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COMPOSITES THEORY AND PRACTICE

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LOW VELOCITY IMPACT RESISTANCE OF ALUMINUM/CARBON-EPOXY FIBER METAL LAMINATES

Fiber metal laminates are a new kind of hybrid materials. There are good candidates for advanced aerospace structural applications due to their high specific mechanical properties. The study researches the resistance to low-velocity impact of hybrid laminates based on aluminum alloys and a carbon/epoxy composite (Al/CFRP). These are completely new materials which have higher strength properties compared to other materials of this type (GLARE, ARALL), high fatigue strength, low weight, etc. The tested laminates were prepared by the autoclave method, which provides the best possible and repeatable quality of the received components. The laminates were analysed in terms of a comparison of their impact resistance according to different layer configurations and different energy levels. The laminates response to low velocity impact using a hemispherical tipped impactor (diameter 12.7 mm) were analyzed. The variation of the impact load as a function of force-time for different layer systems at each energy level was determined. After the tests, the damage zone was evaluated by using ultrasonic and image analysis methods. On this basis the dependencies of the damage zone area and maximum depth of the deformation depending on the layer configurations and energy level were determined. It was noted that Al/CFRP laminates are innovative materials characterized by high impact damage resistance (at low-velocity) because of the superior properties of both metals and fibrous composite materials with strong adhesion bonding. There is a combination of high stiffness and strength from the carbon/epoxy composite layers and good mechanical, ductile properties from aluminum. Generally, specific parameters such as incipient load (P_i), peek load P_m, maximum depth and damage area increased with impact energy. For lower impact energies (up to 10 J) and the first stage of the impact process, minor matrix cracking and delamination in the polymer composite and at the aluminum/composite interface may be observed. However, as the impact energy increased, fiber failures were observed to be the dominant damage mode. The first crack of FMLs (on the back side) was connected with the fiber directions in the finally layer of the carbon epoxy composite. The ply configuration (fiber directions) in Al/CFRP laminates has been particularly important for their impact resistance. The FML with (0/90) and ((±45) ply sequences in the carbon fiber reinforced composite have the best behavior followed by the (0) configuration.

Keywords: **fibre metal laminates, hybrid composites, impact resistance, carbon fibers, failure**

ODPORNOŚĆ LAMINATÓW METALOWO-WŁÓKNISTYCH TYPU ALUMINIUM/KOMPOZYT WĘGLOWO-EPOKSYDOWY NA UDERZENIA PRZY NISKICH PRĘDKOŚCIACH

Laminaty metalowo-włókniste (FML) są nowoczesnymi materiałami hybrydowymi mającymi potencjalnie szerokie zastosowanie w technice lotniczej ze względu na wysokie właściwości mechaniczne (szczególnie wytrzymałość zmęczeniową, odporność na uderzenia). W pracy scharakteryzowano odporność na uderzenia (impact) przy niskiej prędkości laminatów metalowo-włóknistych na bazie stopu aluminium i kompozytu węglowo-epoksydowego (Al/CFRP). Materiały te, będące w sferze zainteresowań przemysłu lotniczego, powstały na podstawie prowadzonych badań i zastosowań innych laminatów FML (typu GLARE oraz ARALL). Badane laminaty Al/CFRP wytworzono metodą autoklawową, zapewniającą możliwie najwyższą i powtarzalną jakość otrzymanych elementów. Laminaty charakteryzowano pod kątem porównania ich odporność na impact w zależności od konfiguracji warstw [(0), (0/90), (±45)] i energii uderzenia (10 J, 20 J, 25 J). Zastosowano urządzenie typu drop-weight oraz pólsferyczny impactor o średnicy 12,7 mm (0,5”). Wyznaczono przebieg siły uderzenia w czasie, siłę maksymalną oraz siłę, przy jakiej występuje początek procesu zniszczenia materiału (P_i). Ocenie poddano także strefę zniszczenia metodami ultradźwiękowymi oraz technikami analizy obrazu. Określono obszar zniszczenia oraz głębokość odkształcenia w stosunku od układu warstw i energii uderzenia. Odnotowano, że laminaty Al/CFRP charakteryzują się wysoką odpornością na impact (przy niskich prędkościach uderzenia) związaną z właściwościami poszczególnych komponentów: sprężysto-plastycznego metalu i wysoką sztywnością kompozytu epoksydowo-węglowego. Wartości siły maksymalnej, inicjacji uszkodzenia, maksymalnego odkształcenia i strefy zniszczenia wzrastają wraz ze wzrostem energii uderzenia. Przy energiach nieprzekraczających 10 J odnotowano delaminacje pomiędzy aluminium i kompozytem oraz pękanie osnowy kompozytu polimerowego. Kierunek pękania badanego laminatu FML jest ściśle związany z kierunkiem ułożenia warstw w kompozycie polimerowym. Konfiguracja warstw kompozytu w laminacie Al/CFRP ma bezpośrednie znaczenie na odporność na impact. Laminaty (0/90) i (±45) charakteryzują się wyższą odpornością na impact w porównaniu do laminatów o jednokierunkowym ułożeniu warstw (0) w kompozycie epoksydowo-węglowym.

Słowa kluczowe: **laminaty metalowo-włókniste, kompozyty hybrydowe, odporność na impact, włókna węglowe, zniszczenie**

INTRODUCTION

Fiber Metal Laminates (FML) are a group of modern hybrid materials consisting of alternately stacked layers of sheet metal and fiber reinforced polymer. These materials combine the characteristics of metals and composites, which provide previously unknown properties of construction materials such as the ability to retain cracks, inhibition of water adsorption and resistance to brittle cracking. The conducted research and preliminary performance results of these materials allow one to conclude that they are characterized by high strength properties, including static strength primarily in relation to density and fatigue resistance [1-3]. The autoclave method of manufacturing provides the highest properties of FML [4]. FMLs can be divided into groups depending on the reinforcement or used metal.

The most commonly used and best known are GLARE (Glass Reinforced Epoxy Aluminum) and ARALL (Aramid Reinforced Aluminum Layers) types of laminates, on which there are numerous publications describing their favorable mechanical properties and performance [1, 5, 6], including high resistance to impact damage [5-7]. Laminates which combine aluminum with a carbon composite are not yet widely used in industry. Research on these materials is still being conducted. These laminates are characterized by higher strength properties compared to other types of FMLs, which makes them even more attractive in aerospace applications [8]. Due to the operating conditions (e.g. high static loads, fatigue loads, impact loads) and the risk of delaminations of aircraft materials structure, besides strength properties, impact resistance is very important [1].

The paper presents the response of an FML, aluminum/carbon fiber reinforced polymer (Al/CFRP), to low velocity impact. Laminates with various fiber configurations were studied for their resistance to low velocity impact by analysis of load-time history, damage area and damage depth in relation to different energy levels.

MATERIALS AND EXPERIMENTAL PROCEDURE

The subject of examination was FML composites composed of thin aluminum layers with a carbon fiber reinforced polymer (Al/CFRP). Aluminum alloy (EN AW-2024 (AlCu4Mg1)) sheets with a 0.5 mm thickness were used. On the aluminum surface, anodic oxidation in an aqueous solution of chromic acid was performed. Next, on the formed oxide layer, an active agent (primer) based on an epoxy resin with a corrosion inhibitor was applied. The composite consisted of high-strength carbon fibers AS7J with an epoxy resin matrix (Hexcel, USA). The nominal fiber content was about 60 vol.%. The Al/CFRP laminates were prepared in a 2/1 system (Fig. 1) in the following configurations:

1. Al/CFRP $(0)_4$ /Al
2. Al/CFRP $(\pm45)_2$/Al
3. Al/CFRP $(0/90)_2$/Al

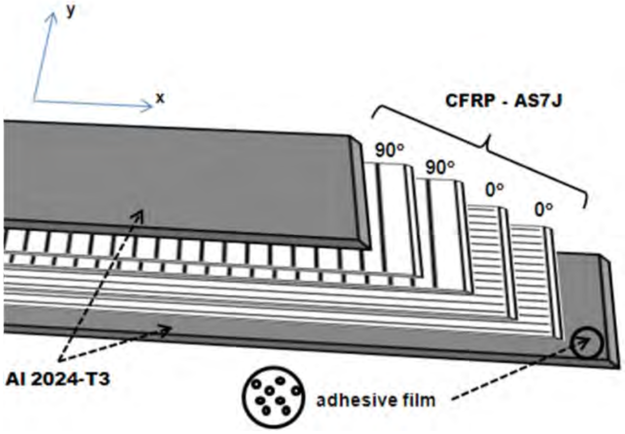

Fig. 1. Scheme of Al/CFRP laminate – 2/1 $(0/90)_2$

Rys. 1. Schemat konfiguracji laminatu Al/CFRP - 2/1 $(0/90)_2$

The laminates were produced by the autoclave method with the following parameters: pressure 0.5 MPa, vacuum 0.08 MPa, temperature 135°C, curing time 120 min, heating and cooling rate 2°C/min.

Samples with dimensions of 150 x 100 mm were subjected to low velocity impact at room temperature using a drop-weight impact tester (INSTRON 9340) with a possibility to record load-time history. As the impactor, a hemispherical steel tip with a diameter of 12.7 mm (0.5”) was used. All the low velocity impact tests were conducted in accordance with the ASTM D7136 standard [9]. The impact was realized with three different energies - 10 J, 20 J, 25 J. The impactor mass was 1.926 kg (10 J); 2.926 (20 and 25 J). The impactor velocity immediately before contact with the samples was 3.22 m/s for 10J, 3.7 m/s for 20 J and 4.13 m/s for 25 J.

After the impact test the samples were visually and NDT (ultrasonic testing) evaluated. The damage area and maximum depth of deformation were calculated by image analysis, using Image ProPlus software.

RESULTS AND DISCUSSION

A typical load-time (f-t) history of the Al/CFRP laminates corresponding to various fiber directions ((0), (±45), (0/90)) under 10, 20 and 25 J are shown in Figure 2.

The each f-t curve has an ascending section of loading, reaching a maximum load value and a descending section of unloading. The ascending section of the f-t curve is called bending stiffness due to the resistance of the composite to impact loading, and at this section the maximum load value reached the highest maximum load (named peek load - P_m, see Fig. 2c) [10, 11].

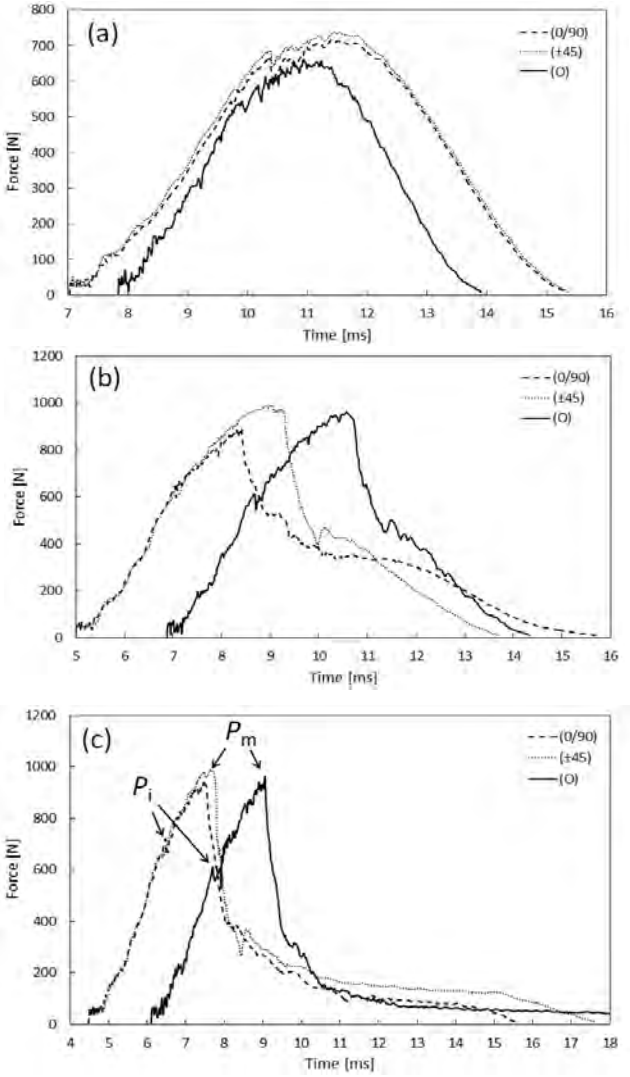

Fig. 2. Impact load-time history of FML - Al/CFRP regarding ply sequence and energy levels: a) 10 J, b) 20 J, c) 25 J

Rys. 2. Wykres siła-czas przy próbie na impact laminatów Al/CFRP w zależności od układów włókien i poziomów energii: a) 10 J, b) 20 J, c) 25 J

The force-time curves are rather smooth, however, some fluctuation of the peak force after incipient load P_i was detected. Then the f-t curves become sharper as was observed in several other studies [12-14]. These oscillations, suggesting possible failures in the material, are due to a decrease in the local bending stiffness in the structure [12, 15]. P_i indicates where the impact load drops due to the first failure in the ascending part of the diagram (see Fig. 2c). P_i can be used as a measure of the material's ability to resist initial damage, namely impact damage resistance [10].

The first load drop is due to delamination propagation in the polymer composite and (or) at the aluminium/composite interface, whereas major damage in the Al/CFRP is induced around the maximum load. The progressive decrease in load beyond the maximum is mainly associated with the penetration and perforation processes of the specimen by the impactor.

Figure 3 shows the incipient load with impact energy for the Al/CFRP laminates. With increasing impact energy, the P_i values increased almost linearly. The linear trend obtained in these studies is confirmed by Sohn et al. [10] for impact damage characterization of carbon fiber epoxy composites.

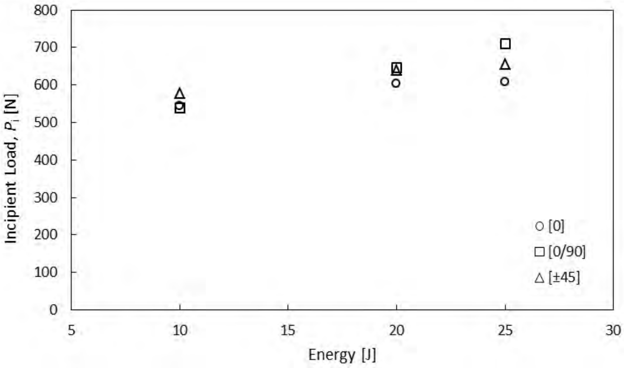

Fig. 3. Incipient load (P_i), vs impact energy

Rys. 3. Inicjacja uszkodzenia (P_i) w zależności do energii uderzenia

From the Figure, it is clear that the P_i for 10 and 20 J on different ply sequences of the composites in the FML are similar. In the other case (25 J), the highest value of incipient load for (0/90) was noted, whereas the lowest was for (0).

Peak load P_m values also increase with the impact energy. The P_m for the (0) ply sequence were 659, 962, 736 N under 10, 20 and 25 J impact energies and 736, 992, 991 and 716, 894, 940 N for the (±45) and (0/90), respectively. The (±45) has the best behavior.

The highest value of force (peak P_m) increases with impact energy. Generally, the Pm peak is reached faster with increasing impact energy. The time to peak load of Al/CFRP with the (0) fibers direction in the polymer composite was 3.08÷2.94 ms while the time to peak load of the (±45) was 4.42÷3.15 ms. For the laminate with the (0/90) ply sequence, indirect values of 4.37÷2.99 were obtained.

A typical example of results can be seen in Figure 4, which presents the impact damage hole and cracks of panels made of Al/CFRP with different kinds of layer configurations.

The destruction of Al/CFRP panels was complete after all the used impact energies (metal and fiber cracks and deformations). For the first energy level (10 J), for most of the samples, it was observed that cracks run perpendicular to the fiber direction (Fig. 4 – (0)/10 J). However, in the (0/90) and (±45) it was observed that on the background, cracks were propagated along the fiber directions (Fig. 4 - (0,90)/10 J). Under higher energy levels (20 and 25 J) the character of the damage was disastrous - perforation and penetration by impactor. During the research it was observed that the first crack was in the same direction as the bottom prepreg layer. The direction of the composite cracking decided the final character of the Al/CFRP destruction. The sheet metal rolling direction had no effect on the direction of aluminum cracking.

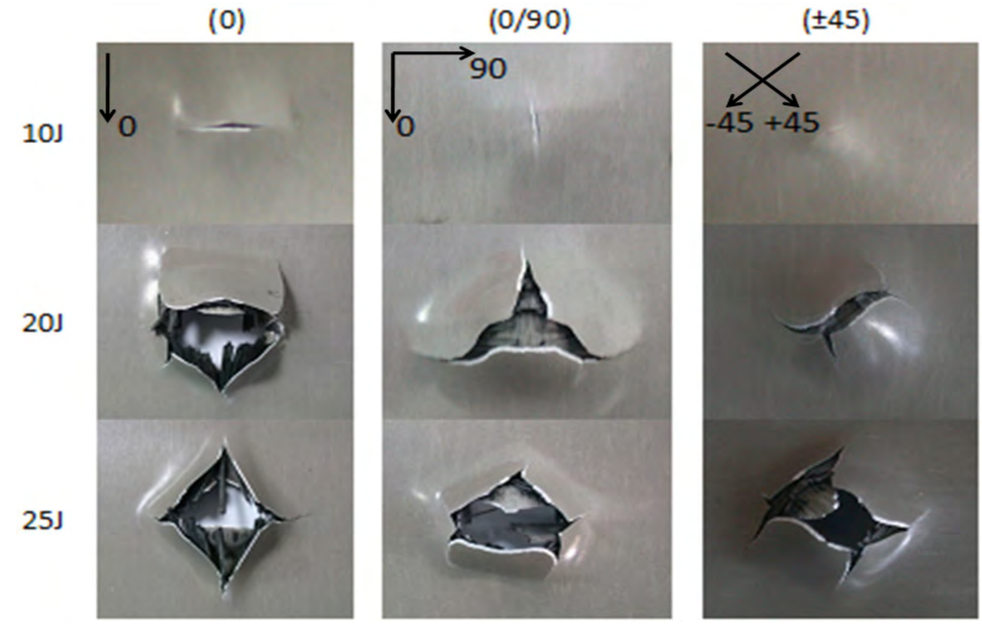

Fig. 4. Al/CFRP laminates after impact

Rys. 4. Laminaty Al/CFRP po próbie odporności na impact

The description of the FML impact damage mechanism according to Liaw B.M. et al. tests [5], indicated that for GLARE (glass fibers/aluminum) laminates, the cracking direction is consistent with the direction of the fibers.

The diagrams below (Fig. 5) present a comparison of the damage area and maximum depth for lay-up configurations at different impact energy.

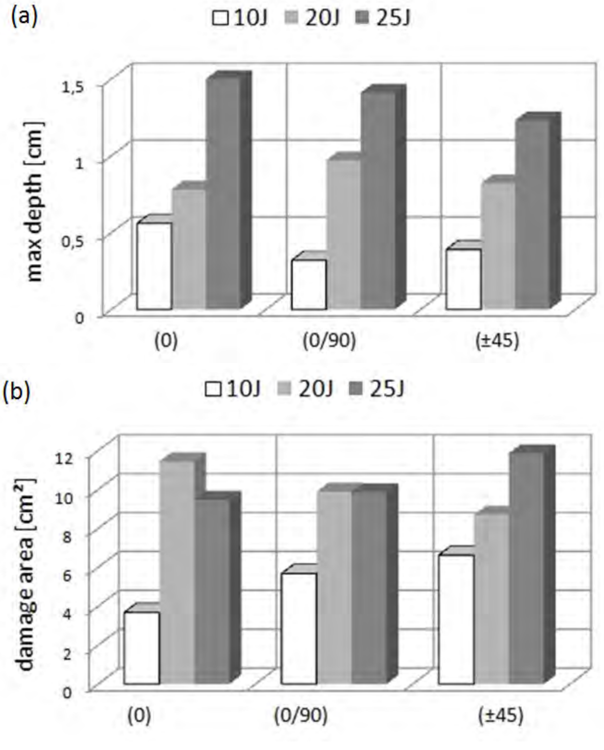

Fig. 5. Comparison of maximum depth (a) and damage area (b) for various layer configurations

Rys. 5. Porównanie głębokości (a) i obszaru (b) zniszczenia różnych układów warstw

A higher impact energy causes a higher maximum depth. The same conclusions were observed by Ardakani et al. [6]. The damage area and max depth are comparable for configurations (0,90) and (±45). These values are different for layer system (0). The damage area or maximum depth is always higher in comparison to the (0) system. For system (0), impact energy will only create significant cracks and a strong increase in strain (not delamination). Configurations (0,90) and (±45) have a lower maximum depth but the damage area is more extensive.

The impact resistance of Al/CFRP is higher than CFRP composites, which results from research conducted on the composites and the obtained results by Zupmano and Li et al. [16, 17]. This is probably due to the good adhesion connection between the brittle and rigid composite with the elastic-plastic metal.

CONCLUSIONS

The work presented the low velocity impact response and damage process of hybrid aluminum/carbon fiber reinforced composites. The following conclusions can be drawn from this study:

1. Al/CFRP laminates are innovative materials characterized by high impact damage resistance (at low-velocity) because of superior properties of both metals and fibrous composite materials with strong adhesion bonding. There is a combination of high stiffness and strength from the carbon/epoxy composite layers and good mechanical, ductile properties from aluminum.
2. Generally, the specific parameters such as incipient load (P_i), peek load P_m, maximum depth and damage area increased with the impact energy.

3. For lower impact energies (up to 10 J) and the first stage of the impact process, minor matrix cracking and delamination in the polymer composite and at the aluminum/composite interface may be observed. However, as the impact energy increased, fiber failures were observed to be the dominant damage mode. The first crack of FMLs (on the back side) were connected with the fiber directions in the finally layer of the carbon epoxy composite.
4. The ply configuration (fiber directions) in Al/CFRP laminates has particularly importance for their impact resistance. The FML with the (0/90) and (±45) ply sequences in the carbon fiber reinforced composite have the best behavior followed by the (0) configuration.

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REFERENCES

[1] Vlot A., Gunnink J.W., Fiber Metal Laminates, Kluwer Academic Publishers, Dordrecht 2001.

[2] Alderliesten R.C., Homan J.J., Fatigue and damage tolerance issues of Glare in aircraft structures, International Journal of Fatigue 2006, 28, 10, 1116-1123,.

[3] Vogelesang L.B., Vlot A., Development of fiber metal laminates for advanced aerospace structures, Journal of Materials Processing Technology 2000, 103, 1, 1-5.

[4] Bieniaś J., Fiber Metal Laminates – some aspects of manufacturing process, structure and selected properties. Composites 2011, 11, 1, 39-43.

[5] Liaw B.M., Liu Y.X., Villars E.A., Impact Damage Mechanisms in Fiber Metal Laminates, Proceedings of the SEM Annual Cenference on Experimental and Applied Mechanics, Portland, Oregon.

[6] Ardakani M.A., Khatibi A.A., Ghazavi S.A., A study on the manufacturing of Glass-Fiber-Reinforced Aluminum Laminates and the effect of interfacial adhesive bonding on the impact behavior, Proceedings of the XI International Congress and Exposition, June 2-5, Orlando, Florida USA, 2008.

[7] Vlot A., Krull M., Impact Damage Resistance of Various Fiber Metal Laminates, J. Phys IV France 7, Paris, France 1997.

[8] Arai N., Ogasawara T., Yokozeki T, Ogawa T., Mechanical properties of CFRP/Ti-alloy laminated composites. 16th International Conference on Composites Materials, Kyoto, Japan, 2007.

[9] ASTM D7136, Standard test method for measuring the damage resistance of a fiber-reinforced-polymer matrix composites to a drop-weight impact event, Book of Standards, 2005, Volume 15.03.

[10] Sohn M.S., Hua X.Z., Kimb J.K., Walker L., Impact damage characterization of carbon fiber/epoxy composites with multi-layer reinforcement. Composites: Part B 2000, 31, 681-691.

[11] Sayer M., Bektas N.B., Sayman O., An experimental investigation on the impact behavior of hybrid composite plates. Composite Structures 2010, 92, 1256=1262.

[12] Nakatani H., Kosaka T., Osaka K., Sawada Y., Damage characterization of titanium/GFRP hybrid laminates subjected to low-velocity impact, Composites: Part A 2011, 42, 772-781.

[13] Lawcock G.D., Ye L., Maia Y.W., Sun C.T., Effects of fibre/matrix adhesion on Carbon-fibre-reinforced metal laminates-II. Impact behaviour, Composites Science and Technology 1997, 57, 1621-1628.

[14] Song S.H., Byun Y.S., Ku T.W., Song W.J., Kim J., Kang B.S., Experimental and numerical investigation on impact performance of carbon reinforced aluminum laminates, J. Mater. Sci. Technol. 2010, 26(4), 327-332.

[15] Caprino G., Spatarob G., Del Luongo S., Low-velocity impact behaviour of fibreglass–aluminium laminates, Composites: Part A 2004, 35, 605-616.

[16] Zupmano G., Sutcliffe M.P.F., Monroy Aceves C., Stronge W.J., Fox M., Impact damage to 3D woven CFRP composite plates, 17th International Conference on Composite Materials, ICCM' 09, Edinburgh, Scotland 2009.

[17] Li C.F., Hu N. Yin Y.J, Sekine H., Fukunaga H., Low-velocity impact-induced damage of continuous fiber-reinforced composite laminates. Part I. An FEM numerical model, Composites: Part A 2002, 33.