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THEORY AND
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Piotr Czarnocki

Warsaw University of Technology, Institute of Aeronautics and Applied Mechanics, ul. Nowowiejska 24, 00-665 Warsaw, Poland
Corresponding author. E-mail: pecz@meil.pw.edu.pl

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LINK BETWEEN REINFORCEMENT GEOMETRY OF LAMINA AND DELAMINATION RESISTANCE OF LAMINATES

The purpose of this research was to determine the relationship between the delamination resistance of fabric reinforced laminates and the areal weight (*AW*) of reinforcing fabrics and fibre tow orientations. The laminates were reinforced with 2x2 twill fabrics of *AW* = 161 g/m^2 and *AW* = 395 g/m^2. The tows making up the wefts and warps were oriented at 0°/90° (denoted +) and +45°/–45° (denoted x) relative to the delamination propagation direction. The delamination tests were carried out under Mode I and Mode II quasi static and cyclic loading conditions. These tests were complemented with impact tests. For Mode I loading, it was found that G_{Ic} was not dependent either on the *AW* of the fabrics nor on the tow orientations. Similar results were obtained for cyclic loading. Unlike for Mode I, for Mode II loading the highest G_{IIc} value was found for the laminate reinforced with fabric of *AW* = 395 g/m^2 and tow orientation "x" while the lowest one was for laminates reinforced with the same fabric but of a "+" tow orientation. Drop tests indicated that the laminates reinforced with fabrics of the higher *AW* had better resistance to impact induced damage.

Keywords: laminates, delamination, fatigue, impact

POWIĄZANIA MIĘDZY GEOMETRIĄ WZMOCNIENIA LAMINATÓW A ICH ODPORNOŚCIĄ NA DELAMINACJĘ

Wygodną w zastosowaniach formą wzmocnienia, ze względu na łatwość formowania, są tkaniny. W szczególności jest to istotne, jeśli formowany wyrób ograniczają opływowe powierzchnie, o podwójnej krzywiźnie, jak ma to miejsce np. w przypadku samolotów. Celem badań było wyznaczenie zależności pomiędzy odpornością na delaminację laminatów wzmocnionych tkaninami a gramaturą tkanin oraz orientacją wiązek włókien (wątku i osnowy). Wyników takich badań w dostępnej literaturze nie znaleziono. Wzmocnienie stanowiły tkaniny Interglas 92110 i Interglas 92140 o gramaturach 161 i 395 g/m^2 i splocie skośnym. Rozpatrywano dwie orientacje wiązek włókien: wiązki tworzące wątek i osnowę były zorientowane odpowiednio pod kątem 0° i 90° (oznaczenie „+") oraz pod kątem +45° i –45° (oznaczenie „x") w stosunku do kierunku rozwoju delaminacji. Spoiwo stanowiła żywica epoksydowa L335 utwardzana utwardzaczem H335+H340. Odporność na rozwarstwienia badano w warunkach I i II sposobu pękania, spowodowanych obciążeniami quasi statycznymi i cyklicznymi. Ze względu na brak norm do badania odporności na rozwarstwienia laminatów wzmocnionych tkaniami, w warunkach obciążeń quasi-statycznych, tam gdzie było to możliwe, starano się wykorzystać normy ASTM, oryginalnie opracowane do badań laminatów zawierających wzmocnienie w postaci jednokierunkowej. Z powodu braku jakichkolwiek norm do wykonania analogicznych badań w warunkach obciążeni cyklicznych zastosowano autorską procedurę. Wykonano także próby udarnościowe laminatów o takiej samej strukturze. Wszystkie badania przeprowadzono w temperaturze pokojowej. Wyniki badań w odniesieniu do obciążeń quasi-statycznych wykazały, iż w warunkach I sposobu pękania nie ma statystycznie istotnych różnic między średnimi wartościami współczynników uwalniania energii, otrzymanych dla laminatów różniących się gramaturą tkanin ani ich orientacją. Na tej podstawie wysnuto przypuszczenie, iż zachodzący w tych warunkach proces delaminacji jest kontrolowany przez właściwości mechaniczne spoiwa. W przypadku II sposobu pękania różnice takie występowały. Najwyższą odporność na delaminacje wykazał laminat wzmocniony tkaniną o gramaturze 161 g/m^2 i konfiguracji „x", a najniższą laminat o tym samym wzmocnieniu i konfiguracji „+". Próby zrzutu wykazały, iż większą odpornością na uszkodzenia udarowe charakteryzował się laminat wzmocniony tkaninami o większej gramaturze. Można to uzasadnić wyższą wytrzymałością na zerwanie wiązek wzmocnienia o większym przekroju, znajdujących się w tkaninach o większej gramaturze.

Słowa kluczowe: laminaty, delaminacja, zmęczenie, uderzenie

INTRODUCTION

The main weakness of polymer matrix laminates (PML) consists in their low resistance to delamination and as a consequence of this property, the susceptibility of laminates to impact damage. Laminates are often reinforced with fabrics because of their good formability which is of particular importance in the case of products with a double curvature surface, e.g. streamline airframe parts. Laminates of the same reinforcement volume or mass fraction can be obtained with fabrics of different areal weights (*AW*) by varying the number of fabric layers accordingly. For fabrics of the same weave patterns, the *AW* and the cross-sections of warp end and weft peak cross-sections, and yarn crimps are mutually connected to each other, i.e. a reduction in warp end and weft peak cross-sections results in a reduction in *AW* and yarn crimp. (For a definition of the technical terms used in the industry related to textile fabrics see [1]). A great deal of attention has been paid to the effects exerted on the G_{Ic} and G_{IIc} values by the reinforcement arrangement. However, the majority the published papers have focused on UD reinforcement, e.g., [2-8]. In spite of the broad use of fabric reinforcement, relevant, accessible literature is rather scarce. Some information can be found in [9-13] in the case of quasi static loading, and in [14-18] in the case of cyclic loading. In particular, the influence of such fabric features like the size, spacing and yarn crimp on the G_c values are still not well understood. In undertaking the presented research, the assumption was made that resistance to delamination under static and cyclic loadings as well as laminate impact resistance could depend on the reinforcement orientation with respect to the direction of delamination propagation and on the reinforcing fabric areal weight (*AW*) being a derivative of the tow cross-sections.

Due to some issues being out of the scope of this paper and related to the manufacture of laminate structures, the *AWs* of the commonly used fabrics range between 150 and 400 g/m^2, approximately. For this reason, the laminates selected for testing were reinforced with commercially available 2x2 twill fabrics: Interglas 92110 of *AW* = 165 g/m^2 ±5% and Interglas 92140 of *AW* = 395 g/m^2 ±5% (determined according to DIN EN 12127 recommendations), which could be regarded as ones representing the lower and upper limits of the mentioned parameter, from a practical point of view.

In the case of the former, the warp tex and yarn tex were the same and equal to 68 g, and in the case of the latter, the warp yarn tex was 340 g and the weft yarn tex was 272 g (determined according to DIN EN 12654 recommendations). It can be estimated based on the standard recommendations, (i.e., the accuracy of length measurement should not be lower than 0.3% and the balance accuracy should not be less than 0.1 mg) that the tex measurement errors were not higher than ±.0015 g/m in all the cases. The thicknesses of the dry fabrics were 0.18 mm ±5% and 0.45 mm ±5%, respectively (determined according to DIN ISO 4603/E recommendations) [19]. Assuming that the E-glass density is equal to 2.55 g/cm^3, one can calculate the filament numbers. In the case of Interglas 92140, they were equal to 2097 and 1678 in the warp and weft directions respectively, and in the case of Interglas 92110, they were equal to 419 g/m^3 in both directions. The tows making up the wefts and warps were oriented at 0°/90° (denoted by "+") and +45°/–45° (denoted by "x") relative to the delamination propagation direction. The delamination tests were carried out under Mode I and Mode II quasi static and cyclic loading conditions. For laminates, the G_c values significantly differ depending on the fracture mode. It has been noticed that for embedded delaminations, fracture Modes I and II prevail and Mode III can be neglected. In such a case, the lower and upper bands for G_c are G_{Ic} and G_{IIc}, respectively. In the case of quasi-static loading, the tests for determining G_{Ic} and G_{IIc} have been standardized [20, 21], unfortunately it is not the case for cyclic loading. In this case, delamination resistance can be defined via the Paris law (3) and several procedures for obtaining this relationship can be used [22-24]. Often, the procedure designed for metals is adopted, [25], however, it involves the so-called 7-point interpolation procedure used for determining the $da/dn = f(n)$ relationship. Unfortunately, this procedure yields a large scatter of results in the case of laminates. Therefore, for the presented research another procedure was used involving interpolation of the $da/dn = f(n)$ relationship based on the consideration of a complete set of raw data, at the same time. This procedure yields a much lower result scatter. The details can be found in [26]. Delamination is among several damage mechanisms that contribute to impact damage, but perhaps it is the most significant one. Therefore, impact tests were performed to investigate how the change in fabric *AW* transforms into changes in the resistance of laminates to impact damage.

TESTS

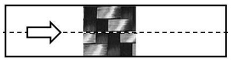
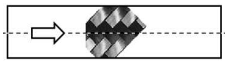
Scope of experimental work

The laminates were tested for delamination resistance under Mode I and Mode II quasi static and cyclic loadings. These tests were complemented with impact tests.

Tested laminates

L335 resin with an H335+H340 hardener system was used for fabric impregnation done with a vacuum-assisted, wet lay-up technique. Nominal mass fiber volume fraction m_f = 0.5. The *AWs* of the laminates reinforced with Interglas 92110 and 92140 were 6600 g/m^2 and 7800 g/m^2, respectively. The laminates were cured for 24 h at room temperature and then post cured for 8 h at 55°C. Information concerning the structures of the tested laminates are given in Table 1.

TABLE 1. **Structures of tested laminates**
TABELA 1. **Struktura badanych laminatów**

	Laminate denotation	**Fabric denotation**	**No. of layers**
	LA92110 +	92110	20*
	LA92140+	92149	10**
	LA92110x	92110	20*
	LA92140x	92140	10**
Resultant thickness of laminate: *) 2.6 mm, **) 3.6 mm			

Quasi static delamination tests

When possible, Mode I and Mode II delamination tests were carried out adopting ASTM standards [18, 19]. In principle, these standards were designed for testing UD laminates and for this reason the standard's recommendations could not be strictly followed. The tests were carried out at room temperature with the help of an Instron 8650 machine equipped with a 1 kN load cell. The cross-head speed for Mode I tests was 5 mm/min and for Mode II 1 mm/min. Six specimens were tested for each laminate design.

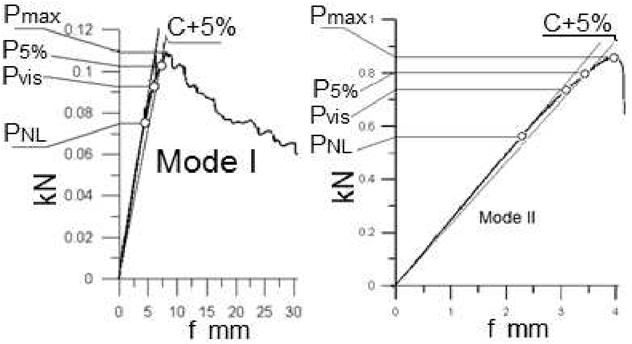


Fig. 1. Typical force-displacement plots for Mode I (DCB) and Mode II (ENF) delamination tests

Rys. 1. Typowe wykresy zależności siła-przemieszczenie dla I(DCB) i II (ENF) sposobu pękania

Typical $P(f)$ diagrams obtained from Mode I and Mode II tests run with the use of DCB [20] and ENF [21] specimens, are shown in Figure 1. Several characteristic force values can be distinguished: P_{NL}, corresponding to the onset of nonlinearity, $P_{5\%C}$, corresponding to the 5% increase in compliance and P_{max}. By substituting these force values for P in (1), one can get different of G_{Ic} values, however, for further analysis the P_{max} values were considered since they were clearly defined.

To determine G_{Ic}, the Modified Beam Theory Method was used and the G_{Ic} values were calculated with the help of

$$G_{Ic} = \frac{3Pf}{2b(a_0 + \Delta)} \tag{1}$$

where: P - the load, f - the load point displacement, b - the beam specimen width, a_0 - the delamination length measured from the load application point, Δ - the delamination length correction accounting for imperfect build-in of loaded DCB specimen parts.

The delamination length correction, Δ, was determined experimentally by constructing a least squares plot of the cube root of compliance $C^{1/3}$ as a function of delamination length, a, as recommended in [20]. In the case of Mode II, the tests were run with the help of ENF specimens [21]. For typical initial delamination length, a_0, the delamination propagation process is not stable and delamination initiation is clearly defined by P_{max}. The G_{IIc} values can be calculated with

$$G_{IIc} = \frac{3mP^2 a_0^2}{2b} \tag{2}$$

where m is the slope of compliance $C = A + ma^3$ determined experimentally with the least squares plot of compliance C versus a^3 relationship determined according to [21].

Fatigue delamination tests

Three specimens were tested for each laminate design to determine the delamination rates. They can be defined by the Paris law

$$\frac{da}{dn} = \alpha (G_{\max})^{\beta} \tag{3}$$

Often for this purpose, a standard method [25] designed for metals, in principle, is adopted [22, 23] and the procedure to determine the Paris law is as follows. The tests are run under displacement amplitude control and P_{max} variations with the number of cycles, n, and delamination growth, a, with the number of cycles, n, recorded yielding a complete set of raw data. The delamination growth is monitored with the help of a travelling microscope and the elapsed numbers of cycles are recorded for the assumed Δa intervals. Relationship $a(n)$ is obtained in a discrete form. The G values are calculated for the recorded pairs of the corresponding delamination length values, a, and the elapsed number of cycles, n. Next, the da/dn relationship is constructed with the help of the 7-point interpolation procedure [25] and the values of the α and β coefficients (3) are determined by curve fitting.

The procedure applied in the presented research was a modification of the aforementioned one. The modification consisted in determining specimen compliance $C = f/P$ needed to determine the delamination length versus the number of elapsed cycles, $a(n)$. This relationship was approximated with a sigmoidal function involving the entire set of data. The resulting analytical form of the $a(n)$ relationship was differentiated to obtain the da/dn relationship. Such a procedure allowed for eliminating the 7-point interpolation procedure which yielded a large scatter of data and for eliminating the need for visual monitoring of the delamination growth as well. The procedure was described in detail in [26]. Both the Mode I and Mode II tests were run at room temperature with cycle asymmetry coefficient $R = 0.1$, and frequency 5 Hz.

Impact test

Impact tests were carried out at room temperature with the help of an Instron Drop Tower 9350 tester. 100x150 mm plates of the same structure as in the case of the specimens for delamination tests were subjected to 16, 18 and 20 J impacts exerted by an impactor ended with a 12.7 mm diameter hemisphere. In the course of impacts, the plates were supported by an 80 mm diameter steel ring. For each laminate design one specimen was tested.

RESULTS AND DISCUSSION

Quasi static loading

Bar charts representing the G_{Ic} and G_{IIc} values for quasi-static loadings are shown in Figure 2.

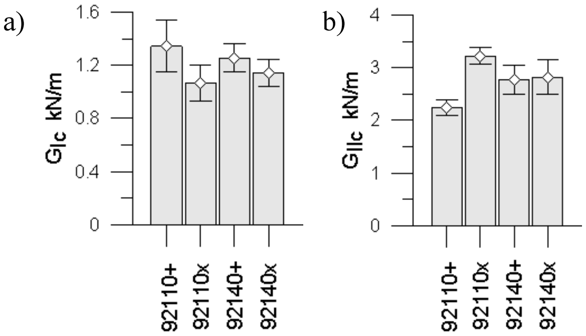


Fig. 2. Results of quasi static tests with 95% CI marked: a) G_{Ic} values; b) G_{IIc} values

Rys. 2. Wyniki prób quasi-statycznych z zaznaczonymi 95% przedziałami ufności: a) wartości G_{Ic}; b) wartości G_{IIc}

To state the statistically significant differences in the average G_c values for laminates reinforced with fabrics of $AW = 161$ g/m^2 and of $AW = 395$ g/m^2, and for laminates reinforced with the same fabrics, but of two different configurations, i.e.: "+' and "x", *t*-tests were carried out. At the 95% confidence level, the following null hypotheses were tested for Mode I and Mode II fracture concerning "+" and "x" reinforcement configurations as well:

H_{01}: there is no difference between the G_{Ic} averages for laminates reinforced with fabrics of $AW = 161$ g/m^2 and $AW = 395$ g/m^2

H_{02}: for laminates reinforced with a fabric of $AW = 161$ g/m^2 there is no difference between the G_{Ic} averages for laminates reinforced with fabrics of "+" and "x" configurations

H_{03}: for laminates reinforced with a fabric of $AW = 395$ g/m^2 there is no difference between the G_{Ic} averages for laminates reinforced with fabrics of "+" and "x" configurations

The same null hypotheses were tested for Mode II loading.

The following conclusions were drawn:

1. In general, all the laminates displayed higher resistance to delamination for Mode II loading than for Mode I.
2. The differences between the average G_{Ic} values for laminates reinforced with fabrics of low and high *AWs* were not statistically significant either for the "+" nor for the "x" configuration.
3. The differences between the average G_{IIc} values for laminates reinforced with fabrics of low and high *AWs* was statistically significant for both the "+" and "x" configurations.
4. For laminates reinforced with fabrics of $AW = 161$ g/m^2, the statistically significant difference of the average G_{IIc} values occurred for laminates with "+" and "x" reinforcement configurations.

The aforementioned lack of significant difference in delamination resistance suggested that this property could be matrix controlled.

Cyclic loading

The results of fatigue tests are presented in the form of Paris law (3). The coefficients of equation (3) are provided in Table 2 and the corresponding plots are shown in Figure 3. Inspection of the graphs in Figure 3 indicated that the delamination propagation rates for Mode I were higher than those for Mode II for both the *AWs* of reinforcement and reinforcement configurations. The differences in the delamination propagation rates were smaller for Mode I loading than that for Mode II which reflected the lack of statistically significant differences in G_{Ic} values as opposed to G_{IIc} values. For Mode II loading, the delamination rate was the highest for Laminate 92110+ which displayed the lowest G_{IIc} value. However, for the other laminates such a correspondence was not noticed.

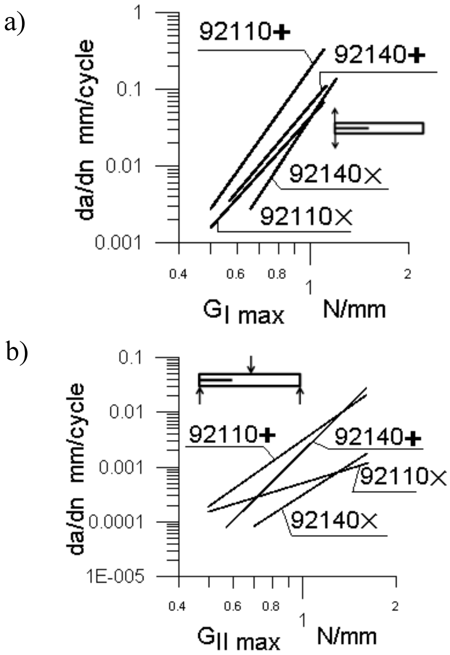


Fig. 3. Paris laws for: a) Mode I and b) Mode II

Rys. 3. Prawo Parisa: a) I i b) II sposobu pękania

TABLE 2. **Coefficients of Paris law equation**

TABELA 2. **Współczynniki równania prawa Parisa**

Mode I			Mode II	
Laminate	α	β	α	β
LA92110 +	0.183	6.05	0.0031	4.03
LA92110 x	0.042	4.75	0.00051	1.74
LC92140 +	0.062	5.10	0.00192	5.66
LC92140 x	0.041	6.53	0.00031	3.67

Impact tests

The results of the impact tests are presented in Figure 4. A higher ability of energy dissipation was observed in the case of the laminate reinforced with a larger number of lower *AW* fabrics (Fig. 4a). On the other hand, the laminate reinforced with fabrics of the higher *AW* displayed higher resistance to damage. The maximum contact forces were higher for this laminate, (Fig. 4b), and the amounts of dissipated energy were lower comparing to that of the laminates reinforced with fabrics of the lower *AW*. Such a response could be attributed to the larger cross sections of tows forming the fabrics of the higher *AW* making them less vulnerable to rupture.

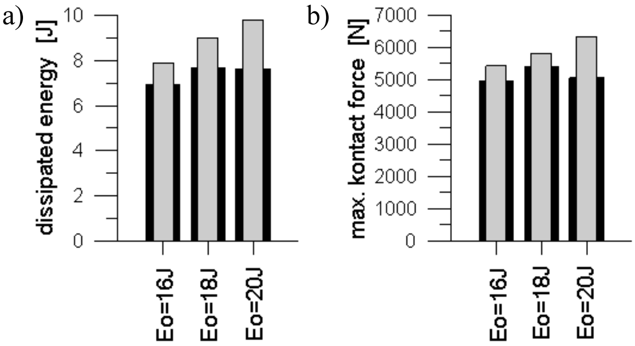


Fig. 4. Results of impact tests. In gray results for laminate reinforced with fabric of *AW* = 395 g/m^2, in black results for laminate reinforced with fabric of *AW* = 161 g/m^2

Rys. 4. Wyniki próby zrzutu. W kolorze szarym wyniki dla laminatu zawierającego wzmocnienie o gramaturze 395 g/m^2, w czarnym o gramaturze 161 g/m^2

CONCLUSIONS

Four glass-epoxy laminates reinforced with fabrics of *AW* = 161 g/m^2 and *AW* = 395 g/m^2, and of "+" and "x" reinforcement configurations were tested for their resistance to delamination under quasi static and cyclic Mode I and Mode II loadings. In addition, several impact tests were performed to investigate the resistance of the aforementioned laminates to impact damage. It was found that there was no statistically significant difference in the average values of G_{Ic} for laminates made of low and high *AW* fabrics. In the case of Mode II quasi static loading, it was found that the average G_{IIc} values displayed statistically significant differences for laminates of different reinforcement *AWs* and different reinforcement configurations. The highest resistance against delamination was displayed by the laminate of the "x" reinforcement configuration and *AW* = 161 g/m^2 while the lowest one was the laminate made with the same fabrics but of a "+" reinforcement configuration. The delamination rates for all the tested laminates were higher under Mode I than under Mode II loading conditions and were similar to the former. Under Mode II loading, the differences in the delamination rates were pronounced and the lowest one was displayed by the laminate of the "x" reinforcement configuration and reinforced with fabrics of *AW* = 395 g/m^2, while the highest was for the laminate of the "+" reinforcement configuration and reinforced with a fabric of *AW* = 161 g/m^2. The impact tests indicated that the laminates reinforced with fabrics of the higher *AW* offered higher resistance to impact induced damage than those reinforced with fabrics of the lower *AW*. It could be attributed to the larger cross sections of fibre tows in the case of the higher *AW* fabric and resulting from this lower vulnerability to fibre rupture.

One should bear in mind that the aforementioned statements make reference to the particular laminates tested and do not constitute a basis for generalizations yet.

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