TRANSACTIONS OF THE INSTITUTE OF AVIATION
No. 4 (245), pp. 227-238, Warsaw 2016
DOI: 10.5604/05096669.1226897

ISSN 0509-6669
eISSN 2300-5408

NUMERICAL MODELLING OF FATIGUE DELAMINATION GROWTH IN LAMINATES UNDER MODE I LOADING CONDITIONS USING VCCT

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Abstract

The article presents a numerical method of modelling the fatigue growth of delaminations in laminates with the use of Virtual Crack Closure Technique. The principle of the method is an algorithm based on the user subroutines of finite element method software MSC MARC. It uses experimentally determined Paris' law to calculate the number of load cycles needed for specified length of delamination propagation. As a result, the relationship between delamination growth and number of fatigue cycles can be established.

The 2D numerical model of a double cantilever beam made of carbon epoxy laminate was created and the calculations were conducted for two sets of input values. They corresponded to the specimens that were tested experimentally. This allowed for the comparison of the results and verification of the numerical method against experimental investigations.

Keywords: delamination, fatigue crack propagation, FEM, VCCT.

1. INTRODUCTION

1.1. Problem statement

Typical composite structures used in aerospace industry are made of several layer of reinforcement impregnated with resin. Such structures display relatively low resistance to interlaminar fracture and delamination growth due to variation in the reinforcement and stratified structure. Delaminations are areas inside the laminated structure where separation between two layers occurred. They can be caused by the faulty fabrication process, being a manufacturing flaw, or can be a result of a low energy impact during service. They can significantly deteriorate the strength of the composite structure. Once a delamination is detected the decision must be made whether the defected structural element is still safe for use or should be repaired or replaced. This decision depends on the safety of the delamination – its potential for growth under expected loading conditions. Helpful tools in assessing it are numerical methods. The basic analysis should be conducted for quasi-static loading conditions to check whether an instant growth is to be expected. However, if the energy release rate is below critical values the effects of the cyclic loading should be taken into account before claiming the composite structure safe.

The article presents a numerical method of modelling the fatigue growth of delaminations in laminates with the use of Virtual Crack Closure Technique. The principle of the method is an algorithm based on the user subroutines of finite element method software MSC MARC. It uses experimentally determined Paris' law to calculate the number of load cycles needed for specified length of delamination propagation. As a result, the relationship between delamination growth and number of fatigue cycles can be established. The presented method was used to analyze delamination growth in the two-dimensional model of a double cantilever beam, which allowed for comparison of the results with the experimentally obtained data.

1.2. Literature review

Delamination growth, with the focus on buckling of delaminations, has been an object of attention for at least three decades. Early models represented through-the-width delaminations in plates of infinite width (Chai at al., 1981; Kachanov, 1988). However, analytical expressions were difficult in applications in the analysis of delamination growth. Much better use was found for the numerical models based on the finite elements method. Virtual Crack Closure Technique (VCCT) was used to determine the Strain Energy Release Rate (SERR) along the delamination front and divide it into G_I, G_{II} and G_{III} parts corresponding to single loading modes (Whitcomb, 1990). These approaches however did not cover the simulation of delamination growth, not to mention the cyclic loading conditions. Such issues have been studied only in the more recent papers. An extensive description of the VCCT used for this purpose was given by Krueger (2002). He also presented work concerning application of the VCCT in analyzing fatigue delamination growth (Krueger, 2010). Other FE based methods are also used in analyses of delamination growth, including the effect of cyclic loading. They mostly take advantage of cohesive elements (Harper & Hallet, 2010; Roe & Siegmund, 2003; Turon at al., 2007). Numerical simulations of fatigue growth verified against experimental data were presented in the last years. They were based on cohesive zone approach (Landry & LaPlante, 2012) or Energy Release Rates evaluation (Riccio, Ronza, Sellitto, & Scaramuzzino, 2015).

2. ALGORITHM OF DELAMINATION PROPAGATION

The presented algorithm of delamination propagation is based on Virtual Crack Closure Technique, which allows for obtaining the Strain Energy Release Rate (SERR) values in the finite elements mesh nodes that form the delamination front. The calculated values of G_I, G_{II}, and G_{III}, corresponding to I, II and III cracking modes, can be then used to determine the magnitude of delamination growth. In case of cyclic loading Paris law, represented by Eq. 1, is used.

$$\frac{da}{dN} = C \cdot G_{\max}^{m} \tag{1}$$

where: da/dN – delamination growth rate; G_{max} – maximum SERR in cycle; C, m – experimentally determined parameters.

It allows for calculating the number of cycles needed for given amount of delamination growth for specified SERR value and stress ratio R. The scheme of the algorithm used in numerical analyses in presented in Fig. 1. The base is the concept of crack growth in the vicinity of the finite element mesh node in the delamination front. It is assumed that the connection between the mesh representing the delaminating layer and the mesh forming the base composite is broken when the amount of crack growth equals the length of the element's edge. In the proposed procedure the algorithm calculates the number of load cycles needed for breaking the connection in the node in the delamination front. The result becomes the number of loading cycles realized in the current step of analysis.

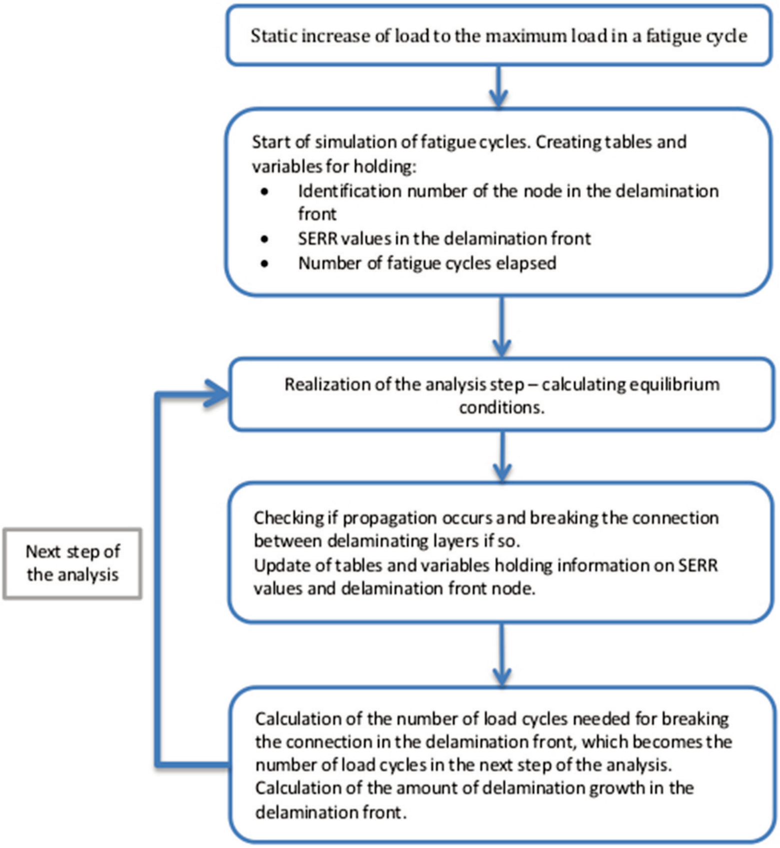

Fig. 1. Scheme of the algorithm of fatigue delamination propagation [own elaboration]

3. NUMERICAL MODEL

3.1. Modeled structure

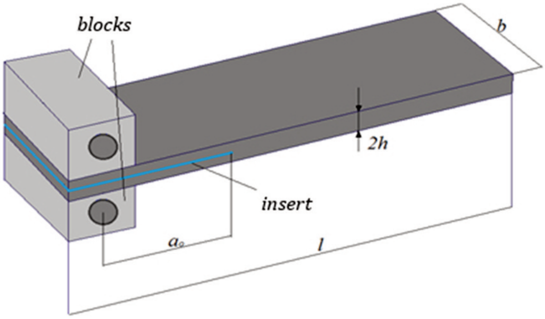

Fig. 2. Schematic view of the DCB specimen (own elaboration)

The object of the analysis was a model of double cantilever beam (DCB) specimen – a laminated plate with the through-the-thickness delamination on one of the edges. The schematic view of the model is presented in Fig. 2. During the experimental test the gap is opened by metal blocks attached to the specimen, based on the guidelines provided in the ASTM D6115-97 (ASTM International, 2011). The numerical analyses were conducted for two sets of input data concerning the specimen geometry and Paris law used, denoted as DCB-1 and DCB-2. The two cases corresponded to experimental data for two specimens, LK14-9-9 and LK14-9-7, included in the report by Czajkowska (2014).

The specimens were made of layers of unidirectional carbon-epoxy composite. The material properties were taken from the experimental data provided by the manufacturer and are listed in table 1 along with the dimensions of the specimens.

Tab. 1. Geometry and material properties

Material properties			
Young Modulus in the longitudinal direction		E_1 [MPa]	120 000
Young Modulus in the transverse direction		E_2 [MPa]	8 759
Poisson's Ratio		v_{12} [-]	0.288
Kirchhoff's Modulus		G_{12} [MPa]	4 270
Geometry			
Dimension		**DCB-1**	**DCB-2**
Length	l [mm]	150	150
Width	b [mm]	20.63	20.72
Thickness	$2h$ [mm]	1.620	1.638
Initial delamination length	$a0$ [mm]	53	53

3.2. Finite element mesh

The numerical model was a two-dimensional one. The finite element mesh was homogenous and composed of linear four-node *Plane Strain* elements (denoted in MSC MARC nomenclature as Type 115 elements), which are adequate for the analysis of the structures with infinite thickness. It was assumed as good enough approximation of a real specimen, which however neglects the effect of the delamination front curving during propagation. The element edge length was 0.25 mm and the delamination front for the two-dimensional case was reduced to just one node. MSC MARC does not require any additional elements for application of VCCT.

3.3. Boundary conditions

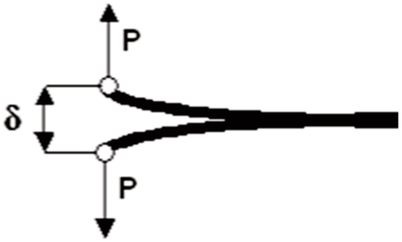

Fig. 3. Schematic view of the loading conditions [Czajkowska, 2014]

The boundary conditions of the model reflected the actual set-up of the experimental test. A schematic view of the specimen loading is shown in the Fig. 3. The load is applied as the opening δ caused by the force P. In the experiment the force is carried through metal blocks and the other end is free. In the numerical model the load in the form of displacement was applied in the center of gravity of the blocks and the free end was fixed. It resulted from the need of preventing the rigid body movement in the FEM analysis.

In the actual test sinusoidal fatigue cycles with the stress ratio $R = 0.1$ are applied to the specimen in the form of displacement. In the numerical analysis the cyclic loading is modeled with a static one with maximum value form a single cycle.

In both analyzed cases the experimentally determined Paris law was used in the form presented in Eq. 1. The relationships used are shown in the Eq. 2 for the DCB-1 case and Eq. 3 for the DCB-2 case.

$$\frac{da}{dN}\left[\frac{mm}{cycle}\right] = 2.572 \cdot 10^{12} \cdot \left(G_{\max}\left[\frac{N}{mm}\right]\right)^{13.828} \tag{2}$$

$$\frac{da}{dN}\left[\frac{mm}{cycle}\right] = 1.905 \cdot 10^{21} \cdot \left(G_{\max}\left[\frac{N}{mm}\right]\right)^{20,500} \tag{3}$$

4. RESULTS

Two numerical analyses were conducted, for DCB-1 and DCB-2 initial data. The number of cycles in numerical calculations covered the whole range of the experimental data, which were 1.5M cycles for DCB-1 and 2.5M for DCB-2. For each case several relationships were obtained: delamination length vs. number of cycles, maximum force in cycle vs. number of cycles, SERR vs. number of cycles, SERR vs. delamination length and delamination growth rate vs. SERR (Paris law). The delamination growth rate was calculated according to Eq. 4, where *a* and *N* are delamination length and number of cycles in the *i* step of analysis.

$$\left(\frac{da}{dN}\right)_i = \frac{a_{i+1} - a_i}{N_{i+1} - N_i} \tag{4}$$

The results of the numerical analyses compared with the experimental data for the DCB-1 case are presented in fig. 4 to 8 and for the DCB-2 case in fig. 9 to 13. Fig. 4 and 9 show the increase of delamination length during the fatigue cycling. In the experiment the delamination length was calculated based on the established relationship between the delamination length and the compliance of the specimen. Fig. 5 and 10 present the plots of force loading the specimen (measured by the load cell in the experiment) vs. number of fatigue cycles. Fig. 6 and 11 show the change of SERR during the fatigue cycling and fig. 7 and 12 show the dependency of SERR from the length of the delamination. For the experimental data the SERR values were calculated according to MBT method from ASTM D6115-97 (ASTM International, 2011). The comparison of the relationships between the delamination growth rate *da/dN* and SERR value obtained from calculations and experimental data is shown in fig. 8 and 13.

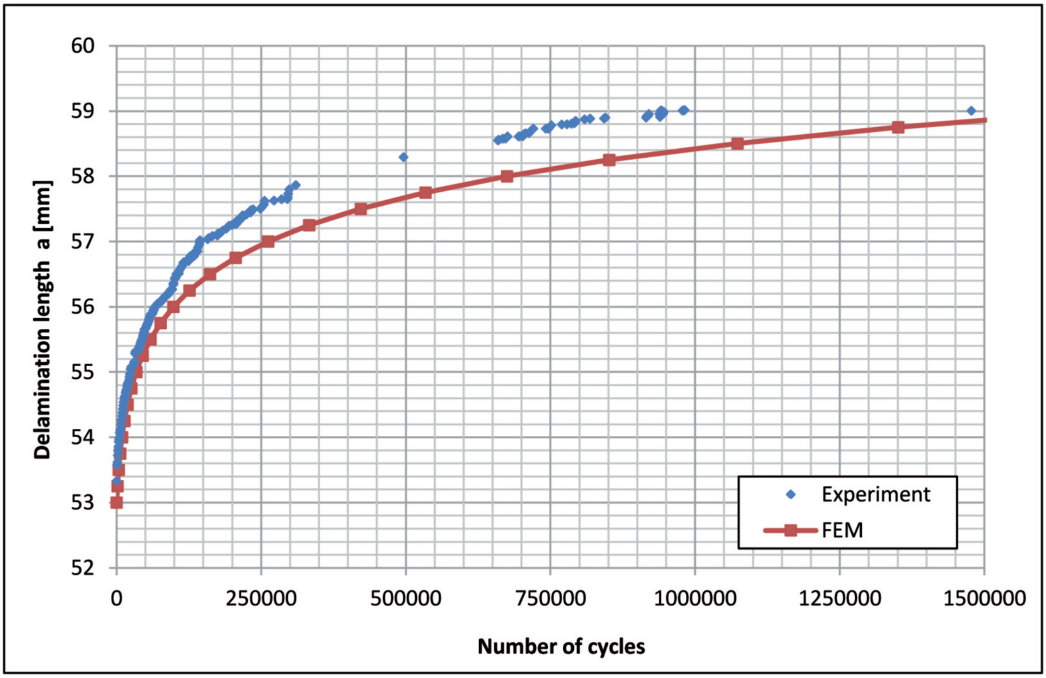

Fig. 4. Comparison of DCB-1 results and experimental data – delamination length vs. number of cycles [own elaboration]

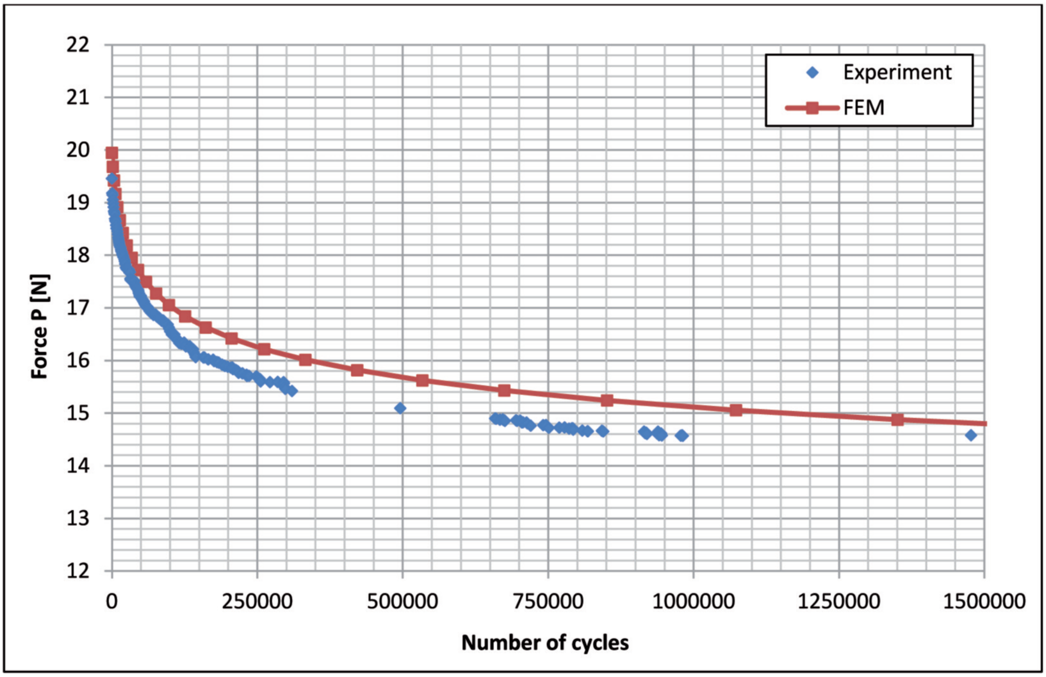

Fig. 5. Comparison of DCB-1 results and experimental data – maximum force in cycle vs. number of cycles [own elaboration]

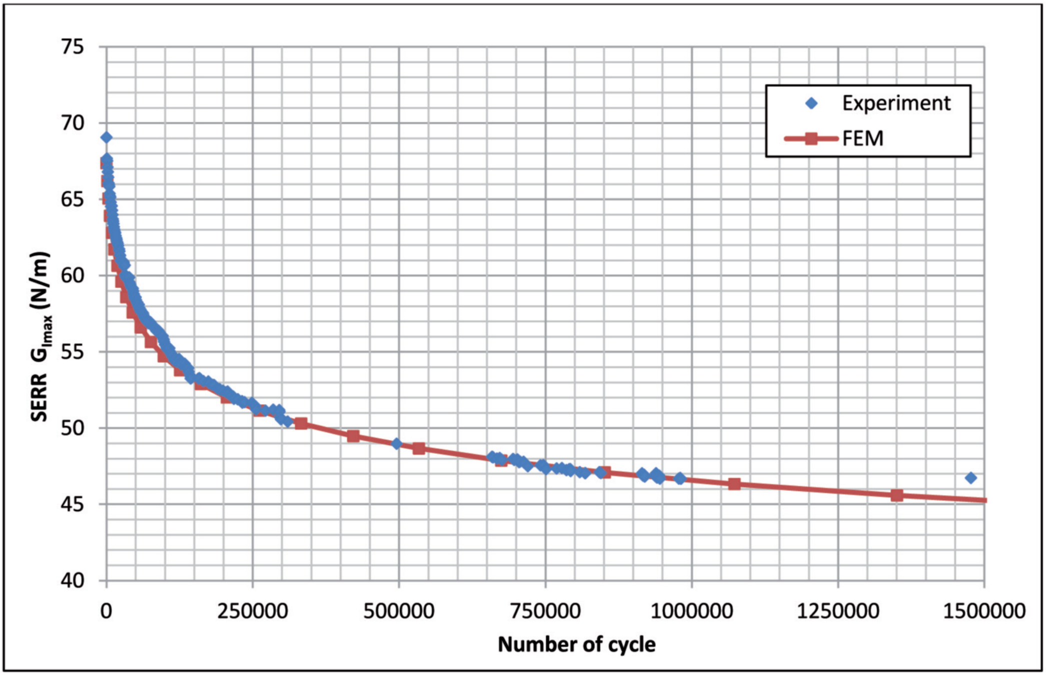

Fig. 6. Comparison of DCB-1 results and experimental data – maximum SERR in cycle vs. number of cycles [own elaboration]

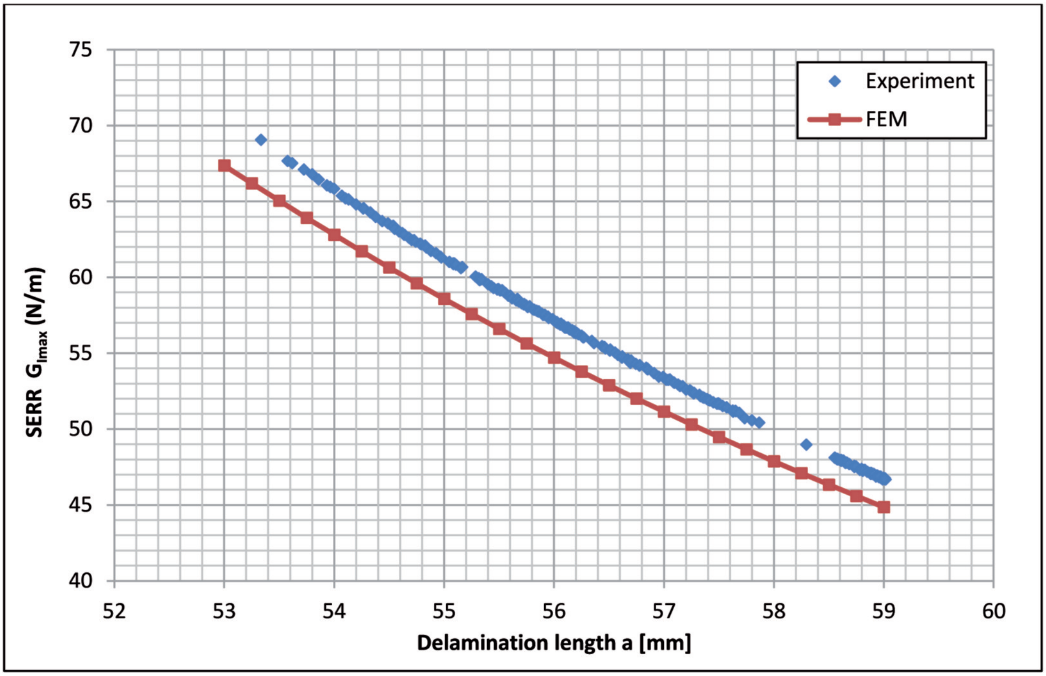

Fig. 7. Comparison of DCB-1 results and experimental data – maximum SERR in cycle vs. delamination length [own elaboration]

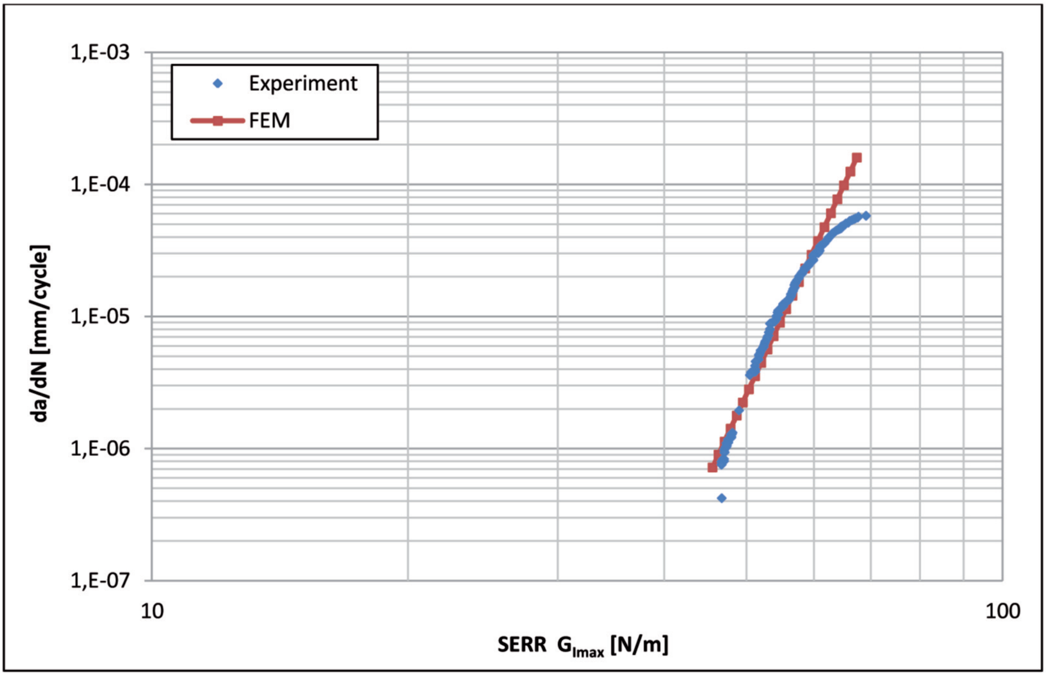

Fig. 8. Comparison of DCB-1 results and experimental data – delamination growth rate vs. maximum SERR in cycle [own elaboration]

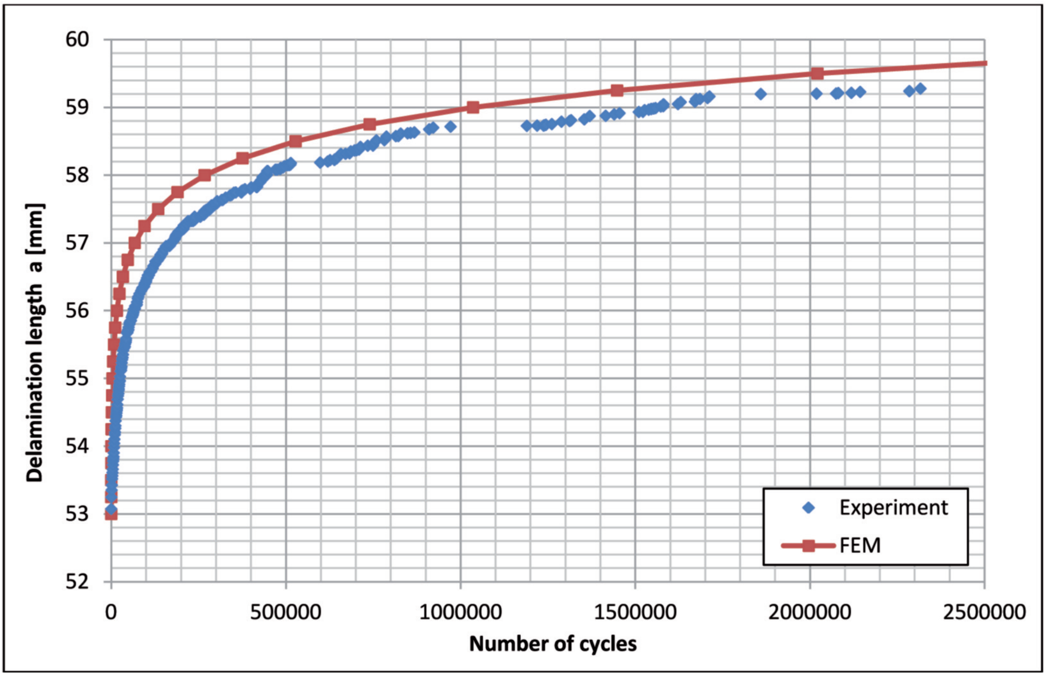

Fig. 9. Comparison of DCB-2 results and experimental data – delamination length vs. number of cycles [own elaboration]

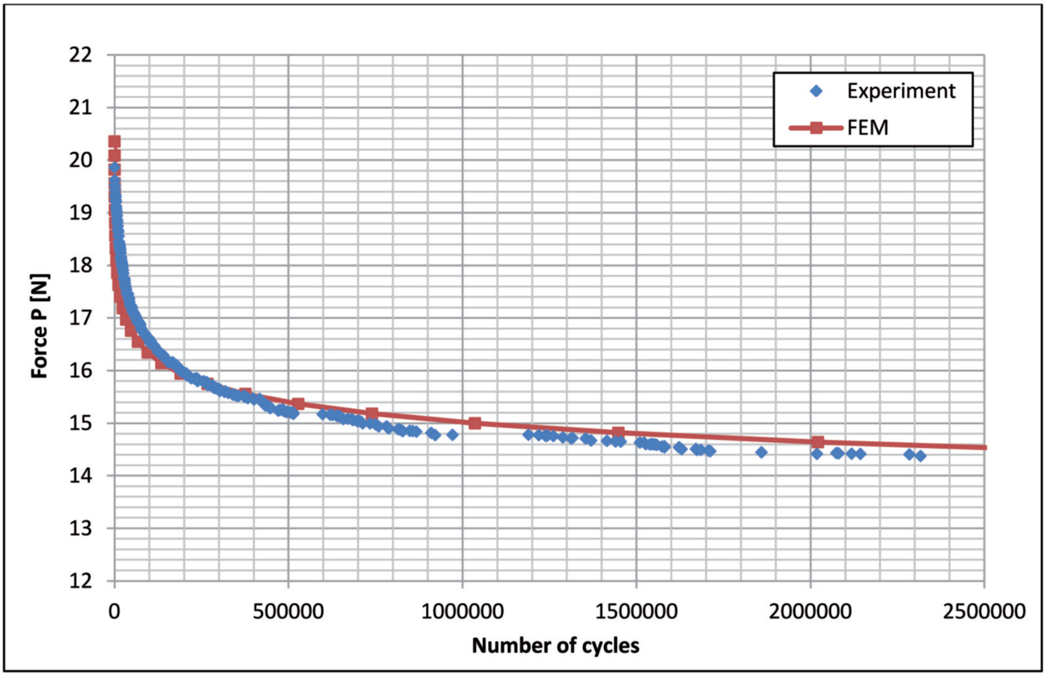

Fig. 10. Comparison of DCB-2 results and experimental data – maximum force in cycle vs. number of cycles [own elaboration]

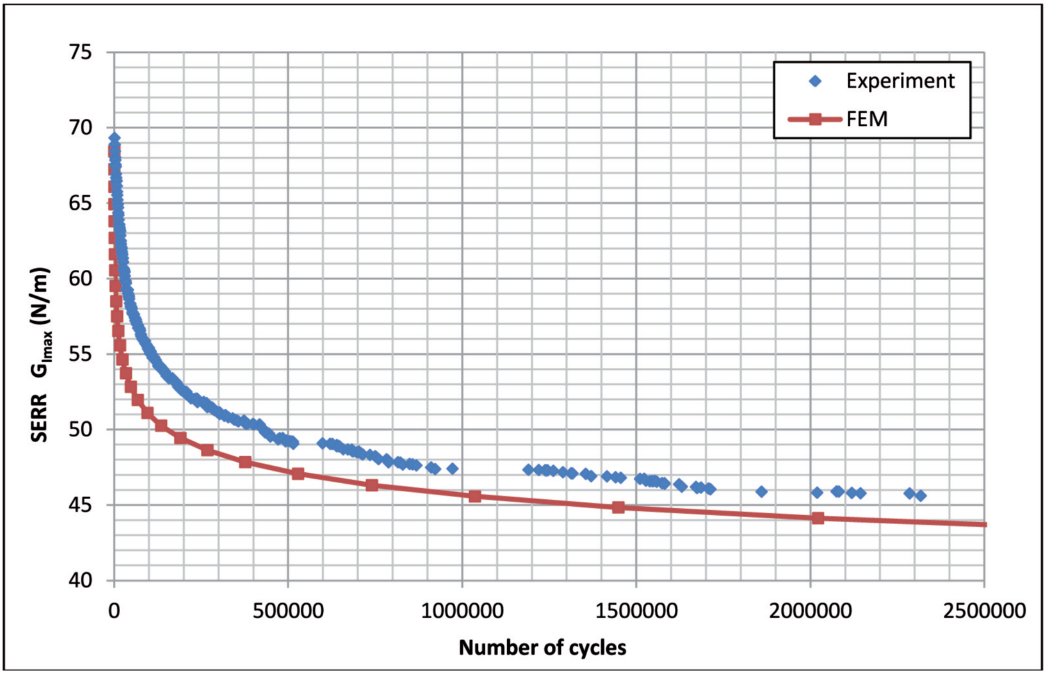

Fig. 11. Comparison of DCB-2 results and experimental data – maximum SERR in cycle vs. number of cycles [own elaboration]

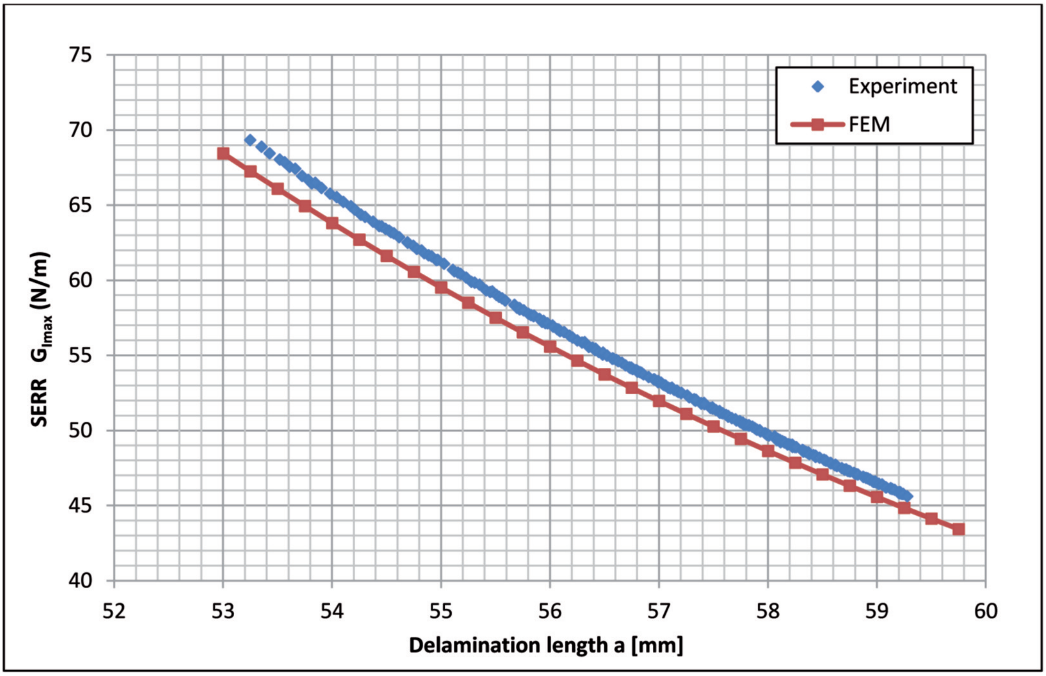

Fig. 12. Comparison of DCB-2 results and experimental data – maximum SERR in cycle vs. delamination length [own elaboration]

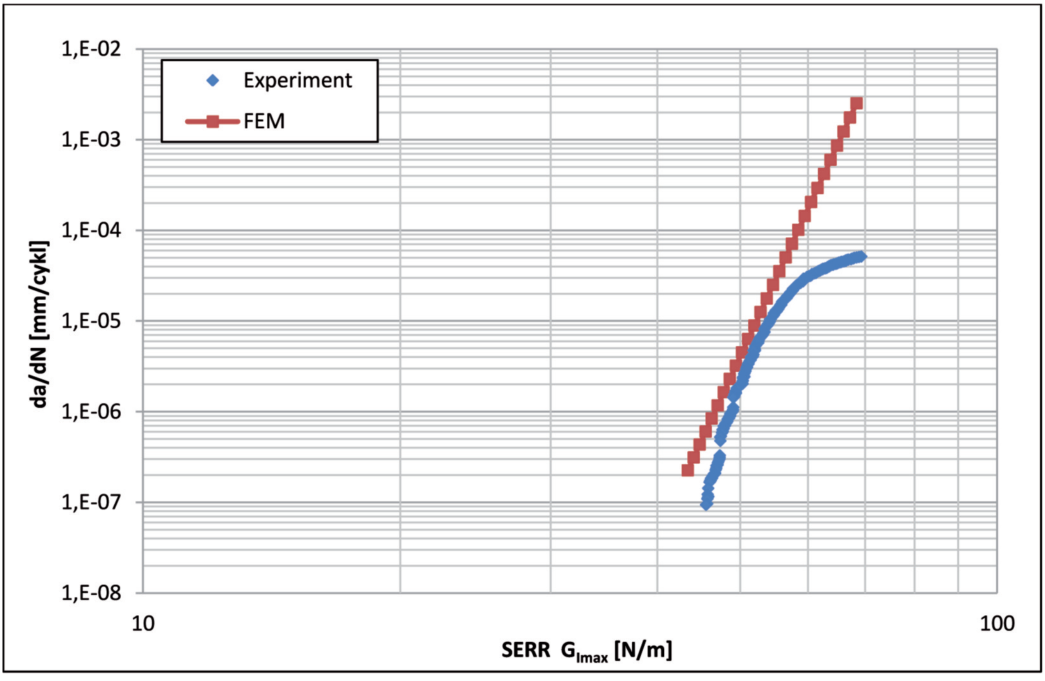

Fig. 13. Comparison of DCB-2 results and experimental data – delamination growth rate vs. maximum SERR in cycle [own elaboration]

5. CONCLUSIONS

The results of the numerical analysis are qualitatively consistent with the experimental investigations of delamination growth in cyclic loading conditions. The quantitative comparison does also not produce significant differences. However for the case DCB-2 the numerical calculations produce the results that suggest slower delamination growth than actually observed. It is not considered to be advantageous as one should want to obtain more conservative results from the numerical analysis. For both analyzed cases the numerically calculated Paris law was similar to the experimental one. It must be however stated that the presented model is able to represent only the linear part of the relationship between the delamination growth rate and the SERR value and does not capture the deviation from linearity that can be observed in the experimental results.

The presented approach can be a basis for developing a method for analyzing fatigue delamination propagation in 3D models. At the same time more experimental and analytical work should be performed for improving the accuracy of representing real phenomena by numerical calculations.

The work presented in the paper was carried out under the project TEBUK “Development of the technology for testing the resistance to damage of aviation and space composite load bearing structures” POIG.01.01.02-14-017. The project was financed by the European Regional Development Fund under the Innovative Economy Program.

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MODELOWANIE NUMERYCZNE ZMĘCZENIOWEGO ROZWOJU DELAMINACJI W WARUNKACH I SPOSOBU PĘKANIA METODĄ VCCT

Streszczenie

W artykule przedstawiono numeryczną metodę modelowania zmęczeniowego wzrostu delaminacji w kompozytach warstwowych z wykorzystaniem metody *Virtual Crack Closure Technique*. Podstawą metody jest algorytm oparty na procedurach użytkownika dostępnych w oprogramowaniu do obliczeń metodą elementów skończonych MSC MARC. Wykorzystuje on wyznaczone eksperymentalnie prawo Parisa w celu obliczenia liczby cykli zmęczeniowych potrzebnych do wzrostu delaminacji o określoną długość. Pozwala to na wyznaczenie związku pomiędzy rozwojem delaminacji a liczbą cykli obciążenia zmęczeniowego.

Stworzony został dwuwymiarowy model belki dwuwspornikowej wykonanej z laminatu węglowo-epoksydowego oraz przeprowadzone zostały obliczenia dla dwóch zestawów wielkości wejściowych. Odpowiadają one próbkom badanym eksperymentalnie. Pozwoliło to na porównanie wyników i weryfikację metody numerycznej względem badań eksperymentalnych.

Słowa kluczowe: delaminacje, zmęczeniowa propagacja pęknięcia, MES, VCCT.