CMMT(MN)067

Environmental and Fatigue Testing of Fibre-Reinforced Polymer Composites

Effective use of composite structures for combined stress, thermal and chemical environments hinges on the availability of validated data applicable for the entire service life of the structure, which may be 20 to 50 years, or longer. Generating long-term data involves substantial capital and labour costs, and in many cases impractical timescales. The approach commonly adopted by industry has been to use laboratory based methods that employ severe environmental conditions and/or high cyclic loading rates to induce an accelerated response in standard composite specimens or sub-components. These techniques offer rapid and cost effective evaluation of materials for quality assurance or design purposes.

This Measurement Note describes test methods for inducing an accelerated response in unidirectional and cross-ply glass and carbon fibre-reinforced epoxy laminates. The use and limitations of these methods for characterising tensile and flexural properties under static and cyclic (tension-tension) loads and/or aggressive environments are discussed. The Measurement Note includes tensile fatigue data and experimental data from mechanical tests conducted on specimens that have been exposed to a variety of environments, including: hot/humid air (70°C and 85% RH), water immersion at elevated temperatures, superheated pressurised steam, sulphuric acid or sodium hydroxide solution. Methods for monitoring progressive damage accumulation (e.g. transverse crack formation in cross-ply laminates) and reduction in tensile properties are also covered.

This Measurement Note was prepared as a result of investigations undertaken within the DTI funded project "Composite Performance and Design (CPD2) - Life Assessment and Prediction".

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Introduction

A review of test methodologies and standards [1] revealed that the approach commonly adopted by industry has been to use laboratory based methods that employ severe environmental conditions and/or high cyclic loading rates to induce an accelerated response in standard composite specimens or sub-components. For example, conditioning at 70°C and 85% relative humidity (RH) is frequently used in aerospace/defence applications. These techniques offer rapid and cost effective evaluation of materials for quality assurance or design purposes.

This Measurement Note describes test methods for inducing an accelerated response in unidirectional and cross-ply (i.e. $[0°_n/90°_m]_S$) and carbon fibre-reinforced epoxy laminates. The use and limitations of these methods for characterising tensile and flexural properties under static and cyclic (tension-tension) loads and/or aggressive environments are discussed. The Measurement Note also includes the results of a study in which optical techniques and acoustic emission (AE) were used to monitor progressive transverse cracking in cross-ply laminates as a function of applied load and loading cycles. It is shown that stiffness and strength reduction can be directly related to transverse crack density.

Specimen Geometry And Preparation

This section describes test methods and specimen geometries that can be used for tensile and flexural testing of unidirectional and cross-ply laminates under static and cyclic (tension-tension) loads and/or aggressive environments.

Unidirectional Tensile Specimens

Both longitudinal (i.e. fibres parallel to loading direction) and transverse (i.e. fibres perpendicular to loading direction) specimen geometries as specified in BS EN ISO 527-5 [2] are suitable for determining the tensile properties of unidirectional composite materials. Longitudinal specimens (Figure 1) are 250 mm in length, 15 mm wide and 1 mm (i.e. 8 plies) thick. Transverse specimens are 250 mm long, 25 mm wide and 2 mm thick (i.e. 16 plies). The overall gauge-length (i.e. region between grips) is 150 mm for both specimen geometries.

Figure 1: Continuous unidirectional glass fibre-reinforced laminate.

End tabs are recommended to avoid mechanical damage to the specimen ends and to ensure failure occurs within the gauge length. **For cyclic loading, the use of end tabs minimises the possibility of fibre fretting/wear within the gripped region.**

The end tabs (50 mm long) are manufactured from a plain woven glass fabric/epoxy laminate (1.6 mm thick), with the fibre axes of the fabric set at ±45° to the specimen axis, and are adhesively bonded to all the specimens. The tab angle is 90° (i.e. not tapered). A high elongation adhesive is recommended for bonding the end tabs to the specimen. The use of a film adhesive with carrier to bond the end tabs has been found to reduce both preparation time and adhesive wastage. Specimen preparation is also relatively clean in comparison to paste adhesives. The carrier ensures good contact and constant bondline thickness.

It is important to minimise the possibility of debonding between the end tabs and the specimen, which can result in a shorter specimen fatigue life. This is particularly relevant to testing of carbon fibre-reinforced composite laminates, which have high fatigue resistance at loads approaching the ultimate tensile strength (UTS) of the material. End tabs should be dried before bonding to remove moisture, which can compromise the adhesive bond.

Cross-Ply Tensile Specimens

Straight-sided specimens as specified in BS EN ISO 527-4 [3] are suitable for determining the tensile properties of cross-ply laminates under static and cyclic (tension-tension) loads and/or aggressive environments. Specimens are 250 mm in length, 25 mm wide and 2 mm (i.e. 16 plies) thick (Figure 2). The overall gauge-length (i.e. region between grips) is 150 mm. End tabbing is identical to that used for the unidirectional specimens.

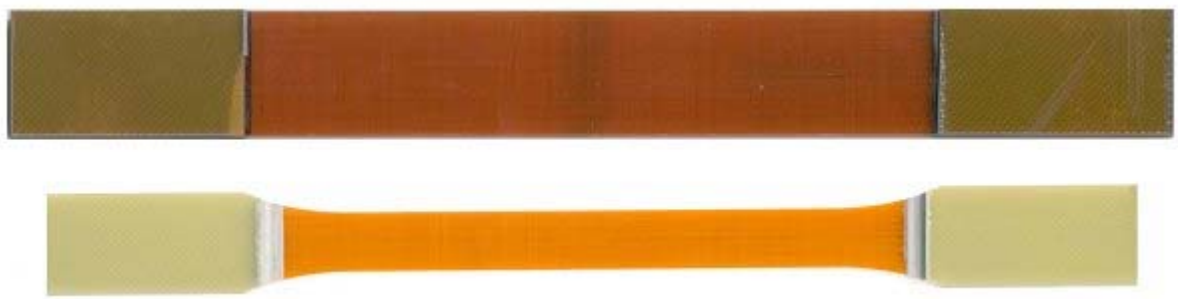

Figure 2: Straight-sided (top) and dumbbell (bottom) cross-ply laminate specimens.

There is a tendency for end failures to occur in straight-sided specimens under tension-tension cyclic loading conditions at high loads and/or high cycles. It was expected that this mode of failure could be eliminated by using a dumbbell geometry (Figure 2), thus increasing the specimen fatigue life. The results presented in Figure 3 clearly show an improvement in fatigue performance when the specimen was waisted. This was possibly due to stress relief at the fillet radii as a result of longitudinal splitting (Figure 4). Using dumbbell specimens also eliminates the tendency for the end tabs to debond, which can occur at high loads and/or high cycles.

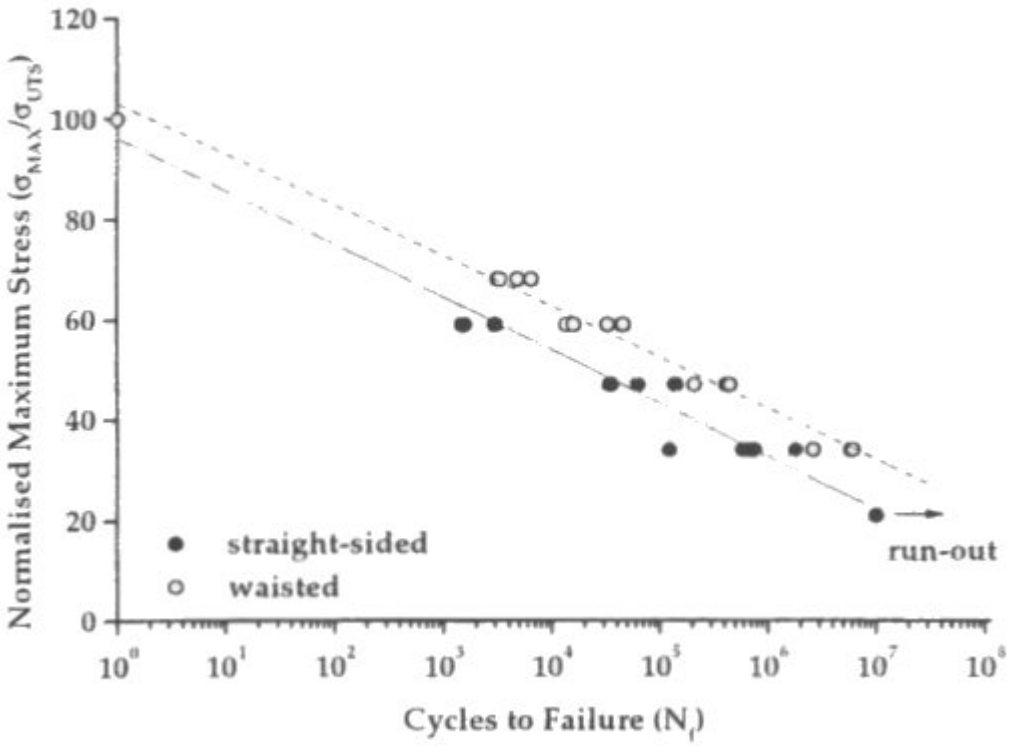

Figure 3: S-N curves for straight-sided and dumbbell cross-ply E-glass/913 [4].

Figure 4: Failure in the straight-sided and dumbbell specimen types.

The dumbbell specimens were 250 mm long and 2 mm thick with an overall gauge-length of 150 mm. The length and width of the straight portion of the gauge-section was 110 mm and 15 mm, respectively. The fillet radius at the intersection of the gauge-section and end tabs was 60 mm. End tabbing was identical to that used for the straight-sided specimens. Specimens were surface ground to the final shape.

It was apparent from the tensile data [4], that the ultimate tensile strength measured for straight-sided glass and carbon fibre-reinforced epoxy specimens was approximately 10% higher than that measured using the dumbbell specimens. The elastic properties remained unaffected. Failure in the dumbbell specimens invariably occurred in the vicinity of the fillet radii; a region of high tensile stress concentration. A larger fillet radius would probably improve the tensile strength results obtained using this specimen type.

Flexure Specimens

Transverse flexure tests offer a rapid and economic method of assessing environmental degradation. Tests can be carried out under combined environment and applied loading (static or fatigue) conditions. **Transverse flexural properties are particularly sensitive to changes in moisture content.**

Preparation and testing of flexure specimens is carried out to BS EN ISO 14125 [5] specifications. Four-point loading provides a more uniform stress field and hence is the preferred method for determining longitudinal and transverse flexural properties of fibre-reinforced laminates. Continuous unidirectional glass and carbon fibre-reinforced laminates are typically 2 mm thick. An outer to inner span ratio of 3:1 is employed in four-point bending. The longitudinal and transverse specimens are 100 mm and 60 mm in length, respectively. The width for both specimens is 15 mm.

Moisture Conditioning

The two main types of basic moisture conditioning are: (i) fixed conditioning, where a test specimen is exposed to a conditioning environment for a specified time; and (ii) equilibrium conditioning, where a specimen is exposed until the material reaches equilibrium with the conditioning environment. The first technique is routinely employed for screening purposes. This approach results in non-uniform moisture distribution through the thickness of the test specimen. In principle, test data obtained from specimens conditioned in this manner are only considered suitable for comparing different batches of the same material or for quality control tests. This approach, however, is also widely used for generating engineering data. It is essential that test specimens used in this manner are identical in dimensions and have similar surface finishes.

Ideally, comparative studies of water absorption properties of materials should be carried out only using the equilibrium moisture content of materials exposed to identical conditions. Comparisons between composite systems with different moisture absorption characteristics are possible if the materials are conditioned to equilibrium. The thicker the material the longer the time required to reach equilibrium, hence the use of relatively thin specimens to determine the "through-the-thickness" moisture diffusion coefficient. The large timescales involved, even under accelerated testing conditions, can make this approach impractical.

The International standard BS EN ISO 62 [6] describes a procedure for determining the moisture absorption properties and/or diffusion coefficients in the "through-the-thickness" direction of flat and curved solid plastics. BS EN ISO 62 is suitable for use with composite specimens and is applicable to vapour exposure and liquid immersion.

Travellers are recommended for monitoring moisture content of a test specimen throughout the environmental history (i.e. manufacture, storage, pre-conditioning and testing). Traveller specimens have identical material properties, geometry and processing history as the test specimen. It is important that the moisture content be established prior to testing and that specimens be tested within an hour of removal from the conditioning environment in order to ensure that minimal water loss occurs.

A method for determining the moisture content within the gauge-length of conditioned specimens is described below:

i. The end tab regions are removed using a diamond-cutting wheel (dry cut - no lubrication to be used).
ii. The separated gauge-length is then weighed to determine the weight of the conditioned section.
iii. The gauge-length is dried in an oven (50 ± 2°C) until specimen weight reached a constant value.

The difference between the weights recorded for (ii) and (iii) is the moisture weight gain due to hot/wet conditioning; providing there is no loss of material to the surrounding environment.

Accelerated Conditioning

A number of techniques may be used to accelerate moisture uptake by a composite (e.g. exposure to 70°C and 85% RH or superheated pressurised steam). The reduction in the tensile properties of a composite material when exposed to these environments may be severe. A period of six weeks (or 1,000 hours) is commonly used for assessing the effects of environmental degradation on mechanical properties of composite materials.

Tensile properties of carbon fibre-reinforced epoxy laminates are generally insensitive to environmental attack from water immersion, steam, and sulphuric acid and sodium hydroxide solutions (see [7]). In general, any changes in tensile properties that occur in carbon/epoxy systems through moisture ingress are likely to be due to matrix plasticisation. The loss of mechanical properties is reversible on drying.

In contrast, glass/epoxy laminates undergo irreversible degradation in hostile environments. Longitudinal tensile strength of continuous aligned glass/epoxy laminates was substantially reduced when immersed in water at elevated temperatures or when exposed to either hot/humid air or steam.

As previously mentioned, 70°C and 85% RH is frequently used for qualifying materials for aerospace applications. This environment, which can be considered harsh in comparison to most service conditions, had a significant adverse effect on the longitudinal tensile properties of continuous aligned E-glass/913 and E-glass/F922 epoxy laminates (see Figure 5). Within 6 weeks of exposure, the tensile strength of both materials was reduced by between 30 and 36% of the ultimate tensile strength of the dry material. This loss of strength was only partially recoverable after drying. When dried the strength of conditioned material was reduced by at least 12%. The permanent loss in strength was mainly attributable to corrosion of the glass fibre reinforcement.

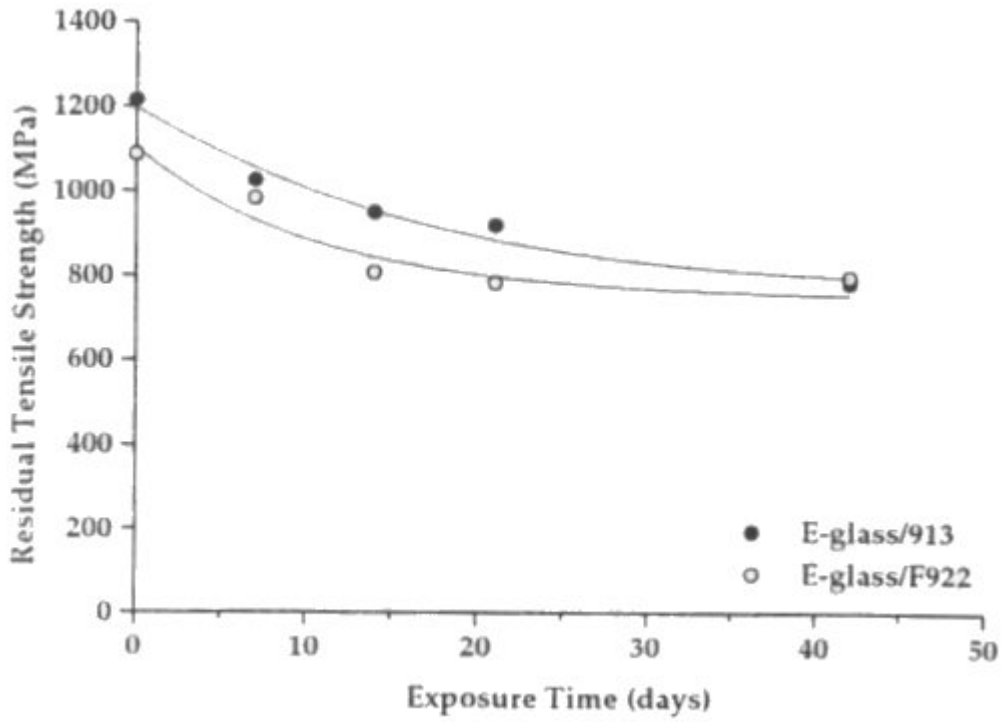

Figure 5: Longitudinal tensile strength of hot/wet conditioned glass/epoxy laminates.

The degrading effect of 70°C and 85% RH on tensile strength was less for the larger transverse and cross-ply laminate specimens. The rate of moisture absorption in these specimens was also slower since moisture uptake decreases with increasing laminate thickness and width, and fibre content. In fact, the presence of moisture resulted in higher first ply failure (FPF) and ultimate tensile failure stresses for cross-ply HTA/F922 carbon/epoxy laminates that had been moisture conditioned (see Table 1). The level of damage (i.e. maximum transverse crack density) was also reduced in conditioned glass/epoxy and carbon/epoxy laminate materials.

Table 1: Tensile Property Data for E-glass/F922 and HTA/F922 Cross-Ply Laminates (Dry/6 weeks conditioning at 70°C and 85% RH)

Material	FPF Stress (MPa)	Tensile Strength (MPa)	Maximum Crack Density (cracks/mm)
E-glass/F922			
$[0_2/90_2]_S$	150/178	486/340	1.90/1.55
$[0_2/90_4]_S$	99/134	316/282	1.75/1.18
$[0_2/90_8]_S$	65/98	170/159	1.27/1.07
HTA/F922			
$[0_2/90_2]_S$	360/399	814/864	1.12/0.87
$[0_2/90_4]_S$	135/267	516/569	0.84/0.79
$[0_2/90_6]_S$	149/189	407/413	0.81/0.77

Absorbed moisture produces hygroscopic residual stresses. These stresses partially counteract the deleterious effects that thermal residual stresses (induced during processing) have on the tensile properties of the individual layers of the laminate. For prolonged exposure times (6 to 12 months), this effect can be expected to disappear as the material degrades.

Steam autoclave conditioning can induce levels of moisture of between 2 and 3 wt % within 48 hours exposure. Tests conducted using a Midas 40 bench top autoclave (Prior Clave Ltd) at a temperature of 136°C and a pressure of 2.2 bar were able to produce these levels of moisture in glass/epoxy and carbon/epoxy laminates. The rate of moisture absorption is increased by a factor of 100, or more, compared with conditioning at 70°C and 85% RH.

However, conservative strength and stiffness values are obtained using this approach (see Table 2). E-glass/F922 was highly sensitive to this extreme environment. The material showed a 50% strength loss within 48 hours. No further changes were observed after 48 hours. The loss in strength can be attributed mainly to fibre degradation (i.e. corrosion and leaching). Small blisters were observed on the surface of the glass/epoxy specimens. Tensile modulus was far less sensitive to environmental exposure.

Table 2: Tensile Properties of Hot/Wet Conditioned Unidirectional Laminates

Condition	Moisture Content (wt %)	Tensile Strength (MPa)	Tensile Modulus (GPa)
E-glass/F922			
Dry (unconditioned)	0.00	1087 ± 29	43.0 ± 0.9
70 °C/85% RH (6 weeks)	1.00	763 ± 42	37.2 ± 1.4
Steam autoclave (24 hrs)	2.09	654 ± 22	38.3 ± 1.3
Steam autoclave (48 hrs)	2.94	579 ± 47	38.1 ± 0.8
Steam autoclave (72 hrs)	2.83	585 ± 50	37.6 ± 1.0
HTA/F922			
Dry (unconditioned)	0.00	1684 ± 132	126 ± 5
70°C/85% RH (6 weeks)	1.06	1728 ± 132	130 ± 4
Steam autoclave (24 hrs)	2.12	1691 ± 91	125 ± 1
Steam autoclave (48 hrs)	1.90	1725 ± 42	128 ± 2
Steam autoclave (72 hrs)	2.20	1784 ± 94	123 ± 9

Transverse flexural properties are particularly sensitive to the combined effect of moisture and elevated temperature. Figure 6 shows the combined effect of moisture and temperature on the transverse flexural strength of continuous aligned E-glass/913 specimens that have been immersed in deionised water at 60°C for periods of up to 6 weeks prior to testing.

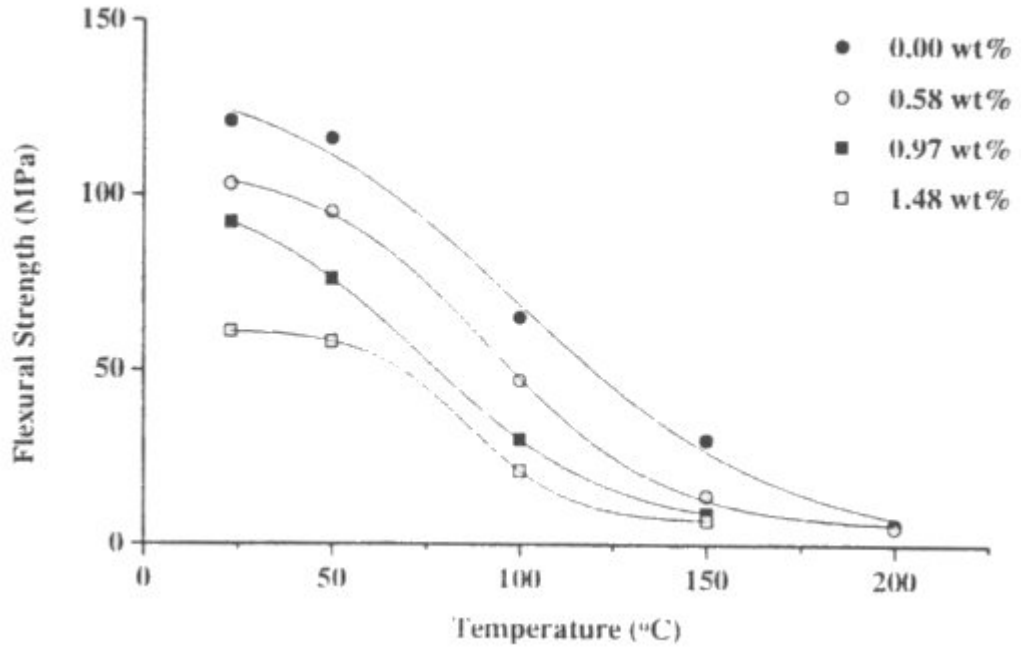

Figure 6: Transverse flexural strength of hot/wet conditioned continuous aligned E-glass/913.

Chemical Resistance

Exposure to sulphuric acid or sodium hydroxide solution results in a substantial reduction in the tensile properties of E-glass/epoxy composite materials. Table 3 compares tensile properties of unconditioned and chemically aged continuous aligned E-glass/F922 and HTA/F922. These materials were exposed to either 1 N solution of sulphuric acid, 1 N solution of sodium hydroxide or deionised water at 23°C in an unstressed state for a period of 2 weeks

Note: A one normal (1 N) solution contains one gram-equivalent weight of a particular substance dissolved in 1 litre of solution).

Exposure to the sulphuric acid solution had a greater degrading effect on the tensile strength of E-glass/F922 than either the deionised water or sodium hydroxide solution. In comparison, HTA/F922 carbon/epoxy showed far superior chemical resistance. Exposure to sodium hydroxide for 2 weeks had no affect on the tensile properties of this material, whilst the reduction in tensile strength after exposure to the acidic solution was relatively small (6.6%).

Table 3: Chemical Resistance of Unidirectional E-glass/F922 and HTA/F922 Laminates

Material	Environment	Tensile Strength (MPa)	Tensile Modulus (GPa)
E-glass/F922	Unconditioned	1087 ± 29	43.0 ± 0.9
	Deionised water	859 ± 59	36.6 ± 8.4
	Sodium hydroxide	875 ± 57	37.8 ± 2.0
	Sulphuric acid	775 ± 59	35.7 ± 1.4
HTA/F922	Unconditioned	1684 ± 132	126 ± 5
	Sodium hydroxide	1670 ± 56	125 ± 3
	Sulphuric acid	1573 ± 61	124 ± 2

Changes in colour and gloss were also evident in the glass and carbon fibre-reinforced composite laminates. Pigment change was most noticeable for those specimens that had been immersed in the sulphuric acid solution. The predominantly orange E-glass/F922 specimens were tinged green as a result of chemical reactions between the sulphuric acid the glass fibres and the epoxy resin. The colour change of E-glass/913 was more dramatic with the colour of the conditioned specimens being black with an aquamarine hue. Changes in colour have been used in previous studies (see [8]) as an indicator of degradation of the composite substrate, although colour transformation may be misleading as to changes in mechanical properties.

Dynamic mechanical analysis (DMA) carried out on chemically conditioned E-glass/F922 and HTA/F922 revealed permanent changes in the glass transition temperature $\mathbf{T_g}$ of these materials (see Table 4). Specimens were pre-dried to a constant weight at 50°C, weighed, conditioned and reweighed. Test specimens were weighed prior to DMA tests. ISO 6721-1 [9] specifies a method of using DMTA for plastics and composites.

Table 4: Permanent Change in T_g for Chemically Aged Unidirectional Laminates

Material	Environment	T_g (°C)
E-glass/F922	Unconditioned	226.8
	Sodium hydroxide	244.6
	Sulphuric acid	249.6
E-glass/913	Unconditioned	176.5
	Sodium hydroxide	170.2
	Sulphuric acid	165.2
HTA/F922	Unconditioned	219.2
	Sodium hydroxide	244.5
	Sulphuric acid	249.2

The $\mathbf{T_g}$ values of conditioned E-glass/F922 and HTA/F922 after drying were higher than the $\mathbf{T_g}$ measured for unconditioned material, whereas $\mathbf{T_g}$ for E-glass/913 is permanently depressed following conditioning. The reduction in $\mathbf{T_g}$ observed for E-glass/913 can be attributed to a permanent loss in stiffness of the epoxy matrix. A probable cause for the increase in $\mathbf{T_g}$ observed for the E-glass/F922 and HTA/F922 composite materials is antiplasticisation of the F922 epoxy through leaching of uncured monomer from the unmodified epoxy resin.

ISO 175 [10] specifies a method of exposing plastic test specimens to liquid chemicals. The method can be used for determining changes in physical and chemical properties resulting from immersion in a liquid chemical. This standard covers a wide range of organic (e.g. acetone, ethanol and toluene) and inorganic (e.g. hydrogen peroxide, sulphuric acid and sodium carbonate solution) liquids.

Cyclic Fatigue

Constant amplitude (sinusoidal waveform) fatigue tests were carried out on unidirectional and cross-ply specimens in load control using a servo-hydraulic test machine at a frequency of 5 Hz under standard laboratory conditions (i.e. 23°C and 50% RH). The stress ratio $\mathbf{R\ (\sigma_{MIN}/\sigma_{MAX})}$was either equal to 0.1, 0.5 or 0.75. In order to limit the duration of tests, the number of cycles was limited to a maximum number of 10^7 cycles (equivalent to 23 days).

Testing, particularly at high loads, was best carried out using fatigue rated servo-hydraulic (wedge-action) grips.

Five duplicate tests (generally) were carried out at five stress levels (i.e. 80%, 70%, 55%, 40% and 25% UTS). The fatigue strength data was normalised with respect to the ultimate tensile strength, σ_{UTS}, of identically conditioned specimens measured at an equivalent loading rate to the fatigue test. This allows a direct comparison

to be made between **S-N** data from different fatigue tests; independent of material, coupon geometry, temperature and moisture content of the specimen.

Unidirectional Laminates

Continuous aligned carbon fibre-reinforced laminates are known to have excellent tensile fatigue resistance under constant amplitude tension-tension loading conditions. The results from cyclic fatigue tests conducted on unidirectional T300/924 and HTA/F922 carbon/epoxy supported this statement. The stress-life or **S-N** (**S** is the applied stress and **N** is the number of cycles to failure) response for these materials was almost flat.

Continuous aligned glass/epoxy laminates were less resistant to fatigue loading compared with the carbon/epoxy laminates. The normalised fatigue life (**S-N** data) for these materials (Figure 7) can be generalised by the following relationship as follows:

$$\sigma_{MAX} / \sigma_{UTS} = 1 - k \log_{10} N_f$$

where σ_{MAX} is the maximum applied load, σ_{UTS} is the ultimate tensile strength, **k** (the slope) is the fractional loss in tensile strength per decade of cycles and N_f is the number of cycles to failure. The value of **k**, which is dependent on the stress ratio **R**, is approximately 0.1 for a stress ratio **R** = 0.1.

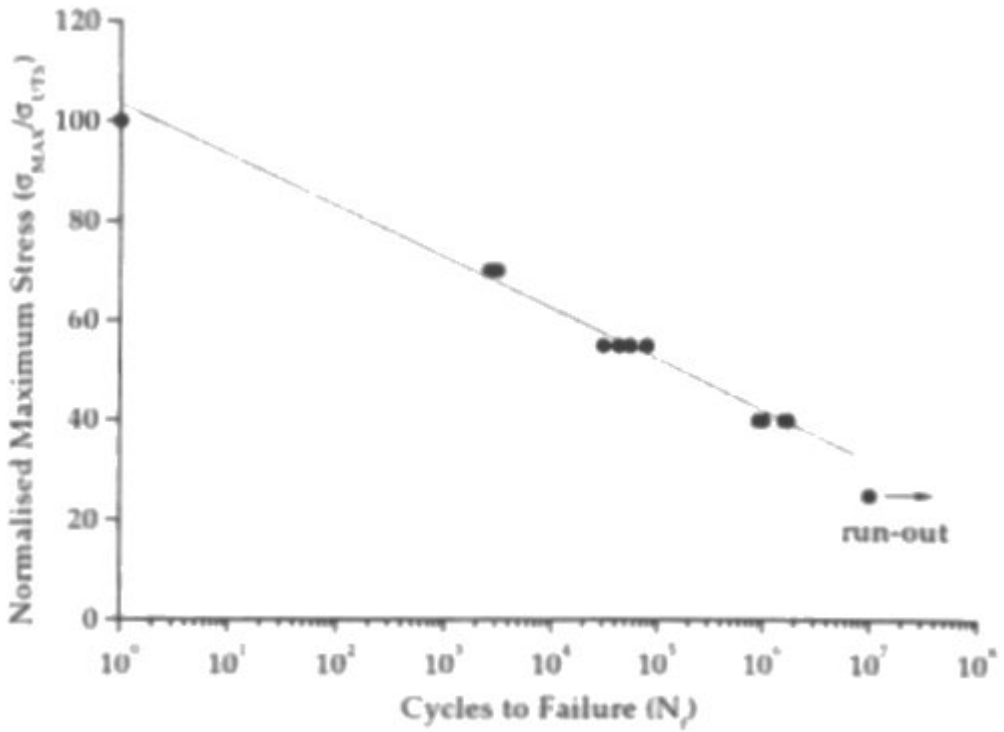

Figure 7: S-N curve for unidirectional E-glass/F922 (R = 0.1).

The normalised **S-N** data (i.e. normalised maximum stress σ_{MAX} versus N_f) at different stress ratios (Figure 8) can also be approximated by the above mentioned relationship with the fractional loss in tensile strength per decade of cycles, **k**, decreasing as **R** increases (Figure 9).

The relation between **k** and **R** can be approximated by a linear relationship:

$$k = 0.11 - 0.07R$$

The **S-N** data clearly shows that the stress ratio has a significant effect on the fatigue life of unidirectional laminates. Increasing either the amplitude or mean value of the sinusoidal load reduces fatigue life. To achieve a given life, a lower stress range is required as the mean stress level is increased.

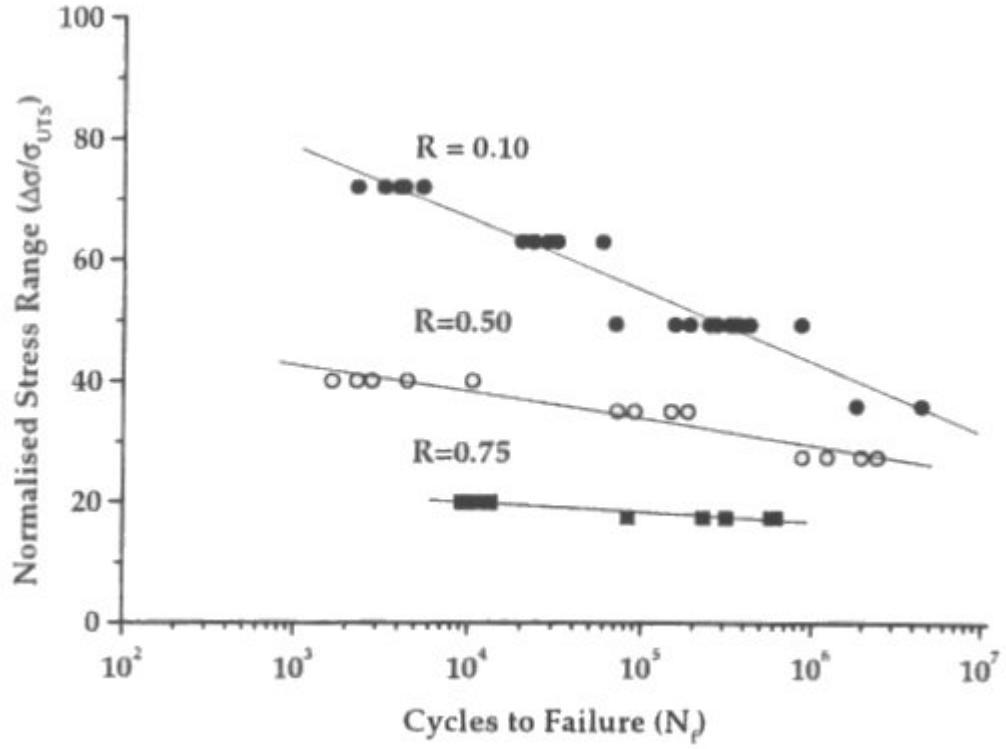

Figure 8: S-N data at R = 0.1, 0.5 and 0.75 for unidirectional E-glass/913 where $\Delta\sigma = (\sigma_{MAX} - \sigma_{MIN})/2$.

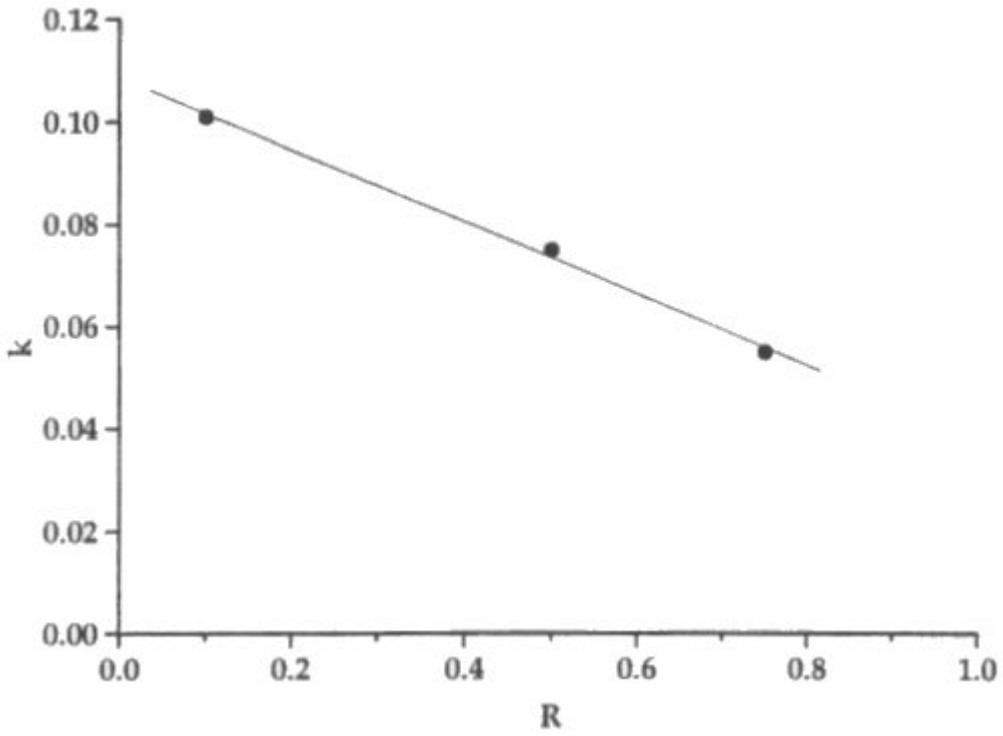

Figure 9: Plot of k as a function of R for unidirectional E-glass/913.

Cross-Ply Laminates

Carbon/epoxy cross-ply laminates showed excellent fatigue resistance. The fatigue life $\mathbf{N_f}$ exceeded 4 x 10^6 cycles at loads approaching 90% UTS for $[0/90]_{4S}$ T300/924 and 70% UTS for $[0_2/90_2]_S$ (Figure 10). End tabs were prone to debond during testing, and hence prevention of end tab debonding is essential for ensuring reliable

fatigue data.

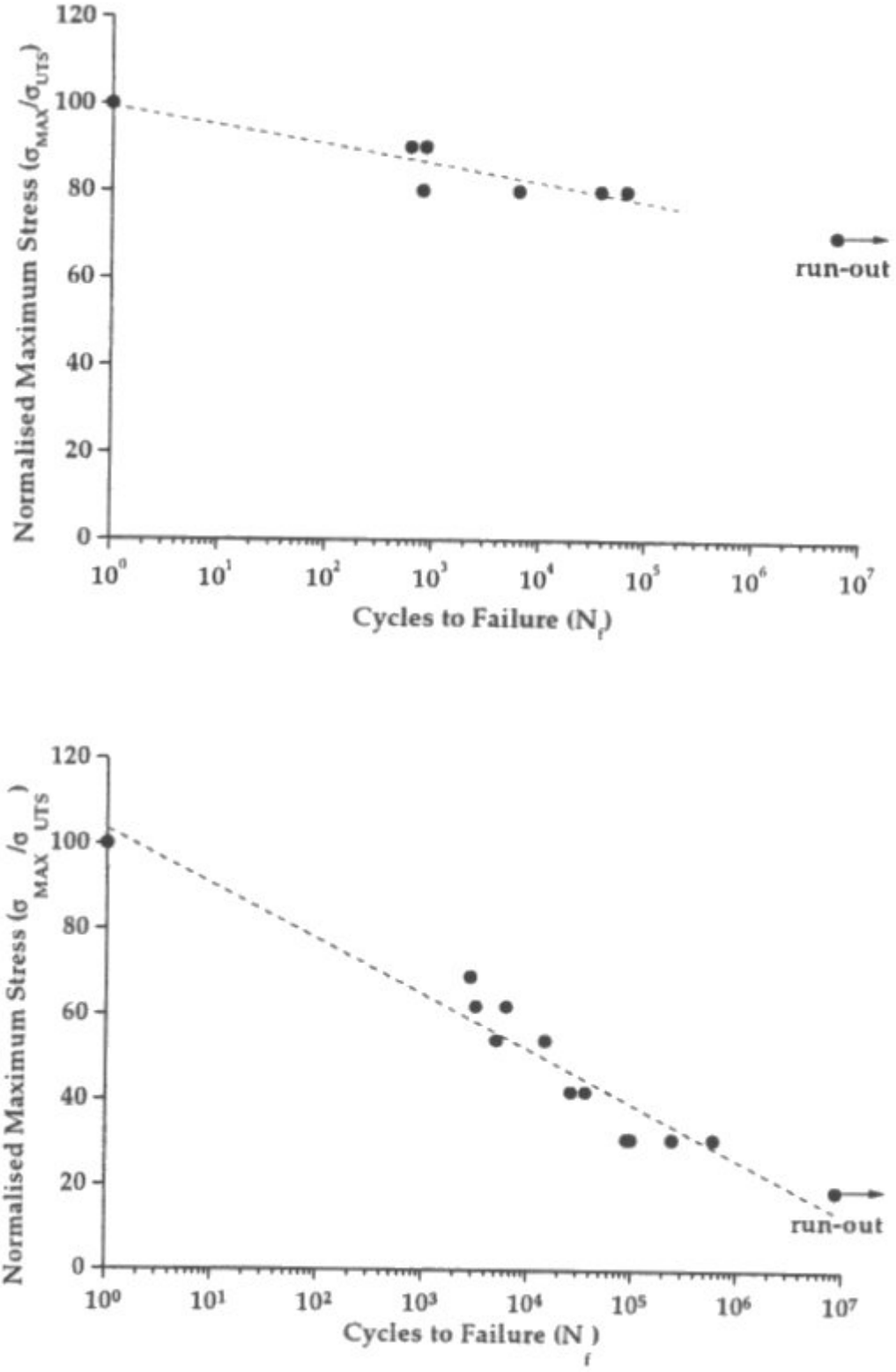

Figure 10: S-N curve for $[0_2/90_2]_S$ HTA/F922 (top) and E-glass/F922 (bottom).

The normalised fatigue life (**S-N** data) of $[0/90]_{4S}$ E-glass/913, and $[0_2/90_2]_S$ E-glass/F922 (Figure 10) and HTA/F922 laminates can be generalised by the following relationship:

$$\sigma_{MAX} / \sigma_{UTS} = 1 - k \log_{10} N_f$$

For a stress ratio **R** = 0.1, the value of **k** is approximately 0.10, 0.13 and 0.044 for E-glass/913, E-glass/F922 and HTA/F922 laminates, respectively.

Transverse Cracking

The appearance of transverse cracks in the 90° plies of cross-ply laminates is usually the first visible indication of damage in cross-ply laminates (see Figure 11). Transverse cracking will often cause adverse affects, such as stiffness and strength reduction. An experimental study was carried out to investigate progressive transverse cracking in the 90° plies of cross-ply E-glass/F922 and HTA/F922 laminates resulting from monotonic tensile and tension-tension fatigue loading conditions.

Figure 11: Transverse cracking of a cross-ply E-glass/F922 laminate.

Transverse crack density was measured as a function of applied stress under monotonic loading conditions. Optical techniques and acoustic emission (AE) were used to monitor transverse crack formation. Laminates were cracked using a step-wise monotonic mechanical loading technique. This method consisted of loading specimens to a specific stress level and then unloading, at which time the resultant crack density and elastic property data were measured. The specimen was then reloaded to a higher stress level and the process was repeated until the applied stress approached the ultimate tensile strength of the material.

In the case of the glass/epoxy specimens, transverse cracks can be directly observed by illuminating the back of the specimen with a light source (Figure 11). This transmission technique, however, cannot be applied to carbon/epoxy and therefore an alternative approach was adopted. This consisted of smoothing the longitudinal edges of the coupon specimen with 1200 grade silicon carbide paper, wiping the surfaces with acetone and then coating the surfaces with a film using an Edding white paint marker. Specimens were left for several hours to dry.

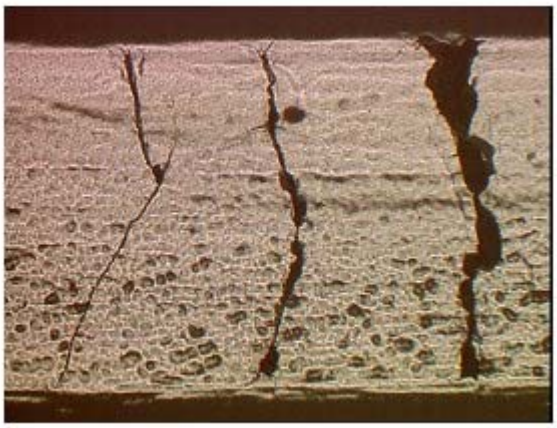

Figure 12: Magnified image of transverse cracks along an edge of a cross-ply laminate.

The marker pen produces a thick brittle layer that clearly shows crack formation in the cross-ply laminates. A Vickers optical microscope (x 50 magnification) was used to count the transverse cracks (see Figure 12). This technique, however, was not entirely satisfactory. A test conducted on a $[0_2/90_2]_S$ glass/epoxy laminate showed that the number of cracks detected along the specimen edge was slightly less than the number of transverse cracks detected by the transmission technique as shown in Figure 13. The transmission technique is a more reliable method for transverse crack density measurements, and hence its preferred use for glass/epoxy laminates. Figure 14 shows crack density measurements obtained for $[0_2/90_2]_S$ glass and carbon/epoxy laminates.

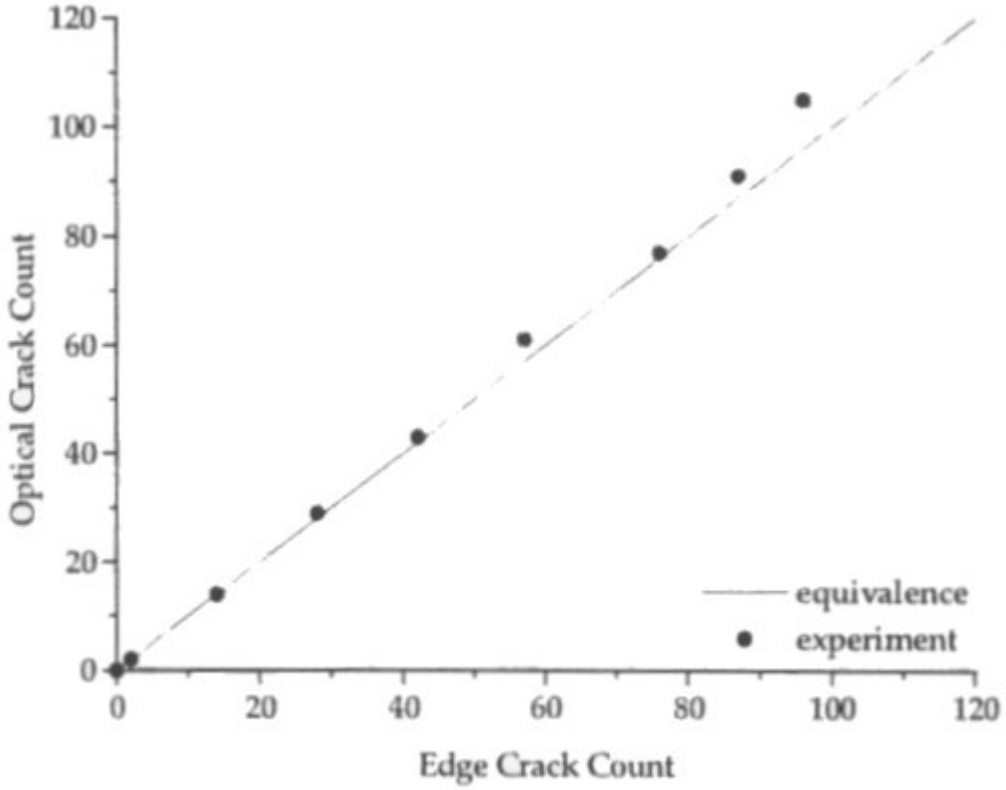

Figure 13: Optical crack vs edge crack counts for $[0_2/90_2]_S$ E-glass/F922 laminate.

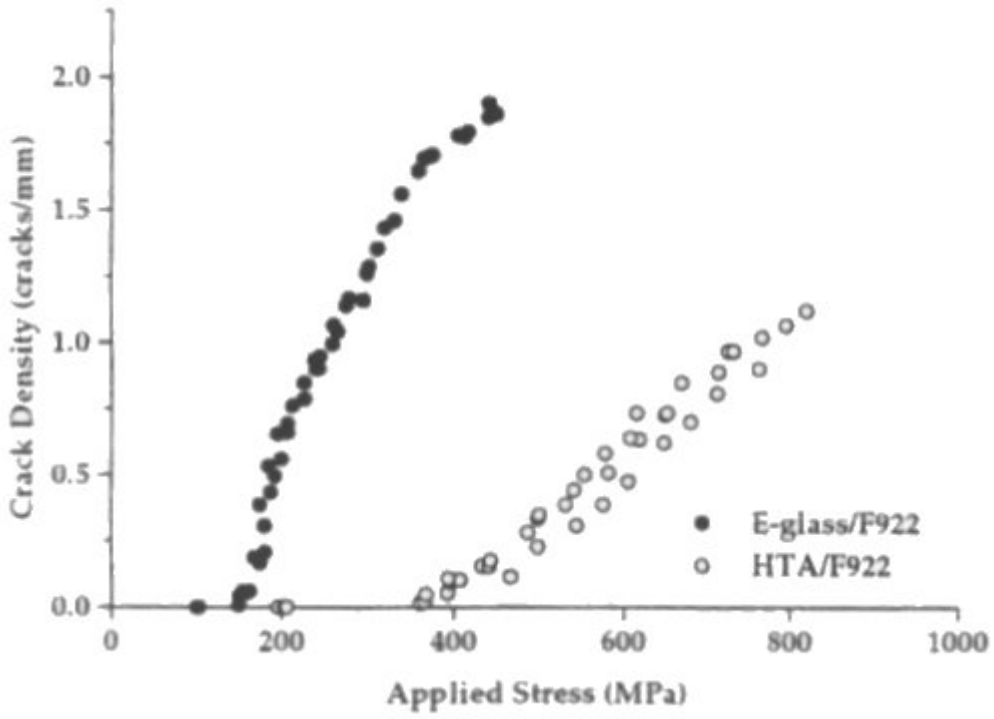

Figure 14: Crack density data for $[0_2/90_2]_S$ E-glass/F922 and HTA/F922.

Acoustic emission proved of limited use in detecting transverse cracking as it was not possible to differentiate between causes of AE events with increasing damage. The reliability of the technique deteriorates with increasing thickness of the internal 90° plies.

Elastic properties were sensitive to crack formation, particularly Poisson's ratio, with the reduction in elastic properties appearing to be directly related to the transverse crack density (Figure 15).

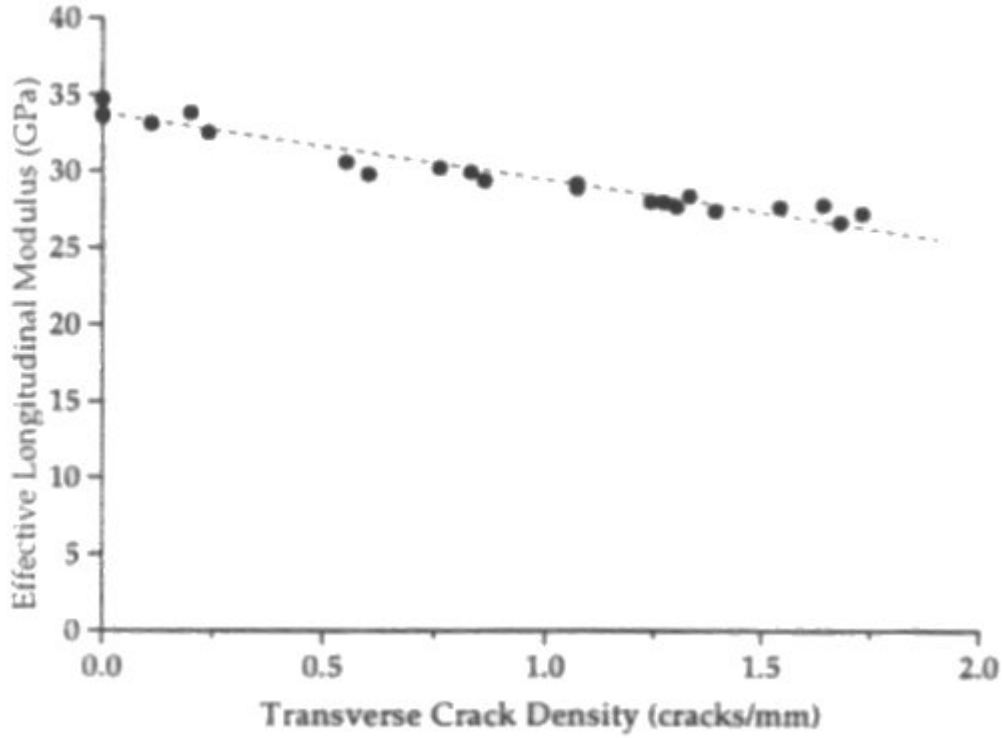

Figure 15: Axial stiffness vs crack density for $[0_2/90_2]_S$ E-glass/F922 laminate.

Tensile Property Reduction

The axial elastic properties and residual tensile strength decrease with loading cycles under tension-tension loading conditions (Figure 16). Transverse crack density at failure (i.e. $\mathbf{N = N_f}$) for tension-tension fatigue of cross-ply glass and carbon/epoxy laminates is similar in magnitude to that observed close to failure for monotonic tension tests. The elastic properties at failure are also in close agreement for the two loading modes.

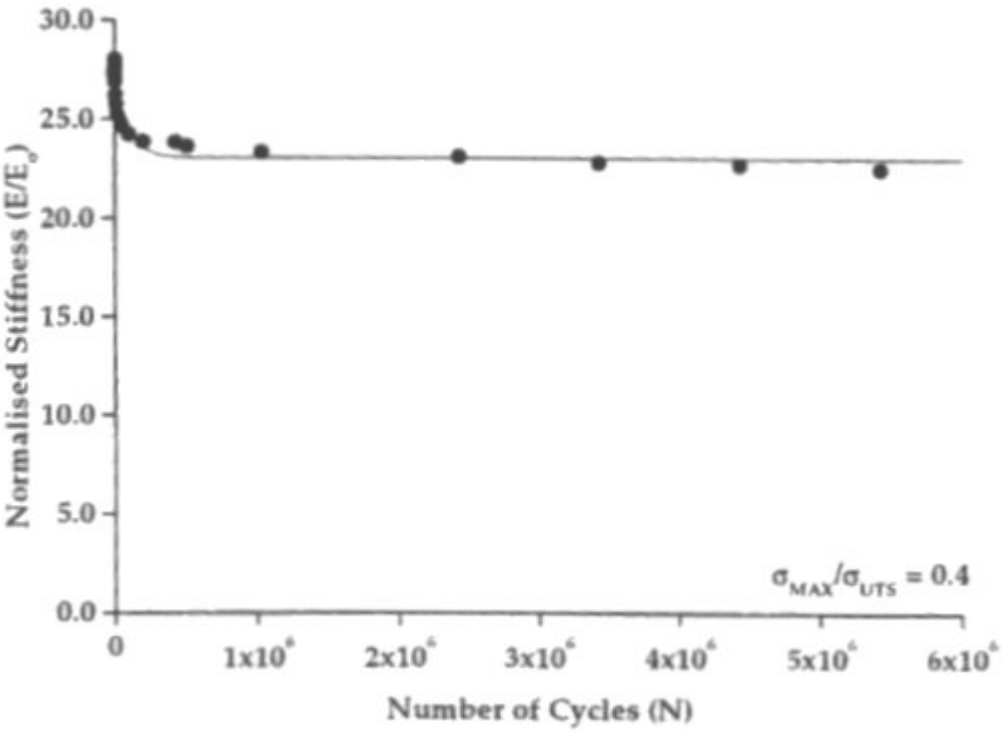

Figure 16: Axial stiffness vs crack density for $[0_2/90_2]_S$ E-glass/F922 laminate.

Crosshead displacement was monitored throughout the entire duration of fatigue tests. A contact extensometer was also used in a number of tests to measure longitudinal strain with loading cycles. The stiffness measurements for the two techniques produced similar results. The effective modulus determined from the crosshead was always slightly lower than that measured directly from the specimen with the contact extensometer. Differences were due to the loading train compliance, which when taken into account should result in almost identical values to the contact technique. The results shown in Figure 16 were obtained using a contact extensometer. Care should be taken to avoid possible extensometer damage as a result of fatigue loading or final failure. It is also important that extensometer knife-edges do not nick or cut the specimen edges as the damage may reduce fatigue life.

Concluding Remarks

The use of laboratory data obtained from accelerated tests on coupon specimens tends to result in conservative design practices. It would be preferable to use larger test pieces or actual components and to condition these materials for 12 months, or longer, under milder and more realistic conditions than those generally employed to accelerate degradation.

The results from the accelerated tests, however, clearly indicate that it is possible in many cases to relate the changes in tensile stiffness and strength to applied load (monotonic tension), loading cycles (tension-tension fatigue), or moisture content, etc. These changes can be directly related to the level of damage present within the composite (i.e. transverse cracking in cross-ply laminates under either monotonic or cyclic loading conditions). Remnant life can also be reliably estimated for tension-tension fatigue using simple formulations.

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