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On multiple transverse cracking in glass fibre epoxy cross-ply laminates

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An investigation has been made of multiple transverse cracking in glass fibre epoxy cross-ply laminates. Four laminates of differing transverse ply thicknesses were investigated. Transverse crack spacing was found to decrease with increasing applied stress and decreasing transverse ply thickness. Very close agreement has been found between the experimental results and a multiple cracking theory based on shear lag analysis in which the plies remain essentially elastically bonded. In these composites a small modulus change is observed at a strain lower than that at which cracking initiated. This phenomenon is associated with a visual, under some circumstances reversible, whitening effect.

1. Introduction

In a recent paper, Garrett and Bailey [1] described the occurrence of systematic multiple cracking in glass fibre reinforced polyester 90° cross-ply laminates. The crack spacing in the transverse plies was found to decrease with increasing applied stress and in general was not accompanied by delamination between the plies. A simple multiple cracking theory based on shear lag analysis in which the plies remained elastically bonded could explain the general trend of the experimental results. However, there was an apparent underestimate of the crack spacing values for a given applied stress in their work.

In this paper, more detailed studies of the nature of the cracking behaviour are reported for a glass fibre reinforced epoxy composite. The aim of these experiments is to explain the apparent discrepancy between theory and experiment mentioned above. The experiments formed part of a wider investigation into cracking mechanisms in these systems; the effect of ply geometry on initial transverse cracking behaviour has been reported, Parvizi *et al.* [2].

2. Experimental procedure

0, 90, 0 cross-ply and unidirectional laminates were made from epoxy resin (Shell Epikote 828 cured with 80 PHR Epikure NMA and 0.5 PHR BDMA) reinforced with "E" glass fibre rovings (Silenka 1200 TEX). The glass rovings were wound onto open metallic frames of about 2 mm thickness and then the laminate was built up over an aluminium sheet by stacking up a sufficient number of frames in each direction. Fibres were wetted thoroughly by the liquid resin after each frame was laid down and the air entrapped was expelled by using a hot air blower. The laminate was eventually covered with a glass sheet to ensure a smooth surface and the excess resin squeezed out by applying sufficient pressure onto the laminate. Curing took place at 100° C for 3 to 4 hours followed by three hours of post curing at 150° C.

Cross-ply laminates were made, as illustrated in Fig. 1, with a transverse ply thickness $2d$ ranging from 0.4 mm to 4 mm whilst the longitudinal ply thickness, b, remained constant at about 0.5 mm on either side of the laminate. The fibre volume fraction of laminates was also kept constant at an average value of 0.55. Parallel sided specimens of dimensions 220 mm × 20 mm were cut from each cross-ply laminate so that their length was parallel to the fibre direction in the longitudinal outer plies, i.e. y-direction in Fig. 1. The specimen ends were reinforced with GRP tabs to prevent their premature failure at the grips.

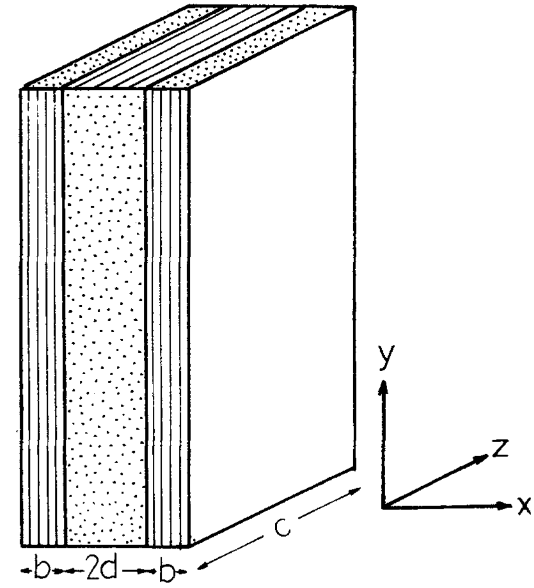

Figure 1 Specimen model.

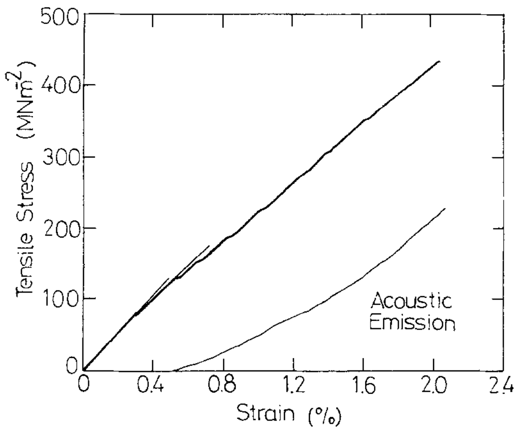

Figure 2 Typical stress–strain curve of glass fibre reinforced epoxy cross-ply laminate with two "knees". The first "knee" at a strain of ~ 0.3% is associated with the whitening effect and the second "knee" at ~ 0.55% is accompanied by the onset of transverse cracking in a specimen with a transverse ply thickness of 1.2 mm. The lower curve is the integrated acoustic emission (arbitrary units).

Specimens were tensile tested to differing strain levels on a TTD model Instron machine at a cross-head speed of 0.5 mm min^{-1} (0.5 x 10^{-4} sec^{-1} strain rate). The strain was recorded by electrical resistance strain gauges attached to the specimen and connected to the Instron recorder via a suitable bridge circuit. An acoustic emission transducer was also fixed to each specimen to give additional information during failure.

Tensile tests were also carried out on the uni-directional laminates, parallel and perpendicular to the fibre axis. Specimen preparation and test procedure were similar to those for the cross-ply laminates.

Transverse crack spacing in the inner ply was measured using a travelling microscope. The initial crack is clearly detectable both visually and acoustically and thus the transverse failure stress ϵ_{tu} is easily measurable.

3. Experimental results

The stress/strain curve of a typical laminate is shown in Fig. 2. The first "knee" observed at approximately 0.3% strain is associated with an apparent whitening effect. This whitening effect partially disappears when the specimen is unloaded and can be completely removed by a thermal treatment of a few minutes at 100° C. While the whitening phenomenon is observed in all samples, the magnitude of the departure from linearity at the "knee" is dependent upon the thickness of the inner ply, the greater the thickness the larger the change of modulus.

The second "knee" occurs at a strain of approximately 0.55% and is associated with the appearance of the first crack in the inner ply and acoustic emission; with increasing stress the crack spacing progressively reduces. Examples of the crack spacing are shown in Fig. 3.

In general, cracks formed span the inner ply (Fig. 4a) without causing debonding at the interface between the plies. At comparatively thick inner ply spacings, approximately 3 mm, a limited amount of debonding occurs, together with

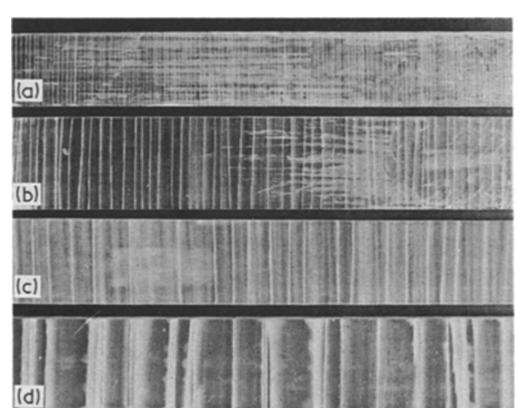

Figure 3 Transverse cracking in specimens with transverse ply thickness of (a) 0.42 mm, (b) 1.2 mm, (c) 2 mm, and (d) 4 mm. All specimens have been loaded to 1.4% strain.

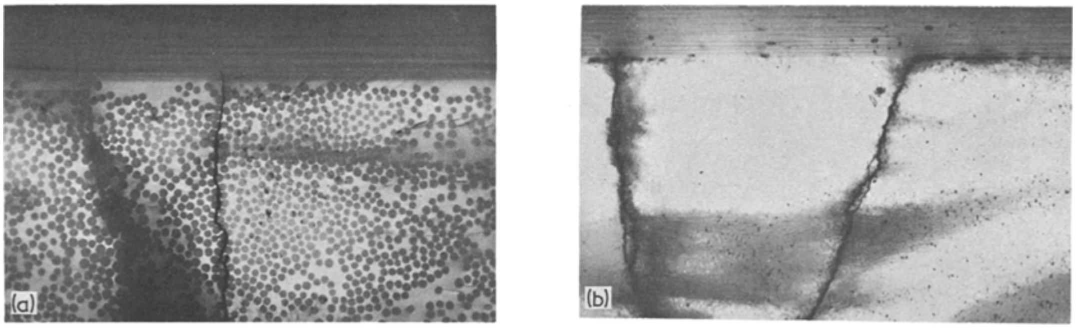

Figure 4 (a) Typical transverse crack for a specimen with transverse ply thickness of 1.2 mm; there is no evidence of debonding between the plies. (b) Transverse cracking at a transverse ply thickness of 4 mm; small amount of debonding between the plies and 45° oblique cracks are observable.

oblique approximately 45° cracks, see Fig. 4b; these cracks and debonding generally occur at decreasing strain levels with increasing inner ply thicknesses.

After initial crack formation, the rate of decrease of crack spacing is high but slows down with increasing stress, appearing to approach zero at high stresses. Results for four inner ply thicknesses are given in Fig. 5.

Young's modulus in the transverse, E_t, and longitudinal, E_l, directions of unidirectional laminates of identical glass fibre volume fraction, and the failure strain ϵ_{tu} in the transverse direction were measured. The values were: $E_t = 14 \pm 0.5\,\mathrm{GN\,m^{-2}}$; $E_l = 42 \pm 1\,\mathrm{GN\,m^{-2}}$; and $\epsilon_{tu} = 0.5\%$. Values of the initial modulus, E_c, of the composites as a function of inner ply thickness, $2d$, are given in Table I.

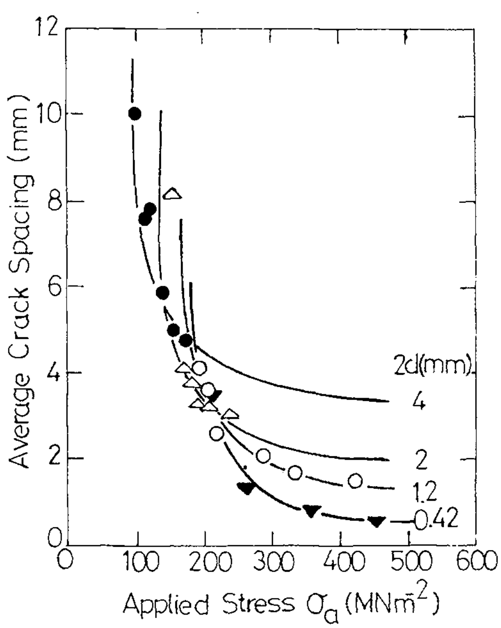

Figure 5 Experimentally observed average crack spacing as a function of applied stress for specimens with different transverse ply thicknesses.

4. Theory

Following Garrett and Bailey [1], after the first crack has occurred in the transverse ply at a strain ϵ_{tu}, an additional stress $\Delta\sigma$ is placed onto the longitudinal plies. This additional stress has its maximum value $\Delta\sigma_0$ in the plane of the crack and decays with distance y (see Fig. 1) from the crack surface as the load is progressively transferred back into the transverse ply. Using a modified shear lag analysis, the value of the additional stress $\Delta\sigma$ at a distance y from the crack is given by:

$$\Delta\sigma = \Delta\sigma_0 \exp\left(-\phi^{1/2} y\right) \quad (1)$$

where

$$\phi = \frac{E_c G_t}{E_l E_t} \cdot \frac{(b+d)}{b d^2} \quad (2)$$

E_c is the initial Young's modulus of the composite in the y-direction and G_t is the shear modulus of the transverse ply in the y-direction. Therefore the load F transferred back into the transverse ply at a

TABLE I

Transverse ply thickness $2d$ (mm)	Initial modulus of the composite E_c (GN m^{-2})
4	17.4
2	19
1.2	26.39
0.42	29

distance y can be easily calculated (see Garrett and Bailey [1]) and is given by:

$$F = 2bc\,\Delta\sigma_0\,(1 - \exp(-\phi^{1/2}y)) \qquad (3)$$

where b, c and d are defined in Fig. 1.

The transverse ply can crack again when the load F transferred back to it equals $2\,\epsilon_{tu}E_t dc$, and this will occur at infinity if the applied stress on the composite, σ_a, is just the value at which the ply first cracks, i.e. $\epsilon_{tu}E_c$. For another crack to occur σ_a, and hence $\Delta\sigma_0$, must be increased to such a value that the load in the transverse ply reaches $2\,\epsilon_{tu}E_t dc$ at the farthest end of the specimen from the first crack. Similarly, the next series of cracks will form midway between the existing cracks when $\Delta\sigma_0$ is again large enough to produce a load $2\,\epsilon_{tu}E_t dc$ in the inner ply midway between the two cracks. The value of $\Delta\sigma_0$ required to form a crack midway between two cracks of spacing t is given by:

$$\Delta\sigma_0 = \epsilon_{tu}E_t\frac{d}{b}\left[1 + \exp(-\phi^{1/2}t) - 2\exp\left(-\phi^{1/2}\frac{t}{2}\right)\right]^{-1} \qquad (4)$$

By definition, $\Delta\sigma_0$ is the additional stress on the longitudinal plies at $y = 0$ which would have been on the transverse ply if there had been no cracks, and therefore it can be related to the applied stress σ_a by the following general equation:

$$\Delta\sigma_0 = \sigma_a\frac{(b+d)}{b} - E_1\frac{\sigma_a}{E_c} \qquad (5)$$

where σ_a/E_c indicates the strain in the composite in the absence of any cracks. For the first crack σ_a is equal to $\epsilon_{tu}E_c$ and therefore $\Delta\sigma_0$ for this case will be given by:

$$\Delta\sigma_0 = \epsilon_{tu}E_c\frac{(b+d)}{b} - E_1\epsilon_{tu} = \epsilon_{tu}E_t\frac{d}{b} \qquad (6)$$

Figs. 6a and b show the theoretical crack spacings for specimens of length approximately 190 mm with transverse ply thicknesses of 1.2 mm and 4 mm respectively, as a function of the applied stress; using the equation of Halpin and Tsai [3] a value of $5\,\mathrm{GN\,m^{-2}}$ has been deduced for G_t. Also shown in Fig. 6 are the experimental results for the two laminates. The stepped curves indicate the theoretical crack spacings for these particular specimen lengths when the first crack has occurred in the middle of the specimen. However, the con-

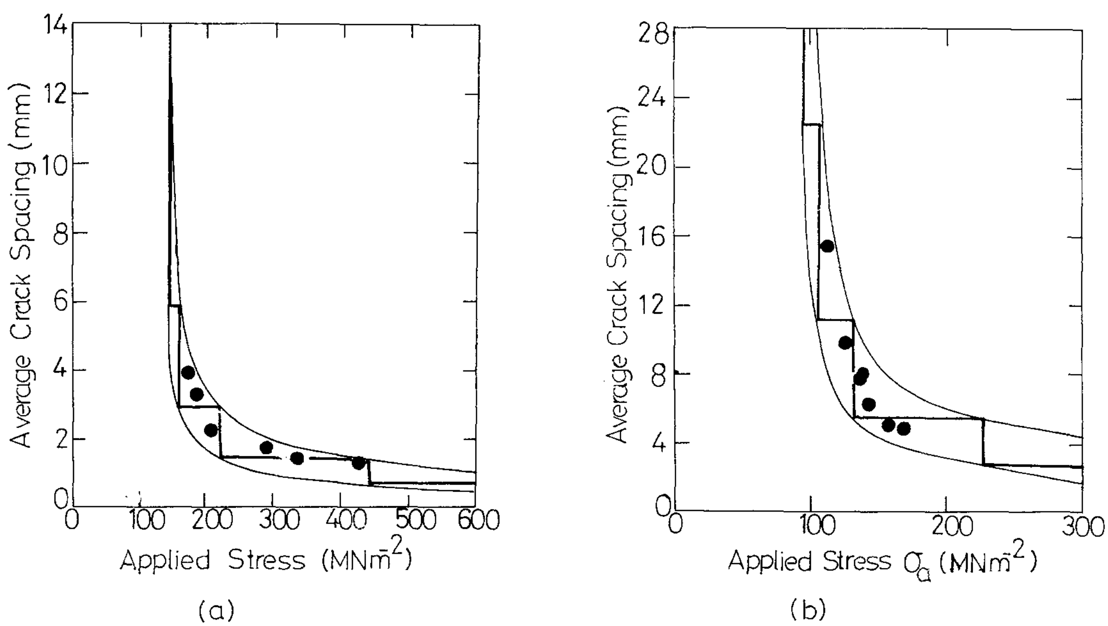

Figure 6 Comparison of experimental results with theoretical curves of crack spacings as a function of applied stress for 190 mm long glass fibre reinforced epoxy cross-ply specimens with a transverse ply thickness of (a) 1.2 mm and (b) 4 mm. The stepped curves show the crack spacing when the first crack occurs in the middle of the specimens of this particular length, and the upper and lower continuous curves indicate the range of crack spacings for specimens of any length with an arbitrary position of the first crack.

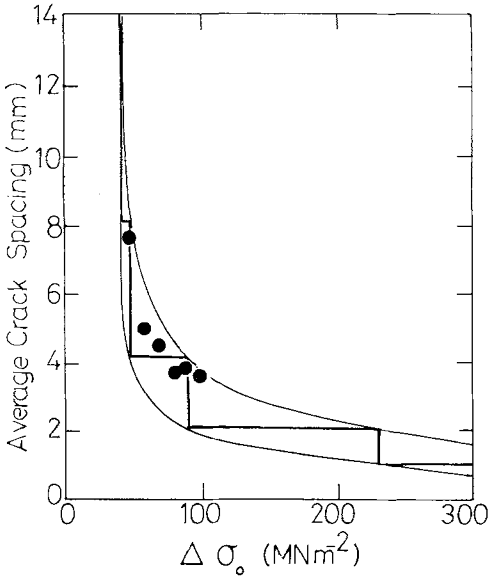

Figure 7 Comparison between the multiple transverse cracking theory and experiment for a glass fibre reinforced polyester cross-ply laminate with a transverse ply thickness of 3.2 mm; data taken from Garrett and Bailey [1], showing close agreement between the corrected theory and experiment.

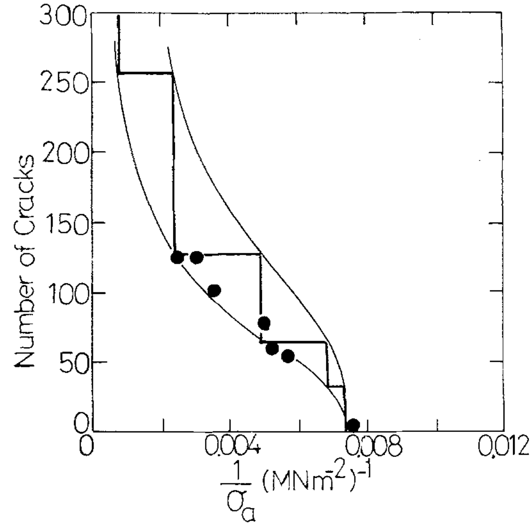

Figure 8 Theoretical and experimental relationships between number of cracks per specimen and the reciprocal of the applied stress, indicating an approximately linear relationship over the experimentally observable range. Data taken from Fig. 6b.

tinuous upper and lower curves provide a range for the crack spacing for an arbitrary specimen length and any position of the first crack, as discussed elsewhere [1].

5. Discussion

Figs. 6a and b show that there is very close agreement between the transverse multiple cracking theory proposed and the experimental results; this close agreement was found for all four inner ply thicknesses investigated experimentally (see Fig. 5). The discrepancy apparently observed between theory and experiment by Garrett and Bailey [1] resulted from their use of Equation 6 to relate $\Delta\sigma_0$ to the applied stress. We have recalculated the value of $\Delta\sigma_0$ from the applied stress using the correct Equation 5 and find their results to fit the multiple cracking theory closely; an example of the corrected results is shown in Fig. 7.

Stevens and Lupton [4] have recently reported briefly on transverse cracking in a cross-ply fibreglass epoxy laminate, emphasizing an apparent linear relationship between the number of cracks and the reciprocal of the applied stress. We would point out that the theory presented here can be shown numerically to predict such a relationship over a limited crack spacing range and it is not necessary therefore to introduce an arbitrary assumption concerning the transfer of load from the longitudinal to the transverse ply when cracking occurs. This point is illustrated by Fig. 8, which shows a theoretical plot of the number of cracks as a function of the reciprocal of the applied stress, together with experimental results for one particular laminate.

The whitening phenomenon associated with a small "knee" in the stress/strain curve at about 0.3% strain has not been fully explained. However, this association with a small change in modulus suggests that it is a fibre–matrix localized debonding phenomenon. The apparent reversibility of the whitening effect implies that this debonding behaviour is reversible, i.e. rebonding is possible. An alternative explanation may be considered in terms of resin crazing but there is no evidence of crazing occurring during the straining of unfilled epoxy resins. This phenomenon is the subject of further study.

6. Conclusions

Multiple transverse cracking has been studied in four laminates of differing transverse ply thickness for glass fibre epoxy cross-ply composites. Transverse cracks initiate at a strain of 0.55% and multiply with increasing applied stress. Close agreement between the proposed multiple cracking theory and the experimental results is obtained and the discrepancy between theory and experiment observed by Garrett and Bailey [1] has been resolved.

At a lower strain of 0.3% a small modulus change is observed, the magnitude of which is dependent upon transverse ply thickness and is accompanied by a visual whitening effect.

Acknowledgement
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