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The effect of resin failure strain on the tensile properties of glass fibre-reinforced polyester cross-ply laminates

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An investigation has been made of the effect of resin properties on the transverse cracking behaviour of glass fibre-reinforced polyester resin three-ply laminates. The polyester resin properties were modified by the addition of a flexibilizing resin to produce five resin systems with failure stresses ranging from 1.75 to 11.1%. The mechanical properties of the resins which were determined, are observed to affect the stress level at which transverse cracking is initiated and the nature of the cracking behaviour. If fibre bunching is taken into account the Kies strain magnification theory can predict the general trend of the results. However, it is concluded that strain-rate effects associated with fibre bunching are worthy of further investigation.

1. Introduction

A major limitation of unidirectional glass fibre-reinforced plastics (GRP) is their poor mechanical performance in the transverse (90°) direction, often possessing transverse strengths less than the strength of the unreinforced plastic. However, it is rare to find engineering applications where strength and stiffness in one direction only is required, and this necessitates the use of cross-ply laminate structures. Unfortunately the poor transverse performance of unidirectional composites is reflected in the cross-ply properties, as cracks develop in the transverse ply at low strains. For a typical glass fibre/polyester laminate these cracks develop at strains of about 0.4%, compared with the ultimate failure of the laminate of about 2.5% and a resin failure strain of 4%.

Garrett and Bailey [1] have shown that these cracks develop under a rising stress and form with a very even crack spacing. The crack spacing was found to be a function of transverse ply thickness and applied stress, and to be consistent with the ideas of multiple cracking, normally associated with unidirectionally reinforced brittle matrix composites. In the case of the cross-ply laminates the transverse ply acts as a brittle layer sandwiched between layers (0° orientation) of higher failure strain. Although the integrity of the laminate is maintained during cracking, these cracks are very undesirable, for example, in the walls of pressure vessels and liquid containers where leaks might develop. In wet or corrosive environments, transverse cracking can be serious because chemical attack within these cracks can weaken the fibre–matrix bond, and cause premature failure of a material otherwise known for its excellent chemical resistance. Under these conditions, the usable working strain range of GRP is greatly curtailed. It has also been found that transverse cracking plays a major role in the development of fatigue damage as demonstrated by Broutman and Sahu [2] on a glass/epoxy system.

Kies has shown that the low-strain damage in the transverse ply is a consequence of a strain magnification between close transverse fibres. As the fibres are much stronger and stiffer than the resin most of the strain is concentrated in the thin resin layer between the fibres. Kies [3] found that in the limit, when the transverse fibres are virtually touching, a strain magnification factor of E_f/E_m exists in the resin (E_f and E_m are the

Young's moduli of the fibres and resin respectively). Thus the onset of transverse cracking can be delayed by a closer matching of the moduli of the constituents, or by using resins with higher failure strains. Lavengood and Ishai [4] have compared the effect of a so-called "brittle" and "ductile" epoxy (failure strains of 3.5 and 5.6% respectively) and have shown that the transverse-cracking threshold strain was increased from 0.5 to 1.0% by using the more flexible resin. Also Stevens and Lupton [5] have shown that a substantial increase in this threshold strain can be achieved using a resin that undergoes yielding and cold drawing under stress, thus relieving the stress concentrations around fibres.

In this paper we describe tensile experiments on $(0°, 90°, 0°)$ cross-ply glass fibre/polyester laminates where we have investigated the effect of a variation of the resin failure strain, by using a flexibilized resin system, on the strain threshold for transverse cracking and the resulting cracking behaviour.

2. Experimental details

The experiments were carried out using composites made from unidirectional glass fibre roving (Silenka 'E' glass of 1200 tex* with a silane finish) and a polyester resin T400 supplied by ICI. A flexibilizing resin D1015 could be added to the T400 in differing proportions to produce resins with failure strains of between 2 and 12%.

Three-ply laminates were constructed in the configuration $(0°, 90°, 0°)$ and were made by winding the roving around a square metal frame in the required manner and impregnating them with the resin taking care to eliminate any air bubbles. The wet rovings were placed between glass plates and were squeezed to expell excess resin. The specimens were gelled at room temperature for 12 h and then post-cured at 80° C for 4 h.

Five sets of laminates were constructed with resin failure strains of 1.75, 2.4, 3.3, 7.0 and 11.1%, and for each resin system neat resins specimens were cast in "dog-bone" shaped moulds. These specimens were carefully polished down to 10 μm before being subjected to testing. The glass volume fraction of the specimens was measured to be 30% by resin burn-off techniques.

Straight-sided specimens of width 20 mm were cut from each of the laminates using a diamond wheel and were tested in tension on an Instron machine at a cross-head speed of 0.05 cm min^{-1}. Strain was measured with resistance strain gauges glued on to the specimens and a direct load/strain plot was recorded. An acoustic emission transducer was mounted onto the specimens under test to record the acoustic noise emitted from the specimen as damage occurs in the transverse ply. This gave a good indication of the strain at which transverse cracking initiated.

Tests from a given set of specimens were stopped at different strains so that a complete record of the extent and type of damage could be obtained.

3. Experimental results and discussion

The experimental data for the unreinforced resins are shown in Fig. 1 and 2. Increasing the proportion of the flexibilizing resin produced resins with correspondingly higher elongations to break, but it is apparent from Fig. 2 that the more flexible systems have both lower strengths and Young's Moduli. The tests were performed at a strain rate of 1.2×10^{-4} sec^{-1}.

As the tensile cross-ply specimens were straight-sided ultimate failure generally occurred prematurely in or near the grips at about 1.8%, and so

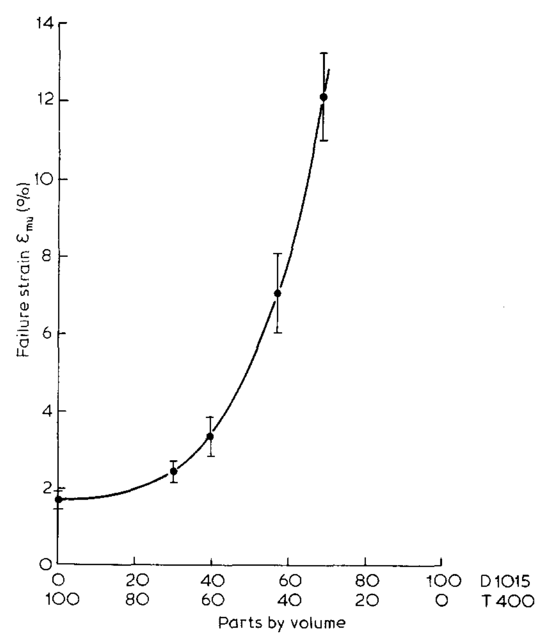

Figure 1 Resin failure strain as a function of the amount of flexibilization. T400 is the polyester resin and D1015 is the flexibilizing resin.

*1 tex = 1 mg m^{-1} = 9 denier.

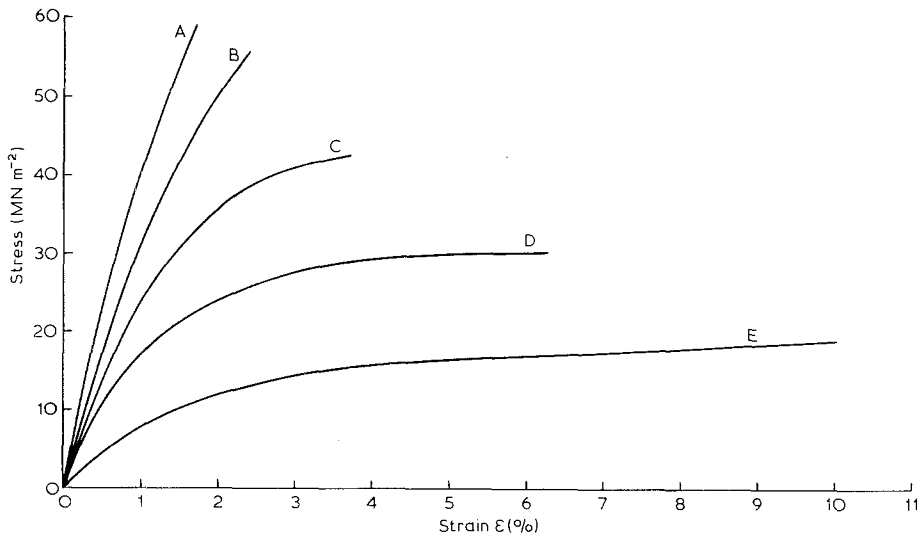

Figure 2 Stress–strain of the resins used in the laminates. Curve A is the neat polyester resin and curve E is the most flexibilized resin.

tests were stopped just before this occurred. However, the laminate made with the most flexible resin consistently failed by shear in the grips at about 1.4% strain and so no data could be obtained above this value for this laminate.

Generally transverse cracking initiated at correspondingly higher strains for the resin systems of higher failure strain, as indicated in Fig. 3. No cracking was observed in the most flexibilized laminate up to its failure strain of 1.4%. The onset of transverse cracking is associated with a "knee" in the stress–strain curve and a sharp increase in the acoustic noise recorded by the transducer. This is especially so for the more brittle resin systems (see Fig. 4) but is less apparent for the more flexible systems, where the knee is less distinct and a fair level of acoustic noise is recorded before damage is seen. The stress–strain curve for the most flexibilized laminate exhibits no knee and no visible damage occurred in the specimen.

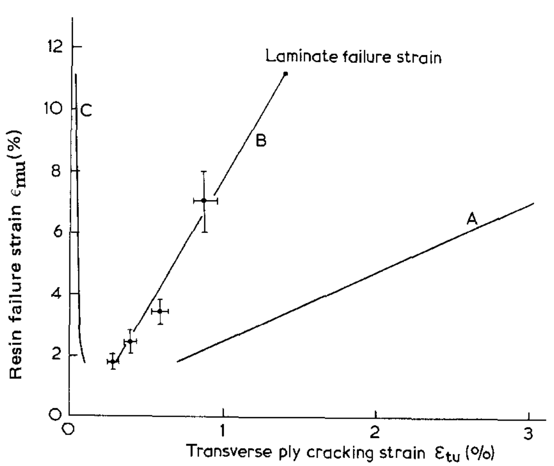

Figure 3 Observed transverse ply cracking strain as a function of resin failure strain. Curves A and B are the theoretical predictions of the Kies theory for a regular cubic array of fibres for $V_f = 30$ and 58% respectively (see text). Curve C is the Kies theory when the fibres are touching.

Two distinct types of transverse cracking were observed in the laminates. Laminates made from the resins of failure strain 1.7, 2.4 and 3.3% cracked in a brittle fashion. These cracks form in a direction perpendicular to the applied stress and a regular crack spacing is built up under a rising stress. They propagate noisily and rapidly across the whole cross section of the transverse ply. These evenly spaced cracks are a result of the multiple cracking of the transverse ply, sandwiched between the longitudinal plies of higher failure strain (This phenomenon is fully discussed elsewhere [1]). Occasionally longitudinal cracks formed in the outer plies at strains above 1% for the laminate made from the 1.7% failure strain resin. An example of this can be seen in Fig. 5.

In contrast to the above laminates, those made from the 6.5% failure strain resin failed in a less catastrophic manner. The damage was more diffuse and developed in a more controlled manner. At high strains a fairly even crack spacing is set up but the cracks are less distinct and straight than those in the more brittle systems. Fig. 6 shows

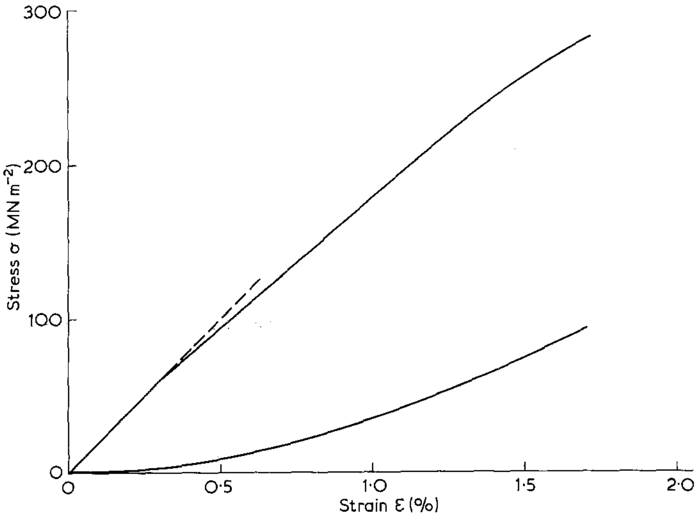

Figure 4 Stress–strain curve of laminate made from resin with a failure strain of 1.75%. The lower curve is the integrated acoustic emission counts (arbitrary units).

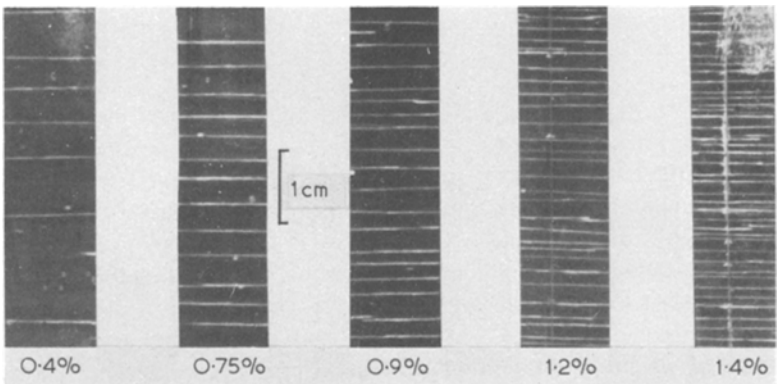

Figure 5 The build-up of the "brittle" transverse cracking as the strain is increased from 0.4 to 1.4%. Resin failure strain = 1.75%.

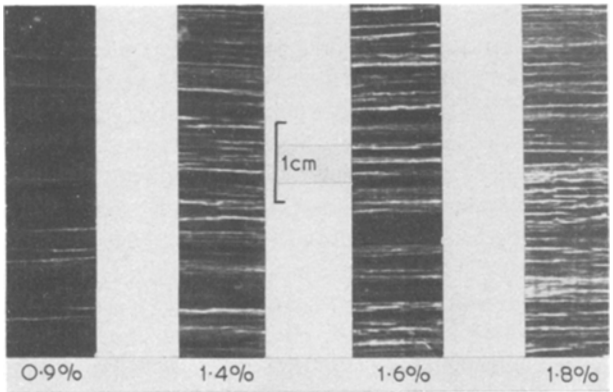

Figure 6 The build-up of "diffuse" transverse cracking as the strain is increased from 0.9 to 1.8%. Resin failure strain = 6.5%.

these two types of cracking behaviour and demonstrates how the crack spacing develops as the stress increases. Kies [3] in a theoretical argument showed that a strain magnification in the resin between transverse fibres can account for the low-failure strain in the transverse ply.

The strain magnification factor (SMF) between transverse fibres is defined as:

$$\text{SMF} = \frac{\text{strain in the resin between fibres}}{\text{overall strain in the transverse ply}}$$

At failure in the transverse ply:

$$\text{SMF} = \frac{\epsilon_{mu}}{\epsilon_{tu}} \tag{1}$$

where ϵ_{mu} and ϵ_{tu} are the matrix and transverse-ply failure strain respectively. Kies [3] found that

$$\text{SMF} = \frac{2R + D}{2RE_m/E_f + D}$$

where R = fibre radius, and D is the interfibre spacing which for a square array is given by:

$$D = R[(\pi/V_f)^{1/2} - 2]. \tag{3}$$

The equation, derived by substituting equation 3 into Equation 2, is plotted in Fig. 7 for resin moduli of 0.2, 2 and 10 GN m^{-2}. This is the range in which resin moduli generally fall. It is obvious from the plot that the resin modulus has little effect below 50 vol% so the transverse ply failure strain and volume fraction only. This can be deduced from Equation 2 by assuming $D \gg 2RE_m/E_f$. Hence,

$$\text{SMF} = 1 + 2R/D, \tag{4}$$

and for a square array,

$$\text{SMF} = 1 + 2[(\pi/V_f)^{1/2} - 2]^{-1}. \tag{5}$$

Thus, from Equations 1 and 5:

$$\epsilon_{tu} = \epsilon_{mu}/[1 + 2[(\pi/V_f)^{1/2} - 2]^{-1}]. \tag{6}$$

In contrast to the above result, when the fibres are virtually touching at a volume fraction of $\pi/4$, Equation 2 reduces to

$$\text{SMF} = E_f/E_m. \tag{7}$$

Thus

$$\epsilon_{tu} = \epsilon_{mu}E_m/E_f. \tag{8}$$

Under these conditions, the transverse-ply failure strain is proportional both to the resin modulus and to its failure strain.

The comparison between the experimental results and Equation 6 for $V_f = 30\%$ is shown in Fig. 3; clearly the theory overestimates ϵ_{tu} when a regular array of fibres is considered. If, on the other hand, we assume that the fibres are distributed in a random manner, cracks may develop between very close transverse fibres because of the high SMF present. In this situation Equation 8 will be applicable and its predictions are shown in Fig. 3. The resin stress–strain curves are highly non-linear and in the analysis we have chosen a secant modulus drawn from the origin to the point of failure. In contrast to the regular fibre array, Equation 8 underestimates the transverse ply failure strain but, more importantly, it predicts that ϵ_{tu} decreases with increasing resin flexibility. This is not borne out by the experimental data. This decrease in ϵ_{tu}, derived from Equation 8, is a consequence of the average resin modulus decreasing at a faster rate than the corresponding increase in the failure strain (see Fig. 2). It is interesting to note that there is a possibility that

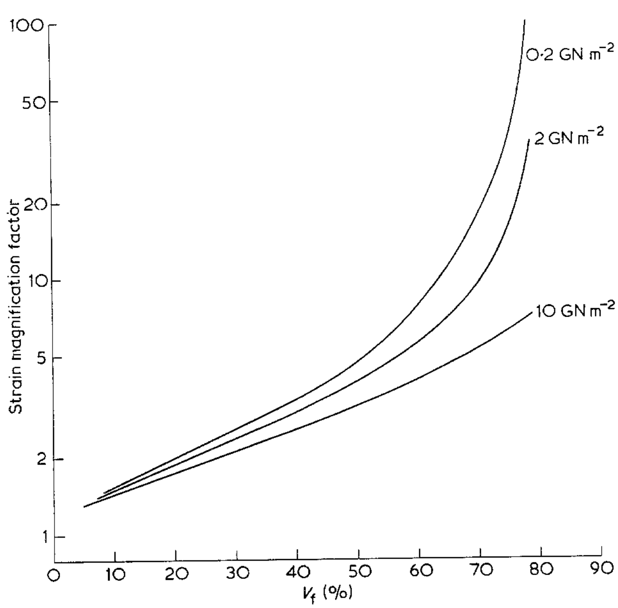

Figure 7 The Kies strain magnification theory as a function of volume fraction for resin moduli of 0.2, 2, and 10 GN m^{-2}

transverse cracking may initiate at lower strains in very high V_f composites when flexible resins are used.

Clearly the experimental data falls between these two cases considered, and, indeed, it can be fitted to the theory by using a volume fraction of 53%. This possibly reflects fibre bunching in the laminate with the closeness of approach of the fibres limited by the moulding process.

TABLE I

Resin failure strain ϵ_{mu} (%)	Regular array $V_f = 30\%$		Fibres touching	
	ϵ_{tu}(%)	SMF	ϵ_{tu}(%)	SMF
1.75	0.75	2.4	0.080	21
2.4	1.0	2.5	0.075	32
3.4	1.4	2.6	0.053	64
7.0	2.9	2.6	0.050	140
11.1	4.6	2.6	0.032	350

The application of SMF is further complicated by possible strain-rate effects in the resin. The strain rate in the resin between transverse fibres is not that of the overall laminate but is scaled up in proportion to the SMF present. Table I shows the calculated SMF for both regular fibre packing for $V_f = 30\%$ and for fibres touching. Obviously for the latter case very high SMF, and hence high strain rates, occur in the resin. This is to be compared with the low SMF when the fibres are arranged in a regular way for $V_f = 30\%$. It has been shown that the failure strain of flexibilized polyesters are very rate-dependent [6] and tests on the resins systems used in this work have shown that a 40 fold increase in strain rate from $1.2 \times 10^{-4}\ \text{sec}^{-1}$ to $4.8 \times 10^{-3}\ \text{sec}^{-1}$ reduced the failure strain of the highly flexibilized resin by a factor of 2, and the initial modulus was increased to a small extent. In other words, the resin becomes less ductile. For the unflexibilized resin system little change was observed. From Table I it can be seen that when a regular fibre array is considered the SMF is relatively low (~2.4) and little strain-rate effect will be felt by the resin and so the earlier comparisons between theory and experiment will be relatively unchanged. However, the SMF between close fibres is high especially for the more flexibilized resins and major changes in the resin properties will occur. However, the present results suggest that the predictions of Equation 8 may be relatively unaffected as the *average* modulus (secant modulus) increases as the failure strain decreases; clearly a more detailed investigation of this point is called for.

4. Conclusions

It is readily apparent that the properties of the resin play an important role in both the strain level at which transverse cracking occurs and the type of cracking behaviour. The onset of cracking can be delayed using more flexible resins of higher failure strain and indeed eliminated (up to 1.4% strain) with resins of failure strain in excess of 10%.

The Kies strain magnification theory predicts the general trend of the results if a regular fibre array is assumed but it overestimates the magnitude of the effect. However, consideration of fibre bunching largely removes the discrepancy. The importance of strain rate for ductile matrix laminates requires further investigation but the rather limited results obtained suggest that this may not be a major effect.

Laminates made from low failure strain (<4%), high modulus resins exhibit catastrophic cracking of the transverse ply which builds up in a regular fashion to produce regularly spaced cracks parallel to the transverse fibres. For higher failure strain, lower modulus resins (~6%) a more diffuse type of damage occurs with cracks growing in a controlled manner as the applied stress increases.

Thus, more flexible resins can extend the usable strain range of a GRP cross ply laminate in situations where microdamage is undesirable but the poor long-term properties of flexibilized resins may limit the usefulness of these systems.

References

1. K. W. GARRET and J. E. BAILEY, *J. Mater. Sci.* **12** (1977) 157.
2. L. J. BROUTMAN and S. SAKU, "Progressive Damage of a Glass Reinforced Plastic During Fatigue", Proceedings of the 24th Annual Technical Conference, SPI Reinforced Plastics/Composites Division, Paper 11-D, New York (1969).
3. J. A. KIES, U.S. Naval Research Laboratory, Report No. 5752 (1962).
4. R. E. LAVERGOOD and O. ISHAI, Polymer Eng. Sci. **11** (1971) 226.
5. G. T. STEVENS and A. W. LUPTON, *J. Mater. Sci.* **11** (1976) 569.
6. G. D. SIMS, Private Communication, 1977.

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