MODELLING OF THE 90° PLY FATIGUE CRACK GROWTH ALONG THE WIDTH OF CROSS-PLY CARBON/EPOXY COUPONS

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ABSTRACT

This study focuses on fatigue mechanisms of matrix cracking in carbon/epoxy cross-ply laminates. A particular attention is given to the specimen width influence on the damage development.
In a first step, a fracture mechanics analysis for the strain energy release rate associated with the 90° ply matrix fatigue crack formation and growth is developed. This analysis, based on shear lag assumptions, takes into account both crack number and length, for a given specimen geometry.
Then, the experimental evolutions of crack density, crack length and crack propagation rates are obtained in the case of a simple cross-ply laminate submitted to fatigue loading. It is observed that these evolutions are independent of the specimen width. Moreover, once the crack number has reached its saturation value, the average crack propagation rate becomes constant.
These experimental results are in very good agreement with the predictions of the developed model.

KEYWORDS

Fatigue, composite, carbon/epoxy, transverse ply cracking, specimen width, crack length, shear lag analysis, strain energy release rate.

INTRODUCTION

In long fiber carbon/epoxy cross-ply laminates, the first damage generally observed under quasi-static and fatigue tests consists in matrix cracking in the 90° plies (Stinchcomb and Reifsnider, 1979).
Transverse cracks appear early in the fatigue life of a specimen, initiate at the specimen free edges and grow stably like fatigue cracks across the width (Lafarie-Frenot and Rivière, 1988 ; Boniface et al, 1987). The crack density per ply increases rapidly up to a saturation value (Reifsnider, 1977). This crack spacing saturation value is a characteristic of the laminate which depends on the constituents and on the stacking

sequence (Stinchcomb and Reifsnider, 1979). Moreover, throughout tests, the average crack length increases (Henaff-Gardin et al, 1992).
Recently, Lafarie-Frenot and Henaff-Gardin (1991) have developed a fracture mechanics analysis for the strain energy associated with 90° ply matrix crack formation and growth. In the study presented here, we compare the results obtained by a simple practical model with the experimental observations on a simple cross-ply laminate. We have particularly focused our attention on the influence of specimen width on the fatigue transverse ply crack propagation across the width.

MATERIALS AND EXPERIMENTAL CONDITIONS

Tension-tension fatigue tests are carried out in a load controlled testing mode, with a 0.1 load ratio and a 10 Hz frequency. The applied maximum stress is equal to 60% of the static failure stress of the studied T300/914 carbon/epoxy $[0_2/90/0]_s$ laminate.
The test coupons are approximately 1 mm thick, 180 mm long with end-tabs 40 mm long for gripping in the Instron servo-hydraulic machine. Moreover, in order to study the influence of the coupon width, three specimen widths are studied : 15, 30 and 60 mm.
The widthwise growth of the transverse ply cracks is investigated throughout tests by means of penetrant enhanced X-radiography (Zinc Iodide penetrant).

ANALYSIS OF MATRIX CRACKING

In 1983, Steif (quoted in Ogin et al, 1984) proposed a shear lag analysis which has been developed by Ogin et al (1985) and Caslini et al (1987). Compared with our previous observations (Lafarie-Frenot and Henaff-Gardin, 1991), the assumption that all the transverse cracks span the entire specimen width is inadequate and we have therefore incorporated the average crack length in our analysis (Henaff-Gardin et al, 1992).

Assumptions. This model allows to study the case of cross-ply $[0_p/90_q]_s$ laminates : so, we have replaced laminate $[0_2/90/0]_s$ with two adjacent $[0_{1.5}/90/0_{1.5}]_t$ ones.
Two parameters are used to represent more simply the crack distributions in the specimen width : the edge crack density d, and the average crack length $\bar{a}$. The problem is studied by considering a repeating cell, as shown in Fig. 1.
A fracture mechanics analysis is applied to develop a tool capable of predicting onset and growth of matrix cracking. The cracked surface variation is related to the strain energy release rate, G, which is defined as :

$$G = \left(\frac{\partial U_{el}}{\partial S_c} \right)_{\sigma} \qquad (1)$$

where U_{el} and S_c are respectively, the stored elastic energy and the cracked surface area in a L_u mm-long part of the specimen.
With the chosen assumptions (refer for more details to Lafarie-Frenot and Henaff-Gardin, 1991), G is finally expressed as a function of laminate parameters (both geometry and material ones), of average applied stress σ and of the derivative of damage laminate stiffness E_L (depending on crack density d and length $\bar{a}$) :

$$G = \frac{w(t_0+t_{90})\sigma^2}{4t_{90}} \frac{\partial\left(\frac{1}{E_L}\right)}{\partial(\bar{a}d)} \qquad (2)$$

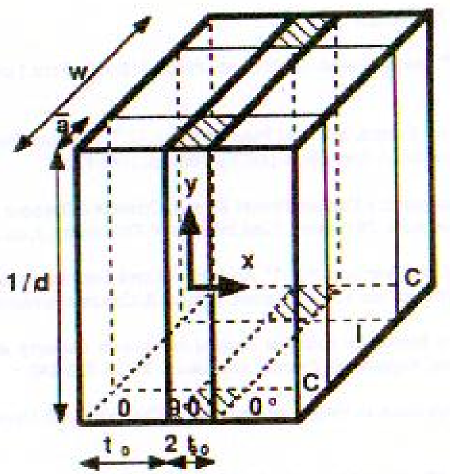

Fig. 1 : Cell geometry used for modelling the transverse ply fatigue cracking

In order to simplify, two extreme situations are then considered :

(1) $\bar{a}$ tends to zero, d is varying : this case corresponds to the very beginning of fatigue tests when the increase in the number of short cracks is prevailing;

(2) d is equal to its saturation value, $\bar{a}$ is varying : this situation is that of crack propagation, once the edge crack density saturation is reached.

Crack initiation. In Fig. 2, the strain energy release rate G is plotted against the edge crack density d, when the average crack length approaches zero.
It appears that the evolution of G(d) with density is almost independent of the specimen width. So, width should have no influence on transverse crack initiation and multiplication. Moreover, G decreases with increasing crack density : this should lead to an increasingly difficult generation of new cracks.

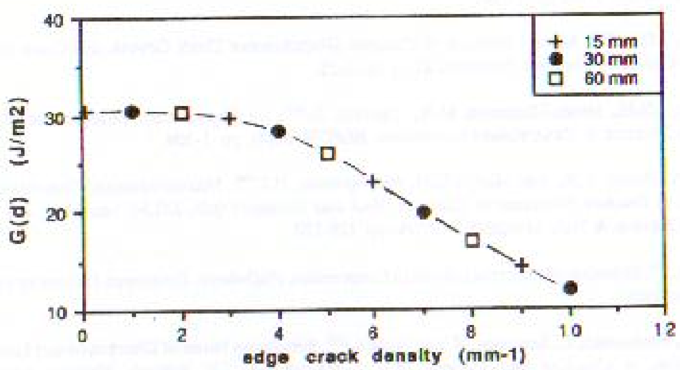

Fig. 2 : Cracks formation strain energy release rate G(d) vs crack density d.

Crack propagation. Fig. 3 is a representation of the variation of G(ā) with the average crack length ā. The edge crack density is taken to be equal to 5 mm^{-1}. The evolutions of G(ā) in the studied ā range can be considered as independent of the specimen width. Moreover, the strain energy release rate is almost independent of the average crack length : cracks should grow at a constant rate which does not depend on the specimen width, once the density has reached its saturation value.

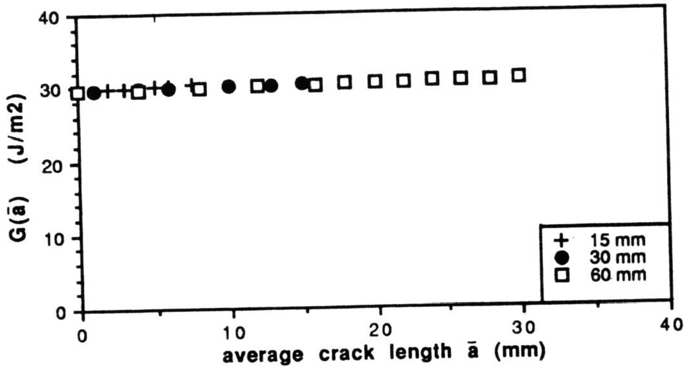

Fig. 3 : Crack propagation strain energy release rate G(ā) vs average crack length ā

EXPERIMENTAL RESULTS AND DISCUSSION

Edge crack density per ply. When observing transverse ply crack initiation and multiplication, it appears that these cracks initiate at the specimen edge, span instantaneously the ply thickness, and that they are regularly spaced for a given cycle number.

Fig. 4 shows the density evolutions versus the cycle number logarithm, for the three specimen widths. Two or three specimens have been tested for each specimen geometry, with a rather good scattering visualized on Fig. 4.

Throughout tests, the evolution of edge crack density per ply is independent of the specimen width.

The first cracks appear after approximately 10^4 cycles. Then, the density increases rapidly up to an average saturation value of 5 cracks per millimeter and per ply, from one million cycles.

These results are in accordance with the previous analysis : the edge crack density is independent of the specimen width, and its evolution is becoming more and more difficult with increasing fatigue cycle number.

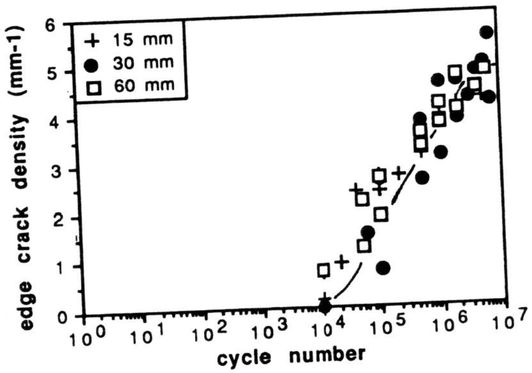

Fig. 4 : Edge crack density evolution per ply, vs cycle number

Average crack length. First cracks are very short, and none of them is spanning the entire specimen width. At the end of tests,because of their growth, some cracks may reach the other edge, only in the 15 mm wide specimens. Fig. 5 represents the average crack length evolution versus the cycle number logarithm.

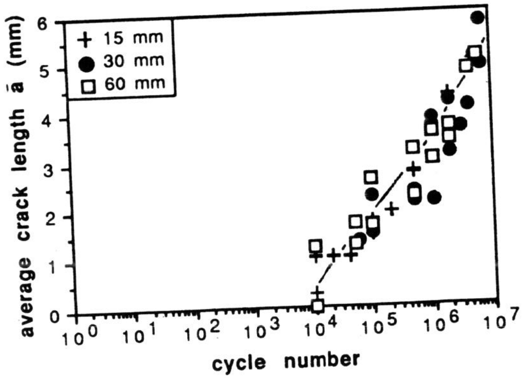

Fig. 5 : Average crack length evolution, vs cycle number

The average crack length is independent of the width w. Moreover, from 10^4 cycles to the end of tests, it increases continuously up to approximately 5 millimeters.

Crack distribution in the specimen width. The crack distribution inside the specimen width is obtained from the X-ray radiographs. First of all, the total number of cracks is counted on the specimen edge. Then, we measure the percentages of cracks which are present at different distances from this edge. An example of such histogram obtained at 2.10^6 cycles for the three geometries is given in Fig. 6.

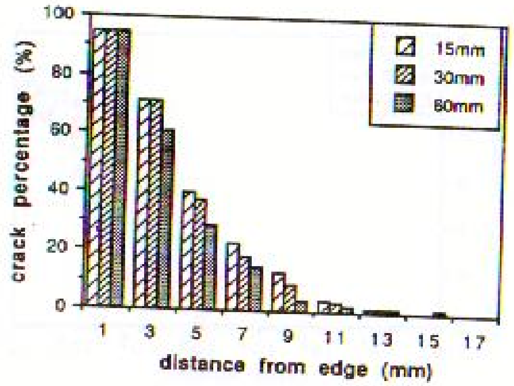

Fig. 6 : Crack length histogram, after 2.10^6 fatigue cycles, vs distance from edge.

For a given cycle number, cracks have approximately the same length, whatever is the specimen. In these experimental conditions, the damage distribution depends only on the distance from the free edge where cracks initiate, but in an important way.

Crack propagation rate. A hundred cracks have been individually followed up in 30 and 60 mm wide specimens along the fatigue test. In these two cases, cracks coming from opposite edges are far enough one from the other not to interfare in their growth. Fig. 7 is the representation of the average crack propagation rate, versus cycle number.

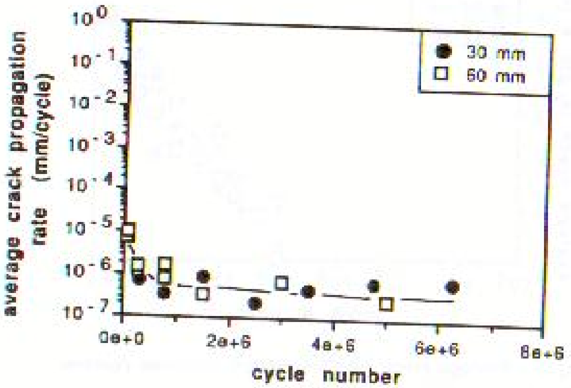

Fig. 7 : Average crack propagation rate, vs cycle number

At the beginning of tests, crack growth rate is decreasing rapidly while crack number is increasing. Then, the rate tends to a constant value (10^{-6}-10^{-7} mm/cycle) which is independent of the specimen width from about one million cycles, once the crack density has reached its saturation value. This observation is in complete accordance with the previously developed analysis.

CONCLUSION

The results presented here are part of a study concerning transverse cracking in carbon/epoxy T300/914 laminates, under quasi-static and fatigue loading. The fatigue tests conducted on $[0_2/90/0]_s$ laminates have allowed us to show that the specimen width does not modify the evolution of the considered damage. The evolutions of edge crack density, average crack length and of crack propagation rate are all independent of the specimen width, fatigue transverse cracking resulting from edge effects.
Moreover, once the edge crack density has reached its saturation value, the average crack growth rate remains constant.
All these results are in complete accordance with the presented simple shear lag analysis of a cracked laminate, analysis which takes into account both crack density and average length.

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