INFLUENCE OF THE IMPACTOR GEOMETRY ON THE DAMAGE CHARACTER IN COMPOSITE STRUCTURES

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Summary

The impact damages occur during normal operation of many structural elements, primarily in the aircraft structures, but also in the ground machinery, whose elements made of polymeric composites. According to the specific conic-shaped character of the impact damages initiation and propagation it is often difficult to analyze the damage extent basing on the surface characterization only. Moreover, the shape of the impacted body has a significant influence on the resulted damage. In the following paper the influence of the impactor geometry was analyzed basing on the force responses during the impact and the area of resulted damages, which were obtained using transmitted light imaging technique and image processing methods. The obtained results allowed for comparison of damage states and conclusions about characteristic stress distributions during impact for various geometries of impactors.

Keywords: composite structures, impact damage, drop weight test, transmitted light imaging, delamination

WPŁYW GEOMETRII BIJAKA NA CHARAKTER USZKODZEŃ W STRUKTURACH KOMPOZYTOWYCH

Streszczenie

Uszkodzenia udarowe występują w trakcie normalnej eksploatacji wielu elementów strukturalnych, głównie w strukturach stosowanych w lotnictwie, ale także w maszynach lądowych, których elementy wykonane są z kompozytów polimerowych. Z uwagi na specyficzny charakter inicjacji i propagacji uszkodzeń udarowych w kształcie stożka często trudno analizować rozległość uszkodzenia jedynie na podstawie charakteryzacji powierzchni. Ponadto kształt uderzającego ciała ma znaczący wpływ na powstające uszkodzenie. W niniejszym artykule wpływ geometrii bijaka został przeanalizowany na podstawie odpowiedzi siły udaru podczas kontaktu oraz powierzchni uzyskanych uszkodzeń, które zostały otrzymane przy pomocy techniki fotografii prześwietleniowej i metod analizy obrazów. Uzyskane wyniki pozwoliły na porównanie stanów uszkodzeń i konkluzje o charakterystycznych rozkładach naprężeń podczas udaru dla różnych geometrii bijaków.

Słowa kluczowe: struktury kompozytowe, uszkodzenie udarowe, próba ze spadającym ciężarkiem, fotografia prześwietleniowa, delaminacja

1. INTRODUCTION

One of the most serious damages which could occur in the polymeric composite structures is the impact damage. Such damage may significantly decrease strength parameters as well as integrity of a structure. In the case of low-velocity impacts the damages could be practically undetectable on the surface of a structure by visual inspection, but the internal damage may have a complex structure of cracks and delaminations, which have a shape of a truncated cone [1]. Under the influence of typical workloads of a structural element the damage may propagate which consequently may cause the breakdown of this element. Therefore, the characterization of low-velocity impacts occurred in composite structures has great practical importance both for analysis of mechanical behavior of a structure and development of non-destructive techniques of their detection and localization.

The problem of impact damaging of composites has been widely studied by many research groups, who used different analyzing parameters and different techniques for performing these analyzes. Damaged structures are, most often, prepared in the artificial way, mainly by using drop weight tower [2,3], Charpy machine [4], spring or air guns [5]. The authors of [6] performed impact tests on the specimens obtained from an aircraft covering element, which allowed for evaluation of impact resistance of these structures of an aircraft being ca. 30 years in service.

In the impact tests performed on composite structures several parameters are measured and selected for the structural health evaluation. The authors of [7] analyzed the force response and indentation of a structure after tests. The force response was also analyzed by several other authors [8-14]. The other parameters, which were studied during such tests concerned with a damage, e.g. the authors of [15,16] analyzed the delamination extent. Many of authors analyzed the influence of impactor shape on the resulted damage [9-11,13,14,17]. However, sometimes the non-trivial methods were used for the structural damage evaluation, e.g. the authors of [18] used the modal analysis for evaluation of damage occurrence, while the others analyzed a microstructure of composites after impact using microscopy [1,8,16] and ultrasound measurements [9,10,13].

The aim of a presented study is to compare the influence of impactor shapes during the impact of various energies on the resulted damages basing on character and areas of damages. Among the classical shapes of impactors we studied also the resulted damages of impactors with immersed stones with specific orientations. Such analysis allows to simulate the realistic stone impact damages occurred e.g. during the lofting of stones when the aircraft starts. The proposed technique of acquisition of area of the damages is based on the image processing methods which is a novelty in such applications.

2. PREPARATION AND PERFORMING THE TESTS

2.1 SPECIMENS AND THEIR ARTIFICIAL DAMAGING

The tests were carried out on 12-layered square plates with a side dimension of 300 mm and a thickness of 2.5 mm made from plain weave glass fibre reinforced epoxy laminate with a symbol EP GC 201, manufactured and supplied by Izo-Erg S.A.

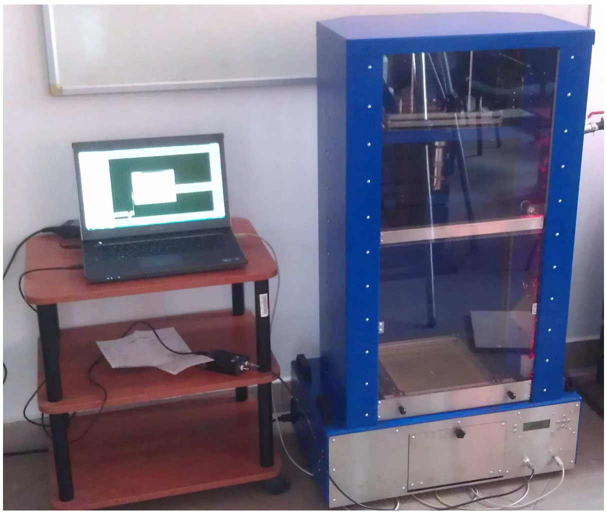

Fig. 1. A test rig for a simulation of impact damages

In order to simulate impact damages in the plates an own-designed test rig for the drop weight impact tests was used (see Fig.1). A detailed description of the test rig could be found in [19].

A procedure of performing the damage simulation was as follows. During the tests several types of impactors were considered. Two general types of impactors were used (see Fig.2): with metallic indenter part and with a stone indenter part (for the simulation of stone impacts). The impactors presented in Fig.2a-e contain the rounded end of R17, R14, R11, R8 and R5, respectively; Fig.2f presents a flat-ended impactor of R17; Fig.2g presents a ring-ended impactor of R9.5; Figs.2h-I present the conical and bullet-like indenters; and Figs.2j-n present impactors with immersed stones: with flat impact surface, with rough impact surface, edge-ended, vertex-ended and angle-oriented vertex-ended, respectively. The damaging was performed with various energies of impact starting from 10 J to 40 J with a step of 10 J. An exemplary planar view of a damaged plate was presented in Fig.3. For convenience hereinafter we use the following notation of the damaged cases: in

M20 the letter denotes a type of impactor according to those presented in Fig.2 and the number denotes the energy of impact.

The specimens were simply supported on their edges during the impact.

Fig. 2. Impactors used for the tests

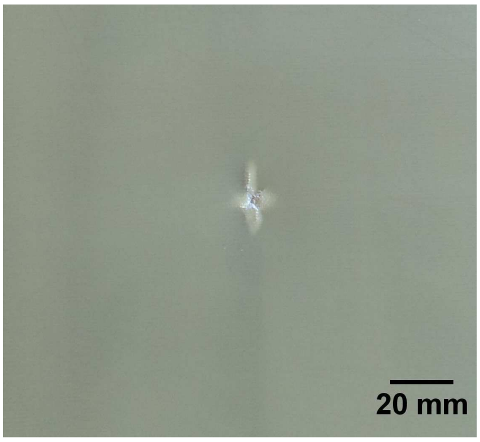

Fig. 3. Exemplary planar view of a damage case M20

2.2 TRANSMITTED LIGHT IMAGING

In order to examine the internal damage states in the investigated plates and considering a fact that the material was semi-transparent it was decided to analyze the damages using transmitted light imaging (TLI) technique. For the light transmission the bottom lighting table was used (which allow to improve the contrast between damaged and undamaged regions of the plates) and for the image acquisition the NIKON COOLPIX S9100 camera was used. The experimental procedure was presented in Fig.4.

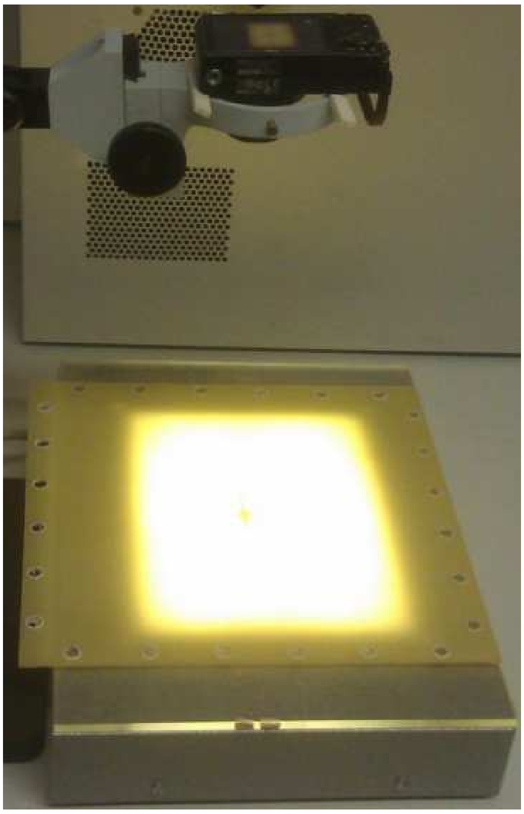

Fig. 4. Experimental setup during TLI

The 24-bit pictures with a resolution of 300 dpi and the dimensions of 2048x1536 px (3.1 Mpx) were collected for the further analysis.

3. RESULTS AND ANALYSIS

3.1 VISUAL INSPECTION AND EVALUATION

The evaluation of damages was started from the visual inspection. Due to the application of various impactor shapes some characteristic damage shapes were obtained. Selected images, obtained using LTI technique, were presented in Fig.5.

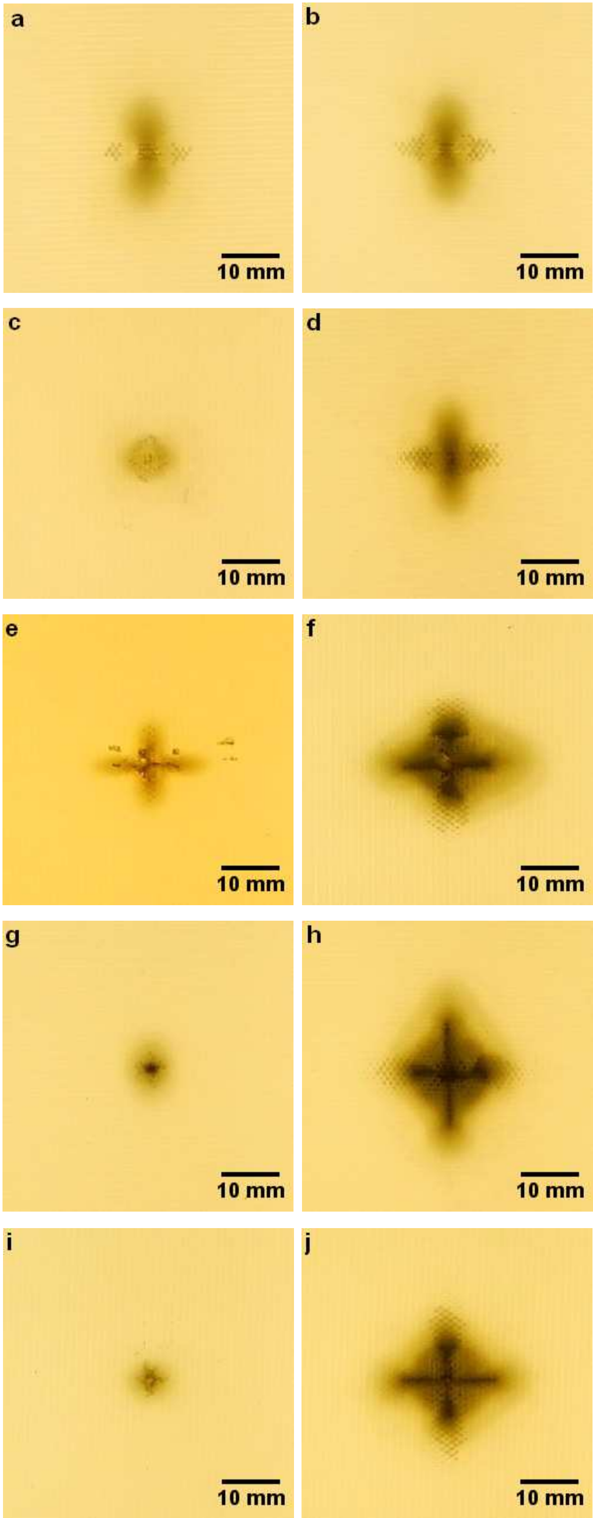

Fig. 5. Selected TLI images for the cases: a) A40, b) B40, c) C20, d) C40, e) E20, f) E40, g) H10, h) H40, i) I10, j) I40

In some investigated cases the impact did not caused any visible changes in the structures, these cases were excluded from further analysis. The cases N were also excluded because of similarity with cases M.

The great attention should be paid to the results of impact tests using impactors with immersed stones. Selected TLI images for these cases were presented in Fig.6.

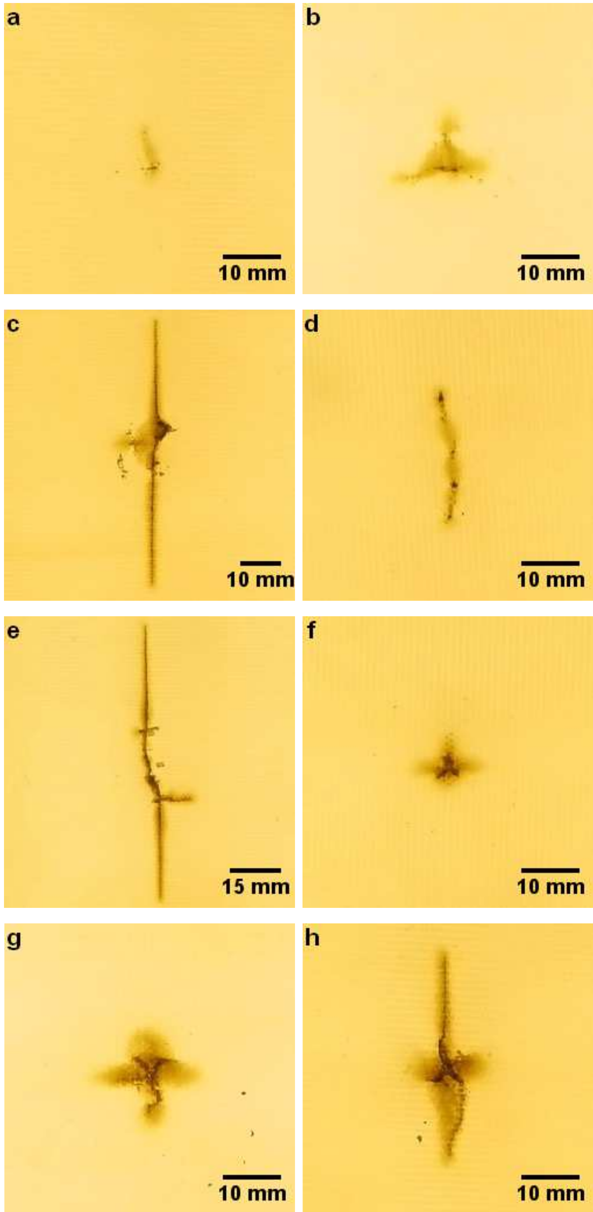

Fig. 6. Selected TLI images for the cases: a) K10, b) K30, c) K40, d) L30, e) L40, f) M10, g) M20, h) M40

Results presented in Fig.5 show that the geometry of impactor has significant influence on the resulted damages. The impactors with rounded (hemispherical) ends cause mainly tensile stresses [20] which cause characteristic delamination shapes (see Fig.5a,5b,5d) and do not cause perforation in the case of small impact energies. Small energy impacts by impactor with rounded end cause circular delamination areas (see e.g. Fig.5c). However, during decreasing of a radius of the end of impactor the bending and shear stresses dominate the tensile ones (cf. Fig.5a,5b,5d,5e). The same was observed for the low-energy impacts (cf. Fig.5c and Fig.5e). The conical and bullet-like impactors have a great ability of penetration of matrix and thus break the fibres in the area of impact [21]. Here the bending and shear stresses are dominant. Comparing the damages after impacts of conical and bullet-like impactors one can observe that the conical impactors has better perforation ability than the bullet-like (cf. Fig.5g and Fig.5i). The impacts by these impactors with higher energy (Fig.5h,5j) seems to be comparable considering only the visual inspection results.

For the cases of impactors with immersed stones the resulted damages have more complex character. In the case of impactor with flat and rough surfaces of impacted stones it could be observed that the damages have non-regular shape, but cause only delaminations without cracks (see Fig.6a,6b). In these cases the tensile stresses are dominant, similarly as for the cases presented in Fig.5a,5c. The increase of impact energy for this case causes domination of shear stresses and cracking of a structure without delaminations near the region of crack (Fig.5c). Similar results were obtained for the case with edge-ended impactor with immersed stone. Here the shear stresses are also dominant which resulted in delamination for the lower impact energy (Fig.6d) and crack with perforation for the higher energy of impact (Fig.6e). The vertex-ended impactor with an immersed stone resulted in damages similar to the conic and bullet-like impactors, however the shear stresses dominate the bending ones which cause the larger cracks for the higher impact energy (Fig.6h).

3.2 ESTIMATION OF IMPACT DAMAGE AREAS

In order to evaluate damage areas the images obtained during TLI were processed using segmentation algorithm. The images were loaded into the Matlab® environment and processed with use of the Image Processing Toolbox™. The processing consisted of the following steps. The RGB channels were firstly normalized to the unitary range and the thresholding operation was applied (with empirically determined threshold value of 0.8) in order to extract the damaged region from the image. Then, the resulted image was binarized. Finally, the boundary tracing algorithm was applied in order to select the damage region and evaluate its area in pixels. These steps were presented in Fig.7. From the proportions of specimens' dimensions with respect to the damage area the latter was determined in mm. The determined areas of damages were stored in Table 1.

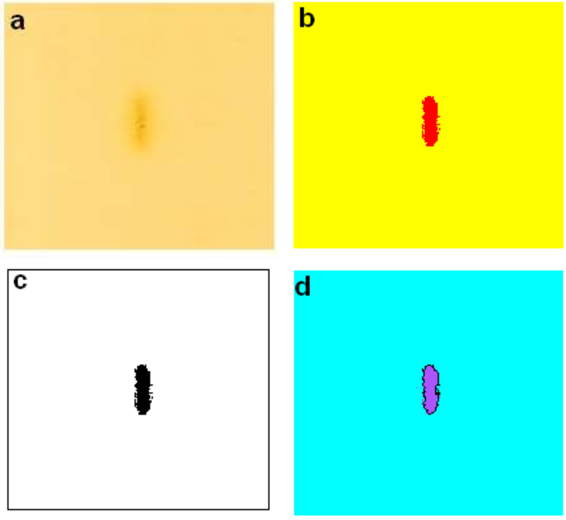

Fig. 7. Steps of image processing of A20 case: a) original TLI image, b) normalized and thresholded image, c) binarized image, d) image with a traced boundary of damage

Table 1. Area of impact damages

Case	Area, mm^2	Case	Area, mm^2
A20	25.68	H20	138.92
A30	188.20	H30	354.00
A40	195.80	H40	495.40
B20	48.12	I10	50.28
B30	135.00	I20	150.84
B40	190.84	I30	263.48
C20	91.52	I40	432.84
C30	161.76	K10	23.16
C40	302.56	K20	44.12
D20	122.80	K30	55.80
D30	168.36	K40	314.44
D40	405.32	L30	90.64
E10	31.72	L40	315.96
E20	177.32	M10	76.88
E30	250.80	M20	148.08
E40	478.56	M30	123.48
H10	82.24	M40	241.84

As it could be noticed from the results presented in Table 1 the damage area increases with the increase of impact energy. However, depending on type of impactor the damage extents significantly differed. Analyzing the results it could be observed that during the decrease of radius of ends of hemispherical impactors the damage extents grow. This was resulted by the type of stresses occurred in these cases, i.e. the decrease of radius of the ends cause mainly bending and shear stresses, which results in matrix cracking and larger delamination areas. For the same reason the conic and bullet-like impactors cause the largest damage areas from the group of considered cases. In the cases of impactors with immersed stones the damage areas were generally smaller than those caused by similar metallic impactors, however they were mainly consisted the cracks without delaminations despite the similar impact damages caused by regular-shaped metallic impactors, where the cracks were occurred together with quite large delaminated areas.

4. CONCLUSIONS

In the presented paper the character of impact damages with respect to the various impactors shapes was under consideration. The experimental results show that the geometric properties of an impacted body have a significant influence of the character of a damage (cracks and/or delaminations) and the damage state of the structure (extent of a damage, perforation, etc.). The proposed method of estimation of damage extent based on the images obtained by TLI technique and tracking of damage boundaries allows both for qualitative and quantitative evaluation of character of the simulated damages. Obtained results show that the impacted bodies with smoother surface of impact cause much smaller damages than the bodies with sharp contact surface. In the latter cases such bodies cause both extended cracks and delaminations. The presented examination method could be useful during inspection of thin composite structures. Due to the simplicity of performing the tests, simple and quick image processing and a lack of necessity of application of advanced measurement devices the proposed method allows for its successful application as a non-destructive method for diagnosing and continuous monitoring of composite structures in mechanical and civil engineering applications.

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References

1. Bełzowski A., Rechul Z., Stasieńko J.: Impast-related damage in glass roving reinforced laminate (in Polish). "Kompozyty" 2002, Vol. 2, p. 394 - 399.
2. Belingardi G., Vadori R.: Low velocity impact tests of laminate glass-fiber-epoxy matrix composite material plates. "International Journal of Impact Engineering" 2002, Vol. 27, p. 213 - 229.
3. Tita V., de Carvalho J., Vandepitte D.: Failure analysis of low velocity impact on thin composite laminates: Experimental and numerical approaches. "Composite Structures" 2008, Vol. 83, p. 413 - 428.
4. Woodward R. L., Egglestone G. T., Baxter B. J., Challis K.: Resistance to penetration and compression of fibre-reinforced composite materials. "Composites Engineering" 1994, Vol. 4, p. 329 - 341.
5. Asp L.E., Juntikka R.: High velocity impact on NCF reinforced composites. "Composites Science and Technology" 2009, Vol. 69, p. 1478 - 1482.
6. Komorek A., Przybyłek P.: Examination of the influence of cross-impact load on bend strength properties of composite materials, used in aviation. "Eksploatacja i Niezawodnosc – Maintenance and Reliability" 2012, Vol. 14, p. 265 - 269.
7. Kim S.J., Goo N.S.: Dynamic contact responses of laminated composite plates according to the impactor's shapes. "Computers & Structures" 1997, Vol. 65, p. 83 - 90.
8. Imielińska K., Wojtyra R., Kozłowski M.: On delamination threshold loads in low velocity impact on glass-carbon/epoxy composites. "Kompozyty" 2005, Vol. 5, p. 69 - 74.
9. Mitrevski T., Marshall I.H., Thomson R., Jones R., Whittingham B.: The effect of impactor shape on the impact response of composite laminates. "Composite Structures" 2005, Vol. 67, p. 139 - 148.

10. Mitrevski T., Marshall I.H., Thomson R.: The influence of impactor shape on the damage of composite laminates. "Composite Structures" 2006, Vol. 76, p. 116 - 122.
11. Mitrevski T., Marshall I.H., Thomson R., Jones R.: Low-velocity impacts on preloaded GFRP specimens with various impactor shapes. "Composite Structures" 2006, Vol. 76, p. 209 - 217.
12. Yang F.J., Cantwell W.J.: Impact damage initiation in composite materials. "Composites Science and Technology" 2010, Vol. 70, p. 336 - 342.
13. Dhakal H.N., Zhang Z.Y., Bennett N., Reis P.N.B.: Low-velocity impact response of non-woven hemp fibre reinforced usaturated polyester composites: Influence of impactor geometry and impactor velocity. "Composite Structures" 2012, Vol. 94, p. 2756 - 2763.
14. Sevkat E., Liaw B., Delale F.: Drop-weight impact response of hybrid composites impacted by impactor of various geometries. "Materials and Design" 2013, Vol. 52, p. 67 - 77.
15. Kozioł M., Kulawik A., Śleziona J.: Shape of a delamination in stitched laminate after a drop weight impact test (in Polish). "Kompozyty" 2007, Vol. 7, p. 25 - 31.
16. Barcikowski M., Semczyszyn B.: Impact damage in polyester matrix glass firbe-reinforced composites. Part I: Impact damage extent. "Kompozyty" 2011, Vol. 11, p. 230 - 234.
17. Icten B.M., Kiral B.G.: Impactor shape effect on low velocity impact response of woven glass epoxy composites. "Advanced Composites Letters" 2012, Vol. 21, p. 118 - 125.
18. Nossol P., Czech A., Kroll L.: Experimental investigation of dynamic behaviour of thermoplastic firbe reinforced laminate. "Composites Science and Technology" 2013, Vol. 13, p. 128 - 134.
19. Katunin A., Sznura M.: Stanowisko badawcze do kontrolowanych testów udarowych płyt kompozytowych. "Aparatura Badawcza i Dydaktyczna" 2013, Vol. 18, p. 297 - 302.
20. Ulven C., Vaidya U.K., Hosur M.V.: Effect of projectile shape during ballistic perforation of VARTM carbon/epoxy composite panels. "Composite Structures" 2003, Vol. 61, p. 143 - 150.
21. Barcikowski M.: Wpływ materiałów i struktury laminatów poliestrowo-szklanych na ich odporność na udar balistyczny. Rozprawa doktorska. Szczecin: Zachodniopomorski Uniwersytet Technologiczny, 2012.