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Interlaminar shear fatigue of pultruded graphite fibre-polyester composites

C. K. H. DHARAN
Western Development Laboratories, Ford Aerospace and Communications Corporation, Palo Alto, California, USA

The effect of cyclic loading on the interlaminar shear strength of pultruded graphite fibre–polyester was determined. Two fibre volume fractions, 0.5 and 0.33, were studied. The results indicate that the deterioration in the interlaminar shear strength with cycling is significantly greater than in flexural fatigue. The higher volume fraction material showed a greater drop in the interlaminar shear strength than the lower volume fraction material. Unlike the monotonic strengths, the effect of the fibre volume fraction on interlaminar shear fatigue strength at high cycles is small, indicating that there is little advantage in increasing the fibre volume fraction to improve the interlaminar shear strength in high cycle fatigue environments. A critical stress was determined above which interlaminar shear fatigue failure did not occur within 10^7 cycles for the materials tested.

1. Introduction

The decline in the price of graphite and aramid fibre production is making composites available for applications other than in aerospace and in some sporting goods. An area where advanced composites can be expected to be used in the future is the automotive industry where weight reduction using composites can result in direct benefits in fuel savings. For cost-effective application of composites to high-volume production, however, suitable mass-production techniques must evolve to produce parts with the designed fibre orientation and strength at a much faster rate than current methods of compression-moulding pre-impregnated sheets.

One such process is pultrusion where straight extrusion-like shapes can be produced continuously at 1 to 3 m min^{-1}. In pultrusion, continuous fibres (and sometimes mat) are pulled from creels through a resin bath, where they are wetted, and through a heated die, where the fibres are consolidated and the excess resin removed. A post-cure oven cures the pultrusion as it is continuously pulled through the die. The structural shapes produced have fibres oriented in the longitudinal direction only and are therefore extremely stiff and strong. To increase the transverse strength, a fibre mat is often incorporated during pultrusion.

Pultrusions may be used in applications where high bending and axial loads are to be sustained, for example, in leaf springs. In flexure, however, shear stresses are developed which reach a maximum at the neutral axis of the beam. These stresses may be significantly large for unidirectionally reinforced materials where the interlaminar shear strengths are very low compared to their flexural strengths. Thus, it is important to know the interlaminar shear strengths, especially if the beams are cyclically loaded, since shear failure can occur at stresses well below the flexural fatigue strength of the composite.

The cyclic shear response of a single fibre volume fraction unidirectional graphite fibre-epoxy was reported by Pipes, who showed that the shear strength decreases much faster than the flexural strength as the number of cycles to failure increases [1]. In the present investigation, the cyclic shear response of unidirectional pultruded graphite fibre–polyester was determined as a function of two fibre volume fractions. It is a continuation of an earlier investigation in which the flexural fatigue response and failure modes of the same materials were characterized [2].

2. Experimental procedure

Composites of unidirectional high-modulus graphite fibre (polyacrylonitrile precursor) in a polyester matrix were obtained in the form of pultruded strips 3 mm x 25 mm in cross-section and in two fibre volume fractions: 0.33 and 0.50. These materials were studied earlier when their flexural fatigue responses and fatigue failure modes were characterized [2]. Cross-sectioned micrographs revealed the presence of flaws characteristic of a pultruded product. These flaws could be broadly classified into three categories: resin-rich zones, voids and fibre misorientation. Of the three, the most serious, fibre misorientation, resulting from die friction during processing, occurred only at the surfaces of material and, therefore, would not be expected to play a significant role in initiating cracks during shear fatigue since the maximum shear stress occurs at the mid-plane. However, specimens in which these defects could be detected at the surface were not used.

Three-point short-beam bend tests were conducted in which the specimen span-to-depth ratio was 8. Cyclic loading was performed on an electrohydraulic fatigue testing machine operating in the load control mode in which the applied load was varied from essentially zero load to the set maximum load ($R = 0.05$). A constant strain rate was imposed during loading and unloading by using a triangular strain–time profile. (When the load amplitude was changed, the frequency was adjusted to maintain the same cyclic strain rate). The cyclic frequency range for the tests was low (2 to 4 Hz) to minimize heating effects.

In order to preserve the specimen after interlaminar shear failure, displacement error limits were set to shut the test off when the displacement amplitude exceeded these limits. After each test, the failed specimen was inspected to ensure that the failure mode was in interlaminar shear and not in flexure. All data shown correspond to interlaminar shear fatigue failures only.

3. Results and discussion

In the earlier investigation of flexural fatigue behaviour of pultruded graphite–polyester [2], it was shown that flexural failure initiates in the form of a Mode I (opening mode) crack at the compression surface which propagates transversely into the specimen at right angles to the fibres. After some distance, the crack changes direction and becomes a Mode II (shearing mode) crack which was observed (in cross-sectional micrographs) to propagate along resin-rich zones of the pultrusion and parallel to the fibres. Similar behaviour was also observed by Novak who noted that in compression-moulded graphite–epoxy, shear fatigue cracks propagate in the resin-rich zones between layers of prepreg [3]. In [2], scanning electron micrographs further showed that fibre buckling during compression cycling appeared to initiate the opening mode crack propagation and subsequent fatigue failure. Flexural fatigue response for both the 0.50 and 0.33 fibre volume fraction materials could be better represented by plotting the data in terms of the strain amplitude versus number of cycles to failure. In the high cycle regime, no failures were encountered for both volume fraction materials below a certain critical strain level.

In this investigation, data obtained on the shear fatigue response is shown in Fig. 1. The applied cyclic shear stress is plotted against log number of cyclic reversals to failure (twice the number of cycles) for 0.5 and 0.33 fibre volume fraction (V_f) graphite–polyester. Several interesting conclusions can be immediately drawn from Fig. 1:

(1) Monotonic ($2N_F = 1$) shear strengths of graphite–polyester are low. For the 0.5 V_f material it is 26 MPa and 21 MPa for the 0.33 V_f material. These values compare with the considerably higher values of 55 to 97 MPa associated with the shear strengths of compression-moulded unidirectional graphite–epoxy. One of the reasons for the low shear strength of pultruded graphite fibre–epoxy is the higher occurrence of flaws introduced during processing as discussed earlier.

(2) Deterioration in the interlaminar shear strength is more severe for the higher fibre volume fraction material. The 0.33 V_f material declines in strength from its lower monotonic strength of 21 MPa to 15 MPa at 10^7 reversals, a reduction of only 27% compared to a 41% decrease in strength for the 0.50 V_f material.

(3) In the low cycle regime (1 to 1000 reversals), the fatigue response is markedly different for the two fibre volume fraction materials. The 0.5 V_f materials responds with little dependence on cycling. The fatigue curve is relatively flat indicating that in the low cycle region, significant damage probably occurs in the first few cycles in the form

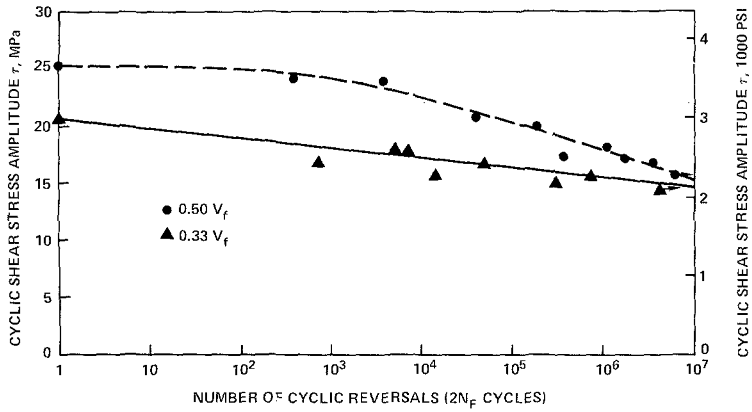

Figure 1 Applied cyclic shear versus number of cyclic reversals to failure ($2N_F$ cycles) for 0.50 and 0.33 fibre volume fraction pultruded graphite–polyester.

of macroscopic interlaminar cracks. These then propagate during subsequent cycling until failure occurs. According to this hypothesis, when the stress is slightly below that required to cause major cracking in the first few cycles, the effect of cycling is more important: the stress is now low enough that, during cycling, crack initiation (from voids and other defects discussed earlier) and crack propagation occur over several thousand cycles before failure. This behaviour is exhibited by the 0.5 V_f material beyond 1000 cycles and by the 0.33 V_f material over the entire cyclic range. The 0.33 V_f material does not show the flat response at low cycles exhibited by the 0.5 V_f material.

(4) At high cycles, the data shows little dependence of the fibre volume fraction on the shear fatigue strength. The two curves approach each other and at 10^7 reversals appear to coincide. The applied cyclic shear stress at this point is about 15 MPa and represents a minimum stress below which fatigue damage is not produced within 10^7 reversals for unidirectional pultruded graphite fibre–polyester. The magnitude of this stress level probably varies for other unidirectional graphite–polymer materials; however, if the fatigue failure mechanisms in interlaminar shear are the same, one would expect the dependence on the fibre volume fraction to be small in this region. Unfortunately, to the author's knowledge, there is no data on the effect of volume fraction on interlaminar shear fatigue response in other composites to check this hypothesis.

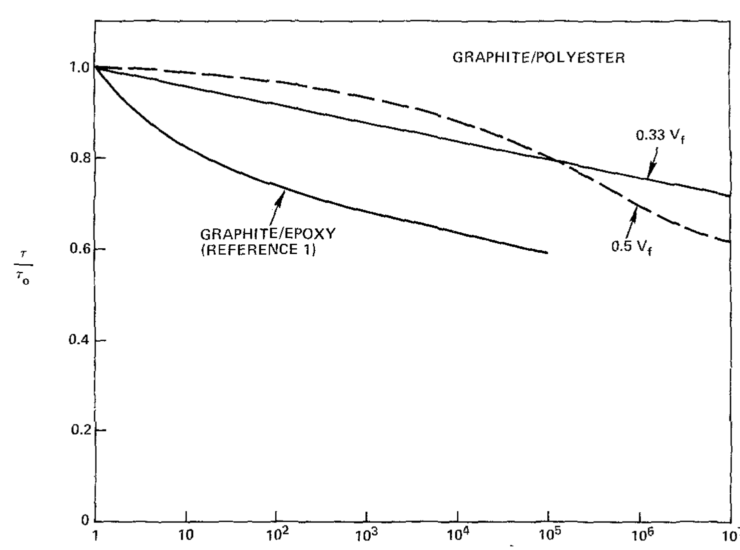

Figure 2 Ratio of the applied cyclic shear stress (τ) to the monotonic shear strength (τ_0) as a function of the number of cyclic reversals to failure for 0.50 and 0.33 fibre volume fraction pultruded graphite–polyester. Also shown is data on graphite–epoxy (HTS/4617) reported in [1].

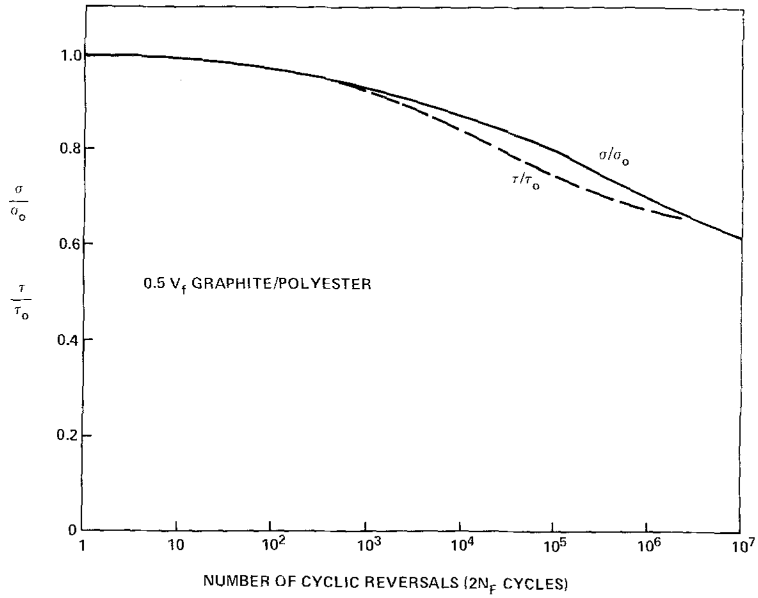

Figure 3 Relative flexural (σ/σ_0) and shear (τ/τ_0) fatigue strengths for 0.50 fibre volume fraction graphite–polyester.

Fig. 2 shows the data in Fig. 1 replotted in terms of the ratio of the applied cyclic shear stress (τ) to the monotonic shear strength (τ_0) as a function of the number of reversals to failure. Also shown in the figure is the shear fatigue response of graphite–epoxy (HTS/4617) reported by Pipes [1]. The graphite–epoxy data shows the largest relative decrease in strength (approximately 50% of its monotonic strength when the data is extrapolated to 10^7 cycles). The graphite–polyester data shows a smaller decrease in strength with cycling although the absolute value of the interlaminar shear strength of the graphite–epoxy is much higher (76 MPa). Beyond 10^5 cycles, the 0.33 V_f graphite–polyester has a relative fatigue response that is better than the 0.5 V_f material.

It is interesting to compare the relative decrease in interlaminar shear strength with the flexural fatigue response. This is shown in Figs. 3 and 4 for the two fibre volume fractions in which the flexural fatigue data on graphite–polyester was reported on earlier [2]. For the 0.5 V_f material, the relative decrease in interlaminar shear strength coincides with that of the flexural strength in the

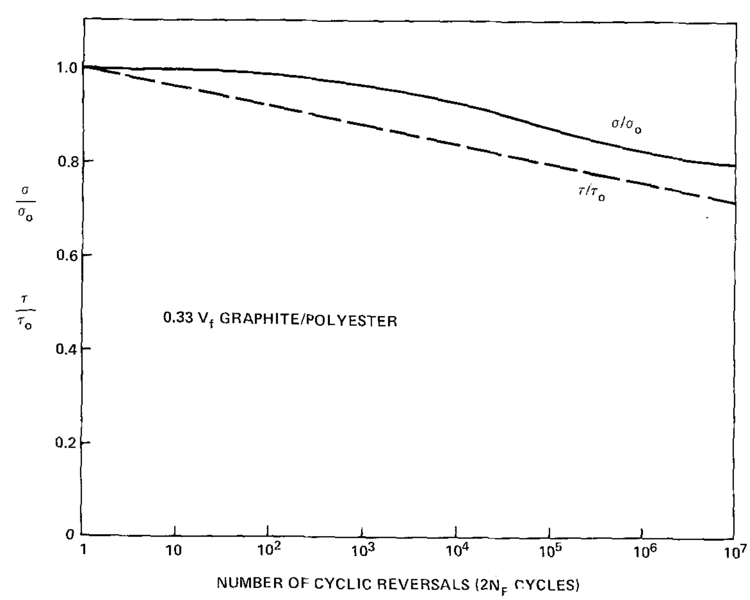

Figure 4 Relative flexural (σ/σ_0) and shear (τ/τ_0) fatigue strengths for 0.33 fibre volume fraction graphite–polyester.

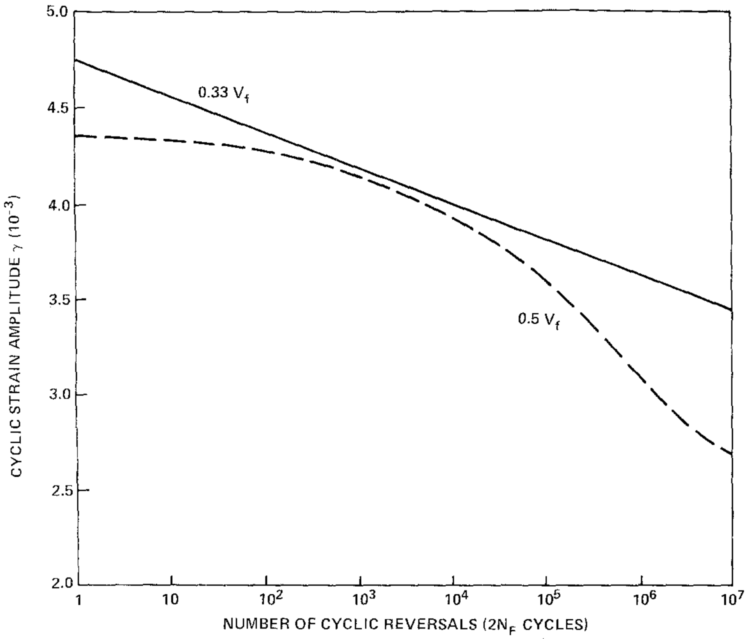

Figure 5 Fatigue response in terms of the applied cyclic shear strain (γ) for 0.50 and 0.33 fibre volume fraction graphite–polyester.

low cycle regime and once again at 10^6 to 10^7 reversals. Between 10^3 and 10^6 reversals, the relative shear strength falls below the flexural strength although the amount by which this happens is small (about 6% at the point of greatest deviation). For the 0.33 V_f material (shown in Fig. 4), the shear response lies well below the flexural fatigue curve over the entire range. The maximum deviation occurs at 10^4 cycles where it is about 10% below the flexural fatigue curve.

The data on graphite–epoxy reported by Pipes, shows a much greater drop in the shear strength relative to the flexural fatigue strength [1]. This underlines the importance of characterizing the fatigue response in shear as well as in flexure since the interlaminar shear strength decreases more rapidly with cycling than the flexural strength. It must be remembered, however, that the graphite–epoxy interlaminar shear strengths obtained by Pipes were much higher than the interlaminar shear strengths of graphite–polyester measured in this investigation. For example, in spite of its rapid deterioration with cycling, the interlaminar shear strength of graphite–epoxy at 10^5 cycles is 43.6 MPa as compared to 19.3 MPa for the 0.5 V_f graphite–polyester.

To determine the strain levels at which interlaminar shear fatigue occurred for the two volume fractions, the data was plotted in terms of shear strain in Fig. 5. The strain was obtained by determining G_{12} for each material and dividing by the appropriate cyclic stress amplitude. Obviously, the assumption of a linear elastic relationship between shear stress and shear strain is implied when this is done. For significant non-linearity, the strain levels will be larger than shown; however, the aim of Fig. 5 is to show the relative cyclic failure strain levels for the two materials. It is evident that no significant trend is indicated when fatigue failure strains are examined. The 0.33 V_f material experiences larger failure strain levels than the 0.5 V_f material over the entire range of cycles to failure. However, until 10^5 cyclic reversals, the difference between the cyclic failure strain levels for the two materials is less than 10%.

4. Conclusions

(1) The interlaminar shear strengths of pultruded graphite fibre–polyester measured in this investigation are low when compared with the interlaminar shear strength of compression-moulded graphite fibre–epoxy measured by other investigators. The values obtained were 26 MPa and 21 MPa for the 0.5 and 0.33 fibre volume fraction materials respectively, as compared with 76 MPa for graphite fibre–epoxy reported by Pipes [1].

(2) The interlaminar fatigue shear strength at low cycles was found to be a function of the fibre volume fraction. This dependence on fibre volume fraction decreases as the number of cycles to failure increases.

(3) In the high cycle regime (10^6 to 10^7

cycles), there was little effect of volume fraction on the interlaminar shear fatigue strength for the two fibre volume fractions of graphite fibre–polyester investigated. There is, therefore, little advantage in increasing the fibre volume fraction to improve the interlaminar shear fatigue strengths in high-cycle fatigue environments.

(4) For unidirectional pultruded graphite fibre–polyester, there is a minimum critical shear stress (independent of the volume fraction) below which interlaminar shear failure does not occur within 10^7 cyclic reversals. The value of the critical stress is 15 MPa for the materials investigated and may be used as a safe design limit for high-cycle fatigue applications. This value could change, however, for cyclic loading in other environmental conditions where the humidity or temperature is different from the laboratory conditions under which these materials were tested.

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