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

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**Abstract**

With no standardized methods for experimental characterization of fatigue delamination growth in laminates available the paper presents a testing method for mode I loading conditions. The distinctive feature of the proposed method is determination of crack length based on the specimen compliance and an additional compliance calibration procedure. This approach eliminates the need of visual observations. The testing methodology, using the double cantilever beam specimen, 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 I cracking mode was determined.
Keywords: composites, delamination, fatigue, mode I, mechanical testing.

## 1. INTRODUCTION

Fiber-reinforced polymer matrix composites are becoming more and more important as a material used in the aerospace industry. This leads to growing need of addressing the weak points of the structures made of layers of reinforcement impregnated with resin, one of most dangerous being delaminations – areas inside the laminated structure where separation between two layers occurred. Because of the stratified structure, often with different reinforcement orientation in adjacent layers laminates display relatively low resistance against interlaminar fracture. Resistance to delamination propagation, especially under cyclic loading, is an important characteristic, useful in the design of composite structures with the special focus on the damage tolerance analysis. Clearly 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 I 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; $\alpha$, $\beta$ – experimentally determined parameters.

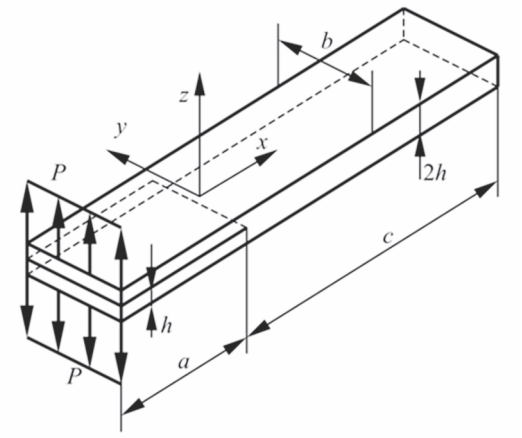


Fig. 1. DCB specimen [9]

In the last three decades a number of studies has 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 JSA (Japanese Standard Association). The survey of the work performed until the end of the 20th century is presented in [3]. Mode I fracture in quasi-static loading conditions has been widely studied and three standards are available – ASTM D5528-13 [4], ISO 15024:2001 [5] and JIS

K7086-1993 [6]. All of them utilize the so-called double cantilever beam (DCB) specimen, shown schematically in figure 1, in which pure mode I fracture is caused by loading both arms with edge force. Initial crack is introduced by placing a non-sticking thin film insert in the middle of the specimen thickness. The load is introduced either via two stiff load-blocks or hinges. As regarding fatigue loading conditions only one standard, ASTM D6115 [7], is available. It contains a method of determining the delamination growth onset in unidirectional fiber-reinforced laminates by loading the specimens with constant amplitude cycles at various SERR levels. However, it does not cover crack propagation. There is no standardized procedure for testing the delamination propagation under cyclic loading for laminates. ASTM E647 [8] standard contains guidelines for measuring the fatigue crack growth rate for metals and they can be adapted to composites to some extent. However, there is a need for a procedure dedicated specifically to fiber-reinforced composites.

Several studies of the fatigue delamination propagation under Mode I loading conditions have been conducted in the last years. The procedures for quasi-static testing offer various methods of calculating SERR values which can also be utilized in cycling testing. The simplest of them is simple beam theory (SBT), used in [10], where $G_I$ is calculated from the Eq. (3).

$$G = \frac{3P\delta}{2ba} \tag{3}$$

where: $P$ – applied force, $\delta$ – deflection at loading point, $b$ – specimen width, $a$ – crack length.

However, since ISO 15024:2001 [5] recommends corrected beam theory (CBT) and modified compliance calibration (MCC) methods, these are the most common ones used in literature. In the CBT method, used in [10-12], the SERR is calculated from the Eq. (4) while in the case of the MCC method, used in [10, 13, 14] the Eq. (5) determine G value.

$$G = \frac{3P\delta}{2b(a+\Delta)} \cdot \frac{F}{N} \tag{4}$$

where: $P$ – applied force, $\delta$ – deflection at loading point, $b$ – specimen width, $a$ – crack length, $\Delta$ – correction coefficient usually calculated from quasi-static testing, $F$ – large displacement correction, $N$ – load-blocks correction.

$$G = \frac{3m}{2 \cdot 2h} \cdot \left(\frac{P}{b}\right)^2 \cdot \left(\frac{bC}{N}\right) \cdot F \tag{5}$$

where: $P$ – applied force, $h$ – specimen half thickness, $b$ – specimen width, $C$ – specimen compliance, $m$ – slope width-normalized cube root of the compliance plotted as a function of the thickness-normalized delamination length, $F$ – large displacement correction, $N$ – load-blocks correction.

One of the points of concern when calculating SERR from experimental data is the method of measuring the delamination length. Majority of the studies adapt the method proposed in the standards for the quasi-static testing – the experiment is stopped at specified time intervals and the crack length is measured with the help of a travelling microscope [11-16]. It is time-consuming and requires 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. Other methods of determining the crack length are presented in [10, 15, 16]. One of them is based on establishing the experimental relationship between the crack length and the compliance of the specimen. In that way a limited number of visual observations during the test allows for calculating the crack length for all fatigue cycles. The effective crack length method

on the other uses the corrected beam theory to calculate the crack length based on the specimen compliance and flexural Young modulus measured beforehand according to the Eq. (6).

$$a_{eff} = \frac{h}{2} \cdot \left( \frac{E_{11} C b}{N} \right)^{1/3} \tag{6}$$

where: $h$ – specimen half thickness, $b$ – specimen width, $C$ – specimen compliance, $E_{11}$ – flexural Young modulus, $N$ – load-blocks correction.

The procedure presented in the article is based on the experimental compliance calibration method. It 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. (7). The experiment can be performed without stopping and visual observations of the crack length which reduces the time and work related to performing the test and produces a lot of data points to process. After the fatigue cycling the compliance calibration is performed on the tested specimen and the SERR is calculated for each data point according to the Eq. (8).

$$C = ma^3 + A \tag{7}$$

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

$$G = \frac{3mP^2a^2}{2b} \tag{8}$$

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

## 2. DESCRIPTION OF THE PROCEDURE

### 2.1. Overview of the procedure

The principle of the procedure is a calculation of crack length and maximum SERR value based on the specimen compliance. The schematic view of the test is presented in figure 2. The requirements concerning specimen geometry and preparation are in accordance with ASTM D5528 [4] and ISO 15024:2001 [5]. For introducing the load a pair of aluminum load-blocks connected to the testing frame by rotating pins is used. Following the guidelines all the specimens are precracked to avoid influence of the resin accumulation at the tip of the insert on the SERR values at delamination growth onset. The precracking is performed automatically and the special clamp is mounted on the specimen at the desired crack length to prevent unstable crack growth and ensure straight crack front. The set-up for precracking is presented in figure 3. Fatigue cycling is performed in the displacement control conditions with the sinusoidal wave shape and the frequency 5 Hz to avoid heating of the specimen. The maximum and minimum values of the loading force and displacement in the loading cycle – $P_{max}$, $P_{min}$, $\delta_{max}$ and $\delta_{min}$, 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. (9). Using the difference between maximum and minimum values ensures that the compliance is taken from the linear range of the load-displacement curve.

$$C = \frac{\delta_{\max} - \delta_{\min}}{P_{\max} - P_{\min}} \tag{9}$$

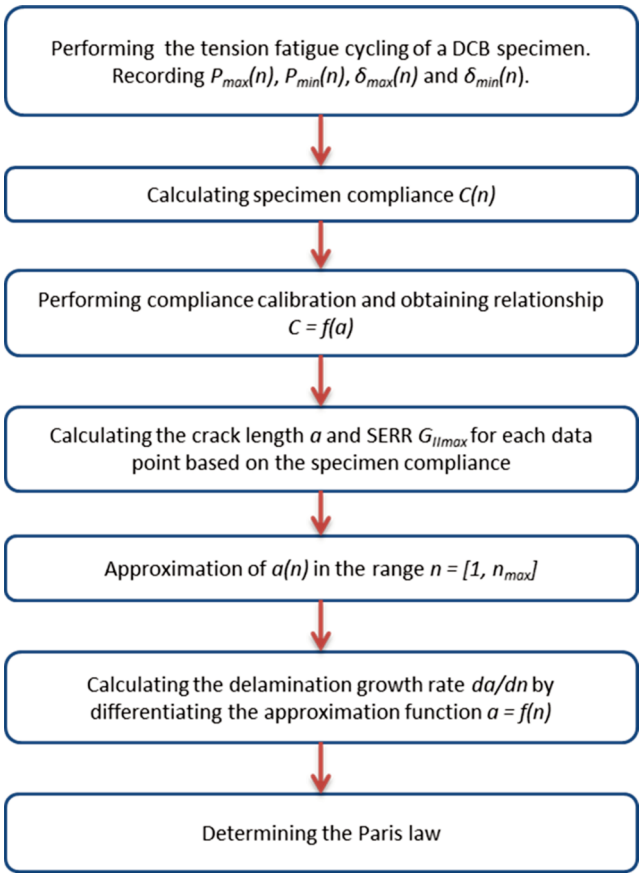


Fig. 2. Schematic view of the testing procedure [Wilk, 2016]

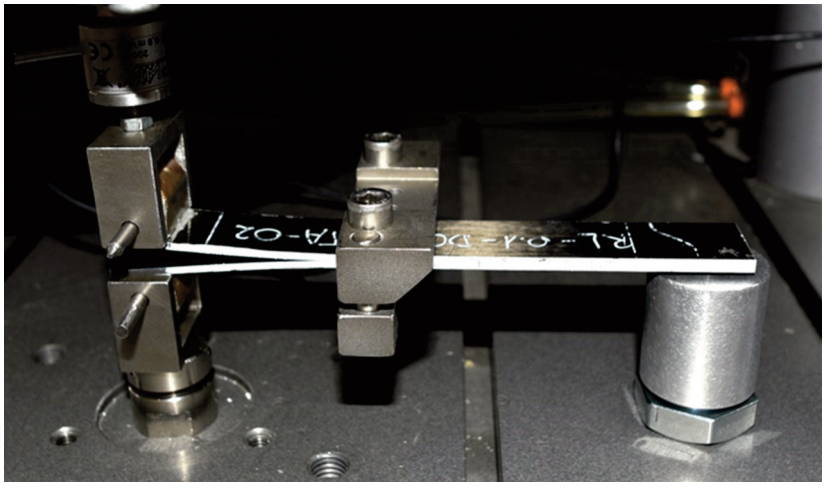

Fig. 3. Preckracking of a DCB specimen [Wilk, 2016]

### 2.2. Compliance calibration

The compliance calibration is performed after the completion of the fatigue cycles with the use of specially designed fixture, shown in figure 4. The clamp allowing reducing the crack length is mounted on the specimen which is then loaded and unloaded with the recording of force and displacement. The compliance is calculated from the slope of the linear part of the force-displacement curve. The clamp is then moved by a length of $\Delta a$ elongating the crack length and the procedure is repeated. The fixture is designed to facilitate and ensure the precision of mounting the clamp. The compliance should be measured at least for the whole range of delamination propagation. The maximum force can be set to the maximum force recorded during the fatigue cycling – the clamp prevents the crack from growing during the procedure. After performing the measurements for a series of clamp positions the relationship between the delamination length and the compliance can be approximated by the function specified in Eq. (7).

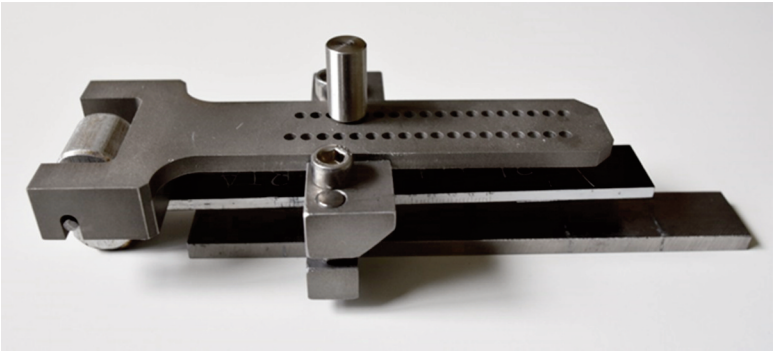

Fig. 4. Procedure of compliance calibration [Wilk, 2016]

### 2.3. Detemination of Paris' law

After performing the compliance calibration the delamination length $a$ can be calculated form Eq. (7) 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 $da/dn$. In the case of DCB specimens power or logarithmic 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. (8). In logarithmic scale the Paris' law takes the form of Eq. (10), where parameters $\beta$ and $log(\alpha)$ can be determined by the linear regression.

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

where: $da/dN$ – delamination growth rate; $G_{Imax}$ – maximum SERR in a cycle; $\alpha$, $\beta$ –parameters.

## 3. EXPERIMANTAL TESTING

### 3.1. Test parameters

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 D5528 [4] – their length was 150 mm, width 20 mm, thickness 3.2 mm. The initial delamination was introduced

by placing the 55 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 D5528 [4]. All the specimens were precracked to obtain the initial delamination length of 50 mm. The specimen set-up for both static and dynamic testing is presented in figure 5. All tests were performed on electrodynamic testing frame Instron ElectroPuls E3000 in the displacement control mode. The sinusoidal waveform was selected for the dynamic cycles.

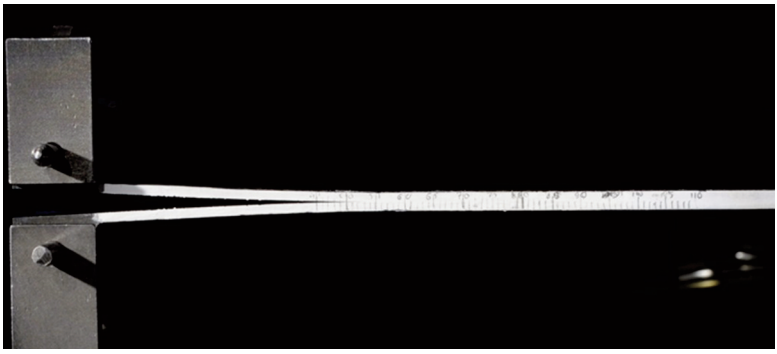

Fig. 5. Test set-up for the DCB specimen [Wilk, 2016]

### 3.2. Results of the static testing

The results of the static tests are presented in Table 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. According to the ASTM D5528 [4] nine values of $G_{Ic}$ are determined for each specimen. For the purpose of choosing the testing parameters for fatigue cycling the lowest value was taken as a result.

Table 1. Results of the static tests, presented acc. to ASTM D5528 [4]. The critical SERR value was determined for three initiation points specified in the standard (NL, VIS, 5%/MAX) using three methods recommended by the standard (Modified Beam Theory, Compliance Calibration, Modified Compliance Calibration).

| Specimen designation | Width, mm | Thickness, mm | Maximum force, N | Displacement at maximum force, mm | Initial crack length, mm | Initiation point determination | Critical SERR $G_{Ic}$, J/m$^2$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | MBT | CC | MCC |
| ST-1 | 20.03 | 3.229 | 28.1 | 3.9 | 50.0 | NL | 145 | 149 | 145 |
| | | | 28.7 | 4.1 | 50.0 | VIS | 156 | 162 | 155 |
| | | | 28.7 | 4.3 | 50.0 | 5%/MAX | 161 | 166 | 157 |
| ST-2 | 20.02 | 3.266 | 30.9 | 4.0 | 50.0 | NL | 155 | 162 | 156 |
| | | | 29.7 | 4.0 | 50.5 | VIS | 150 | 156 | 150 |
| | | | 31.1 | 3.9 | 50.0 | 5%/MAX | 156 | 162 | 157 |
| ST-3 | 19.97 | 3.302 | 30.0 | 3.6 | 50.0 | NL | 137 | 143 | 136 |
| | | | 30.4 | 3.6 | 50.0 | VIS | 141 | 147 | 139 |
| | | | 30.4 | 3.8 | 50.0 | 5%/MAX | 147 | 153 | 143 |
| Mean | 20.01 | 3.265 | 29.7 | 3.8 | 50.0 | NL | 146 | 151 | 146 |
| | | | 29.6 | 3.9 | 50.2 | VIS | 149 | 155 | 148 |
| | | | 30.1 | 4.0 | 50.0 | 5%/MAX | 154 | 161 | 153 |
| Standard deviation | 0.03 | 0.037 | 1.4 | 0.2 | 0.0 | NL | 9 | 9 | 10 |
| | | | 0.8 | 0.2 | 0.3 | VIS | 8 | 7 | 8 |
| | | | 1.2 | 0.2 | 0.0 | 5%/MAX | 7 | 7 | 8 |
| Coefficient of variation | 0.15% | 1.11% | 4.83% | 4.96% | 0.00% | NL | 6.19% | 6.25% | 6.98% |
| | | | 2.86% | 6.36% | 0.58% | VIS | 5.35% | 4.84% | 5.22% |
| | | | 4.13% | 5.76% | 0.00% | 5%/MAX | 4.68% | 4.21% | 5.26% |

### 3.3. Results of the dynamic testing

Specimens for the dynamic testing were prepared in the same way at those for the quasi-static tests. Five specimens were tested with the same maximum displacement in the cycle being 92% of the displacement at the crack propagation initiation for the quasi-static testing. Each specimen was cycled through 1 M cycles. The parameters of the test for each specimen are shown in Table 2. Values of maximum and minimum displacement and force were recorded every 100 cycles.

Table 2. Parameters of the fatigue testing and geometry of the specimens. The fatigue cycles were determined by the maximum opening displacement, stress ratio R and the cycling frequency.

| Specimen designation | Width, mm | Thickness, mm | Maximum displacement, mm | Frequency, Hz | Stress ratio R |
|---|---|---|---|---|---|
| F-1 | 20.06 | 3.336 | 3.5 | 5.0 | 0.1 |
| F-2 | 20.05 | 3.327 | 3.5 | 5.0 | 0.1 |
| F-3 | 20.03 | 3.307 | 3.5 | 5.0 | 0.1 |
| F-4 | 20.03 | 3.300 | 3.5 | 5.0 | 0.1 |
| F-5 | 20.04 | 3.300 | 3.5 | 5.0 | 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. (9), (7) and (8) respectively. The relationship between the SERR value and delamination length is shown in figure 6, while the crack propagation during fatigue cycling is presented in figure 7. For the calculation of delamination growth rate the dependence of crack length on the number of cycles was approximated by the power function in the form of Eq. (11), which ensured good correlation with the lowest coefficient $r^2$ being 0.952.

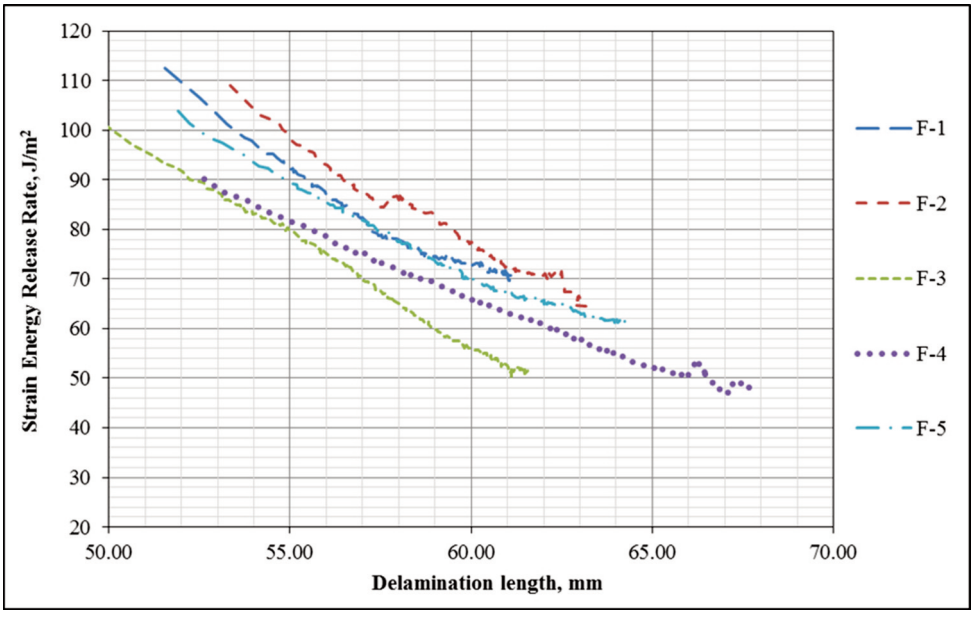


Fig. 6. Relationship between SERR value and delamination length [Wilk, 2016]

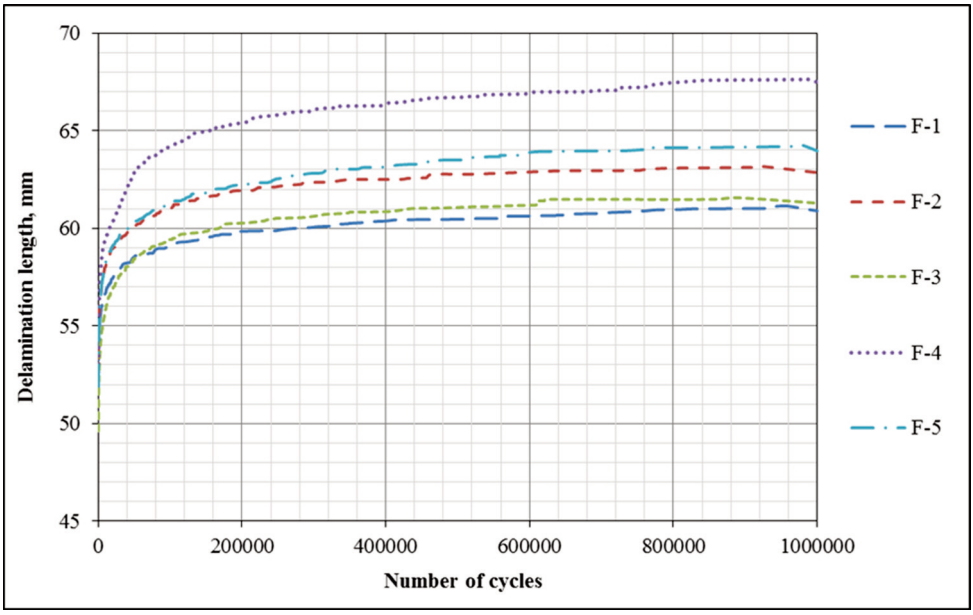


Fig. 7. Crack propagation during fatigue cycling [Wilk, 2016]

$$a(n) = Qn^{v} \qquad (11)$$

where: $a$ – crack length, $n$ – number of cycles, $Q$, $v$ – coefficients.

The Paris law was calculated for each specimen according to the method described in paragraph 2.3. The results are presented in Table 3 together with the maximum and minimum SERR value during the experiment. The graphs of delamination growth rate vs. SERR values are presented in figure 8 with the average Paris law plotted in the continuous line. The Paris law was calculated from the linear part of the curves. The nonlinearity observed for the lower SERR values is connected with approaching the threshold value $G_{th}$ under which no crack growth is observed.

Table 3. Results of Paris' law determination – maximum and minimum SERR values recorded during the test and coefficient of Paris law acc. to Eq. (2).

| Specimen designation | Maximum SERR, J/m$^2$ | Minimum SERR, J/m$^2$ | β | logα | α |
|---|---|---|---|---|---|
| F-1 | 112.50 | 69.15 | 15.34 | -33.52 | $3.00 \times 10^{-34}$ |
| F-2 | 108.93 | 63.70 | 15.25 | -33.19 | $6.48 \times 10^{-34}$ |
| F-3 | 102.40 | 50.41 | 14.81 | -31.86 | $1.37 \times 10^{-32}$ |
| F-4 | 90.26 | 46.41 | 14.81 | -30.86 | $1.38 \times 10^{-31}$ |
| F-5 | 103.84 | 59.83 | 13.97 | -30.29 | $5.16 \times 10^{-31}$ |
| Mean | | | 14.84 | -31.94 | $1.14 \times 10^{-32}$ |
| Standard deviation | | | 0.49 | 1.26 | $4.49 \times 10^{-34}$ |
| Coefficient of variation | | | 3.27% | 3.95% | 3.95% |

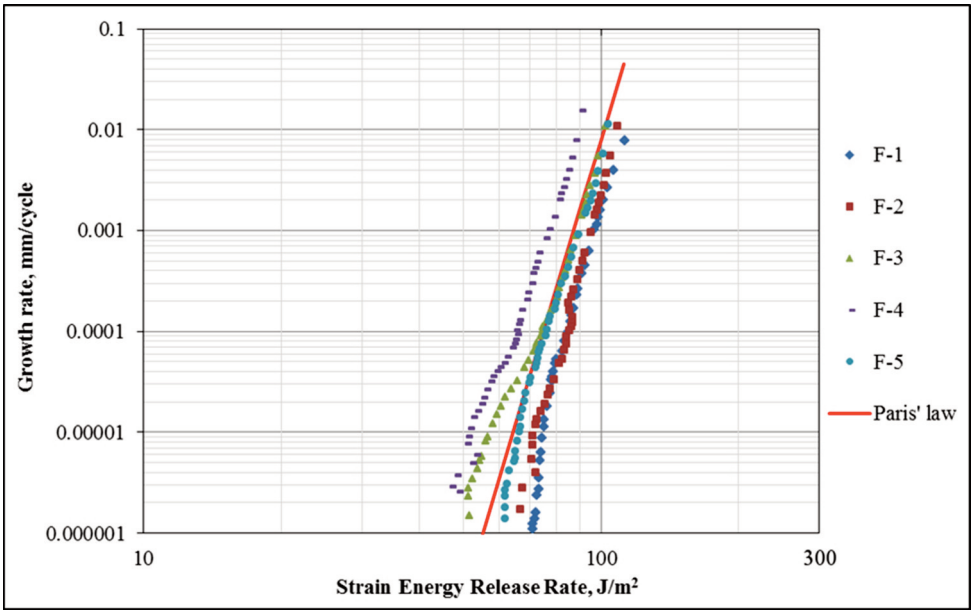


Fig. 8. Relationship between the delamination growth rate and SERR value for the tested specimens [Wilk, 2016]

## 4. CONCLUSIONS

The method presented in the paper was successfully implemented in the laboratory. Its major advantage is the elimination of the need of visual inspection of the crack front propagation. It allows for conducting the experiment in automated way, without stops and supervision. Each specimen was subdued to 1 M cycles and a single test was realized in almost 56 hours, which covered two nights: visual observations would considerably extend the duration of the experiment. The approximation of the delamination growth with a power function seems to be the right choice giving good correlation with the lowest coefficient $r^2$ being 0.952 and leading to obtaining consistent results even in the presence of noise in the recorded data. 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 4%, which is considerably lower than 19% obtained in previous testing of the same material using different method [17]. The Paris law was determined for a wide range of SERR, between 46 J/m$^2$ and 112 J/m$^2$. It covered the values from close to critical $G_{Ic}$ to approaching the threshold value below no propagation is observed. The lowest crack growth rates were close to $10^{-6}$ mm/cycle. Further work should include a comparison between the proposed method and one using visual observation of the crack growth.

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

**Streszczenie**

W świetle braku dostępnych unormowanych metod zaprezentowano procedurę eksperymentalnego badania zmęczeniowego rozwoju delaminacji w warunkach I sposobu pękania. Wyróżniającą cechą zaproponowanego algorytmu jest wyznaczanie długości pęknięcia za pomocą podatności badanej próbki oraz dodatkowo przeprowadzanej kalibracji podatności. Zaprezentowane podejście pozwala wyeliminować konieczność obserwacji długości pęknięcia podczas testu. Opisana została krok po kroku metodologia, wykorzystująca próbkę w postaci podwójnej belki wspornikowej (*Double Cantilever Beam*), 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 I sposobu pękania.
Słowa kluczowe: kompozyty, delaminacje, zmęczenie, sposób I pękania, badania mechaniczne.