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DEVELOPMENT AND IMPLEMENTATION OF A TESTING METHOD FOR THE CHARACTERIZATION OF INTERLAMINAR DELAMINATION PROPAGATION IN LAMINATES UNDER FATIGUE MODE II LOADING CONDITIONS

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Abstract

With no standardized methods being available the paper presents a procedure for experimental characterization of fatigue delamination growth under mode II loading conditions. The distinctive feature of the proposed algorithm is determination of crack length based on the specimen compliance. It eliminates the need of visual observations replacing it with compliance calibration performed at the end of the test. The testing methodology, using the end notch flexure set-up, is described step by step as well as calculations leading to obtaining the relationship between the delamination growth rate and strain energy release rate values in the form of Paris' law. The method was implemented in the Composites Testing Laboratory in the Institute of Aviation and the experimental investigations of crack resistance properties of laminates made of unidirectional prepreg MTM 46 were performed. Consistent results were obtained and the Paris law for II cracking mode was determined.
Keywords: composites, delamination, fatigue, mode II, mechanical testing.

1. INTRODUCTION

Fiber-reinforced polymer matrix composites are more and more widely used in the aerospace industry. One of the largest points of concern regarding such structures made of layers of reinforcement impregnated with resin are delaminations, which are areas inside the laminated structure where separation between two layers occurred. Due to the variation of reinforcement orientation and stratified structure laminates display relatively low resistance against interlaminar fracture. Resistance to delamination propagation, especially under cyclic loading, is an important characteristic of such materials. It can be very useful in the design of composite structures with the special focus on the damage tolerance analysis. This considered there is a need for widely available and recognized methods for testing delamination propagation in layered composites. Institute of Aviation in Poland has constantly growing experience in testing composite materials [1]. This article presents a procedure for the experimental characterization of delamination growth under cyclic mode II loading conditions. It is used to determine the rate of delamination growth, described with Paris' law, of the carbon-epoxy laminate.

In layered composites fracture mechanics is used to characterize the resistance to delamination growth by the means of strain energy release rate (SERR) denoted by G, which is the energy needed to extend the crack by an infinitesimal length. In linear, two-dimensional systems it can be described by Eq. (1).

$$G = \frac{p^2}{2b} \cdot \frac{dC}{da} \tag{1}$$

where: P – applied force, b – specimen width, a – crack length, C – specimen compliance.

Usually SERR is divided into three orthogonal components corresponding to three kinematically admissible ways of crack propagation called Mode I (opening), Mode II (sliding shear) and Mode III (tearing shear) [2]. In the case of layered composites the loading conditions usually induce cracking in mode I, mode II or in a combination of these two (mixed I/II fracture mode). For static loading conditions the quantity characterizing material resistance to fracture is critical value of SERR – G_{Ic}, G_{IIc}, G_{IIIc}, for Mode I, Mode II and Mode III respectively. When analyzing cyclic loading conditions the properties of layered composites are often described by the power law relationship between the rate of delamination growth with fatigue cycles to maximum applied SERR, called Paris' law, which can be described by Eq. (2) [2].

$$\frac{da}{dN} = \alpha \cdot G_{\max}^{\beta} \tag{2}$$

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

In the last three decades number of studies have been performed that focused on the development of standards for testing the fracture resistance of polymer matrix composites. The groups most actively involved were the Polymers and Composites technical Committee (TC4) of ESIS (European Structural Integrity Society), the D30.06 subcommittee of ASTM (American Society of Testing and Materials) and the JIS (Japanese Industrial Standards) group. The survey of the work performed in till the end of the 20th century is presented in [3]. As regarding mode II fracture until recently there was no widely used standard for testing composite materials and the researchers employed different specimen set-ups, the most common being ENF (end notched flexure), ELS (end-loaded split) and 4ENF (four-point end notched flexure) specimens [4]. In 2014 two standards presenting methods for testing the resistance to delamination of fiber-reinforced laminates in quasi-static loading conditions were published – ASTM D7905/D7905M [5] proposed performing the test in the ENF configuration while ISO 15114:2014 [6] used C-ELS (clamp-calibrated end-loaded split) specimen. Yet, there is no standardized procedure for testing the delamination propagation under cyclic loading for laminates. ASTM E647 [7] standard covers measuring the fatigue crack growth rate for metals and can be adapted to composites to some extent. However, there is very limited literature containing guidelines on fatigue testing methods for mode II cracking. There is a need for a procedure dedicated specifically to fiber-reinforced composites.

Several studies of the fatigue delamination propagation under Mode II loading conditions have been performed in the last years and various methods of calculating SERR value were employed. One of frequently used is a formula derived from simple beam theory (SBT) [8–10], described by Eq. (3) for ENF specimen. Its accuracy can be affected by the fact that the relationship between the specimen compliance and the delamination length is based on a simple bending analysis.

$$G = \frac{9Pa^2\delta}{2b(2L^3 + 3a^3)} \tag{3}$$

where: P – applied force, a – crack length, δ – deflection at loading point, b – specimen width, L – half of the support span.

Experimental compliance calibration method [11] derives the formula for G directly from Eq. (1) but uses the experimentally determined relationship between the specimen compliance and the crack length in the form of Eq. (4).

$$C = ma^3 + A \tag{4}$$

where: a – crack length, m, A – constants.

The resultant formula is described by Eq. (5). This method is suggested for SERR determination in static testing by the ASTM D7905 standard [5] as well as used in fatigue testing [9, 12].

$$G = \frac{3mP^2a^2}{2b} \tag{5}$$

where: m – constant from compliance calibration, P – applied force, a – crack length, b – specimen width.

Another method used in studies of fatigue delamination growth is effective crack length method [13]. It was also implemented in the ISO 11415:2014 [6] standard for testing in quasi static loading conditions. The SERR value is determined based on the formula in Eq. (6) for the ENF specimen. The calculation of the effective crack length is based on the specimen compliance according to Eq. (7).

$$G = \frac{9P^2a_e^2}{16b^2E_1h} \tag{6}$$

where: P – applied force, a_e – effective crack length, b – specimen width, E_1 – flexural modulus of elasticity, h - specimen half thickness.

$$a_e = \sqrt{\frac{8E_1bh^3C - 2L^3}{3}} \tag{7}$$

where: E_1 – flexural modulus of elasticity, b – specimen width, h - specimen half thickness, C – specimen compliance, L – half of the support span.

One of the points of concern when calculating SERR from experimental data is the method of measuring the delamination length. Most procedures involve stopping the experiment at specified time intervals and measuring the crack length with the help of a travelling microscope [8–10], which is more time-consuming and require presence of the operator during the test precluding overnight testing. It also does not count for uneven crack front and the number of data points is limited. The effective crack length method uses the corrected beam theory to calculate the crack length based on the specimen compliance [13]. Performing compliance calibration allows to calculate the crack length from the experimental relationship according to Eq. (4) [12]. Studies confirmed good correlation between this values and the crack length observed visually [14].

The procedure presented in the article is based on the experimental compliance calibration method due to the profits from eliminating the need of visual observation of the specimen during the test. It reduces the time and work related to performing the test and produces a lot of data points to process. Yet, it is a relatively new approach and there is not a lot of literature on the topic.

2. DESCRIPTION OF THE PROCEDURE

2.1. Overview of the procedure

The principle of the procedure is calculation of crack length and maximum SERR value based on the specimen compliance. The schematic view of the test is presented in fig. 1. The requirements concerning specimen geometry and preparation are in accordance with ASTM D7905/D7905M [5] with the length of the uncracked part of the specimen at least 130 mm to allow for compliance calibration. The specimen configuration is shown in fig. 2. Fatigue cycling is performed in the displacement control conditions with the sinusoidal wave shape and the frequency lower than 10 Hz to avoid heating of the specimen. The maximum and minimum values of the loading force and displacement in the loading cycle – P_{max}, P_{min}, δ_{max} and δ_{min}, should be recorded with the interval chosen to produce satisfactory yet reasonable to process number of data points. The specimen compliance is then calculated for each data point according to Eq. (8). Using the difference between maximum and minimum values ensures that the compliance is taken from the linear range of load-displacement curve.

$$C = \frac{\delta_{\max} - \delta_{\min}}{P_{\max} - P_{\min}} \tag{8}$$

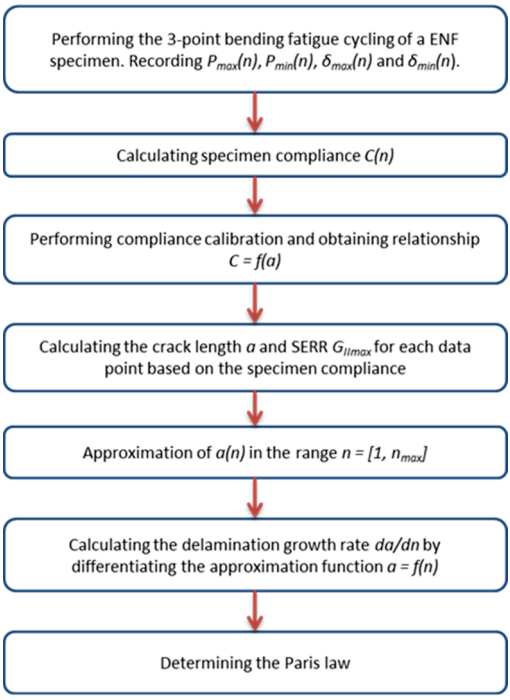

Fig. 1. Schematic view of the testing procedure [own elaboration]

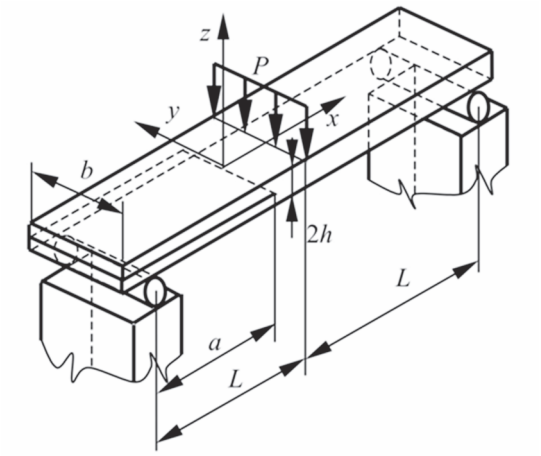

Fig. 2. ENF specimen [4]

2.2. Compliance calibration

The compliance calibration, shown schematically in fig. 3, is performed after the completion of the fatigue cycles. Starting from the final position the specimen is loaded and unloaded with the recording of force and displacement and the compliance corresponding to the final crack length is calculated from the slope of the linear part of the force-displacement curve. The specimen is then moved on the support by a length of Δa lowering the crack length and the procedure is repeated. The compliance should be measured at least for the whole distance of delamination propagation. The maximum loading force should be about 50% of the force corresponding to the G_{IIc} as per ASTM D7905/D7905M [5] and can be calculated from Eq. (9).

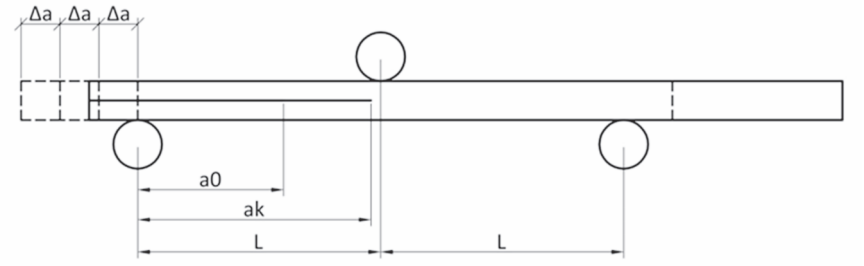

Fig. 3. Procedure of compliance calibration [own elaboration]

$$P_c = \frac{4b}{3a_0}\sqrt{G_{IIc}E_1h^3} \tag{9}$$

where: b – specimen width, a_0 – initial crack length, G_{IIc} – critical SERR, E_1 – flexural modulus of elasticity, h - specimen half thickness.

After measuring the compliance in each position the specimen should be opened and the actual length of the delamination should be registered. The correction can then be made to the final length observed at the end of the fatigue cycles. The relationship between the delamination length and the compliance should be approximated by the function specified in Eq. (4) in accordance with the ASTM D7905/D7905M [5] guidelines.

2.3. Detemination of Paris' law

After performing the compliance calibration the delamination length a can be calculated form Eq. (4) for each data point registered. The obtained data set $a(n)$ should be approximated with a differentiable nondecreasing monotonic function in the range of $(n = 1, n_{max})$. The resultant function should be differentiated in order to obtain the delamination growth rate da/dn. The sigmoidal functions proved to give very good correlation. The approximation function should be differentiated in order to obtain the delamination growth rate da/dn. SERR values for each data point should be calculated from Eq. (5). In logarithmic scale the Paris' law takes the form of Eq. (10), where parameters β and $\log(\alpha)$ can be determined by the linear regression.

$$\log\left(\frac{da}{dN}\right) = \beta \log\left(G_{II\,max}\right) + \log\alpha \tag{10}$$

where: da/dN – delamination growth rate; G_{IImax} – maximum SERR in a cycle; α, β –parameters.

3. EXPERIMANTAL TESTING

3.1. Test parameters

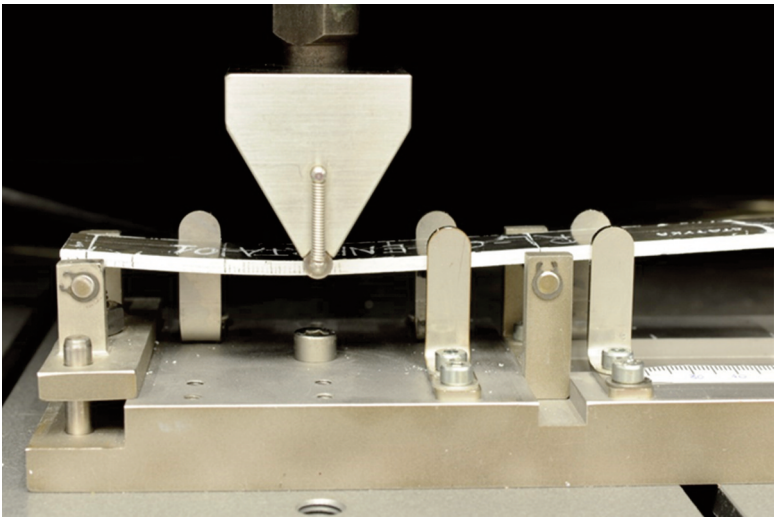

Fig. 4. Test set-up for the ENF specimen [own elaboration]

The proposed procedure was used in testing the specimens made of unidirectional carbon-fiber prepreg MTM 46. The specimens dimensions were designed in accordance with ASTM D7905/D7905M [5] – their length was 175 mm, width 20 mm, thickness 3.2 mm. The initial delamination was introduced by placing the 35 mm long Teflon insert in the mid-surface of the specimen. Prior to the fatigue a static test was conducted on three specimens to determine critical SERR value according to ASTM D7905/D7905M [5]. The point to consider when testing delamination propagation is precracking the specimen, that is intentionally extending the crack from the insert before the measurement. During the specimens manufacturing the resin accumulation may be created at the tip of the insert resulting in higher SERR values at delamination growth onset. This is the reason why precracked specimens may give more reliable results. However, there is a possibility of fiber bridging that increases the SERR value with the increasing crack length, especially in

laminates composed of unidirectional plies. Taking these factors into consideration the static tests were performed for both non-precracked and precracked specimens. In the analysis of delamination growth rate under fatigue loading, the influence of resin accumulation is limited to the very beginning of delamination growth. It may affect the number of cycles to the crack growth onset but has no impact on the further propagation. The specimen set-up for both static and dynamic testing is presented in fig. 4. All tests were performed on electrodynamic testing frame Instron ElectroPuls E3000 in the displacement control mode. For the dynamic cycles the sinusoidal waveform was selected.

3.2. Results of the static testing

The results of the static tests are presented in tab. 1. They were used to estimate the critical SERR value in order to choose parameters for the fatigue testing therefore three specimens was considered sufficient. Experiments performed on precracked specimens yielded considerable lower results regarding critical SERR values. It would indicate the presence of resin accumulation at the tip of the Teflon insert that produced unrealistic high results for non-precracked specimens.

Tab. 1. Results of the static tests [own elaboration]

Specimen designation	Width, mm	Thickness, mm	Non-precracked specimen			Precracked specimen		
			Maximum force, N	Maximum deflection, mm	Critical SERR, J/m^2	Maximum force, N	Maximum deflection, mm	Critical SERR, J/m^2
S-1	20.03	3.209	510	2.39	759	398	2.14	588
S-2	20.02	3.119	489	2.08	610	451	2.00	535
S-3	20.02	3.233	557	2.39	758	387	1.85	456
Mean	20.02	3.187	518	2.29	709	412	2.00	526
Standard deviation	0.01	0.060	35	0.18	86	34	0.15	67
Coefficient of variation	0.04%	1.89%	6.68%	7.90%	12.07%	8.29%	7.26%	12.64%

3.3. Results of the dynamic testing

Since the effect accumulation of resin at the crack tip is limited to delamination onset as regarding fatigue testing the static tests results for precracked specimen were used to determine the parameters of dynamic cycles. Six specimens were tested with different initial loads defined as the maximum displacement in the cycle. The aim was to cover wide range of SERR values for determining the Paris law – in the case of the ENF specimen the distance of delamination growth is limited by the loading roller to approximately 20 mm. The parameters of the test for each specimen are shown in tab. 2. Values of maximum and minimum displacement and force were recorded every 100 cycles.

Tab. 2. Parameters of the fatigue testing [own elaboration]

Specimen designation	Width, mm	Thickness, mm	Maximum deflection, mm	Frequency, Hz	Stress ratio R
F-1	20.05	3.256	1.58	9.0	0.1
F-2	20.04	3.259	1.50	9.0	0.1
F-3	20.02	3.269	1.40	9.0	0.1
F-4	20.06	3.238	1.30	9.0	0.1
F-5	19.98	3.271	1.20	9.0	0.1
F-6	19.97	3.233	1.10	9.0	0.1

After realization of dynamic cycles for each specimen the compliance calibration was performed according to the paragraph 2.2. Based on the recorded data the specimen compliance, crack length

and SERR values were calculated according to Eq. (8), (4) and (5) respectively. The relationship between the SERR value and delamination length is shown in fig 5, while the crack propagation during fatigue cycling is presented in fig 6. For the calculation of delamination growth rate the dependence of crack length on the number of cycles was approximated by the sigmoidal function in the general form of Eq. (11), which ensured very good correlation with lowest the coefficient r^2 being 0.998.

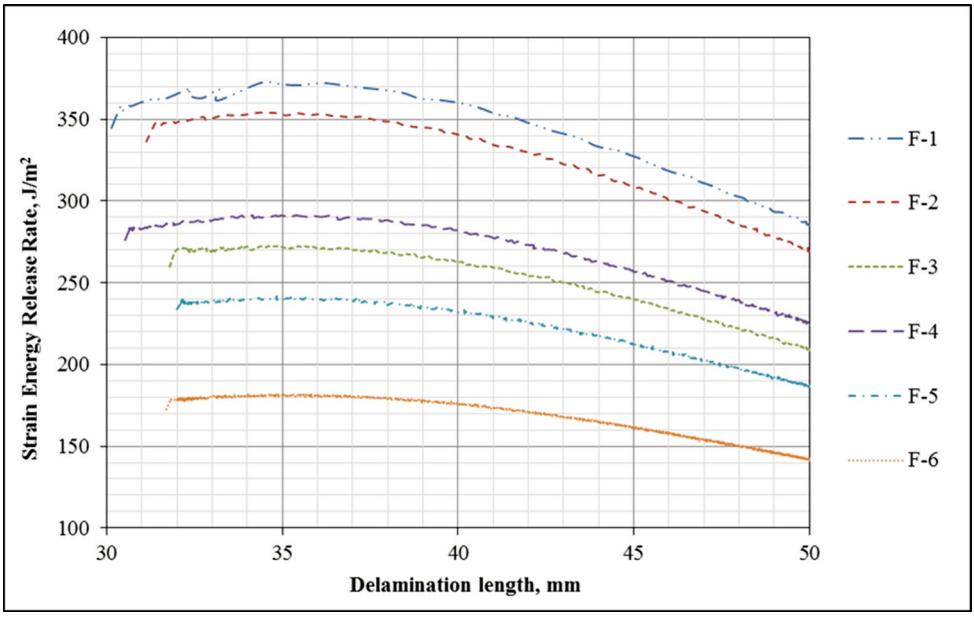

Fig. 5. Relationship between SERR value and delamination length [own elaboration]

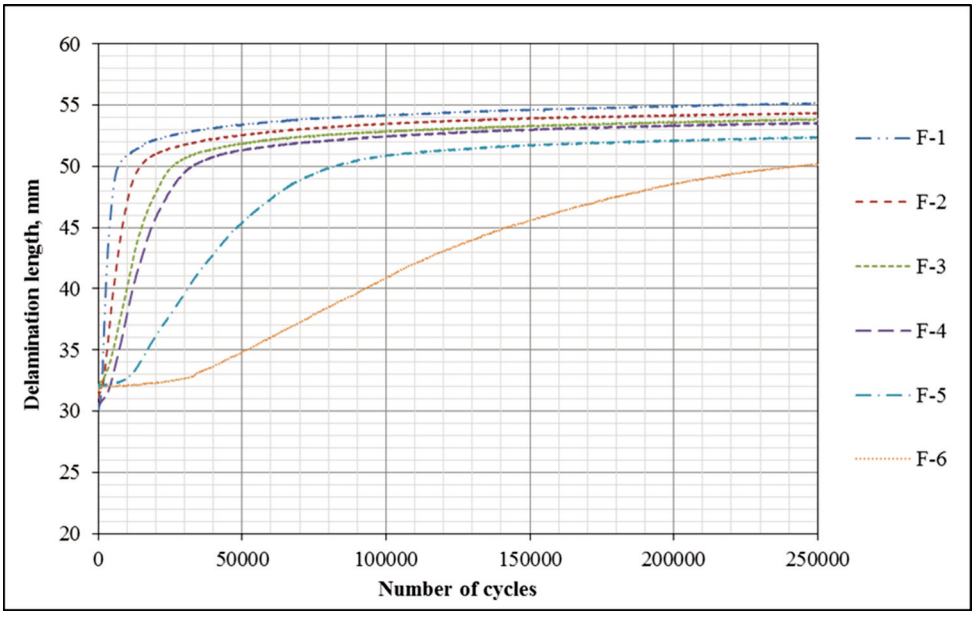

Fig. 6. Crack propagation during fatigue cycling [own elaboration]

$$a(n) = Q_1 + \frac{Q_2}{\left(Q_3 + Q_4 e^{-Q5(n)}\right)^{Q_6}} \tag{11}$$

where: a – crack length, n – number of cycles, Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, – coefficients.

The Paris law was calculated for each specimen according to the method described in paragraph 2.3. The results are presented in tab. 3 together with the maximum and minimum SERR value during the experiment which limits the applicability of the determined relationship and the statistical data from the series of specimens. The graphs of delamination growth rate vs. SERR values are presented in fig. 7 with the average Paris law plotted in the continuous line. The Paris law was calculated from the linear part of the curves. The nonlinearity for the higher SERR values is connected with the unstable delamination growth at the beginning of the test. The ENF specimens often display unstable crack propagation for the crack length lower than 35 mm. The nonlinearity observed for the lower SERR values is caused by the crack front approaching the loading pin and the effects of compression in the crack front region.

Tab. 3. Results of Paris' law determination [own elaboration]

Specimen designation	Minimum SERR, J/m^2	Maximum SERR, J/m^2	β	logα	α
F-1	224	372	11.11	-30.18	6.62 x 10^{31}
F-2	178	273	10.04	-26.85	1.41 x 10^{27}
F-3	168	242	9.61	-25.82	1.52 x 10^{26}
F-4	196	291	10.86	-29.18	6.56 x 10^{30}
F-5	230	354	9.65	-26.76	1.74 x 10^{27}
F-6	133	182	10.13	-26.30	5.07 x 10^{27}
Mean			10.24	-27.51	3.06 x 10^{28}
Standard deviation			0.57	1.59	1.77 x 10^{29}
Coefficient of variation			5.54%	5.80%	5.80%

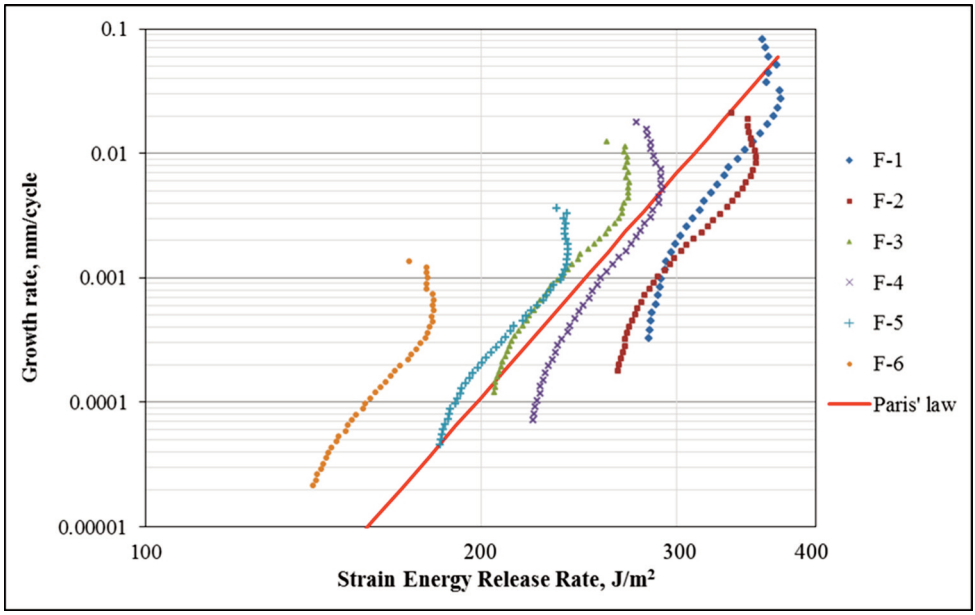

Fig. 7. Relationship between the delamination growth rate and SERR value for the tested specimens [own elaboration]

4. CONCLUSIONS

The paper presented an original method of testing fracture toughness of laminates which was successfully implemented in the laboratory. Its major advantage is the elimination of visual inspection of the crack front propagation. It allows for conducting the experiment in an automated way, without stops and supervision. The 500 000 cycles that covered the whole test for a single specimen was realized in 16 hours, overnight. The approximation of the delamination growth with a sigmoidal function gives very good correlation with lowest the coefficient r^2 being 0.998 and leads to obtaining consistent results even in the presence of noise in the recorded data. It also allows to capture the phenomena of unstable delamination growth for shorter crack length as seen in Fig. 7. The method can be implemented in most laboratories as it does not require special equipment other than a testing frame able to apply cyclic loading.

The experiment conducted according to the proposed algorithm produced consistent results with the coefficient of variation below 6%, which is considerably lower than as much as 40% obtained in previous testing of the same material using different method [15]. Due to the different values of maximum deflection applied to the specimens it was possible to determine the Paris law for a wide range of SERR values, between 133 J/m^2 and 372 J/m^2. This relationship is considered to be valid between two limiting SERR values – G_{IIc}, determined in the static test, and G_{th}, the threshold value below which no delamination growth is observed. The latter was not reached in the presented series of specimens and requires additional testing performed for maximum deflection lower than 1.10 mm. Short distance of delamination propagation in the ENF set-up increases the number of specimens needed to cover the whole range of SERR values between the limiting points.

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OPRACOWANIE I WDROŻENIE METODY BADANIA ROZWOJU DELAMINACJI MIĘDZYWARSTWOWYCH W LAMINATACH W WARUNKACH ZMĘCZENIOWEGO II SPOSOBU PĘKANIA

Streszczenie

W świetle braku dostępnych unormowanych metod zaprezentowano procedurę eksperymentalnego badania zmęczeniowego rozwoju delaminacji w warunkach II sposobu pękania. Wyróżniającą cechą zaproponowanego algorytmu jest wyznaczanie długości pęknięcia za pomocą podatności badanej próbki. Pozwala to na wyeliminowanie konieczności prowadzenia obserwacji, zastępując ją wykonaniem kalibracji podatności po zakończeniu testu. Opisana została krok po kroku metodologia, wykorzystująca zginanie trójpunktowe próbki z rozwarstwieniem (ENF), jak również przedstawione zostały obliczenia prowadzące do wyznaczenia zależności szybkości wzrostu delaminacji od wartości współczynnika uwalniania energii w postaci prawa Parisa. Metoda została wdrożona w Laboratorium Badań Kompozytów w Instytucie Lotnictwa. Przeprowadzono badania doświadczalne odporności na pękanie laminatu wykonanego z jednokierunkowego preimpregnatu MTM 46. Uzyskano zgodne wyniki oraz wyznaczono prawo Parisa dla II sposobu pękania.
Słowa kluczowe: kompozyty, delaminacje, zmęczenie, sposób II pękania, badania mechaniczne.