Damage mechanics of bonded joints in composite material under fatigue

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ABSTRACT. *In the present paper the evolution of fatigue damage in composite bonded joints is extensively analysed and discussed, with particular reference to the influence of layer orientation at the adhesive-adherend interface, corner geometry at the end of the overlap area and stacking sequence. Single lap bonded joints manufactured from autoclave-moulded laminates were investigated under tension-tension fatigue loading. Two laminate lay-ups* $[45/0_2]_s$ *and* $[45_2/0]_s$ *, two overlap lengths (20 and 40 mm) and two corner geometry (square edge and fillet) were considered. The evolution of fatigue damage, a crack initiation followed by propagation up to a critical length, was investigated at macroscopic and microscopic level, by monitoring stiffness trends and by optical and scanning electron microscopy and it is extensively discussed in the paper. The presence of a 45° oriented layer at the adhesive-interface layer makes damage patterns and crack paths much more complicated with respect to 0° interface joints, previously investigated by the authors. As a result the resistance to crack propagation is increased.*

INTRODUCTION

The fatigue behaviour of single lap bonded joints in composite has been discussed in [1] as well as the associated evolution of fatigue damage. Few investigations are however available in the literature about the potential influence of ply orientation at the adhesive/adherend interface on the fatigue behaviour of these joints.

Renton and Vinson [2] tested glass/epoxy single lap joints with all 0° or 45/0/45/0 laminate adherends. They reported a reduction of about 20-40% in the high cycle fatigue strength of the joints with 45° oriented plies. The 0° interface joints experienced adhesive failure, while the 45/0/45/0 failed in the 45° ply adjacent to the adhesive. Ferreira et al., [3], found an average decrease of about 30% in the fatigue shear strength of $[\pm 45/45/\bar{0}]_s$ glass/polypropylene single joints when compared to similar joints with $[0]_7$ lay-up. In their extensive review, [4], De Goeij et al. suggested a better fatigue strength for all 0° joints with respect to those with 45° and 90° oriented ply at the interface. On the other hand, Johnson and Mall [5] indicated that 45/45 interfaces in carbon/epoxy cracked lap shear joint turned out to be slightly stronger than 0/0 and 90/90 interfaces, at least in terms of threshold for crack initiation.

In this work the fatigue behaviour of carbon fabric/epoxy single lap bonded joints is investigated with particular reference to the possible influence of stacking sequence and orientation of the layer at the adhesive-adherend interface. For this aim, the new results are compared with those of the previous research [1] on single lap joints made from $[0]_6$ laminates of the same material.

MATERIALS, JOINT GEOMETRY AND TEST PROCEDURES

Single lap bonded joints, manufactured from autoclave-moulded laminates (Seal Texipreg® CC206, T300 twill 2x2 carbon fibre fabric/ET442 toughened epoxy matrix) and bonded with the two-part epoxy adhesive 9323 B/A by 3M were fatigue tested under tension-tension loading (R=0.05). Their overall geometry is shown in Fig. 1. For each condition, two load levels were considered, named "high load level, H" and "low load level, L", depending on the number of cycles to failure. High level was defined as a load level corresponding to a fatigue life ranging from 10000 to 100000 cycles, low level is referred to a fatigue life ranging from 500000 to 1000000 cycles. The test frequency was kept in the range of 10÷15 Hz.

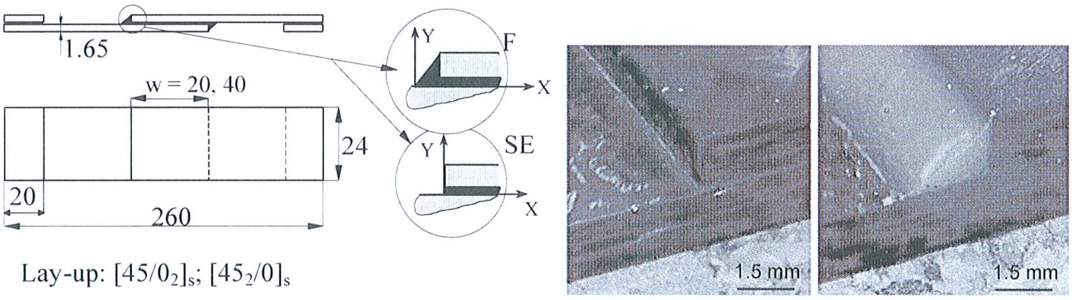

Figure 1. Geometry of the single lap bonded joint (w = 20 and 40 mm) and details of the corner geometry SE = Square Edge joint; F = Fillet joint.

The influence of the lay-up ($[45/0_2]_s$ and $[45_2/0]_s$), corner geometry (square edge and fillet) and overlap length (20 and 40 mm) on fatigue behaviour was investigated. Particular attention was devoted on the analysis of damage mechanisms and their evolution during fatigue life, by considering two different levels: macroscopic and microscopic level, as discussed in the following paragraphs.

FATIGUE DAMAGE EVOLUTION AT MACROSCOPIC LEVEL

Available fatigue data are plotted in Figs. 2 and 3. Results from previous investigations on joints made from $[0]_6$ laminates, [1], are reported for comparison. As it can be seen, the influence on fatigue life of both overlap length and corner geometry is greater than that of stacking sequence and ply orientation at the interface. The results of the fatigue testing program and their modelling are extensively discussed in ref. [6].

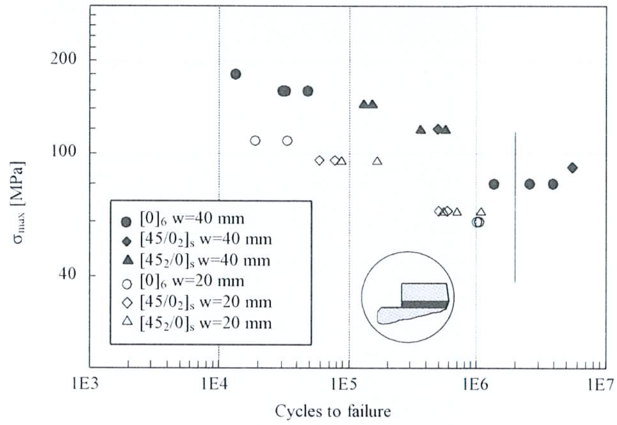

Figure 2. Influence of the overlap length on the fatigue strength of square edge joints. (Data for $[0]_6$ joints are taken from [1]).

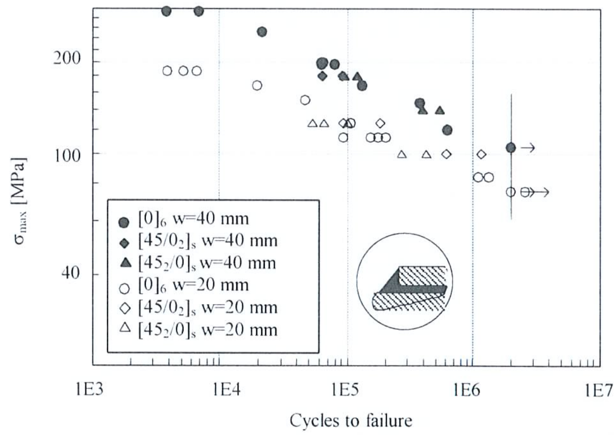

Figure 3. Influence of the overlap length on the fatigue strength of spew fillet joints. (Data for $[0]_6$ joints are taken from [1]).

During the fatigue tests, joint stiffness trends were monitored by measuring the instantaneous joint stiffness as the ratio between the imposed load range measured by the load cell and the resulting range of the actuator stroke measured by the displacement transducer of the testing machine. Figure 4 show examples of normalised stiffness trends as a function of the normalised fatigue life: the global analysis of the results indicated that stiffness trends are not influenced by lay-up, overlap length and only slightly by corner geometry, with a tendency of the fillet corner to delay crack initiation (identified by the beginning of the stiffness drop). This general insensitivity is quite important in view of using measured stiffness data for the development of a simplified technique to assess the crack propagation during fatigue life. This part of the research program is presented and discussed in ref. [7].

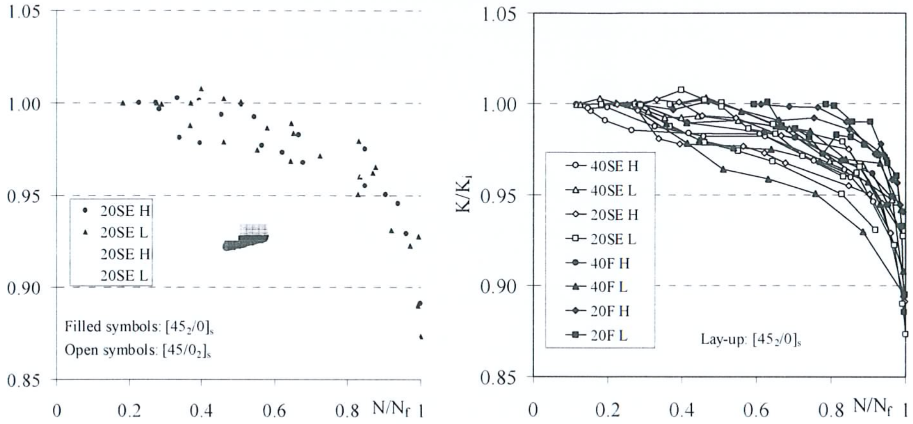

Figure 4. Influence of lay-up and corner geometry on stiffness trend during fatigue life for SE joints, 20 mm overlap length (H = high load level, L = low load level).

FATIGUE DAMAGE EVOLUTION AT MICROSCOPIC LEVEL

Damage evolution at microscopic level was investigated by integrated use of optical and scanning electron microscopy. To investigate damage evolution and assess the fraction of life spent for crack nucleation and propagation, joints were subjected to repeated blocks of fatigue loading at constant amplitude, up to the failure. At the end of each block, the damage patterns were observed and measured on the polished edges of the joints, by using a Leica Metallux 3 optical microscope equipped with a Leica camera DC 100 providing a geometrical accuracy of 0.05 mm.

As already discussed in ref. [1], the crack onset was defined when one of the cracks emanating from the corners (named as A, B, C and D) reaches a length of 0.3 mm, arbitrarily chosen, and measured on the polished edges, as shown in Fig. 5.

The definition of a technical crack was necessary due to two main reasons:

- the practical difficulty in detecting cracks smaller than that size, especially for square edge joints;
- the need for identifying precise, even though conventional locations for the damage analysis. In fact in the case of fillet joints, cracks nucleated mainly as indicated in Fig. 5 but also in alternative ways, as shown in Fig. 6c.

On the basis of this definition of crack onset, the number of cycle to crack initiation N_i and the crack lengths during the fatigue life were identified. Examples of the growth of the cracks emanating from the four corners are shown in Fig.7. It can be observed that nucleation at the different corners does not occur simultaneously, thus making the damage pattern rather complicated. One can also notice that the presence of a fillet delays the crack nucleation with respect to the square edge configuration, as already mentioned above. This is confirmed by the overall analysis of the crack/delamination evolution measured on several joints.

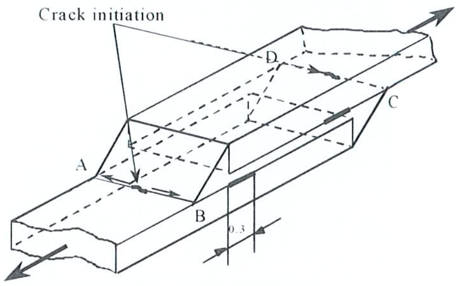

Figure 5. Definition of the "technical" crack for the conventional assessment of the crack initiation, at the four corners of the joint overlap

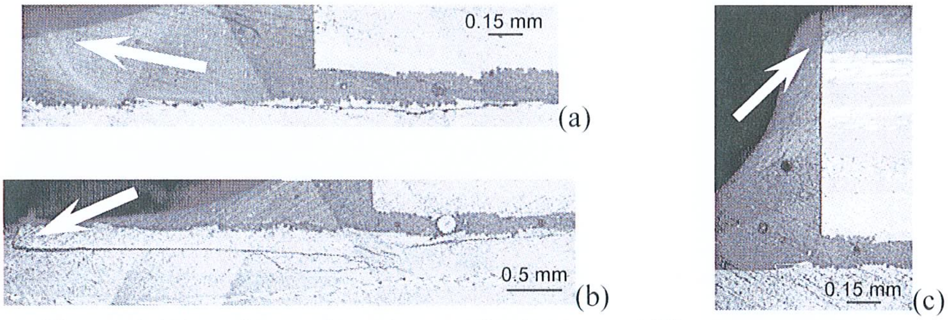

Figure 6. Edge views of crack onset in the case of fillet corner geometry

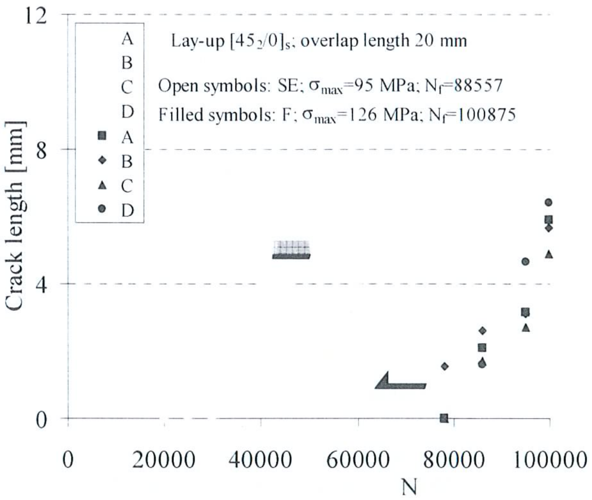

Figure 7. Influence of corner geometry on crack onset and growth.

On the other hand, the available experimental results (61 specimens) indicate that stacking sequence, overlap length and load level do not have a significant influence on the fraction of life spent for crack nucleation. The comparison of previous data [1] on joints with 0° oriented layer at the adhesive-adherend interface suggests also a weak influence by the ply orientation at the interface. The available results are summarised in table 1, in terms of fraction of life to crack initiation: it is seen that a significant part of the fatigue life of a joint is spent for initiating a crack or a delamination of measurable size. In this situation it is also clear the opportunity of or the need for, depending on the point of view, describing the fatigue life using prediction models suitable to account for and describe both the initiation and the propagation phase [8].

The adhesive-adherend interface plays however an important role during the second part of fatigue life, that involving propagation of cracks and delaminations up the final failure of the joint. In the case of 0° interface, the cracks propagated mainly at the adhesive-adherend interface [1]. The presence of 45° layer complicates significantly the damage pattern: once spread over the entire joint width, the nucleated cracks grow propagating at the adhesive-adherend interface as well as inside the adherends, in the layers nearest to the bonded zone, following multiple and/or inter/intralaminar delamination paths, independently from the stacking sequence of the adherends. Representative examples are shown in Figs 8a and 8b for $[45/0_2]_s$ joints.

Table 1. Fraction of fatigue life to crack initiation for several joint configurations

Lay-up	Corner geometry	N_i/N_f range
$[45/0_2]_s$	Square edge	0.2-0.4
$[45/0_2]_s$	Fillet	0.6-0.9
$[45_2/0]_s$	Square edge	0.1-0.4
$[45_2/0]_s$	Fillet	0.25-0.8
$[0]_6$, ref. [1]	Square edge	0.2-0.7
$[0]_6$, ref. [1]	Fillet	0.25-0.75

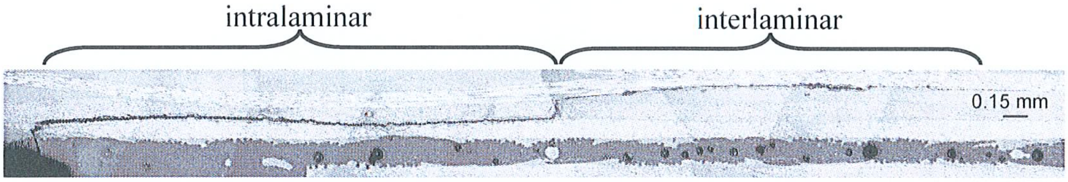

Figure 8a: Crack initiation and intralaminar/interlaminar crack path in a fillet joint (lay-up $[45/0_2]_s$, w=20 mm, σ_{max}=100 MPa, N_f=1163120 cycles).

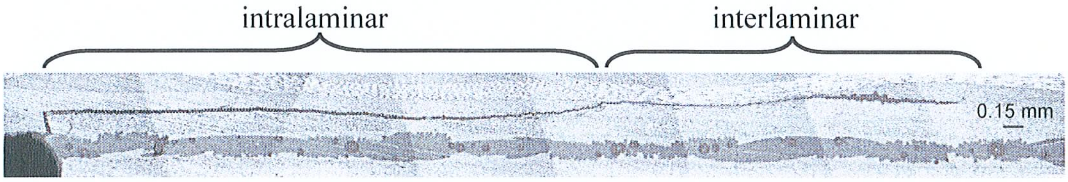

Figure 8b. Crack initiation and intralaminar/interlaminar crack path in a square edge joint (lay-up $[45/0_2]_s$; w=20 mm, σ_{max}=95 MPa, N_f=78209 cycles).

The more complex damage pattern resulted in a significant increase in the resistance to crack propagation, quantified by the comparison of the Paris curves for joints with 45° and 0° interface, presented in ref. [6]. Further clarifications on damage patterns can be obtained from the fractographic analysis of failure surface. Figure 9 shows an example of SEM observations, after failures over the bonded area. The relevant edge view taken few cycles prior to failure is reported for comparison.

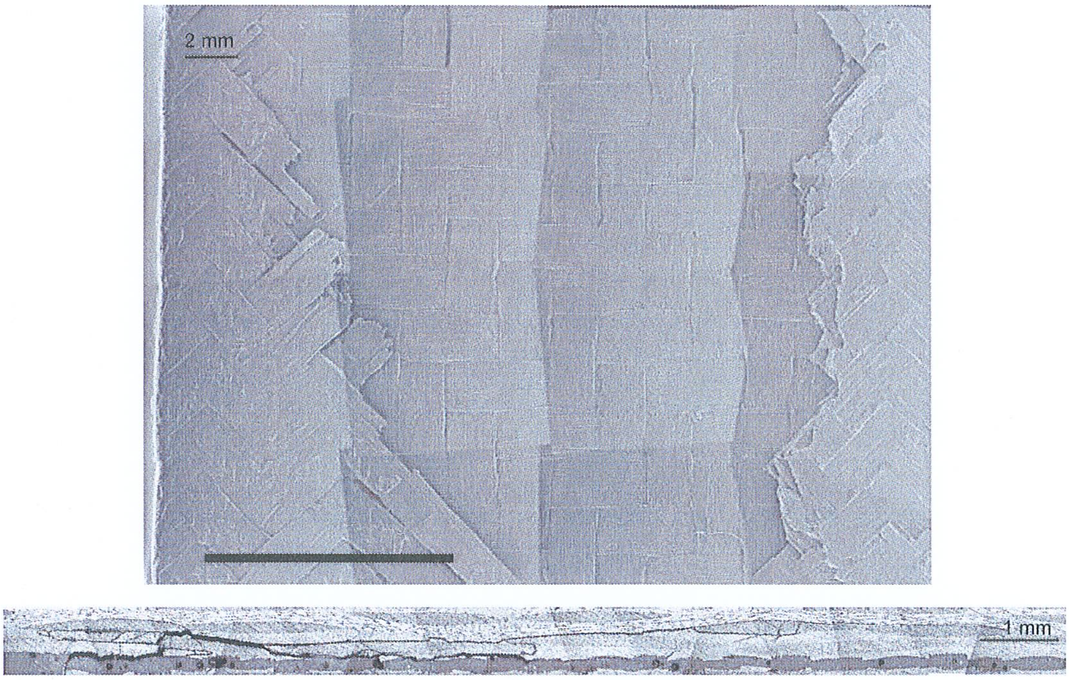

Figure 9. Fracture surface morphology and edge view for a fillet joint (lay-up $[45/0_2]_s$, w=40mm , σ_{max}=180MPa, N_f=63735), black bar indicates the position of the edge view.

The intralaminar evolution of the delamination can be observed: in the central part of Fig. 9 the 0° oriented layer is visible; this means that part of the external ply oriented at 45° was removed and probably remained on the other half of the joint, as one can guess from the edge view reported in the same figure.

CONCLUSIONS

Damage evolution in composite bonded joints under fatigue loading was investigated by using optical and SEM microscopy. The influence of different stacking sequence, geometry corner and overlap length on the evolution of damage mechanisms was analysed. Moreover the effectiveness of the optical microscopy technique to analyse the damage evolution was investigated.

The main conclusions are as follows:

- In terms of stress-life data, the influence of stacking sequence and ply orientation at the interface is limited, even in comparison with previous data on all 0° adherend joints. Fillet corner geometry and a longer overlap result instead in improved fatigue strength.
- Damage evolution is characterised by a nucleation phase followed by the crack/delamination growth up the final failure.
- The combined presence of a 45° oriented layer at the adhesive-adherend interface and a fillet corner geometry delays the crack nucleation with respect to the square edge configuration.
- The presence of a 45° layer interface complicates significantly the damage evolution with respect the 0° layer interface. After nucleation, cracks and delaminations propagate at the adhesive-adherend interface or following interlaminar and/or intralaminar paths. As a result, the resistance to crack propagation is increased.
- The use of microscopic observations of the damage on the polished edges of the joints turned out suitable to provide information representative of the damage evolution over the entire joint width.
- The complexity of the damage evolution and the long time required for an accurate optical observations for the assessment of the crack growth suggest the need for an alternative approach for the damage and crack length monitoring. As a possible solution, an engineering stiffness-based approach for the crack length measurement has been presented by the authors (see reference [7]).

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