# ASSESSMENT OF DELAMINATION CRACK GROWTH RATE OF CO-CURED STEPPED LAP JOINTS IN COMPOSITE MATERIALS

Mauro Ricotta[a], Marino Quaresimin[b], Michele Ferrari[a]

[a] *Department of Industrial Engineering, University of Padova, Via Venezia, 1, Padova*
[b] *Department of Management Engineering, University of Padova, Stradella San Nicola, 3, Vicenza, Italy)*
**mauro.ricotta@unipd.it*

**Keywords:** co-cured joints, delamination, fatigue, Strain Energy Release Rate.

**Abstract**
*In this paper the fatigue behavior of co-cured stepped-lap joints in composite materials is discussed in terms of Strain Energy Release Rate. Previous works showed that the fatigue life of those joints is characterized by an early nucleation phase of transversal matrix cracks followed by a propagation phase. In this paper 2D finite element models were developed and the mode I and mode II component of the SERR were calculated by using the Virtual Crack Closure Technique. It was found that the propagation phase is under mixed mode (mode I + mode II) loading with a mode I predominance. Therefore the range of the mode I SERR was adopted to define a suitable Paris-like curve able to rationalize in a single scatter band the Delamination Growth Rate data.*

## 1. Introduction

The fatigue life of co-cured stepped lap joints in composite material is characterized by an early nucleation phase, with the onset of transversal cracks in the zones where two plies are joined, followed by a propagation phase, characterized by the growth of delaminations at the layer's interface up to failure: the fatigue strength, therefore, is mainly controlled by the delamination growth [1,2]. In [2] it was shown that the traditional approach for life prediction, based on S-N curves, turned out to be useful to highlight the influence of the main design parameters, as the ply overlap length, $w$, and the stacking sequence. In fact the fatigue strength, calculated in terms of nominal tensile stress referred to the laminate cross section, was found to increase with $w$. However, in the scenario described above, the S-N curve based approach does not seem to have the general validity needed for the fatigue design of these joints, since it does not incorporate the main damage mechanism.
In literature several methods are available for delamination growth assessment and they can be divided in four classes [3]: Stress/strain based-, Fracture mechanics based-, Cohesive zone model based- and Extended finite element based-methods. In the past the present authors have developed a Fracture Mechanics based-tool for the assessment of fatigue life of *single lap bonded* joints in composite materials, based on the actual damage mechanics, by distinguishing an initiation phase and a propagation phase on the basis of the experimental detection of a small technical crack [4,5]. The nucleation phase is described by using a generalised Stress Intensity Factor (SIF) approach, which rationalises the fatigue life to crack

initiation. The number of cycles expended for crack propagation is evaluated by the integration of a Paris-like power law, which relates the Strain Energy Release Rate (SERR) to the fatigue crack propagation rate. The parameters involved in the Paris model are determined from experiments.

As stated above concerning the *co-cured stepped lap* joints, the nucleation phase can be considered negligible with respect to the total fatigue life, at least in the preliminary design of the joint. Consequently the number of cycles to failure can be assumed equal to the number of cycles spent in the propagation phase. Aim of this paper is therefore to present the results of several two-dimensional Finite Element (FE) analyses carried out for evaluating SERR in co-cured stepped lap joints subjected to tension-tension loading. According to the actual fatigue damage mechanics, the FE model was characterised by the presence of transversal cracks where two plies are joined and the propagation was assumed to be at layer’s interface. The numerical results illustrated here will be integrated with the experimental results already presented in [2 for the definition of a suitable Paris-like curve able to rationalize the Fatigue Delamination Growth Rate (FDGR).

## 2. Experimental background: materials, geometry of joints, test procedures and damage evolution.

The geometry of the joints tested in [1,2] is sketched in Figure 1, where it is also reported the configuration chosen for simulating the connection. The stepped lap joints were obtained from laminate panels manufactured starting from a SEAL - TEXIPREG® CC206 - ET442 prepreg (twill 2x2 T300 carbon fibre fabric, CIBA 5021 toughened epoxy matrix, $V_f$ =60%). $[0]_8$ panels were produced by vacuum bag autoclave moulding and three ply overlap lengths (w=3, 5, and 8 mm) were considered. All the specimens were tested in tension at room temperature on a servo-hydraulic MTS 809 machine with 10/100 kN load cells. The fatigue tests were carried out under load control, with a sinusoidal wave, nominal load ratio R=0.05 and a test frequency variable in the range of 10 o 15 Hz depending on lay-up and loading conditions. For the analysis of the fatigue damage evolution, the joints were subjected to constant amplitude blocks of loading up to failure; at the end of each block the damage evolution was analysed by means of microscopic observation of the polished edges of specimens and, in some cases, by ultrasonic C-scan [2]. It was found that the fatigue damage starts at very early fractions of fatigue life (5-10%) with the nucleation of transversal matrix cracks in the zones where two plies are joined (Figure 2). Then they propagate as delaminations at the layer’s interface up to a critical length (Figure 2). By comparing the microscopic observations of the polished edges with the ultrasonic C-scan results, it was pointed out that, in the case of *w=3 and 5 mm*, the delamination length measured by microscopic observations of polished edges is suitable to describe the damage evolution. On the contrary, in the case of *w=8 mm*, the results of microscopic observations were not in good agreement with the delamination measured by ultrasonic C-scan. In fact when the delamination length, detected on the edges, propagated very slowly, the damage increased mainly inside the joint. However, in [2] the *average delamination length*, calculated by averaging the delamination lengths propagating from the transversal matrix cracks, was defined as a mono-dimensional damage parameter able to describe and quantify the damage evolution in a stepped-lap joint under fatigue loading. Once the evolution of the delamination length during the fatigue life was available, it was possible to calculate the Fatigue Delamination Growth Rate as a function of both the number of cycles and the average delamination length.

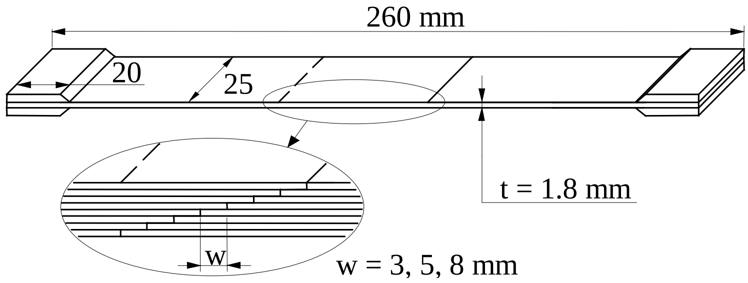


**Figure 1.** Geometry of co-cured stepped lap joint

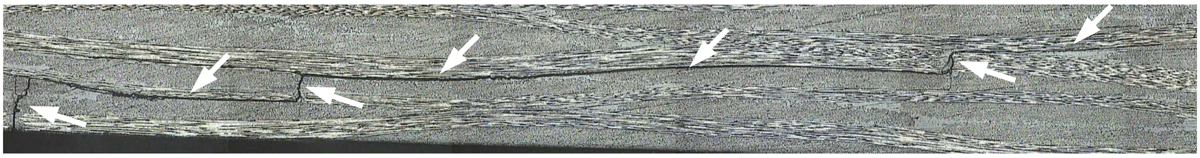

**Figure 2.** Transversal cracks and delamination in the first, second and third layer of a $[0]_8$ joint (overlap 3mm) loaded at 45% of $\sigma_{UTS}$ after 90% of its fatigue life; $N_f$=81600 cycles

## 3. Finite element model and numerical results

The geometry of the joints, the loading conditions and the assumption of a uniform front for the crack propagation [2] let us to consider the evaluation of the SERR as a 2D problem. The mode I and mode II components of the SERR, $G_I$ and $G_{II}$, were then calculated by using the Virtual Crack Closure Technique (VCCT) [6], modified as suggested in [7] to account for the actual deformed shape of the joints. 2D geometrically-non linear FE analyses were performed, by using the eight-nodes plane strain condition element (PLANE183) of Ansys® 14.0 commercial code.

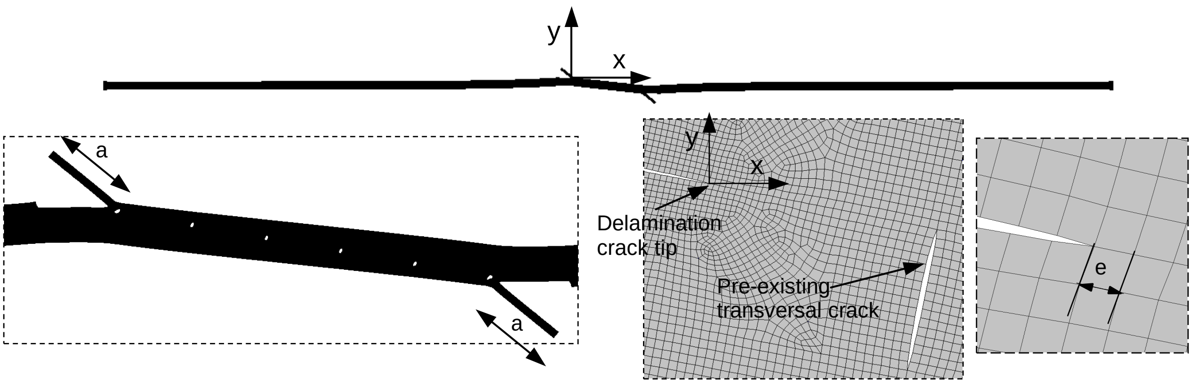


**Figure 3.** Deformed shape and details of the mesh at layer's interface for a model of the joint in the presence of a delamination and transversal crack. Two symmetric delaminations of equal length a were modeled

As required by VCCT, the region near the crack tip was modeled with regular shape elements of uniform size, as shown in Figure 3, by choosing the size of the smallest element, *e*, equal to 10 μm. Moreover, since the actual fatigue damage evolution was characterized by an early nucleation phase, with the onset of transversal cracks in the zones where two plies are joined [2], those cracks were introduced in the FE model, as shown in Figure 3. The delamination was modeled at the layer's interface. For a better simulation of the loading condition imposed during the experimental tests, the joints were entirely modeled and the boundary conditions were applied as follows: the displacement of the tab nodes at one end were restrained in X and Y direction, those at the other end were restrained in the Y direction only and in this position was applied a pressure in the X direction simulating the applied tensile force. Finally, the elastic material properties implemented in the model are summarized in Table 1 and the subscripts are in agreement with the coordinate system shown in Figure 3.

| $E_x$ [MPa] | $E_y$ [MPa] | $E_z$ [MPa] | $G_{xy}$ [MPa] | $G_{yz}$ [MPa] | $G_{xz}$ [MPa] | $\nu_{xy}$ | $\nu_{yz}$ | $\nu_{xz}$ |
|---|---|---|---|---|---|---|---|---|
| 58050 | 6000 | 58650 | 500 | 500 | 3300 | 0.27 | 0.27 | 0.06 |

**Table 1.** Material elastic properties adopted for FE analyses

Figure 4a and Figure 4b show the trends of mode I and mode II SERR components in joints with w=3,5 and 8 mm in the case of low and high stress level, respectively. The stress levels were selected from the fatigue curves presented in [2] in correspondence of medium (about 50,000 cycles) and long (about 1 million cycles) fatigue life. For an easier comparison of the results related to joints with different ply-overlap length, the SERR values are plotted as a function of the delamination length normalized with respect to the ply-overlap length. Concerning the low stress level, in spite of the different overlap length, the results present quite similar trends with a mode I predominance with respect to $G_{II}$ for a/w > 0.3. On the other hand, in the case of high stress level, $G_I$ is always higher than $G_{II}$ (see Figure 4b).

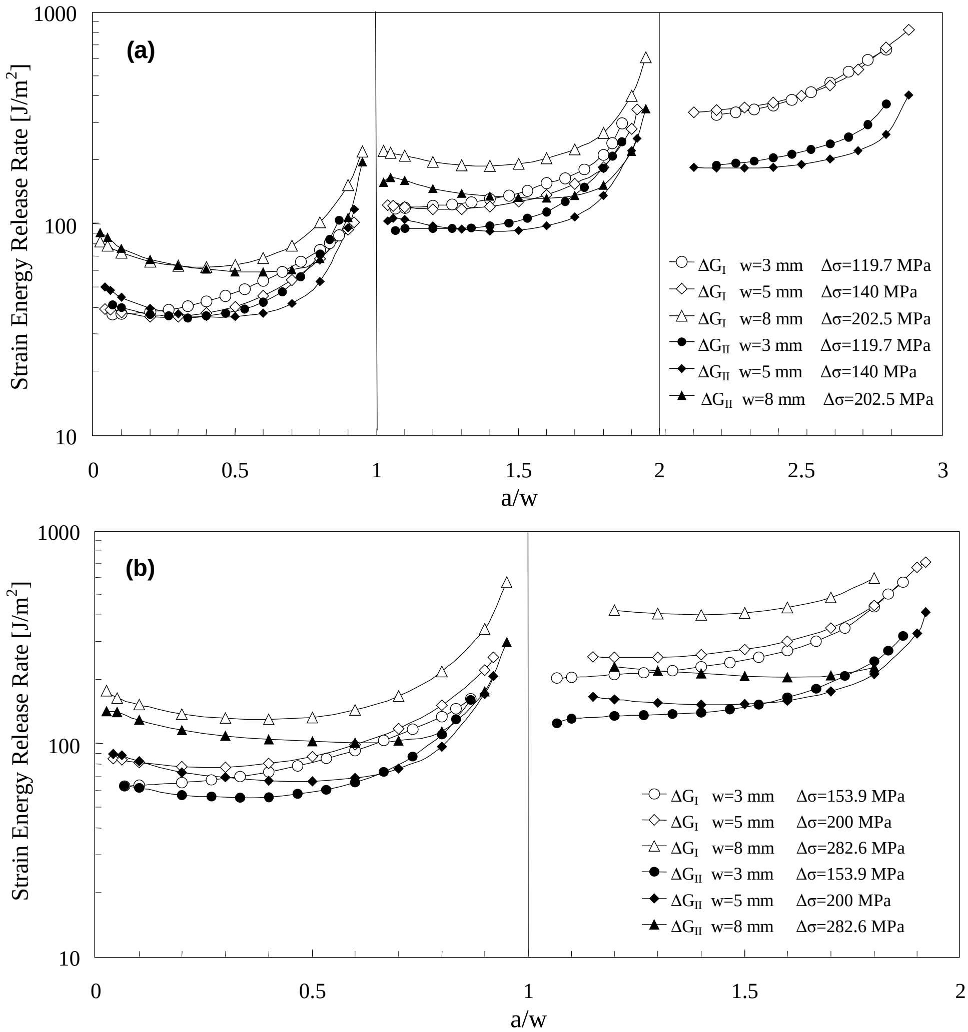


**Figure 4.** $G_I$ and $G_{II}$ vs the delamination length normalized with respect to the ply-overlap length: (a) low stress level; (b) high stress level

The mode I predominance is more evident by plotting the Mode-Mixity ratio MM (defined as $G_{II}/(G_I + G_{II})$) vs the normalized delamination length, as shown in Figure 5. It can be see that MM is lower than 0.55 with a continuous change in its value.

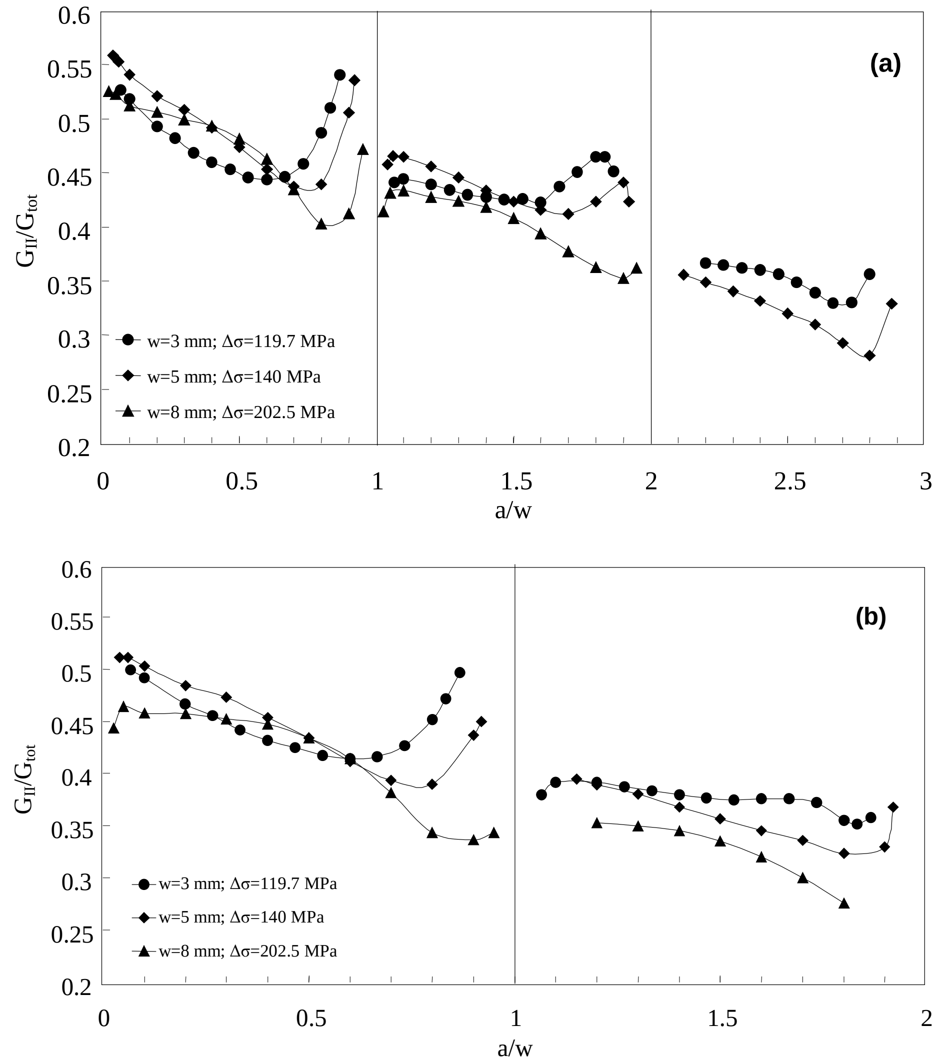


**Figure 5.** Mode-mixity ratio vs the normalized delamination length: (a) low stress level and (b) high stress level

## 4. Definition of a Paris-like curve

As stated in the previous section, FE analyses showed that delamination growth occurs under mode I predominance. In the case of *bonded joints*, it was found that when MM<0.5 the propagation phase can be rationalized by considering simply the range of $G_I$. According to [5], in this paper it was assumed that the $\Delta G_I$ is the driving force for the delamination growth also for co-cured stepped lap joints. Therefore the FDGR data can be rationalized by using a Paris-like law expressed in the form:

$$\frac{da}{dN} = D \cdot \left[\Delta G_I(a)\right]^n \tag{1}$$

where D and n are parameters that can be calculated by fitting the experimental data.

| | |
|---|---|
| 50% P.S. | $D=2.88\cdot10^{-9}$<br>$n=2.05$ |
| 90% P.S. | $D=1.63\cdot10^{-8}$<br>$n=2.05$ |

**Table 2.** Paris-like curve data calculated for different probability of survival (see Eq. (1)), valid for FDGR expressed in mm/cycle and SERR in J/m$^2$.

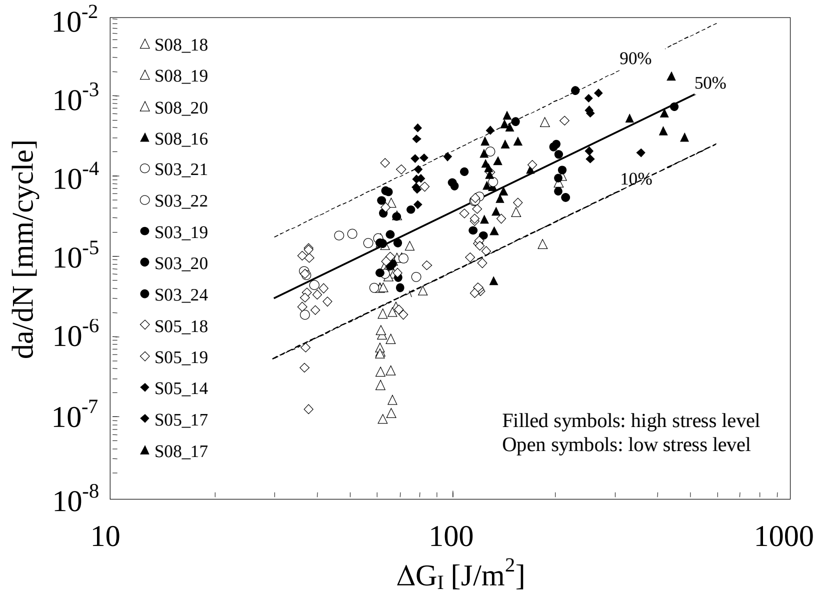


**Figure 6.** Fatigue delamination growth rate scatter band for all the joints tested (FDGR vs range of the mode I SERR, $\Delta G_I$)

Results are summarized in Table 2 and in Figure 6 where the relevant 10–90% probability of survival (P.S.) scatter band is also plotted. It is worth noting that the scatter band and D and n values were calculated by considering the experimental data having a delamination growth rate higher than $2\cdot10^{-6}$ mm/cycle. Figure 6 collects all the FDGR data available, which refer to joints with different ply-overlap length and applied stress level [2].

## 5. Conclusions

In this paper delamination growth of co-cured stepped lap joints in composite materials under tension-tension fatigue loading is investigated in terms of Strain Energy Release Rate and the results of several 2D finite element analyses carried out for evaluating SERR by using the Virtual Crack Closure Technique are presented. The 2D finite element model was developed taking into account the actual fatigue damage observed during the fatigue tests. Therefore transversal cracks were modelled in the zones where two plies are joined and the delamination was introduced at the layer's interface.

The SERR vs delamination length trends show that the delamination growth occurs under mixed-mode (mode I + mode II) conditions with a mode-mixity ratio continuously changing with the delamination length. Nevertheless it was found that the contribution of the mode I component is significantly more important than that of mode II. Consequently, according to a damage-based model developed by the authors for *bonded joints*, the Fatigue Delamination Growth Rate data, experimentally measured on *stepped lap joints* having different ply overlap length and fatigued at different stress amplitude, were successfully collected all together in a single Paris-like curve, which correlates the delamination growth rate with the mode I component of the SERR.

## References

[1] M. Quaresimin. The fatigue behaviour of joints in composite materials: a literature review and experimental investigation. *Proceedings of ICCM14*, 2003.
[2] M. Quaresimin and M. Ricotta. Delamination growth analysis of co-cured joints in composite materials. In *Proceedings of ICEM12*, 2004
[3] J.A. Pascoe, R.C. Alderliesten, R. Benedictus. Methods for the prediction of fatigue delamination growth in composites and adhesive bonds – A critical review. *Engineering Fracture Mechanics*, 112-113:72-96, 2013.
[4] M. Quaresimin and M. Ricotta. Life prediction of bonded joints in composite materials. *International Journal of Fatigue*, 28:1166-1176, 2006.
[5] P.A. Carraro, G. Meneghetti, M. Quaresimin, M. Ricotta. Crack propagation analysis in composite bonded joint under mixed-mode (I + II) fatigue loadings: A damage-based model, *Journal of Adhesion Science and Technology*, 2013, 13, 1393-1406.
[6] E.F. Rybicki and M.F. Kanninem. A finite element calculation of stress intensity factors by a modified crack closure integral. *Engineering Fracture Mechanics*, 9:931–8, 1977;
[7] R. Krueger, P.J. Minguet, T.K. O'Brien. Implementation of interlaminar fracture mechanics in design: an overview. In: *Proceedings of ICCM14*, 2003.