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COMPOSITES THEORY AND PRACTICE

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THE INFLUENCE OF IMPACTOR ENERGY AND GEOMETRY ON DEGREE OF DAMAGE OF GLASS FIBER REINFORCED POLYMER SUBJECTED TO LOW-VELOCITY IMPACT

The presented research was devoted to determining the influence of impactor geometry on the degree and character of failure of a glass fibre reinforced epoxy matrix subjected to low-velocity impact. Furthermore, the relevance of impact energy and lay-up configuration of each composite plate were analysed. The subject of the tests were autoclave manufactured 8-ply glass/epoxy prepregs of the following lay-up $[0/90]_{2s}$, $[\pm45]_{2s}$ and $[0/\pm45/90]_s$. The laminates were subjected to low-velocity impact tests according to norm ASTM D7136 with the application of hemispherical impactors: 12.7 mm (0.5"), 25.4 mm (1") and 38.1 mm (1.5"), for three impact energies 5, 10 and 15 J. The conducted tests indicate the correlation between the diameter of the indenter and the load applied, on the degree and character of damage of the glass/epoxy composites, i.e. the higher the load, the greater the laminate failure, regardless of the lay-up configuration. Similarly, the degree of failure is greater when the diameter of the hemispherical impactor is smaller. The dominating types of failure are delaminations at the interface between the composite layers, and matrix cracks. This might occur as a result of considerable shear stresses at the laminate interface and delamination observed after impact with a smaller-diameter impactor. This is best observed in the case of a quasi-isotropic lay-up configuration, where the superposition of the delamination surface area was the highest. The use of a hemispherical impactor of the largest diameter causes bending stresses in the lower layers of the composite, and the presence of characteristic cracks in the matrix and/or at the fibre/matrix interface.

Keywords: fibre-reinforced polymer composite, low-velocity impact, delamination, impactor geometry, failure

WPŁYW ENERGII I GEOMETRII WGŁĘBNIKA NA STOPIEŃ ZNISZCZENIA KOMPOZYTÓW O OSNOWIE POLIMEROWEJ WZMOCNIONYCH WŁÓKNAMI SZKLANYMI PODDANYCH OBCIĄŻENIOM DYNAMICZNYM O NISKIEJ PRĘDKOŚCI

Celem pracy było określenie wpływu geometrii wgłębnika na stopień i charakter zniszczenia kompozytów o osnowie epoksydowej wzmacnianych włóknem szklanym poddanych obciążeniom dynamicznym o niskiej prędkości. Ponadto w pracy dokonano analizy wpływu energii uderzenia oraz konfiguracji laminatu o różnym ułożeniu poszczególnych warstw kompozytowych. Przedmiotem badań były 8-warstwowe laminaty o osnowie epoksydowej wzmocnionej włóknem szklanym w układach $[0/90]_{2s}$, $[\pm45]_{2s}$ oraz $[0/\pm45/90]_s$, wytworzone metodą autoklawową. Laminaty zostały poddane testom obciążeń dynamicznych zgodnie z normą ASTM D7136 z zastosowaniem wgłębnika półsferycznego o średnicach 12,7 mm (0,5"), 25,4 mm (1") oraz 38,1 mm (1,5") dla trzech energii uderzenia 5, 10 oraz 15 J. Wyniki przeprowadzonych badań wskazują na wpływ średnicy wgłębnika w zależności od energii uderzenia na stopień i charakter zniszczenia laminatów o osnowie epoksydowej wzmacnianej włóknem szklanym. Wraz ze wzrostem wartości energii obciążenia dynamicznego wzrasta stopień zniszczenia laminatów, niezależnie od konfiguracji warstw. Analogicznie, stopień zniszczenia wzrasta wraz ze zmniejszeniem średnicy wgłębnika półsferycznego. Dominującym charakterem zniszczenia są deliminacje na powierzchni rozdziału poszczególnych warstw kompozytowych oraz pęknięcia. Prawdopodobnie związane jest to z obecnością w strukturze kompozytowej dużych naprężeń ścinających na powierzchni rozdziału warstw i powstawaniem delaminacji przy obciążeniach dynamicznych wgłębnikami o mniejszych średnicach. W szczególności widoczne jest dla laminatu o układzie quasi-izotropowym o największej zmienności ułożenia poszczególnych warstw kompozytowych, w którym odnotowano największą superpozycję obszaru zniszczenia badanych laminatów. Zastosowanie natomiast wgłębnika o największej średnicy powoduje powstawanie naprężeń zginających w dolnych strefach kompozytu i obecność charakterystycznych pęknięć w materiale osnowy i/lub na powierzchni rozdziału włókno-osnowa.

Słowa kluczowe: kompozyty polimerowo-włókniste, obciążenia dynamiczne, delaminacje, geometria wgłębnika, zniszczenie

INTRODUCTION

Polymer matrix composites with fibre reinforcement are modern materials applied in e.g. the aircraft industry. They are characterised by high strength properties achieved at low density. Despite the numerous advantages, the composite in question does, however, exhibit an array of disadvantageous properties. Such material is highly susceptible to low-energy impact, which occurs in operation. In terms of aircraft structures, such loads might be applied when hit by e.g. ice, birds, stones or service tools. When compared with the effect of such loads on classic materials (e.g. metals) here the degradation of the internal structure of the composite is incomparably higher, even under relatively small impact loads. Depending on the energy and the geometry of the impactor, such an impact can produce Non Visible Impact Damage (NVID), Barely Visible Impact Damage (BVID) or perforation of the composite plate. Among laminate failure mechanisms, we can distinguish matrix cracks or fibre fractures [1, 2]. Another type of failure is delamination [3]. Frequently, this damage is difficult to diagnose [4-6], however, if undetected it can lead to a decrease in the strength of the composite structure in operation [1-3]. It is for that reason that composite laminate failure caused by low-velocity impact and their structure degradation mechanisms are carefully studied.

In the majority of published academic research, the tests are conducted on a single type of impactor, usually hemispherical. Nevertheless, in real conditions the objects which come in contact with the composite structure can be of various geometries. Available literature in the field describes research into the low-velocity impact of composite plates with respect to the influence of impactor geometry and impact energy on the form and degree of delamination. Lee et al. [7] conducted low-velocity impact tests on carbon, glass and Kevlar fibre-reinforced hybrid composite plates with a polyester matrix. The tests analysed three types of impactors: conical, hemispherical and flat. It was observed that flat and hemispherical impactors cause comparable damage and dissipation of energy, whereas the conical shape caused a different type of material failure, i.e. local penetration of the plate.

Mitrevski et al. [8] analysed the results of low-velocity impact tests of carbon/epoxy plates with conical, ogival and hemispherical impactors. His prominent observation was that a plate under the load of a hemispherical impactor exhibits higher load-carrying capabilities than in the case of an impactor of a different shape. In addition, the time of contact between the impactor and carbon/epoxy plate, at a given impact energy, was the shortest. In the case of a conical impactor, the opposite tendency was observed: the time of contact of the impactor with the plate was the longest. Simultaneously, the conical impactor caused the lowest impact response of the plate of all the analysed geometries. The author of [8] concluded that prolonged contact is connected with perforation of the plate by the sharp tip of the impactor as well as with friction, effectively decreasing the velocity of the impactor. The results of low-velocity impact tests with the ogival indenter, impact response of the plate and plate-indenter contact time, were in-between the hemispherical and conical indenters.

Sevkat et al. [9] performed low-velocity impact tests on hybrid carbon/glass composite plates with an epoxy matrix. Four types of impactors were used in the tests: flat surface and round cross-section 12.7 mm (0.5") in diameter, flat surface and square cross-section (Charpy type), surface length 25.4 mm (1"), and two hemispherical impactors: 12.7 mm (0.5") and 25.4 mm (1"). According to the author of [9], the contact area between the indenter and composite is critical for the phenomena required for the impact response to occur. The largest delamination area was observed under loading with Charpy impactor type. When loaded with a hemispherical tip, the 25.4 mm in diameter one produced a larger area of delamination than the 12.7 mm one. The results obtained under loading with the indenter with a flat surface and round cross-section were in between the Charpy and hemispherical impator.

Literature data analysis confirms the need for further research into determining the influence of impact energy and geometry of the impactor and laminate lay-up configuration on the degree and character of failure. The presented research is aimed at evaluating the influence of impact energy and geometry of the impactor on the degree and character of failure of composites with an epoxy matrix reinforced with glass fibre under low-velocity impact. Moreover, the paper analyses the influence of such factors as impact energy and lay-up configurations.

MATERIALS AND METHODS

Glass fibre reinforced polymer (GFRP) was subjected to tests. Unidirectional epoxy prepregs (Gurit SE 70, UK) were used to produce 8-ply composite plates of the following lay-up $[0/90]_{2s}$, $[\pm 45]_{2s}$ and $[0/\pm 45/90]_s$. Composite plates with dimensions 150 x 100 mm and 2 mm thick were produced at the Materials Science and Engineering Department of Lublin University of Technology using the autoclave method (Scholz Maschinenbau, Germany). Curing was conducted in the following conditions: curing time 120 min, curing temperature 135°C, heating/cooling rate 2°C/min, pressure 0.4 MPa, vacuum 0.08 MPa. Selected strength parameters of the laminate are shown in Table 1.

The manufactured GFRP laminates were subjected to low-velocity impact tests, according to standard ASTM D7136 [10], with the use of a drop-weight impact tower (INSTRON 9340, UK). Low-velocity impact tests of GFRP plates were carried out with hemispherical impactors of 12.7 mm (0.5"), 25.4 mm (1") and 38.1 mm (1.5"), for three impact energies - 5, 10 and 15 J. The created indentation was evaluated using macroscopic analysis of the impact area, for which the superposition of the damage area of delamination was determined with the use of computer image analysis software (Image Pro-Plus).

TABLE 1. **Selected strength parameters of tested laminate**
TABELA 1. **Wybrane właściwości wytrzymałościowe badanych laminatów**

Young's modulus in longitudinal direction	Young's modulus in perpendicular direction	Shear modulus	Poisson ratio	Tensile strength in longitudinal direction	Tensile strength in perpendicular direction	Shearing strength	Compression strength in longitudinal direction	Compression strength in perpendicular direction
E_1	E_2	G_{12}	ν_{12}	T_1	T_2	S_{12}	C_1	C_2
[GPa]	[GPa]	[GPa]	[-]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]
38.5	8.1	2.0	0.27	792	39	108	679	71

RESULTS AND DISCUSSION

Figures 1-3 show macroscopic photographs of composite damage as a result of different impact energies and different impactor diameters. Two types of laminate failure were considered dominating in the tests - delamination and transverse cracking.

Delamination under loading with 0.5" and 1" indenters and at higher energy appears as darker and lighter areas. This indicates that delamination occurred at different interfaces between the layers in the cross-section and that it differs in terms of shape and area.

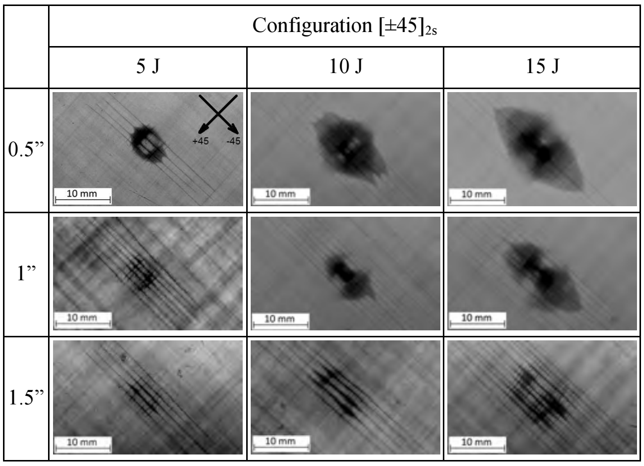


Fig. 1. Typical failure of GFRP plates with $[\pm 45]_{2s}$ configuration
Rys. 1. Typowe zniszczenia płyt GFRP w układzie $[\pm 45]_{2s}$

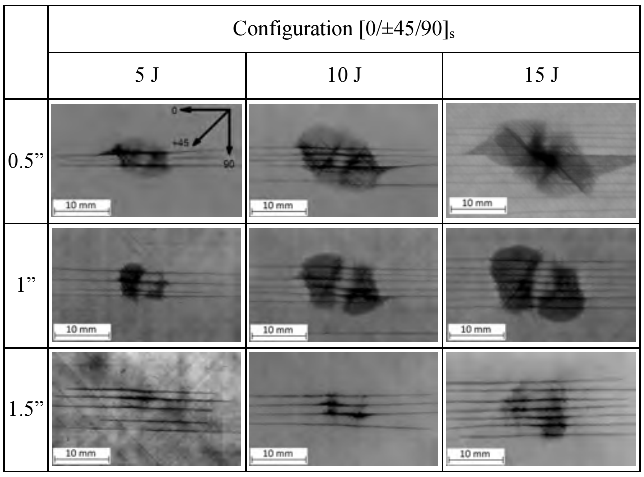


Fig. 2. Typical failure of GFRP plates with $[0/\pm 45/90]_s$ configuration
Rys. 2. Typowe zniszczenia płyt GFRP w układzie $[0/\pm 45/90]_s$

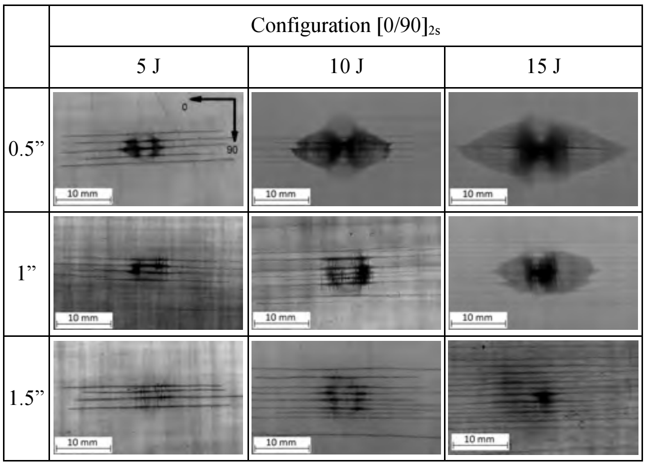


Fig. 3. Typical failure of GFRP plates with $[0/90]_{2s}$ configuration
Rys. 3. Typowe zniszczenia płyt GFRP w układzie $[0/90]_{2s}$

The size and shape of superposition of the delamination damage area showed significant differences in the various tested configurations - $[0/\pm 45/90]_s$, $[0/90]_{2s}$, and $[\pm 45]_{2s}$. In all the analysed configurations, the overall shape of the delamination resembled an ellipsis, with major axes of delamination parallel to that of the composite fibres.

The observations of the authors of this paper and the literature review indicate that the orientation of the major axes of delamination between two laminae of different lay-up will correspond to the orientation of the lower laminate layer [3, 11, 12]. According to literature [13], the phenomenon of delamination occurs as a result of differences in bending stiffness of the composite laminae of a quasi-isotropic lay-up. These differences in bending stiffness are related to the considerable anisotropy of the mechanical properties of fibrous laminates, especially of the Young’s modulus in the longitudinal and perpendicular direction to the fibre arrangement (E_1/E_2). Similar relationships were observed by Greenhalgh et al. [14], who researched the low-velocity impact of carbon/epoxy plates. The researchers' conclusion was that delamination propagates towards areas of the greatest difference in the stiffness of the structure. In addition, delamination is caused by lowered stiffness of the material at the laminae interphase, where reinforcement fibre content is lower and matrix content is higher [3, 14].

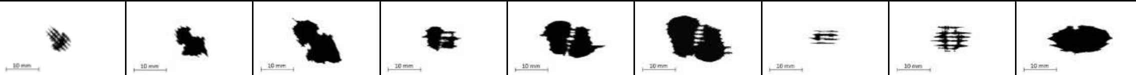
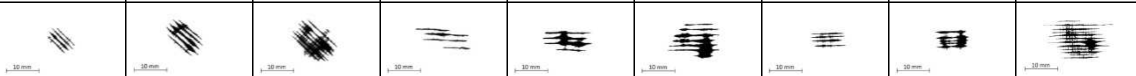
Considerable differences in the character of laminate failure in the composite plates were noted for particular laminae lay-up configurations subjected to equal impact energy with impactors of different geometry. Under impact with a higher-diameter impactor, particularly the 1.5", the dominating failure type was transverse cracking, and to a lesser degree, delamination. The cracks probably occur in the lowest part of the laminate and result from the process of bending in that area, initiated by low-velocity impact. Cracks in the laminates of similar character were noted by Richardson et al. [12] in laminae directed parallel to the reinforcement fibres, and were identified as cracks in the matrix, resulting from mismatch of the mechanical properties of particular components. Delamination and cracking can be alternatively explained by comparing the influence of different impactor geometries on the stress state in loaded plates. Zhou et al. [15] conclude that the higher the diameter of the impactor, the larger the area of impactor-laminate contact, which in turn provides better distribution of load and more favourable stress concentration in the laminate. Smaller-diameter impactors have the opposite effect: more concentrated impactor-plate contact leads to a considerably higher concentration of stresses in the structure of the laminate, particularly in the impact area.

Table 2 shows the delamination surface area and the superposition of the delamination surface area.

The observations indicate the correlation between the size of composite damage, impact energy and impactor geometry in all the analysed laminates. The correlation can be clearly seen in the case of delamination. The highest rate of laminate failure was observed under low-velocity impact with the impactor of the smallest diameter - 0.5". Performing indentation with a 1" impactor produced medium values whereas the highest values were recorded for the highest-diameter impactor - 1.5". It can be noted that applying a higher impact energy of load leads to a more extensive damage surface area in the laminate, regardless of the diameter of the hemispherical impactor. The damage area of laminate failure was the highest in the case of the [0/±45/90]$_s$ configuration, medium values were recorded for the [0/90]$_{2s}$, and the lowest values for the [±45]$_{2s}$ lay-up configuration.

Figure 4 shows the area of delamination with relation to low-velocity impact parameters (energy and geometry of impactor) for GFRP laminates in different configurations.

TABLE 2. **Values of delamination surface area**
TABELA 2. **Wartości pola powierzchni delaminacji**

Diameter \ Energy	[+/–45]$_{2s}$			[0/+45/–45/90]$_s$			[0/90]$_{2s}$		
	5 J	10 J	15 J	5 J	10 J	15 J	5 J	10 J	15 J
Ø 0.5"									
Area [mm^2]	30	113	169	71	142	248	24	135	241
Ø 1"									
Area [mm^2]	23	55	113	46	125	177	17	36	117
Ø 1.5"									
Area [mm^2]	13	35	71	17	36	58	15	29	63

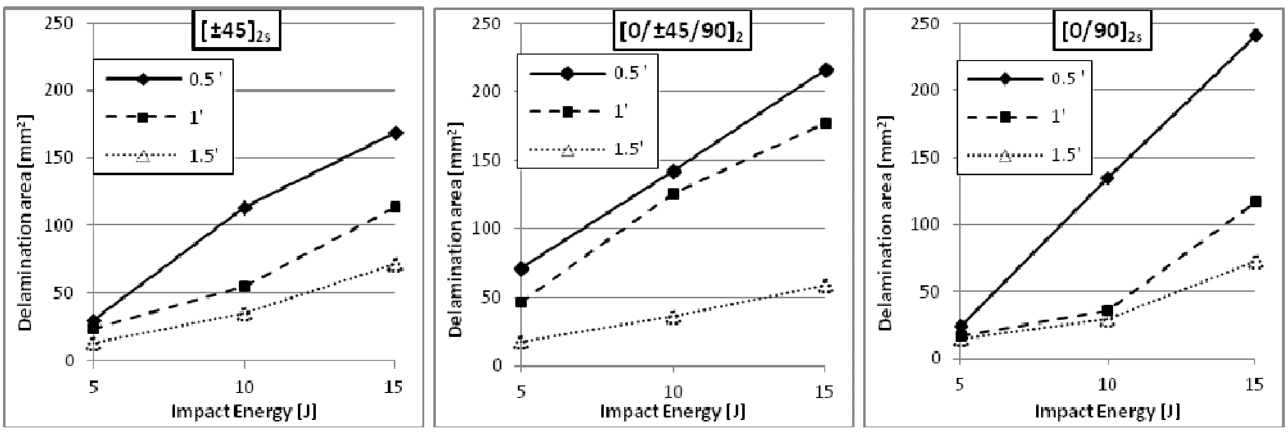


Fig. 4. Relationship between area of delamination and impact energy for analysed laminates

Rys. 4. Zależność pomiędzy polem powierzchni delaminacji a energią obciążenia dynamicznego dla analizowanych laminatów

The analysis of the relationship of the superposition of the delamination area on the value of impact energy concludes that in all the tested configurations, the highest intensity and damage growth in the energy range of 5-15 J is obtained when using the 0.5" impactor. The lowest values were noted in the case of the 1.5" impactor, in all the analysed configurations. The results of damage caused by the 1" impactor were mid-values between the two other impactor diameters.

CONCLUSIONS

The paper presents the test results of low-velocity impact of laminates with different lay-up configurations, with impactors of different geometry and with different impact energy.

The results of the research indicate that, depending on the impact force, the diameter of the impactor influences the character and degree of laminate failure of the glass fibre reinforced epoxy matrix. An increase in impact energy results in more extensive failure of the laminate, regardless of the lay-up configuration. In a similar manner, the degree of damage increases with a decrease in hemispherical impactor diameter.

The dominating type of failure is delamination at the interfaces between the composite layers and cracking. They probably occur on account of shear stresses at the interfaces in the laminate and delamination observed under impact with smaller-diameter impactors. This can be most easily observed in laminates of a quasi-isotropic lay-up configuration, where the superposition of the delamination area was the highest. The use of a large-diameter impactor produces higher bending stresses in the lower layers of the composite, which occur together with characteristic cracks in the matrix and/or at the fibre/matrix interface.

The conducted tests provide information on the character and degree of laminate failure depending on the geometry of the impactor, impact energy and lay-up configuration of the composite. The data can find their application in the preparation of numerical models of laminate failure and in research requiring experimental data of composite structure damage.

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