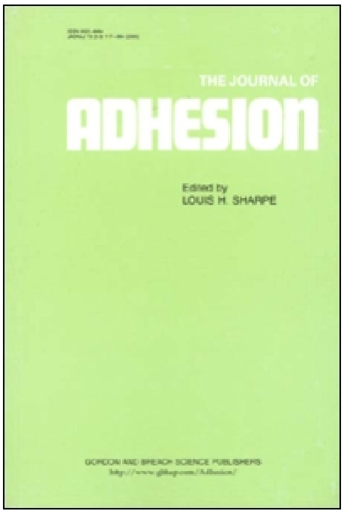

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Effect of Temperature on the Quasi-static Strength and Fatigue Resistance of Bonded Composite Double Lap Joints*

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Fibre reinforced polymer composites (FRP's) are often used to reduce the weight of a structure. Traditionally the composite parts are bolted together; however, increased weight savings can often be achieved by adhesive bonding or co-curing the parts. The reason that these methods are often not used for structural applications is due to the lack of trusted design methods and concerns about long-term performance. The authors have attempted to address these issues by studying the effects of fatigue loading, test environment and pre-conditioning on bonded composite joints. Previous work centered on the lap-strap joint which was representative of the long-overlap joints common in aerospace structures. However, it was recognised that in some applications short-overlap joints will be used and these joints might behave quite differently. In this work, double-lap joints were tested both quasi-statically and in fatigue across the temperature range experienced by a jet aircraft. Two variants on the double-lap joint sample were used for the testing, one with multidirectional (MD) CFRP adherends and the other with unidirectional (UD) CFRP adherends. Finite element analysis was used to analyse stresses in the joints. It was seen that as temperature increased both the quasi-static strength and fatigue resistance decreased. The MD joints were stronger at low temperatures and the UD joints stronger at high temperatures. It was proposed that this was because at low temperature the strength was determined by the peak stresses in the joints, whereas, at high temperatures, strength is controlled by creep of the joints

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which is determined by the minimum stresses in the joint. This argument was supported by the stress analysis.

Keywords: Fatigue; Adhesive joints; Creep; CFRP; Finite element analysis

INTRODUCTION

The use of structural adhesives in the construction of military aircraft can offer numerous advantages over traditional joining techniques such as mechanical fastening. Major benefits include improved aircraft performance, *e.g.*, agility, payload and range, together with considerable scope for reductions in both procurement and life-cycle maintenance costs. Additionally, adhesive bonding would be of paramount importance in the development and construction of advanced lightweight composites. Unfortunately, a lack of confidence in the ability of adhesive joints to withstand defence and aerospace operating conditions has prevented their more widespread use in these industries. Areas of most concern to design and airworthiness authorities have included: long-term durability under the particularly harsh environmental conditions experienced by military aircraft, and fatigue, particularly when superimposed upon harsh environmental conditions.

Previous work at the UK's Defence Evaluation and Research Agency (DERA) on the fatigue behaviour of bonded composite joints has centred on the lap-strap joint, as this is representative of many of the long-overlap joints (defined here as overlap/adherend thickness >40) found in aerospace applications [1–4]. In this work, it was found that there was little variation in the fatigue threshold in the temperature range -50 to 90°C when testing at ambient humidity. A high level of moisture within the joint materials only exerted a significant effect on fatigue performance when testing at elevated temperatures. This was attributed to a depression of the glass transition temperature (T_g) of the adhesive from water absorption, which reduced this parameter close to the test temperature, thus, resulting in a reduction in mechanical performance. The mode of failure was seen to be dependent on environmental conditions, with temperature having a significant effect. Low temperatures resulted in failure predominantly in the composite substrate; as temperature increased there was a shift in the locus of failure to the adhesive. A number of fracture mechanics and stress/strain failure criteria were evaluated [5] by their ability to predict fatigue thresholds in lap-strap joints with multidirectional CFRP adherends, using the results from tests with unidirectional adherends to calculate the critical failure parameters. A number of these failure criteria were able to predict the fatigue thresholds to within the experimental scatter for a range of environments.

It was recognised, however, that in many non-aerospace applications short overlap joints (defined here as overlap/adherend thickness < 20) are commonly used, and that short overlap joints are also being considered for future aerospace applications. It was decided to test short-overlap joints, made of the same materials as the lap-strap joints and tested in the same environments, in order to compare the behaviour of the different types of joint and to see if a common failure criterion can be applied. A number of differences are apparent, however, between the lap-strap and short-overlap joints. In the former, the "strap" adherend spans the loading point. You do not get catastrophic failure of the joint, therefore, but a progressive separation of the lap and strap parts. When tested in fatigue, this sample is used either to monitor crack growth rates or to define a threshold at which no damage is seen for a specified number of cycles [6–10]. In the short-overlap joints, crack growth leads to catastrophic failure of the joint. This type of failure lends itself to the construction of $S-N$ curves, which are plots of the average stress amplitude against the number of cycles to complete failure of the joints. Thresholds can also be used with $S-N$ curves. The threshold is the highest stress than can be sustained without total failure of the joint after a certain number of cycles (typically 10^6-10^8). If we assume that failure of the short overlap joint is rapid after initiation, this threshold can be compared with the threshold obtained using the long-overlap joint. However, if crack propagation is dominant in the short-overlap joint, then the number of cycles to the first detectable sign of damage in the joint (using the same method of detection as that used for the long-overlap joints) should be used to compare with the long-overlap joint threshold.

The effect of temperature on the quasi-static and fatigue behaviour of short overlap joints has been reported by a number of investigators.

Adams *et al.* [11] studied the effect of temperature on the strength of epoxy/steel lap joints tested from −60°C to 200°C. They found that joints were strongest in the region 0–70°C. At low temperature the adhesive became brittle, leading to lower strength and increased scatter. At higher temperatures the adhesive softened and failed by plastic yielding. Ashcroft *et al.* [12] tested FRP/epoxy/peek single-lap joints both quasi-statically and in fatigue over a range of temperatures. They found that with GFRE substrates the joints were strongest at room temperature and weakest at −40°C, a significant decrease in strength also being observed at 90°C. The reduction in strength at low temperatures was accompanied by a change in the failure locus from predominantly cohesive failure of the adhesive to predominantly interlaminar failure of the adherend. The fatigue tests showed that as the stress amplitude decreased the effect of temperature lessened and at the 10^6 fatigue threshold there was no difference between the joints tested at −40, RT and 70°C. Harris and Fay [13] tested steel single-lap joints, bonded with modified epoxy and polybutadiene adhesives, quasi-statically and in fatigue over the temperature range −30 to 90°C. They found that the quasi-static strength reduced quickly as T_g was approached. Fatigue resistance was also greatly reduced at temperatures around T_g. They noted that the dynamic stiffness decreased during the fatigue tests and that the maximum deflection increased, which they attributed to creep. They identified an initiation phase in which the dynamic stiffness reduced steadily and creep deflection increased steadily, and a growth phase in which the rate of change of creep deflection and dynamic stiffness rapidly increased leading to catastrophic failure. They suggested that the fatigue life of the joints was dominated by the initiation phase. Moreover, they noted that at loads below the fatigue limit there was no discernible creep. They postulated that the endurance limit was determined by the stress level required to cause creep and that this explained the decrease in endurance limit with temperature. Hart-Smith [14] noted that lap joints with small overlaps that could survive 10^7 cycles at high-frequency loading, failed in only a few hundred cycles when tested at the low cyclic rates representative of service conditions. Joints with large overlaps, however, were able to withstand the low-frequency loading without failure. This was attributed to the fact that with the short overlap, creep occurs over the whole adhesive layer; creep damage, therefore, accumulates with each cycle and leads to premature failure. With the large overlap, creep is restricted to the edges of the overlap and on unloading the elastic adherends reverse the creep direction at the ends of the overlap, thereby preventing the accumulation of creep damage. Marceau *et al.* [15] also suggested that slow cycle fatigue of adhesive bonded joints resulted in a creep-rupture type failure.

Like Harris and Fay [13], Crocombe [16] also identified initiation as being the dominant phase in the fatigue life of steel/epoxy single-lap joints. However, Taylor [17], using the same materials as Crocombe and utilising a back-face strain technique to monitor crack growth, claimed propagation to be the dominant phase. This view was supported by the subsequent work of Little [18] on aluminium/epoxy single-lap joints. In this work, three phases were seen: an initiation phase in which there was some creep, a stable crack growth phase and a fast crack growth phase. Romanko and Knauss [19] tested aluminium/epoxy thick-adherend shear test samples in fatigue in the range −65°F to 140°F. They monitored the major axis of the fatigue hysteresis loops and noted a decrease in stiffness of the joint and progressive deformation during the fatigue tests. The effect of raising the temperature was to increase the rate at which stiffness decreased and, hence, decreased the joint life. They used optical microscopy to observe crack growth and attributed the change in stiffness entirely to crack growth. It can be seen, therefore, that there is no consensus in the literature on the relative contributions of the initiation and propagation phases in the fatigue life of short-overlap bonded joints. There is no reliable model for the interaction of creep and fatigue crack growth in cyclic loading tests of bonded joints and the effects that parameters such as geometry, materials, environment, load rate and amplitude will have are poorly understood at present. There is little work in this area on joints with FRP adherends and these systems are complicated by the environmental sensitivity of the mode of failure.

The double-overlap joint was selected for this work as this is representative of short-overlap joints that might be seen in aerospace applications such as the bonding of spars or ribs to wing skins. The stresses at the crack tip in the double lap joint are a mixture of modes I and II, the ratio being dependent on the thickness of the adherends and the length of overlap [20, 21]. The mode ratio also changes as the crack grows [20]. It is notable that, in the double-lap joint, crack initiation and growth is not limited to a single bondline, as in the single-lap joint and lap-strap joint, but to two short bondlines. Crack initiation is equally likely to occur in either bondline. This type of joint is also more susceptible to creep than the lap-strap joint as the overlap is shorter and there, is not an adherend spanning the loading points. All the joints tested in this programme were uncracked initially and were used to investigate the effect of test temperature on the static and fatigue performance of the joint. The temperature range selected was −50°C to 90°C. This represents the extremes experienced by high altitude flight and frictional heating at high speeds, respectively.

EXPERIMENTAL

Sample Manufacture

The CFRP used in the test programme was a modified bismaleimide/epoxy system, with intermediate-modulus carbon fibre reinforcement. The pre-preg material was laid up as unidirectional (0°) or multi-directional $[(0°/-45°/+45°/0°)_2]_S$ panels, which were cured at 182°C for 2 hours, with an initial autoclave pressure of 90 p.s.i (0.62 MPa). The adhesive used was a proprietary modified epoxy, which was supplied as a nominally 0.2 mm film with a non-woven nylon carrier. The adhesive was based on a diglycidyl ether of bisphenol A epoxy, crosslinked with a primary amine curing agent. A reactive liquid polymer, based upon a carboxyl-terminated butadiene acrylonitrile rubber, was used as a toughening agent. The formulation also contained a silica filler. The adhesive was cured for 60 minutes at 120°C.

Samples were produced by adhesive bonding cured panels of the CFRP. Figure 1 shows the dimensions used for joints with the multidirectional CFRP substrate. The outer adherends are 16 plies (2 mm) and the middle adherend is 32 plies (4 mm). The unidirectional samples were made with the middle adherend the same thickness (2 mm) as the outer adherends. This was due to manufacturing problems with the 32-ply unidirectional panels. This had the effect of changing the mode mix in the joint. Finite element analysis predicted

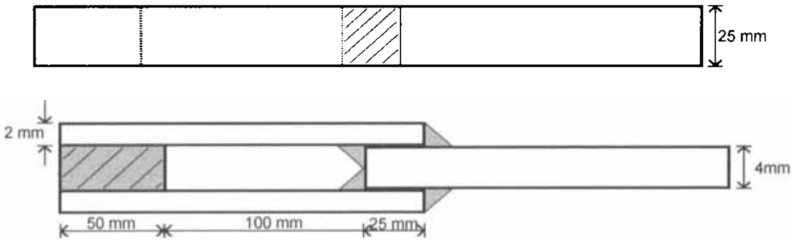


FIGURE 1 Double lap joint dimensions (M/D).

that the mode mix experienced by a crack in the centre of the bondline in a double lap joint was dependent on the crack length and that at small crack lengths the MD samples had a higher proportion of mode I loading than the UD samples [20]. For example, at a crack length of 0.5 mm, the proportion of mode I loading was calculated as 0.28 for the multidirectional joints and 0.24 for the unidirectional joints, using the virtual crack closure method.

Test Procedures

Both static and fatigue testing were carried out using servohydraulic machines fitted with temperature chambers and computerised control and data logging. The quasi-static tests were conducted in displacement control with a ramp rate of 1 mm/minute, with five repetitions of each test. Fatigue testing was carried out in load control, using a constant amplitude sinusoidal waveform, at a frequency of 5 Hz and a load ratio of 0.1. These conditions were selected as being typical of those found in defence and aerospace standards. Quasi-static and fatigue testing were conducted at temperatures of −50, 22 and 90°C (all at ambient humidity). The fatigue tests were carried out at a number of different loads in order to construct plots of maximum load (L) against number of cycles to failure (N). Load was used rather than stress amplitude because it was thought that an average shear stress (as is frequently used with bonded lap joints) is misleading, considering the non-uniform nature of the shear stresses and the existence of significant peel stresses, which most likely contribute to failure. Between 10 and 20 samples were used in the construction of each $L-N$ curve and a fatigue threshold was defined as the highest maximum load at which a sample could survive 10^6 cycles. Failed samples (*i.e.*, those that had completely fractured) were examined using optical microscopy to determine the fracture path. Three distinct failure modes were observed and these were termed "cohesive", "interlaminar" and "interfacial" failures. It should be realised, however, that these terms are a simplification of the actual fracture mechanisms. The "cohesive" fracture type indicated failure entirely in the adhesive layer. This fracture surface was macroscopically rough. Electron microscopy [20] showed evidence of toughening by rubber particles and exposed carrier fibres could be seen. The "interfacial" fracture type was smoother and occurred in the interfacial region between the adhesive and one of the adherends. Electron microscopy of this fracture surface [20] showed that the interfacial (or apparent interfacial) failure was not a clean fracture at the interface between the adhesive and the adherend, but a mixed failure mode which included elements of fracture in both the adhesive and the composite matrix. Electron microscopy also showed that the "interlaminar" failure type was a combination of fracture in the matrix of the 0° ply adjacent to the adhesive and stripping of the matrix form the carbon fibres. Only isolated incidents of fibre fracture were observed.

STRESS ANALYSIS

The commercial finite element package LUSAS was used to analyse the stresses in the double-lap joint. Quadratic, plane strain, isoparametric elements were used in the model. The symmetric nature of the joint meant that only half of the joint needed to be modelled. The model was supported in the y-direction along the line of symmetry of the joint and was supported in the x and y directions at the end of the outer adherend. The load was applied in the x-direction at the end of the central adherend. The adhesive was modelled using the elastic–plastic properties shown in Figure 2, with a modified von-Mises yield criterion using a ratio of compressive to tensile yield of 1.3. As there was no well-defined yield point a 0.1% proof strain was used to define yield, which allowed the experimental stress–strain curves to be accurately followed by the FE approximation. However, this definition of the yield strength does not necessarily indicate plasticity in the adhesive as non-linearity is observed in the elastic region. The

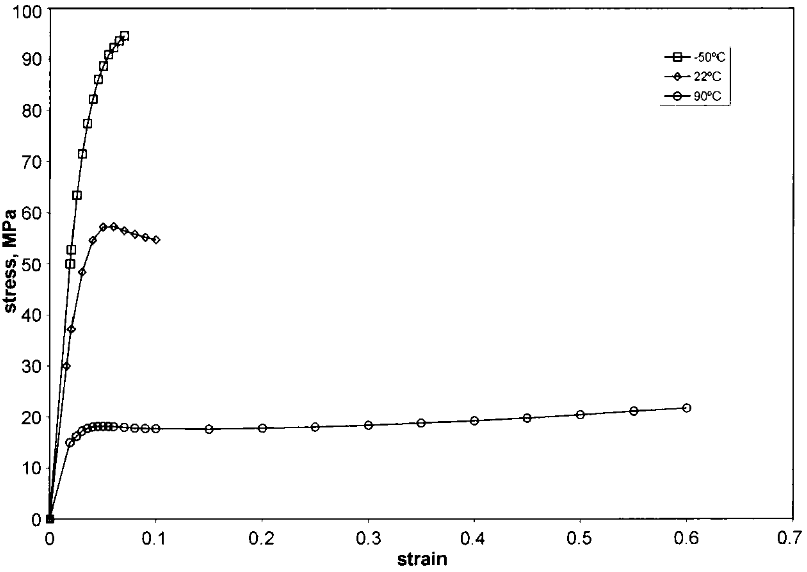


FIGURE 2 Tensile stress–strain curves for the epoxy adhesive.

TABLE I Mechanical properties of CFRP

Property	*Unidirectional*	*Multidirectional*	*Units*
E_1	174	99.8	GPa
E_2	9.64	28.1	GPa
G_{12}	7	25.7	GPa
ν_{12}	0.36	0.69	
ν_{21}	0.02	0.2	

composite was modelled as an elastic orthotropic solid using the properties presented in Table I. A non-linear analysis was required to model the non-linear properties of the adhesive and to account for geometric non-linearity.

Figure 3 shows the deformation of the mesh (greatly exaggerated) on loading. This shows that although there are no large-scale deformations or rotations of the joint there are internal bending moments, which cause the outer adherend to deflect inwards at point *B* and outwards at point *A*, thus inducing peel stresses in the adhesive. The maximum principal stresses in the overlap region of the joint are shown in Figure 4, for the joint with unidirectional adherends loaded to 20 kN at 22°C. In this joint, the central adherend is the same

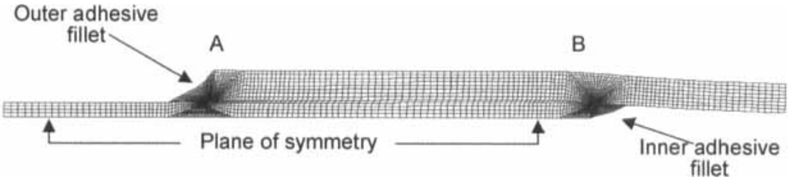


FIGURE 3 Deformed finite element mesh in overlap region.

FIGURE 4 Maximum principal stress contours in overlap region. 22°C, unidirectional adherend, 20 kN load. (See Color Plate I).

thickness as the outer adherends and must, therefore, take twice the load. This is clearly seen in the stress contours of Figure 4. It can also be seen that the highest stress concentrations are in the central adherend, below the outer adhesive fillet. Figure 5 shows the maximum principal stresses in the adhesive, at the outer adhesive fillet, for the same joint. The highest stresses can be seen to be in the fillet, at the embedded corner of the outer adherend. In Figure 6 the stresses in the adhesive at the inner adhesive fillet can be seen. The highest stresses are in the fillet at the embedded corner of the central adherend. Comparison of Figures 5 and 6 show that the highest stresses are in the outer adhesive fillet and this is where failure would be expected to initiate, especially as tensile peel stresses are experienced at A and compressive peel stresses at B.

Figure 7 shows the variation in different stress components through the centreline of the adhesive with an applied load of 10 kN. It can be seen that the longitudinal and peel stresses reach a tensile maximum at the outer adhesive fillet and are compressive at the inner adhesive fillet. The shear stress also reaches a maximum at the outer adhesive fillet

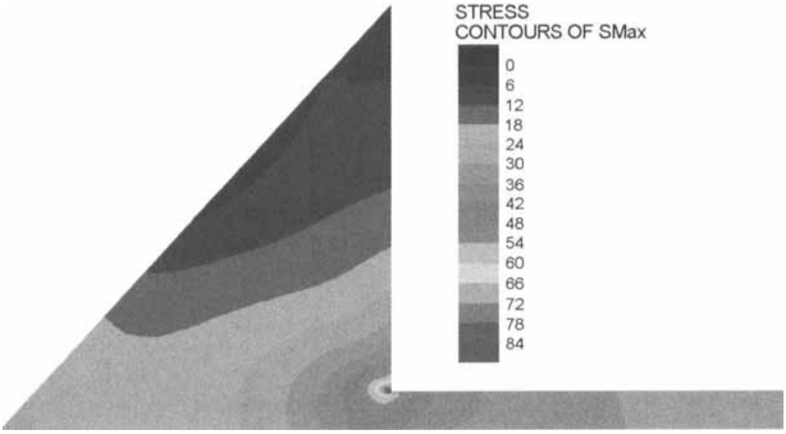


FIGURE 5 Maximum principal stress contours in outer adhesive fillet. 22°C, unidirectional adherend, 20 kN load. (See Color Plate II).

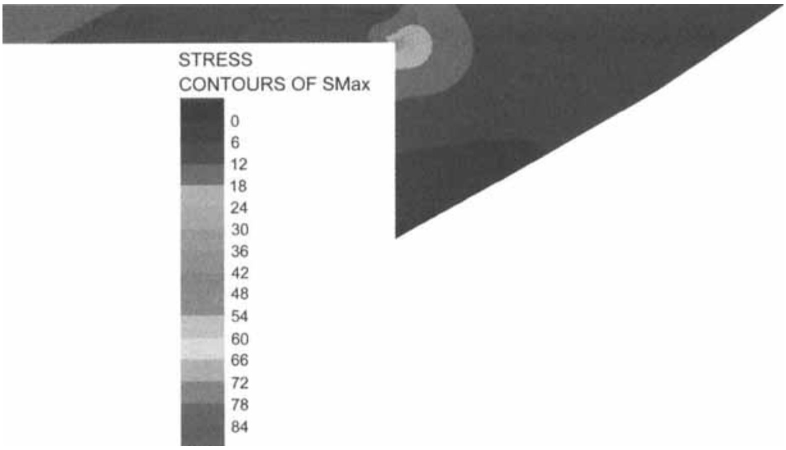


FIGURE 6 Maximum principal stress contours in inner adhesive fillet. 22°C, unidirectional adherend, 20 kN load. (See Color Plate III).

but, in addition, exhibits a peak at the other end of the overlap. It is notable that the shear stresses are still significant in the middle of the overlap, whereas the longitudinal and peel stresses rapidly decrease away from the ends.

Figure 8 shows the effect of temperature on the maximum principal stress at the adhesive centreline with an applied load of 10 kN. It can

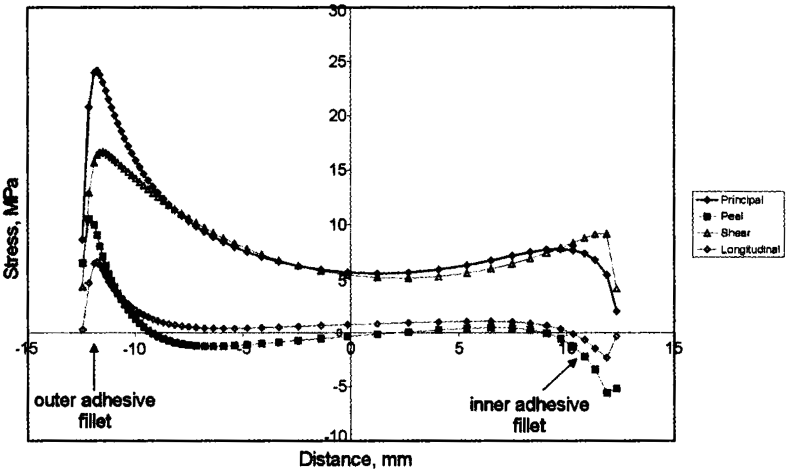


FIGURE 7 Comparison of different stress components through the adhesive centreline. 22°C, unidirectional adherend, 10 kN load.

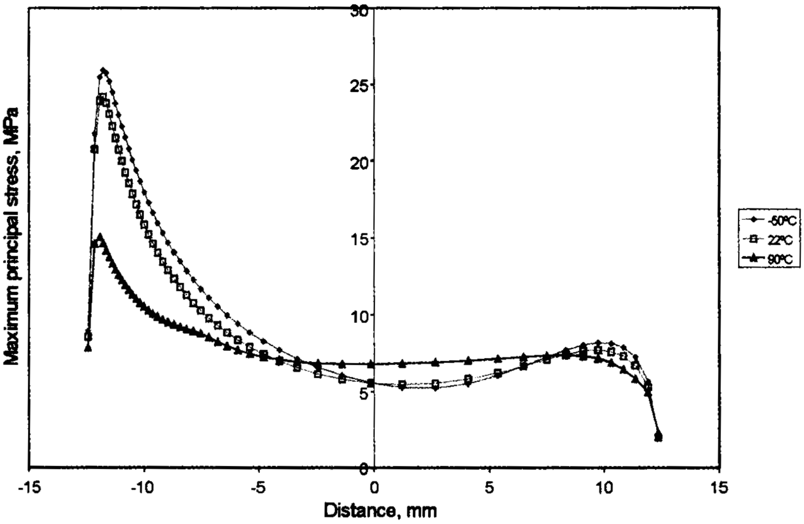


FIGURE 8 The effect of temperature on the maximum principal stress at the adhesive centreline. Unidirectional adherend, 10 kN load.

be seen that as the temperature increases the stresses in the joint become more evenly distributed. This has the effect that at the higher temperatures the peak loads are reduced but the loading at the middle of the overlap is increased. It should also be remembered that the strength and creep resistance of the adhesive is also lower at higher temperatures.

The maximum principal stress contours in a joint with multi-directional adherends can be seen in Figure 9. In this joint, the central adherend is twice the thickness of the outer adherends and, therefore, the average stress in the central adherend is the same as in the outer

FIGURE 9 Maximum principal stress contours in overlap region. 22°C, multi-directional adherend, 20 kN load. (See Color Plate IV).

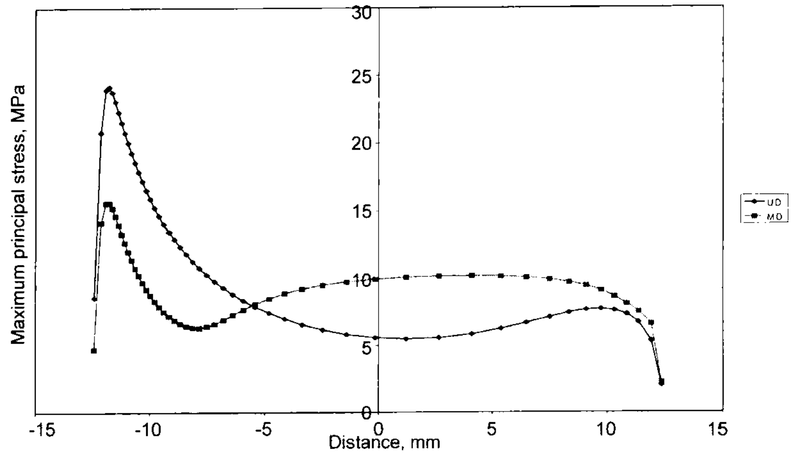


FIGURE 10 The effect of adherend type on the maximum principal stress at the adhesive centreline. 22°C, 10 kN load.

adherends. This is clearly shown in the stress contours in Figure 9, which are more symmetrical than those seen in Figure 4 for the joint with unidirectional adherends. The effect this has on the stresses in the adhesive is shown in Figure 10. It can be seen that the joint with multidirectional adherends has a lower peak stress at the outer adhesive fillet but higher stresses in the middle of the joint.

RESULTS

Quasi-static Tests

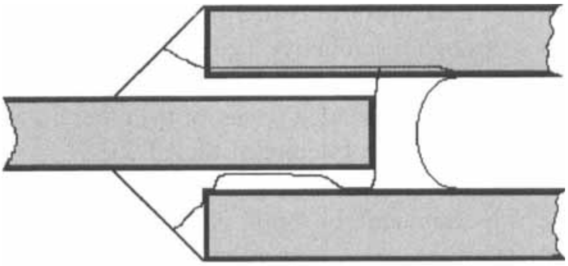
The results from the quasi-static testing of the double lap joints are summarised in Table II. It can be seen that for the unidirectional substrate, the joints were strongest at room temperature and weakest at 90°C. At −50 and 22°C the joints with the multidirectional adherends failed at higher loads than those with unidirectional adherends. This is consistent with the stress analysis which predicted higher peak stresses in the unidirectional joints for a given load. The highest stresses in the middle of the joint are seen at 90°C and at this temperature the adhesive has a lower stiffness and is more likely to fail by plastic deformation. The stress analysis also shows that although the multidirectional joint has a lower peak stress, the stresses in the middle of the joint are higher than in the unidirectional joint. Therefore, the global plastic deformation of the joint would be more severe with the multidirectional adherends.

The mode of failure of the joints was also seen to be dependent on both the temperature and the adherend. The discussions below regarding failure locus are based on examinations of all the samples

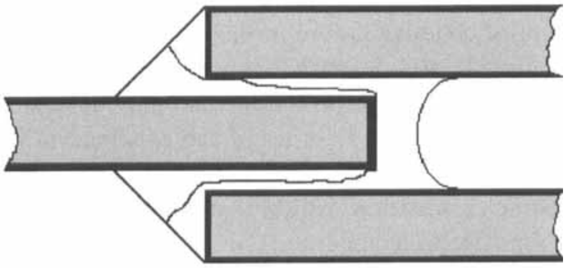
TABLE II Summary of quasi-static test results

Test temperature	*Substrate type*	*Failure load (kN)*	*Standard deviation (kN)*
22°C	U/D	27.6	1.79
	M/D	28	0.25
90°C	U/D	12.8	0.9
	M/D	9.14	1.45
−50°C	U/D	20.2	2.64
	M/D	24	1.92

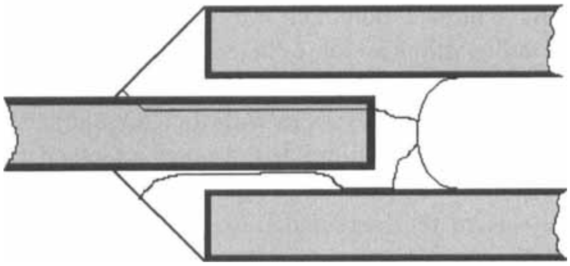
tested. In most cases, similar fractures were observed for all samples tested at any particular condition; where this was not the case it is indicated in the text. Figure 11(a) shows a schematic representation of the fracture path seen in a unidirectional joint tested at 22°C. Cohesive



(a) joints tested at 22°C



(b) joints tested at 90°C



(c) joints tested at –50°C

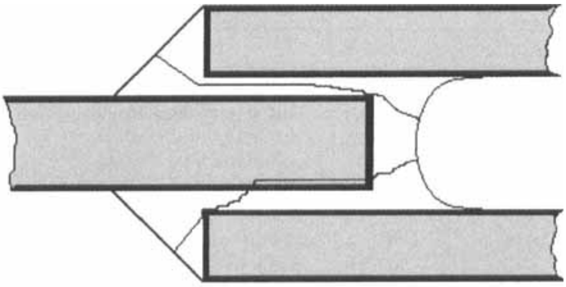
FIGURE 11 Schematic diagrams of failure loci in UD joints tested quasi-statically.

failure in the adhesive was dominant on one side of the joint, with some apparent interfacial failure. Interlaminar failure of the outer adherend was the dominant failure mode on the other side of the joint. Failure appears to have initiated at the outer adhesive fillet but, due to the speed of failure, it was impossible to monitor the crack growth using conventional video microscopy. The most likely scenario is that failure initiates at the embedded corner of one of the outer adherends and progresses through the adhesive, being driven towards the central adherend. The crack formation induces bending of the joint and high peel stresses arise at the embedded corner of the other outer adherend, which promote interlaminar fracture of the CFRP.

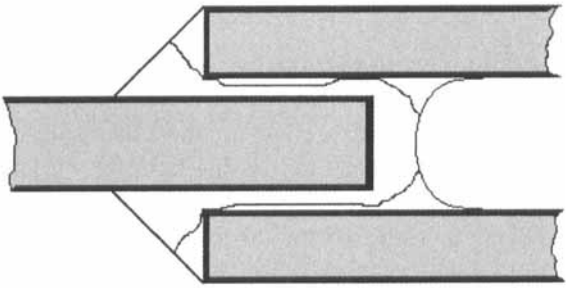
At 90°C, the failure mode changed, so that cohesive failure in the adhesive was dominant on both sides of the joint, as seen in Figure 11(b). Here we see a slower, more uniform and consistent failure path. Figure 11(c) shows a failure typical of a unidirectional joint tested at −50°C. Interlaminar failure of the middle adherend was dominant on one side of the joint. On the other side of the failed joint was a mixture of cohesive failure in the adhesive and fracture at the outer adherend/adhesive interface. Whether the interlaminar crack propagates in the outer or central adherend may depend on whether initiation is at the embedded corner of the adherend in the adhesive or in the middle adherend at the end of the adhesive fillet. Clearly, we have a complex situation with both adherend and adhesive properties being sensitive to temperature and the stress distributions in the joint changing continuously as cracks propagate.

At room temperature, the failure mode in the MD samples was similar to that observed in the UD specimens at −50°C, *i.e.*, cohesive failure of the adhesive dominant on one side of the joint, and interlaminar failure of the middle adherend dominant on the other (see Fig. 12(a)). At 90°C the dominant failure in the MD joints was cohesive fracture of the adhesive, as with the UD joints, but also with some apparent interfacial failure at the outer adherend (Fig. 12(b)). At −50°C, interlaminar fracture of the middle adherend was dominant on one side of the joint and fracture at the central adherend/adhesive interface was dominant on the other side (Fig. 12(c)).

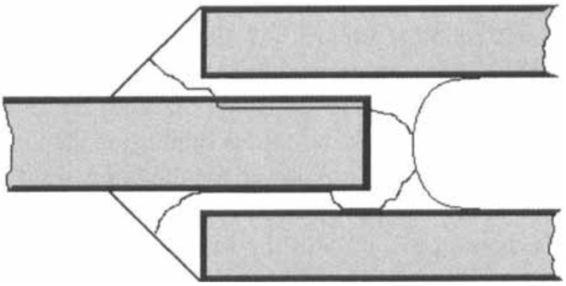
The different failure modes encountered in the static tests are summarised in Table III. It is apparent that as temperature increases failure in the composite decreases and cohesive failure of the adhesive



(a) joints tested at 22°C



(b) joints tested at 90°C



(c) joints tested at – 50°C

FIGURE 12 Schematic diagrams of failure loci in MD joints tested quasi-statically.

TABLE III Summary of quasi-static failure modes

Temp.	*Substrate*	*Side*	*Failure path*
22°C	U/D	Top	Cohesive in the adhesive
		Bottom	Interfacial/interlaminar (outer)
	M/D	Top	Cohesive in the adhesive
		Bottom	Interlaminar (middle)
90°C	U/D	Top	Cohesive in the adhesive
		Bottom	Cohesive/interfacial (outer)
	M/D	Top	Cohesive in the adhesive
		Bottom	Cohesive/interfacial (outer)
−50°C	U/D	Top	Interlaminar (middle)
		Bottom	Cohesive (no. middle) to interfacial (outer)
	M/D	Top	Interfacial/interlaminar (middle)
		Bottom	Interfacial/interlaminar (middle)

Forward slash denotes two failure modes possible, or a combination of both.
Descriptor in brackets defines dominant failure adjacent to a particular adherend.

increases. It is also obvious that the two bondlines in the joint usually show a different mode of fracture. This indicates that one side fails first, redistributing the loads acting on the other side of the joint, which then favour a different failure mechanism. This needs to be investigated further and high-speed photography and back-face strain methods are being investigated for this purpose.

Fatigue Tests

Plots of maximum load, L, against number of cycles, N, from the fatigue tests can be seen in Figures 13 and 14 for the UD and MD joints, respectively. In Figure 13 it can be seen that there is a step in the $L-N$ curves for the joints tested at RT and 90°C, which is indicative of a fatigue threshold (or endurance limit). The joints tested at −50°C have a much flatter $L-N$ curve indicating that they are less affected by fatigue loading. The fatigue threshold is similar for the joints tested at −50 and 22°C and significantly lower for the joints tested at 90°C.

The step in the $L-N$ curves indicative of the fatigue threshold at RT and 90°C is less obvious with the MD joints, as shown in Figure 14. However, this is probably because there are few points below 10^4 cycles where most of the reduction in fatigue strength is observed. Therefore, most of the points in Figure 14 are in the flat region around the fatigue threshold load. This is by design rather than by chance, as the major objective of the testing was to define the fatigue threshold

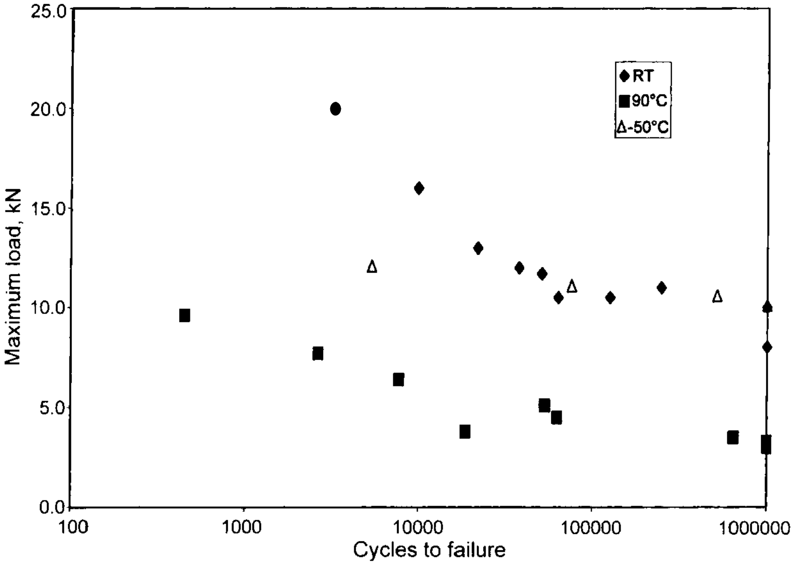


FIGURE 13 Fatigue of joints with unidirectional substrate.

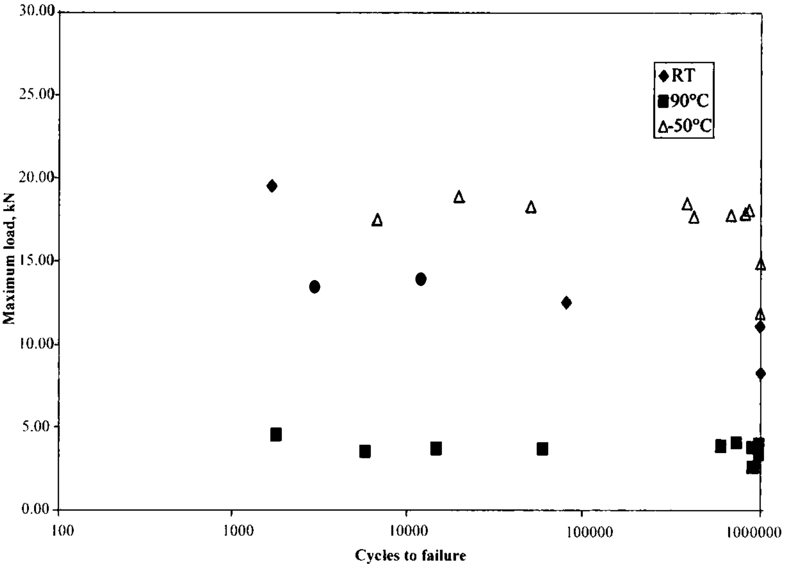


FIGURE 14 Fatigue of joints with multidirectional substrate.

accurately, rather than to monitor the high-load/low-cycle region in which the fatigue life is highly load-dependent and large scatter is seen. This is because the fatigue threshold, where one exists, is a more attractive design parameter than predicting the number of cycles to failure from data in the low-cycle region. In Figure 14 it can be seen that with the multidirectional adherends the fatigue threshold is lowest at 90°C and greatest at −50°C.

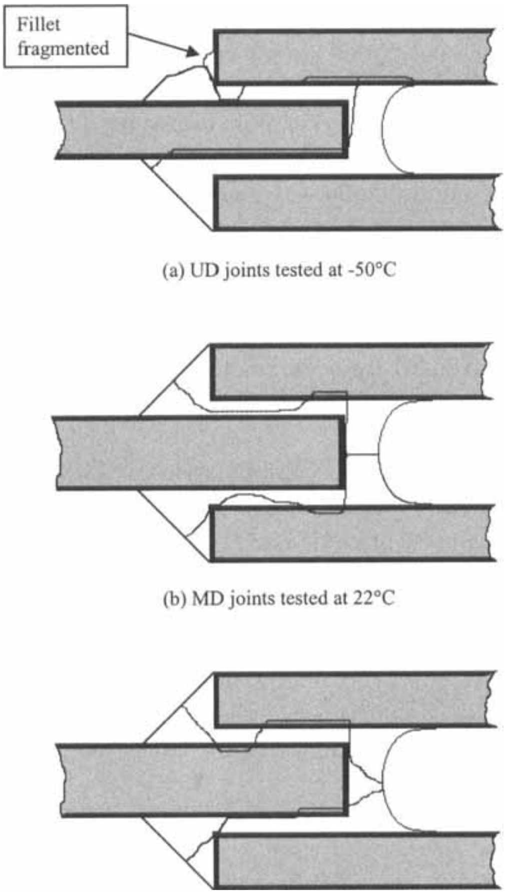
A summary of the fatigue results is presented in Table IV. It can be seen from this table that the fatigue threshold is higher with the multidirectional adherends at 22 and −50°C, but higher with the unidirectional adherends at 90°C. This is similar to the trend seen in the static tests and can be explained using similar arguments. At −50 and 22°C joint failure is controlled by the peak stresses in the adhesive, which stress analysis has shown to be greater with the unidirectional adherends. At high temperatures, the adhesive has a lower stiffness and is more prone to creep. As the stresses in the middle of the joint are higher with the multidirectional adherends, creep would be more severe in this joint. The ratio of quasi-static failure load over the fatigue threshold load indicates the reduction in joint strength on cyclic loading. It can be seen in Table IV that the joints become more affected by cyclic loading as the temperature increases and that the UD joints are more sensitive to cyclic loading than the MD joints at all temperatures.

The fatigue failures seen at room temperature for the UD joints were similar to those already described for the quasi-static tests (see Fig. 11(a)). On one side of the joint interlaminar failure of the outer adherend is dominant and on the other side is a mixture of cohesive failure in the adhesive and apparent interfacial failure at the outer adherend. At 90°C the failure of the UD joints was, again, similar to

TABLE IV Summary of fatigue test results

Test temperature	*Substrate type*	*Fatigue threshold load (kN)*	$\frac{\textit{Static failure load}}{\textit{Fatigue threshold load}}$
22°C	U/D	10 (± 0.5)	2.76
	M/D	11.2 (± 1)	2.5
90°C	U/D	3.3 (± 0.2)	3.9
	M/D	2.6 (± 0.5)	3.5
−50°C	U/D	10.1 (± 0.5)	2
	M/D	15 (± 2)	1.6

that seen in the statically-tested joints. Failure was predominantly cohesive in the adhesive, with some interfacial failure, as shown in Figure 11(b). The failure at −50°C was somewhat different, with part of the outer fillet on one side of the joint fragmenting. The failure path advanced from the fillet area to the interface at the middle adherend, and then across to the interface with the outer adherend, eventually progressing to interlaminar failure of the outer adherend (see Fig. 15(a)). The other side of the joint exhibited either interfacial or interlaminar failure at the middle adherend, with the fracture linking



(a) UD joints tested at -50°C

(b) MD joints tested at 22°C

(c) MD joints tested at -50°C

FIGURE 15 Schematic diagrams of failure loci in joints tested in fatigue.

up with the crack in the top adherend. This left the whole central fillet intact on the bottom adherend, with carbon fibres clearly visible on the end that had been removed from the top adherend.

The fatigue failures for joints with multidirectional CFRP substrates were quite different from those for the unidirectional joints. At room temperature, failure was predominantly cohesive fracture of the adhesive as shown schematically in Figure 15(b). Towards the end of the middle adherend there was a tendency towards interfacial or interlaminar failure of both the outer adherends. At 90°C, three different types of failure were observed with the multidirectional joints. Some specimens exhibited purely cohesive failure in the adhesive. Others had cohesive failure dominant on one side of the joint and apparent interfacial failure at the outer adherend dominant on the other side. The third type of failure was entirely interfacial, at the outer adherend on one side and at the middle adherend on the other side. No single failure mode was dominant at this temperature. Failure at −50°C was again quite characteristic. One side began as interlaminar failure of the middle adherend, then progressed to interlaminar failure of the outer adherend. On the other side of the joint there was some apparent interfacial failure at the outer adherend as the crack advanced from the fillet, leading to apparent interfacial then interlaminar failure at the middle adherend. This is shown in Figure 15(c).

The fatigue failure modes are summarised in Table V. A progressive change in the mode of failure can be seen as the temperature increases. At low temperatures, interlaminar failure, in both middle and outer adherends, is dominant with some apparent interfacial failure. At 22°C interlaminar and apparent interfacial failure are only seen at the outer adherend, cohesive failure in the adhesive is also observed at this temperature. At 90°C, no interlaminar failure of the adherends is observed. Failure is a mixture of apparent interfacial fracture, at both adherends, and cohesive fracture in the adhesive.

Creep

It is suggested that creep of the adhesive might explain the reduced fatigue resistance of the double-lap joints when the temperature is increased to 90°C. The stress analysis showed that shear stresses are

TABLE V Summary of fatigue failure modes

Temp.	*Substrate*	*Side*	*Failure path*
22°C	U/D	Top	Cohesive/interfacial (outer)
		Bottom	Interlaminar (outer)
	M/D	Top	Cohesive (no. middle)/interfacial (outer)
		Bottom	Cohesive (no. middle)/interlaminar (outer)
90°C	U/D	Top	Cohesive in the adhesive
		Bottom	Interfacial (outer)/cohesive/interfacial (middle)
	M/D	Top	3 different failure modes
		Bottom	
−50°C	U/D	Top	Interlaminar (middle)
		Bottom	Interfacial (middle)/interfacial (outer)/interlaminar (outer)
	M/D	Top	Interlaminar (middle)/interlaminar (outer)
		Bottom	Interfacial (outer)/interfacial (middle)/interlaminar (middle)

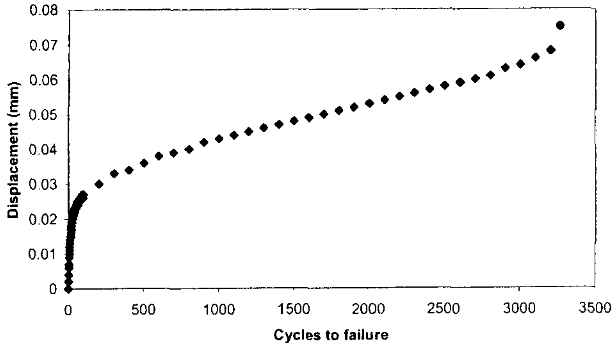


FIGURE 16 Example of creep in a fatigue-loaded double-lap joint at room temperature.

significant across the whole adhesive overlap, particularly at elevated temperatures. It is not unreasonable, then, to expect creep to occur at high temperatures when the adhesive has a lower stiffness. It was decided to investigate this by monitoring the maximum displacement of the joints with increasing cycle count in fatigue. The fatigue testing was conducted at constant load and in the absence of creep the maximum displacement should remain constant until a crack large enough to increase the compliance of the sample noticeably has developed. The presence of creep would be indicated by an increase in displacement with cycles that would be dependent on the test temperature and the maximum load. Figure 16 plots the change in maximum displacement against number of cycles for a sample fatigued at room temperature with a maximum load of 20 kN. The result appears to be a classic creep curve; however, the overall change in maximum displacement is quite small. An increase in the maximum fatigue load was seen to increase the creep rate. At lower loads, close to the fatigue threshold, little creep was observed.

A summary of the creep behaviour in double lap joints tested at 90°C is shown in Figure 17. This differs from the curves seen at room temperature in that the creep rates are much greater and that creep

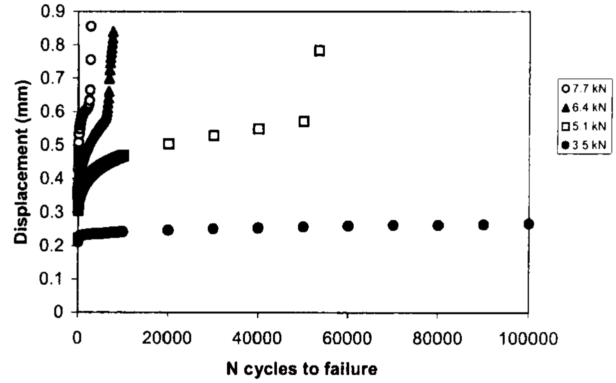


FIGURE 17 Summary of creep in fatigue-loaded double-lap joints at 90°C.

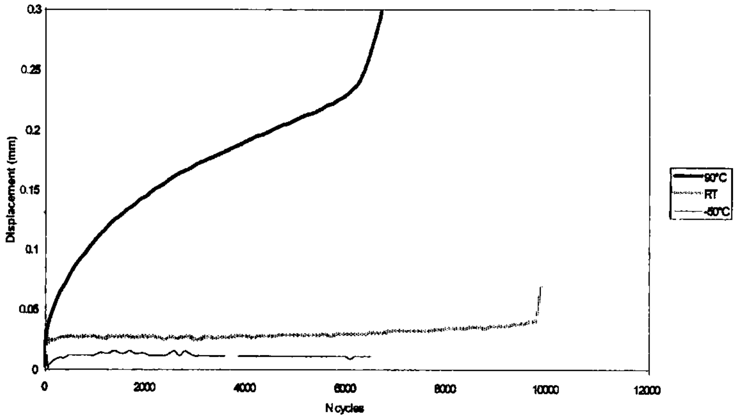


FIGURE 18 Comparison of creep at different temperatures.

behaviour can still be observed at the lower loads. At −50°C, there was no evidence of creep in the double-lap joints. This can be seen in Figure 18, which shows a comparison of the creep behaviour at different temperatures for samples with similar cycles to failure. At −50°C, there is no evidence of creep; at room temperature creep may be just discernible, whereas at 90°C creep is quite marked.

DISCUSSION

Work has been conducted to assess the extent to which extreme (but realistic) environments impinge on the fatigue characteristics of polymer composite joints of the type which could feature in aircraft construction. Specifically, the most likely temperature extremes have been considered, *i.e.*, −50°C and 90°C, when applied to joint types designed to simulate realistic bonded structures.

Double lap joints, designed to represent short-overlap joints such as spar-skin bonds, were tested at −50, 22 and 90°C in both quasi-static and cyclic-fatigue loading. In the quasi-static tests, it was seen that the strength was greatest at 22°C and least at 90°C for samples with both unidirectional and multidirectional adherends. In fatigue, the fatigue thresholds with the unidirectional joints were similar at 22 and −50°C, but considerably lower at 90°C. With the multidirectional joints, the fatigue threshold was greatest at −50°C and least at 90°C.

In both static and fatigue testing, the joints with the multidirectional adherends were stronger at 22 and −50°C, and the joints with the unidirectional adherends were stronger at 90°C. The results at 22 and −50°C are consistent with the stress analysis, which predicts higher stresses in the adhesive with unidirectional adherends for a given load. The large reduction in the fatigue threshold at 90°C is in contrast to results with the lap-strap joint, where little reduction in fatigue threshold was seen at elevated temperatures [4, 20]. Monitoring the maximum displacement during fatigue showed that there was significant creep, *i.e.*, a continuous deformation under load, in the double-lap joints at elevated temperatures prior to failure. This is not unexpected, as the stiffness of the adhesive decreases significantly at high temperatures and the stresses across the overlap become more evenly distributed. The stress analysis also showed that the stresses in the adhesive are more evenly distributed with the multidirectional adherends than with the unidirectional joints. This explains why the unidirectional joints are stronger than the multidirectional joints, when creep affects failure of the joint. The argument that creep plays a significant role in the fatigue life of the short-overlap joint at elevated temperatures, is supported by the fact that in the lap-strap joint (where creep is restrained by the long overlap and the strap adherend spans the loading points) the fatigue threshold is little affected by temperature in the same range. It is proposed, therefore, that creep/fatigue interactions in short-overlap joints can considerably shorten the fatigue life of a joint, particularly at elevated temperatures. This needs to be taken into account in designing a joint and indicates caution must be taken when using data taken from one type of joint and using it to predict the behaviour of a different type of joint.

The failure paths in the double-lap joints were exceedingly complex; however, there was a tendency for the favoured fracture path to shift from the composite to the adhesive as the temperature increased from −50 to 90°C. The exact nature of crack development is not known at present and the stress analysis of the uncracked joint only indicates the likely sites for crack initiation. Once a crack has formed the stresses redistribute and this affects further crack growth. It is proposed in future work to use advanced strain gauging and high-speed video techniques to observe crack formation in greater detail and to simulate this in the finite element analysis of cracked joints.

CONCLUDING REMARKS

It was shown in this work that temperature, in the range experienced by jet aircraft, had a significant effect on the quasi-static and fatigue performance of epoxy/CFRP double-lap joints. Complex failure paths were seen in the joints and there was a tendency as temperature increased for the fracture path to change from failure in the composite adherends to cohesive failure of the adhesive. The lowest quasi-static strength and lowest fatigue resistance were observed at the highest test temperature. This is in contrast to fatigue results from lap-strap joints made with the same materials. With the lap-strap joints, temperature had only a minor effect on the fatigue threshold in the same range. It was noted that accumulative creep was restrained by the presence of the strap and by the long overlap in the lap-strap joints but not in the double-lap joints and, therefore, it was proposed that creep played a part in accelerating the failure of the double-lap joints subjected to cyclic loading. This effect may be barely noticeable at room temperature but at elevated temperatures creep may be the controlling factor in the failure of fatigue-loaded joints. The designer must always be aware, therefore, of the viscoelastic nature of adhesives when designing bonded composite joints and the effect that both geometry and temperature can have in affecting the mechanisms of failure in bonded joints. This work also illuminates the dangers in applying results from one joint geometry to a different joint type when the various mechanisms of failure are not fully understood.

A quantitative measure of this creep effect on the fatigue life of bonded joints would be extremely useful to designers. This would involve determining the creep properties of the adhesive and applying a failure criterion that accounted for any fatigue–creep interactions. This is the subject of ongoing work by the authors.

Acknowledgements

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