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COMPOSITES THEORY AND PRACTICE

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COMPARISON OF POLYMER COMPOSITES BEHAVIOR TO LOW-VELOCITY IMPACT AND QUASI-STATIC INDENTATION

Abstract Fibre Reinforced Polymers (composites) are widely used in the aerospace industry due to their excellent quasi--static mechanical properties in relation to density. However, it is known that polymer composites do not have good resistance to dynamic loads, especially to low-velocity impact phenomena, which is one of the most important issues for composite structures, particularly in aerospace due to the effect it has on material structures. The purpose of this study was to investigate the differences in polymer composite behavior between low-velocity impact and the similar (the same boundary conditions) quasi--static indentation. The composites used in this study were: Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP) manufactured by the autoclave method (materials used in aerospace technology). Impact tests were carried out according to the ASTM D7136 standard. Quasi-static indentation was performed according to the ASTM D6264 standard. After the tests, the samples were subjected to non-destructive and microscopic testing methods to investigate the damage size and failure character. It was noted that low-velocity impact causes significant damage to both kinds of composite structures, while the quasi-static indentation under the same impact force level results in some internal degradation of the laminate structures (barely visible damage). However, the size of it is extremely different to the case of low-velocity impact. The failure types of composite structures after static and dynamic loads are similar. The major failure type in composites after static and dynamic loads are matrix cracks, delaminations, and in the case of impact fibres-cracks. To obtain similar damage character and size (as in the impact effect) in the composite structure on account of quasi-static indentation, a much higher force level in comparison to dynamic loads is necessary.

Keywords: polymer composites, static and dynamic loads, failure

PORÓWNANIE ODPOWIEDZI KOMPOZYTÓW POLIMEROWYCH NA OBCIĄŻENIA DYNAMICZNE O NISKIEJ PRĘDKOŚCI ORAZ WCISKANIE STATYCZNE

Polimerowo-włókniste materiały kompozytowe są szeroko stosowane w technice lotniczej z uwagi na korzystne właściwości mechaniczne w odniesieniu do gęstości. Jednak, materiały te charakteryzują się niską odpornością na obciążenia dynamiczne, szczególnie na uderzenia dynamiczne o niskiej prędkości, co jest jednym z najważniejszych zjawisk eksploatacyjnych w technice lotniczej z uwagi na uszkodzenia, jakie może powodować w strukturach kompozytowych. Celem przeprowadzonych badań było porównanie reakcji polimerowo-włóknistych materiałów kompozytowych na obciążenia dynamiczne o niskiej prędkości oraz na analogiczne (te same warunki obciążenia) statyczne wciskanie wgłębnika. Do badań wykorzystano laminat wzmacniany wysokowytrzymałym włóknem węglowym w osnowie żywicy epoksydowej oraz laminat wzmacniany wysokowytrzymałym włóknem szklanym w osnowie żywicy epoksydowej (materiały stosowane w technice lotniczej). Obciążenia dynamiczne zostały przeprowadzone zgodnie z normą ASTM D7136. Próba statycznego wciskania wgłębnika w kompozyt została przeprowadzona zgodnie z normą ASTM D6264. Po badaniach próbki poddano nieniszczącej oraz mikroskopowej ocenie stanu struktury w celu określenia rozmiaru i charakteru powstałego uszkodzenia. Zaobserwowano, że obciążenia dynamiczne o niskiej prędkości powodują znaczące uszkodzenie struktury obu rodzajów kompozytów. Analogiczne obciążenie statyczne przy tej samej sile wywieranej przez wgłębnik na materiał powoduje jedynie makroskopowo niewidoczne uszkodzenie wewnętrzne. Rozmiar uszkodzenia jest skrajnie różny w przypadku obciążeń dynamicznych i statycznych, przy czym charakter uszkodzenia jest zbliżony. Dominującym rodzajem degradacji kompozytów są pęknięcia osnowy i rozwarstwienia oraz pęknięcia włókien w przypadku obciążeń dynamicznych. W celu otrzymania podobnego uszkodzenia laminatów przez statyczne wciskanie wgłębnika niezbędna jest znacznie większa siła wywierana przez wgłębnik na materiał w porównaniu do obciążeń dynamicznych.

Słowa kluczowe: kompozyty polimerowe, obciążenia statyczne i dynamiczne, uszkodzenie

INTRODUCTION

Fibre Reinforced Polymers (composites) are widely used in the aerospace industry due to their excellent quasi-static mechanical properties in relation to density [1-3]. The most common are the Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP). The most important feature (in the context of aerostructure applications) is high tensile, shear and bending strength, high stiffness and fatigue resistance [3]. In fact, composites are most frequently applied in thin-walled plates, rods, tubes or bars which permit one to save energy and reduce the costs of exploitation [4]. This is associated with the fact that many of the elements are exposed to the environment during exploitation. However, it is known that polymer composites do not have good resistance to dynamic loads, especially to low-velocity impact phenomena. According to Vogelesang et al. [5] and Sohn et al. [6] impact damage occurs during pre-flight and taxiing operations, by runway debris, hail, bird strikes, maintenance damage (e.g., dropped tools), collisions with service cars or cargo and the structure, ice from propellers striking the fuselage, engine debris and tire shrapnel from tread separation and tire rupture. The authors [5] noted that 13% of repairs of the primary structure in 71 Boeing 747 aircraft were caused by impact damage. In recent years, some studies have been conducted to investigate the possibilities of predicting the low-velocity impact resistance of some materials [7]. They concluded that the best solution is to use the similar (as the impact phenomena) quasi-static indentation. According to Davies et al. [8] it is possible to use quasi-static indentation to simulate the low-velocity impact resistance of some materials (e.g. carbon composites), but it has a general character. Li Y. et al. [9] showed that there are some similar phenomena between the material reaction scale to impact and quasi-static indentation. On the other hand, Li Y. et al. [9] characterized foam core sandwich composites, so their conclusions can be only indicative in relation to fibre-polymer composites. However, all the studies are consistent, in the fact that low-velocity impact phenomena is one of the most important issues for composite structures, particularly in aerospace due to the effect it has on material structures [6-12].

The purpose of this study was to investigate the differences in polymer composite behavior between low-velocity impact and the similar (the same boundary conditions) quasi-static indentation.

MATERIALS AND EXPERIMENTAL PROCEDURE

The composites used in this study were: Carbon Fibre Reinforced Polymer (CFRP) based on M12 AS7J carbon/epoxy prepreg (0.131 mm thick) (Hexcel, USA) and Glass Fibre Reinforced Polymer (GFRP) based on R-type high-strength glass fibres with an epoxy matrix resin (0.25 mm thick) (Hexcel, USA). The nominal fibre content in both cases was about 60 vol.%. The final thickness of the laminates was 1.5mm. Composites with lay-up in (0/90) stacking sequences were used. The selected basic properties are presented in table 1.

All the composites were made using the autoclave method in the Materials Engineering Department at the Lublin University of Technology according to the following parameters: curing time 120 min, curing temperature 135°C, heating/cooling rate 2°C/min, pressure 0.4 MPa, vacuum 0.08 MPa. Samples of the dimensions 150x100 mm were tested.

TABLE 1. **Selected properties of studied composites.**
TABELA 1. **Wybrane właściwości badanych kompozytów**

Feature material	Density [g/cm^3]	Tensile strength [MPa]	Tensile modulus [GPa]
CFRP (0)	1.55	1867	131
CFRP (90)		26	6
GFRP (0)	1.97	1560	56
GFRP (90)		55	16

The low-velocity impact tests were performed at room temperature using a drop-weight impact tester (InstronDynatup 9340). The impact tests were carried out according to the ASTM D7136 standard [13]. A hemispherical impactor tip with a diameter of 12.7 mm and mass of 1.93 and 2.93 kg was used. The impact velocity was maintained between 3.7 and 4.2 m/s. The impact energy levels of 10 and 25 J were achieved by changing the drop height and mass.

The quasi-static indentations were performed at room temperature using testing machines (ZWICK Z100) according to the ASTM D6264 standard [14]. A hemispherical tip as in the impact test was used. The test speed of the indenter was 1.25 mm/min. The limit of loading force was similar to that received after impact (depending on impact energy) and ranged between 490÷590 N.

After the tests, the samples were studied by using non-destructive (OmniScan MX1 with phased array technique), microscopic (stereoscopically microscope - NIKON SMZ100) and optical microscope (NIKOM MA200) testing methods. The identified damage area was measured using Image ProPlus software.

RESULTS AND DISCUSSION

The comparison of the force as a function of displacement (F-d curves) under low-velocity impact and quasi-static indentation is shown in Figure 1.

The force-displacement curves which represent low-velocity impact are characterized by a section of increasing loading until maximum force (*Pm*) (see Fig. 1a) and next a sharp decline in force. *Pm* is the point where the composites lose their stiffness and continued ability to carry loads such as impact [15, 16]. Some fluctuations in the first part of the loading sections (see Fig. 1) are the result of preliminary vibrations of the sample - indenter system [15, 16]. In the case of quasi-static indentation, the F-d curves are smooth and much more progressive (to obtain the same force value as in the case of low-velocity impact) [15]. The F-d curves obtained from the quasi-static indentation are similar to classic tensile curves in their elastic range. However, one characteristic feature was noted. It is point *Pi* (see Fig 1a) which is called incipient force [17]. *Pi* suggests the first micro-failure in the composite such as matrix cracks or propagated delamination (gradual loss of stiffness of the composite). The same conclusions have been described in several studies [18].

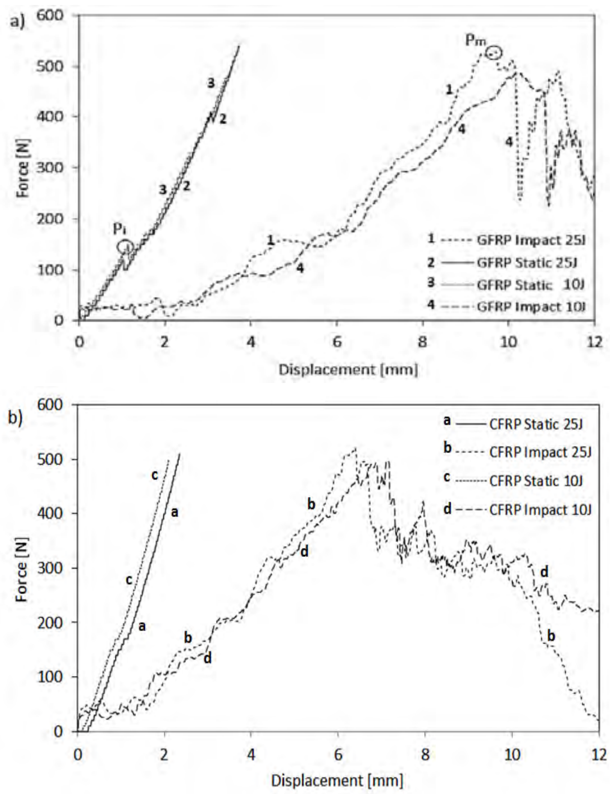

Fig. 1. Typical F-d curves of GFRP (a) and CFRP (b) after low-velocity impact and quasi-static indentation

Rys. 1. Typowe krzywe przebiegu F-d kompozytów GFRP (a) oraz CFRP (b) na skutek uderzeń dynamicznych o niskiej prędkości i wgłębiania statycznego

It was observed that the ability to deform GFRP is higher than in CFRP composites. It is probably caused by the higher stiffness of CFRP. Moreover, this is the reason for the faster destruction of CFRP laminates under low-velocity impact. The higher stiffness of CFRP is proven by the greater angle of inclination of the F-d curve as a result of quasi-static indentation (steeper F-d curve) (see Fig. 1b).

It was noted that between impact energy 10 and 25 J in the case of composites, in principle there are some differences (displacement and angles of the straight part of curves) in force and displacement levels. It is probably caused by the complete degradation of the composites (perforation of CFRP and total delamination of GFRP). Furthermore, a comparison between both kinds of F-d curves indicates that quasi-static indentation does not cause as much composite damage as low-velocity impact [9]. Additionally, this difference is extreme. This is fulfilled for both the CFRP and GFRP laminates (see Fig. 2).

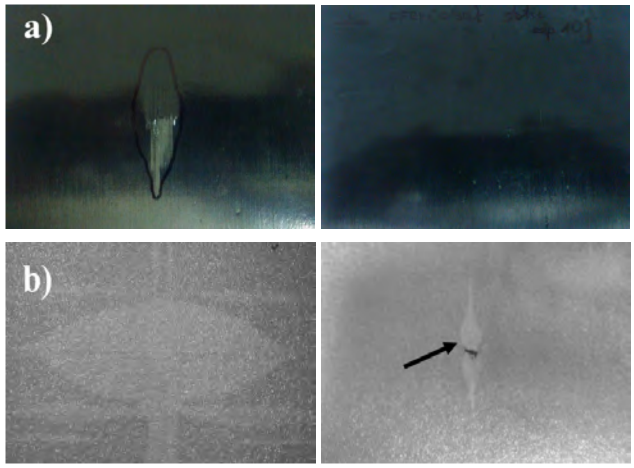

Fig. 2. Macroscopic views of CFRP (a) and GFRP (b) after low-velocity impact 10 J (left) and quasi-static indentation (as 10 J) (right)

Rys. 2. Makroskopowy obraz laminatów CFRP (a) oraz GFRP (b) po obciążeniu dynamicznym o niskiej energii (strona lewa) i statycznym wciskaniu wgłębnika (strona prawa)

As can be noted from the macroscopic view, low-velocity impact causes high degradation of the composites. In the case of the CFRP laminates, the major damage is perforation, but in GFRP there is extensive delamination. This is due to the differences in stiffness between these two materials [19].

The impact damage scale in relation to quasi-static indentation damage is completely different. In the CFRP laminates, damage after static loading is invisible. The composites reaction to static loading under the subjected force level is characterized by barely visible damage (BVD), it means no perforation or any external damage. This degradation character is similar to that caused by low-velocity and low-energy impact (barely visible impact damage) [8]. However, it is known, that BVD is also a kind of internal degradation of composite structures and it is detectable and measurable [20]. GFRP laminates are transparent, therefore the degradation after static loading is visible and occurs in the form of delaminations, as after low-velocity impact (see Fig 2b). Besides that, it was noted that in both types of loading, the direction of delamination propagations is closely related to the fibre directions. The same observations have been noted in several studies [17].

In Figure 3, the results of non-destructive testing of CFRP composites after quasi-static indentation are presented.

It was found that quasi-static indentation is the reason for the internal degradation of CFRP laminates, but not in the case of the equivalent of the 10 J impact (see Fig. 3a). The damage in the second case is very subtle. The structure degradation of CFRP reflected by ultrasonic waves is characterized only by the disappearance of the bottom echo. It can indicate that the major damage character is transverse cracks which are the cause of scattering of ultrasonic waves [21]. However, the damage area was measured, the results of which are presented in Table 2.

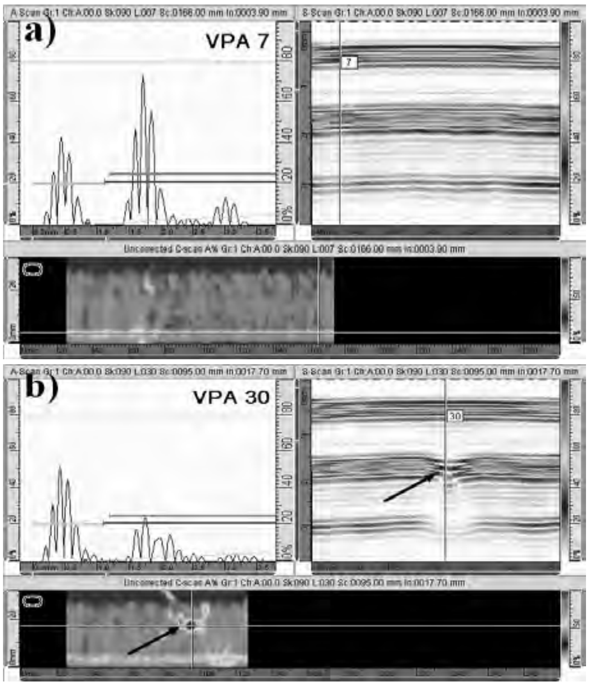

Fig. 3. C-scan views of CFRP after quasi-static indentation equivalent to impact energy 10 J (a) and 25 J (b)

Rys. 3. Obraz typu C-scan laminatów CFRP po statycznym wciskaniu odpowiadającym obciążeniom dynamicznym 10 J (a) oraz 25 J (b)

TABLE 2. **Damage area of composites as result of low-velocity impact and quasi-static indentation**

TABELA 2. **Obszar zniszczenia kompozytów jako efekt obciążeń dynamicznych o niskiej prędkości oraz statycznego wciskania**

Material Damage area	CFRP	GFRP
Low-velocity impact 10 J [cm^2]	6.16	36.12
Low-velocity impact 25 J [cm^2]	9.92	52.95
Quasi-static indentation equivalent 10 J impact [cm^2]	undetectable	2.78
Quasi-static indentation equivalent 25 J impact [cm^2]	1.1	3.23
Quasi-static indentation until perforation [cm^2]	5.88	not tested

The obtained values confirm that the damage area after low-velocity impact and quasi-static indentation are completely different. It is seen especially in case of GFRP laminates where delaminations are many times bigger after dynamic loads. The level of the observed differences is the result of impact energy absorption by the composite, while during quasi-static indentation, energy is not transformed or absorbed [9]. The expansion of the damage area in CFRP laminates is much less because energy absorption is transformed to perforation (fibres cracking), which is the result of their much higher stiffness in comparison to glass fibres. The failure mechanism of both kinds of composites as a result of quasi-static indentation is presented in Figure 4.

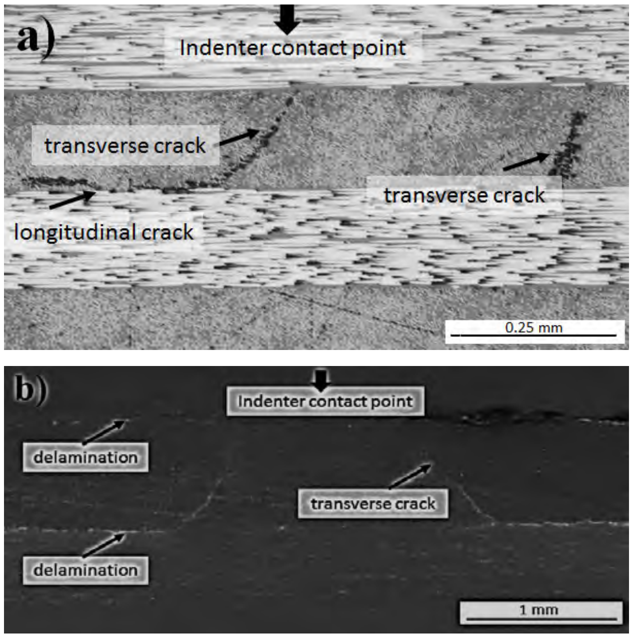

Fig. 4. Cross-section views of CFRP (a) and GFRP (b) laminates after quasi-static indentation as equivalent of 25 J impact energy

Rys. 4. Przekroje poprzeczne laminatów CFRP (a) oraz GFRP (b) po statycznym wciskaniu odpowiadającym obciążeniu dynamicznemu z energią 25 J

It was noted that the major failure of CFRP laminates are transverse cracks (see Fig 4a), which confirms previous conclusions from the non-destructive analysis. However, single longitudinal cracks were observed. The transverse cracks are directly caused by the indenter and the direction of the applied load. The longitudinal cracks, which are the first step to creating delaminations are the results of shear stress between the layers (stress state - bending model) [20]. In GFRP laminates the major failure mechanism is delaminations, which propagate between several layers (see Fig. 4b). Besides extensive delaminations, some transverse cracks can also be observed, but only around the indenter contact point [20]. The observed failure type was similar in the case of the low-energy and low-velocity impact [20].

The major failure mechanism is different for CFRP and GFRP because of the different level of shear stress. Although the forces during quasi-static indentation were similar in both kinds of composites, the shear stresses were higher in the GFRP laminates due to their greater deformation.

The F-d curve representing the perforation of CFRP laminates under quasi-static indentation is shown in Figure 5.

It was noted that the force necessary to cause CFRP perforation is much higher than in case of low-velocity impact. However, the obtained displacement level until *Pm* is similar. This phenomena is caused by the differences between the energy transfer and transformation during static and dynamic loads. The shape of the F-d curve is rather smooth, which indicates that quasi-static indentation has monotonic features. The characteristic suddenly loss of strength is the same as in the low-velocity impact behavior of polymer composites.

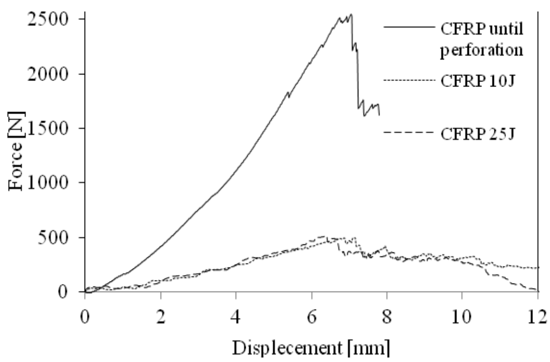

Fig. 5. F-d curve of CFRP laminates representing low-velocity impact and quasi-static indentation until perforation

Rys. 5. Krzywa F-d laminatów CFRP reprezentująca obciążenia dynamiczne o niskiej prędkości (10 i 25 J) oraz statyczne wciskanie do perforacji

CONCLUSIONS

The following conclusions can be drawn from this study: Low-velocity impact causes significant degradation of composite structures. Even a small impact energy level (10 J) is the reason for perforation or extensive delamination in the composite.

1. Quasi-static indentation under the same force level as in impact causes some internal degradation of the laminate structure. However, its size is much lower than in the case of low-velocity impact.
2. The composite structure failure types after static and dynamic loads are similar. However, for CFRP laminates the major failure type is transverse cracks, while for GFRP laminates it is delaminations. A similar nature and extent of composite structure damage on account of quasi-static indentation requires much larger force values in comparison to dynamic loads.

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