Do transverse cracks affect the in-situ strength and fibre breaks accumulation in longitudinal plies of cross-ply laminates?

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Abstract

When loaded in the fibre direction the final failure of cross-ply laminates is controlled by the process of fibre breakage in the longitudinal (0°) plies. Long before the fibre breakage becomes significant, however, the plies transverse to the loading direction (90°) start cracking. Although these cracks are often not considered critical for the composite performance, their presence can affect failure of the 0° plies and therefore the composite strength. In the present work, we quantify this effect using a fibre break model that accounts for stress concentrations induced by transverse cracks. Our results reveal the preferential clustering of fibre breaks near crack tips and a reduction of the longitudinal ply strength. Further research is needed to better understand how the presence and evolution of transverse cracks and other damage modes affect the strength of composite laminates and its variability.

1. Introduction

Cross-ply fibre reinforced composites are prone to damage of several types [1]. The first major damage mechanism in cross-ply laminates under tension is transverse cracking which occurs in the plies with fibres oriented transverse to the load direction. This process can be described by the evolution of crack density in function of the applied load or strain. The first transverse crack appears independently from the moment when the first fibre break appears [2]. Later, crack density increases with the applied load and in some systems reaches saturation, well before the final failure of the composite [3]. Apart from the damage types already mentioned, delaminations can occur between plies, growing from transverse cracks and laminate edges. They are suppressed in thin ply cross-ply laminates [4].

The transverse cracks are often not considered to be critical for the composite performance, although they reduce the laminate stiffness [5]. It is also expected that their presence can affect the failure of the longitudinal plies and therefore the composite strength. Unfortunately, while the transverse cracks' effect on stiffness was investigated previously in much detail, the existing experimental evidence of their effect on the strength is inconclusive [6]. Investigation of the influence of this damage mechanism on the strength of the longitudinal plies is necessary to increase the accuracy of the strength predictions for cross-ply laminates and to reduce their overdesign.

Theoretically, the appearance of a crack or multiple cracks would induce strong non-uniformity in the stress fields in the 0° plies, concentrating stress at the crack tips. These stress concentrations have been shown to cause a local increase in the number of fibre breaks [7]. Such localisation of the fibre breaks may lead to premature failure of the 0° plies compared to a pure unidirectional (UD) composite and therefore to the earlier failure of the whole cross-ply laminate.

The paper aims to answer the question posed in the title, namely whether the transverse cracks in cross-ply laminates influence the strength of longitudinal plies and to which extent. The study is performed using a numerical approach.

2. Materials and methods

2.1. Material and geometry of the laminate

The material modelled in the study was carbon fibre/epoxy AS4/3506-1 cross-ply laminate $[0_n,90_m]_s$. Two laminate configurations were simulated: one was with n=m=1 (referred to as "thin"), and the other one was with n=1, m=2 (referred to as "thick"). Elastic properties of the UD plies in these laminates are listed in Table 1 (from [8]). There exists experimental data of crack density evolution for this material [3], required as input for the model. The experimental data captures only initial stage of rapid transverse cracking with the applied stress up to 500 MPa ("thick" laminate) and 600 MPa ("thin" laminate). The thickness of the plies is 0.125 mm.

The model dimensions were 0.125 mm in thickness (the same as the thickness of the longitudinal ply), 0.5 mm in width and 1 mm (for the case of a single crack) and 10 mm (for the case of multiple cracks) in length. Fibres were divided into longitudinal elements with a length of 0.0035 mm.

Table 1. Elastic properties of AS4/3506-1 UD ply [8]. *l* and *t* stand for longitudinal (fiber) and transverse directions, respectively.

E_l, GPa	E_t, GPa	υ_{lt}	υ_{tt}	G_{lt}, GPa	G_{tt}, GPa
139	9.7	0.3	0.4	5.2	4.2

2.2. Model description

The approach merges three models together:
1) The model of a UD composite (representing a longitudinal ply in a cross-ply laminate) under longitudinal deformation (generally non-uniform) to predict fiber breaks and composite strength.
2) The model of a cross-ply laminate with homogenized properties and transverse cracks in the 90° ply to predict strain fields in the 0° ply generated by these cracks.
3) The model to generate formation of transverse cracks in the 90° ply based on the Weibull statistics for this ply extracted from experimental data.

The approach is described below in more details.

2.2.1. Modelling of fibre breaks

The strength model for UD composites of Swolfs et al. [9] was extended to the case of non-uniform strain distribution over the fibre bundle (here: ply). More specifically, a pre-defined non-uniform strain field was imposed over the fibres and successive fibre breaks were predicted according to the local stresses generated by this field, local statistics of the fibre strength distribution and stress redistribution after fibre breaks appeared. The reader is referred to [9] for the details of the original model.

This model captures a sequence of the fibre break events, with their spatial positions and the value of the average strain applied to the composite when they appear. The fibre breaks tend to form clusters; finally, at a certain strain level, one such cluster will grow unstably leading to the failure of the whole ply [10]. The unstable growth of a cluster is a stopping criterion in the model. The nominal average stress value at the moment the model stops is taken as the strength of the longitudinal ply.

The non-uniformity of strains in UD plies due to the presence of transverse cracks was assigned with the help of analytical solutions of Varna & Berglund [8] (see Fig. 1). The method to find these solutions is based on the variational method of Hashin [11]. Although being called “analytical”, this method includes iterative procedures of minimising the complementary energy of the system to find suitable parameters for the solutions mentioned before. The solutions are therefore approximate and contain inaccuracies in the stress fields near the crack tip.

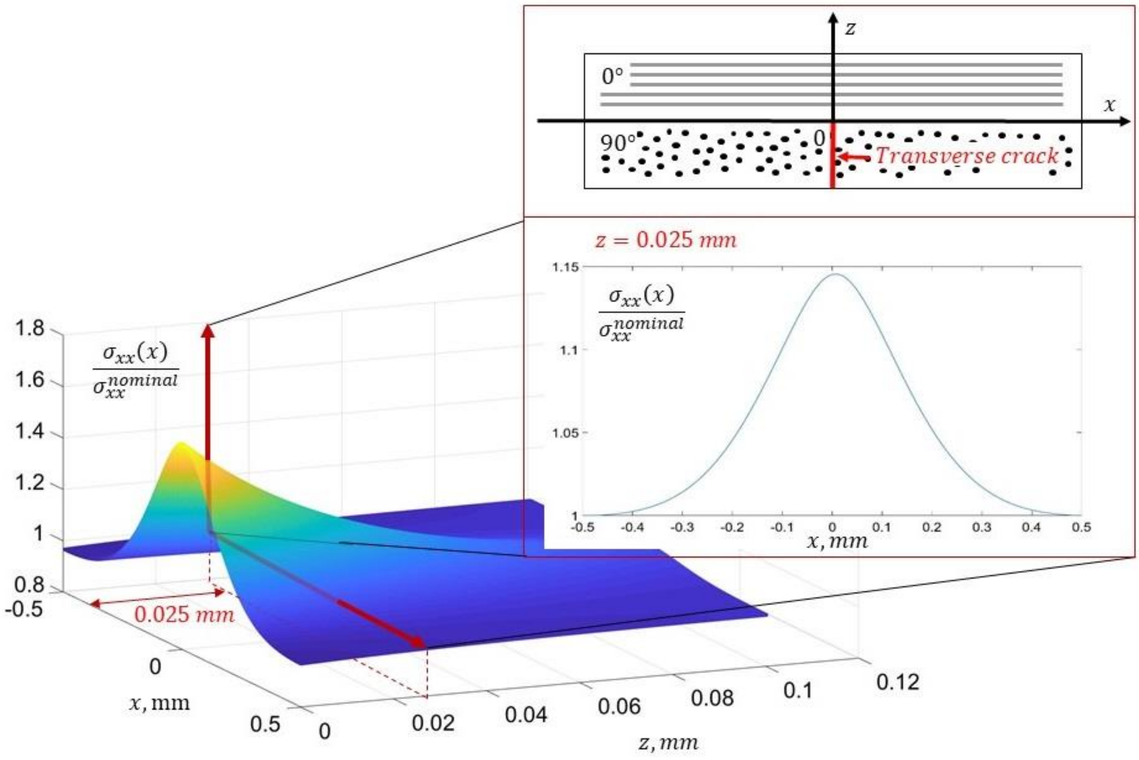

Figure 1. Stress factor $\left(\frac{\sigma_{xx}(x)}{\sigma_{xx}^{nominal}}\right)$ distribution in the 0° ply according to the analytical solutions [8].

2.2.2. Accounting for transverse cracks

Transverse cracks form in the laminate as it is being loaded. To simulate this process, the 90° (transverse) ply is divided into longitudinal elements with the length of 0.0035 mm and with one element per thickness of the transverse ply. A strength value was assigned to each element of the transverse ply according to Weibull distribution (Eq. 1):

$$\sigma_f = \sigma_0 \left(\frac{L_0}{L}\right)^{\frac{1}{m}} \ln\left(\frac{1}{1-RAND(0,1)}\right)^{\frac{1}{m}} \tag{1}$$

where σ_f – strength of an element, σ_0 – Weibull scale parameter, m – Weibull shape parameter, L_0 – reference length, L – characteristic length and $RAND(0,1)$ – a number from the uniform quasi-random generator, representing the probability of an element to have this strength.

A non-uniform distribution of the longitudinal stress was applied in the transverse ply using the solution from [8] for the stress in the transverse ply when transverse cracks appear. At each strain increment, the stress value in an element was compared to its strength, and if the stress was higher than the strength value, this element was considered to be fully cracked. New stress values, representing stress redistribution due to the crack appearance, were applied to the cracked and affected intact neighbouring elements according to the solutions. The analytical solutions are only available for the case of a single crack or two cracks. The solution for two cracks was also used in the case of multiple cracks by including interaction with the closest crack only and neglecting the "far field" influence of other cracks.

Parameters of the unknown Weibull distribution for the transverse ply σ_0, m (with defined L_0=150 mm, L=0.0035 mm) were adjusted to give the best fit to the experimental data of the transverse crack density [3].

3. Results and discussion

3.1. Crack density in the transverse ply

The Weibull parameters for the transverse ply elements strength were chosen based on their variation according to Table 2.

Table 2. Tested Weibull parameters.

Laminate	"Thin" cross-ply									"Thick" cross-ply								
σ0, MPa	20	20	20	25	25	25	30	30	30	20	20	20	25	25	25	30	30	30
m	5	6	7	5	6	7	5	6	7	5	6	7	5	6	7	5	6	7

50 Monte Carlo simulations were run for each combination of the parameters values. Based on the resulting average crack densities for each case, the best parameters were chosen as follows: for the "thick" laminate as σ_0 = 20, m = 7 and for the "thin" laminate as σ_0 = 25, m = 7. The crack density data for the selected parameters in comparison with the experimental data is shown in Fig. 2.

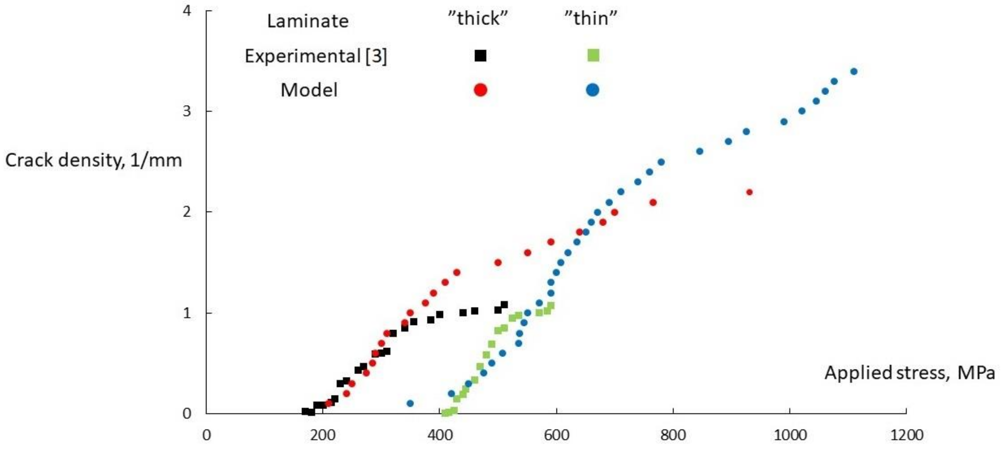

Figure 2. Comparison of experimental [3] and simulated crack densities with Weibull parameters σ_0 = 20, m = 7 and σ_0 = 25, m = 7 for the thick and thin laminates, respectively.

3.2. Fibre breaks distribution and strength of the longitudinal ply

Using the Weibull parameters from the previous section, the influence of the transverse cracking on the strength of the longitudinal ply was studied. But first, a simple virtual case of a single pre-defined crack in the transverse ply was simulated to investigate the fibre breaks distribution near the crack tip. Fig. 3 presents a typical fibre breaks distribution at the moment the model stops.

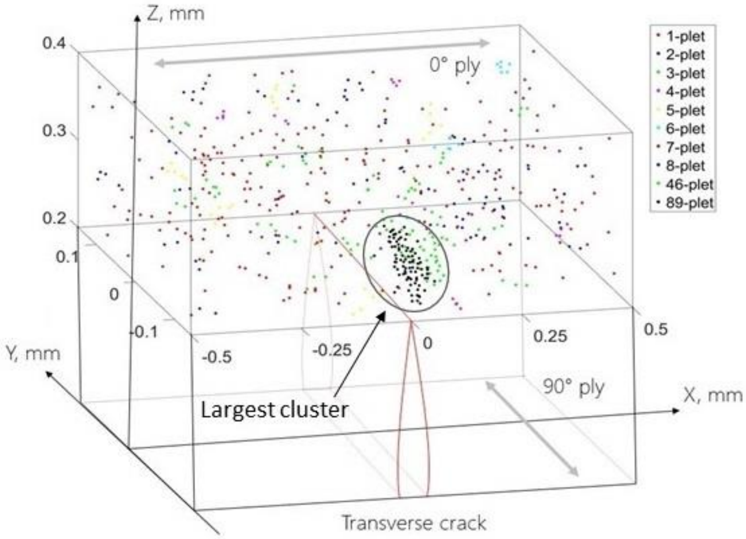

Figure 3. Fibre breaks in the longitudinal ply in the case of a single crack after the model stops.

Noticeable localisation of fibre breaks can be seen near the crack tip. The largest cluster at the moment the model stops is always located close to the crack tip as encircled in Fig. 3. This can be explained by the stress concentration induced in the vicinity of the crack tip as was shown in Fig.1.

The clustering of fibre breaks due to stress concentrations is expected to have an effect on the strength. If that influence is negligible, the use of simplified models to estimate the strength of composites having transverse cracks can be justified. But if this influence cannot be omitted, the use of more complex fibre breaks models is necessary for accurate strength predictions. The strength of the longitudinal ply is reported in Table 3.

Table 3. Strength of the longitudinal ply in the laminates for the models with single and multiple cracks.

Model length	1 mm (single crack)			10 mm (multiple cracks)		
Laminate	UD composite	“Thin” cross-ply	“Thick” cross-ply	UD composite	“Thin” cross-ply	“Thick” cross-ply
Strength, MPa	2310 ± 37	2220 ± 37	2167 ± 55	2155 ± 35	2108 ± 41	2029 ± 41
Difference (from UD composite)	n/a	- 3.9 %	- 6.2 %	n/a	- 2.2 %	- 5.8 %

For each model length, two different laminates were compared with a UD composite of the same size as the longitudinal ply in the cross-ply laminates. If strength of the models with different lengths is compared, one must take into account size effects in the length direction, which can be noticeable in UD composites (see Table 3). These effects can be explained by the increased probability to find the weakest spot when the volume of the composite is increased, which leads to failure at a lower stress. Transverse cracks formed in “thick” or “thin” plies generated different level of stress concentrations around their tips due to the difference in their opening displacement directly linked to their length. Even for the “thin” laminate, with lower stress concentrations, the reduction was 3.9 % for 1 mm long model and 2.2 % for 10 mm long model. In the case of multiple cracking with the model length of 10 mm the reduction of the strength of the longitudinal ply is lower than for the 1 mm long model. The calculated *p*-value less than 0.001 in these cases means that this reduction is statistically significant and not due to the stochasticity of fibre strength.

In general, one would expect the reduction of the strength to vanish if the thickness of the transverse ply in relation to the longitudinal ply is decreased significantly, due to reduced crack lengths. Using multiple cross-ply blocks with very thin plies to construct a composite, where the effect of transverse cracks is minimized, should positively influence the strength [12].

4. Conclusions

The influence of transverse cracks on the longitudinal plies in the cross-ply laminates was studied with the use of the fibre break model extended to account for the applied strain non-uniformity. The answer to the question whether transverse cracks in cross-ply laminates affect the strength of the longitudinal plies is “Yes, the model predicts preferential clustering of fibre breaks near tips of the transverse cracks and report strength reduction for the longitudinal plies”. To further understand and quantify this effect for different laminate designs, more research is needed. For example, capturing of stress fields in the vicinity of the crack tip needs higher precision than allowed by analytical solutions, which can be achieved with the help of the finite element method. Furthermore, composites rarely fail in the absence of delaminations, therefore including them into the analysis and understanding their effect on the process of fibre breakage are important, especially for laminates with thick plies and/or weak interlaminar interfaces.

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