TEMPERATURE EFFECT ON THE DAMAGE DEVELOPMENT OF A CFRP LAMINATE UNDER CYCLIC LOADING.

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SUMMARY: The objective of the present paper is to evaluate experimentally the effect of temperature on fatigue damage of polymeric composite materials (T300/914). Tension-tension fatigue tests were conducted on $[0/\pm45/90_3]_S$ laminates undergoing different temperatures : 24°C, 70°C and 120°C. Only transverse ply matrix cracking and delamination have been considered in this study. The effect of damage on the stiffness loss has also been measured. Finite element simulation was carried out to study the transverse matrix cracking effect on the stresses distribution. Residual stresses which depend on thermoelastic properties of the materials, have been taken into account. This numerical model gives an approach to the understanding of the CDS.

KEYWORDS: temperature effect, matrix cracking, delamination, stiffness loss, fatigue.

INTRODUCTION

The engineering application of composite materials is continuously in progress. These materials are considered to be ideal candidates for high technology structures, such as aircraft, because of their high specific strength and stiffness and the extremely low coefficient of longitudinal thermal expansion. During their life, composite materials may be submitted to a drastic mechanical load as well as a high level temperature. This work condition leads to the appearance and development of different failure modes such as fibre debonding, fibre fracture, matrix cracking and delamination. Moreover, composite materials exhibit significant levels of cure residual stresses due to the mismatch in the thermal expansion coefficients of adjacent plies [1]. So under such work conditions, residual stresses and matrix behaviour, which depend on the temperature level, would influence the development and interaction between the different failure modes. In this study, we examine the effect of temperature on the fatigue of $[0/\pm45/90_3]_S$ T300/914 laminates. We are interested in the transverse matrix cracking and delamination development and their mutual interaction. An important characteristic of the matrix cracking is to reach a final cracking pattern called the "Characteristic Damage State (CDS)" which is independent of the load sequence and the matrix crack growth process [2]. The explanation of the CDS [3] seems to be somewhat insufficient. Here we give a numerical result concerning the evolution of stress distribution in the transverse ply versus the crack density and hence an attempt to a more detailed explanation concerning the CDS.

EXPERIMENTS

The material concerned by this study is a thermosetting matrix composite : carbon fibre (T300) and epoxy resin (914). Specimens were obtained from panels of $[0/\pm45/90_3]_S$ stacking sequence. An Instron servo-hydraulic machine equipped with hydraulic grips was used to perform tension-tension load controlled fatigue with a sine wave form loading at a 5Hz-frequency. The load ratio was set at a value of 0.1 and the maximum stress was equal to 70% of the ultimate failure stress. A part of the specimen between the machine grips was heated in a circulating hot air chamber. This part has a reduced section in order to avoid higher stress levels near the tabs of the sample. X-rays radiography was used to monitor the matrix cracking and delamination development in the specimens. Specimens were removed from the machine and soaked in an alcoholic solution of Zinc Iodide then they were replaced into the grips and reloaded until the next control. The thickness of the 45° layer is so small that it has been impossible to visualise matrix cracking in this ply. So only transverse plies matrix cracking was considered in this study.

DAMAGE OBSERVATIONS

The X-ray controls show that under cyclic loading there are two damage modes which appear : matrix cracking and edge delamination. Depending on the test temperature, damage accumulation shows qualitative and quantitative differences.
Fig. 1 presents, at different temperatures, the matrix cracking formation in 90° plies versus the number of cycles.

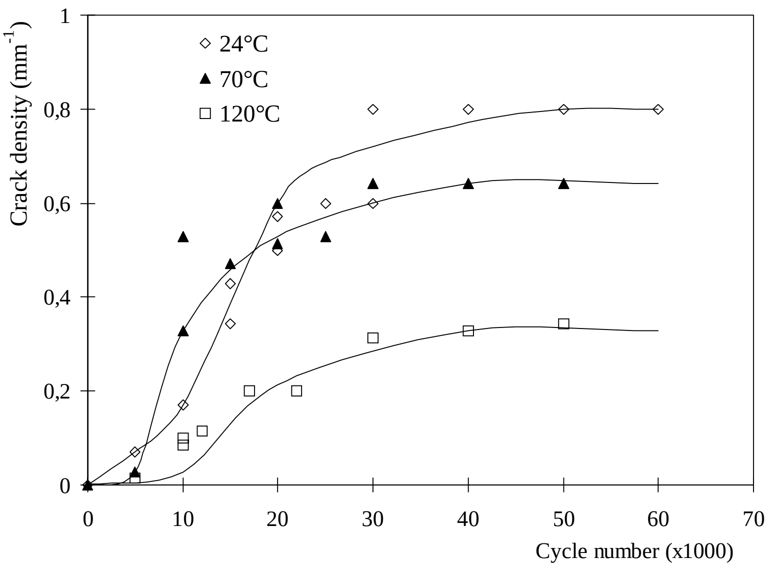
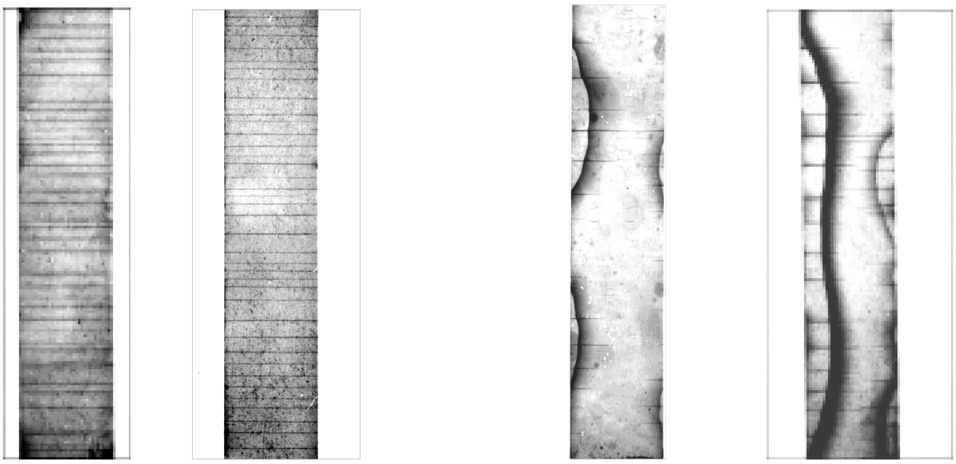


Fig. 1 : Matrix cracking accumulation on $[0/\pm45/90_3]_S$ under cyclic loading.

At 24°C and 70°C the matrix cracks in 90° plies develop in the same way but accumulate faster than at 120°C. For each test temperature the matrix cracking reach a saturation level. This CDS decreases as the temperature increases. For 24°C and 70°C transverse cracks occur before delamination takes place at the 45/90 interface. This later damage mode starts from the transverse crack-tips and the free edge stress concentration zones as soon as the CDS is reached. But at 120°C edge delaminations are observed after the appearance of the first transverse ply cracks. The extension of the delamination zones goes on with the growth of the matrix cracks located in the same zone. Only a few cracks are present in the undelaminated portion.



(a) 24°C (b) 70°C (c) 120°C

Fig. 2 : X-radiographs of transverse cracks formation under tension-tension fatigue loading: (a), (b) and interaction between free edge delamination and transverse crack (c).

Fig. 2 shows an X-ray plane view after fatigue cycling. As can be seen at 24°C and 70°C transverse cracks go through the entire width of the specimens. On the contrary we notice that at 120°C the already initiated edge cracks don't go through the width at once but keeps on propagating slowly towards the opposite side simultaneously with the delamination development.

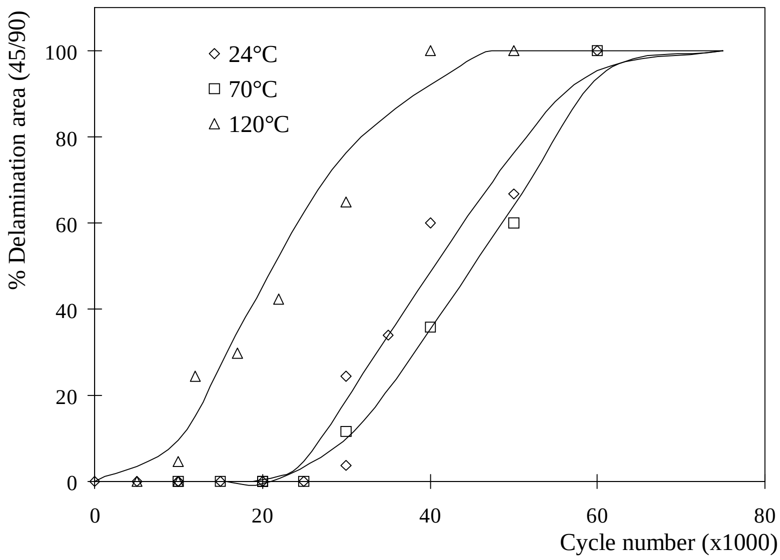


Fig. 3 : Effect of temperature on the edge delamination development in $[0/\pm45/90_3]_S$

Fig. 3 displays the edge delamination growth at the 45/90 interface versus the cycles number. The comparison of Fig. 1 and 3 shows the delamination and transverse cracking are simultaneous when the test is conducted at 120°C. So these two damage modes are continually interacting together through complex mechanisms. The examination of the X-ray radiographs shows that delaminations spread simultaneously into the two directions of the plane, Fig. 2, independently of the temperature test. This is a result of the combined effect of mixed mode (I and II) crack propagation. The cumulative effect of the two damage modes on the longitudinal modulus of specimens is shown in Fig. 4.

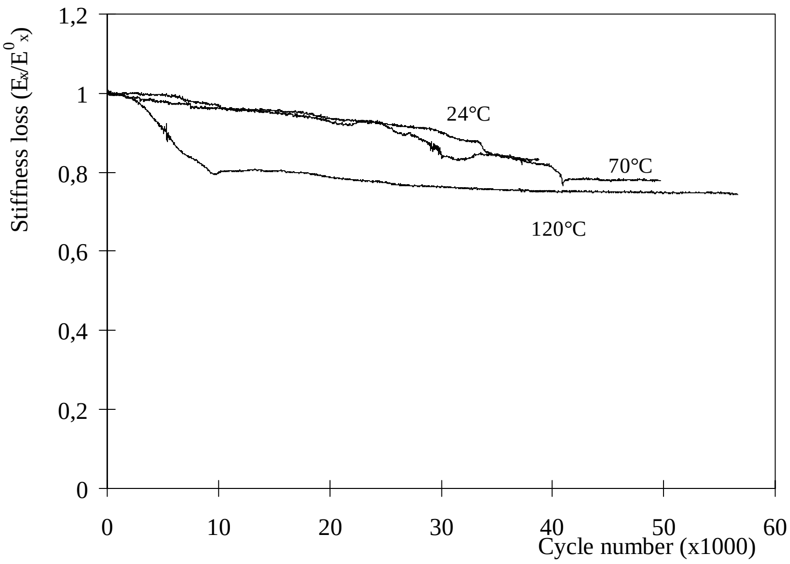


Fig. 4 : Temperature effect on the stiffness loss versus the number of cycles.

The reduction of stiffness versus the cycles number depends on the test temperature. For 120°C the laminate shows a faster change in stiffness than it is the case for 24°C and 70°C. This relatively fast change may be due to the development of the edge delamination.

FINITE ELEMENT STUDY

The numerical procedure used for the present analysis uses the SAMCEF finite element software. The aim of that simulation is to evaluate the stress distribution in composite plate as a function of crack density. A plane strain model for laminates composite with a quadrangular axi-symmetric multi-layer element is employed. The degree of the field displacement is equal to 2. Because of the symmetries only a quarter of the repeated region between two cracks is modelled Fig. 5.

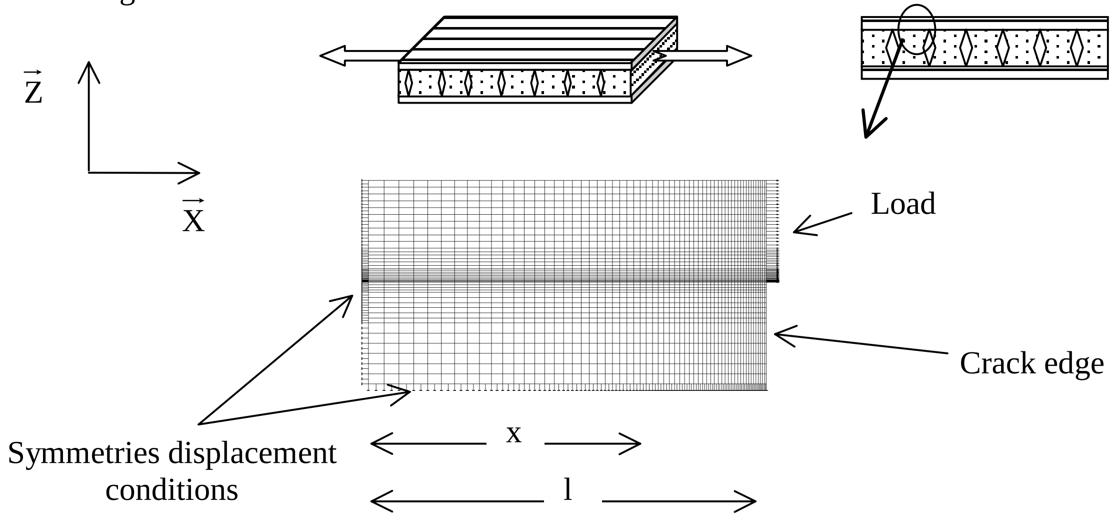
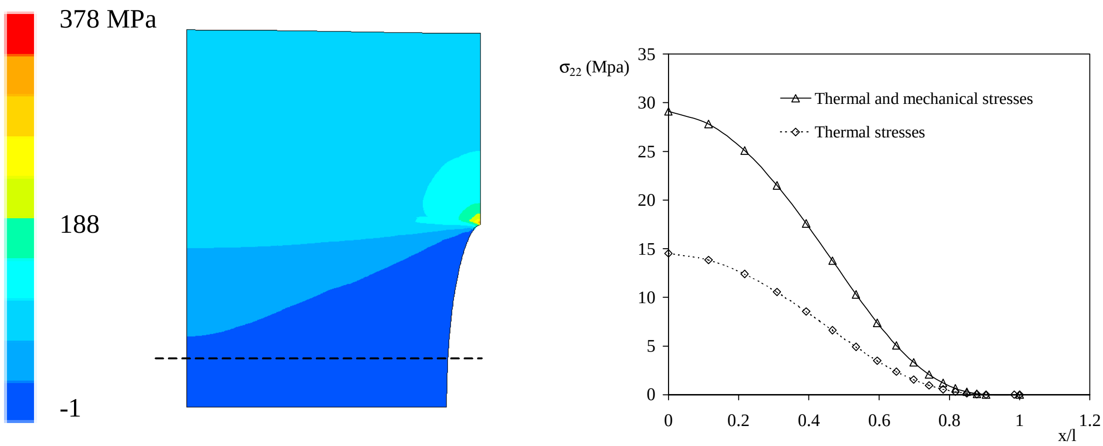
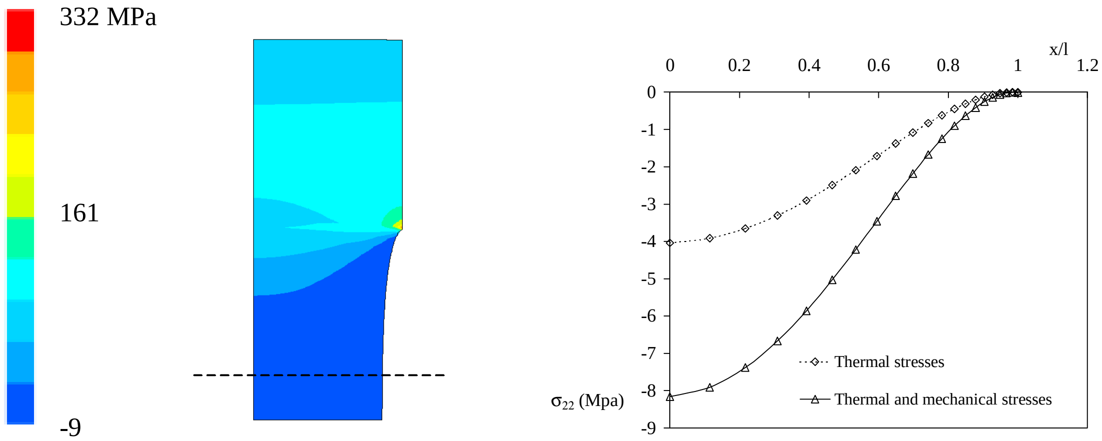


Fig. 5 : Finite element mesh.

The thermal stresses and the non-linear stress-strain behaviour of the material are taken into account. The loading is defined by means of load increments applied successively to the structure. It is separated into two categories : thermal loading and external mechanical loading. At the first increment the residual thermal stresses are generated by changing temperature from the cure temperature [4] to the test temperature. The mechanical loading, corresponding to the ultimate failure stress, is then applied during the second increment. The tow displays on the left of Fig. 6 represent the distribution of the σ_{22} stresses component calculated at 24°C and for two crack density values. The curves present the evolution of σ_{22} stress calculated on the first transverse ply above the plane of symmetry as function of x/l parameter. In the case of d = 1 crack mm^{-1} transverse plies are submitted to a tensile σ_{22} stress. Indeed residual thermal stresses are found to be positive. After the mechanical loading the stress rises. The same σ_{22} stress state is found when considering a crack density lower than 1 mm^{-1}. However, when considering a transverse crack density equal to 2 crack mm^{-1} we notice that the stress field in transverse ply includes a compression σ_{22} stress zone after thermal cooling and also after applied mechanical loading.



(a)- d = 1 crack mm^{-1}



(b)- d = 2 cracks mm^{-1}

Figure 6. σ_{22} stress distribution in the transverse ply of the $[0/\pm45/90_3]_S$ laminates.

For 70°C and 120°C the finite element calculation gives a similar σ_{22} stress state distribution as calculated for 24°C but not the same stress values. Using the data concerning the σ_{22} stress versus the crack density, the CDS can be predicted to be between 1 and 2 cracks mm^{-1}. In fact when an inherent defect, such as the voids caused by volatile elements evaporated during the polymerisation of the resin and considered to be the origin of the matrix cracking, is present

inside the compression zone, it does not transform into a crack. This compressed zone may be linked to the CDS reach. However the experimental CDS values at 24°C, 70°C and 120°C are respectively 0.8, 0.64 and 0.34 cracks mm^{-1} far lower than the numerical estimation.
This difference may be due to the appearance of delamination. In the region near the crack tip there are comparatively higher values of interlaminar normal stress σ_{zz} and interface shear stress σ_{zx}. The combined action of the two stresses gives rise to a mixed-mode delamination at interface (45/90). The appearance of this delamination causes a drop of the tensile stresses value in the transverse plies. This phenomenon delays the growth of the inherent flaws into a cracks. Then it stops the initiation of new cracks but the propagation of already initiated edge cracks through the width continues by a complex interaction with the delamination Fig. 2c.

CONCLUSIONS

This paper has attempted to determine how the temperature can influence the damage mode development and stiffness loss in composite materials. Matrix cracking and edge delamination occurs on $[0/\pm45/90_3]_S$ under cyclic mechanical loading. At 24°C and 70°C delaminations of the 45/90 interface develop after the matrix cracking reached the CDS. These cracks go straight through the specimens width. However at 120°C there's a mutual interaction between the two damage modes. Matrix cracks and delamination propagate together slowly through the width. The stiffness loss rate is faster at 120°C than at either 24°C or 70°C. A thermo-mechanical analysis of the laminates using a two dimensional finite element has been described. The thermal stresses resulting from thermal cooling from cure temperature to the test temperature was taken into account and this analysis include also the material non-linear behaviour of the lamina. It was found that when increasing crack density a compressive zone appears in the transverse plies. The appearance of that zone may give a numerically explanation of the CDS value. But as the experimental results showed the appearance of the delamination stops the cracks nucleation and may defined the CDS value.

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