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IMPACT DAMAGE IN POLYESTER-MATRIX GLASS FIBRE-REINFORCED COMPOSITES. PART II. RESIDUAL LOAD BEARING ABILITIES

In the course of their "life", fibre-reinforced plastics (FRP) are subjected to impacts which can cause damage. This damage may lead to a reduction of FRP strength and static load-bearing abilities. In this contribution, new results of three-point flexural tests on glass fibre/polyester composites after non-penetrating ballistic impact are presented. Composite materials were reinforced using a continuous filament mat and a woven roving, and the fibre content varied in the range of 42÷61% wt. The materials were produced using the Resin Transfer Moulding (RTM) method. The impactor was a free-flying 3 g steel ball, and the impact velocities approached 130 m/s. After the impact and evaluation of the extent of damage, the samples were subjected to three-point bending tests under fixed conditions. Reduction in the critical load value was noticed. A novel approach to the evaluation of residual strength has been presented. This approach allows estimation of the actual load-bearing ability of damaged material without removing the undamaged parts of the sample. The said approach involves testing samples including a damaged area as well as undamaged samples. It was considered what effect complete elimination of the damaged field would have on the load-bearing ability of the sample. The load transmitted through the undamaged area surrounding the area of delamination was then subtracted. This allowed for evaluation of the percentage of residual properties in the damaged area. It was found that reinforcement in the form of a continuous-filament mat compares favourably to loose woven roving. Higher-reinforced composites after the impact test seem to lose their properties to a higher extent.

Keywords: **polymer composites, laminates, unsaturated polyester resin, glass fibre, ballistic impact, residual properties**

USZKODZENIA UDAROWE WE WZMOCNIONYCH WŁÓKNEM SZKLANYM KOMPOZYTACH O MATRYCY POLIESTROWEJ. CZĘŚĆ II. POZOSTAŁA ZDOLNOŚĆ DO PRZENOSZENIA OBCIĄŻEŃ

W ciągu swojego „życia" tworzywa sztuczne wzmocnione włóknami poddawane bywają udarom, które mogą spowodować ich uszkodzenie. Uszkodzenia te prowadzą do obniżenia wytrzymałość takich tworzyw i ich zdolności do przenoszenia obciążeń statycznych. W prezentowanym artykule przedstawiono nowe wyniki próby trójpunktowego zginania kompozytów poliestrowo-szklanych po niepenetrującym udarze balistycznym. Materiały w niniejszym badaniu zostały wzmocnione z użyciem maty i tkaniny rovingowej, a zawartość wzmocnienia była zmieniana. Materiały wytworzono z użyciem metody RTM (*Resin Transfer Moulding*). Udar wywierano przy użyciu 3-gramowej stalowej kulki, a prędkości udaru sięgały 130 m/s. Po udarze i ewaluacji rozległości uszkodzeń próbki zostały poddane trójpunktowemu zginaniu w ustalonych warunkach. Zaobserwowano spadek wartości obciążenia krytycznego. Zaprezentowano nowatorskie podejście do ewaluacji wytrzymałości pozostałej, obejmujące badanie próbek zawierających uszkodzone pole oraz próbek nieuszkodzonych. Rozważając wpływ, jaki miałoby całkowite wyeliminowanie pola uszkodzonego na zdolność do przenoszenia obciążeń przez próbkę i odejmując wpływ nieuszkodzonego pola otaczającego pole zdelaminowane, uzyskuje się procentowe właściwości pozostałe. Badania wykazały, że wzmocnienie w postaci maty z włókien ciągłych wypada korzystnie w porównaniu do tkanin rovingowych o luźnej strukturze. Kompozyty o większej zawartości wzmocnienia wydają się tracić większą (procentowo) część swoich pierwotnych właściwości.

Słowa kluczowe: **kompozyty polimerowe, laminaty, nienasycona żywica poliestrowa, włókno szklane, udar balistyczny, właściwości pozostałe**

INTRODUCTION

Increasingly wide usage of fibre-reinforced plastics (FRP) brings about questions regarding their impact resistance. Laminated elements are subject to a high probability of being struck by objects of varying mass, shape and speed. The very thing that provides the ease of tailoring FRP properties - the multitude of structural components and the links between them - causes easy dissipation of impact energy and often irreversible damage to the material itself.

Multiple phases and the bonding between them allow relatively easy dissipation of impact energy, while at the same time lead to irreversible damage.

It must be emphasized that energy absorption and damage resistance are to some extent conflicting - the main mode of energy absorption is the damage itself [1].

There are several modes of energy absorption and damage mechanisms in laminated composites. Most frequently cited are the kinetic energy of the displaced part of the target object, fibre tension, fibre destruction through tensile failure or shearing, delamination, matrix cracking and friction between the impactor and target material [1-6]. Of these, the most important are target kinetic energy and fibre failure [2-5], while delamination and matrix cracking are the primary cause of post-impact strength reduction [1, 4, 6-9]. Since matrix cracking and delamination occur together - in fact, the former initiates the latter - no attempt to discern between the two damage types is feasible [4]. Fibre breakage and misorientation is expected after sufficiently heavy impacts [10].

It is important to evaluate how the impact and the damage caused by it affect the strength of a laminated panel - in other words, what its residual load-bearing abilities are. Works addressing this question have been done previously. There are a few methods of evaluating residual strength. Both dynamic and static post-impact properties may be evaluated. Some researchers prefer to test repeated impact at a previous impact site [1, 8, 11]. Other choose to perform Charpy impact tests on samples cut from the area damaged by ballistic impact [9, 12].

To evaluate the reduction of the ability to carry a static load, quasi-static tests of the impacted samples (or samples cut from the impacted panel) are often conducted. The mode of quasi-static testing of impacted samples is a contentious issue with no clear solution. Depending on the typical working conditions of the element in question, the preferences of researchers and available equipment, the samples may be tested in the tensile [9, 12], compressive [4, 13, 14] or flexural [11, 15-17] mode. Impact damage reduces mostly the compressive strength. Its effects on the tensile strength are less serious, and delamination in particular will have a very small effect. Since compression resistance is important in many aircraft parts, the industry developed a test called "compression after impact". A flexural test is easier to carry out than a compression test, requires very little special equipment and does not have the uncertainties associated with the compression test [10]. The results are reported as the apparent strength of the entire sample [9-17].

MATERIALS

For this study multi-ply composites (laminates) made of unsaturated polyester (UP) resin and E-type glass fibre in various forms were prepared. The laminates were manufactured in the form of flat, square plates with a thickness of 4 mm, produced using the Resin Transfer Moulding (RTM) method in a stiff double mould.

Three different composites were produced:

1. 6CFM45, six plies of 450 g/m^2 CFM combining to total area weight of 2700 g/m^2 and reinforcement weight fraction 44% (volume fraction 27%, porosity 2.5%),
2. 6WR43, six plies of 430 g/m^2 WR combining to total area weight of 2580 g/m^2 and reinforcement weight fraction 42% (volume fraction 26%, porosity 3.2%), in $[0°/90°]_3$ lay up,
3. 10WR43 - ten plies of 430 g/m^2 WR combining to total area weight of 4300 g/m^2 and reinforcement weight fraction 61% (volume fraction 43%, porosity 3.5%), in $[0°/90°]_5$ lay up.

The laminates were cut into square plate samples 100x100 mm using a diamond saw.

The preparation of the materials for the study was further elucidated in Part I of the paper.

TESTING

The composites in this study were subjected to impact using a compressed-air gun test assembly, propelling a 3 g sphere of hardened steel to velocities ranging 90÷130 m/s.

In order to evaluate the residual load-bearing abilities of the composites, the samples were tested under quasi-static three-point bending conditions, both after ballistic impact and without prior impact. Three-point quasi-static bending (Fig. 1) was conducted on an Instron 4206 universal testing machine with computerized data acquisition. The samples were square plates 100 x 100 x 4 mm. Due to their nonstandard width, the testing method was based on the ISO 178:1996 standard (Plastics - Determination of flexural properties), but modified to suit the specific experimental needs. Authors did take into consideration the reduced comparability of the results with other studies. One parameter measured in the 3-point bending test was given the most attention - the critical load. Critical load is hereafter defined as a load at which breaking of a sample occurs, signified by a sudden drop in force acting upon a sample.

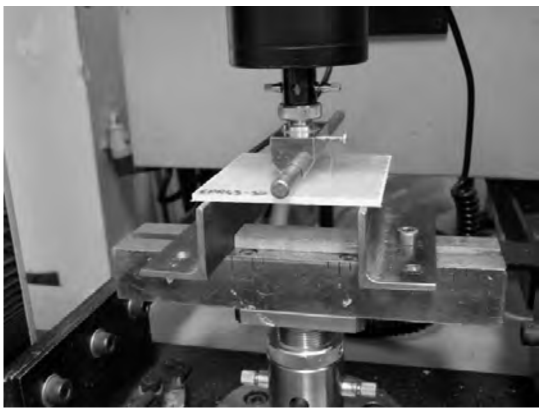

Fig. 1. Sample undergoing three-point quasi-static flexural test

Rys. 1. Próbka podczas testu quasi-statycznego zginania

RESULTS AND DISCUSSION

Impact damage clearly leads to a significant decrease in critical load (Fig. 2) in post-impact flexural tests - up to 30% after the highest tested energies in the case of our samples. Higher energy leads, of course, to higher damage and higher loss of mechanical properties, though this relation is not strictly linear - the the regression model uses linear approximation, but the sample scatter is high (see Table 1 for correlation coefficients), which will be discussed further on. The regression lines for the residual critical load for the two WR-reinforced composites seem to slightly converge on a distant point - the overall mechanical properties are of course higher for the material with the higher reinforcement content. The composite with the higher reinforcement content - 10WR43 samples - lost a higher percentage of critical load after a 22 J impact, than the 6WR43 (30% compared to 23%) did. The CSM-reinforced composite seems to lose its properties slower than those with woven roving - after a 22 J impact these samples lost only 14% in critical load and might be expected to become stronger than the other two materials after impact with energy of only about 30 J. It should be remembered, that the above-mentioned percentage is proper only for samples of given dimensions. The larger the sample is, compared to the damaged area, the lower percentage of properties it shall lose.

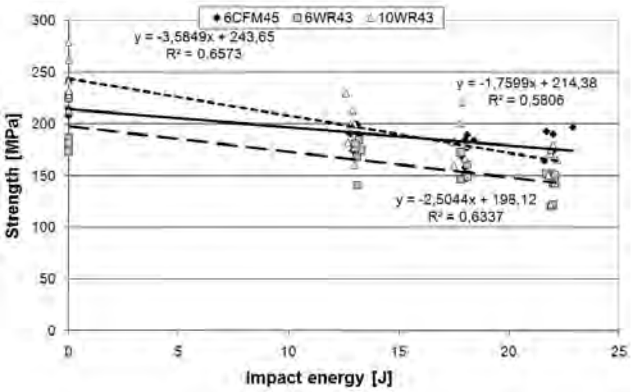

Fig. 2. Residual critical load vs. impact energy graph

Rys. 2. Wykres zależności obciążenia krytycznego od energii udaru

TABLE 1. **Correlation coefficients for various relations presented in the study for each material**

TABELA 1. **Współczynniki korelacji dla różnych zależności przedstawionych w pracy i dla każdego materiału**

Material	Delamination vs. impact energy (see Part I)	Critical load vs. impact energy	Strength vs. impact energy	Strength vs. critical load
6WR43	0.996	0.679	0.796	0.688
10WR43	0.987	0.723	0.811	0.815
6CFM45	0.987	0.431	0.762	0.548

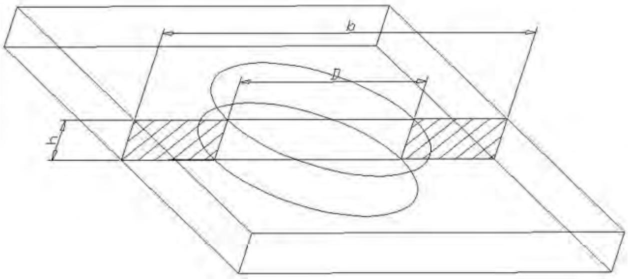

Fig. 3. Sample with cut-out circular hole. Remaining effective cross-section highlighted. For symbols - see main text

Rys. 3. Próbka z wyciętymi otworami okrągłymi. Pozostały przekrój efektywny jest zacieniony. Oznaczenie symboli - patrz tekst główny

It may be interesting to compare the properties degradation from another viewpoint - by evaluating the loss in load-bearing abilities only for the damaged area. We may consider what effect the complete elimination of the damaged field would have on the critical load of the sample. Since the impact damage has roughly a a circular shape in the plane of the plate, we will use the surface area of a circle for further consideration. If If we imagine (Fig. 3) cutting a circular hole with a surface area (S) equal to the surface area of the damaged field (S_D), we will lose from the sample a total cross-sectional area (A_{tot}) a rectangle with a length equal to the circle diameter (D) and width of the sample thickness (h). Since A_{tot} is a rectangle with the length of 100 mm and width h, the effective cross-sectional would be expressed as in Equation (1):

$$A_{eff} = A_{tot} - D \times h = (100\ \text{mm} - D) \times h \quad (1)$$

This would lead to the ratio expressed in Equation (2):

$$A_{eff} / A_{tot} = D / 100\ \text{mm} \quad (2)$$

The critical load which the sample is able to bear is directly proportional to A_{eff}; thus, the critical load of a sample with a cut-out hole should be equal to an undamaged sample critical load multiplied by a D/100 mm ratio. This logic is supported by previous works ([18-22] and unpublished work done by one of the authors of this contribution).

This would be the most severe form of damage - removing the load-bearing abilities of the entire damaged field. The least severe would be of course a load-bearing ability equal to that of the undamaged field in the sample. The real samples with impact damage should fall somewhere in-between. For each of them, we may assume a maximal critical load (F_{max}), which it could bear if undamaged. We can also calculate (from the damaged area) a theoretical minimum critical load (F_{min}) that it could bear if the entire damaged area were removed. By taking this minimal critical load and subtracting it from the actual tested critical load (F_{act}) of the sample, we may evaluate the actual residual load-bearing ability (F_{res}) of the damaged area. We may present it as a value (F_{res}, expressed in Equation (3)) or as a percentage ($F_{\%res}$, expressed in Equation (4)) assuming a worst-case scenario (damaged area entirely removed) critical load as 0% and best-case scenario (no real damage) critical load as 100%:

$$F_{res} = F_{act} - F_{\min} \quad (3)$$

$$F_{\%res} = \frac{F_{act} - F_{\min}}{F_{\max} - F_{\min}} \times 100\% \quad (4)$$

For the averaged results, see Figure 4. The residual load-bearing abilities of the damaged area decreases with an increasing impact energy, which is to be expected. The highest residual critical load of the damaged area is obtained by the composite reinforced with continuous filament mats (even as high as over 90% after 13 J impact). The residual critical loads are much lower for woven roving-reinforced composites, and comparing those two, one can see that the laminate with a higher fibre content loses more of its originally higher critical load.

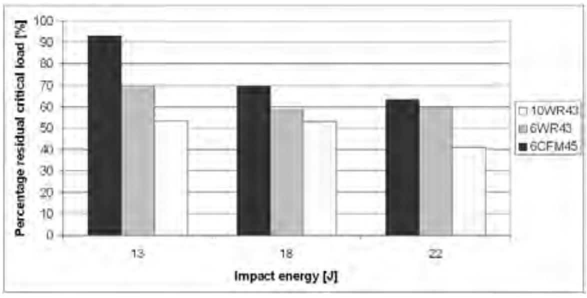

Fig. 4. Calculated residual critical load for damaged area only

Rys. 4. Obliczone pozostałe obciążenie krytyczne samego obszaru uszkodzonego

A number of questions arise from the results. First, the ability to bear loads is lowered by the impact damage, but still existent. It may be so, because the loads in FRP are transmitted mostly through the reinforcement fibres, due to their much higher modulus, not through the polymer matrix. The matrix serves mainly to bind the fibres and transfer loads between them. Even a cracked matrix still binds a number of fibres. In addition, a composite, even divided to individual laminae by delamination, still transmits tensile loads almost equally effectively [10] - and in flexion, half of the stresses are tensile.

Second, the surprisingly good performance of the continuous-filament mat-reinforced composite needs explanation. In the microscopic view (see Part I of the paper), one may see that the severity of damage is lower in these composites, and the delamination does not produce such a separation as in the woven roving reinforced composites. The fibres are not fractured, either. Since the most severe damage lies directly under the impact point and directly on the opposite face, mainly the fibre strands lying in these areas are virtually eliminated from bearing loads. In woven rovings, the strands are long, straight and wide, containing many individual fibres. By contrast, the strands in continuous-filament mats are tortuous and narrow, thus the eliminated fibres cover a lower contiguous area than in the case of woven rovings.

Third, the composites with a higher fibre content lose a higher percentage and higher absolute number of their load-bearing abilities. It may be hypothesized that in the higher-fibre-content laminates, pockets of neat matrix between the fibre strands are smaller and larger in number. If those pockets are fragmented in the phenomenon of matrix cracking, the resultant fragments are smaller as well. Smaller matrix fragments bind together a smaller number of fibres, deteriorating the effectiveness of load transmission. The deteriorating effects of matrix cracks on the load transmission have been noted previously ([23] among others).

CONCLUSION

A new approach to the evaluation of residual strength has been presented. This approach allows to one to estimate the actual load-bearing ability of damaged material without removing the undamaged parts of the sample. Such cutting might further damage the already damaged material. There is also the question of the proper size of the samples of damaged materials in order not to bias the measurement.

In the course of this study, it was proven that even noncritical impact event leads to a sometimes serious decrease in the load-bearing properties of composites. The extent of the reduction is varied and dependent on the reinforcement factors such as the reinforcement type and structure, as well as the total amount of reinforcement in the composite. Composites with a higher reinforcement content seem to lose a higher percentage of their original properties. Further investigation of this issue using different reinforcements is advisable.

Regarding the reinforcement types, continuous-filament mats are superior to loose-structure woven rovings - the relative loss in mechanical properties is lower in CFM-reinforced composites than in WR-reinforced ones. This is worth noting and needs further research.

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