INITIATION OF DELAMINATIONS INDUCED BY TRANSVERSE CRACKS IN CROSS-PLY LAMINATES UNDER STATIC LOADINGS: MODELLING AND EXPERIMENTS

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Abstract

In this paper, the delamination onset induced by the presence of transverse cracks in cross-ply laminates subjected to static loadings is thoroughly investigated.
Initially, a theoretical analysis is developed, taking advantage of Lekhnitskii's complex potentials approach. Analytical expressions for the stress distributions are derived, the intensity of which is expressed as a function of Generalized Stress Intensity Factors (GSIFs). The accuracy of the analytical solutions is verified comparing theoretical results with the ones obtained by finite element analyses.
Then, a fracture criterion based on the GSIF to predict the initiation of delaminations from transverse cracks is proposed and validated on experimental data taken from the literature and obtained from an experimental campaign carried out on glass/epoxy cross-ply laminates. In particular, laminates with three different thickness values have been tested under tensile static load and the evolution of damage has been analysed for each configuration. The stress level required for the initiation of delamination is found to strictly depend on the transverse ply thickness, and it is proved that the thickness effect is intrinsically considered in the GSIF-based criterion.

1. Introduction

In the last decades, composite materials have increasingly replaced metals, becoming the preferred material system in a variety of industrial applications. The factors that contributed to their success include the high specific stiffness and strength, the potential for structural tailoring and the excellent mechanical properties. Composite structures are often made of multidirectional laminates, based on the stacking of differently oriented laminae, and therefore prone to delamination phenomena, i.e. the separation along the interface of adjacent layers. Delaminations act redistributing the stresses in the plies and influencing both residual stiffness and strength, leading to the final failure of composite structures. Therefore, the development of reliable models to predict the initiation of delamination is of primary importance. The topic has been widely investigated in the literature, however in the best of the authors' knowledge, there is not a criterion that describes the initiation and interaction of delaminations with transverse cracks.
The first experimental works dedicated to the topic were conducted by Rodini and Eisenmann [1], Crossman et al. [2] and Wang [3]. In particular, the latter observed that delamination onset occurred triggered from transverse cracks.

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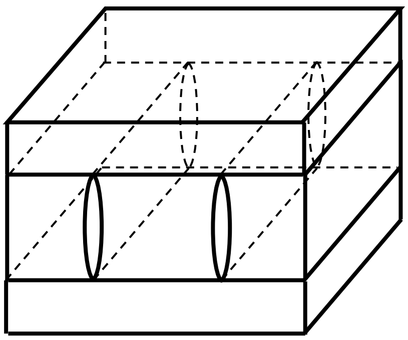
Later, O'Brien [4] developed a model, based on the strain energy release rate assessment, to predict delamination initiation and growth on $(\pm30/90)_s$ and $(\pm45/0/90)_s$ laminates both under static and fatigue loadings.
Also Takeda and Ogihara [5], [6] investigated experimentally the delamination onset for $(0/90_n/0)$ laminates, developing a shear lag based approach to predict stiffness loss. Other similar studies, based on shear lag techniques, were carried out by Dharani and Tang [7], and Kashtalian and Soutis[8].
Conversely, Nairn and Hu [9] adopted a variational based approach to include the effect of delaminations induced by transverse cracks to the analysis developed by Hashin [10].
In this study, the problem of delamination onset is tackled both theoretically and experimentally. First, general equations for stress and displacement fields are obtained, based upon the formalism of Lekhnitskii. The intensity of the stress fields is described by means of Generalized Stress Intensity Factors (GSIFs), obtained through finite element analyses, considering the effect of either the thickness and crack density of the laminates. This parameter is considered to be representative for the prediction of the delamination onset. This assumption has been validated by means of an experimental campaign conducted on cross-ply laminates manufactured for this purpose, characterized by different lay-ups. The results confirm the effectiveness of the GSIFs in summarizing the data and quantifying the scale effect, due essentially to the thickness of the transverse layers.

2. Stress analysis

Consider a $(0/90_n)_s$ laminate. Under tension loading, the first damage occurring consists of the formation of transverse cracks in the 90° plies, which run along the whole width of the laminate. The cracks are assumed to be uniformly spaced, as shown by the unit cell of the laminate in Fig. 1. This has been divided into three zones: zones 1 and 3 at each side of the crack and zone 2 which fully includes the 0° ply. In the following analysis the subscript k will identify the subdomain considered.



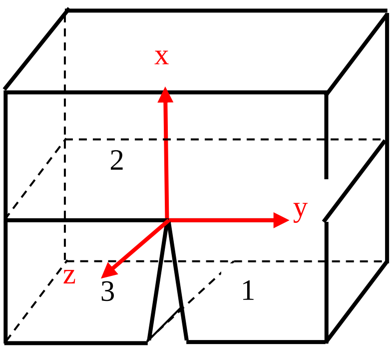


Figure 1. a) Schematic of the damaged cross-ply laminate and b) of the unit cell.

The stress-strain relationships in each region can be described assuming an orthotropic material behaviour.
In proximity of the crack tip, all the three principal loading modes may exist, depending on the load applied to the laminate.
Accordingly to some recent studies (i.e. [11], [12]), the three-dimensional problem can be solved considering separately the plain strain and the anti-plane cases.
Considering only mode I loading, stress fields in the neighbourhoods of the crack tip can therefore be expressed in terms of the product of stress angular function $f_{ts}(\theta)$ and the Generalized Stress Intensity Factor K_1:

$$\sigma_{ts,k}^{(1)} = \frac{K_1}{\sqrt{2\pi}} r^{\lambda_1 - 1} f_{ts}(\theta) \tag{1}$$

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K_1 being defined as:

$$K_1 = \lim_{r \to 0} \sqrt{2\pi} \cdot \sigma_{\theta\theta}\big|_{\theta=0} \cdot r^{1-\lambda_1} \tag{2}$$

More details, omitted for conciseness, can be found in [14].
The GSIF represents the intensity of the local singular stress field. Assuming that the initiation of delaminations from transverse cracks is driven by the singular stress components, the GSIF can be considered a valid parameter to predict the onset of the phenomenon, especially in the case of a laminate under tensile loading N_y. The onset of delaminations is assumed to occur when the GSIF reaches a critical value K_{1c}, which is dependent on the interface toughness and materials.

3. Numerical validation

In order to validate the analytical model developed, a campaign of finite element analyses was performed and the stress fields obtained numerically were compared with theoretical predictions.
FE analyses were carried out using Ansys14 software package, with 8 nodes isoparametric elements (Plane183). The symmetry of the problem allows to model only a quarter of the laminate, as represented in Fig. 2. The figure represents also the boundary conditions applicated to the model, which include a uniform displacement applied on the nodes located at y=L/2 and symmetry conditions imposed on the y=0 and x=-h_{90} coordinates. The dimensions of the laminate modelled are L=20 mm, h_{90}=2 mm and h_0=3 mm while the displacement applied was chosen as the one resulting in an average stress σ=100 MPa.

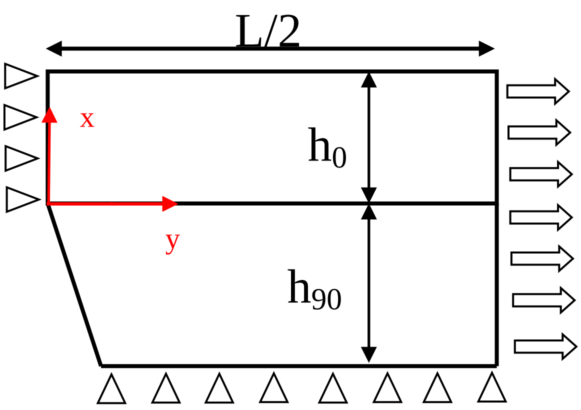

Figure 2. Schematic of the FE model

The material properties used for the FE model are those typical of a carbon-epoxy unidirectional lamina:

E_1=128 GPa E_2=7.2 GPa G_{12}=4 GPa G_{23}=2.4 GPa ν_{12}=0.3

Stresses were evaluated along a circular path centred at the crack tip with radius $3 \cdot 10^{-5}$ mm and along the interface 0°/90°. The model predictions agree very well with the numerical calculations, as illustrated in Fig.3 and Fig.4.

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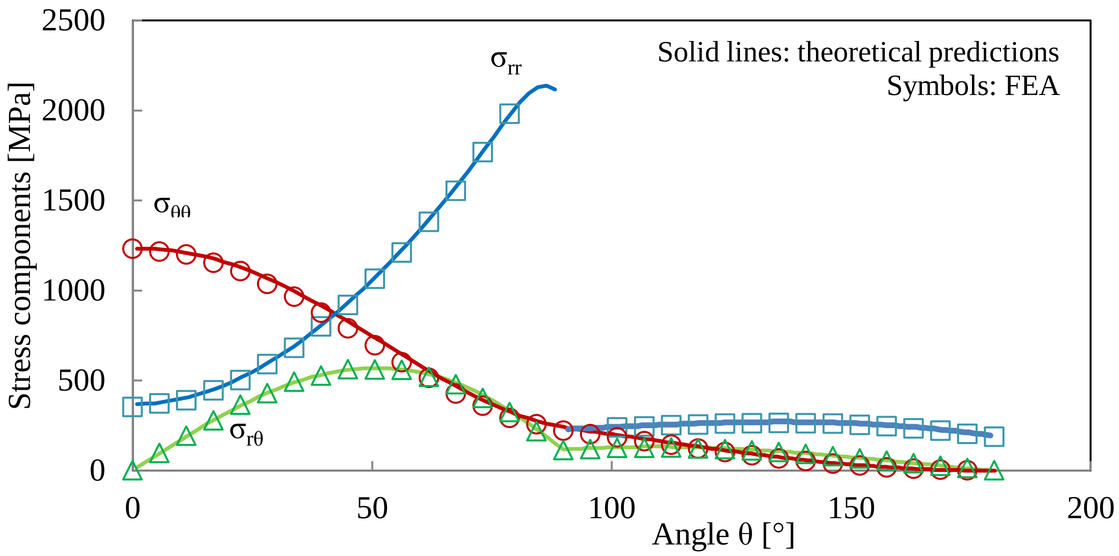

Figure 3. Comparison between stresses obtained by FE analysis and theoretical predictions. Stresses are evaluated along a circular path ($R=3\cdot10^{-5}$), centered on the apex of the transverse crack.

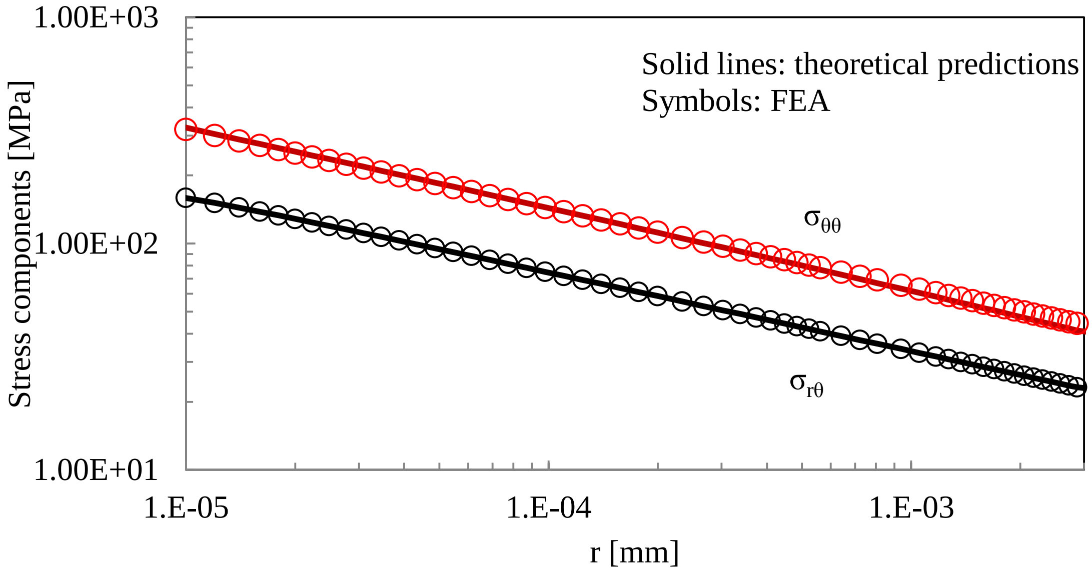

Figure 4. Comparison between stresses obtained by FE analysis and theoretical predictions. Stresses are evaluated along the interface 90°/0°.

4. Experimental investigation

300x300 mm laminates were manufactured by liquid resin infusion. The materials used were dry unidirectional glass fibres UT-E500 (500 g/m^2, Gurit) and the epoxy system Epikote RIMR235-Epikure RIMH235 (Hexion). The laminates were cured for three days at room temperature and then post-cured in an oven at 60°C for 12 hours.

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With the aim of studying the influence of the thickness of 90° plies, two different lay-up were manufactured, i.e. $(0/90_2)_s$ and $(0_2/90_4)_s$. The thickness of each ply was measured equal to 0.34mm.
From the laminates, specimens of 25 mm x 250mm were cut, polished on the edges and tabbed such that the gage length was 140 mm.
Quasi-static tests were performed on a Mini-bionix MTS 858 servo-hydraulic machine equipped with a 25 kN load cell, under displacement control with a rate of 2 mm/min. Specimens were tested with a series of load ramps, interrupted when new transverse cracks were formed, and visually inspected to verify the presence of delaminations originated from transverse cracks tips.

5. Results

For each test performed, the first five delaminations were considered. During each test, after each load ramp, the stress applied to the laminate corresponding to the delamination onset, the crack density of the laminate and the associated K_1 values were determined.
The results of the experimental tests highlighted that the critical tension σ_c at which the delaminations onset is dependent on the thickness of the laminate (see Fig. 5). In particular, as the thickness of the 90° plies increases, the tension σ_c decreases. It can be seen that a slope of -0.423, equal to the singularity degree of stress fields, fairly agrees with the average experimental values. Then, the GSIF correspondent to each delamination onset was calculated. The results are presented in Fig. 6, which shows how all the data, reanalysed in GSIF terms, can be included within a horizontal scatter band (K_{1c}=79.5 MPa mm$^{0.423}$± two standard deviation). The cause of the wide dispersion is principally due to the experimental procedure.
Both the figures show that the initiation of delaminations is influenced mainly by the intensity of the local stress fields. The GSIF value, which quantifies the intensity of the stress fields, confirms to be a valid parameter to predict the onset of delaminations, implicitly considering the effect of 90° plies thickness.

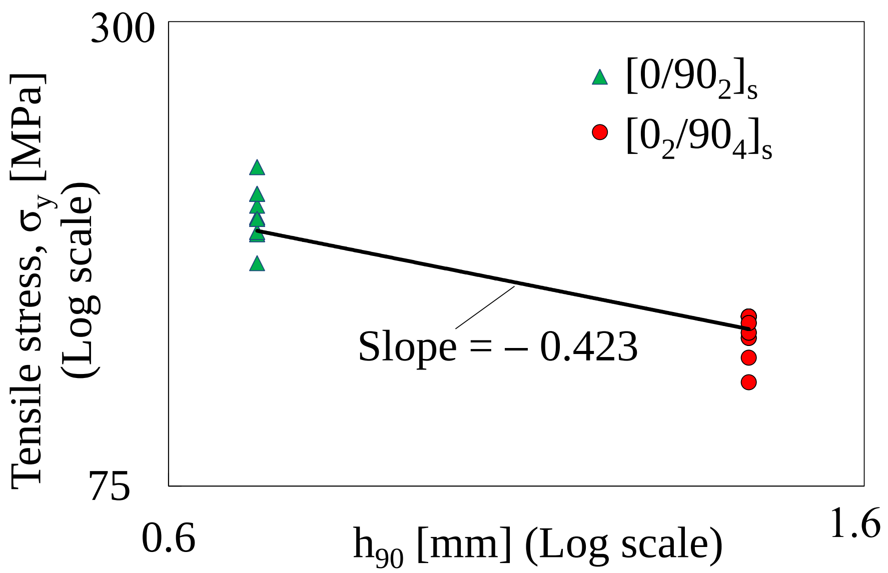

Figure 5. Far applied stress at the onset of the first five delaminations

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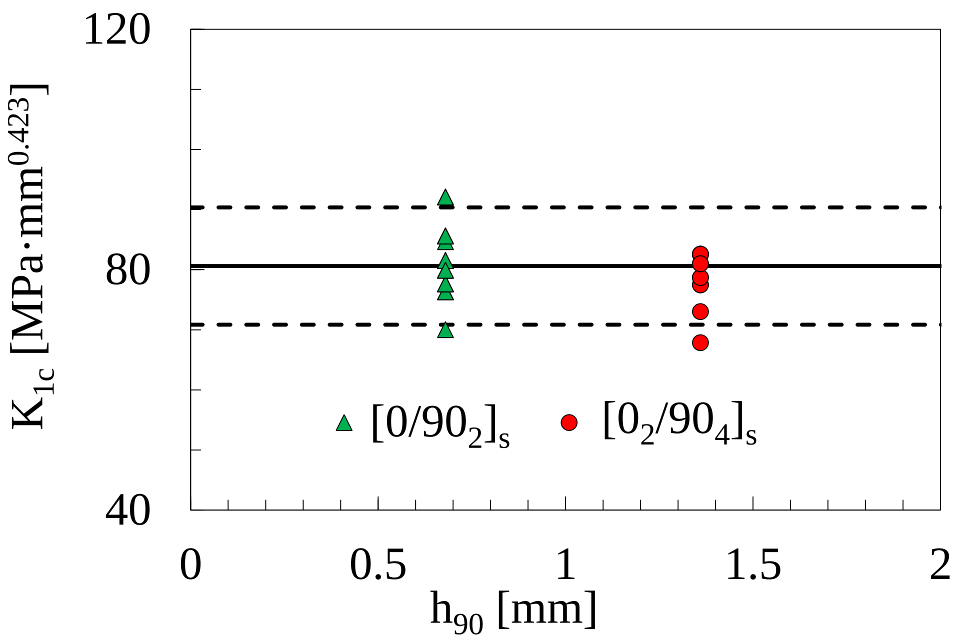

Figure 6. Generalized **s**tress intensity factor at the onset of the first five delaminations

Experimental data presented by Takeda and Ogihara [5,6], referred to the delamination onset on $[0/90_n/0]$ laminates were reanalysed in terms of critical GSIF. For each configuration, the critical nominal strain at which the authors observed delamination onset, and relevant GSIF value were calculated, as reported in Table 5. As evident, the K_{1c} collects all the data around an average value, while the nominal strain varies with the thickness of the 90° plies, confirming the validity of the proposed approach.

Table 1. Data of strain ε_c at which delamination onset occurred [7] and correspondent K_{1c} values.

No 90° plies, n	ε_c [%]	Crack density [no cracks/cm]	K_{1c} [MPa mm$^{1-0.6466}$]
4	1.33	13.3	133.45
8	0.80	2.8	131.16
12	0.73	1.85	136.44

6. Conclusions

In this paper the results of a recent research activity carried out in order to develop a criterion to predict the delamination onset from transverse cracks in cross-ply laminates have been presented. Initially, an analytical formulation based on the Lekhnitskii formalism has been developed to obtain the formulation of stress fields in the close neighbourhood of the tips of transverse cracks. The intensity of the singular stress fields has been expressed in terms of Generalized Stress Intensity Factors (GSIFs). Afterwards, a fracture criterion for the delamination onset based on the value of the GSIF has been formulated. The comparison with the results of an experimental campaign conducted at this purpose clearly indicates the soundness of the approach proposed.

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