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# Fatigue life-limiting parameters in fibreglass composites

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A study was conducted to determine the fatigue life-limiting parameters in E-glass fibre-reinforced vinyl esters. Because of the viscoelastic nature of fibreglass composites and the adiabatic heating during rapid fatigue cycling, the cyclic frequency has a significant effect on the fatigue resistance of the composites. For these same reasons, creep phenomena must also be considered in rationalizing fatigue characteristics of the materials. The surface condition of the composite, stress level, curing condition, and the surface integrity of fibreglass were also found to alter the fatigue behaviour of fibreglass composites.

## 1. Introduction

The axial fatigue failure sequence and mechanisms of unidirectional fibreglass composites have been determined from the modulus change, hysteresis loop area change, and the microstructural change during the fatigue cycling in this laboratory [1]. The onset of permanent fatigue damage was found to occur by fibre surface flaw propagation. These fibre surface flaws then coalesce to produce gross fibre surface cracks, which in turn create interface failures. As the fatigue cycling continues, the interface failures induce matrix cracks which propagate in both transverse and shear directions. The fatigue specimen was found to fail completely by through-delamination paralled to the loading direction. A diagram of the axial fatigue failure sequence and mechanisms is illustrated in Fig. 1.

The response of materials to cyclic loading is affected by many parameters other than the amplitude of repetitive stress or strain. The fibreglass-reinforced polymers, which consist of at least two components, involve more parameters in a complex way than do the homogeneous metallic materials. The complexity of fatigue life-limiting factors for the fibreglass composites stems chiefly from the structural anisotropy, viscoelastic behaviour of the composite, and appreciable adiabatic heating of the material during the fatigue cycling.

A cognizance of any parameter which significantly alters the fatigue life of the composite is important not only to take account of such variations in the service condition from a practical standpoint, but also to verify the proposed fatigue failure sequence and mechanisms of the composite from a more basic point of view. Most recently, studies of the influence of stress state, frequency, and environment on the fatigue of composites [2–5] pointed out that these parameters affect the fatigue life of composites, but a complete understanding of their influence has yet to be made.

In the present study, the parameters which are relevant to each fatigue failure mechanism were studied to verify the proposed fatigue failure mechanism and to uncover their influence on the fatigue life of the composites. Other factors which relate to the service and manufacturing conditions were also considered.

## 2. Experimental procedure

Two types of fibreglass composites, both consisting of the Owens-Corning Fiberglas Type 30 E-glass and the Derakane 470-45 vinyl ester resin [6], were used for the study.

The first composites (identified as System 1) were fabricated by dry filament winding and vacuum resin infiltration [1]. The fibreglass strand was untwisted and softened by passing the glass strand through four consecutive steel rods with tension. The dimensions of the System 1 com-

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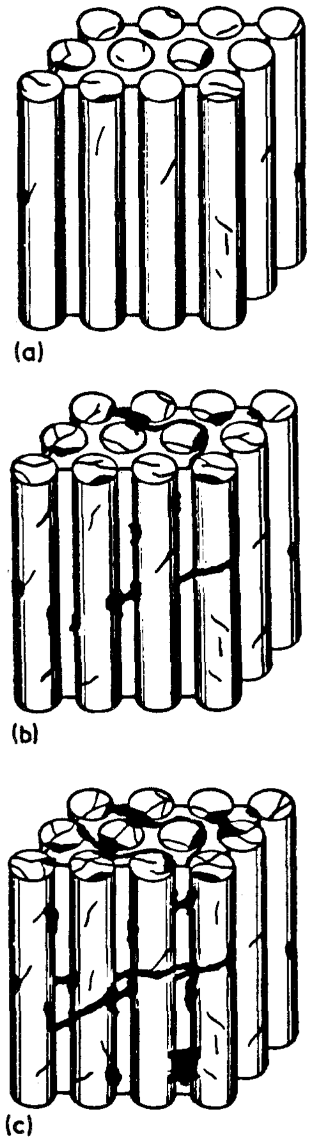


*Figure 1* A diagram of the tension–tension axial fatigue failure sequence and mechanisms of fibreglass composites (as-moulded surface condition). (a) Onset of fatigue damage; fibre surface flaw propagation and subsequent fibre surface cracking. (b) Crack propagation; interface failure, and matrix crack propagation in both transverse and shear directions. (c) Through-delamination; coalescence of transverse and shear crackings, and complete fibre failure.

posites were $\frac{1}{2}$ in.* wide, $\frac{1}{2}$ in. thick, and 12 in. long The general quality of these composites is shown in Fig. 2. The diameter of the fibreglass used in the study varies from 10 to 19 $\mu$m. Some fibres appearing discontinuous in Fig. 2b are not broken, but are fibres tilting slightly from 0°. Although a

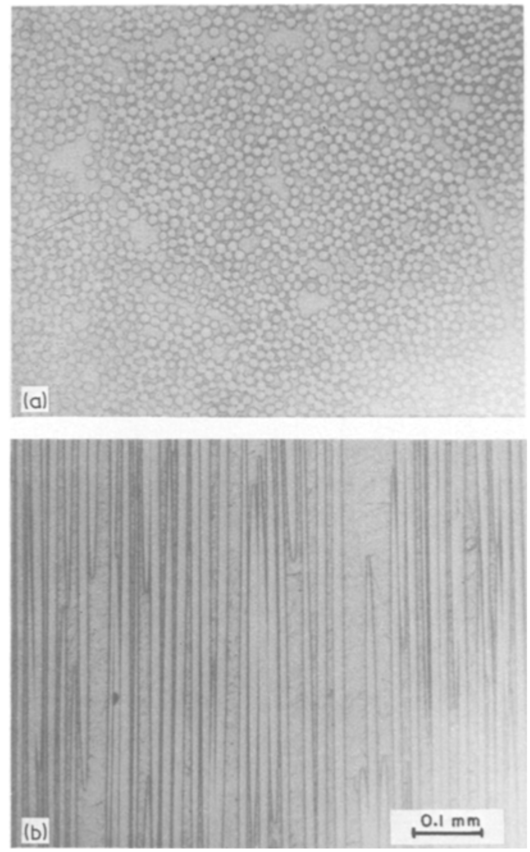


*Figure 2* Micrographs of (a) transverse and (b) longitudinal sections of a System 1 composite, which show uniform fibre distribution, absence of voids or cracks, and excellent fibre alignment.

small amount of resin-rich area was present in the System 1 composites, these composites were free from voids and cracks. The 0.060 in. thick fatigue test pieces (Fig. 3) were cut from these composites with either one or both surfaces in the machined condition.

In order to obtain the as-moulded surface condition, the second group of composites (System 2) was directly moulded in a simple compression mould to the final dimensions of the fatigue specimen. While the quality of the System 2 composites was slightly inferior to that of the System 1 composites, the physical and mechanical properties of two composites were almost identical (except the proportional limit) as shown in Table I. The low proportional limit of the System 2 composites might be attributed to the fibre weaving, larger resin-rich area, and possibly to the different residual stress state in the System 2 composites.

*1 in. = 25.4 mm.

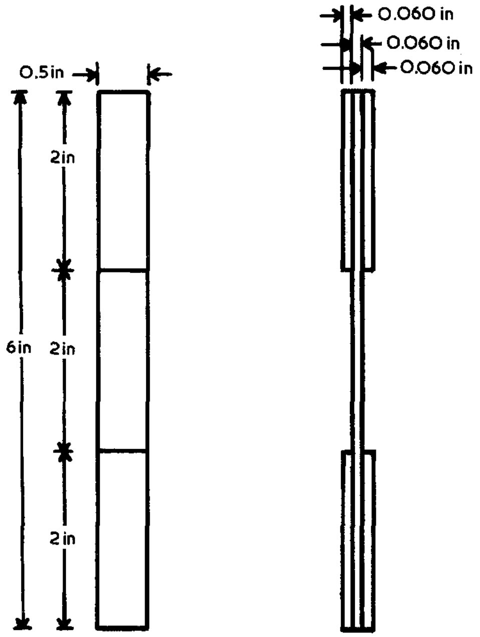


*Figure 3* Dimensions of tab-ended test pieces used for the uniaxial tension and axial fatigue tests.

TABLE I Physical and mechanical properties of two fibreglass composites investigated

| Properties | System 1 | System 2 |
|---|---|---|
| Fibre volume fraction (%) | 57.4–59.8 | 56–60 |
| Density ($g\,cm^{-3}$) | 1.94 | 1.91–1.95 |
| Elastic modulus (GPa) | 44–48 | 45 |
| Poisson's ratio | 0.28–0.30 | 0.28 |
| Proportional limit (MPa) | 455–558 | 325 |
| Ultmate tensile strength (MPa) | 1034–1138 | 1063 |
| Fracture strain (%) | 2.44–2.75 | 2.49 |

All fatigue and creep tests were conducted on an MTS servo-hydraulic testing machine (55 KIP* load frame and actuator) under the load control. The secant modulus during the fatigue cycling and the fatigue life of fibreglass composites were measured as a function of various values of the parameters under study. The specimen surface temperature measurements, stress relaxation tests, and the investigation of microstructures were also employed to discover the fatigue life-limiting factors.

## 3. Results and discussion

### 3.1. Variation in fatigue life of fibreglass composites

The fatigue life of fibreglass-reinforced polymers often scatters over one order of magnitude for a given set of parametric values. This large scatter stems largely from the highly anisotropic nature of the composite, and additionally from the variation of fibre volume fraction within the test piece, density of defects, distribution and alignment of fibres, etc.

In an attempt to determine the nature of the distribution of the fatigue life of fibreglass composites, ten fatigue tests were conducted with 462 MPa mean stress, 234 MPa alternating stress and 10 Hz frequency. It was found that the fatigue life of the fibreglass composites used in the study has an approximately log-normal distribution between 10% and 90% probability of failure at the above specified condition, as plotted in Fig. 4.

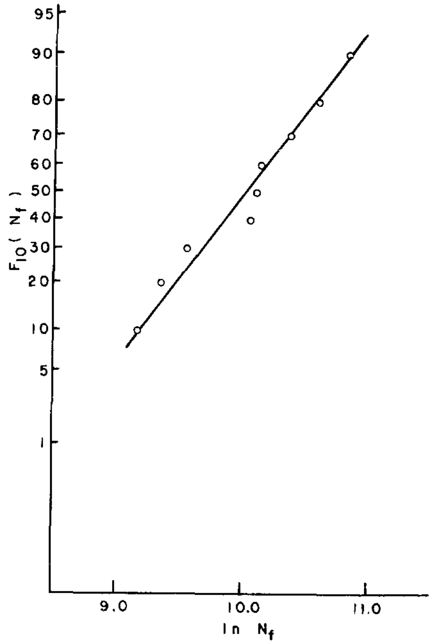


*Figure 4* Plot of the scatter of fatigue life on a log-normal probability paper, which shows that the fatigue life of fibreglass composites has an approximately log-normal distribution between 10% and 90% probability of failure.

### 3.2. Effects of surface condition

It is well known that the fatigue crack usually initiates on the surface of materials, and hence the surface condition greatly alters the fatigue resistance of materials. In order to investigate the surface condition effects on the fatigue behaviour of fibreglass composites, the degradation of secant modulus during the fatigue tests and the fatigue resistance were measured for three different surface conditions.

*1 KIP = $10^3$ lb ~ 454 kg.

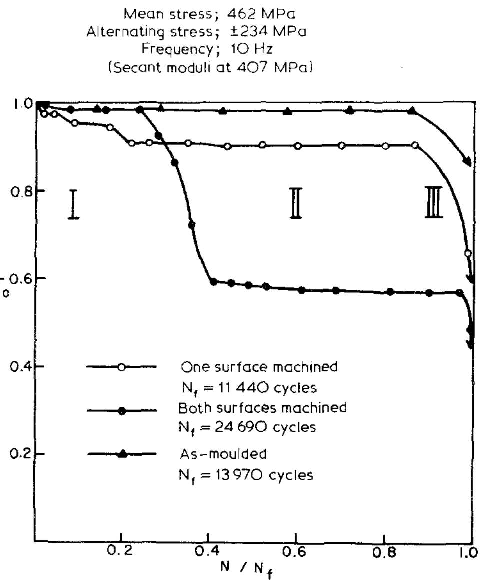


*Figure 5* Secant moduli degradation behaviour during the fatigue tests for three different surface conditions, and three failure steps ($E/E_0$, ratio of instantaneous to initial secant modulus; $N/N_f$, ratio of interrupted cycles to the number of cycles to failure).

Fig. 5 shows the typical modulus degradation behaviour (from at least three repetitive tests) of each surface condition. It was noted from this plot that the fatigue performance (stiffness change) is significantly affected by the surface condition. In the machined surface condition, a coalescence of interior cracks and machined surface cracks creates surface spalling on the machined surface, and this surface spalling causes greater modulus drop during the fatigue failure "Step I" (Fig. 5) [1].

The effect of surface condition on the fatigue resistance of the composites, however, was difficult to be separated from the large intrinsic scatter of the fatigue life. For example, the fatigue life of the both surfaces machined specimen chosen (24 690 cycles) might have been at the far right-hand side of the scatter span which overlaps that of the one surface machined condition.

## 3.3. Effects of stress level

In order to confirm the proposed model of fatigue failure and to determine the effects of stress level on the fatigue performance and resistance, both alternating and mean stress magnitudes were altered.

As shown in Fig. 6, it was found that the magnitude of alternating stress not only affects the fatigue life, but also changes the mode of modulus degradation. At 283 MPa alternating

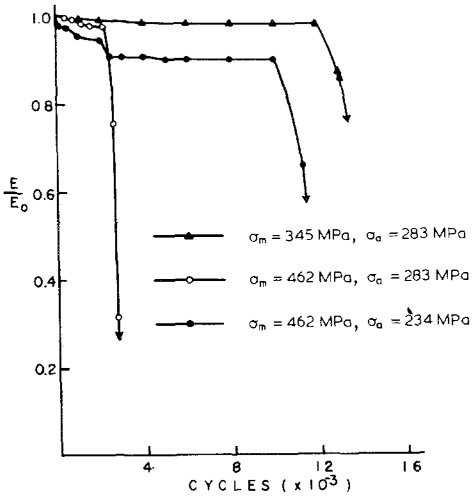


*Figure 6* Effects of stress level on the fatigue behaviour of System 1 composites (one surface machined condition) tested with 10 Hz frequency.

stress (745 MPa maximum stress), the surface spall was much larger than that at 234 MPa alternating stress. Consequently, the modulus dropped continuously without passing the steady state (matrix crack propagation step – "Step II" in Fig. 5), because of greatly reduced cross-sectional area.

The effect of mean stress level was also studied by conducting fatigue tests at different values of mean stress, while keeping the alternating stress constant. The modulus degradation behaviour at 345 MPa mean stress and 283 MPa alternating stress (627 MPa maximum stress) was similar to that at 462 MPa mean stress and 207 MPa alternating stress (669 MPa maximum stress).

The effects of stress level on the fatigue behaviour of fibreglass composites are summarized as follows:

(1) The alternating stress amplitude determines the fatigue life at constant mean stress.

(2) The mean stress level determines the alternating stress magnitude for a constant fatigue life.

(3) The maximum stress magnitude determines the modulus degradation mode and extent.

## 3.4. Effects of creep

The fibreglass composites have been known to creep at room temperature [7] because of the viscoelastic behaviour of the polymeric matrix of the composite. In addition, the mean stress level (462 MPa) employed in this study was rather high; hence it was deemed possible that the creep might have a significant effect on the fatigue life of fibreglass composites.

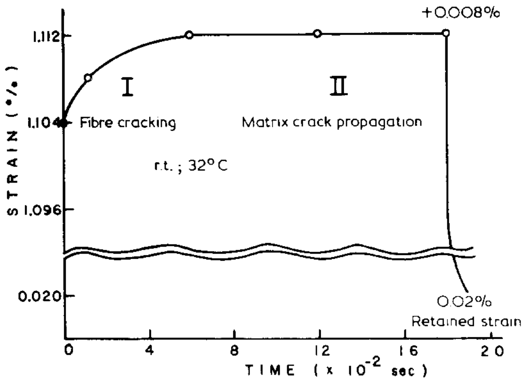


*Figure 7* Creep curve of a System 1 composite, tested at 462 MPa for 30 min.

In an attempt to find out the nature of the relevant creep mechanisms and the pre-creep effect on the fatigue life, a specimen was loaded to the 462 MPa stress level and held at that stress level for 30 min while monitoring the concomitant strain. the strain increased by 0.008% from 1.104% initial strain, and 0.02% strain was retained upon unloading (Fig. 7). The specimen was then quickly reloaded to 462 MPa mean stress, and the fatigue life was measured at 234 MPa alternating stress and 10 Hz frequency. The fatigue life was shortened significantly to 1090 cycles from 24 690 cycles of fatigue life of the specimen with no creep pre-treatment.

In order to find out the source of this deleterious effect of creep, another specimen was held at 462 MPa for 30 min, and the microstructure of the specimen was examined. The microstructure showed that all fibres had cracked substantially and a matrix crack was propagating, as shown in Fig. 8. This microstructure was quite similar to that of the composite in the steady state (Step II) during the dynamic fatigue cycling. In addition, the creep behaviour (initial strain increase and steady state) is similar to the initial decay and the steady state of the modulus (Fig. 5) during the dynamic fatigue loading. Therefore, it would appear that the failure mechanisms of fibreglass composites are the same in both dynamic and static fatigue loading conditions.

## 3.5. Effects of cyclic frequency

In metallic materials, the frequency of load application in a fatigue test does not significantly influence the fatigue life over a wide range of frequencies. In fibreglass composites, however, the frequency of load application has been known to affect the fatigue life substantially on some occasions [2,3].

In order to clarify the effects of frequency, an initial attempt was made to investigate the fatigue failure mechanisms at different frequencies. The moduli degradation behaviour at 1, 10 and 30 Hz (Fig. 9) showed that the fatigue failure sequence and mechanisms are not affected by the frequency, except for the presence of more heterogeneous surface spalling at 30 Hz for the machined surface condition.

The fatigue endurance, however, was found to be affected by the cyclic frequency, as shown in Fig. 10. While the fatigue lives at 1 and 10 Hz are nearly identical, the fatigue life at 30 Hz scatters over the same number of cycles as those for 1 or 10 Hz but at about a 69 MPa lower stress level. This would indicate that cycling at 30 Hz produces more damage than cycling at 1 or 10 Hz.

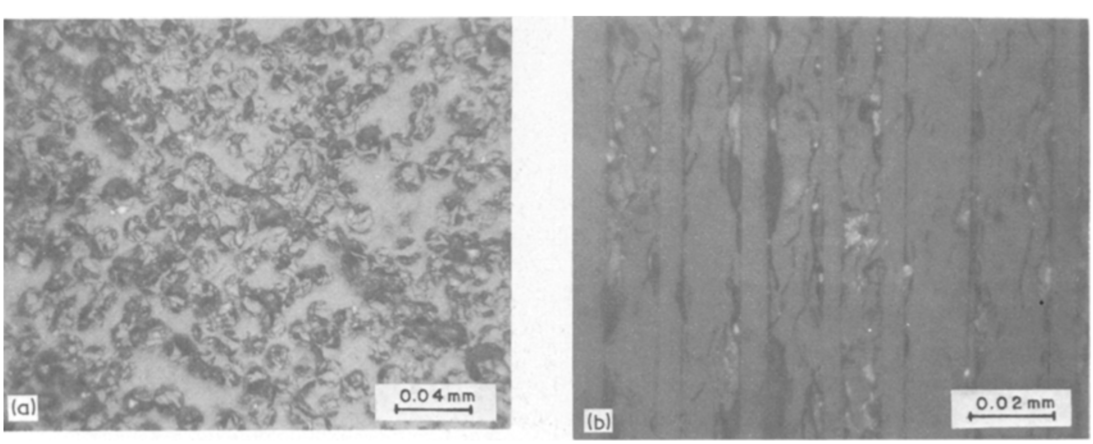


*Figure 8* Micrographs of System 1 composites after 30 min creep at 462 MPa (etched in hydrofluoric acid). (a) transverse section; (b) longitudinal section.

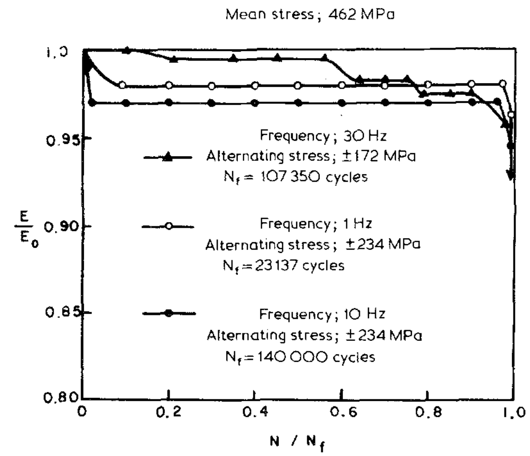


*Figure 9* Comparison of dynamic modulus (slope of the hysteresis loop) degradation behaviour between 1 and 10 and 30 Hz frequencies during the fatigue tests.

In order to rationalize the frequency effect on the fatigue lfie of fibreglass composites, an attempt was made to measure the surface temperature of the fatigue specimen with a copper–constantan thermocouple. The surface temperature was found to rise quickly at the early stage of the fatigue test. It then reaches the steady state condition followed by an abrupt increase resulting from the final fracture, as shown in Fig. 11. The steady state surface temperature at 10 Hz was 5.6° C higher than that at 1 Hz, and 30 Hz produced greater temperature increase than 10 Hz even at lower alternating stress. From this observation, it was clear that the specimen heating was substantial, and might conceivably influence the fatigue resistance of fibreglass composites to a significant degree.

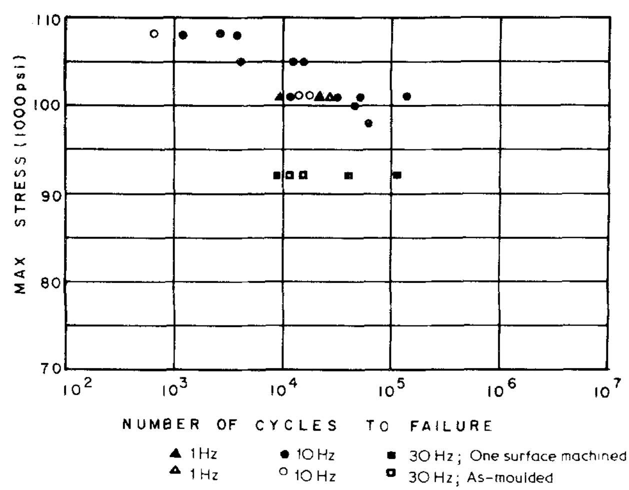


*Figure 10* Fatigue endurance of composites for three different frequencies at 462 MPa (67 ksi) mean stress.

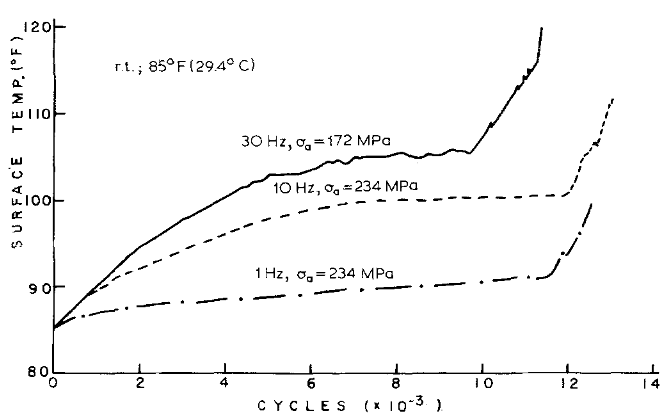


*Figure 11* Specimen surface temperature increase during the fatigue tests for three different frequencies at 462 MPa mean stress.

In an attempt to find out the mechanism by which temperature might affect the fatigue life, the tensile strength of the composite was measured at the observed steady state temperature. The composite strengths at 40.6° C (the steady state surface temperature measured at 30 Hz) and at 46.1° C (considering that the interior temperature is higher) were within the scatter range of the strength values at room temperature. Therefore, the temperature effect was considered to be related to one of the fatigue failure mechanisms.

As mentioned in the previous section, the axial fatigue test was essentially terminated by the complete fibre failure. It is a well-established fact that the glass fracture is caused by the water vapour stress corrosion at the crack tips [8,9]. If this fracture mechanism is valid for the fibreglass embedded in the polymeric matrix, the temperature effect could be explained by the differential corrosion rate at different temperatures. In other words, the corrosion rate of pre-absorbed moisture, and the diffusion rate of water vapour from the environment can be enhanced by the specimen heating during the fatigue cycling [10]. Therefore, the fibre failure may be caused by the "corrosion fatigue", and hence at higher temperatures, the accelerated corrosion process may tend to shorten the fatigue life of fibreglass composites.

In order to verify the proposed corrosion fatigue model, stress relaxation tests were conducted on an Instron testing machine at two different temperatures. As shown in Fig. 12, stress was relieved much more rapidly, and to a greater degree, at 43° C than at room temperature because of the increased creep (fibre cracking, matrix creep, and matrix crack propagation) at higher temperatures. This result strongly suggests that the fracture of fibreglass is caused by the thermally activated stress corrosion.

When a material is subjected to corrosion fatigue condition, there is a definite dependence of fatigue properties on testing speed. Since corrosive attack is a time-dependent phenomenon, the higher the testing speed, the smaller the damage due to corrosion. Fig. 13 shows the strain rate effect on the strength of System 1 composites. The strength of the composite, which comes mostly from the glass fibres, increases with the strain rate. This is probably due to the presence of less corrosion damage on the glass fibres at higher strain rate. Therefore, lower frequency (longer time span per cycle) is more damaging to the materials subjected to corrosion fatigue, if the temperature rise resulting from the hysteresis heating is negligible.

Based on the above investigations, it was concluded that there are two competing parameters – testing time and temperature – originating from the cyclic frequency. The fatigue lives at 1 and 10 Hz are nearly identical, even though the specimen heating is higher at 10 Hz. This is probably due to the balance between two opposing factors. The cycling at 30 Hz is more damaging than that at 10 Hz, probably because of the overwhelming effect of temperature at 30 Hz.

## 3.6. Other factors

Besides the previously discussed parameters, several other factors related to the manufacturing and service conditions were also investigated.

While the contribution of the matrix to the composite strength is very small, the polymer matrix plays an important role as a binder to achieve a continuum of mechanical properties in the composite. Consequently, the curing condition

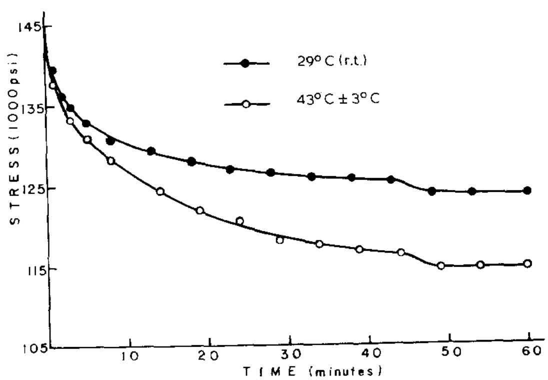


*Figure 12* Stress relaxation curves for System 2 composites tested at 29° C and 43° C (initial stress, 145 ksi = 1000 MPa.

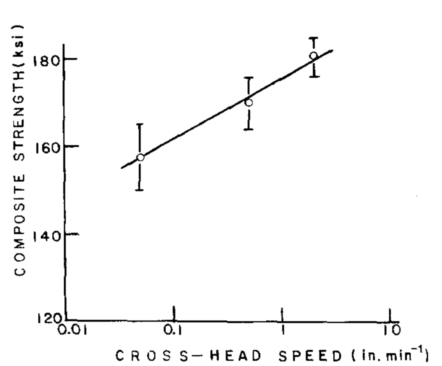


*Figure 13* Strain rate effects on the strength of System 1 composites.

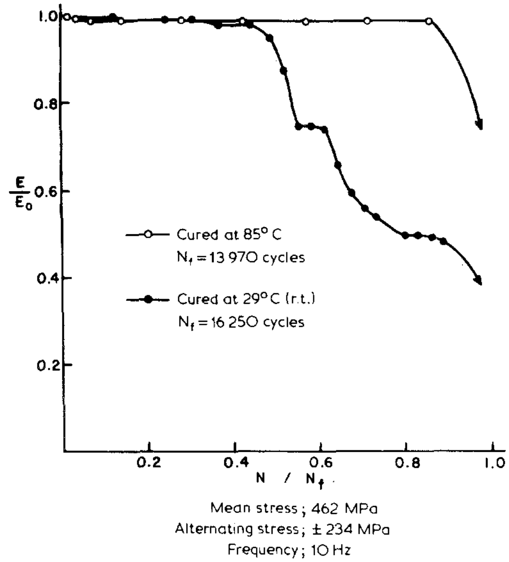


*Figure 14* Comparison of secant moduli (at 407 MPa) degradation behaviour during the fatigue tests for two different curing conditions used on System 2 composites.

could be one of the factors affecting the fatigue behavour of fibreglass composites. Fig. 14 shows the secant moduli degradation behaviour of two composites cured under different schedules. The composite cured at room temperature (DDM* as a catalyst) showed much greater modulus drop than the composite cured at 85° C because of the poor surface bonding. The fatigue life, however, appeared not to be significantly affected by the curing condition, since the fatigue life is essentially determined by the fibreglass failure in the tension–tension axial fatigue.

The variation of fibre volume fraction in the test piece appeared to influence strongly the fatigue life of the composite. As summarized in Table II, higher fibre volume fraction manifests itself in a higher initial modulus of the composite, which in turn correlates with higher fatigue resistance at the fixed test condition. The maximum deviation range of the fibre volume fraction in the test piece was 4%.

The fatigue property of individual component of the composite is also one of the fatigue life-limiting parameters. In particular, the surface integrity of fibreglass (flaw density and dimensions) is critical in limiting the fatigue life of the composite, since the onset of fatigue damage occurs on the fibre surface, and subsequent fibre crack propagation and failure determine the fatigue resistance of fibreglass composites.

*DDM = diamine diphenyl methane.

TABLE II Correlation between elastic modulus and fatigue life of fibreglass composites

| Fatigue test condition | Elastic modulus (GPa) | Fatigue life (cycles) |
|---|---|---|
| $\sigma_m$ = 462 MPa, $\sigma_a$ = 234 MPa, $f$ = 10 Hz | 41.7 | 11 330 |
| | 42.3 | 31 210 |
| | 44.5 | 140 000 |
| $\sigma_m$ = 462 MPa, $\sigma_a$ = 172 MPa, $f$ = 30 Hz | 43.0 | 16 000 |
| | 44.3 | 107 350 |
| $\sigma_m$ = 462 MPa, $\sigma_a$ = 283 MPa, $f$ = 10 Hz | 43.8 | 644 |
| | 44.5 | 1 700 |
| | 44.7 | 2 819 |
| $\sigma_m$ = 462 MPa, $\sigma_a$ = 234 MPa, $f$ = 1 Hz | 42.1* | 24 093 |
| | 43.9* | 39 382 |

Note: $\sigma_m$ mean stress; $\sigma_a$ alternating stress; $f$ cyclic frequency; * dynamic Young's modulus.

## 4. Conclusions

From the study described herein, the following conclusions can be drawn:

(1) The fatigue life of the fibreglass composites used in the study has an approximately log-normal distribution between 10% and 90% probability of failure.

(2) The surface condition of the composite significantly affects the fatigue performance. The effect of surface condition on the fatigue life was difficult to separate from the large intrinsic scatter of the fatigue life.

(3) The stress level not only affects the fatigue life, but also alters the mode and extent of modulus degradation during the fatigue cycling.

(4) Fibre and matrix cracking occurs during creep, and hence pre-creep is damaging to the subsequent fatigue of the composite.

(5) The cyclic frequency has significant effects on the fatigue life of fibreglass composites. This is due to specimen heating during the fatigue cycling, and to the testing time effect.

(6) The curing condition influences the fatigue behaviour of fibreglass composites.

(7) The surface integrity of fibreglass is most critical in limiting the fatigue resistance of fibreglass composites in tension–tension axial fatigue.

## Acknowledgement

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