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Frequency effects on the fatigue behaviour on carbon fibre reinforced polymer laminates

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Test frequency exerts a considerable influence on dynamic mechanical behaviour of carbon fibre reinforced materials. In this study the effect of test frequency on the fatigue behaviour of the T300/914C system, a carbon fibre/epoxy matrix composite, is examined. Tension-tension fatigue tests were carried out at various stress levels and at three test frequencies (5, 10 and 20 Hz) for three specimen orientations (unidirectional, $(0)_8$, crossply $(0^\circ/90^\circ)_{4s}$ and angleply $(\pm 45^\circ)_{4s}$). A number of dynamic mechanical properties were monitored throughout specimen lifetimes and subsequently analysed — stress/life behaviour, maximum strain, normalised fatigue modulus, dynamic loss modulus, damping factor and specimen temperature. Frequency effects are found to profoundly influence the fatigue behaviour of both crossply and angle ply specimens. Angleply specimen fatigue response exhibits a strong dependence on test frequency, a fact that is reflected in the dynamic mechanical property responses monitored. The data obtained for unidirectional specimens is inconclusive due to the large degree of fatigue scatter observed.

1. Introduction

Frequency effects have been observed during the fatigue of most engineering materials. The objective of this work is to elucidate the influence of test frequency on the fatigue behaviour of carbon fibre reinforced polymer laminates. Various authors have studied the affect of fatigue on polymer composite materials [1–6]. Composite materials present complex failure mechanisms in fatigue because of their inhomogeneity and anisotropy [2]. Laminates containing off-axis laminates are more matrix dependent and hence more susceptible to fatigue damage [3]. For carbon fibre composites the frequency effects are complex because of the simultaneous and conflicting effects in changes in time under load, strain rate, hysteresis heating and the fact that carbon fibres act as thermal conductors and carry the heat away from the damage zone.

Rotem [4] used finite element analysis to study frequency effects in graphite-epoxy laminates. The suggestion is that edge effects dominate and this was supported by experimental work on tension/compression fatigue on $(0, \pm 45, 90)_{2S}$ laminates at 2, 8 and 10 Hz. Failure is initiated at free edges, followed by crack propagation and buckling of remaining thin laminae. While no temperatures were measured, it was suggested that the increasing test frequency increased temperature through hysteresis effects in the matrix and that this lead to deterioration of the matrix properties thus leading to lower fatigue performance. The importance of temperature is also demonstrated in a paper by Miyano [5]. Although this paper does not concern itself with hysteretic heating, testing frequencies are low 0.02, 0.2, and 2 Hz, fatigue testing at higher temperatures lead to lower fatigue life through a decrease in matrix properties. Xiao [6] suggests that the fatigue behaviour of composites is reduced with increasing frequency in those materials, which have significant hysteretic heating. He studied ±45 APC2 laminates and treating the phenomenon as one of viscoelasticity derived a shift factor to predict behaviour. He computed temperature rises of up to 135°C from the hysterisis loops.

Temperature rises occur during fatigue testing of carbon fibre reinforced composites have been reported in other work [7–12]. At significantly high test frequencies significant hysteresis heating occurs. The temperature rise can be attributed to a number of heat sources including friction and the viscoelastic behaviour of the matrix.

2. Materials

A widely available carbon fibre reinforced epoxy matrix composite; Fibredux T300/914C was chosen for the study. Since specimen orientation has a significant effect on composite properties, three different orientations were utilised in this investigation; namely unidirectional $(0)_8$, crossply $(0/90)_{4s}$, and angleply $(\pm 45)_{4s}$.

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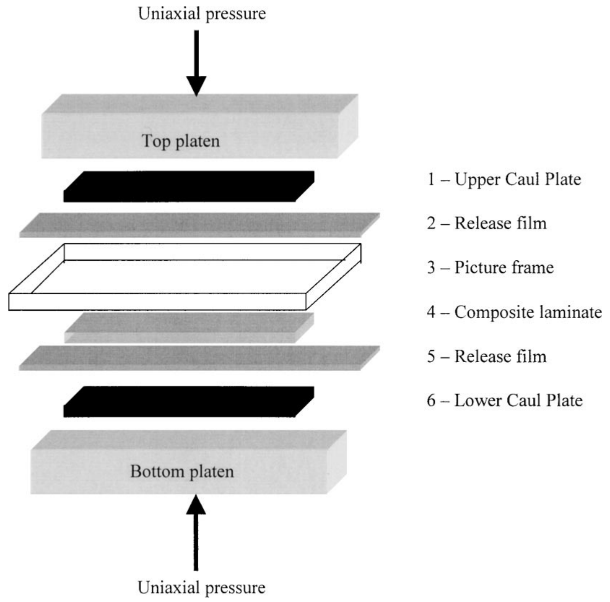

Figure 1 Transverse view of the lay-up used for curing T300/914C in the hydraulic press.

The unidirectional specimens were of nominal thickness 1 mm, while the crossply and angleply laminates were of nominal 2 mm thickness.

3. Experimental procedure

Pre-preg sheets were cut into 300 mm × 300 mm plies, laid up and placed in a picture frame mould, to prevent transverse flow of the matrix resin and cured using a compression moulding process [12] (Fig. 1). A two stage laminate curing process was used in the production of the final laminate and consisted of

Stage 1

- Apply 700 kPa pressure
- Heat to 175°C at 10°C/min.
- Cure for 1 hour at 175°C
- Cool to below 60°C before removal of pressure.

Stage 2

- Post cure at 190°C for 4 hours in a standard air-circulating oven.

The specimen geometries used are those recommended by ASTM D3039 and D3479 and are illustrated in Fig. 2. Soft aluminium tabs were bonded to the specimens using Redux 403, to ensure a better load transfer between the Instron grips and the composite specimen.

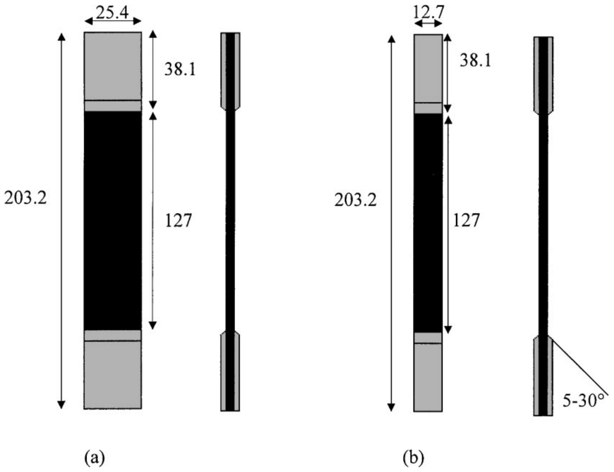

Figure 2 (a) Crossply and angleply specimen geometry (b) Unidirectional specimen geometry (Units mm).

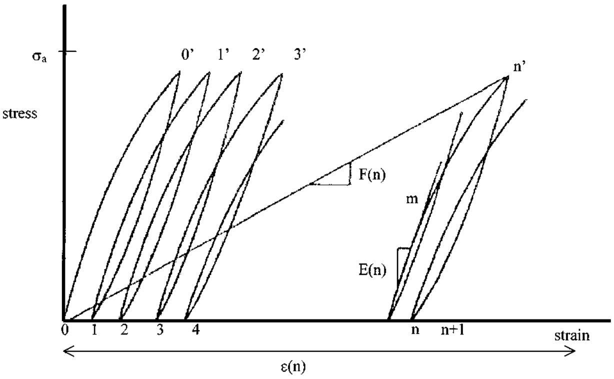

Figure 3 Fatigue modulus concept [14].

Static tensile tests were carried out according to ASTM D3039 initially to characterise the tensile strength of the material. A computer package called CMAP (Composite Material Analysis Plates) was utilised to study the tensile properties. Dynamic testing was carried out on an Instron 8501 in accordance with ASTM D3479 and were performed in sinusoidal tension-tension cycling under load control with a load ratio $R = 0.1$. These tests were performed at different stress levels to produce S-N curves at frequencies of 5, 10, and 20 Hz. Data logging was performed by a software package called FLAPS (Fatigue Laboratory APplications Software). The data logging function in FLAPS was configured to capture 10 position and load cycles representing one full cycle. This technique allows the capturing of stress/strain hysteresis loops which when analysed yields the following data:

- Maximum strain
  The maximum strain was examined in this study in an attempt to quantify the change in compliance of the specimens as the lifetime progresses.
- Normalised fatigue modulus
  Due to the degradation of the composite material under cyclic loading, the stress strain curve changes as the cycles progress. The fatigue modulus is the slope of the line on' as shown in Fig. 3 and can be used as a damage analogue, since the sequence of damage development can be correlated with the mechanical response of the composite specimen [14]. Therefore

  $$F(n,r) = \frac{\sigma_a}{\varepsilon(n)}$$

  where $F(n,r)$ = fatigue modulus at nth loading cycle
  σ_a = applied stress
  $\varepsilon(n)$ = resultant strain at the nth loading cycle
- Dynamic loss modulus
  The loss modulus is proportional to the net energy dissipated per cycle and thus can provide significant information about hysteresis heating of the specimen.

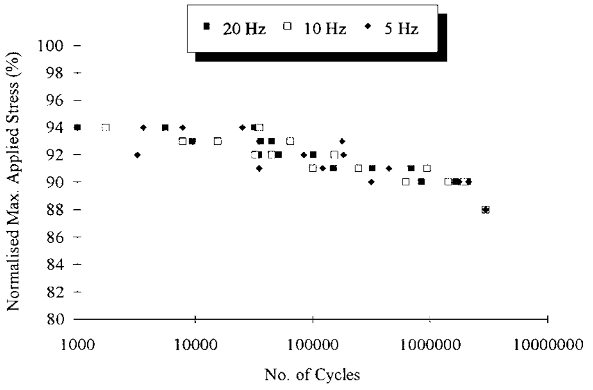

Figure 4 S/N curve behaviour for unidirectional specimens.

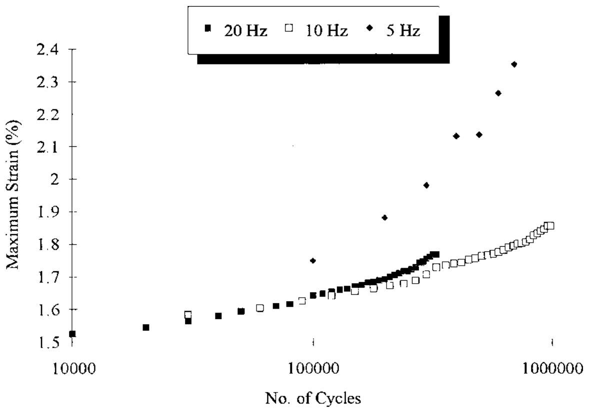

Figure 5 Maximum strain versus number of cycles for unidirectional specimens.

- Damping factor
  The damping factor is the ratio of the energy dissipated per cycle to the maximum potential energy stored per cycle and can also provide information regarding hysteresis heating of the sample.
- Specimen Temperature
  Specimen temperature was also monitored during the fatigue cycling, using a platinum resistance thermocouple located in the centre of the specimens with a working range of −50°C to 260°C.

4. Results

There is a large amount of scatter observed in the S-N curves for the unidirectional specimens in Fig. 4, which makes it difficult to investigate the properties of these composites. The effect of test frequency on the dynamic mechanical properties is also difficult to examine. There are no discernible trends in maximum strain, normalised fatigue modulus, dynamic loss modulus, and damping factor, as shown seen in Figs 4–8. Figs 9–15 depict the effect of test frequency on the fatigue behaviour of crossply laminates. As seen with the U-D laminates, there is a high degree of scatter in the S/N curves in Fig. 9, which makes it difficult to interpret trends in fatigue behaviour. However Fig. 10 illustrates the frequency effects very effectively in the manner utilised by Sun and Chan [9]. It is immediately noticeable that there is a notable variance in lifetimes between specimens tested at identical stress levels at different frequencies. An increase in test frequency from 5 to 10 Hz results in a sharp decrease in the

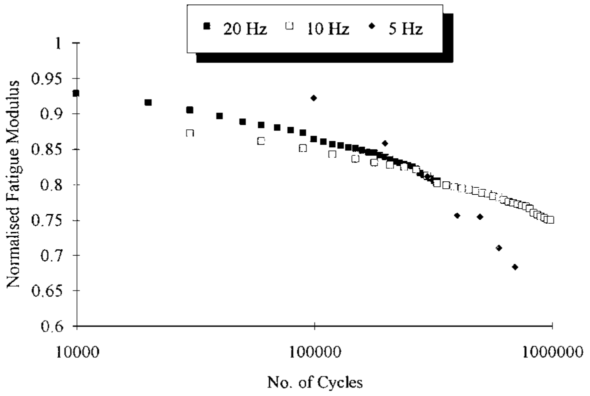

Figure 6 Normalised fatigue modulus for unidirectional specimens.

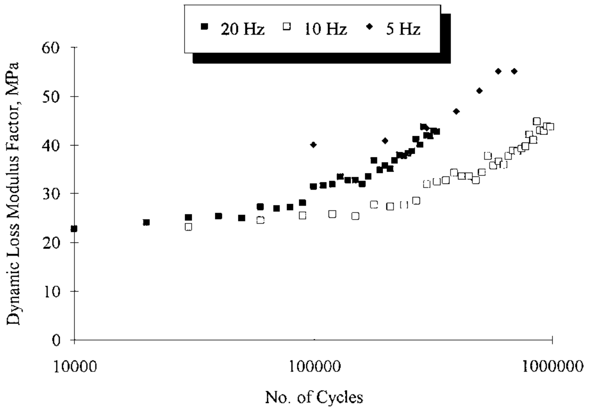

Figure 7 Dynamic loss modulus for unidirectional specimens.

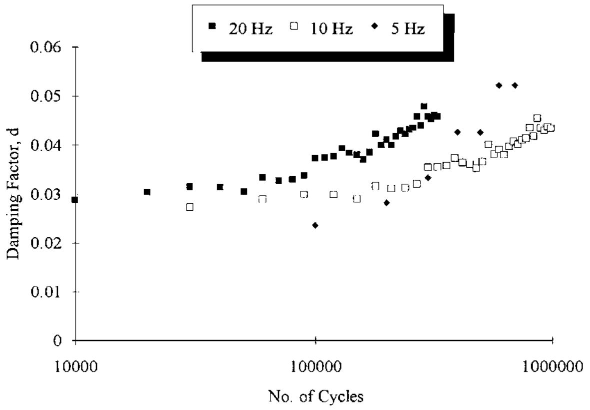

Figure 8 Damping factor for unidirectional specimens.

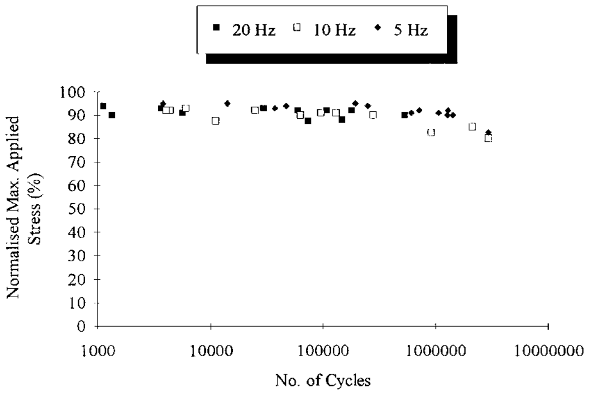

Figure 9 S/N curve behaviour for crossply specimens.

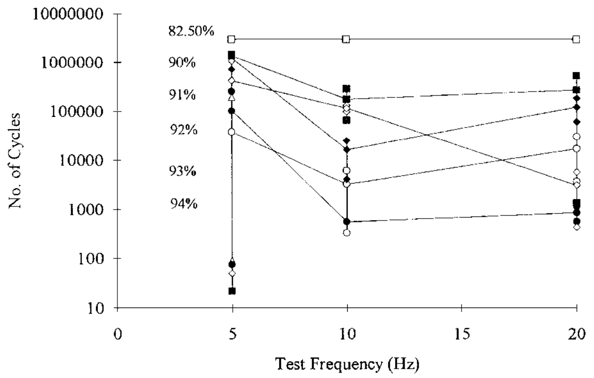

Figure 10 Specimen lifetime for crossply specimens.

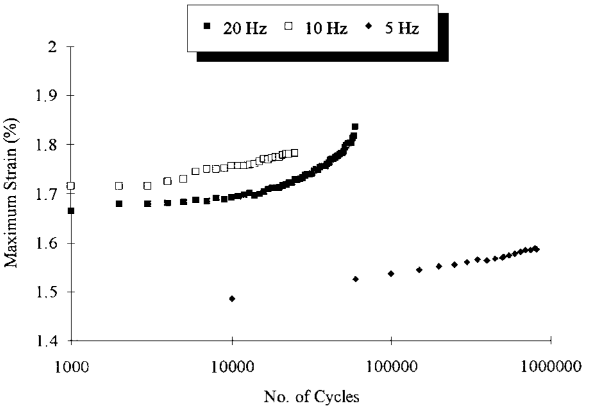

Figure 11 Maximum strain versus number of cycles for crossply specimens.

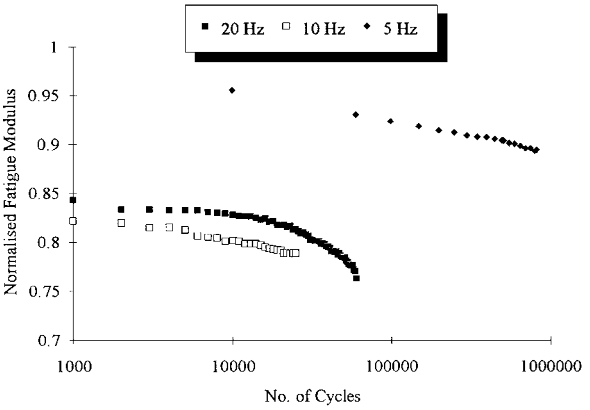

Figure 12 Normalised fatigue modulus for crossply specimens.

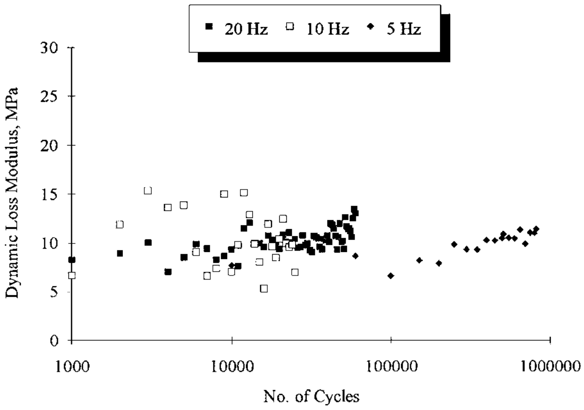

Figure 13 Dynamic loss modulus for crossply specimens.

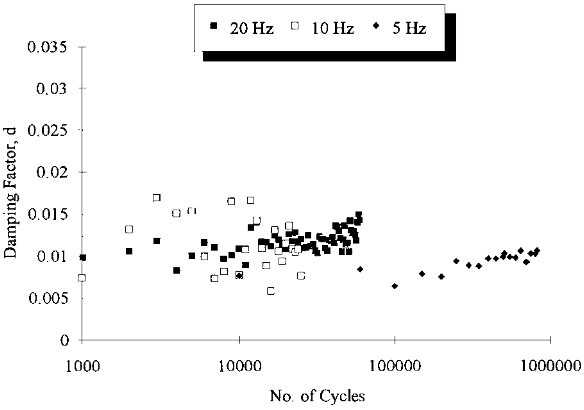

Figure 14 Damping factor for crossply specimens.

specimen life span, while a further increase from 10 to 20 Hz results in a slight increase in specimen lifetime. Fig. 11 illustrates the effect of the test frequency on maximum resultant strain of crossply specimens. The results obtained mirror those observed for the S/logN results. As the test frequency is initially increased from 5 to 10 Hz, the observed strain in crossply specimens is considerably increased. A further increase in the cyclic frequency form 10 to 20 Hz results in a decrease in strain values. It is interesting to note that test frequency does not seem to alter the characteristic shape of the curve, since fibre strain is the maximum resultant strain-limiting factor during fatigue. This increase in resultant maximum strain with test frequency shown in Fig. 11 demonstrates a change in the compliance of the material as the frequency is increased. Fig. 12 illustrates the behaviour of normalised fatigue modulus as a function of test frequency for the crossply specimens. As the test frequency is increased from 5 to 10 Hz the normalised fatigue modulus decreases from 0.9 to 0.8. As seen previously a further increase in frequency from 10 to 20 Hz has the opposite affect with a slight increase in fatigue modulus observed. The dynamic loss modulus curves are shown in Fig. 13. Again these results echo those previously seen. The dynamic loss modulus factor values increase substantially as the frequency is increased from 5 to 10 Hz, while a further increase to 20 Hz results in a decrease. The results shown in Fig. 14 for the damping factor response are the same as those observed for the dynamic loss modulus factor. Again at the highest stress levels, fatigue scatter overshadows the effects of the test frequency on the cross ply specimens. The behaviour of specimen temperature differs from that observed for other mechanical properties monitored in this study. Increase in the test frequency results in a comparative increase in test specimen temperature as shown in Fig. 15. The lowest temperature rise was observed for the specimens tested at 5 Hz. By increasing the test frequency from 5 to 10 Hz an increase in specimen temperature occurred. This may be related to the increase in specimen fatigue resistance observed at higher frequencies, as an increase in specimen temperature may result in crack blunting. Figs 16–21 depict the test frequency effect on the fatigue behaviour of angleply composites. The results obtained for these angleply specimens are almost completely opposite to those observed for the crossply specimens. For all

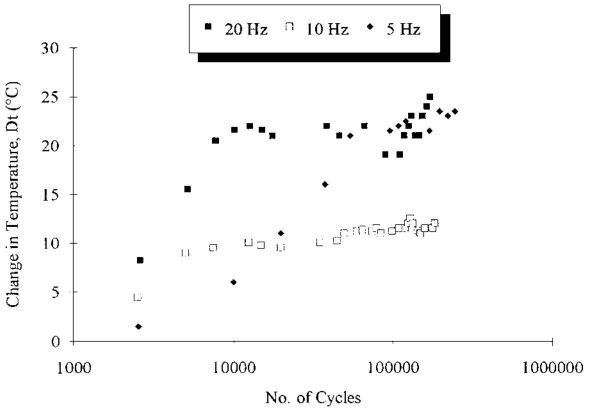

Figure 15 Specimen temperature for crossply specimens.

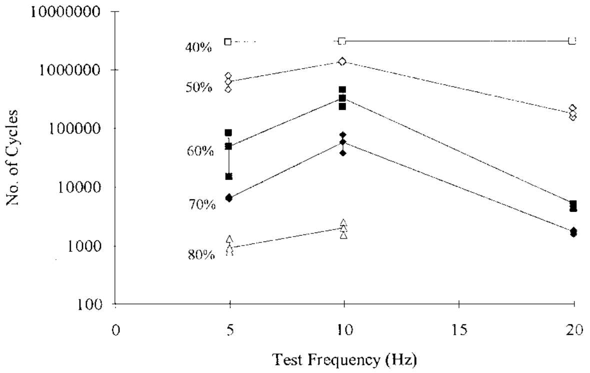

Figure 16 Specimen lifetime for angleply specimens.

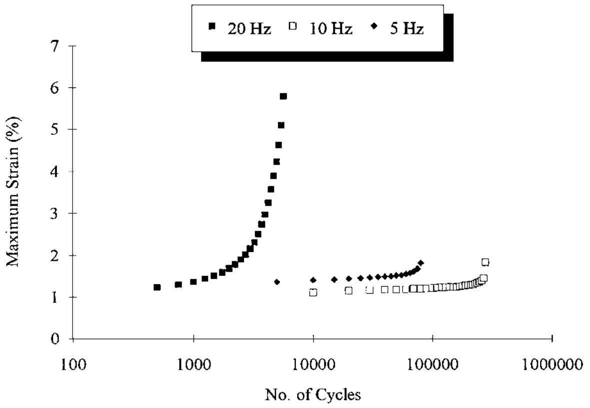

Figure 17 Maximum strain versus number of cycles for angleply specimens.

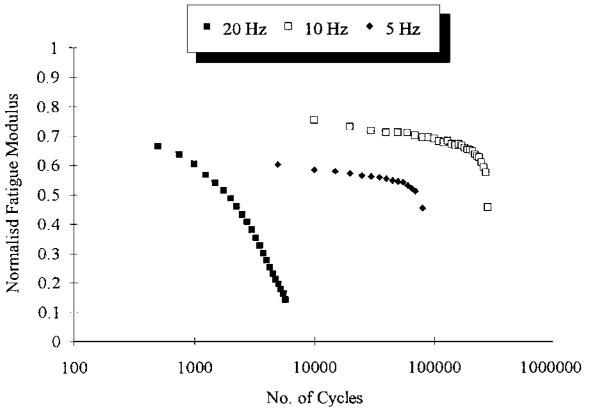

Figure 18 Normalised fatigue modulus for angleply specimens.

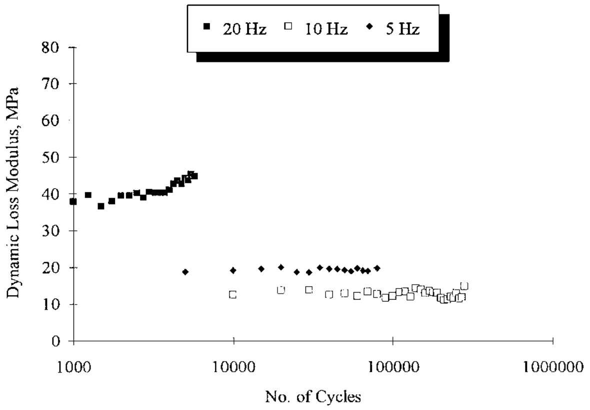

Figure 19 Dynamic loss modulus for angleply specimens.

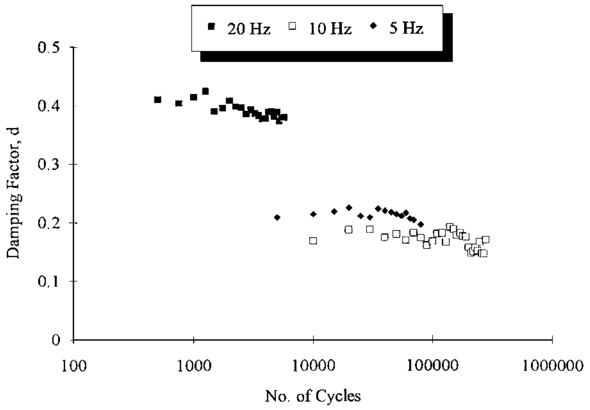

Figure 20 Damping factor for angleply specimens.

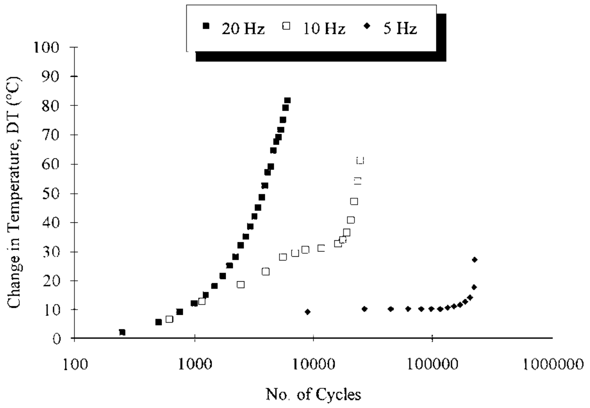

Figure 21 Specimen temperature for angleply specimens.

levels of stress applied an increase in test frequency from 5 to 10 Hz results in a consequent increase in specimen lifetime as seen in Fig. 16. A further increase in test frequency results in a distinct decrease in the specimen life span, the magnitude of which is quite remarkable. In some cases the lifetimes of specimens tested at 20 Hz were one tenth of those tested at 10 Hz. As the frequency is increased from 5 to 10 Hz the maximum strain in the angleply specimen decreases as seen in Fig. 17. In particular the plateau stage of strain behaviour at 10 Hz is at a lower maximum strain level than that observed at 5 Hz. A further increase in test frequency results in a considerable increase in strain values. The frequency effect phenomenon is especially significant 60% UTS as shown in Fig. 17. The change in the resultant maximum strain with test frequency observed demonstrates an alteration in the compliance of the material as the test frequency is increased. This increase can be attributed to the significant degree of hysteretic heating, which occurs during the fatigue testing of these angleply laminates. As the frequency increases, the hysteretic heating also increases leading to an increase in maximum strain, specimen temperature, and specimen compliance. Fatigue modulus increases as the test frequency increases from 5 to 10 Hz as shown in Fig. 18. This may be attributed to crack blunting since it reduces the rate of crack propagation and therefore decrease the amount of specimen damage. On subsequent increasing of the test frequency from 10 to 20 Hz a huge decrease in fatigue modulus is observed with values approaching 0.1–0.2 of the original modulus. As seen in Fig. 19 the dynamic loss modulus factor decreases as the test frequency increase from 5 to 10 Hz. However as seen previously a further increase to 20 Hz results in a huge increase with values approaching 4 times those observed at 10 Hz. Again a similar trend is observed for the damping factor results as illustrated in Fig. 20. A decrease is observed as the test frequency is increased form 5 to 10 Hz, while on a subsequent increase from 10 to 20 Hz, the damping factor undergoes a huge increase with values at 20 Hz approaching twice those observed at 10 Hz. The influence of test frequency on specimen temperature is illustrated in Fig. 21. Increasing the test frequency results in a comparative increase in specimen temperature. The lowest temperature rise occurred for the angleply specimens tested at 5 Hz. Temperature rises of almost 90°C were recorded for specimens which were subjected to fatigue testing at 20 Hz. It is obvious from the experimental data obtained that test frequency plays a pivotal role in determining the dynamic mechanical response of angle ply composites. This can be almost completely attributed to the matrix domination of the angleply mechanical properties.

This factor allows significant hysteresis heating to occur during fatigue testing, which results in an increase in specimen temperature, which is the main source of frequency effects.

5. Discussion

It is evident from the results that frequency effects significantly influence the fatigue behaviour of carbon fibre reinforced composites, as illustrated in Table I where a summary of results are given.

Unfortunately, due to the high incidence of scatter the fatigue results for the unidirectional laminates were inconclusive. However, both crossply and angleply laminates demonstrated a clear and distinct dependence of dynamic mechanical response on test frequency. In the case of the crossply laminates, it was found that an initial increase in test frequency results in decreased fatigue resistance. However, on increasing the test frequency from 10 to 20 Hz, in increase in specimen life span was observed. Angleply laminates, because of their matrix-dominated nature exhibit the greatest dependency on test frequency. An initial increase in test frequency resulted in a consequent increase in specimen fatigue resistance. A further increase in test frequency caused a decrease in the specimen fatigue resistance. These observations are broadly in agreement with the general trends seen in other studies [1, 3]. The dynamic mechanical properties monitored in this investigation mirrored the changes in specimen lifetime observed for both crossply and angleply specimens. As the test frequency increased from 10 to 20 Hz for angle ply laminates the specimen lifetime reduced. Concurrently, as the test frequency increased, maximum resultant strain levels, fatigue damage levels, dynamic loss modulus factor and damping factor all increased, as did the specimen temperature. It is thought that the frequency effects observed could be attributed to hysteretic heating, which significantly alter dynamic response of the mechanical properties of carbon fibre reinforced polymer composites. At low-test frequencies composites specimens fail as a result of mechanical failures caused by the propagation of fatigue damage. At intermediate frequencies hysteresis heating begins to take affect, especially for the matrix dominated angleply specimens, where temperature increases are considerable. As specimen temperature increases, the polymer matrix begins to soften, which results in crack blunting and decreased interfacial bond strength. It is thought that the latter produces a significant reduction in the life span of crossply specimens. A decrease in interfacial bond strength reduces the ability of the polymer matrix to distribute stresses evenly among the fibres and encourages the formation of interfacial cracking. In contrast the lifetime of the angleply specimens is believed to be increased by the mechanism of crack blunting, which in turn reduces the fatigue damage propagation rate. At higher test frequencies the influence of hysteresis heating is considerable. A reduction in fatigue damage propagation rate as a result of crack blunting results in an increased fatigue lifetime for crossply specimens. However, in the case of angle ply

TABLE I Summary of effects of frequency on fatigue behaviour of carbon fibre reinforced polymer composites

Composite	UD	Cross-ply		Angle-ply	
Increase frequency	Too	5–10 Hz	10–20 Hz	5–10 Hz	10–20 Hz
Fatigue life	Much	Decrease	Increase	Increase	Decrease
Max. Strain	Scatter	Increase	Decrease	Decrease	Increase
Dynamic Modulus		Decrease	Increase	Increase	Decrease
Loss Modulus		Increase	Decrease	Decrease	Increase
Damping factor		Increase	Decrease	Decrease	Increase
Specimen Temperature		Increase	Increase	Increase	Increase

specimens a reduction in specimen lifetime is thought to be a result of the specimen compliance and specimen temperature.

6. Conclusion

Matrix-dominated orientations such as angleply specimens exhibit greater frequency effects on their fatigue behaviour than the fibre-dominated orientations such as unidirectional and crossply specimens. In addition frequency effects on the fatigue behaviour are mostly due to hysteretic heating.

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