STUDY OF THE TEMPERATURE EFFECT ON THE MATRIX CRACKING IN CARBON/EPOXY CROSS-PLY LAMINATES UNDER CYCLIC LOADING

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This paper deals with the effect of temperature on matrix cracking in Carbon/Epoxy cross-ply laminates. Static tension and tension-tension fatigue tests were conducted on cross-ply laminates at different temperatures : room temperature, 70°C and 120°C. Damage onset, damage accumulation and residual properties were measured. The transverse cracking damage was monitored during the tests by using various non-destructive evaluation (NDE) techniques, acoustic emission (AE) and X-ray radiography. A finite element model was achieved for predicting the variation of the stiffness as a function of crack density in the 90° plies of the laminate. This model takes into account the variation of material properties due to the temperature and also the cure residual stresses. The influence of temperature on the matrix cracking kinetic and stiffness degradation is then analysed.

INTRODUCTION

Composite laminates materials are submitted, during their life, to severe work conditions. This leads to the development of damage altering mechanical characteristics such as stiffness, and this, long before laminates failure. Matrix cracking is the primary damage mechanism in composite structures under mechanical loading. This damage is highly sensitive to the material components, the laminates sequence and the loading history. As the matrix properties are strongly influenced by the temperature, it seems the matrix damage history and level in a composite will then depend upon this parameter. Moreover, composite materials exhibit significant levels of cure residual stresses. These thermal stresses are due to the mismatch in the thermal expansion coefficients of adjacent plies. So under thermal exposure, residual stresses and matrix behaviour would influence the response of the laminate to the mechanical loading. Unfortunately, little information regarding the effect of isothermal and mechanical fatigue on polymer matrix composites is available (Strait (1), Han and Hahn (2)). In this study, we examine the effect of temperature on the fatigue and static damage of cross-plied (0/90) T300/914 laminates and basically the matrix cracking.

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MATERIALS, TEST EQUIPMENT AND EXPERIMENTAL PROCEDURES

The material used in this study is a thermoset matrix composite : carbon fibre (T300) and epoxy resin (914). All the test specimens were cut from panels obtained by the laying-up of unidirectional plies with respect to the desired stacking sequence : $[0/90_3]_S$. The end tabs, made of a glass-epoxy composite material, were glued using a high strength epoxy adhesive before cutting the specimens.

The specimens were heated in a circulating hot air chamber. Along the heated length of the sample it was observed that there was no temperature gradient. However the heated part of the specimen has a reduced section in order to avoid higher stress levels near the tabs of the sample. Temperature was also controlled with a thermocouple placed near the specimen. Mechanical loading was achieved by an Instron servo-hydraulic machine equipped with hydraulic grips. The quasi-static loading tests were conducted with a speed of 2mm/min. Tension-tension load controlled fatigue tests were performed with a sine wave form loading at a 5 Hz-frequency. The load ratio was set at a value of 0.1.

Two acoustic emission sensors were attached to specimens using a viscous coupling agent. The collection of acoustic emission data during test gave additional information regarding the matrix failure history. The strain was recorded by a length gauge fixed to the specimen. The counting of the number of cracks was performed using X-rays on specimens which have been loaded, removed from the machine and then soaked in an alcoholic solution of Zinc Iodide. For the fatigue tests, the specimens were then replaced into the grips and reloaded until the next measure of the number of cracks.

Mechanical strength and elastic constants were determined for the T300/914 unidirectional ply at room temperature, 70°C and 120°C. The tests were conducted on specimens according to the Aerospace Standard Test Methods. The composite behaviour in the fibres direction is linear and does not depend on the test temperature. The transverse (plotted in Figure 1) and shear laminate behaviours are non linear and depend upon the temperature. The non linearity of the stress versus strain curves increases with the temperature. The in-plane shear laminate properties data are summarised in Table 1.

NUMERICAL SIMULATION

Stiffness losses in the $[0/90_3]_S$ laminates composite are obtained by using the SAMCEF finite elements code. A plane strain model for laminates composite with a quadrangular axi-symmetric multi-layer element was employed to model the repeated region between two transverse cracks. The thermal stresses due to the curing process and the non-linear stress-strain behaviour were taken into account in this calculation.

TABLE 1- Summary of T300/914 properties at different temperatures.

Temperature (°C)	E_t (MPa)	ε_{22} (%)
24	9200	0.57
70	9200	0.75
120	9150	0.88

EXPERIMENTAL RESULTS

Static-tension Tests

The effect of temperature on the accumulation of matrix cracking can be seen on Figure 2. In this figure, the crack density is plotted versus the strain for the different test temperatures. For a same strain, the crack density decreases as the temperature increases. Hence at 120°C, no transverse cracks were observed. Some cracks may be closed after unloading of the specimens (Andersen and Lilhct (3)). So, in order to control the results given by X-rays, different specimens were polished and observed by laser scanning confocal microscope. Specimens tested at 120°C remain without transverse matrix cracks until their ultimate failure. As for the other temperatures tested specimens, good correlation is obtained between X-rays measurements and microscopic observations.

The failures at 70°C and 120°C are sudden and the stress/strain curves remain linear up to the failure as it can be seen on Figure 3. On the contrary, at room temperature, the stress/strain curve presents a little non-linearity. Prior to final failure, there is a decrease of the stiffness which is mainly associated with the development of the matrix cracks. This is confirmed by the numerical simulations of the stiffness reduction versus the number of cracks. As it can be seen on Figure 3, the stiffness loss is about 3% near the final failure for room temperature, lower than 1% at 70°C and zero at 120°C.

The strain values at which the matrix cracking initiates are given by acoustic emission monitoring. The level of this strain is defined as the level where the cumulated number of events starts to rise significantly. The values of these critical strains are of 0.46% and 0.68% at room temperature and 70°C respectively. These values increase with the temperature. This result can be explained on the one hand by the cure residual stresses in transverse ply (higher for lower temperature) , and on the other hand by the strain to failure (Table 1) that varies in proportion with the temperature.

After the specimens failure, a second damage mode is clearly observed on the fracture surface. It is the delamination of the transverse and longitudinal plies. This damage initiates at the free edges of the specimen and extends over a large surface. The delamination area is larger at room temperature than it is at 70°C. However when tests are performed at 120°C, the delamination is absent. This may be explained by the presence of significant cure residual stresses at low temperature but also by the lower ductility of the matrix at high temperature which may be associated with low restitution energy rates (G). Ultrasound control have to be performed in order to determinate if the delamination damage appears before the failure of the specimen.

Fatigue Tension-tension Tests

The maximum sinusoidal load is equal to 70% of the laminate static failure load. This ratio is chosen to amplify the matrix cracking development (Raud (4)). The fatigue damage accumulation versus cycle number is plotted in Figure 4. As it can be seen, the transverse crack growth depends on the test temperature. The higher the temperature, the faster the crack growth development. As shown in Figure 4, the saturation state of matrix cracks is reached more rapidly at room temperature than at 70°C and 120°C. Thus, the saturation crack density is higher for low temperature than high temperature.

The cyclic loading was interrupted at different cycle numbers to monitor the damage with X-rays radiographs and to determine the static stiffness decrease. The effect of matrix cracking and temperature on the specimens longitudinal modulus is shown in Figure 5. We notice that finite elements simulation shows a good agreement with experimental data and that temperature has no influence on the stiffness reduction. In fact, for the same cracks density the stiffness reduction is the same for the different temperature tests. However, the stiffness loss at saturation is lower for high temperature than it is for low temperature.

CONCLUSION

The purpose of this work was to study experimentally and numerically the temperature effect on the matrix cracking development on Carbon/Epoxy cross-plied laminates. The results given by the different tests indicate that temperature has a significant influence on the matrix cracks onset and on their development. At 120°C, static failure mechanism is governed by fibre deformation ; this is explained by the absence of transverse cracking. However, at 70°C and at room temperature, the specimens failure is preceded by matrix cracking and adjacent plies delamination. Concerning the fatigue results, the temperature influences both the kinetic behaviour of cracks formation and the number of cracks at saturation which are respectively faster and higher at low temperature.

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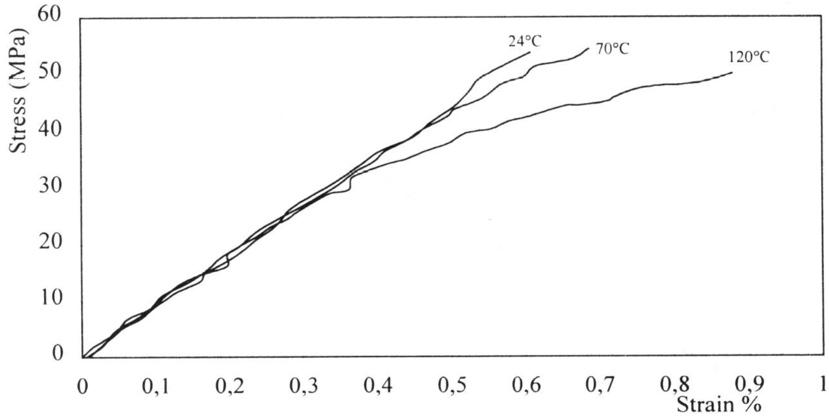

Figure 1 : Effect of temperature on transverse behaviour of T300/914.

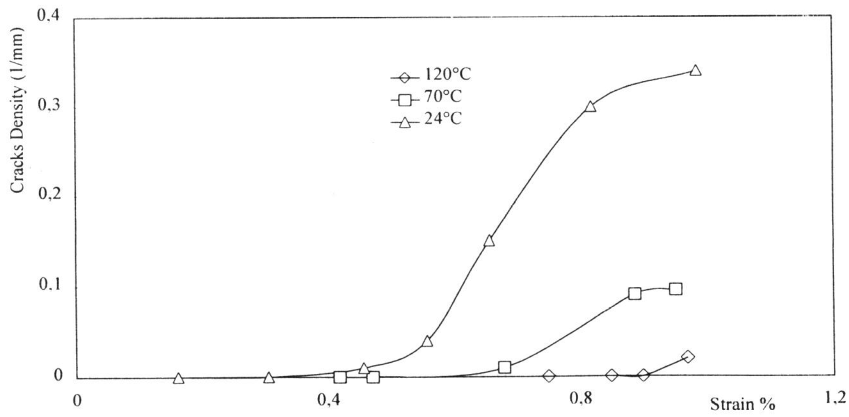

Figure 2 : Matrix cracking accumulation on $[0/90_3]_S$ under a monotonic mechanical tensile test.

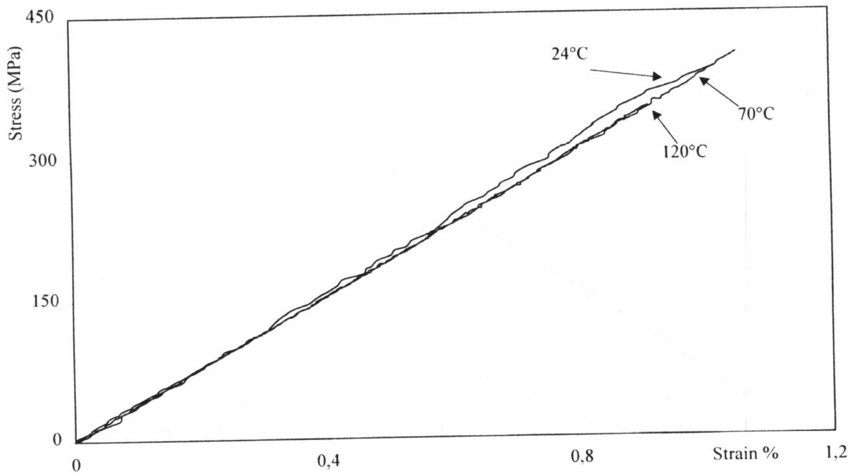

Figure 3 : Mechanical loading of $[0/90_3]_S$ at different temperatures.

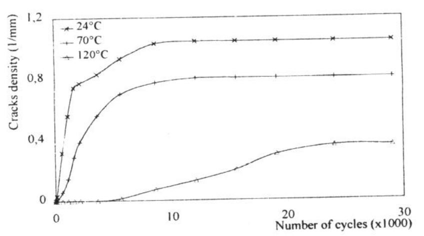

Figure 4 : Matrix cracking accumulation on $[0/90_3]_S$ under mechanical tensile-tensile loading.

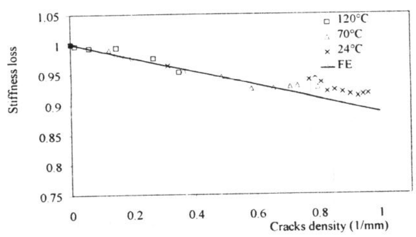

Figure 5 : Experimental measurement and finite elements prediction of stiffness loss as function of cracks density.