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Static and fatigue behaviour of glass-fibre-reinforced polypropylene composites

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Abstract

This paper is concerned with fatigue of polypropylene/glass-fibre thermoplastic composites produced from a bi-directional woven cloth mixture of *E* glass fibres and polypropylene fibres. The latter becomes the matrix after the application of heat and pressure. This composite was manufactured with a fibre volume fraction V_f of 0.338. The effect of layer design on the static and fatigue performance was investigated. The S–N curves, the rise in the temperature of the specimens during the tests and the loss of stiffness, were obtained and discussed. The loss of stiffness was related to the rise of temperature and stress release observed in the material. The effect of load rate on the static properties was also studied and discussed accordingly. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Fatigue; Damage; Thermoplastic composites

1. Introduction

Recent advances in thermoplastic resins have improved their mechanical and thermal properties. These have made them more competitive compared to the traditional thermoset applications, especially for transport industry where they are used for panels, door frames, bearings, gears, etc. Thermoplastic resins with high molecular weight and high crystallinity increase the melting temperature and also the mechanical properties. Advanced fibre-reinforced thermoplastic composite fabrics, which consist of thermoplastic filaments such as polypropylene, nylon, etc, interwoven with reinforced fibres based on glass, aramide, carbon or hybrid mixtures have been developed and are good alternatives to thermosetting resin systems. These composite materials can be manufactured by the moulding process and offer a number of advantages. The raw and moulded materials can be recycled. Their toughness and impact resistance are improved. Moreover, fabrication of rigid components in one operation with no fumes and rapid cycle times.

This paper investigates static and fatigue behaviour for a glass-fibre-reinforced polypropylene composite. The influence of the fibre orientation and the strain rate of a quasi static loading were studied. The fatigue strength was obtained in terms of the number of cycles to failure versus the stress range. In previous works [1,2], other parameters such as frequency and stress concentration were studied.

Fatigue tests showed that damage [3–5] is due to the rise in specimen temperature which increases with the fatigue life especially close to the final

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failure. The specific rise in temperature was measured for all of the tests using the thermocouple method with one instrumentation system based on three thermocouples placed in the failure region.

The fatigue damage in composite materials can be modelled by theoretical and experimental approaches such as those based on the number of debonded fibres, fracture mechanics parameters, the strain energy density, the loss of stiffness [1,2,7,8] and residual strength [6]. The damage zone size can be measured by X-rays, replica technique, C-Scan and acoustic emission [9]. The study presented in this paper uses the loss of stiffness to quantify the damage. This is a easy parameter to measure and model the damage.

The effect of fibre size and fibre orientation of the laminate layers is well documented in the literature. Analysed in Ref. [10] is the sensibility to load frequency for lay-ups with different plies on graphite epoxy laminates. The effect of lay-up geometry on the fatigue of carbon/epoxy composite laminates was also investigated in Refs. [11–13].

One of the objectives of this study is to analyse the lay-up geometry and loading conditions on the static and fatigue failure. Loading is considered to be quasi-static.

2. Material and experimental procedures

Composite sheets were manufactured using multi-layers of Vetrotex "Twintex T PP" which were compressed in a mould under a pressure of 5 bar for 10 min after heating at 190°C. This temperature is above the melting temperature of the polypropylene. Each sheet is made up of seven woven balanced bi-directional layers. The overall dimension of the plates is 160 × 250 × 3 mm. A fibre volume fraction (V_f) of 0.338 is reported by the manufacturer. The quality control of the plates was done only by visual inspection of the colour and void content.

Three layered plates were manufactured. For one series, all the layers have one of the two fibre directions orientated with the axis of the plate. The other two-layer distribution was obtained with the following laminate orientation in respect to the axis of the sheet: +45°/0°/−45°/0°/+45°/0°/−45° and +30°/−30°/+30°/0°/+30°/−30°/+30°. The layer distributions are designated by 0°, +45°/0°/−45° and +30°/−30°/0°.

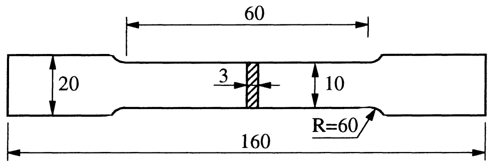


Fig. 1. Specimen for tension tests (dimensions in mm).

The specimens used in the tensile and fatigue tests were cut from thin plates. The geometry and dimensions of the tension specimens are shown in Fig. 1. The geometry of the fatigue specimens was similar with a cross-section width of 10[20] mm. The fatigue tests were carried out in an electromechanical machine whose frequency and stress ratio can be changed and the load is monitored by a load cell. The load wave was sinusoidal with constant amplitude.

The fatigue tests were performed in tension-tension. The stress ratio was $R = 0.025$ with a frequency of 10 Hz. All tests were performed at ambient temperature.

The tensile mechanical properties were obtained using an electromechanical Instron Universal Testing machine. The tests were carried out for the five different strain rates: 0.333, 0.0333, 0.00333, 0.00033 and 0.000033 s^{-1}. For each condition, four specimens were tested. Average values obtained for the tensile strength are presented in Table 1 for the five different strain rates and three different layer distributions.

3. Results and discussion

The static tests were made to study the influence of layer distribution and strain rate. Plotted in Fig. 2 are the stress versus strain curves obtained for the three-layer distributions with a strain rate of 0.00333 s^{-1}. The curves represent the average data of four tension tests for a given test condition. The result shows that the material has a non-linear behaviour including in the low stress/strain levels. This behaviour is strongly influenced by the matrix. There is no linear region that corresponds to

Table 1
Static properties

Rate of strain loading (RSL) (s^{-1})	Laminate	Static strength (σ_{UTS}) (MPa)	Stiffness coeff. (MPa)
0.333	0°	438	15916
0.0333	0°	369	15955
0.00333	0°	365	14994
0.000333	0°	304	14632
0.0000333	0°	323	14508
0.333	+45°/0°/−45°	196	10138
0.0333	+45°/0°/−45°	181	10394
0.00333	+45°/0°/−45°	182	10442
0.000333	+45°/0°/−45°	174	9991
0.0000333	+45°/0°/−45°	155	8464
0.333	+30°/−30°/0°	211	9113
0.0333	+30°/−30°/0°	206	8009
0.00333	+30°/−30°/0°	198	9623
0.000333	+30°/−30°/0°	208	9046
0.0000333	+30°/−30°/0°	162	7954

the elastic stiffness modulus. Hence it is necessary to define a stiffness modulus as the tangent of the stress–strain curves for zero strain. The values obtained are presented in Table 1.

The results of the static strength are plotted in Fig. 3. As reported in [4,5] for other glass-fibre composites, the static strength σ_{UTS} increases with strain rate, although in this case the influence is very low for the +45°/0°/−45° and +30°/−30°/0° laminates. The influence is more pronounced for the 0° laminate where the static strength increases by about 25% when the strain rate increases from 0.0000333 to 0.333 s^{-1}. The results in Table 1 shows that load rate has little influence on the stiffness modulus. Both static strength and stiffness modulus for the +45°/0°/−45° and +30°/−30°/0° laminates are nearly the same, they are much lower than those for the 0° laminate which has a strength and stiffness approximately twice and 1.5 times the other laminates, respectively. The improvement of strength for the 0° laminate is caused by the change in failure mechanism. In the +45°/0°/−45° and +30°/−30°/0° laminates, the main failure mechanism is the delamination of the inclinated fibres while for the 0° laminate the failure begins by delamination of the transverse fibres as the load is transferred to the longitudinal fibres. The final failure occurs by breaking of the longitudinal fibres.

During the fatigue tests, the stress and the temperature rise for three typical points of the surface of the specimens were recorded in a com-

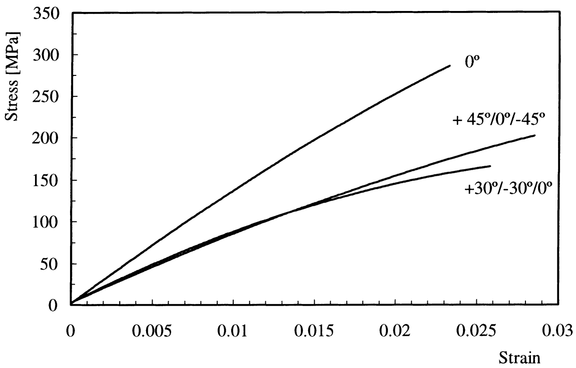


Fig. 2. Stress–strain curves. Influence of layer geometry. RSL = 0.00333 s^{-1}.

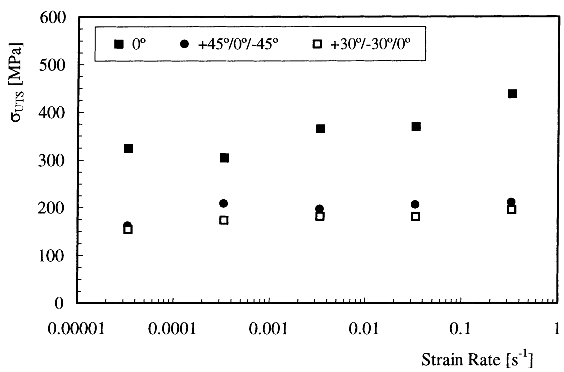


Fig. 3. Static strength versus strain rate.

puter. Periodically, the static stiffness modulus was obtained using a stress versus strain plot. When the maximum stress in the fatigue tests is less than one half of the static strength, the stress versus strain curve in this region is nearly linear. The stiffness modulus was then calculated by the linear regression of the stress–strain curves. This parameter will be used as a measure of damage.

As the fatigue tests were performed under displacement-controlled conditions, the stress decreases during the test. Fig. 4(a)–(c) plot the variations of the stress with the number of cycles for the 0°, +45°/0°/−45° and +30°/−30°/0° laminates, respectively. The ordinate plots the normalised stress, $\Delta\sigma/\Delta\sigma_0$, and the abscissa plots the normalised life N/N_f, where N is the number of cycles at one instant of the test, N_f is the number of cycles to failure, $\Delta\sigma$ the stress range and $\Delta\sigma_0$ the initial stress range. These data show that all the three laminates have similar behaviour. A significant drop of the stress (5–10%) occurred at the early stage of the fatigue life (5%). The stress then decreases slowly up to and near the final failure. During the last 5% of fatigue life, the stress has a sudden drop. This behaviour is related to the decreasing stiffness modulus, the temperature rise in the specimen and stress release.

Fig. 5(a) and (b) plot the E/E_0 versus N/N_f where E is the current stiffness modulus and E_0 is the initial stiffness modulus for 0° and +45°/0°/−45° laminate, respectively. These curves are very similar to the plots of Fig. 4 which means that the changes of stress range are primary influenced by the loss of stiffness.

A temperature rise of the specimen surface was observed for all the fatigue tests. Fig. 6(a) and (b) show the increase in temperature for the 0° and +45°/0°/−45° laminate, respectively. The plotted temperature corresponds to the maximum of the temperatures measured at the three thermocouples. The temperature difference of the three thermocouples was less than 3°C up to and close to failure. For each specimen, the maximum temperature was observed at different points. These figures show a similar behaviour for both laminates. The maximum temperature in both laminates was obtained at failure. The trend of these curves was the inverse of that for the stiffness (Fig. 5). It can be seen that after an initial increase of about 10°C there follows a stage where the temperature is nearly stabilised. A very small increase was then observed until failure. At this moment, a sudden increase of temperature occurs and then the specimen fails. During the second stage, there is a balance of the rate of energy by

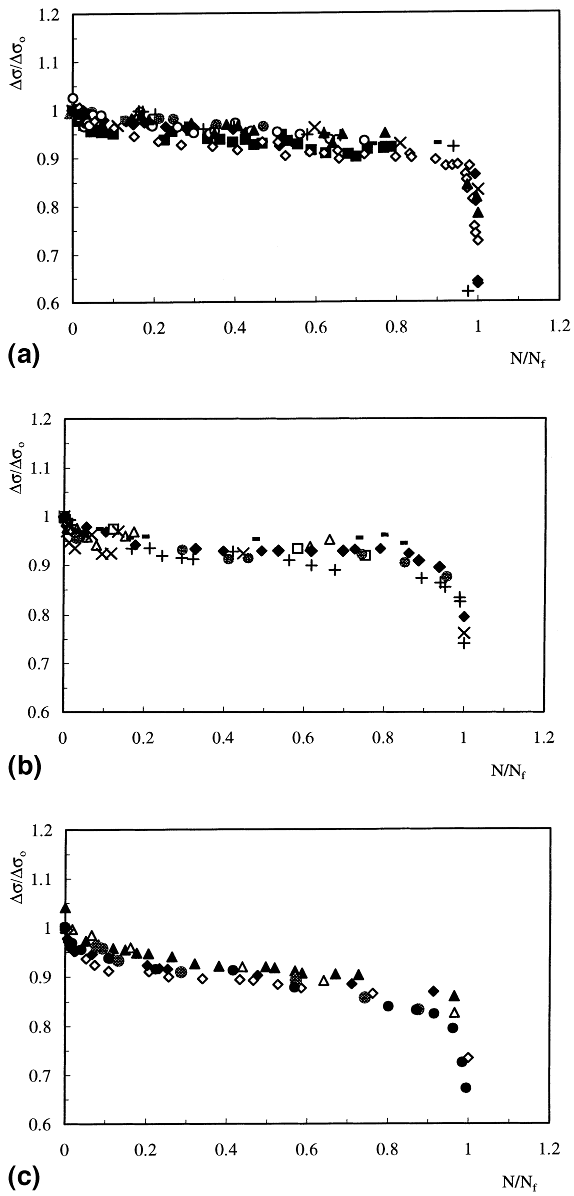


Fig. 4. Stress range variation during the fatigue test. (a) 0°; (b) +45°/0°/−45°; (c) +30°/−30°/0°.

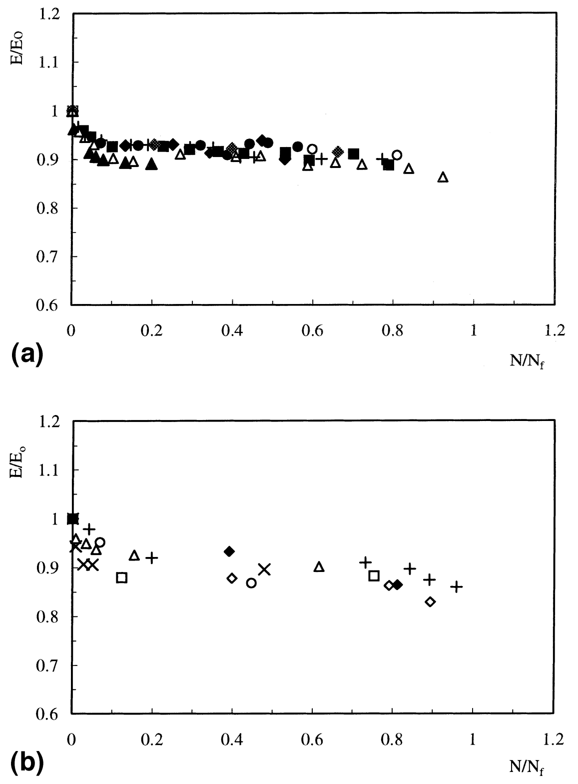


Fig. 5. E/E_0 against the normalised number of cycles N/N_f. (a) 0°; (b) +45°/0°/−45°.

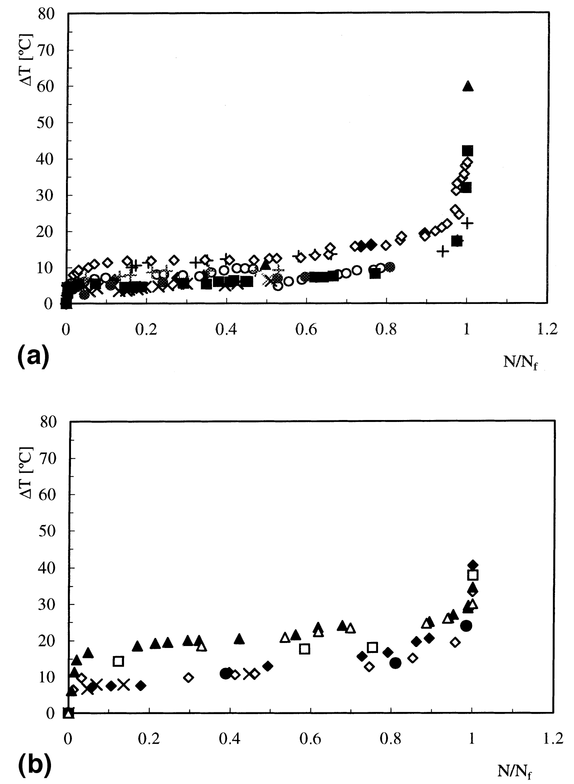


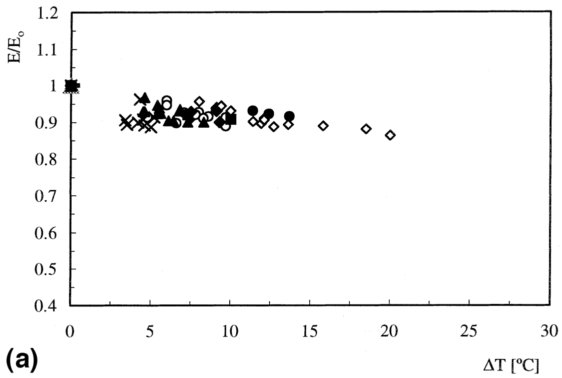
Fig. 6. Increase of temperature on the surface of the specimens. (a) 0°; (b) +45°/0°/−45°.

deformation, cracking and energy dissipation. For the third stage, the rate of energy due to the failure of the matrix and fibres predominates and the temperature increases quickly. The range of temperature rise on the surface at failure depends on the stress level, it varies between 30°C and 75°C for a mean value of about 40°C.

It appears that these parameters are not independent. Plotted in Fig. 7(a) and (b) are the loss of stiffness E/E_0 versus the temperature rise ΔT for 0° and +45°/0°/−45° laminate, respectively. For both laminates, a linear decrease of stiffness with the temperature is observed for the second stage. The analysis shows that for the second stage of fatigue process the rise of temperature, the loss of stiffness and the decrease of stress range are interdependent. The loss of stiffness caused by material degradation can be quantified as a function of temperature rise.

During the first stage of fatigue life, the stress release can also influence the drop observed in the stress range. Tests of stress release were carried out in an Instron Universal Test machine where a fixed displacement was applied and the stress was recorded during the time. The specimen geometry was the same as that used in the tension tests. These tests were done for the three laminates. Fig. 8 shows the variation of the stress with time for the 0° laminates. Plotted are four curves for different strain values. The curves obtained for the other laminates are similar to those plotted in Fig. 8. Stress decrease for this material is especially important for the first 10 min. The behaviour is the same for the three laminates. It can be concluded that stress release causing stress range decrease is important for the first stage of fatigue.

The data plotted in Fig. 8 can be fitted by the equation



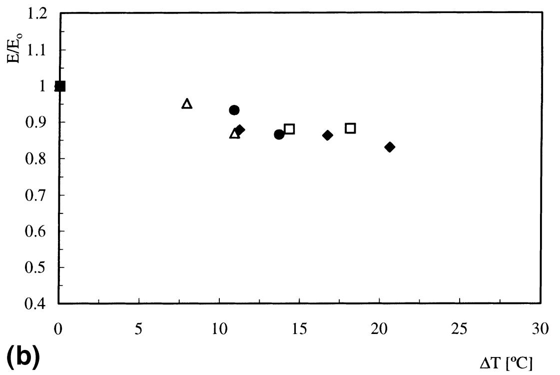


Fig. 7. E/E_0 against the rise of temperature ΔT. (a) 0°; (b) +45°/0°/−45°.

$$\sigma = A \log t + B, \quad (1)$$

where A and B are constants for a fixed initial stress of each laminate. Within the tested range, the parameters A and B are related to the initial stress by

$$A = A_1\sigma_0^2 + A_2\sigma_0 + A_3 \quad (2)$$

and

$$B = B_1\sigma_0 + B_2, \quad (3)$$

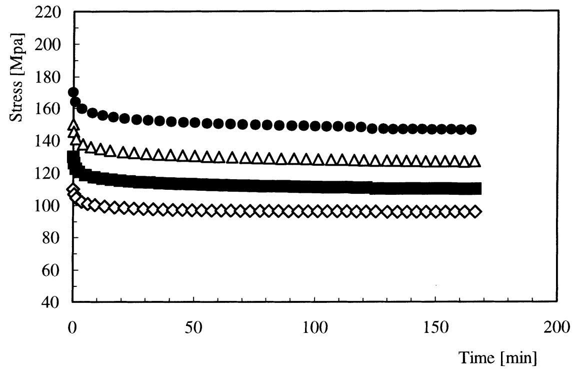


Fig. 8. Stress versus time in the stress release tests for 0° laminate.

where σ_0 is the initial stress. The coefficients A_1, A_2, A_3, B_1 and B_2 are presented in Table 2. Note that the stress is in MPa and the time in minutes.

The results of the fatigue tests were plotted in Fig. 9 in terms of stress range at the beginning of the test versus the number of cycles to failure. It shows that the fatigue strength of the 0° laminates (where one of the fibres direction is always the same of the load for all the layers) is 1.6–1.8 times higher than the other two laminates. This effect was caused by the change of failure mechanism. In the +45°/0°/−45° and +30°/−30°/0° laminates, the predominant fatigue mechanism was debonding between the fibres and matrix caused by the normal stresses. The initial failure was observed along the inclined planes along one of the fiber direction. In the 0° laminate the normal stress was carried mostly by the longitudinal fibres and the failure occurred in the transverse planes. These differences in failure mechanism can be observed in Fig. 10(a) and 10(b) for the 0° and +45°/0°/−45° laminates, respectively. The fatigue strength for +45°/0°/−45° and +30°/−30°/0° laminates was similar for low fatigue lives. A slightly higher fatigue strength prevailed for +45°/0°/−45° with longer lives.

Table 2
Stress release parameters

Laminate	A_1	A_2	A_3	B_1	B_2
0°	0.0011	−0.3708	23.245	0.7623	22.216
+30°/−30°/0°	0.0013	−0.2831	10.292	0.9409	0.579
+45°/0°/−45°	0.0002	−0.0715	0.2693	0.9616	−0.8894

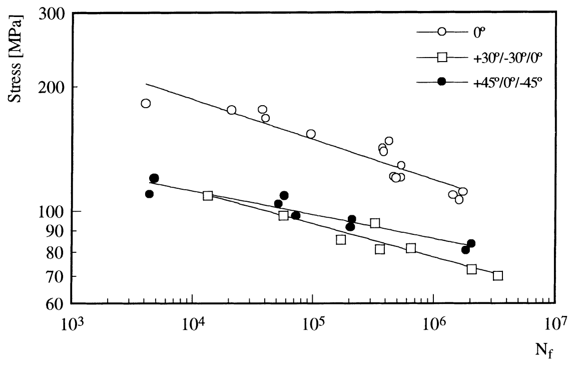


Fig. 9. Influence of layer geometry on the S–N curves.

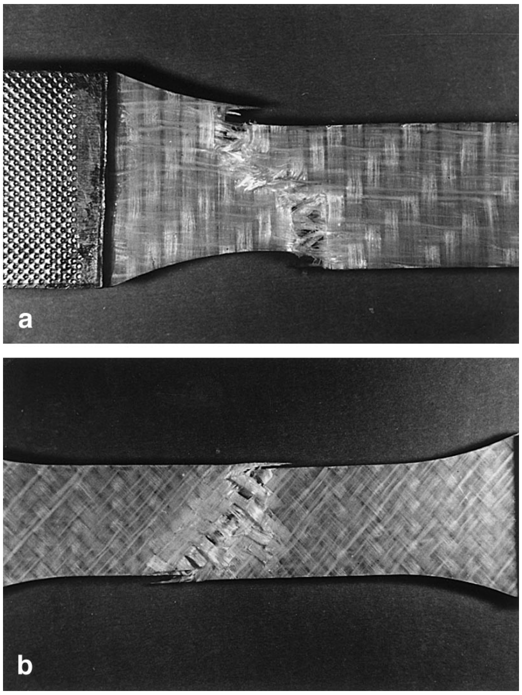


Fig. 10. Failure aspect. (a) 0°; (b)+45°/0°/−45°.

4. Conclusions

- The stress–strain curves obtained in the laminates showed a non-linear behaviour for all stress levels.
- Within the range of stain rate 3.33×10^{-1}–3.33×10^{-5} sec^{-1}, there is a small tendency for the static properties to increase. This tendency was more important for the failure stress of the 0° laminate. The ultimate strength for the +45°/0°/−45° and +30°/−30°/0° laminates was only about 50% of that obtained for 0° laminate. Also the stiffness of the 0° laminate was about 1.5 times higher than that of the other layer distributions.
- The fatigue strength was strongly influenced by the layer design. The +45°/0°/−45° and +30°/−30°/0° laminates have similar fatigue strength and about 1.8 less than that of the 0° laminate.
- The loss of stiffness (E/E_0) started early in the fatigue life. A sudden drop of E/E_0 (about 5%) was observed during the first 5% of the fatigue life and thereafter only a negligible decrease was observed up to failure. The main cause of the initial stiffness drop is probably caused by the observed stress release. An equation is suggested to quantify the results of stress decrease at room temperature.
- The temperature rise on the surface of the specimens reaches the maximum at failure in the range of 30–75°C. The maximum values depend on the stress range with a mean value around 40°C. For the second stage of the fatigue process (which was more than 80% of fatigue life), a linear relationship between the loss of stiffness (E/E_0) and the temperature rise was observed for all the laminates.

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