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Hybrid effects in composites: a comparison between interlaminar and translaminar configurations

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In a recent study the prerequisites for a hybrid effect and the factors which determine the occurrence of a positive or negative effect were examined and specified [2]. In this study, the influence of loading configuration on the hybrid effect is examined by comparing results from interlaminar and translaminar loadings. It is shown that the hybrid effect depends on the loading configuration through its dependence on the mode of failure. A positive hybrid effect under interlaminar loading is more likely to occur when the two types of fibres form an intimate mixture, whereby higher stress and greater energy are required to initiate delamination failure.

1. Introduction

The advantages offered by hybrid composite materials are often considered in terms of the improvement in a particular mechanical property resulting from the addition of a second reinforcement type. The improvement is examined in comparison with a control which does not contain the second reinforcement; i.e. the predicted Rule-of-Mixtures (RoM) value, which sums the proportional contributions of the *three* phases, is ignored. A typical example is the reported "hybrid effect" for the strain at failure in hybrids of epoxy reinforced by 3/1 glass/carbon fibres, where although the observed failure strain of the hybrids exceeds the normal failure strain for carbon fibre-reinforced composite, it is below the RoM value [1].

A different approach is to assume load sharing for the three-phase composite, implying that the RoM is valid. This approach appears to be the more natural since in most cases load sharing (RoM behaviour) is assumed for two-phase composites, and a similar assumption for hybrids may simply be regarded as a generalization. On the basis of the second approach, a hybrid effect has recently been considered as a deviation from the RoM behaviour. Positive or negative deviations are taken as positive or negative hybrid effects, respectively [2]. This view is also analogous with the case of two-phase composites, since it is well known that some of their properties (e.g. fracture energies) exceed the RoM value and exhibit a synergistic improvement relative to the properties of the constituent materials. This happens mostly with mechanical properties which are sensitive to the physical structure of the composite, in particular, to the presence of the interface.

Regarding the second definition of the hybrid effect, the latter work [2] has shown that a prerequisite for a hybrid effect is that the two types of reinforcements differ by both their mechanical properties and by the interfaces which they form with the matrix. Once this condition is fulfilled, the existence of a positive or a negative hybrid effect is determined by three factors as shown for glass/carbon hybrids: (i) the relative volume fractions of the two fibres [3], (ii) the arrangement of the fibres in the hybrid (intimate contact, distinct layers, or sandwich structure) [2, 4], and presumably (iii) the loading configuration.

The present study examines the influence of loading configuration on the hybrid effect by comparing the results from interlaminar and translaminar modes of loading.

2. Experimental details

Unidirectional glass/carbon hybrids (g/c) were constructed from "prepregs" of E-glass fibre and AS-carbon fibre as described in detail in [2]. Three types of such hybrids were prepared and designated by 1/1, 2/2 and 5/5, describing the number of sequential layers of "prepregs" of each reinforcement in the hybrid. The 2/2 and 5/5 hybrids were constructed of alternating plies of glass and carbon, each containing 2 or 5 "prepreg" layers, respectively. The 1/1 hybrids were prepared by a special technique from 1/1 hybrid "prepregs". The total volume fraction of fibres in all the hybrids was 50%, divided equally between the two fibre types. The interlaminar and translaminar loading configurations are illustrated in [5].

The specimens oriented for deformation in the interlaminar mode were tested in three-point bending at a loading rate of 8.3×10^{-6} m sec^{-1} obtained with an Instron Universal Tester. Notched and unnotched specimens were tested, and at least 5 specimens were used to obtain an average for each property.

The unnotched specimens were 0.6 cm deep and 0.5 cm wide, and were tested over a loading span of 8.0 cm. This produced a span to depth ratio of 13.3, satisfactory for measuring the Young's modulus. The notched specimens had similar cross-sectional dimensions, and contained a 0.1 cm wide by 0.2 cm deep notch; the loading span was 4.0 cm. In the 5/5 hybrids, where the thickness of an individual glass or carbon ply was about 0.05 cm, two types of notched specimens were prepared. In one type the notch traversed across alternating plies of glass/carbon/glass/carbon with its tip against a glass ply, and in the second type the notch traversed across alternating layers of carbon/glass/carbon/glass with its tip against a carbon layer.

The mechanical properties measured were the Young's modulus (E), the apparent fracture toughness (K_{IC}), the fracture surface energy (γ_{I}) and the work of fracture (γ_{F}). Also, γ_{σ}, the integral of the load–deflection curve to maximum load per total new fracture surface area was calculated. A detailed description of the calculation method is given in [2].

3. Results and discussion

Table I presents the results for interlaminar loading together with the results obtained previously [2] for translaminar loading. The coefficients of variation for these results were generally about 0.1. These results enable us to study the effect of the arrangement of the fibres in the hybrid (layer sequence) on the occurrence of hybrid effects in interlaminar loading; and to compare interlaminar and translaminar configurations. In the next sections the individual mechanical properties measured are viewed with reference to these two aspects.

3.1. The modulus

The results of Young's modulus indicate that this property is determined by the RoM for interlaminar as well as for translaminar loadings. Also, it is evident that this property does not depend on the construction of the layers in the hybrid. These observations are in agreement with various references, for example [6]. Thus, the modulus of three-phase composites follows the behaviour of that of two-phase composites in the sense that RoM is obeyed, irrespective of the volume fraction and the lay-up sequence of the fibres.

A comparison of the interlaminar moduli with the translaminar moduli shows that the values of the former are slightly lower than those of the latter. This is in contrast to observations made on glass-reinforced composites [5], where interlaminar values were, in general, slightly greater than the translaminar. (This was explained in accordance with Tsai's [7] modified RoM expression for the modulus which includes a factor k, accounting for the different states of fibre misalignment which may exist in the interlaminar and translaminar directions.) We believe, however, that the comparison here is invalid due to the different geometries of the test specimens, which had a 0.5×0.6 cm^2 rectangular cross-section. Thus, the span-to-depth ratio for translaminar specimens was 16 and for the interlaminar 13.3, which may account for the lower interlaminar modulus values [4].

3.2. Fracture initiation

Fracture initiation under interlaminar loading is characterized in this work by the parameters K_{IC},

TABLE I Interlaminar and translaminar properties of glass fibre composites, carbon fibre composites and g/c hybrid

Reinforcement	Interlaminar					Translaminar*				
	E (GPa)	K_{IC} (MN m$^{-3/2}$)	γ_I (kJ m^{-2})	γ_σ (kJ m^{-2})	γ_F (kJ m^{-2})	E (GPa)	K_{IC} (MN m$^{-3/2}$)	γ_I (kJ m^{-2})	γ_σ (kJ m^{-2})	γ_F (kJ m^{-2})
E-glass fibre	24.0†	30.5	19.4	22.8	64.4	25†	27.0†	14.6†	27.6†	54.0†
AS-carbon fibre	82.5	45.3	12.4	22.4	64.6	97	50.8	13.3	33.5	38.0
Hybrid 1/1	55.6	38.7	13.5	23.6	54.9	61	34.7	9.9	21.7	30.6
Hybrid 2/2	53.4	34.9	11.4	22.0	51.4	61	32.4	8.6	17.8	27.9
Hybrid 5/5 ‡	55.7	31.8	9.1	16.9	52.0	62	34.7	9.7	20.6	46.0
Hybrid 5/5 §		27.3	6.7	14.5	44.6					
RoM	53.3	37.9	15.9	22.6	63.5	61	38.9	13.9	30.6	46.0

* Taken from [2].

† Taken from [6].

‡ Notch on carbon fibre layer.

§ Notch on glass fibre layer.

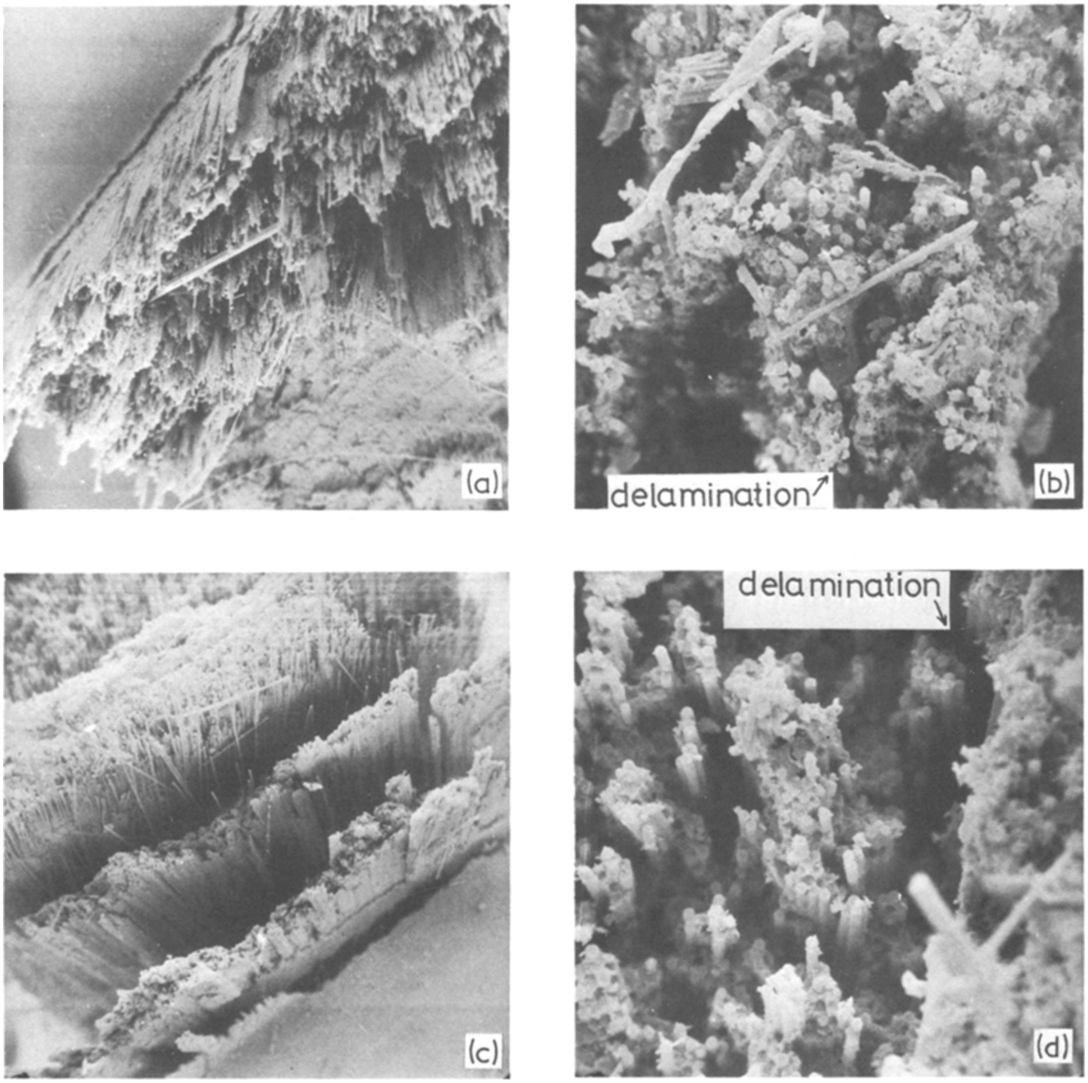

Figure 1 Scanning electron micrographs of the fracture surfaces of hybrids under interlaminar loading: (a) a typical fracture surface of a 1/1 hybrid (× 18); (b) delamination between glass and carbon layers in a 1/1 hybrid (× 98). The diameter of the glass is twice the diameter of the carbon fibre; (c) a typical fracture surface of a 5/5 hybrid (× 18); (d) delamination in a glass/carbon interply in a 5/5 hybrid.

γ_I and γ_σ. The measurements of the critical stress intensity factor in composites is controversial, let alone in this case, where failure occurs by delamination, i.e. by unconventional propagation of the crack at right angles to its axis. However, even if the results cannot be regarded as valid K_IC values they still are a function of stress and crack length, and can be used in a comparative study. The values of these fracture parameters exhibit very similar trends, in which they decrease from RoM values as the plies of the two reinforcements become more segregated. The lowest values belong to the 5/5 hybrids in which the tip of the notch is against a glass layer. Since the 1/1 hybrids were prepared by a special technique from 1/1 hybrid "prepregs", the fibres formed a more intimate mixture with less interply planes than in the 2/2 or 5/5 hybrids. Visual and scanning electron microscopic examinations of the test specimens (Fig. 1) both indicate that failure under interlaminar loading occurs by delamination. When the fibres form a more intimate mixture (Fig. 1a and b), failure by delamination will be more difficult than when they are arranged in distinct layers (Fig. 1c and d). Hence, it is clear that under interlaminar loading where delamination develops, segregation of the reinforcement layers results in a negative hybrid effect.

3.3. The work of fracture

The prominent features of the work of fracture in interlaminar loading are that its values do not depend on the arrangement of layers, and that they exhibit a negative hybrid effect. Also, the interlaminar values are always greater than the translaminar values. These features may be understood by examining the results of the two-phase composites. The interlaminar work of fracture values of glass fibre-reinforced epoxy are slightly higher than the translaminar values, in agreement with a previous study [5]. This results from the fact that the main contribution to the work of fracture of glass–epoxy composites is from pull-out regardless of the loading configuration. Since in interlaminar loading some delamination occurs in addition to pull-out, its work of fracture values are slightly higher. In carbon fibre-reinforced epoxy the pull-out energy is much smaller (as reflected by the four-fold smaller pull-out length), and only in interlaminar loading, where delamination occurs, are the work of fracture values for carbon fibre composites of the same order as for glass fibre composites.

With regard to the hybrids, stress–deflection curves presented in Fig. 2 reflect the different energy dissipation mechanisms in the hybrids under the two loading configurations. Whereas the translaminar results are affected by the structure of the hybrid (manifested by the pull-out lengths) [2], the interlaminar work of fracture is independent of the construction of the layer and is dominated by delamination; hence, the higher interlaminar work of fracture values in the hybrids. The small negative hybrid effect may be explained by the presence of glass/carbon interply planes, where delamination can spread in a less controlled fashion. It is underlined that in the 1/1 hybrids the fibres formed an intimate mixture with no sharp interply planes. Regarding this issue it is interesting to examine results obtained in [4] and [8] for g/c composites tested in impact. For hybrid laminates with alternate and combined constructions mostly a negative deviation from RoM is reported [4], while for hybrid laminates with sandwich construction (with significantly less glass/carbon interplay planes) a positive hybrid effect is reported [4, 8].

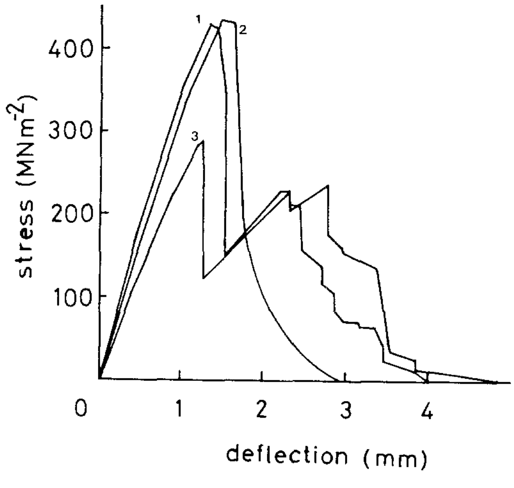

Figure 2 Stress in bent notched beam versus deflection for the hybrids: (1) 1/1 interlaminar; (2) 1/1 translaminar; (3) 5/5 interlaminar (notch on glass).

The fact that delamination is a dominant fracture mechanism of hybrids in interlaminar loading is seen clearly in the scanning electron micrographs of the fracture surfaces presented in Fig. 1. Despite the observation that the pull-out lengths of the two types of fibres change when the layer arrangement in the hybrid is changed, the γ_F values remain unaltered, revealing insensitivity to the pull-out length. It is also seen clearly that delamination develops more readily in the 5/5 hybrids, especially in the glass/carbon interply planes.

4. Conclusions

The present study demonstrates that the loading configuration strongly influences the hybrid effect. The loading configuration is responsible for the mechanism of fracture: under interlaminar loading failure occurs by delamination, and under translaminar loading the prominent mechanism is pull-out. The hybrid effect, therefore, depends on the loading configuration through its dependence on the mode of failure.

Apart from academic interest, more significance is attached to the interlaminar case, since it is applicable to real composite structures. A positive hybrid effect under interlaminar loading is expected to occur when the two types of fibres form an intimate mixture, whereby delamination does not take place. Another possibility for a positive hybrid effect is in sandwich constructions which by nature contain very few interply planes.

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