Delamination growth in epoxy-matrix composites under cyclic loading: implications for design and certification

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Abstract

This paper discusses quantitative results from fatigue delamination tests (MMB) at unidirectional and cross-ply ply interfaces in carbon-fibre/epoxy-matrix laminates at three different mixed-mode loading conditions. The implications for material characterisation, structural design and certification are addressed. The results indicate the critical design parameter for delamination in thermoset-matrix composites under cyclic loading is the strain energy release rate threshold, $G_{\text{threshold}}$. The results suggest that a design optimised for static loading with an appropriate safety factor would be approximately optimised for fatigue loading. This would significantly reduce the number of expensive time-consuming fatigue tests required for certification. The cost of fatigue testing may also be reduced by using accelerated test programmes at appropriate low-load cut-off levels, providing careful consideration is given to creep and environmental effects. There is scope for further optimisation by taking a stochastic approach to represent the local variations in toughness in delamination modelling.

1. Introduction

The full commercial benefits of using high performance fibre reinforced plastics have not yet been realised. This is in part due to insufficient understanding of the conditions which may provoke failure, necessitating the use of high safety factors in design and extensive test matrices for characterisation and certification. One area of concern is the effect on structural performance of delaminations, which arise due to manufacturing defects or impact damage. It is well known that cracks in metals can grow in fatigue at loads well below those which would provoke static failure; the fatigue performance of delaminated composites is yet to be fully characterised and understood. The loading on a delamination crack may be peel (mode I) or shear (mode II); in reality the loading conditions are usually a combination of both peel and shear (mixed-mode loading).

Previous studies of interlaminar fatigue have focused on unidirectional ply interfaces. In real structures, containing multidirectional lay-ups, delamination growth is not observed between plies at the same fibre orientation. Delaminations most frequently occur between orthogonally-oriented plies, i.e. at $+45^\circ/-45^\circ$ and $0^\circ/90^\circ$ ply interfaces. Delamination propagation is essentially the same for both cases since delaminations locally grow parallel to the fibres.

This paper discusses quantitative results from fatigue delamination resistance tests at unidirectional ($0^\circ/0^\circ$) and cross-ply ($0^\circ/90^\circ$) interfaces in carbon-fibre/epoxy-matrix laminates.
at three different mixed-mode loading conditions. The Implications for material characterisation, structural design and certification are addressed. An earlier paper reported results from a fractographic study of the micromechanisms of delamination growth in the same specimens [1].

2. Experimental details

The material under investigation here was a commercial carbon-fibre/epoxy-matrix pre-preg system (Hexcel T800/924), cured and post-cured according to manufacturer’s recommended procedure. Standard 24-ply double cantilever beam (DCB) coupons containing a 10μm PTFE insert film artificial delamination were used to characterise unidirectional ply interfaces, while 32-ply quasi-isotropic specimens with edge inserts [2] were used for cross-ply interfaces. For the the latter a stacking sequence was chosen with a 0º/90º ply interface at the mid-plane which maximised specimen axial and transverse bending stiffnesses whilst minimising residual thermal stresses and bend-twist coupling terms of the stiffness matrix.

Delamination toughness testing was carried out using the mixed-mode bending (MMB) rig [3]. A short 75% mode I pre-crack was generated quasi-statically before testing at a frequency of 5Hz (to a maximum of 1.8x10⁶ cycles) at one of three selected mixed-mode conditions: 25%, 50% and 75% mode I. The amplitude of the cross-head displacement was kept constant during the tests. The maximum displacement was chosen such that the initial peak applied strain energy release rate was in the range of 40% - 80% of the strain energy release rate for static failure. The specimen was almost entirely unloaded during each cycle.

After testing, typical specimens were chosen, sputter-coated and examined using a scanning electron microscope (SEM) at magnifications between 50x and 5 000x. Further experimental details may be found in the earlier paper [1].

3. Analysis

The fatigue results were compared with a theory for crack growth in composites, similar to that proposed by Paris [4]. The Paris theory suggests that for crack propagation in metals under cyclic loading there is a threshold of stress intensity amplitude \( \Delta K_{\text{threshold}} \), below which a crack will not grow. Crack propagation rates \( \frac{da}{dN} \) above this threshold are proportional to a power-law function of \( \Delta K \) (equation 1).

\[
\frac{da}{dN} = C (\Delta K)^m
\]

In fibre reinforced composites the stress-field at the crack tip is highly distorted by the fibres, making a representative evaluation of \( K \) problematic. A more applicable power-law model in terms of the amplitude of applied strain energy release rate, \( \Delta G \), has been used for over thirty years (equation 2) [5]. However, there is some ambiguity in the definition of \( \Delta G \) for reversed cyclic loading, where the maximum and minimum loads are of opposing sign. The stress intensity factors corresponding to maximum and minimum load are then of opposing sign and \( \Delta K > K_{\text{max}} \). The strain energy release rates, however, are of the same sign. Three different expressions of \( \Delta G \) have been used in articles concerning the fatigue behaviour of composites, making direct comparison of results from different sources difficult [6-9].
There is no physical reason for fatigue crack propagation rates in thermoset-matrix composites to depend on the amplitude of strain energy release rates, and some authors [10, 11] have chosen to replace $\Delta G$ in the power-law with peak strain energy release rate $G_{\text{max}}$, avoiding the above ambiguity (equation 3). This was the approach taken here.

Values for $G_{\text{max}}$ were calculated at peak loads using corrected beam-theory expressions [12, 13] and propagation rates $da/dN$ were determined by differentiating polynomial fits of crack length $a$ versus number of cycles $N$. The parameters in the power law were then obtained from the intercept and gradient of the modified Paris plots.

\[
\frac{da}{dN} = A(\Delta K)^p \quad (1)
\]
\[
\frac{da}{dN} = B(\Delta G)^q \quad (2)
\]
\[
\frac{da}{dN} = C(G_{\text{max}})^r \quad (3)
\]

($A$, $p$, $B$, $q$, $C$, $r$ are fitting constants)

4. Results

Figure (1) shows curves of $a$ versus $N$ for two specimens, of which the curve for specimen (1) was more typical.

Figure (2) shows curves of $G_{\text{max}}$ versus $a$ for the same two specimens. The fatigue tests were carried out under constant amplitude of displacement. As the crack length increased the specimen usually became more compliant. It was therefore usual for the applied strain energy release rate to decrease as the test progressed, as in the case of specimen (1). However, as demonstrated by the results for specimen (2), this was not always the case.

The data in Figures (1) and (2) were combined to produce Paris plots of the type shown in Figure (3), showing $da/dN$ versus $G_{\text{max}}$ on log-log scales. The behaviour of specimen (1) was described reasonably well by equation (3). However
for some specimens it was observed that $\frac{da}{dN}$ was falling whilst $G_{\text{max}}$ was constant or even increasing (as in the case of specimen (2)). When these results are included there is significant scatter in the Paris plot. This phenomenon has not been previously reported and such results may in the past have been dismissed as being anomalous. It should be noted that this scatter was not significantly greater than that observed in static tests carried out as part of the same programme.

Figure 4. Modified Paris plots for delaminations at $0^\circ/0^\circ$ ply interfaces in T800/924.

Figure 5. Modified Paris plots for delaminations at $0^\circ/90^\circ$ ply interfaces in T800/924.
Fatigue test results for unidirectional ply interfaces tested at 75%, 50% and 25% mode I loading are shown in Figure 4. Fatigue crack propagation did not occur below the relatively high threshold of $G_{\text{max}}/G_{\text{static}} \approx 30\%$. The tendency for strain energy release rate to increase with increasing proportion of mode II loading [14] was less apparent in the fatigue data (at a given propagation rate) than in comparable static data. There was too much scatter to draw any firm conclusions other than that, in general, $da/dN$ tended to decrease with decreasing strain energy release rate.

Fatigue results for cross-ply interfaces are shown in Figure 5. These results may indicate a slightly enhanced toughness and higher degree of scatter at $0^\circ/90^\circ$ ply interfaces when compared with $0^\circ/0^\circ$ ply interfaces.

Fracture surfaces generated under fatigue at magnifications up to 2000x were not easily distinguishable from surfaces generated quasi-statically at the same mixed mode conditions (Figure 6). At higher magnifications features characteristic of cyclic loading, striations and matrix rollers, have been observed [8]. Further details of surface morphology observed in this study are given elsewhere [1].

![Figure 6. Micrographs of static and fatigue fracture surfaces generated at $0^\circ/0^\circ$ ply interface at 50% mode I (50% mode II) loading. (x1500, 30º tilt).](image)

5. Discussion

The scatter in the critical strain energy release rates of laminated composites was attributed to variations in the local distribution of fibres near the delaminating ply interface [1].

These results indicate that thermoset-matrix composites do not suffer from fatigue in the same manner as metals. Fatigue crack growth in metals relies on the migration of dislocations. Thermosets are amorphous and therefore do not contain dislocations. Furthermore they are cross-linked, severely hindering plastic flow. Crack propagation can only occur when strong covalent bonds are permanently broken. Similar mechanisms and energies are involved, whether the material fails statically or in fatigue; this is reflected in the similarity of static and fatigue fracture surfaces. The domain in which crack rates can be described by a Paris relationship (as used for metals) is therefore narrow. The dependence of propagation rate on applied strain energy release rate is weak, which is reflected in a very high gradient in Paris plots.

As a result of the steepness of the Paris plot, the narrowness of its domain and the significant local variations in toughness exhibited by fibre composites, the Paris propagation model is of
severely limited value in predicting component lifetime. Others [11] have argued that, for a material perfectly obeying the Paris law with an exponent of 9, a 10% uncertainty in the loads would lead to a 61% uncertainty in crack propagation rate. If crack growth in composites is governed by a power-law function of \((G_{\text{max}}/G_{\text{static}})\) and \(G_{\text{static}}\) varies locally by 10% then over short distances a similar uncertainty in propagation rates would result, even if the loads were known perfectly.

In thermoset-matrix composite components where delamination growth over short distances could prove critical, cyclic loads should be kept below their threshold levels \(i.e.\) a “no growth” criterion should be used). This is consistent with current design philosophy. Contrary to the design of metal components, this does not imply a huge safety factor relative to the static case. Figure 7 shows crack propagation rates in terms of the proportion of the static critical strain energy release rate applied from all the laminate tests carried out and, for comparison, published results for 2024 T3 aluminium [15]. An aluminium component containing a crack, loaded cyclically at 10% of its static critical strain energy release rate, will fail relatively quickly (1mm crack growth in \(10^4\) cycles). A composite component containing a delamination, loaded in the same manner, has infinite life.

The suggested ‘safe’ proportion of \(G_{\text{static}}\) of 10% for this material corresponds to about 30% of \(P_{\text{static}}\). Some aircraft manufacturers and operators are currently ignoring the parts of the loading spectrum which fall below 30% of peak load, in order to accelerate certification test programmes. In one example 5000 flights were simulated in 23 000 cycles, compared with 650 000 cycles for the equivalent metal structure. These results indicate that the approach is probably appropriate for thermoset-matrix composites; however more work is required to

![Figure 7. Modified Paris plots for delaminations at 0º/0º and 0º/90º ply interfaces in T800/924. Peak driving force normalised against value for quasi-static failure.](image-url)
confirm how this behaviour observed in coupons may be extrapolated to structures. There must also be some concern over the practise of simulating component life by cycling at frequencies as high as 5-10Hz since creep and environmental effects may not be correctly reflected.

6. Conclusions

The critical design parameter for delamination in thermoset-matrix composites under cyclic loading is the strain energy release rate threshold, $G_{\text{threshold}}$. This may be determined over a long time-scale by using a small number of specimens and incrementing the load until failure is observed, or over a shorter time-scale by using a larger number of specimens to focus rapidly on the relevant part of the S-N curve.

If, as may be indicated in these results, $G_{\text{threshold}}/G_{\text{static}}$ in epoxy-matrix systems does not depend strongly on the mixed-mode loading conditions, then a design optimised for static loading with an appropriate safety factor would be "approximately optimised" for fatigue loading. The design process could be based principally on static tests, with expensive, time-consuming fatigue testing being reserved for verification. The cost of this final phase may also be reduced by using accelerated test programmes at appropriate low-load cut-off levels, providing careful consideration is given to creep and environmental effects.

There is scope for further optimisation by taking a stochastic approach [16] to represent the local variations in toughness and model delamination behaviour. This would further reduce the magnitude of the safety factors. Demonstration of improvements in the understanding of the failure of composites under fatigue loading will lead to reductions in the size of test matrices required for certification.

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References


