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ON DELAMINATION THRESHOLD LOADS IN LOW VELOCITY IMPACT ON GLASS-CARBON/EPOXY COMPOSITES

When a structure is accidentally impacted by an object, (e.g. by dropping a tool) it may be important to know if the impact is likely to cause serious damage in the structure. The easiest way to solve this is to compare the impact energy with the threshold impact energy of the structure. Thus, it is necessary to find the threshold impact energy of the structure which depends on the properties of the material and boundary conditions. In the present work the problem of delamination threshold load assessment was studied for epoxy laminates reinforced with woven glass-carbon laminates. The behaviour of symmetrical and unsymmetrical glass E/carbon C laminate was studied (E/C/E/C/E and E/E/C/E/C).

Instrumented impact and static indentation tests were used. The rebound impact tests were conducted on the 100 mm square specimens in standard instrumented dropping weight tower Ceast Dartester. Indentation tests were performed using the same samples and supports geometry as in impact tests. The acoustic signal was used to assess the load and deflection corresponding to the first damage in the laminate. Damaged samples were examined using SEM. The approximate projected maximum delamination area was assessed and plotted against impact energy and maximum load (Fig. 6). The experimental results obtained in this work show (Figs 5, 6) that, similar to quasi-isotropic fibre reinforcement, for woven glass/carbon/epoxy laminates there exists a threshold impact load corresponding to a sudden jump of the area of delaminations from zero to a certain value (100 mm^2). The threshold impact energy was found 1.5 J independent of the glass fibre stacking sequence. The near-the-threshold damage in woven glass-carbon/epoxy laminates consists of delaminations and fibre/matrix debonding. Good correlation of the projected damage area obtained in this work for static (indentation) and impact measurements confirm that prediction of the threshold impact damage by quasi static tests instead of instrumented impact test is practical and useful.

Key words: **laminates, impact resistance, polymer composites**

BADANIA WARUNKÓW POWSTAWANIA DELAMINACJI W KOMPOZYTACH EPOKSYDOWYCH WZMOCNIONYCH WŁÓKNAMI SZKLANYMI I WĘGLOWYMI POD WPŁYWEM NISKOENERGETYCZNEGO UDARU

Przedstawiono badania charakteru i rozmiaru zniszczeń w laminatach epoksydowych wzmocnionych włóknami węglowymi oraz szklanymi i węglowymi wywołanych przez udary o małej energii. Na podstawie dynamicznych charakterystyk obciążeń w funkcji czasu i odkształcenia płytek określano zależność pola delaminacji w funkcji obciążenia wywołującego te zniszczenia. Ze względu na konieczność posiadania młota spadowego z oprzyrządowaniem do prób dynamicznych badania takie są kłopotliwe. Jednak wyniki prób prowadzonych w zaawansowanych laboratoriach kompozytowych w Wlk. Brytanii i USA wskazują na możliwość wykorzystania badań przy obciążeniach quasi-statycznych o analogicznym układzie podpór i geometrii próbki do oceny progowych obciążeń wywołujących inicjację delaminacji w laminacie. Korzystając z takiej możliwości, porównano zniszczenia powstałe przy obciążeniach quasi-statycznych i udarowych (określonych przez maksymalne obciążenie P_{max}). Posiadane dane z pomiarów dynamicznych o energii udaru wyższej od progowej umożliwiły identyfikację obciążenia wywołującego skokową inicjację delaminacji w laminacie epoksydowym o wzmocnieniu szklano-węglowym. Badania stanowią wprowadzenie do prognozowania obciążeń i energii wywołujących inicjację delaminacji w kompozytach warstwowych.

Słowa kluczowe: **laminaty, odporność udarowa, kompozyty polimerowe**

INTRODUCTION

Impact induced damage, which may be undetectable by visual inspection, can have a significant effect on the strength, durability and stability of the structure. Much attention has been directed towards understanding the causes and failure mechanisms of delamination and towards developing techniques to improve the issue of delamination and impact damage. Numerous analytical and numerical methods have been proposed to predict

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damage development [1-4]. However, due to the complexity of the stress state in the vicinity of impact a general approach for predicting the initiation and propagation of damage during an impact event is absent. The load history for an impact event can yield important information concerning damage initiation and growth. It has been documented by several investigators that damage initiation is manifested in the load-time history as a sudden load drop due to loss of stiffness from unstable damage development [5, 6]. Subsequently, damage growth will arrest, the composite laminate will reload and a cycle of damage propagation and arrest occurs until the impactor begins to rebound and the laminate is unloaded. Several investigators [4, 6, 7] used load-displacement histories to compare structural responses from impact tests and incremental static test with equal maximum load. They found that although the dynamic load-displacement curves contain oscillations, both the dynamic and static responses had corresponding load drops due to failures in the laminates. Although the limits of the equivalence regime between static and impact tests remain to be determined [8] the load-displacement curves for static loading have been used to represent low velocity impact loading [5, 7, 9-11].

For a composite structure in engineering it is important to know what impact energy the structure can sustain without resulting in significant damage. On the other hand, when a structure is accidentally impacted by an object, e.g. by dropping a tool it may be important to know if the impact is likely to cause serious damage in the structure. The easiest way to solve this is to compare the impact energy with the threshold impact energy of the structure. Thus, it is necessary to find the threshold impact energy of the structure which depends on the properties of the material and boundary conditions.

In research, in order to study the post-impact behaviour of a composite specimen at different levels of impact energy, the threshold impact energy for the onset of delaminations needs to be known [8, 12-14].

In the present work the problem of assessment of the threshold impact damage energy and load was studied for epoxy laminates reinforced with woven glass-carbon laminates using dynamic and static tests.

EXPERIMENTS AND RESULTS

Materials used in this study were epoxy laminates reinforced with simple carbon and hybrid interlayer glass/carbon fibres. Laminates were fabricated from woven orthogonal balanced fibre fabrics: carbon (RC660T), E glass (STR 66-110). Carbon fibre fabric was supplied by SP Systems (UK) and glass fibre fabric - by Krosno, Poland. Standard pro-adhesive treatment of the fibres for use with epoxy resins was provided by the suppliers. Laminates consisted of 5 plies of fabric impregnated with epoxy resin by hand lay-up. The resin was Epidian 52 (Organica-Sarzyna), typical Diglycidyl Ether of Bisphenol - A (DGEBA) cured with amine hardener ET (20 wt.%). The approximate fibre volume fraction was $V_f = 50\%$.

The thickness was $t = 2,3 \div 2,9$ mm. The following reinforcement architecture was used: 1) symmetrical - glass E/carbon C: E/C/E/C/E, 2) unsymmetrical E/E/C/E/C. The rebound impact tests were conducted on the 100 mm square specimens in standard instrumented dropping weight tower Ceast Dartester at three energy levels: 2.7, 5 and 9 J. The square laminate samples were clamped horizontally between the two plates with an inner diameter of 38 mm. The impactor tip was hemispherical type with a 12 mm diameter. The three specimens were tested for each material and impact energy. The load-time and load-displacement traces were recorded [15].

Alternatively, static indentation tests were performed using the same samples and supports geometry as in impact test. The acoustic signal was used to estimate the load and deflection corresponding to the first damage in the laminate.

In order to estimate the impact damage size, in the absence of the instruments for non-destructive techniques (demonstrated by the authors in ref [18]), the simple (though time consuming) technique of microscopic examination of sample sections was used. Damaged samples were sectioned throughout the contact zone, polished and examined using SEM. The size of the most extensive delamination was assessed. Since the damage zone was circular the area of projected damage was estimated [16-18].

Figure 1 illustrates typical load-time plot for carbon/epoxy laminate at impact energy 9 J showing change in the laminate stiffness (inflexion of the curve) due to the onset of impact damage. Arrow points to the load 3500 N corresponding to the first crack (acoustic signal) found in the static indentation test (Fig. 2). However, no indentation or damage was observed on front or back face of the plate (Fig. 3a).

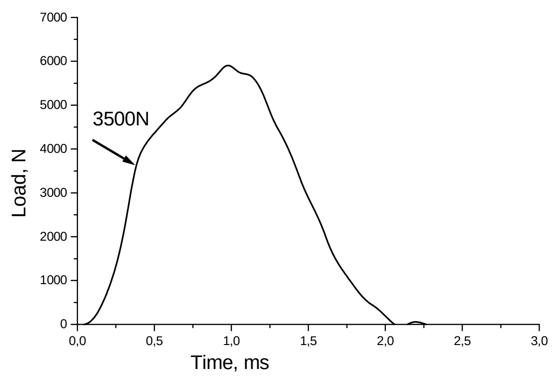

Fig. 1. Load-time plot for woven carbon/epoxy laminate

Rys. 1. Wykres obciążenie-czas dla laminatu epoksydowego wzmocnionego tkaniną węglową

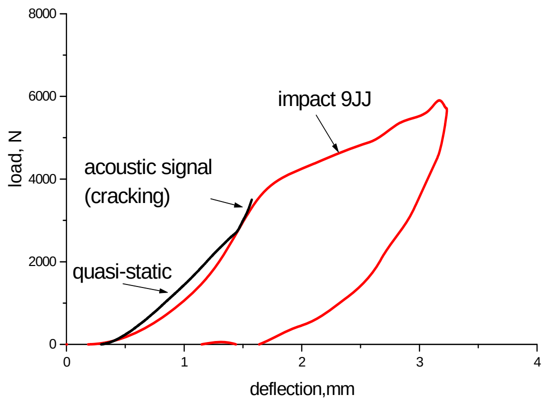

Fig. 2. Load-deflection plots for impact and quasi static indentation tests on woven carbon fibre/epoxy laminate

Rys. 2. Wykres obciążenie-odkształcenie dla laminatu epoksydowego wzmocnionego tkaniną węglową - obciążenie udarowe i quasi-statyczne

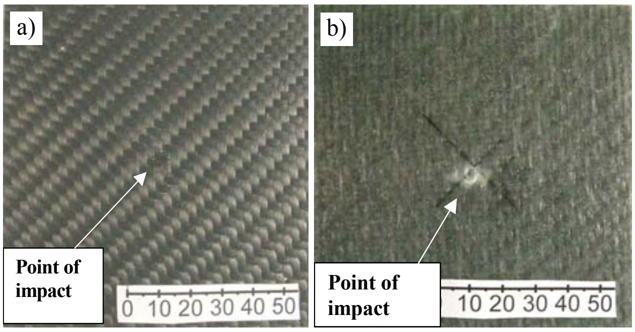

Fig. 3. Front face of the carbon (a), glass/carbon/epoxy (b) plates, impact energy 2,5 J

Rys. 3. Płaszczyzna uderzenia laminatu epoksydowego wzmocnionego tkaniną węglową (a), szklaną i węglową (b). Energia udaru 2,5 J

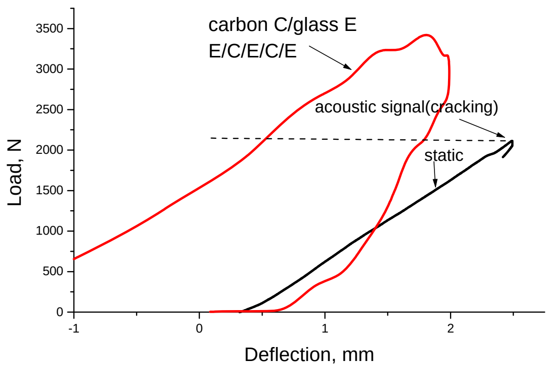

Fig. 4. Load-deflection plots for dynamic and quasi static tests on symmetrical (E/C/E/C/E carbon-glass fibre/epoxy laminate. The plot is shifted to the left, due to delay in data acquisition

Rys. 4. Wykres obciążenie-odkształcenie dla laminatu epoksydowego wzmocnionego tkaniną szklaną i węglową (układ symetryczny E/C/E/C/E), pomiar dynamiczny i quasi-statyczny. Wykres jest przesunięty w lewo na skutek opóźnienia w zapisie danych

Similar tests were performed for two 5-ply glassE/carbonC/epoxy laminates: symmetrical E/C/E/C/E and unsymmetrical E/E/C/E/C. Figures 4 and 5 show the dynamic and quasi static load-deflection plots corresponding to the impact 2.5 J for symmetrical laminate and 9 or 2.5 J (unsymmetrical laminate). Figures 4 and 5 show that, similar to carbon fibre composite (Fig. 2), the acoustic signal corresponding to the first laminate damage (arrow) points to the load at inflection in impact load deflection plot.

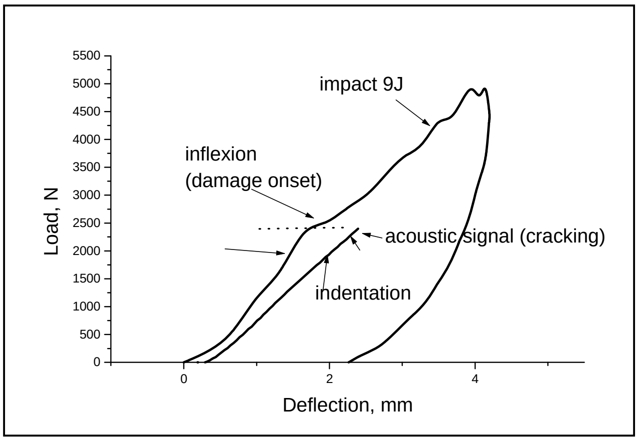

Fig. 5. Load-deflection plots for dynamic and quasi static tests on unsymmetrical (E/E/C/E/C carbon-glass fibre/epoxy laminate

Rys. 5. Wykres obciążenie-odkształcenie dla laminatu epoksydowego wzmocnionego tkaniną szklaną i węglową (układ niesymetryczny E/E/C/E/C), pomiar dynamiczny i quasi-statyczny

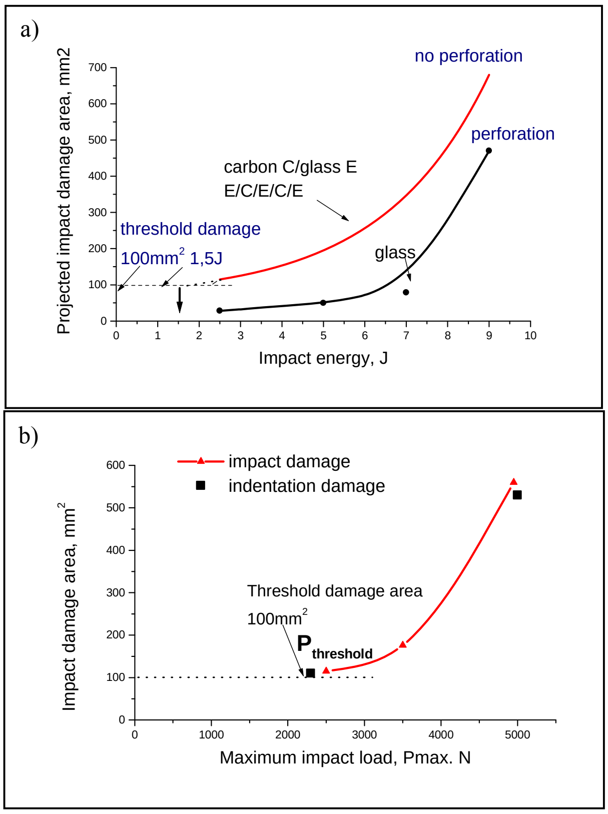

Fig. 6. Projected damage area as a function of impact energy (a), maximum impact load (b) in carbon/glass/epoxy laminate

Rys. 6. Wykres pola powierzchni zniszczeń w funkcji energii udaru (a), największego obciążenia (b) (próba dynamiczna i statyczna) w laminacie epoksydowym wzmocnionym włóknami szklanymi i węglowymi

In static tests the machine was stopped and the sample removed when the first acoustic signal (corresponding to sample cracking) was registered. Damaged samples were sectioned at two perpendicular directions throughout the contact zone, polished and examined using SEM, similar to the impacted specimens. The approximate projected maximum delamination area was assessed [16-18]. The extension of the damage zone was measured and the projected damage area was plotted against impact energy (Fig. 6a).

showing the extent of delamination formed under very low and high indentation load. It is evident that both the results of static and dynamic tests correlate well.

Based on the experiments obtained in this work and of other investigators it may be concluded that static indentation tests may be the source of information about the threshold impact damage load.

The morphology of the damaged sample was examined for impacted and statically loaded samples. Figure 7 shows typical features of undamaged and impact damaged (9 J) samples. For near-the-threshold impact loads the prevailing failure modes were the same: delaminations and matrix/fibre debonding (Fig. 8a). At higher impact (Figs 7b, 8b) energy delaminations were more extensive and numerous fibre breakage and ply cracks were observed.

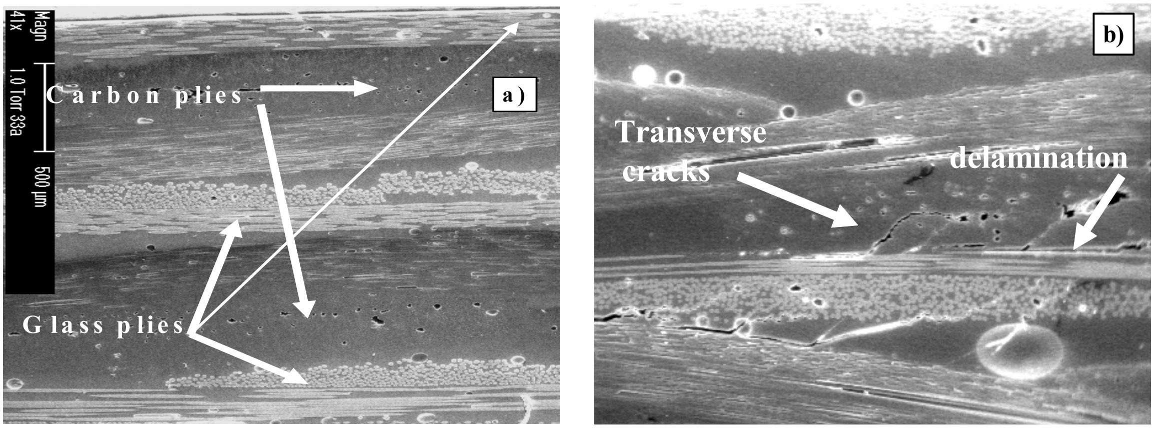

Fig. 7. SEM images of undamaged (a), impact damaged (b) (9 J) carbon/ glass/epoxy sample

Rys. 7. Obrazy SEM próbek laminatu epoksydowego o wzmocnieniu szklano-węglowym w stanie: nieuszkodzonym (a), po udarze o energii 9 J (b)

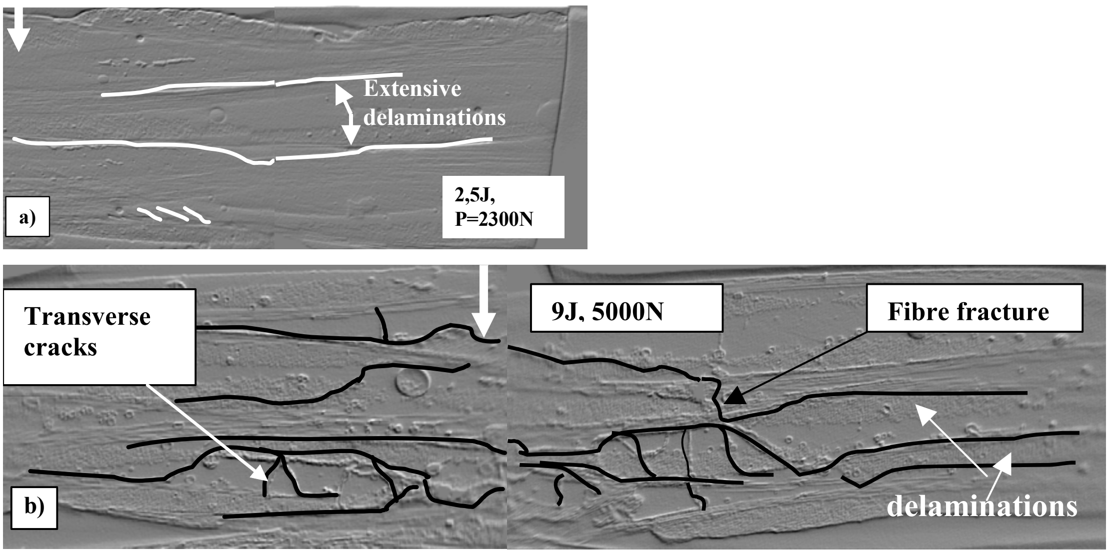

Fig. 8. Schematic of impact damage zone in carbon-glass/epoxy sample following impact 2.5 J (a), 9 J (b)

Rys. 8. Schemat strefy zniszczeń udarowych w laminacie epoksydowym wzmocnionym tkaniną szklaną i węglową

Figure 6b shows the relationship of impact damage and the peak impact load (found from dynamic load-time or deflection curves) which caused such a damage. In parallel the results of static (indentation) tests are plotted

DISCUSSION

The experimental results obtained in this work show (Fig. 6) that in woven glass/carbon/epoxy laminates studied under impact loading, there exists a threshold impact load 800 N (corresponding to the threshold impact energy 1,5 J). When the impact energy is above the threshold level, the delamination takes place instantaneously. This is by a sudden jump of the area of delaminations from zero to a certain value. When the impact energy is above the threshold level, the delamination area seems to increase continuously with the increase in the impact energy. However, the subsequent increase in delamination size with the increase in the impact energy is relatively slow. At high impact energies the considerable jump in damage area is observed. The same has been observed in glass and aramid--glass/epoxy laminates subjected to impact [19]. Since the plates were transparent in the backlighting the internal delaminations were easily identified. Similar results were found in [9, 20]. For example for simply supported 125 mmx75 mm^2 mm quasi-isotropic laminate [10] the delamination size jumps to about 125 mm^2 at the threshold impact energy, whereas when the energy increases to twice the threshold level the damage area is about 175 mm^2. Jang-Kyo Kim [21] studied woven carbon fibre/epoxy laminates and found that the effect of threshold impact energy is also found in woven fibre reinforced laminate. These experiments demonstrated that the initial delamination corresponding to the threshold impact energy plays a vital role in the impact--induced damage an thus the threshold impact energy is an important parameter determining the resistance of a composite structure to impact [8].

The quasi static analysis gives a very accurate prediction of the maximum impact force for the considered laminates under low velocity impacts [8]. Based on this observation, for a given laboratory specimen of composite laminate or part made of a composite laminate in a real structure, the threshold impact energy for the onset of delamination can be predicted using a force driven, semi-empirical model proposed by Davies and Zhang [9, 12]. The model uses the Mode II strain energy release rate G_{IIC}. The authors manufactured the ENF samples with artificial crack for glass and aramid-glass fibre/epoxy laminates and assessed the G_{IIC} [22] The prediction of the critical load for the onset of delamination based on these results and Davies's model is currently studied.

CONCLUSIONS

1. The experimental results obtained in this work show that, similar to quasi-isotropic fibre reinforcement [10], for woven glass/carbon/epoxy laminates studied under impact loading there exists a threshold impact load (800 N) corresponding to a sudden jump of the area of delaminations from zero to a certain value (85 mm^2).
2. The threshold impact energy was found 1.5 J independent of the glass/carbon fibre stacking sequence.
3. The near-the-threshold damage in woven glass--carbon/epoxy laminates consists of delaminations and fibre/matrix debonding.
4. The good correlation of the projected damage area obtained in this work for static (indentation) and impact measurements confirm that the prediction of the threshold impact damage by quasi static tests instead of instrumented impact is practical and useful.

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Recenzent
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