CRACK PROPAGATION ASSESSMENT IN COMPOSITE BONDED JOINTS

Marco Lusiani[1], Giovanni Meneghetti[1], Marino Quaresimin[2] and Mauro Ricotta[1]

[1]Dept. of Mechanical Engineering, University of Padova, via Venezia, 1 35131 Padova-Italy
[2]Dept. of Management and Engineering, University of Padova, Str. S. Nicola, 3, 36100 Vicenza-Italy
marino.quaresimin@unipd.it

ABSTRACT

In the present paper the problem of crack propagation assessment of single lap bonded joints in composite material has been analysed. Experimental tests on carbon fabric-epoxy 1.6-mm-thick single lap specimens were conduced in tension-to-tension fatigue. Crack length was monitored by means of an optical microscope at scheduled number of cycles during each test. Different over lap lengths (20 mm and 40 mm), configurations of corner geometry (square edge or spew fillet) and stacking sequence ($[45/0_2]_s$ and $[45_2/0]_s$) were taken into account. Being a scientific definition of the crack initiation and propagation phases beyond our scope, it has been assumed that initiation phase ceases when a technical crack having size equal to 0.3 mm is observed at the adherend-adhesive interface. Since the tested joint geometry induces combined opening and sliding modes at the crack tip, experimental crack growth rates have been summarized in terms of an equivalent value of the Strain Energy Release Rates (SERR). However, crack monitoring by means of manual optical microscope inspection resulted to be a very time –consuming procedure: then it is proposed to adopt the specimen's stiffness loss, which is easier to be automatically monitored during the fatigue test, as an indicator of the evolution of cracks' length. Calibration by means of a so-called master curve enabled us to convert the stiffness values into corresponding crack lengths and finally crack growth rates, which resulted consistent with the experimental ones. The existence of a unique Paris-like curve correlating crack growth rates in terms of SERR, to be used for engineering crack propagation assessments, has been finally checked.

1. INTRODUCTION

The results of several experimental researches available in the open literature [1-4] indicate that both crack initiation and crack propagation phases involve a significant fraction of the total fatigue life in bonded joints made of composite materials. In the present paper single lap bonded joints characterised by 45°-oriented ply at the adhesive-adherend interface were subjected to tension-tension fatigue tests and fatigue damage was monitored by means of an optical microscope. A detailed presentation of results of experimental observation is reported in refs. [4-5]. Anyway, periodical test interruption for crack length measurement is time consuming. Then in order to simplify the experimental test procedure, automatic stiffness data acquisition was adopted during the fatigue tests in order to calibrate a so-called 'master curve', which enables one to estimate the crack length at a given number of cycles from stiffness drop information. Being a scientific distinction between crack initiation and crack propagation phases beyond the scope of the present paper, crack propagation phase has been assumed as the fatigue life spent to spread cracks having minimum size equal to 0.3 mm and has been analysed both experimentally and numerically with the following aims:

- to present a synthesis of the experimental crack growth rates in terms of range of an equivalent formulation of the Strain Energy Release Rate (SERR) assumed as the damage parameter driving crack propagation in presence of both opening and sliding modes at the crack tip;
- to present an engineering method based on stiffness measurements during the fatigue tests, which simplifies the experimental procedure adopted to estimate the crack length;

- to validate the use of the SERR parameter combined with the proposed stiffness-based method to derive the Paris-like curves useful to assess crack propagation of components containing composite bonded joints.

2. EXPERIMENTS

Specimens are the same described in [4-5]. Single-lap joints having either fillet or square configuration were prepared from 1.6-mm-thick laminates made of toughened epoxy matrix ET442 T300 twill 2x2 carbon fabric (V_f 60%) bonded with 9323 B/A adhesive by 3M. Over lap lengths of 20 mm and 40 mm were considered, while the specimens' width was constant and equal to 24 mm. Single lap joints were fatigue tested on a MTS Minibionix servo-hydraulic testing device equipped with a 15 kN load cell. The nominal load ratio was set to 0.05 and the test frequency was kept in the range 5÷15 Hz. Periodical inspection of the specimens enabled us to measure the crack lengths of all four corners of the joint overlap by means of an optical microscope with magnification equal to 50x or 100x. A detailed analysis of fatigue damage evolution observed during experimental tests is reported in [4-5]. Here we recall only that very complicated crack paths including interface, interlaminar and intralaminar cracks and delaminations were observed. In order to propose an engineering model suitable for estimating crack propagation lives, the measured crack length *a* was the projection of the longest observed crack path onto the interface line. Figures 1 and 2 show some of the available experimental results collected from laboratory tests in terms of number of cycles up to crack initiation and final failure, respectively, versus the applied maximum nominal stress (defined as maximum applied force divided by the cross section area of one of the adherends). The number of cycles for crack initiation N_i was assumed as that required to observe the first 0.3-mm-long crack, defined "technical" crack, at one of the four locations of the joint as illustrated in figure 3. It has already been highlighted in the introduction that both crack initiation and crack propagation significantly contribute to the total fatigue life of the joint. In particular, for the joints under investigation here, the ratio between fatigue life spent for crack propagation and the total fatigue life is on the range of 0.1÷0.4 for square edge joints and 0.25÷0.9 for spew fillet joints. Similar results were found for $[0]_6$ joints, where the fraction of life to crack initiation was in the range of 0.2÷0.75, independently from the corner geometry.

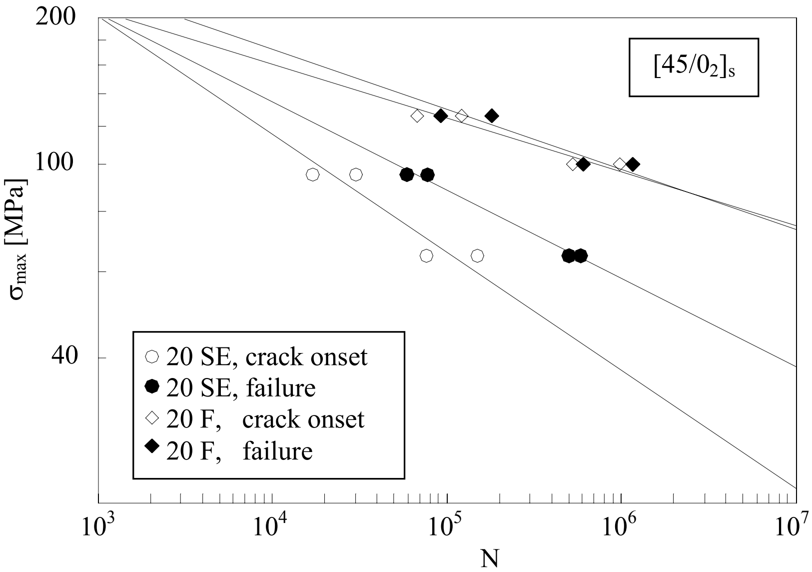


Figure 1: Fatigue data for $[45/0_2]_s$ single lap bonded joints with 20 mm overlap length.

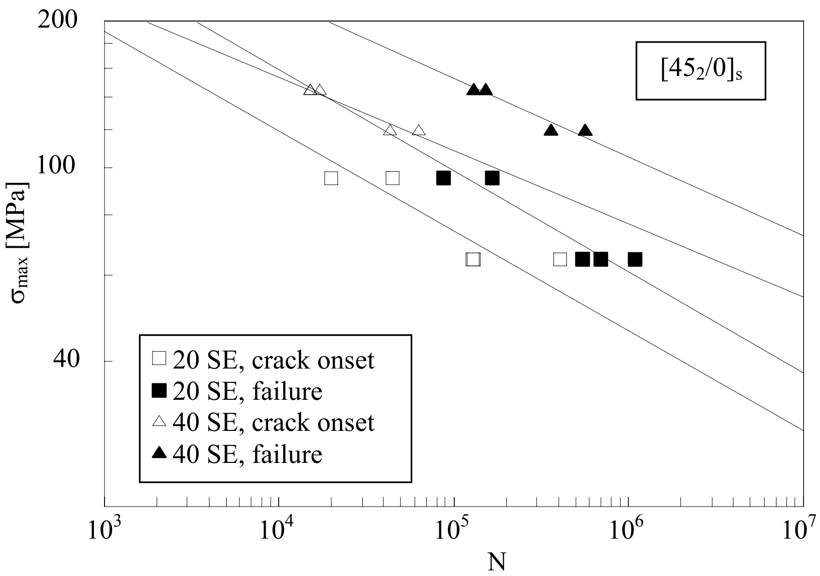


Figure 2: Fatigue data for $[45_2/0]_s$ single lap bonded with square edge corner

In the following, available crack growth rate data measured on the joints during experimental testing are summarised in terms of the range of variation of the Strain Energy Release Rate. The basic assumption is that a suitable definition of SERR as calculated from a non-linear elastic finite element analysis [6] is able to rationalise the observed crack propagation rates in presence of mixed I+II (opening and sliding) modes at the crack tip.
Then an engineering method able to estimate the crack length is presented which simplifies the time-consuming block tests required by the direct observation and measurement of the crack length by means of an optical microscope.

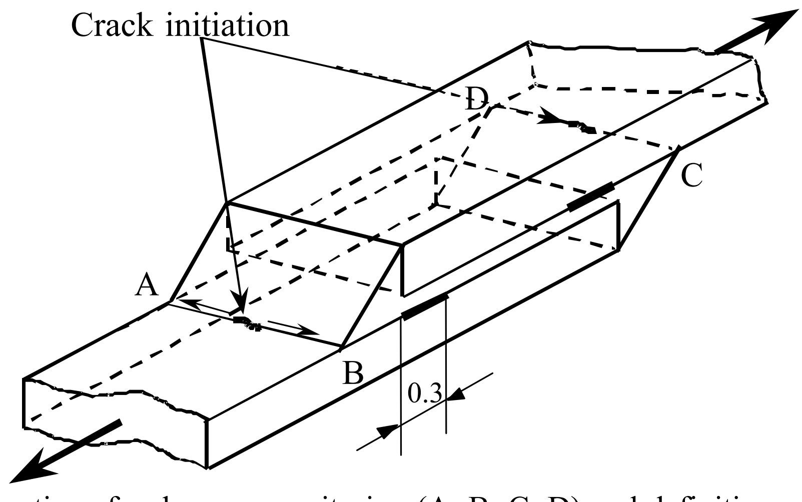


Figure 3: Locations for damage monitoring (A, B, C, D) and definition of the 0.3 mm 'technical crack', which separates initiation from propagation life.

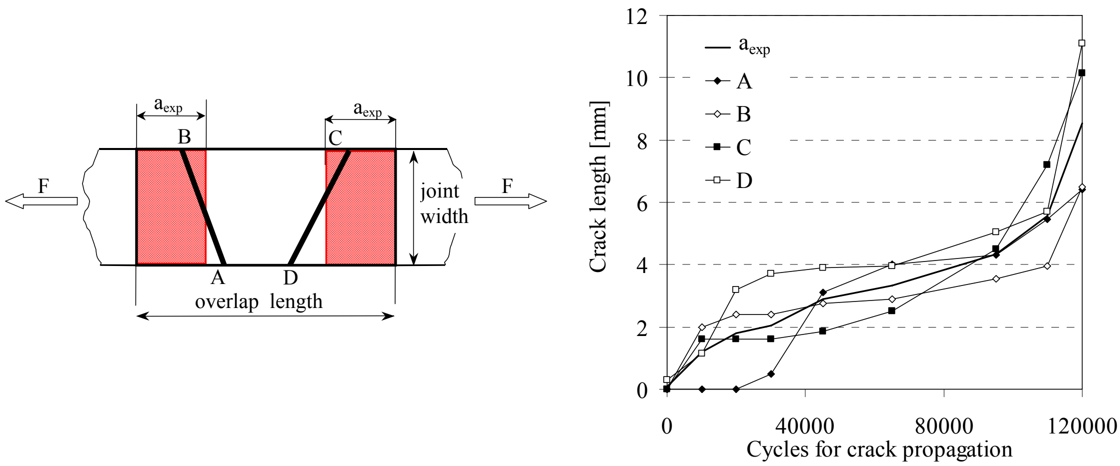
3. SUMMARY OF CRACK GROWTH DATA IN TERMS OF STRAIN ENERGY RELEASE RATE

A Paris-like law is assumed to be valid for summarising crack growth data:

$$\frac{da}{dN} = D(\Delta G)^m \qquad (1)$$

being D and m material parameters to be determined by best fitting of experimental results. For the sake of simplicity, crack growth was modelled to occur symmetrically through the over-lap area by means of straight crack fronts. The length a_{exp} of the two symmetric cracks was then assumed as the mean length of the four measurements available at each block of cycles scheduled during the experimental tests. Definition of a_{exp} is shown in figure 4a while comparison between observed crack lengths at the four locations and assumed mean value a_{exp} is shown by figure 4b.

Curves a_{exp} vs N of the type shown by figure 4b were interpolated by means of piece-wise 2^{nd} order polynomials in order to calculate crack growth rates da_{exp}/dN according to ASTM 647-00 standard.



(a) (b)

Figure 4: Model assumed for describing crack propagation phase where a_{exp} is the mean value of the four cracks (a), and comparison between the observed crack lengths evolution at the four corners and the assumed mean value a_{exp} (lay-up $[45_2/0]_s$; w=20 mm; square edge corner; σ_{max}=95 MPa; N_p=120262 cycles N_f=165262 cycles).

SERR values for various crack lengths were calculated by means of non linear, large displacements finite element analyses in Ansys® 11.0 assuming linear elastic behaviour of the materials. Details about the adopted simulation technique and the post-processing of numerical results are reported elsewhere [6]. In brief, mode I and mode II components of the SERR, G_I and G_{II}, were calculated by using the Virtual Crack Closure Technique [7], modified as suggested in [8] to account for the actual deformed shape of the joints. Particular attention has been paid to the possible inconsistencies associated to the analysis of the SERR for a crack propagation at the interface of a bi-material. A minimum element size of one fifth of the adhesive thickness was adopted, large enough to obtain mesh-insensitive values of the SERR components [6].

Figure 5 plots the crack propagation rate as a function of the range of variation (defined as maximum value minus minimum value) of the equivalent SERR, ΔG_{eqv}, already presented in [6] and defined as:

$$G_{eqv}(a) = G_I(a) + \frac{G_{II}(a)}{G_I(a) + G_{II}(a)} G_{II}(a) \qquad (2)$$

Figure 5 reports also the Paris curve (1) fitted on the available data: in particular the mean regression line and the 10% and 90% probability lines obtained by assuming a log-normal distribution of the crack growth rates for a given range of SERR are reported.

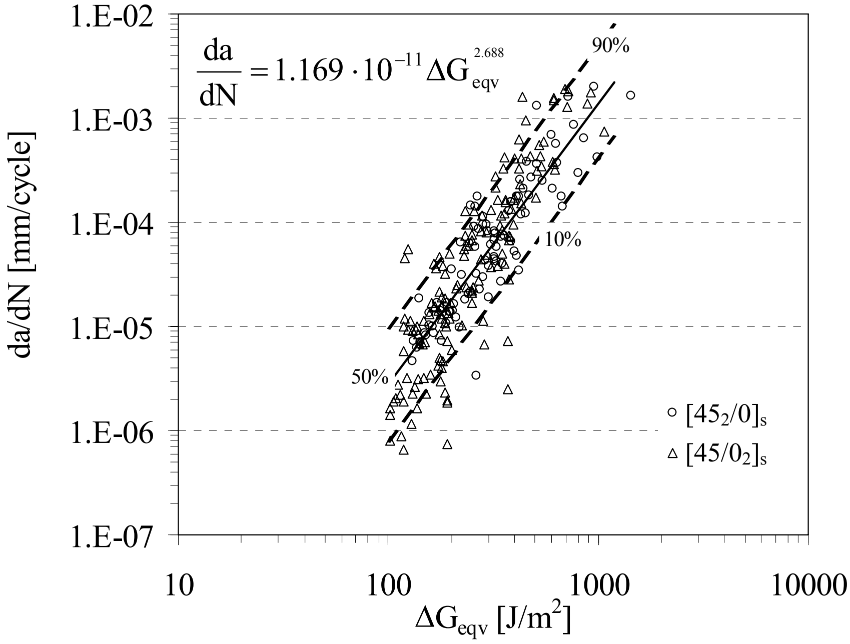


Figure 5: Summary of the crack propagation data.

4. AN ENGINEERING METHOD TO ESTIMATE THE CRACK LENGTH

It has been aforementioned that direct experimental observation of crack length evolution at the four location of the joint by means of periodical specimen's inspection is very time-consuming. Then an engineering method hereafter called 'simplified experimental' was adopted in order to estimate with an alternative procedure the mean crack length a_{exp}.

The stiffness decrease during an experimental tests is much easier and faster to be monitored by simply processing the signals detected by the displacement and load transducers of the testing machine. In particular the stiffness K is defined as the ratio between the range of the applied force (which is a constant during the fatigue test) and the range of the measured displacement (which increases as cracks propagate). Then the stiffness has been assumed as a parameter useful to estimate the mean crack length evolution, according also to previous works available in the literature [9-10]. Figure 6 reports the normalised stiffness decrease (defined as observed stiffness K at a given number of cycles divided by the stiffness K_i measured at the beginning of the fatigue test) versus the normalised crack length a/w for most of the tested specimens.

Despite the scatter shown by the experimental data, a linear rule was assumed to interpolate all the data. More precisely, three trends were considered: the mean stiffness loss evolution, a 35% steeper curve and a 35% flatter curve. The latter curves enabled us to encompass the scatter of all the experimental data. The three curves can be considered as 'master curves'.

The need for considering the stiffer and the more compliant sample comes to the fact that in the expected application of the method, one measures the K-a (stiffness-crack length) relationship for one or two samples and then use those curves as "master".

Hence it is important to assess the sensitivity of the method to the intrinsic variation of the K-a relationship.

Then by recording the normalised stiffness drop K/K_i vs number of cycles N during a new experimental fatigue test and using one of the so-called 'master curves' K/K_i vs a/w, one could estimate the mean crack length evolution a vs N. Here we call a_K the mean crack length calculated by using the mean master curve; $a_{K,+35\%}$ the mean crack length calculated by using the 35% flatter master curve and $a_{K,-35\%}$ the mean crack length calculated by using the 35% steeper master curve.

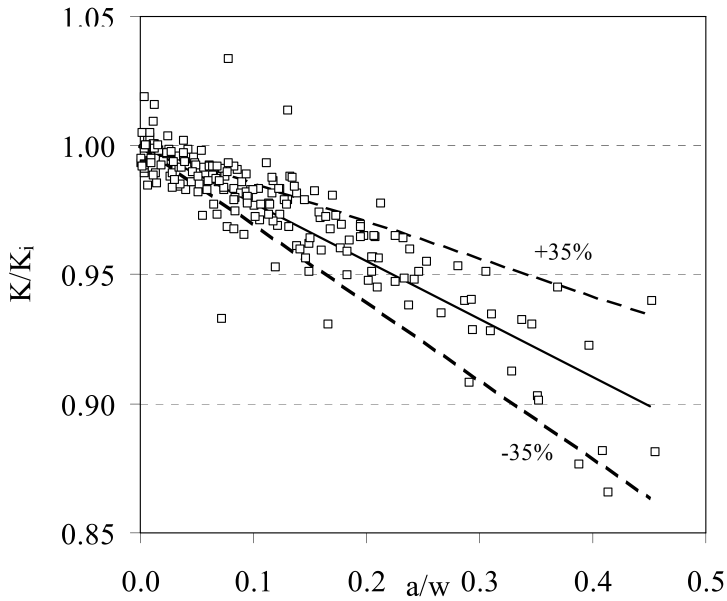


Figure 6: decrease of the normalised stiffness vs the normalised crack length for all the available experimental data.

Figure 7a shows a representative comparison between the mean crack evolution found experimentally (a_{exp}) or estimated from the stiffness drop recorded during the experimental test (a_K). A similar comparison valid for crack growth rates is reported in figure 7b. Despite small differences shown by the two curves, comparable trends can be appreciated. Consequences in fatigue life estimations will be shown later on.

Finally figure 8 reports the Paris curves fitted on experimental results shown in previous figure 5 compared with those calculated by using the three master curves shown in figure 6, respectively. Despite the scatter seen in figure 6 when reporting the stiffness loss observed for the tested specimens, the three Paris-like curves (a_K, $a_{K,+35\%}$, $a_{K,-35\%}$) are close to the mean experimental one (a_{exp}).

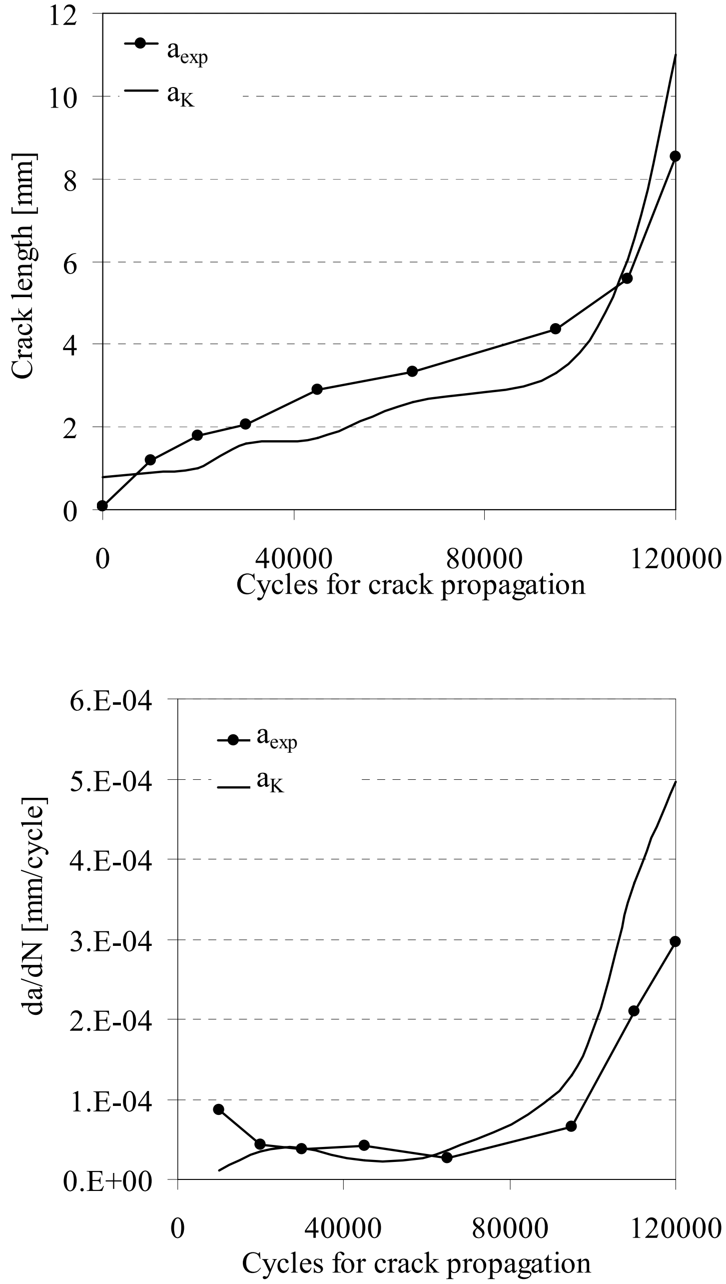


Figure 7a and b: comparison between mean crack evolution (a) and crack propagation rates (b) derived from direct experimental measurements (a_{exp}) or from the mean stiffness loss recorded during the experimental test (a_K) (lay-up $[45_2/0]_s$; w=20 mm; SE; σ_{max}=95 MPa; N_f=165262 cycles).

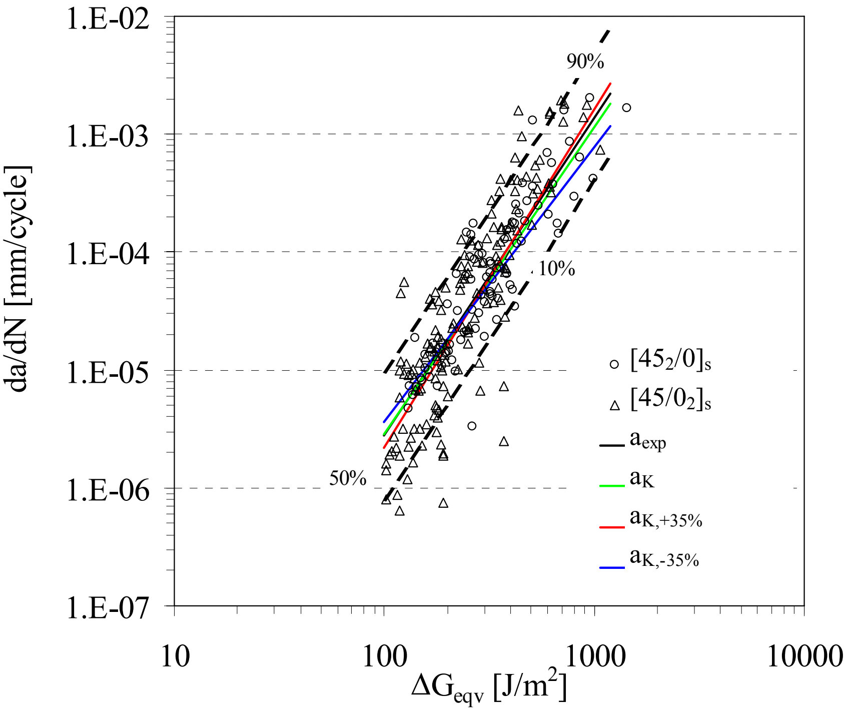


Figure 8: comparison between Paris curves fitted on experimental data (a_{exp}) and generated by using the three master curves reported in figure 6.

5. VALIDATION

In a previous paper [4] it has already demonstrated that the range of the equivalent SERR rationalises crack growth data generated by testing $[45/0_2]_s$ and $[45_2/0]_s$ bonded joints, where the applied external load produces mixed I+II (opening and sliding) modes at the crack tip. Then it is expected that the mean fatigue behaviour of any of the tested series can be successfully estimated by integration of the mean Paris law fitted on experimental data and shown by figure 8 (a_{exp}). In the present section the effect of the deviation of the Paris curves generated by means of the master stiffness curves from the experimental one is evaluated (see again figure 8). In view of this, crack propagation lives for all tested specimens were calculated by integrating the stiffness-based Paris laws. The initial and final crack lengths were a_i=0.3mm while a_f was calculated by equating the equivalent SERR to the mode critical value G_{Ic} = 900 J/m^2, obtained form experimental measurements. Results are reported in figures 9 and 10 for the best and worst prediction, respectively, where the experimental results and scatter bands calculated for 10% and 90% survival probabilities are compared with estimations. Each adopted model refers to one Paris-like curve reported in figure 8.

It is seen that even in the worst case the estimations based on models a_{exp}, a_K, $a_{K,+35\%}$, $a_{K,-35\%}$ are in good agreement with the experimental scatter band, at least in the medium and high cycle fatigue regime.

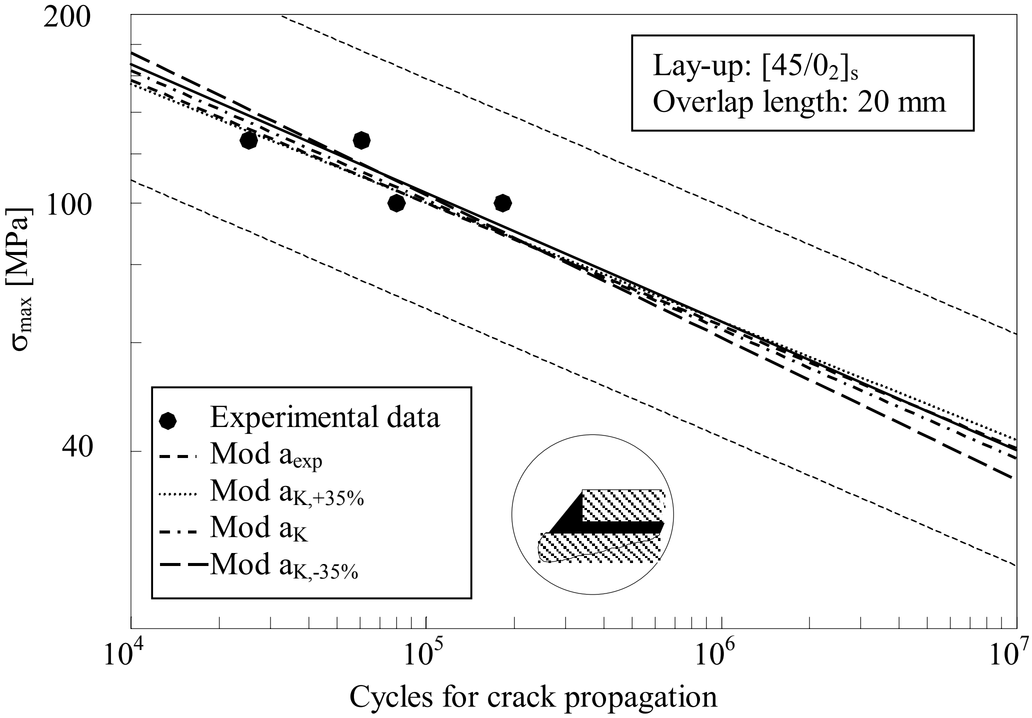


Figure 9: comparison between experimental data and model predictions (best observed case).

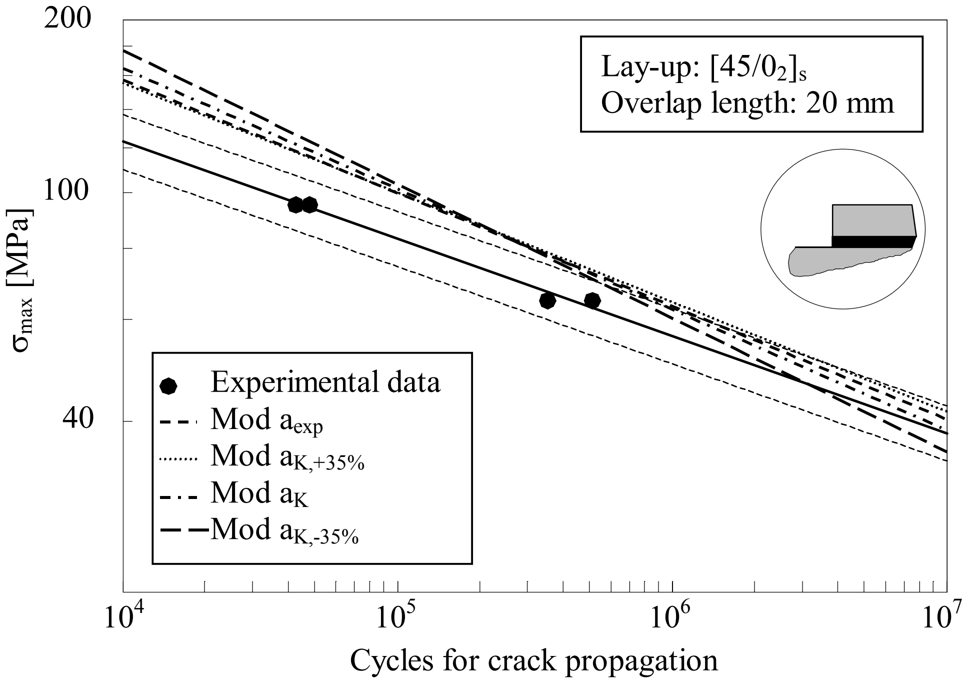


Figure 10: comparison between experimental data and model predictions (worst observed case).

6. CONCLUSIONS

Fatigue tests were carried out on single lap bonded joints made of composite materials with crack length monitored by means of an optical microscope and stiffness decrease monitored by means of the signals coming from the load and displacement transducers of the testing machine. Due to specimens' geometry, cracks are subjected to opening and sliding modes during propagation.

Crack growth rates as measured by means of the optical microscope can be rationalized in terms of range of variation of the equivalent Strain Energy Release Rate.

By observing cracks propagating in some specimens, it is possible to calibrate a master curve, which provides the crack length versus the normalised stiffness loss, and then use this curve to estimate the crack length evolution in other specimens by simply monitoring their stiffness loss. In principle just one specimen can be used to calibrate the master curve. By calculating crack growth rates from the stiffness-based estimations, results consistent with the experimental ones have been obtained.

Then it seems that the use of the range of the SERR combined with the proposed stiffness-based method to estimate the crack length of tested specimens is a procedure suitable for deriving a Paris-like curve to be used in crack propagation assessment of components containing bonded joints.

REFERENCES

1- Ishii K., Imanaka M., Nakayama H., Kodama H., "Evaluation of the fatigue strength of adhesively bonded CFRP/metal single and single-step double-lap joints", *Composites Science and Technology*, 1999, 59:1675-1683.
2- Abdel Wahab M M., Ashcroft I A., Crocombe A D., Shaw S J., "Prediction of fatigue thresholds in adhesively bonded joints using damage mechanics and fracture mechanics", *Journal of Adhesion Science and Technology*, 15 (2001), 763-781.
3- Quaresimin M. and Ricotta M., "Fatigue behaviour and damage evolution of single lap bonded joints in composite material", *Composite Science and Technology*, 2006; 66/2:176-187.
4- Meneghetti G., Quaresimin M., Ricotta M., "Influence of the interface ply orientation on the fatigue behaviour of bonded joints in composite materials", *accepted for publication in International of Fatigue*.
5- Lusiani M., Meneghetti G., Quaresimin M., Ricotta M., "Damage evolution in composite bonded joints under fatigue loading", Proceedings of ECCM 13, 13th European Conference on Composite Materials June 2-5 2008, Stockholm, Sweden.
6- Quaresimin M. and Ricotta M., "Stress intensity factors and strain energy release rates in single lap bonded joints in composite materials", *Composites Science and Technology*, 2006, 66:647-656.
7- Rybicki E.F., Kanninem M.F. "A finite element calculation of stress intensity factors by a modified crack closure integral". *Engineering Fracture Mechanics*, 1977, 9:931–8.
8- Krueger R, Minguet P.J., O Brien T.K., "Implementation of interlaminar fracture mechanics in design: an overview". In: Proceedings of ICCM14, 14–18 July 2003, San Diego, USA.
9- Krenk S., Jönsson J., Hansen L.P., "Fatigue analysis and testing of adhesive joints", *Engineering Fracture Mechanics*, 1996; 53(6):859-872.
10- Pirondi A., Nicoletto G., "Fatigue crack nucleation and propagation in bonded joints", Proceedings of ICF11, International Conference on Fracture, March 20-25 2005, Torino, Italy.