# FATIGUE DAMAGE EVALUATION IN MULTIFASTENED CFRP JOINTS

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ABSTRACT

Fatigue damage in CFRP douple lap joints under constant amplitude load has been evaluated using a computer controlled servohydraulic test machine. The evaluation criterion was: - To define a damage parameter; To measure this parameter (taking into account that it is connected to two coexisting phenomena: the degradation of the mechanical connection and the structural degradation of the material); - To follow the variations of the measured parameter due to the fatigue.

KEYWORDS

Mechanical connection; CFRP joints; fatigue damage propagation; graphite epoxy laminate; hysteresis loop control.

## INTRODUCTION

Fatigue damage evaluation, necessary to predict service behaviour of whatever structural component under variable amplitude loads, is still an unsolved engineering problem, due to the difficulties of understanding the complex alteration and breaking up phenomena in the materials with increasing load cycles. If this problem is realy true for a metallic, simple shape component, like a simply notched or unnotched specimen, it is much more serious for bolted joints, with complete load transfer, and non metallic materials, i.e. graphite-epoxy composites, as evaluated here.
In fact, fatigue degradation in mechanical joints, made by composite laminates, starts with a slippage between the faying surfaces, with subsequent alteration in these surfaces and in bolt clamping forces; later, local high strains arise in the material, bearing increase in the holes where the clearance is lower, until the material delaminates and fibres break. The superimposition of the two phenomena: the degradation of the mechanical connection of the joint and the structural alteration of the laminate, makes it difficult to quantify the damage due to each single phenomenon, despite the fact that the former

prevails over the latter in the beginning of the test, and vice versa at the end. Moreover, the casual distribution of the clearances between holes and bolts justifies the statistical approach, that makes it necessary to test a high number of specimen . Any way , the knowledge of the values of the single clearance can help to interpret the meaning of the variability from specimen to specimen of the fatigue behaviour, under the same loads, test frequency and cycle number.
The technical literature on this subject is not very large (Agarwal, 1979; Castellano and co-workers , 1980; Hart Smith, 1980; Schutz, 1978), despite the extensive investigation over these years (Amijima, 1982; Chi-Hung Shen and Springer, 1977; Garbo and Ogonowski, 1979; Reifsnider, 1976; Whitney and Kim, 1977) of the graphite-epoxy fatigue behaviour (in terms of: material fatigue strength, specimen geometry, environmental and test conditions).
In the meantime the technical interest about the joints of carbon fiber rinforced plastics (CFRP) is increased considerably, expecially in the aeronautic field, due to the possibility to substitute the traditional materials with carbon fiber composites in the secondary structures and later on in the primaries.

## TEST SPECIMENS

The joint considered here is a double lap, with CRES hi loks (HL 18-6-8) in two rows (Fig. 1). The hi lok have protruding heads, and a notched collar, to apply a well defined tightening torque. In the collar there is a washer, in order to limit the damage on the surface of the laminate, and to increase the

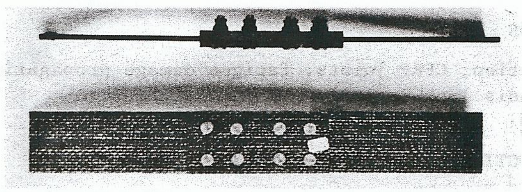

Fig. 1. The double lap joint tested

fatigue strength. The specimens were cut from a graphite-epoxy laminate, with the following stacking sequence:

$$((0,90)/90/0_2/\pm45/0/\pm45/0/(\pm45))_S.$$

The holes were drilled using a jig to control the tolerances, with the pieces in the assembly position. The pneumatic drill had a "house made" tool (D'Apuzzo, 1976). Before the assembly, the fabrication defects were controlled by ultrasonic inspection; the main design and production parameters, that may influence the fatigue strength, were evaluated. These parameters are: 1) hole diameters; 2) delaminations; 3) hole perpendicularity (measured randomly); 4) thickness and width of the joints; 5) hi lok diameters; 6) hi lok taper (measured randomly); 7) hi lok bearing; 8) clamping torque (measured randomly). For each hole, two perpendicular diameters were measured with a micrometer gauge. The delamination due to drilling (Fig. 2) were measured on the external



rows with an optical microscope with a 0.05 mm resolution. The delamination limits are: 0.10 mm minimum, 0.466 average, 2.3 maximum. The hole perpendicularity deviation is much lower than 2°. The thickness and the width of the joints were measured on the line of the external rows of the holes with a vernier gauge. Also for hi loks, as for the holes, the deviations from the nominal diameter were measured with electronic equipment connected to a universal measuring machine. The measured taper was unsatisfactory, and this can be considered to have a detrimental effect on the fatigue behaviour of the joint. The

Fig. 2. The delamination due to the drilling

shank bearing, even low , may be important for the connection of the holes. The clamping torque values, measured with a torquemeter randomly, were in the range of 25÷35 in·lb, as declared by the supplier. All the data on the specimen geometry, even though very close to each other, were always different in all the specimens, and then a big scatter may be expected in the static and fatigue tests. The detailed knowledge of this data can help very much in the evaluation of the results, even though a correlation between the test result and the measured parameters must be made statistically.

## DAMAGE PARAMETERS

Before the start of the assembled specimen tests, the damage must be defined and the parameters for the damage measurement during the fatigue loads application must be identified.
In a notched or unnotched graphite-epoxy specimen, the damage may identified as the delamination that always grows during the load application, until the fiber breakage endangers the static strength (De Iorio and Mignosi, 1983).
In the joint, the mechanical damage occurs before the delaminations from the beginning of the test and there is a little slippage between the joint parts, that increases with the number of cycles. If the load level is higher the slippage rate increases. When the slippage reaches the value of the minimum clearance between the holes, the hi lok involved works in shear, rather then in tension, causing bearing failure on the load side of the hole. It is the same for the other holes as load transfer occurs. In the joint, the load transfer is not the same at the beginning and at the end of the test. In the beginning the hi lok works in tension, each one giving a contribution to the load

transfer, proportional to the applied clamping torque; at the end the same hi loks work almost only in shear. The phenomenon is most critical if the initial clearance is greater. In the middle phase, the hi loks work in a mixed way: in tension and shear. It follows that the laminate damage is different going from a delamination (until the hi loks work in tension and if the loads are high enough, for a long time) to an excessive strain in the bearing area (when the hi loks work in shear). In these conditions, it is a problem to choose a damage parameter able to interpret the complex phenomenon, with sensitivity not only for the geometric and structural differences, but also for the damage due to the fatigue loads.

In a previous work, relative to simply notched specimens (De Iorio, Mignosi and Schiavone, 1983) we spoke about the opportunity of assuming the residual strain as a damage parameter. In the present case it seems better to consider other parameters, instead of the residual strain, which is difficult to interpret for the joints. Initially, the parameter used was the "stiffness", measured before, during and after the test; after that the "damping" was used, also measured before, during and after the test; at the end the "load-strain cycle" was chosen outputted at regular time intervals during computer controlled tests.

## TESTS AND RESULTS

In order to run the tests, the specimens were assembled and the clearance between the hole and the shank were measured. The minimum clearance in the external rows and the average clearance in the first and in the last row were measured, this because during tests the specimens always broke in an external row. In a group of specimens, the stiffness was evaluated before the fatigue test looking at the slope of first straight segment of the load-strain curve, recorded by a universal test machine. The damping coefficient was also measured on the specimens subjected to forced flexural oscillations. The measured values for the specimens were plotted versus the cycle number, showing that the two parameters follow a different law. Therefore was decided to record during fatigue tests the hysteresis loop in order to evaluate both the elastic modulus and the damping coefficient. The hysteresis loop area, A, proportional to the dissipated energy per cycle, $E_d$, is shown in Table 1 together with the total strain, $\varepsilon_t$, and the damping factor, $\eta$, defined as the ratio of the dissipated energy to the maximum elastic strain energy, $E_e$, times $2\pi$, at some partial durations, n, for two specimens under fatigue load level S = 1500 daN.

*TABLE 1 Some Parameters of the Hysteresis Loop During the Fatigue Tests*

| n (cycles) | n/N (%) | $\varepsilon_t$ | A [mm²] | $E_d$ [daN/mm] | $E_e$ | $\eta$ (%) |
|---|---|---|---|---|---|---|
| Specimen II-F-2 ; | N (fatigue life) = 152090 cycles | | | | | |
| 4 000 | 2.6 | .64 | 475 | 237 | 4.80 | 7.8 |
| 8 000 | 5.3 | .69 | 465 | 232 | 5.17 | 7.1 |
| 12 000 | 7.9 | .72 | 455 | 227 | 5.40 | 6.7 |
| 16 000 | 10.5 | .74 | 460 | 230 | 5.55 | 6.6 |
| 20 000 | 13.1 | .73 | 435 | 217 | 5.47 | 6.3 |
| 24 000 | 15.8 | .76 | 450 | 225 | 5.70 | 6.3 |



*continued*

| n (cycles) | n/N (%) | $\varepsilon_t$ | A [mm²] | $E_d$ [daN/mm] | $E_e$ | $\eta$ (%) |
|---|---|---|---|---|---|---|
| Specimen II-H -3 ; | N (fatigue life) = 160 970 | | | | | |
| 4 200 | 2.6 | .108 | 700 | 371 | 9.72 | 6.1 |
| 6 000 | 3.7 | .111 | 680 | 360 | 9.99 | 5.7 |
| 8 000 | 5.0 | .114 | 665 | 352 | 10.26 | 5.5 |
| 11 000 | 6.8 | .122 | 635 | 336 | 10.98 | 4.9 |
| 30 000 | 18.6 | .123 | 610 | 305 | 11.07 | 4.4 |
| 35 000 | 21.7 | .125 | 620 | 310 | 11.25 | 4.4 |
| 40 000 | 24.8 | .127 | 580 | 290 | 11.43 | 4.0 |
| 45 000 | 28.0 | .124 | 550 | 275 | 11.16 | 3.9 |

Furthermore, increasing the cycle number, changes the shape of the hysteresis loop (Fig. 3), due to the deterioration of the mechanical coupling between the lap and overlap during the fatigue. This circumstance encouraged us to continue to investigate by means of the hysteresis loop in order to better understand the meaning of the cycle shape, and to establish a correlation, if possible, with the geometric and load parameters.

At present, a computer program has been written to control the fatigue machine in running tests and to plot the hysteresis loop each 1000 cycles. The results

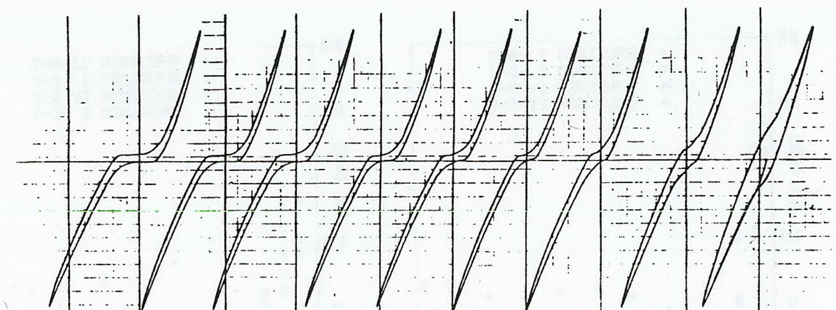

Fig. 3. The hysteresis loop changes during the fatigue

are in Figs. 4 ÷ 6 ; it can be seen that the total cycle area (the central cycle area is related to the slipping phase between the overlapping parts of the joints), the force that causes the slippage, and, at last, the length of the central zone of the cycle due to the recovery of the clearances between holes and hi loks, change during the joint fatigue.

## CONCLUSIONS

The damage mechanism of the CFRP joints is very complex, but it is possible to follow its evolution by measuring the global effects with one of the following parameters: - The total stiffness and/or the damping of the joint evaluated with the hysteresis loop, recorded by a computer controlled test machine during the fatigue test; - That part of the area of hysteresis loop due to

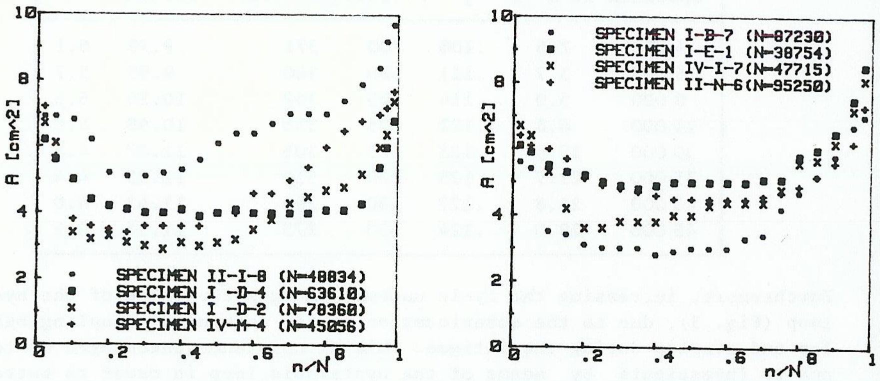


Fig. 4. The total cycle area variation during the fatigue.

the slippage, or the horizontal length of this loop. This length in fact increases regularly from beginning of the test, up to the falure, as well as the fatigue damage. A correlation can be established between the fatigue damage

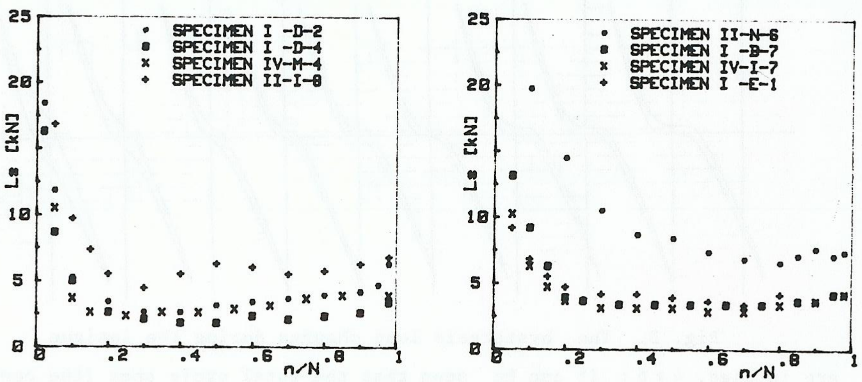


Fig. 5. The slippage load, $L_S$, variation during the fatigue.

and this length, normalized to the largest averaged clearances in the external rows. In this way the damage could be quantified just by means of the length parameter now defined. The length parameter measures the clearance recovery due to "the slippage force" decrease at beginning of the test, and to increase of the bearing.

The material delamination, that arise over of the 50% or 75% of the specimen life, has no easy correlation with the above defined parameters, but surely



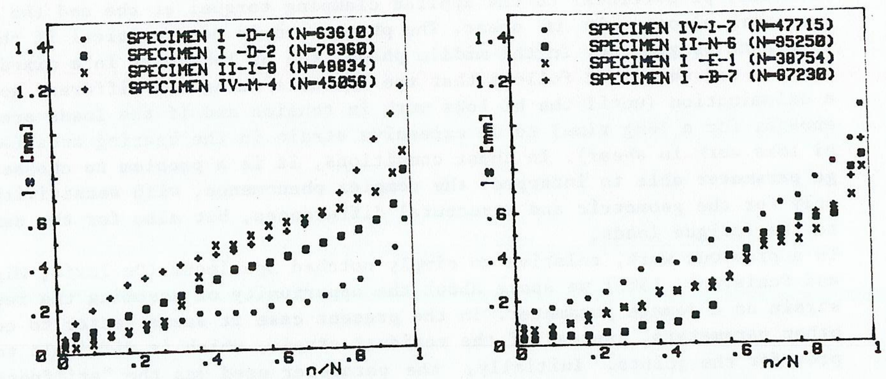


Fig. 6. The slippage length, $l_s$, variation during the fatigue.

influences their behaviour and value.

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