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COMPOSITES

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GLASS FIBRE/POLYESTER COMPOSITES UNDER BALLISTIC IMPACT

This work presents results of ballistic impact tests on glass-fibre/polyester laminates. An effort has been made to manufacture composites with improved tolerance to ballistic impact using inexpensive, common materials like fibreglass and unsaturated polyester resin, by means of modern, yet popular moulding technology. Laminates were made using various E-type glass fibre reinforcements: chopped strand mat, continuous filament mat, cloth and two different woven rovings, with varying weight. Varying number of reinforcement layers were tested, as well as varying reinforcement-to-matrix ratio - from 20 to 60% vol. Samples of manufactured laminates were subjected to impact by a 3 g spherical hardened steel impactor moving at the velocity of 60 and 70 m/s (giving 5.4 and 7.35 Joules of kinetic energy, accordingly) using a gas gun test assembly. Samples were subsequently scanned using optical flat-bed scanner and the obtained images were digitally processed by software to measure the extent of delamination. Two ways of interpreting the extent of delamination in composites were tested - through the evaluation of delaminated volume and through the maximal delaminated surface area - to find usefulness of both methods. Impact energies were kept low such that none of manufactured laminates were perforated. The impact testing and image analysis of delaminated zone has shown similar range of damage in low-weight cloth and continuous filament mat, contrasted to inferior performance of chopped strand mat and high-weight, loose-structure woven rovings. Relationship between coherence of structure and delaminated area reduction has been shown. Unexpected three-dimensional shape of delaminated volume that had been found was discussed. Moreover, two methods of delaminated zone evaluation in composites subjected to impact - by means of delaminated volume and by means of delaminated area - has been discussed, suggesting superiority of the latter.

Keywords: **composites, laminates, impact testing, RTM, ballistic performance**

UDAR BALISTYCZNY KOMPOZYTÓW POLIESTROWO-SZKLANYCH

Praca przedstawia wyniki balistycznych badań udarowych laminatów poliestrowo-szklanych. Wysiłki ukierunkowano na wyprodukowanie kompozytów o podwyższonej odporności na udar balistyczny, wykorzystując niedrogie, powszechnie stosowane materiały, takie jak włókno szklane i nienasycone żywice poliestrowe, przy użyciu nowoczesnej i jednocześnie popularnej technologii formowania. Laminaty wytworzono, wykorzystując wzmocnienie z włókna szklanego typu E w różnych postaciach: mat z włókien ciętych, mat pętlicowych z włókna ciągłego, tkaniny z jedwabiu szklanego oraz dwóch różnych tkanin rovingowych, różniących się gramaturą. Zastosowano zmienną ilość warstw poszczególnych typów wzmocnień oraz zmienny udział wzmocnienia w kompozycie - od 20 do 60% obj. Próbki wytworzonych laminatów poddano udarowi sferycznym impaktorem o masie 3 g ze stali utwardzanej cieplnie poruszającym się z prędkościami 60 i 70 m/s (co daje odpowiednio 5,4 i 7,35 J energii kinetycznej) z użyciem stanowiska badawczego typu działo gazowe (ang. *gas gun*). Następnie próbki poddano skanowaniu na optycznym skanerze płaskim, a uzyskane obrazy poddano cyfrowej analizie w celu określenia wielkości obszaru zdelaminowanego. Przetestowano dwa ujęcia ewaluacji obszaru zdelaminowanego - poprzez objętość zdelaminowaną oraz poprzez największe pole powierzchni delaminacji - w celu określenia przydatności obu metod. Energie udarów utrzymywano na niskim poziomie, tak że żadne z wytworzonych laminatów nie uległy perforacji. Wyniki badań udarowych i analizy obszarów poddanych delaminacji wykazały zbliżony poziom uszkodzeń w wyniku udaru u kompozytów wzmocnionych włóknem szklanym w postaci tkaniny z jedwabiu szklanego o niskiej gramaturze oraz maty z włókien ciągłych i słabszych od nich właściwości w przypadku kompozytów wzmocnionych luźnymi tkaninami rovingowymi o dużych gramaturach oraz matami z włókien ciętych. Wykazano zależność między zwartością struktury wzmocnienia a korzystnym ograniczeniem obszaru uszkodzeń delaminacyjnych kompozytów. Niespodziewany kształt trójwymiarowej objętości zdelaminowanej otrzymano i został on przedyskutowany. Przedyskutowano ponadto dwie metody oceny obszaru zdelaminowanego w kompozycie poddanym udarowi - pod względem objętości zdelaminowanej oraz powierzchni zdelaminowanej - sugerując wyższość drugiego ujęcia.

Słowa kluczowe: **kompozyty, laminaty, badania udarowe, RTM, odporność balistyczna**

INTRODUCTION

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

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 [1-6]. Of these, the most important are target kinetic energy and fibre failure [1, 4-6], while delamination and matrix cracking are primary cause of post-impact strength reduction [3, 5-9]. It must be said, that energy absorption and damage resistance are to some extent conflicting - the main mode of energy absorption is damage itself [5].

Materials subjected to impact behave differently depending upon impact speed, even more so materials viscoelastic like plastics. Impacts may be classified, depending upon their velocity, as low velocity impacts, described also as quasi-static (velocity below 10 m/s), medium velocity impact (10÷100 m/s), high velocity impacts (100÷1000 m/s) and hypervelocity impacts (velocity above 1 km/s) [1, 11, 12]. Low velocity impacts are dubbed quasi-static because of stress placement essentially the same as in static loading [12]. On the contrary, in medium and high velocity impacts, stress is propagating in the form of elastic waves (both longitudinal and transverse) in the material. The maximum speed of stress propagation is the speed of sound in the material [1, 11, 12]. Time of contact between impactor and target is too short for these waves to propagate significant distance through the material and shorter than time needed for the wave to reach materials edge. In high velocity impact of laminated panels, this time is comparable to the time of wave propagation in the direction normal to the surface [12]. Thus, the damage is confined to a relatively small area around impact point. Medium and high velocity impacts are typically produced by objects falling from significant height (hail for example), gravel on high-speed cars, aircraft crashing with birds and by gunfire. The latter is by no means insignificant in our present times even in civilian applications.

This work is a part of studies into composite-construction gas fuel tanks for civilian cars. As most studies concentrate on ballistic impact behaviour of high-end composites with carbon, aramid or oriented UHMWPE fibre reinforcement, examining cheaper fibreglass/polyester laminates is interesting and new. Also, studies into ballistic impact are generally more concentrated on evaluating ballistic limit and damage extent after penetration - one can think, that when penetration happens, remaining strength of composite is of least concern for wearer of penetrated personal armour or driver of a car with perforated gas tank. It is worth to study the effect of less drastic impact event.

MATERIALS

Since the role of reinforcement is much more important than the role of resin, when it comes to coping with impacts altogether, and ballistic impacts in particular, methods for manufacturing laminates with high reinforcement-to-resin ratio is desirable. Composites for this study were produced by Advanced Resin Transfer Moulding (Advanced RTM) method, with and without vacuum assist. In RTM method, resin infuses closed mould cavity and permeates reinforcement placed there. Resin infusion in RTM method is driven by vacuum, overpressure, or both. In Advanced RTM, resin fills the cavity of a rigid mould under high overpressure. In Vacuum Assisted RTM, the air from the mould cavity is evacuated before moulding begins.

All manufactured composites were made using Polimal 1094 AWTP-1 unsaturated polyester resin produced by Zakłady Chemiczne „Organika Sarzyna" S.A. (Poland). It is, according to producer, construction-grade resin, with medium elasticity, ortophtalic, pre-accelerated, with lowered styrene emission. As an initiator of free-radical copolymerisation (curing) of the resin, 1.5:100 weight parts of methylethylketone hydroperoxide were used, dissolved in dimethyl phthalate, produced by Oxytop sp. z o.o. (Poland) under the name Metox 50.

Laminates were manufactured with a variety of glass fibre (type E glass) reinforcements, the first one being Vetrotex M113 350-130 1B mat, with weight 350 g/m^2. It is a chopped strand mat, powder bound, with universal surface treatment. Vetrotex Unifilo-series U750 450-138 is a continuous filament mat with weight of 450 g/m^2, bound with thermoplastic polyesters, with silane treatment. Vetrotex 7533 is a woven cloth with plain weave (1x1) and weight of 200 g/m^2, with universal treatment. Vetrotex RC400 and RC960 are woven rovings with weights of 400 and 960 g/m^2 accordingly, with twill weave (4x1 and 2x2 accordingly) and surface treatment for polyesters.

Composites were manufactured with varying number of layers of all the reinforcements, as presented in Table 1. For all of the materials, reinforcement-to-resin weight and volume ratio were evaluated through calcination. From these composites, samples 100x100 mm were cut with a diamond saw for impact testing. Three to five samples of each composite were tested under each impact speed.

TABLE 1. **Summary of materials used in this study**
TABELA 1. **Zestawienie materiałów użytych do badań**

Material designation	Reinforcement type	Reinforcement layer weight, g/m^2	Number of layers	Total reinforcement surface density g/m^2	Vacuum assist	Reinforcement weight ratio, %	Reinforcement volume ratio, %
M2	Chopped strand mat	350	5	1750	NO	35	22
M3	Chopped strand mat	350	6	2100	NO	41	26
MP1	Continuous filament mat	450	6	2700	NO	39	25
MP2+	Continuous filament mat	450	10	4500	YES	45	29
T1	Woven cloth fabric	200	12	2400	NO	47	30
T2	Woven cloth fabric	200	20	4000	NO	60	42
T3	Woven cloth fabric	200	30	6000	NO	65	49
T4+	Woven cloth fabric	200	31	6200	YES	61	44
4P+	Woven roving	400	17	6800	YES	62	45
4P2	Woven roving	400	22	8800	NO	65	48
4P3+	Woven roving	400	22	8800	YES	65	48
9P+	Woven roving	960	10	9600	YES	76	61

TESTING

Samples manufactured as it has been mentioned above were subjected to impacts using gas gun test assembly. Free flying impactors (projectiles) - spherical balls were accelerated with paper sabot down the barrel 750 mm long by compressed air stored in tank. In this investigation, two levels of compressed air pressure have been used - 1.2 and 2.4 MPa, allowing for velocities of 60 and 70 m/s accordingly, measured by ballistic chronograph. These velocities give 3 g projectile kinetic energies of 5.4 and 7.35 J.

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Square samples 100 by 100 mm were placed on the front side of ballistic pendulum, supported in four corners. Samples were fastened to four cylindrical supports 10 mm in diameter by means of double-sided adhesive tape. The adhesive connection invariably failed during rebounding off the support after impact.

Projectile velocities after impact are minimal, so projectile impacting sample transfers most of its kinetic energy to the sample. Impact energy may thus be treated as a good approximation of transferred energy.

After impact, the extent of delaminated area of samples was measured by means of digital image analysis. Samples have been scanned on a Mustek Bear Paw 1200CU Plus flatbed scanner connected to a PC and then digitally processed and measured using Scion Image for Windows version Beta 4.0.2 software. Both faces of samples were processed the same way. Surface area of delamination was measured for both front and back face of the sample, as well as the largest area if it wasn't the same as back face surface area, being instead in one of the internal layers. Besides delaminated area surface, volume of delamination was also calculated. Due to irregular shape of the delamination, instead of absolutely true volume, calculation volume was used. It was defined as a volume of a truncated quasi-cone with bases surfaces equal to delamination area surfaces on front and back face of the sample, and it's height equal to sample thickness. In case where maximal delaminated surface was in one of the inner layers, calculation volume of delamination is taken as a volume of two truncated quasi-cones joined at the larger base, which is maximal delaminated area. Calculation volume of delamination is regarded good approximation of true volume of delamination.

RESULTS AND DISCUSSION

Figure 1 presents scanned images of sample examples after impact. It is worth to mention high translucency of samples made using fibreglass cloth, as well as shape and size of delaminated areas. A characteristic cross-like shape can be seen in fibreglass cloth-reinforced laminates, while those reinforced with mats show more circular delaminated area. Delamination area on the front face is smaller then on the back face, which is characteristic for impacts. In some cases the largest delaminated area lies neither on the front face nor on the back face, but in one of the internal layers. What cannot be seen on images, but only in personal examination, is that the back face of some samples shows permanent deformation in the form of a flat cone.

Table 2 presents averaged results (front face delamination area, maximal delamination area, back face delamination area and calculation volume of delamination) for each material. Diagrams on Figures 2-4 present calculation volume of delamination at two impact speeds for laminates reinforced with, consecutively, mats, cloths and woven rovings. As can be seen, delamination damage is generally more extensive after higher velocity, thus higher energy impacts, though it is not clear for all the materials.

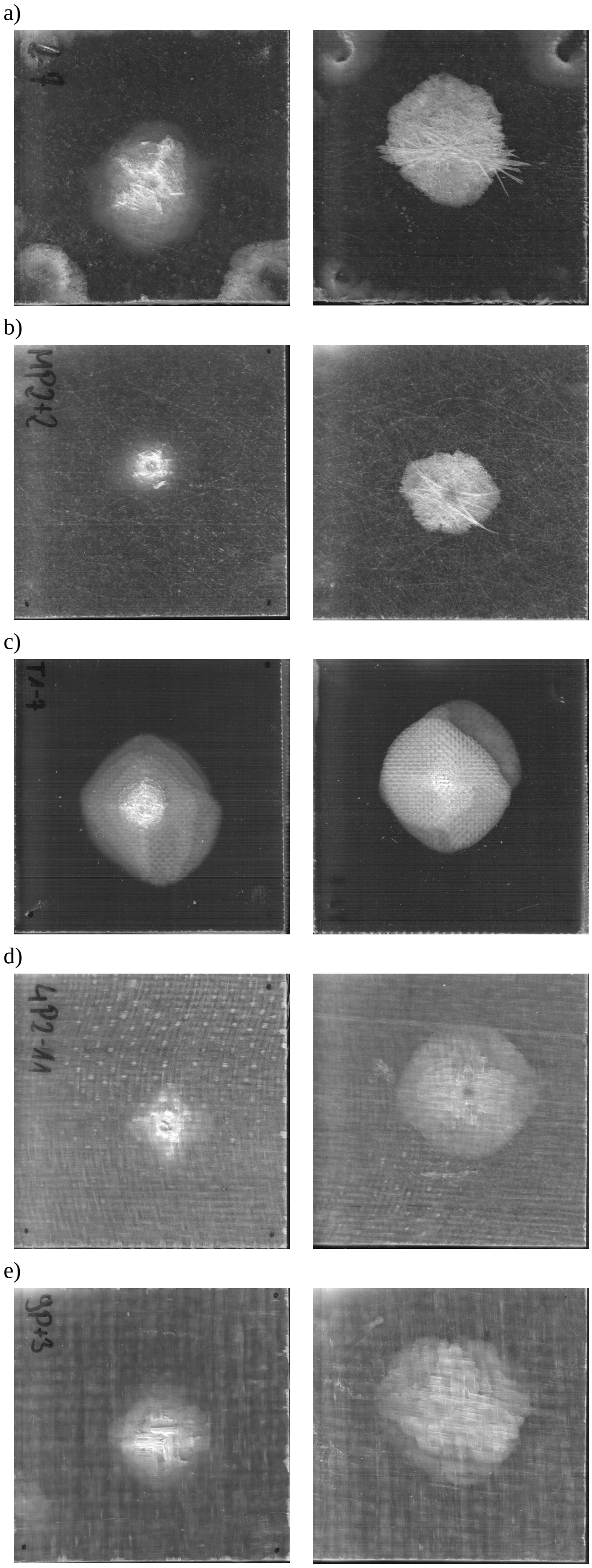

Fig. 1. Scanned images of front and back face of selected samples after impact. Laminates reinforced with: a) chopped strand mat; b) continuous filament mat; c) cloth; d) 400 g/m^2 woven roving; e) 960 g/m^2 woven roving

Rys. 1. Zeskanowane obrazy czołowej i tylnej strony wybranych próbek po udarze. Laminaty wzmocnione: a) matą z włókien ciętych; b) matą z włókien ciągłych; c) tkaniną z jedwabiu szklanego; d) tkaniną rovingową o gramaturze 400 g/m^2; e) tkaniną rovingową o gramaturze 960 g/m^2

TABLE 2. **Averaged results of delamination damage of the tested materials**

TABELA 2. **Uśrednione wyniki obszaru zdelaminowanego dla badanych materiałów**

Material designation	Impact velocity	Front face delamination area	Maximal delamination area	Back face delamination area	Volume of delamination
	m/s	mm^2	mm^2	mm^2	mm^3
M2	60	598	1585	1271	4382
M3	60	674	1392	1003	3581
MP1	60	379	1028	723	2485
MP2+	60	194.5	888.5	743.5	3359
M1	70	1002	1468	1468	4486
M2	70	820	1764	1573	4585
M3	70	576	1218	1165	3965
MP1	70	323	1120	1068	2522
MP2+	70	206	1047	944	4014
T1	60	241	858	631	1844
T2	60	267	1023	444	2314
T3	60	200	892	481	2551
T4+	60	129	773	676	2672
T1	70	220	1406.5	1095	2918
T2	70	351	1126	564	2400
T3	70	249.5	1267.5	616.5	3758
T4+	70	309	1212	893	4477
4P+	60	301	1240	687	4880
4P2	60	216	1030	587	4243
4P3+	60	266	1164	900	5427
9P+	60	348	1555	860	6249
4P+	70	437	1691	1059	7242
4P2	70	340	1433	919	6831
4P3+	70	360	1501	757	6586
9P+	70	563	2068	1364	9248

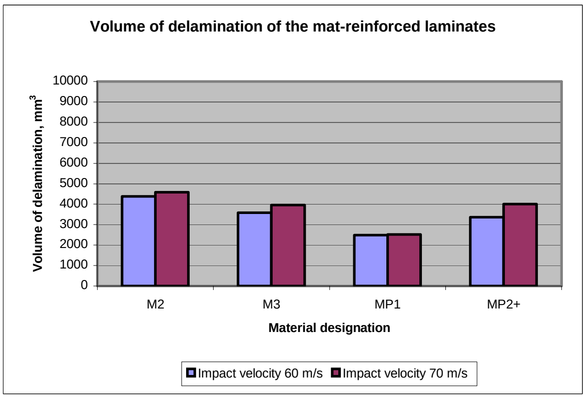

Fig. 2. Volume of delamination of the mat-reinforced laminates

Rys. 2. Objętość obszaru zdelaminowanego dla laminatów wzmocnionych matami

In case of mat-reinforced laminates, there is only a small increase in delaminated volume with increasing impact energy. In composites made with chopped strand mats (M2 and M3), thinner laminate with lower surface density of reinforcement (M2) display more extensive delamination, however in composites made with continuous filament mat (MP1 and MP2+) it is just the opposite. Continuous filament mat seem to be better reinforcement for impact applications than chopped strand mat.

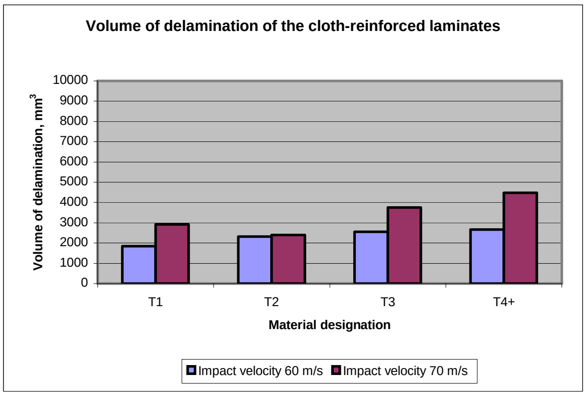

Fig. 3. Volume of delamination of the cloth-reinforced laminates

Rys. 3. Objętość obszaru zdelaminowanego dla laminatów wzmocnionych tkaniną z jedwabiu szklanego

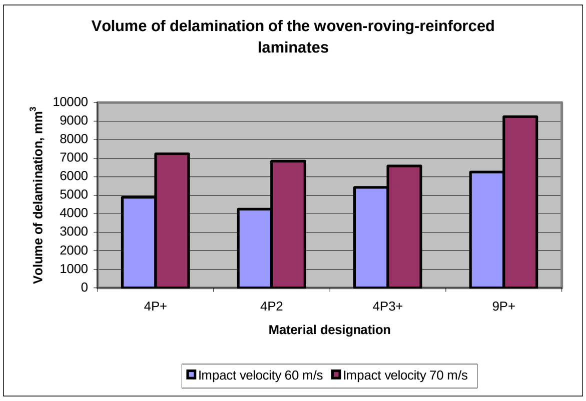

Fig. 4. Volume of delamination of the woven roving-reinforced laminates

Rys. 4. Objętość obszaru zdelaminowanego dla laminatów wzmocnionych tkaninami rovingowymi

In the case of cloth-reinforced laminates, a similar trend as in the case of continuous filament mats can be seen - delaminated volume rises with rising material thickness and reinforcement surface density. This peculiar feature seems to indicate that greater material thickness and number of layers don’t affect positively damage resistance in terms of delamination volume - quite the opposite, the more volume is available, the more is delaminated!

In the case of woven roving-reinforced composites, poor performance (i.e. large delaminated volume) of the 9P+ material is visible, despite its highest thickness, reinforcement surface density and reinforcement content. It seems to be influenced by high weight of individual layers, loose weave and small number of layers.

Among laminates made with woven roving of 400 g/m^2 weight, the best performance (lowest delaminated volume) has material designated 4P2 and the worst - the one designated 4P3+. This is interesting, because the only thing that differentiates this two materials is vacuum assist during moulding of the latter - quite surprising given that vacuum assist is supposed to aid in reinforcement permeation, thus one could expect better performance. Materials designated 4P+ and 4P3+ display similar performance (with slight advantage for heavier 4P3+), even though they were very different in terms of thickness and reinforcement surface density - both however were moulded using vacuum assist and both have similar reinforcement content.

Comparing different groups of reinforcement, cloth used as a reinforcement gives marginally better composite performance than continuous filament mat, while best woven roving-reinforced composite is marginally better than worst chopped strand-mat reinforced one, if a volume of delamination is taken as a criterion.

Figures 5-7 present other take into the question of evaluating laminates impact damage resistance - from the delaminated area surface point. On subsequent diagrams, maximal delaminated area for materials in each group - mat-, cloth- and woven roving-reinforced composites. Yet again a trend in increasing damage extent with increasing impact energy (velocity) is clearly visible, with one exception - material M3 - probably due to statistical flux. One can also see clear advantage of continuous filament mats (MP1 and MP2+) over chopped strand mats (M2 and M3) in terms of delaminated area (read - it is smaller). Also, a trend might be found of decreasing delaminated area with increasing overall reinforcement content in the laminate - a thing not obvious from the delaminated volume point.

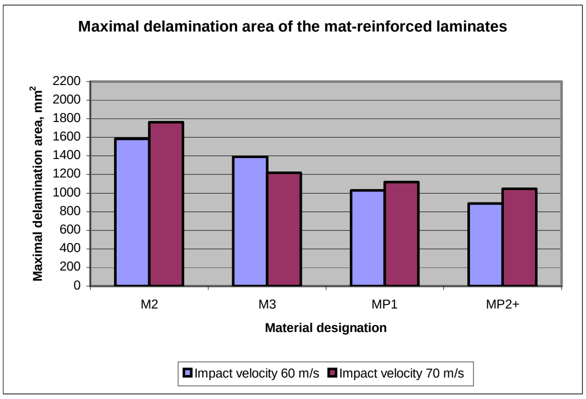

Fig. 5. Maximal delamination area of the mat-reinforced laminates

Rys. 5. Maksymalne pole obszaru zdelaminowanego dla laminatów wzmocnionych matami

Cloth-reinforced composites show the same trend, with the exception of T1, which doesn’t find explanation. What is important, another trend is visible, that delaminated area surface is dependent more on overall reinforcement surface density than on reinforcement-to-

-matrix ratio - material T4+ has better performance than T3, even though the latter contains 49% by volume of fibreglass vs. 44% by volume of the former.

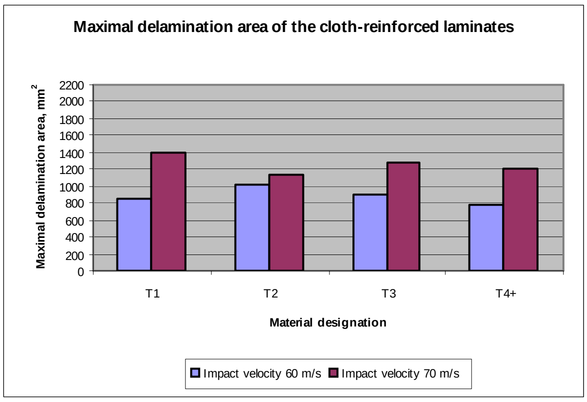

Fig. 6. Maximal delamination area of the cloth-reinforced laminates

Rys. 6. Maksymalne pole obszaru zdelaminowanego dla laminatów wzmocnionych tkaniną z jedwabiu szklanego

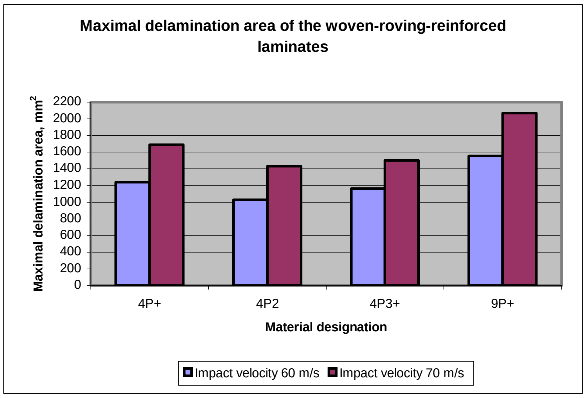

Fig. 7. Maximal delamination area of the woven roving-reinforced laminates

Rys. 7. Maksymalne pole obszaru zdelaminowanego dla laminatów wzmocnionych tkaninami rovingowymi

In the case of woven roving-reinforced laminates, once again the 960 g/m^2 fabric proves to be inferior reinforcement next to the 400 g/m^2 one. Among the latter, again better performance shows the one moulded without vacuum assist. And among the products of vacuum assisted RTM, this time the thicker one with greater reinforcement content is better.

Comparing best performers in each group, woven roving is still inferior to all other reinforcements except chopped strand mat - again the probable cause, as in the case of 960 kg/m^2 versus 400 kg/m^2 fabric, is loose structure and fewer layers, thus more possibility for yarns movement. At this point it is not possible to differentiate between loose structure and small layers count as a cause. The other two reinforcements, continuous filament mat and cloth fabric show similar delaminated area, but for the mat the increase in delaminated area surface with increasing impact energy is less pronounced. The cause may lay in greater thickness of MP2+ material, but proving this is impossible at this point and will need further investigation.

Comparing volume and area aspect of delamination, it seems that better results give the latter one. It gives more coherent, easier in interpretation picture, what is exposed by untypical behaviour of continuous filament mat- and cloth-reinforced composites in the former aspect.

One more phenomenon seems mysterious - that largest surface of delamination lies often in one of the inner layers of laminate. The explanation may be, under ballistic impact conditions a typical, expected cone is formed, with each layer of reinforcement tensed more, leading to delamination, but at some point the kinetic energy of impactor is transferred into work of destruction and subsequent layers are tensed less each, thus there is less permanent damage in them. Never before a phenomenon like this was observed, if one is to believe available literature on this topic, but all of them concentrated on target perforation by a projectile, thus never examining samples at impact energies far below the ballistic impact. In this study, the impact energy was significantly lower than energy necessary for penetration, resulting in a possibility to observe this phenomenon.

CONCLUSIONS

Manufacturing cheap polyester/fibreglass laminates with increased tolerance for non-penetrating ballistic impact through methods as common as Resin Transfer Moulding have been proved to be possible. A possibility of manufacturing glass fibre-reinforced polyester resins with increased ballistic penetration resistance through RTM is deemed probable. It is possible to substitute expensive aramid-based, impact resistant composites with polyester/glass fibre laminates for civilian applications.

Manufacturing laminates with high reinforcement-to-resin ratio is advantageous because of packing large amount of reinforcement into low thickness of laminate. High surface density of reinforcement increases composites impact performance.

Obtaining high surface density of reinforcement is easier using cloth fabric then mats, even more so using woven roving.

Assuming constant surface density of reinforcement, using more low-weight layers seems to be more advantageous than using fewer high-weight, loose-structure layers.

As can be expected, chopped strand mat proves to be bad performer as a reinforcement for composites for ballistic impact applications. However, there is no great difference between continuous filament mat and fabrics.

It is better to evaluate the extent of delamination damage by its area than volume.

Further investigations into the effect of various material parameters on ballistic impact performance of laminated composites are desirable.

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