Effects of temperature on monotonic and fatigue properties of carbon fibre epoxy cross ply laminates

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The effects of test temperature on damage accumulation behaviour has been studied using "Torayca" T800H/#3631 in conditions of monotonic and fatigue loading. The damage accumulation behaviour was found to vary as a function of the test temperature, with the effect of temperature on the damage behaviour being different between monotonic and fatigue loading.

INTRODUCTION

Carbon fibre reinforced plastic (CFRP) is widely applied in aircraft structures. Such structures can experience temperature fluctuations between approximately -40°C and 100°C. It is, therefore, important to understand how the fatigue properties of carbon fibre composites vary with environmental temperature. This paper presents an investigation of the effect of test temperature on the fatigue properties of carbon fibre reinforced epoxy cross ply laminates. The observed effects are compared with the temperature dependence of monotonic properties.

EXPERIMENTAL

"Torayca" T800H, a high tensile strength, 5.49 GPa, and intermediate modulus, 294 GPa, type carbon fibre, and Toray resin system #3631, a semitoughened 180°C cure epoxy resin, were used for this study. The fibre volume fraction was 0.6. Properties of the unidirectional laminate were summarised in Table 1. The laminae of T800H/#3631 were stacked in [0₂/90₄]_s configuration. Specimens 1.6 mm thick, 25 mm wide and with a 140 mm gauge length were carefully polished in both sides with diamond compounds down to 1 µm for optical microscope observations.

Monotonic and fatigue tests were conducted at room temperature (approximately 20°C), low temperature (-40°C) and elevated temperatures (60 and 100°C). Tensile monotonic loading was carried out at a cross head speed of 1.0 mm/min. Fatigue tests were conducted in tension-tension loading at a constant stress ratio, $R=0.1$, with a sinusoidal wave form at 5 Hz. The maximum fatigue stress was fixed at 500 MPa, the stress level just below that for the initiation of transverse cracks in monotonic tests at all temperatures. Optical microscopy was employed to detect the damage accumulation on the polished side edges of specimens. X-ray radiography was also conducted, using zinc iodide (ZnI₂) dye, at the end of each test. Thermal cycling tests were also conducted in the absence of an externally applied load. Temperature was cycled between -40°C and 100°C with a dwell time at each temperature of three minutes. Each cycle took approximately 25 minutes.

A creep test was conducted on the same machine as the fatigue tests at 100°C. Specimens were loaded to 500 MPa and held at constant load for 55 hours, the time for 10⁶ cycles in a fatigue test at 5 Hz.

RESULTS AND DISCUSSION

In both monotonic and fatigue tests, the first damage was transverse cracks in the 90° ply, due to the low transverse properties of unidirectional laminates as shown in Table 1. In some test conditions this is followed by longitudinal cracking in 0° plies, delamination between 0° and 90° plies and fibre fractures.

Monotonic Tests

The damage accumulation behaviour varied significantly as a function of the test temperature, as shown in Fig.1(a). Tensile thermal residual stress is generated in 90° plies because of the mismatch in coefficient of thermal expansion between 0 and 90° plies during cooling process after curing. This thermal residual stress will therefore be larger at lower testing temperatures [1]. Because of the difference in the thermal residual stress, the transverse crack density was expected to fall with increase in test temperature, as observed by Boniface et al. [2]. In the present case, however, Fig. 1(a) shows that the data at low temperature exhibit the expected trend, whereas the data at elevated temperatures also show easier transverse ply cracking than at room temperature. By taking into account the thermal residual stress between each filament and matrix as well as the thermal expansion difference between the plies, an excellent prediction of the behaviour at -40°C can be obtained [3]. However, the data at elevated temperatures still show the opposite trend to the prediction.

SEM observation of the transverse crack surfaces showed that the amount of resin adhesion on fibre surfaces was less at 100°C than at the lower temperatures and the crack propagation path was different from those at room temperature and -40°C. These changes appear to explain the large number of transverse cracks at elevated temperatures. These changes could arise both from changes in chemical bonding and matrix properties.

Fatigue Tests

The damage accumulation behaviour in fatigue was a strong function of the test temperature, as in monotonic tests, but exhibited a slightly different trend, as shown in Fig. 1(b) [4]. The number of cycles to transverse crack initiation and saturation was largest at room temperature. Early initiation and saturation at elevated temperatures may again be attributed to changes in fibre/resin adhesion and crack propagation path, as in the monotonic tests. The number of transverse cracks was largest at -40°C in fatigue, although the data lie between that for room temperature and 100°C under monotonic loading. Such a large number of transverse cracks at -40°C is able to develop because of the combination of high resin flow strength and good resistance to delamination at this temperature.

Damage accumulation behaviour in monotonic and fatigue tests is summarised in Table 2. Almost complete delamination along the entire specimen gauge length occurred in fatigue at 100°C, although no delamination was observed in the 100°C monotonic tests. Resin plastic flow will occur to a larger extent at high temperature in the resin rich region between 0° and 90° plies because of the low yield stress of neat resin [5]. This appears to be an important factor for delamination under fatigue loading.

In both monotonic and fatigue loading the damage accumulation behaviour at room temperature and -40°C shows the effect of temperature observed by Boniface et al. [2], and expected from the increase in thermal residual stress at -40°C. However at elevated temperatures transverse ply cracking develops earlier and to a higher density than would be expected, associated with a change in crack propagation path. These changes would be expected to increase the longitudinal crack density in a similar way to the transverse ply crack density. The absence of longitudinal cracking at 100°C could result from a change in transverse ply crack tip geometry. Resin flow at 100°C is thought to blunt the transverse ply crack tips, making them less effective stress concentrators from the point of view of initiating longitudinal cracking in 0° plies.

Two other factors were thought to be potentially significant in reducing fatigue performance either above or below room temperature: (i) thermal cycling, because crack counting was performed at room temperature for all the tests, and (ii) creep crack growth in the elevated temperature tests.

Thermal Cycling Tests

After 500 cycles of thermal cycling between 100°C and -40°C no cracks were observed. For the fatigue described tests above, crack observation at room temperature, for fatigue tests at -40, 60 and 100°C, involved thermal cycling up to 20 times during each tests. The thermal cycling results indicate that this will have a negligible effect on the fatigue behaviour.

Creep Tests

After 55 hours at a constant load of 500MPa at 100°C, no delamination was observed with X-ray radiography. However transverse cracks were generated, to a crack density of 0.4 cracks/mm. This shows that creep has a strong effect on the transverse cracking behaviour at 100°C, although not on

delamination. Further work to examine the rate of damage accumulation at constant load is currently under way.

CONCLUSIONS

- 1) The damage accumulation behaviour was found to vary significantly as a function of test temperatures. The effect of the temperature on the damage behaviour is different in monotonic and in fatigue loading.
- 2) Changes, with temperature, in fibre/resin adhesion, neat resin properties and thermal residual stress affect the damage accumulation behaviour.
- 3) The main differences in damage accumulation behaviour between monotonic and fatigue tests were in the number of transverse cracks at -40°C and the degree of delamination at 100°C .
- 4) Resin plastic flow at elevated temperatures in the resin rich region between 0° and 90° plies leads to delamination in fatigue.
- 5) At elevated temperatures, transverse ply cracks accumulate under constant load, indicating that creep crack growth plays an important role in elevated temperature damage accumulation.

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Table 1. Unidirectional laminate properties ($V_f=0.6$)

		longitudinal	transverse
Tensile strength	MPa	2840	80
Young's modulus	GPa	160	7.8
Ultimate failure strain	%	1.55	1.0
Coefficient of thermal expansion	$10^{-6}^{\circ}\text{C}^{-1}$	0.1	35.5

Table 2. Summary of damage accumulation behaviour in monotonic and fatigue tests.

		-40°C	RT	100°C
MONOTONIC	Transverse	√√	√√√	√√√√
	Longitudinal	√√√	√	O
	Delamination	√	√	O
FATIGUE	Transverse	√√√√	√√	√√√
	Longitudinal	√√	√	O
	Delamination	√	√	√√√√

(√√√√ = severe, O = no incidence)

(a) monotonic tests

(b) fatigue tests

Fig.1 Effect of test temperature on transverse cracking behaviour in (a) monotonic and (b) fatigue tests.