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REMAINING STRENGTH IN GLASS/POLYESTER LAMINATED COMPOSITES SUBJECTED TO BALLISTIC IMPACT

Fibre-reinforced plastics (FRP) are susceptible to damage resulting from impacts, even non-penetrating ones. This damage, even without outright destruction, may lead to reduction of fibre-reinforced plastics strength and static load-bearing abilities. This paper presents the results of three-point flexural tests on glass fibre/polyester composites after non-penetrating ballistic impact, where the word "ballistic" refers to a high-speed free-flying impactor (projectile). This is a continuation of previous studies, during which the extent of damage in glass/polyester composites after non-penetrating ballistic impact was evaluated. Materials used in the study were laminated composites produced via the Resin Transfer Moulding (RTM) technology. This laminates were produced using Polimal 1094 AWTP-1 unsaturated polyester resin and E-glass reinforcement in the form of multiple perpendicular layers of chopped-strand mats, continuous-filament mats, twisted-yarn fabrics and woven rovings. Composites with varying thickness, number of layers and fibre content were produced. The impactor is a free-flying 3 g steel ball propelled from a gas gun. Two striking velocities were tested - 60 and 70 m/s, producing impact energies of 5.4 and 7.35 J accordingly. After the impact, the extent of damage in samples (100x100 mm square plates) was evaluated through digital image analysis. The as-impacted samples were then subjected to three-point bending under set conditions. The results were compared to the results of identical examination of undamaged samples and the reduction in mechanical properties was determined. In all cases, the reduction in strength and load-at-break value was noticed. Thicker, more reinforced laminates show lower loss of mechanical properties, than thinner ones. Difference between strength and load-at-break approach for load-bearing abilities reduction was discussed, and the conclusion is that the latter is preferred to the former in laminated composites due to high thickness dependence of strength. Comparing reinforcement types, continuous-filament mat is superior to chopped-strand mat and woven-rovings. Tightly woven twisted-yarn fabric compares favourably to the woven rovings.

Keywords: **fibre-reinforced plastics, composites, ballistic impact, remaining strength, strength reduction**

WYTRZYMAŁOŚĆ POZOSTAŁA LAMINOWANYCH KOMPOZYTÓW POLIESTROWO-SZKLANYCH PO UDARZE BALISTYCZNYM

Tworzywa sztuczne wzmocnione włóknami (FRP - Fibre Reinforced Plastics) są wrażliwe na uszkodzenia w wyniku udarów, nawet niepenetrujących. Uszkodzenia te, nawet gdy nie wystąpi całkowite zniszczenie, mogą prowadzić do znacznego obniżenia wytrzymałości i zdolności do przenoszenia obciążeń przez kompozyty wzmocnione włóknami. Artykuł przedstawia wyniki prób trzypunktowego zginania kompozytów poliestrowo-szklanych po niepenetrujących udarach balistycznych, gdzie słowo „balistycznych" odnosi się do szybko lecącego, swobodnego impaktora (pocisku). Artykuł ten jest kontynuacją wyników wcześniejszych badań, w których określono rozległość uszkodzeń w kompozytach poliestrowo-szklanych po niepenetrującym udarze balistycznym. Materiały użyte do niniejszych badań to warstwowe kompozyty poliestrowo-szklane wykonane techniką RTM (Resin Transfer Moulding). Laminaty te wytworzono z wykorzystaniem nienasyconej żywicy poliestrowej Polimal 1094 AWTP-1 i wzmocnienia z włókna szklanego typu E w postaci wielu prostopadłych warstw mat z włókien ciętych, mat z włókien ciągłych, tkanin z jedwabiu szklanego oraz plecionek rowingowych. Wykonano kompozyty o zróżnicowanej grubości, liczbie warstw i zawartości wzmocnienia. Impaktorem jest swobodnie lecąca stalowa kulka o masie 3 g rozpędzona przy użyciu działa gazowego. Próby przeprowadzono przy dwóch różnych prędkościach - 60 i 70 m/s, uzyskując przy tym energie udaru wynoszące, odpowiednio, 5,4 i 7,35 J. Po udarze rozmiary pola uszkodzeń próbek (kwadratowych płytek o wymiarach 100x100 mm) zostały zmierzone za pomocą cyfrowej analizy obrazu. Próbki w takiej samej formie, w jakiej zostały poddane udarowi, poddane zostały 3-punktowemu zginaniu w ustalonych warunkach. Rezultaty badania zginającego zostały porównane z wynikami uzyskanymi dla próbek nieuszkodzonych. Zaobserwowano pogorszenie wytrzymałości i obciążenia przy złamaniu w porównaniu z próbkami nieuszkodzonymi. Różnice pomiędzy podejściem od strony wytrzymałości a podejściem od strony obciążenia krytycznego jako parametrami opisującymi zdolność do przenoszenia obciążeń zostało przedyskutowane. Wzmocnienie w postaci mat z włókien ciągłych i gęsto tkanych tkanin z jedwabiu szklanego wypadają korzystnie w porównaniu z matami włókien ciętych i luźnymi plecionkami rowingowymi.

Słowa kluczowe: **tworzywa wzmocnione, kompozyty, udar balistyczny, wytrzymałość pozostała, spadek wytrzymałości**

INTRODUCTION

In our day we can observe fibre-reinforced plastics (FRP) encroaching into many niches previously occupied by other materials, e.g. metallic alloys. Being so widely used it is inevitable that they will be subjected to a variety of impact loading conditions. Impact events may be classified depending on many characteristics, but one of the most widely used is speed. It is because materials behave differently when impacted with different velocity. In this way impacts may be classified as low-velocity impacts (velocity below 10 m/s) also known as quasi-static, due to stress placement essentially identical as in static loading; intermediate-velocity impacts (velocity between 10 and 100 m/s); high-velocity impacts (velocity between 100 and 1000 m/s) and hypervelocity impacts (velocity exceeding 1 km/s) [1-3]. In intermediate- and high-velocity impacts, contrary to quasi-static impacts, during impact event stress is still propagating through the material in form of elastic waves, both longitudinal and transversal. Time of contact between the impactor and target is too short for this waves to travel all the way to the edges of material and back, thus damage is confined to an area significantly smaller then whole target object [1-3]. Intermediate- and high-speed velocity impacts are typical for objects falling from significant height (hail for example), gravel and debris hits on high-speed cars and airplanes during take-off and landing, bird hits on aircraft and for gunfire or shrapnel fragments. The latter two are by no means insignificant even in civilian applications.

There are many modes of energy absorption and damage mechanisms in laminated composites. Most often cited are: kinetic energy of displaced part of target object, fibre tension, fibre destruction through tensile failure or shearing, delamination, matrix cracking and friction between impactor and target material [1, 4-8]. Of these, the most important are target kinetic energy and fibre failure [1, 6-8], while delamination and matrix cracking are primary cause of post-impact strength reduction [5, 7-11]. It must be said, that energy absorption and damage resistance are to some extent conflicting - the main mode of energy absorption is the damage itself [7]. This is why remaining strength of composite is important subject of research. Typically, it is measured through tensile [11, 12] or flexural [13-16] strength loss in composite after impact.

MATERIALS

For this study multi-layered composites (laminates) made of unsaturated polyester (UP) resin and E-type glass fibre in various forms were used (Tab. 1). Laminates were produced using an Advanced Resin Transfer Moulding (Advanced RTM) method in stiff double mould. In RTM method, resin infuses closed mould cavity and permeates reinforcement placed there, driven by under- or overpressure. Laminates were manufactured in the form of flat, square plates of varying thickness.

The common element for all of the composites in this study was matrix of UP resin under the name Polimal 1094AWTP-1, produced by Z.Ch. “Organika-Sarzyna” S.A. (Poland). It is, according to the producer, construction-grade resin, with medium elasticity, ortophtalic, pre-accelerated, with lowered styrene emission. The resin was cured via free-radical copolymerisation initiated by 1.5% addition of methylethylketone peroxide (MEKP) solution in dimethyl phthalate produced under the name Metox-50 by Oxytop Ltd. (Poland).

TABLE 1. **Summary of materials used in the study**
TABELA 1. **Zestawienie materiałów użytych w badaniach**

Material designation	Reinforcement type	Reinforcement basis weight g/m^2	Number of layers	Total reinforcement surface density g/m^2	Thickness mm	Reinforcement weight ratio %	Reinforcement volume ratio %
M2	Chopped-strand mat	350	5	1750	4.0	35	22
M3	Chopped-strand mat	350	6	2100	3.7	41	26
MP1	Continuous-filament mat	450	6	2700	3.6	39	25
MP2	Continuous-filament mat	450	10	4500	5.9	45	29
T1	Twisted-yarn fabric	200	12	2400	3.1	47	30
T2	Twisted-yarn fabric	200	20	4000	3.9	60	42
T3	Twisted-yarn fabric	200	30	6000	5.1	65	49
T4	Twisted-yarn fabric	200	31	6200	5.5	61	44
4P	Woven roving	400	17	6800	6.5	62	45
4P2	Woven roving	400	22	8800	7.5	65	48
9P	Woven roving	960	10	9600	6.8	76	61

Laminates were reinforced using E-type glass fibre in the form of varying number of mats and fabrics. Five types of reinforcement were used:
– Vetrotex M113 350-130 1B chopped-strand mat (CSM) with weight of 350 g/m^2, powder bound, with universal surface treatment.
– Vetrotex Unifilo-series U750 450-138 continuous-filament mat (CFM) with weight of 450 g/m^2, bound with thermoplastic polyesters, with silane treatment.

- Vetrotex 7533 woven twisted-yarn fabric (TYF) with plain weave (1x1) and weight of 200 g/m^2, with universal surface treatment.
- Vetrotex RC400 woven roving (WR) with twill weave (4x1) and weight of 400 g/m^2, with treatment for polyesters.
- Vetrotex RC960 woven roving (WR) with twill weave (2x2) and weight of 960 g/m^2, with treatment for polyesters.

Reinforcement weight and volume ratios were obtained via calcination. Laminates were cut into square plate samples 100x100 mm using diamond saw.

TESTING

In order to evaluate remaining strength of the composites, samples were tested under quasi-static three-point bending conditions, both after ballistic impact and without prior impact. Three-point quasi-static bending was conducted on the Instron Series IX universal testing machine. Samples used for this test were the same (in case of after-impact strength evaluation) or identical to the ones used for ballistic impact tests - flat square plates 100x100 mm with thickness equal to the thickness of produced laminates. Due to non-standard width and variable (between series) thickness, testing method was based on ISO 178:1996 standard (Plastics - Determination of flexural properties), but modified to suit specific experimental needs. The reduced comparability of results with other studies was taken into consideration.

The as-modified testing conditions were as follows: sample length 100 mm, sample width 100 mm, support span 80 mm, crosshead speed 4 mm/min.

The impact part of study was conducted using gas gun test assembly. Samples identical to those mentioned above were secured to the front of a ballistic pendulum, supported in four corners. Ballistic pendulum is equipped with butts in case of penetrating hits, however all impact were non-penetrating. The impact was exerted by free-flying spherical impactor (projectile) made of hardened steel, having a mass of 3.0 g. Saboted impactor was propelled down the barrel by compressed air. Two impact velocities were used in this study - 60 and 70 m/s, giving 3 g projectile kinetic energy of 5.4 and 7.35 Joules accordingly. Projectile velocity was measured by a ballistic chronograph and ballistic pendulum deflection was measured electromechanically.

The damage extent in impacted composites was evaluated and presented in earlier study [17].

RESULTS AND DISCUSSION

Figures 1 and 2 display the original mechanical properties of the materials used in the study. The trend is for the load-at-break to be rising with increasing number of layers of the reinforcement for each of the material series. Analogical trend regarding materials strength is not clear. This seems to be mainly due to high dependence of strength on material thickness - by definition, material strength is the load-at-break divided by cross-sectional area, which in turn is thickness-dependent. This is perfectly justified in bulk materials, but slightly less so in reinforced materials, especially FRP, where only reinforcement bears considerable load. Taking two materials with exact reinforcements, one containing more matrix then the other and consequently having greater thickness, the former will exhibit lower strength than the other will, despite similar load-bearing abilities. Therefore, while still being informative, strength alone is insufficient and will be supplemented with load-at-break for the following studies.

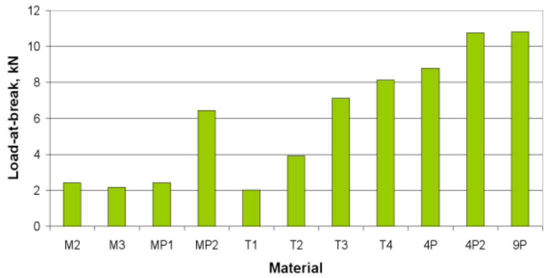

Fig. 1. Original load-at-break of materials used in the study

Rys. 1. Początkowe obciążenie przy złamaniu materiałów użytych do badań

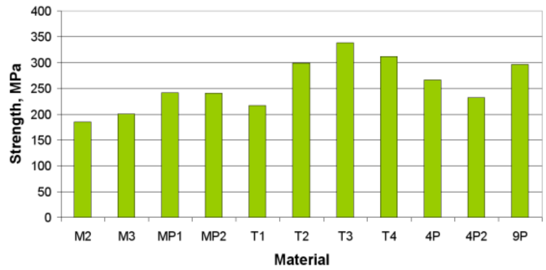

Fig. 2. Original strength of materials used in the study

Rys. 2. Początkowa wytrzymałość materiałów użytych do badań

Impact, even sub-critical like those performed in the study, decreases load-bearing potential of composites. All materials exhibit some decrease of load-at-break value (Fig. 3). Generally, the loss is lower for thicker, more reinforced composites in every reinforcement group. Comparing reinforcement types, load-at-break loss is lowest for CFM-reinforced composites, which again show surprisingly good performance. Loose-structure WR-reinforced composites display higher load-at-break loss than tighter-structure TYF-reinforced does and their performance is by far the worst. The extent to which load-at-break is decreased after impact varies greatly. One material (higher-weight CFM-reinforced composite) loose less than 5% of original value, while another (low-weight WR-reinforced composite) under the same impact conditions loose 25%, which is a significant reduction. After the more energetic impact, more materials exhibited loss of ca. 25% in load-at-break. There can be seen some correlation between the loss and the amount of reinforcement - more reinforced composites tend to loose less of the original (higher) load-bearing abilities.

Although samples damaged by impact ought to show also reduced strength (Fig. 4), there is no clear trend as to the strength loss dependence on total reinforcement surface density and laminate thickness. This is because - as mentioned before - strength is highly thickness dependent, while some of the thickness-forming material contribution to strength is negligible. Thicker laminates with the same reinforcement will have lower strength purely because of higher denominator.

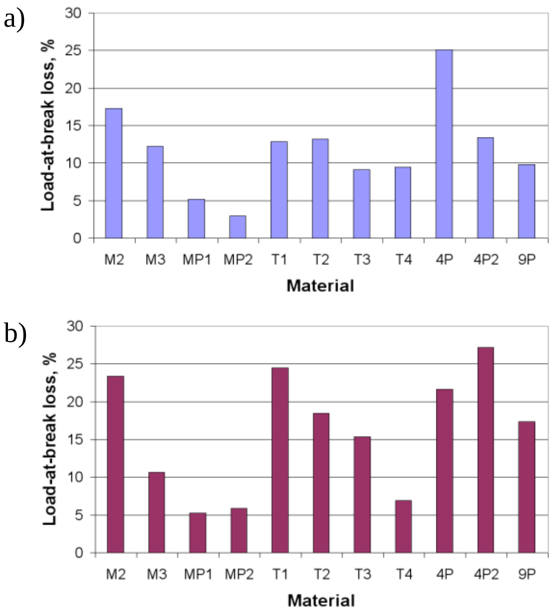

Fig. 3. Load-at-break loss: a) after 5.4 J impact, b) after 7.35 J impact

Rys. 3. Utrata wartości obciążenia przy złamaniu: a) po udarze o energii 5,4 J, b) po udarze o energii 7,35 J

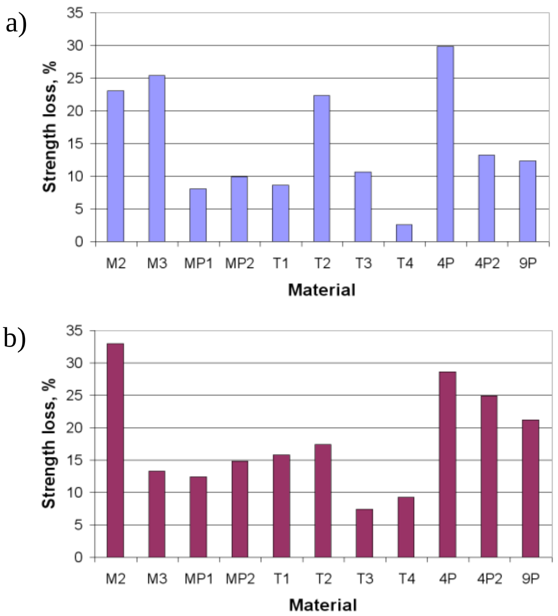

Fig. 4. Strength loss: a) after 5.4 J impact, b) after 7.35 J impact

Rys. 4. Utrata wytrzymałości: a) po udarze o energii 5,4 J, b) po udarze o energii 7,35 J

What can be observed, strength loss is generally higher for composites reinforced with CSM than for composites reinforced with CFM. Similarly, WR-reinforced composites display higher strength loss than TYF-reinforced composites. In some materials, the strength loss is very significant - up to and exceeding 30% of original value, while stronger materials loose no more than 10% of the original strength.

CONCLUSION

In the course of this study it was proven, that even non-critical impact event leads to, sometimes serious, decrease in strength and load-bearing properties of composites. The extent of the reduction is varied and dependent on reinforcement factors such as reinforcement type and structure, as well as total amount of reinforcement in composite. Composites with higher reinforcement content clearly tolerate impact events better - that is, both the damaged area and mechanical properties reduction are lower for them than for composites with lower reinforcement content.

Based on the study, it is conceivable that strength is too much thickness-dependent to accurately characterize laminated composites, in which only the reinforcement bears considerable load. While using the Resin Transfer Moulding technology for manufacturing of FRP generally allows for good thickness control (though not guarantee it), other methods, such as hand lay-up, vacuum bagging or vacuum infusion do not. It is therefore implicit that parts manufactured using those latter technologies will have varying strength despite constant amount of reinforcement and essentially constant load-bearing abilities. Since generally FRP are designed taking loads into account, not strength, characterizing post-impact mechanical properties reduction using load-at-break parameter seems to be a better choice.

Regarding reinforcement types, chopped-strand mats are by far the worst in every aspect of impact tolerance, which is not surprising. However, continuous-filament mats are superior to chopped-strand mats, loose-structure woven rovings and on par with tightly woven twisted-yarn fabrics. This is worth noting and needs further research. Concerning fabrics, tightly woven ones prove to be superior to loose woven rovings.

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