ACOUSTIC EMISSION NDT OF COMPOSITES DAMAGED BY STATIC AND DYNAMIC LOADING IN AQUEOUS ENVIRONMENTS

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SUMMARY: A series of tests has been conducted to investigate the effect of sea water absorption on fatigue damage accumulation in a glass fibre reinforced polyester laminate of the type widely used in the marine and offshore industries, using four-point bend flexural loading to ensure peak strain in the outer layers of the material most subject to sea water absorption. Pre-exposure was found to reduce the flexural strength and enhance damage accumulation in fatigue by stimulating matrix cracking, fibre debonding and delamination. Acoustic emission (AE) was used to characterise damage accumulation. These results were found to correlate well with independent measurements of changing bending stiffness and with observations of the damaged sections.

KEYWORDS: acoustic emission, AE, NDT, composite, offshore, marine, fatigue

INTRODUCTION

Environmentally-assisted damage in polymer matrix composites is known to occur by a number of mechanisms. Water is able to diffuse into the material and weaken the matrix as well as the fibre-matrix interface. The effect of water absorption on the physical and mechanical properties of polyester resins has been known for many years and has been reviewed comprehensively by Ishida & Koenig [1]. Briefly, absorption of water causes swelling, plasticisation and a reduction in the glass transition temperature. Prolonged exposure at elevated temperatures can cause cracking. Exposure of glass-polyester composites to aqueous environments also reduces the fibre-matrix interfacial strength. Glass fibres are usually treated with coupling agents and it is believed that diffusion of water to the interface can hydrolyse and weaken the bonds. However, the reaction appears to be reversible since the strength of a composite, reduced by exposure, can be restored by subsequent drying.

Degradation of matrix and fibre-matrix interfacial strength in composites is known to increase the rate of damage accumulation under cyclic loading and to reduce flexural fatigue life [2].

Acoustic emission (AE) measurements can assist in characterising that environmental damage. There is much work in the literature to show that different modes of failure in composites produce different types of acoustic emission response, the most important difference being amplitude. Barre and Benzeggagh [3] reported that the AE amplitude varies with the different modes of fracture in glass fibre composites. Kumosa et al [4] used the amplitude of AE events in composites to distinguish between types of damage. Low amplitude events were associated with matrix cracking and high amplitude events with fibre breakage. However, no significant work has been reported in the literature on the AE response to the combined effect of cyclic loading and environment.

In the present work, the effects of sea water pre-exposure on damage accumulation in glass/polyester composites were investigated under four point bend monotonic and cyclic loading. The progress of damage accumulation in fatigue was monitored by recording changes in stiffness as a function of the number of strain cycles and by microscopic examination. In addition, damage accumulation was independently characterised by acoustic emission (AE) measurements.

MATERIALS AND METHOD

The fatigue tests are described in detail in the paper "Fatigue Testing of GRP in Aqueous Environments" elsewhere in these proceedings [5]. A brief summary only is given here.

The specimens used in this work were 250×15mm beams cut from woven roving (0/90°) glass reinforced polyester laminate of approximately 10mm thickness. Specimens were conditioned in artificial sea water at 35°C for periods up to six months and tested in four point bending using the rig shown schematically in Figure 1, under monotonic loading and flexural fatigue.

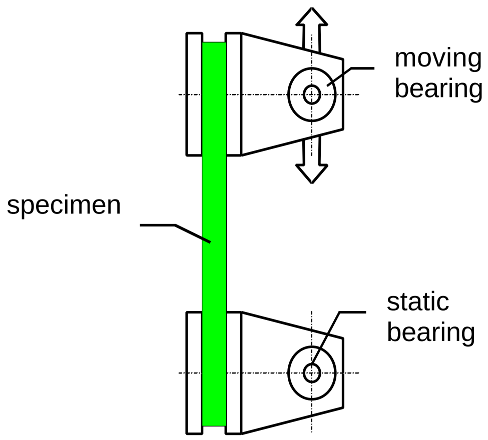

Figure 1. Schematic diagram of bending fatigue rig

For the fatigue loading, the testing machine was cycled either side of the rest position so that the specimens experienced a bending load reversal from tension and compression each cycle, up to a maximum of 10^6 cycles. Displacement control of the testing machine was used so that the nominal outer fibre strain was constant throughout each test. The peak load was monitored, and since the peak strain was constant, this gave an effective measure of beam bending stiffness which was used as a measure of internal damage.

To isolate the specimens acoustically from the testing machine, nylon sleeves and rubber inserts were incorporated into the clamping fixture and loading pins respectively. This prevented extraneous noise being transmitted from the machine and interfering with the acoustic emissions.

The AE transducer was mounted at the side of the test specimen and was acoustically coupled to the specimen surface with silicon grease. Acoustic emission was measured using a Physical Acoustics Corporation monitor (MISTRAS 2001 – AEDSP-32/16), fitted with a PAC U30 D03 low frequency transducer. The equipment is capable of monitoring many features of acoustic emission (number of events, amplitude, energy, counts, frequency, rise time, duration, etc.). In the present work AE events above a threshold amplitude of 45 dB were measured.

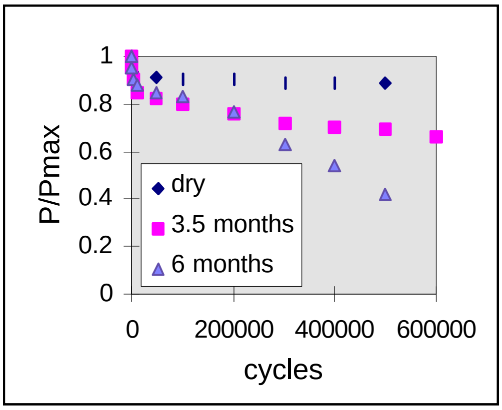

Figure 4. Stiffness variation for dry and wet exposed to sea water for different periods showing effect of fatigue damage

RESULTS

Monotonic Loading

The effect of pre-exposure to sea water on damage under monotonic bending is clearly shown in Figure 2. The number of hits at high strain increases six-fold from dry to saturated material, indicating a greatly increased rate of internal damage prior to final failure.

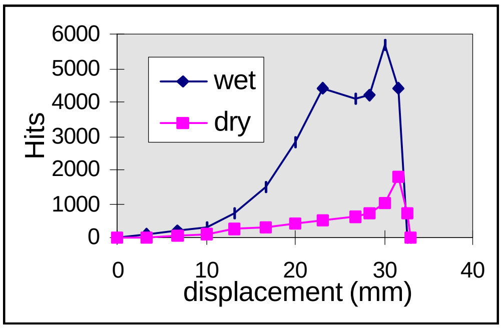

Figure 2 AE hits during monotonic loading showing increased activity at large strains

The nature of that damage is indicated by Figure 3. The number of high amplitude events (summed over the loading period) is unaffected by the water saturation, but there is a greatly increased count of lower amplitude events. As noted above, AE amplitude has been shown to be indicative of the type of damage in GRP.

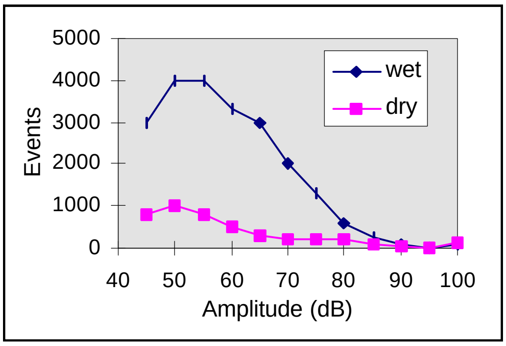

Figure 3. AE amplitude spectrum during monotonic loading showing preponderance of events at moderate amplitude associated with resin damage

The high amplitude events above 80dB are associated with fibre fracture and occurred at the end of the loading period just prior to final failure of the specimen. The consistency of results confirms the established view that absorbed water does not have an adverse effect on the fibres.

The increase in AE activity at lower amplitudes is indicative of damage in the matrix. There is a four-fold increase in low amplitude events in the range 45 - 60dB and a doubling of activity in the intermediate range 60-80dB, associated with matrix cracking and delamination/debonding respectively. Clearly the absorbed water had a serious effect on resin damage.

Fatigue Loading

Damage accumulation due to bending fatigue was compared in dry and pre-exposed specimens by cycling over a peak surface strain in the outer fibres of ±0.7%. This had been established previously as causing minor damage in unexposed material, limited to the surface layers.

The results are shown in Figure 4, where the ratio P/P_{max} is the load amplitude divided by the load amplitude at the start of the test prior to damage occurring. The unexposed specimens show a reduction in stiffness of about 10% over the first few cycles after which the stiffness is effectively constant, indicating no further damage. Specimens that were pre-exposed for three and a half months and six months showed a greater initial loss of stiffness of about 15%, followed by a further progressive reduction in stiffness indicating significant gradual damage.

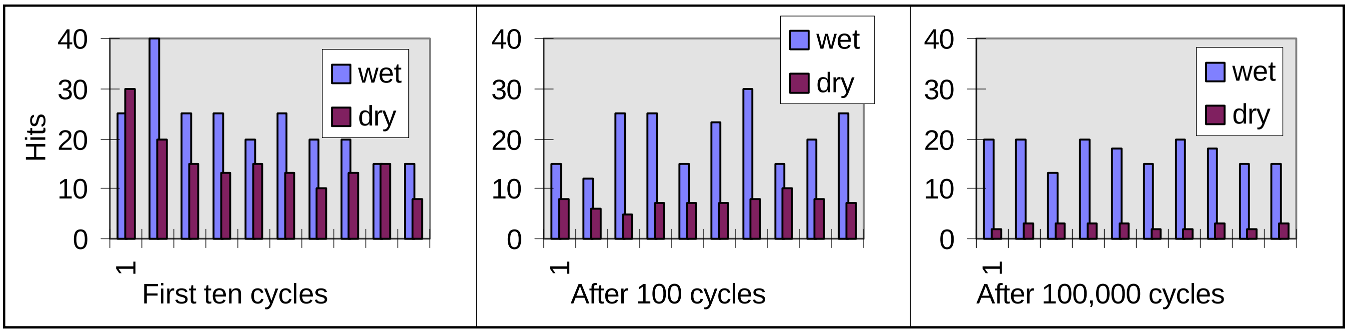

Figure 5. AE activity in ten consecutive cycles at the beginning, middle and end of fatigue loading

Damage accumulation is also shown in the AE measurements in Figure 5, which show three representative ten cycle snapshots at the beginning, middle and near the end of the fatigue tests. The unexposed (dry) specimen shows a high level of AE activity only in the early stages of fatigue, which fall significantly over the first ten cycles to around 10 hits per cycle. At 100 cycles this has fallen further to about six hits per cycle and by 10^5 has dropped to one or two hits per cycle. The pre-exposed specimen shows a similar level of AE activity to the unexposed specimen at the start of cycling, but this quickly reaches a steady level with a mean of fifteen hits per cycle, though with a considerable scatter, particularly in the early part of the test.

DISCUSSION

There is much evidence in the literature [6, 7] to show that prolonged exposure to an aqueous environment reduces the mechanical strength of glass/polyester composites. The damage is widely recognised to be due to a combination of processes such as a reduction of the mechanical strength of the matrix by plasticisation and reduction of the matrix/fibre interfacial strength [8]. In the present work, damage accumulation in fatigue was observed to be significantly increased by the absorption of water. However, it is clear that diffusion of water into the composite is essential a six months pre-exposure had a significantly larger effect than three and a half months pre-exposure. This suggests that a critical concentration of absorbed water is required to reduce the resistance to damage accumulation. However, it should be noted that the effect of water absorption is greatly accelerated by pre-exposure at 35 °C and so the increase in fatigue damaged observed would only occur after much longer exposure at ambient temperature.

The major form of damage accumulation in fatigue of pre-conditioned specimens appears to be associated with a loss of interfacial strength. It is shown in the accompanying paper [5] that on the microscopic scale, fibre debonding was observed to be extensive in fatigued specimens. On the macroscopic scale, delamination occurred progressively with an increasing number of fatigue cycles. Damage accumulation continued at a constant rate above the first thousand cycles in pre-exposed specimens, whereas in unexposed specimens it was exhausted after a few hundred cycles and was limited to the surface layers. The damage consisted mainly of matrix cracking with little sign of delamination.

The AE measurements were consistent with these observations. AE from the unexposed specimens fell to very low levels after a few thousand cycles and only residual emissions occurred at the peak strain in a cycle, indicating little or no damage occurring. In contrast, even though AE activity diminished over the first hundred cycles for the pre-exposed specimens, AE events remained high at high cycles. This indicates continued damage which could be expected to lead to a progressive loss of stiffness.

Similarly in the monotonic tests the level of activity was much higher in the exposed (wet) than the unexposed (dry) material, indicating a high degree of progressive damage prior to final failure of the specimen. The preponderance of low and moderate amplitude events below 80dB is indicative of matrix damage, and this in agreement with the general view that E-glass is not susceptible degradation in aqueous environments and to the observed lack of fibre failure.

High amplitude events (80-100dB) are normally associate with fibre breakage. No events were recorded in this range except at the end of some tests when significant damage had already occurred. The presence of an aqueous environment is not known to degrade E-glass fibres, and the AE observations are consistent with the absence of any evidence of fibre fracture in fatigue.

CONCLUSIONS

(i) A significant effect of water absorption in isophthalic polyester E-glass woven roving laminates has been observed in cyclic flexure tests. Unexposed laminates achieve constant stiffness after an initial decrease indicating no further damage after the first few cycles. In contrast, pre-exposed laminates exhibit a steady reduction in stiffness, indicative of continuous damage accumulation with number of cycles at constant strain amplitude.

(ii) Stiffness reduction, and hence damage accumulation, is increased by water absorption. This effect is more pronounced with longer absorption periods.

(iii) Damage accumulation, as measured by change in stiffness, is well correlated with acoustic emission measurements. Dry laminates show very little acoustic emission activity after the first few cycles of flexure. In contrast, pre-exposed laminates show high AE activity up to 10^5 cycles, indicating continuous damage throughout the fatigue life. This activity is mainly moderate amplitude events below 80dB, associated with damage to the matrix and fibre/matrix interface.

(iv) There is no evidence of fibre fracture in unexposed or pre-exposed laminates due to fatigue. This is consistent with the small number of AE events of high amplitude above 85dB.

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