The first observed damage is usually transverse cracking, causes by interlaminar stress concentration at the crack tips. High interlaminar stress levels may entail the debonding of layers at the interface of the plies with different orientations and/or they may also cause matrix cracking between fibres in the layers parallel to the loading axes. Composite structures damaged by incipient delamination or longitudinal cracking must be repaired. The main objective of this work is to study the initiation and evolution of transverse crack damage, longitudinal crack damage and delamination. For transverse cracking observation, two particulars states: the initiation called "first ply failure (FPF)" and the limiting state named "characteristic damage state (CDS)". After transverse crack damage, the second damage mode observed is either longitudinal cracking or delamination. The nature of this second damage depends on following parameters: the laminate geometry,
thicknesses of the $0^\circ$ or $90^\circ$ layers, the nature of the fibre/matrix constituents, the loading history and the manufacturing cycle. For example, in [1, 2] the initiation and growth of delamination was observed in a thick composite laminate. Ply separation is caused by the increase of interlaminar normal and shearing stresses. In thin composite laminates, the damage mode succession is different. In [1, 3] the second damage mode is longitudinal cracking which follows transverse cracking. In this case, local delamination appears between $0^\circ$ and $90^\circ$ layers. In every case, all the different damage modes causes fibre breaking in the $0^\circ$ layers. All fibre breaks entail "splitting" which appears just before the ultimate failure of the composite laminate.

Analytical and numerical approaches have been proposed for modelling the strain/stress relationship during damage growth mechanism. Some models are more suitable to describe the initiation of the first damage mode. They mainly rely on some stress field distribution and a relationship between loading and crack density is usually proposed. The simplest models, so called "shear lag analyses" [4], usually involve elementary assumptions regarding the displacement and stress distributions. Other models like variational approaches [5] use the principle of minimum complementary energy [6-9]. Other types of studies rely on the finite element method [10, 11]. We can also find some models based on phenomenological approaches [12], self-consistent analyses [13] or approaches based on specific aspects of the cracks [14]. The longitudinal cracking damage is a damage equivalent to transverse cracking damage, but arises in the $0^\circ$ layers. Longitudinal cracks are not always continuous [15]. Generally longitudinal cracking happens very late in the laminate life. For these reasons, the investigation of longitudinal cracking is often ignored by many models in the literature. 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 by Nairn [16] for studying the initiation of the interface debonding between orthogonal plies. In this article, we study the initiation of delaminated surface with only triangular shape. 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 [15], among them maximum stress based approaches. We can also find other types of criteria [17-19] rely on the energy release rates associated with each type of damage (transverse cracking, longitudinal cracking and delamination). For studying damage mechanism evolution and succession lead us to bring out the respective contributions of the transverse or longitudinal or delamination damage mechanism development which can be found in the strain energy release rate [19]. 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 estimate of the role of each strain energy component in the initiation and propagation of a given damage mechanism, such as transverse cracking or longitudinal cracking or delamination.

2. Model

For all numerical simulation, the studied specimen is confined to a $[0_{m} \ 90_{n}]_s$, composite cross-ply laminate as represented in Figure 1. The parameters used to describe the laminate architecture are the $\lambda$ coefficient ($\lambda = t_0/t_{90}$ where $t_0$ is the $0^\circ$ ply thickness and $t_{90}$ is the $90^\circ$ ply thickness). With the proposed approach longitudinal cracks are taken continuous by hypothesis. Based on linear elastic fracture mechanics, the estimated values of the strain energy release rates are computed in a “predamaged” laminate, a method used in several damage models in the literature. Thus, there are already “pre-existing” transverse and longitudinal cracks and/or triangular delamination at the crack type.
Then, the evolution 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 of matrix cracking occurs when the spacing between two consecutive cracks is very large (infinite). For studying longitudinal cracking with the continuous crack hypothesis, a similar method can be used. The laminate is supposed to be "pre-cracked". The initiation of the longitudinal damage is obtained for an infinite value of the damage parameter (ratio of the spacing between two consecutive cracks to the central damaged layer thickness). The accepted assumptions for the crack geometries in the 0° and 90° layers of the laminate are as follows. The cracks 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 damaged 0° layers. With these assumptions, it is sufficient to study the only "unit damaged cell". This "unit damaged cell" thus lies between two consecutive transverse and longitudinal cracks. Triangular delaminated areas are located at the cross of transverse and longitudinal cracks. For the initiation of delamination the size in the x direction \(d_x\) and in the y direction \(d_y\) is supposed equal and called \(d_l\). In [15] the summary of the method is exposed to estimate the stress field distribution in the cracked laminate. In the damaged laminate, the stress field in the two layers has the following form:

\[
\sigma^{T(k)}_{ij} = \sigma^{0(k)}_{ij} + \sigma^{P(k)}_{ij} \tag{1}
\]

In the undamaged laminate loaded in the x direction, the layers experience a uniform plane stress state \(\sigma^{0(k)}_{ij}\) 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 \(\sigma^{T(k)}_{ij}\) [15].

### 3. Strain energy release rate

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 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:

\[
G = \frac{d}{dA} \bar{U}(\sigma, \Phi) \text{ with } \bar{U}_d = N.M. U_{cel} \tag{2}
\]
where $\bar{U}_d$ 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 $U_{cel}$. $N$ ($N = L_1/2\tilde{a}t_{90}$) is the number of transverse cracks and $M$ ($M = L_2/2\tilde{b}t_{90}$) 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 $A = L_1L_2(1/\bar{a} + \lambda/\bar{b})$. 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 $90^\circ$ (resp. $0^\circ$) layers. All details are given in [19]. Then:

$$G_{FT} = \frac{d\bar{U}_d}{d\bar{a}} = \frac{d\bar{U}_d}{d\bar{a}} \frac{da}{dA} \quad G_{FL} = \frac{d\bar{U}_d}{d\bar{b}} = \frac{d\bar{U}_d}{d\bar{b}} \frac{db}{dA}$$

(3)

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

$$G_{del} = \frac{d\bar{U}_d}{d\bar{a}} \frac{d\bar{a}}{d\bar{a}} \frac{da}{dA}$$

(4)

All details are given in [19,20].

For the analysis of the delamination evolution, only isosceles triangular geometries of the debonded area are studied. In [1, 16], the authors have experimentally observed similar triangular areas for the initiation of delamination whereas during its propagation, damage can grow along the longitudinal and/or transverse cracks.

4. Results

The numerical simulations are carried out for a prescribed uni-axial loading of 150MPa. The T300-914 graphite/epoxy material system is studied in the following numerical computations.

<table>
<thead>
<tr>
<th>$E_{LT}$ (GPa)</th>
<th>140</th>
<th>$G_{LT}$ (GPa)</th>
<th>5.7</th>
<th>$\square_{LT}$</th>
<th>0.31</th>
<th>Ply thickness (mm)</th>
<th>0.125</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{TT}$ (GPa)</td>
<td>10</td>
<td>$G_{TT}$ (GPa)</td>
<td>3.6</td>
<td>$\square_{TT}$</td>
<td>0.58</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

The energetical criterion proposed is elastic linear fracture based approach. The parameters involved in the study are the constraining parameter, the thickness of the two $0^\circ$ and $90^\circ$ layers and the material constituent system. All the partial strain energy release rates, associated with the initiation of transverse cracking, longitudinal cracking or delamination are normalized by the critical strain energy release rate. For the 8 ply cross-ply laminate, transverse cracking is thus the first observed damage. We can also observe that the strain energy release rates, $G_{FT}$, $G_{FL}$ or $G_{del}$ have similar variation laws. All the strain energy release rates are decreasing functions of the constraining parameter $\lambda$. For instance, in a 8 ply laminate, when the value of the constraining parameter $\lambda$ is increased, the thickness of the $0^\circ$ plies becomes greater. In this case, the fibers in the $0^\circ$ plies carry most of the tensile loading and the initiation of the three different damage modes is delayed.
Although no experimental data are reported on Figures 2a and 2b, the results of the numerical simulations confirm two main points: the proposed approach agrees with experimental data for the initiation of transverse cracking as the first damage mode. It also predicts the readiness to initiate the three types of damage in the case of a 8 ply laminate containing a thick 90° layer. However, the presence of longitudinal cracks cannot be neglected when characterizing the mechanical properties of a damaged laminate. Longitudinal damage has a noticeable influence on the Poisson ratio as measured from the transverse strain in the specimen. Experimentally, it was observed that, after a certain loading level, the number of longitudinal cracks can become more and more important [3]. At this loading level, delamination can appear along the longitudinal cracks; moreover, some small induced transverse cracks can appear along the longitudinal cracks with delaminated areas.

5 – Conclusion:
In this article, an energetical criterion is proposed to predict and describe the initiation of the different damage mechanisms occurring in symmetrical composite cross-ply laminates under uniaxial loading. The strain energy release rates are always computed in a predamaged state, with "pre-existing" transverse and longitudinal cracks. The curves displayed confirm that transverse cracking first occurs in the 90° layers and longitudinal cracking arrive at the end of the laminate life for important value of the crack density. In a 8 ply
When the value of the constraining parameter is increased, the thickness of the 0° plies becomes greater, carry most of the loading and the initiation of the three damage is delayed.

6 – References


