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Experimental Research of the Impact Response of E-Glass / Epoxy and Carbon / Epoxy Composite Systems

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The impact response of woven carbon/epoxy and E-Glass / epoxy composite systems on vehicle body structures has been investigated – by considering energy profile diagrams and force-displacement curves. For low-velocity impact, drop-weight impact tests performed by EADS (European Aeronautic Defense and Space Company) Corporate Research Center Germany have been carried out. Because the total amount of energy introduced to a composite specimen and the energy absorbed by the composite specimen through the impact event are important parameters to assess impact response of the composite structures they are considered in this paper. It is established that by increasing the impact energy elastic deformation of woven E-glass / epoxy composite systems is 1.5 times higher than that of carbon / epoxy composite systems that defines the formation of smaller areas of damage.
Keywords: low-velocity impact, absorbed energy, damage, delamination.

1. INTRODUCTION

Fibre-reinforced laminated composite materials find increasing use in a wide range of engineering applications due to low weight, high specific stiffness and strength. However, these materials are sensitive to impact damage, especially out-of-plane impact, which can induce damage event at very low impact energies.

Low-velocity impact of fiber-reinforced plastics has been the subject of many experimental and analytical investigations [1 – 4]. In research work of Sutherland and Guedes Soares [5] drop-weight impact tests have been carried out for low fiber-volume glass-polyester laminates for a range of diameter to thickness ratios. They also showed that an energy balance approach gives good correlation between impact force and incident energy. Siddeswarappa and Mohamed Kaleemulla [6] presented the fracture behaviour and failure mechanisms of composite laminates containing woven-glass-fabric under impact loading. In Lessard, Hosseinzadeh and Shokrich [7] study four different fiber reinforced composite plates are studied after being impacted by a standard drop weight with different impact energies. Carbon fiber-reinforced composite plates show the best structural behavior under low velocity impacts meanwhile carbon / glass fiber reinforced (hybrid) plates show suitable behavior under high impact energy.

A Kim and Chung [8] study presents the low-velocity impact response of woven fabric laminates on the composite body shell of a tilting railway vehicle. The impact force, the absorbed energy and the damaged area were investigated according to different energy levels and stacking sequences.

Baucom and Zikry [9] obtained in experimental study a detailed understanding of the effects of reinforcement geometry on damage progression in woven composite panels under repeated drop-weight impact loading conditions. The composite systems included a 2D plain-woven laminate, a 3D orthogonally woven monolith, and a biaxial reinforced warp-knit. It is estimated, that the 3D systems provide both an inherent capability to dissipate energy over a larger area and greater perforation strength than other systems with comparable area densities and fiber-volume-fractions.

The aim of presented work is to carry out the low-velocity impact tests of the composite laminate on vehicle body structure. The influence of impact energy and force on absorbed energy of the carbon / epoxy and E-glass / epoxy composite systems is also analyzed.

2. EXPERIMENTAL

Woven carbon/epoxy (Carbon/E) and E-Glass / epoxy (E-Glass / E) composite systems increasingly used in production of vehicle bodies and load-carrying structures were chosen as an investigation object in this study.

The laminated composite matrix was reinforced with glass 92125 and carbon 98131 fiber woven fabrics 2/2 manufactured in the company CS-Interglass. Carbon filaments of Tenax HTA 5131 type were used in carbon fabric composite materials. Strength characteristics of the laminated composite materials depend on adhesion of fiber and epoxy matrix. Final processing was used for the adhesion strengthening when the fabric was coated with chemical compound improving the adhesion between the fiber and epoxy and strengthening the resistance of laminated composite to inter-laminar stretch and shear. Modified adhesion-improving silicon hybrid provided good and instant fiber saturation with epoxy resin. Epoxy fiber / hardener L285/287 system was used for production of laminated composites. The range of the temperatures of system L285/287 was from – 60 °C to + 60 °C. Due to good toughness and excellent mechanical and thermal properties made it possible to be used in statically and dynamically loaded systems. The ratio of epoxy resin / hardener mixture

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enabled to get optimum characteristics of polymer matrix. The recommended ratio of mass parts was 100 epoxy resin: 40 (+/–2) hardener, and that of parts by volume was 100 epoxy resin: 50 (+/–2) hardener.

Specimens of woven carbon/epoxy and E-Glass/ / epoxy composite systems were produced in the company „Sportinė Aviacija“ in accordance with the Airbus Standard (AIITM 1-0010) [10]. They were made of symmetrically arranged 16 angle fiber and 12 glass fiber laminated composites of 3.8 mm thickness. Quasi-isotropic lay-out scheme was used in the specimen plate. Laminate reinforcement angles: [+45/0/–45/90]. Sample geometry is given in Fig. 1.

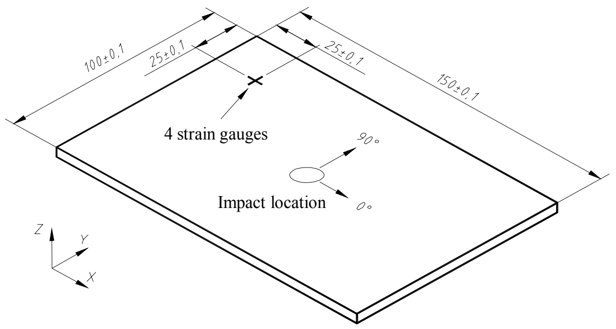
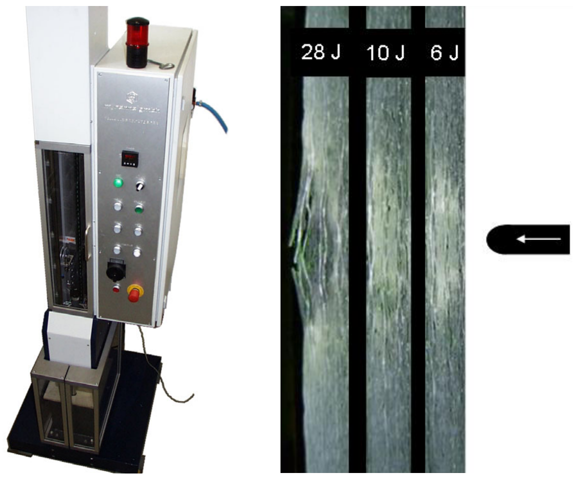


Fig. 1. Laminated composite specimen in accordance with the Airbus Standard (AIITM 1-0010)

To determine the mechanism of impact damage the experiment was performed when laminated composite materials were deformed with low impact energy. Impact test when the impactor moved down at low velocity was performed in EADS − European Aeronautic Defense and Space Company (Corporate Research Center Germany in Ottobrun). Special impact equipment consisting of vertically falling impactor and reaching the greatest impact energy equal to 120 J was used in the test (Fig. 2).



a b

Fig. 2. Impact test: a – impactor equipment; b – E-Glass/epoxy composite specimens

During the test the specimen secured between steel planes and pressed with pneumatic bracket was deformed with the impact of specified energy. The impact energy is predetermined by changing the weight (equal to 1920 g and 2610 g) to the impactor. The downfall distance of the impactor was from 344 mm to 1140 mm. The impact test of the falling impactor was fulfilled with low energy impact varying from 2 J to 28 J. The velocity range used during the test was from 1.50 m/s to 4.63 m/s, respectively. The impactor speed and the energy absorbed by the specimen during the impact were calculated from relationships of force-time and displacement-time.

Table 1. Characteristics of equipment measuring the relationships of force and distance

Characteristics	Unit	Value
Force sensor (Kijstler Press 9333)		
Measurement range	kN	5...50
Sensibility (nominal)	pC/N	4
Displacement sensor (Heidenhain LIDA 100)		
Precision	μm	+/– 1

Table 1 gives the characteristics of the equipment used during the test. The impactor with the end of the semi-circle form manufactured from hardened steel, R_m = 2000 MPa, in accordance with the Standard EN 2760. The head diameter of the impactor was 15.75 mm.

The contact force $F(t)$ during the impact load depend on the impactor mass m and velocity v. Initial impactor speed v_0 depends on the free fall acceleration g and downfall height H:

$$v_0 = \sqrt{2gH} \, . \tag{1}$$

Impactor speed v and displacement s as the time functions are determined by integrating the impact force:

$$v(t) = v_0 - \left(\frac{1}{m}\right)\int_0^t F(t)dt \, , \tag{2}$$

$$s(t) = \int_0^t \left(v_0 - \left(\frac{1}{m}\right)\int_0^t F(t)dt \right) dt \, . \tag{3}$$

After the impact with the specimen the impactor speed gradually decreases as the specimen absorbs the kinetic energy during the impact. The specimen absorbing the impact kinetic energy or the impact energy of the impactor E_{imp} is equal to:

$$E_{imp} = \frac{1}{2} m v^2 \, . \tag{4}$$

The absorbed energy E_{ab} as the time function is:

$$E_{ab}(t) = \frac{m v_0^2}{2} - \frac{1}{2} m \left(v_0 - \frac{1}{m}\int_0^t F(t)dt \right)^2 \, . \tag{5}$$

The value of resistance to damage is rather difficult to measure due to the factors, such as mounting limit conditions, load magnitude, material strength and stiffness, and the sequence of the specimen layer arrangement. Parameters are estimated with standardized method of impact experiment ignoring the influence of the impact form and the bracket limit conditions.

3. RESULTS AND DISCUSSION

During the tests when impact energy was increased from 6 J to 28 J in the case of E-Glass/epoxy composite specimens and from 2 J to 28 J in the case of carbon / epoxy composite specimens the relationships of force-displacement and force-time were obtained disclosing experimental data in a simple and straightforward estimation form (Figs. 3 – 6). Behavior of E-Glass / epoxy composites during the impact (Figs. 3 and 4) showed that the most important peculiarity of these composite materials was decreasing stiffness when the displacement increased due to great specimen deflection related with non-linear membrane effect. Identical relationships obtained at the lowest energy disclosed no significant damage.

Force-time relationships were almost symmetrical. But the area under the force-displacement curve showed the great part of impact energy absorbed with the laminar composite at low velocity impact energies.

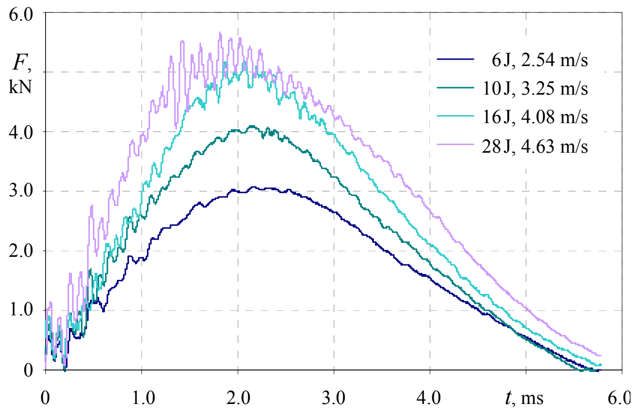


Fig. 3. Force-time relationships when E-Glass / epoxy composite specimens are deformed with low energy impacts

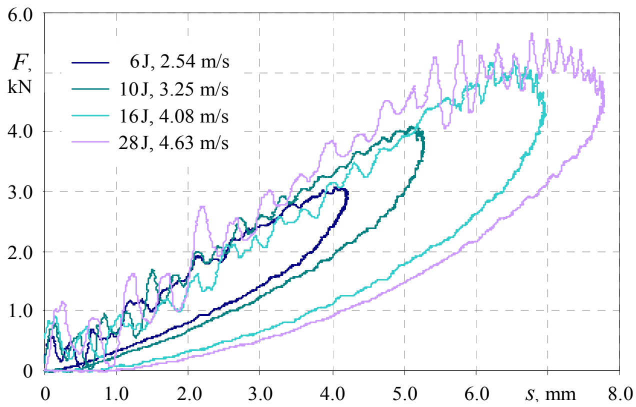


Fig. 4. Force-displacement relationships when E-Glass / epoxy composite specimens are deformed with low energy impacts

Fig. 3 shows that at the impact energy equal to 6 J, the force value of 3.08 kN is the greatest and gradually decreases to zero. But when the impact energy is greater, the maximum force value is reached when the damage under the impactor occurs after the greater total displacement. When the impact-time value is equal to 6.20 ms, the constant residual force shows that the failure process is finished. Initial delamination is not depicted from force-displacement relationships, but some of the factors of this damage can be seen in force-time characteristics.

When the impact energy is equal to 28 J, the effect of layer damage is obvious due to the sharp force reduction subject to the displacement and time, and the basic asymmetry of force-time relationship. The greatest force restriction is seen when the impact energy is 16 J due to fiber breakage. Unlike E-Glass / epoxy composite specimens the carbon/epoxy composite specimens show non-linear change of force-time relationships and this is explained as the abrupt decrease of stiffness after delamination and fibre fracture. When the impact energy is equal to 6 J, delamination is distinct in both force-time and asymmetrically changing force-displacement curves (Figs. 5 and 6). It is determined, that even when the delamination maximizes with the increase of impact energy, the stiffness after the delamination remains almost constant.

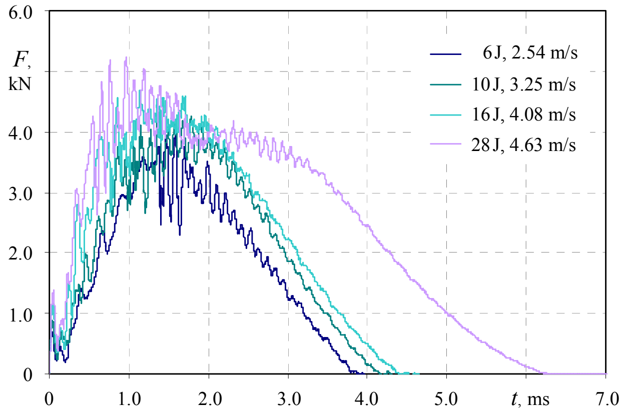


Fig. 5. Force-time relationships when carbon / epoxy composite specimens are deformed with low energy impacts

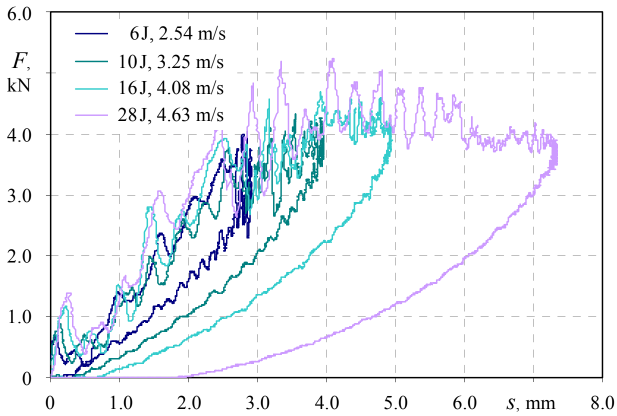


Fig. 6. Force-displacement relationships when carbon / epoxy composite specimens are deformed with low energy impacts

When the specimen is distorted with the impactor the dint damage in the curves is reflected in pulsation form at greater forces.

With reference to great frequency relationships during the tests the conclusion can be made that the structure delaminated because of local damage. At the greatest impact energy provided on the specimen during the test characteristics show the initial processes of the sample perforation. But when low energy impacts are used for deformation the specimen is not fully perforated in both instances when E-glass / epoxy composites and carbon / epoxy composites were used.

The curve forms during the tests show the necessity to fulfill sufficient number of tests with various energy values to describe force-displacement relationships. Small number of tests is sufficient in case of E-Glass / epoxy composites, and thrice as many tests were done with carbon/epoxy composites because 14 various energy values are tested.

As a result, the composite behaviour during impact deformation is investigated and the energy required for damage is estimated. Relationships of the greatest impact force and the greatest displacement of the impactor causing the deflection at various impact energies are given in Figs. 7 and 8.

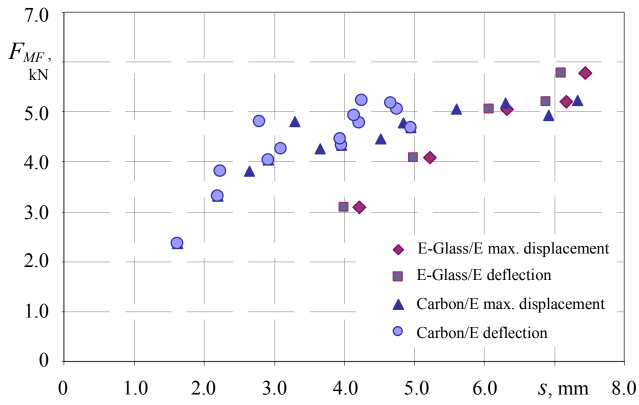


Fig. 7. The greatest force-displacement relationships when carbon / epoxy and E-glass / epoxy composite specimens are deformed with low energy impacts

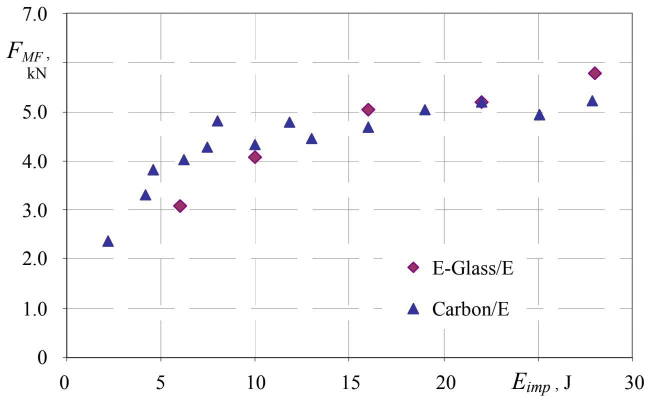


Fig. 8. The greatest force-impact energy relationships when carbon / epoxy and E-glass / epoxy composite specimens are deformed with low energy impacts

The greatest force variation equal to 103 % is defined in the case of carbon / epoxy composites (in the range of impact energy equal to 2 J – 8 J) and variation equal to 32.5 % (in the range of impact energy equal to 6 J – 10 J) in case of E-Glass / epoxy composites. The further greatest force change describing fiber breakage in the case of carbon/epoxy composites remains almost constant.

The greatest force restriction in the case of the specimens of E-Glass / epoxy composites is when the impact energy is equal to 16 J. Up to this energy magnitude the laminar structure of E-Glass / epoxy composites has greater toughness at uniform impact energies. Smaller force and greater total displacement of the impactor is determined when E-Glass / epoxy composites are used (Fig. 7). In the test the deflection is by 1 mm – 3 mm greater if compared with the tests of carbon/epoxy composites.

The low velocity impact is estimated as the static load the upper limit of which can range from 1.0 m/s to 10.0 m/s depending on the specimens nature and impactor mass and stiffness [11 – 12].

Spread of deformation waves prevails in the composite material during the impact in the range of great speeds. Momentary plastic deformations during the initial moment of the impact contact governed the occurrence of local damage. In this case the marginal experiment conditions were not estimated because the impact ended before these waves reached the structure angles. But when disintegrating the laminar composite samples with low energy impacts, the reaction of dynamic structure was very important as the duration of the impact contact was rather significant, i. e., when the impact speed was 2.54 m/s it was equal to 5.78 ms. When the impact energy of 28 J moved at the speed of 4.62 m/s, the contact in the case of E-Glass / epoxy composites lasted for 6.20 ms, meanwhile in the case of carbon/epoxy composites is lasted for 7.07 ms.

Due to rather significant duration of impact contact during the deformation with low energy impacts when the impactor struck against the specimens of carbon/epoxy composites and E-Glass / epoxy composites, the composite absorbed the impact energy after the impact and was encountered with elastic deformation that was less than necessary for the breakdown.

Three mechanisms of the absorption of the laminar composite energy prevailed during the experiment: the transversal matrix fracture, delamination and fiber breakdown. The dint damage was also defined. Some part of the impact energy was absorbed by the elastic part of the specimen structure of carbon/epoxy composites and E-Glass / epoxy composites:

$$E_{imp} = E_{el} + E_{ab} \,. \qquad (6)$$

During the impact when the impactor could not penetrate through the lamina composite specimen, the total impact energy was divided into two parts. Part of the impact energy E_{imp} equal to 6 J was accumulated as elastic energy equal to 3.15 J. E_{el} was transferred to the impactor that sprang back from the specimen.

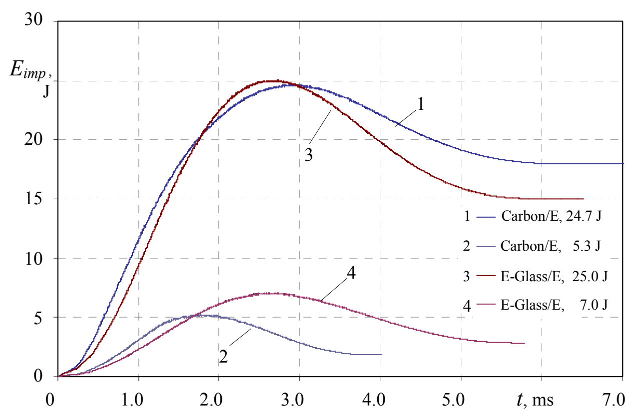


Fig. 9. Relationship of the impact energy-time used to deform the specimens of carbon / epoxy and E-Glass / epoxy composites with energy impacts from 5.3 J to 25 J

The second part of the impact energy equal to 2.85 J That was absorbed by the system and designated as the absorbed energy E_{ab}.

This energy was related with the energy determining the occurrence of the structure damage. The absorbed energy was expressed by the integral under the force-displacement curve

$$\int_{s=0}^{s} F(s)ds|s \supseteq 0\,. \tag{7}$$

The amount of energy absorption during the impact depended on the material nature.

Fig. 9 gives the types of impact, elastic and absorbed energy when the specimen of carbon/epoxy composites and E-Glass / epoxy composites were deformed with energy impacts from 5.3 J to 25 J. In the case of energy impacts equal to 5.3 J and 24.7 J the elastic part in the specimens of carbon/epoxy composites made up 65.1 % and 27.1 %, for the damage occurrence (delamination and fiber breakdown) at the same time absorbing 1.85 J and 18 J of energy, accordingly. When the impact energy was equal to 7 J, in the case of E-Glass / epoxy composites the portion of the elastic energy made up 59.3 % of the total energy.

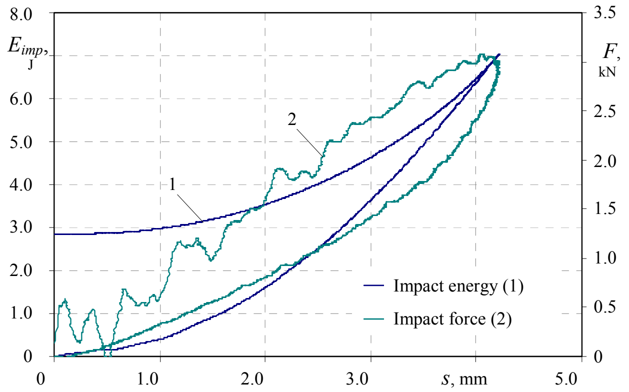


Fig. 10. Relationships of impact energy and impact force – impactor displacement when using 7 J energy impact for deformation of E-Glass / epoxy composites specimen

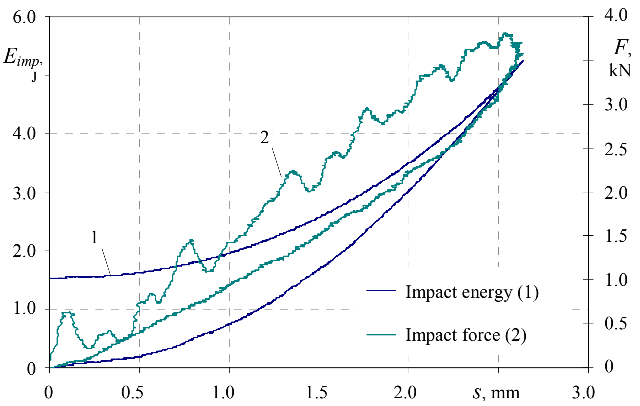


Fig. 11. Relationships of impact energy and impact force – impactor displacement when using 5.3 J energy impact for deformation of carbon / epoxy composites specimen

When the impact energy of 25 J was used, the elastic energy equaled to about 40 % of the total energy. In the case of E-Glass / epoxy composites the portion of the elastic energy if compared with the experimental results of the carbon/epoxy composite specimens was approximately 1.5 times greater at the impact energy of 25 J. The greater elastic deformation of E-Glass / epoxy composites specimens during the impact destined the less damage formation in the specimens, after the energy of 22 J was achieved.

Figs. 10 – 13 depict the energy transferred to the laminar composites and the function of the impact force and displacement change.

When in the case of laminar E-Glass / epoxy composite specimen the impactor could not penetrate through this specimen during the impact the greatest energy equal to 7 J transferred by the impactor during the impact and the greatest impact force 3.08 kN was reached, when the most significant displacement of the impactor was equal to 4.22 mm (Fig. 10).

But already at the impact energy equal to 28 J in the specimens of carbon / epoxy composites and E-Glass / epoxy composites great deformations and local damages that governed the beginning of the impactor penetration occurred (Fig. 12).

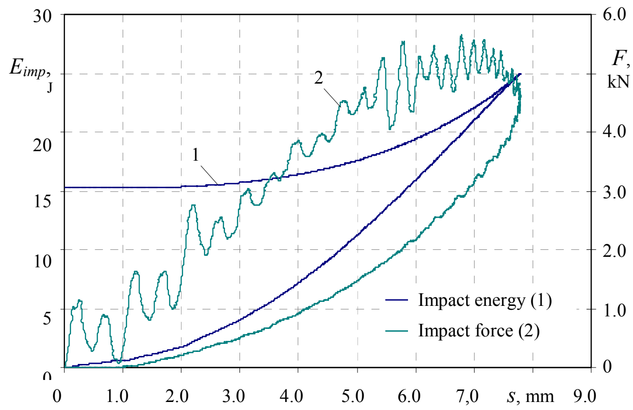


Fig. 12. Relationships of impact energy and impact force – impactor displacement when using 25 J energy impact for deformation of E-Glass / epoxy composites specimen

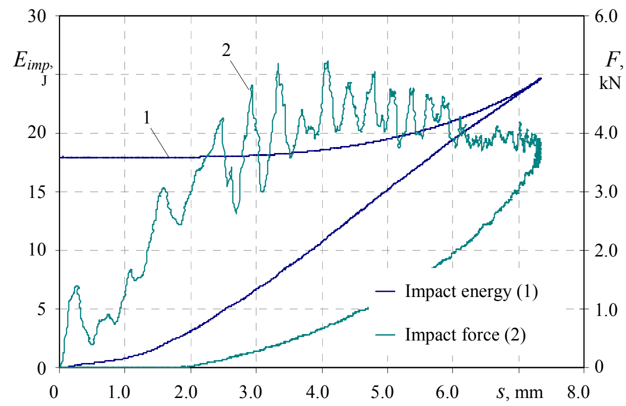


Fig. 13. Relationships of impact energy and impact force – impactor displacement when using 24.7 J energy impact for deformation of carbon / epoxy composites specimen

In this instance, the impact energy was attributed to the critical one because the study investigated the damages when the impactors could not penetrate through the specimen.

4. CONCLUSIONS

The behavior of the carbon / epoxy composites and E-Glass / epoxy composites for vehicle body structures during impact deformation was tested.

After the investigation of the impact effect of low-energy falling impactor on the laminar composites it has been determined that the portion of the energy absorbed for the damage formation was by 20 % and 30 %, accordingly, less than the energy portion of elastic deformation when E-glass / epoxy and carbon/epoxy composites were affected with low-energy impacts (from 4 J to 7 J).

The portion of absorbed energy in E-glass / epoxy composites increased by 20 % and the portion of absorbed energy in carbon / epoxy composites increased by 50 % when the composite specimen were affected with impact energy of 22 J – 28 J. The plastic deformation of E-glass / epoxy composites exceeding the plastic deformation of carbon / epoxy composites during the impact by 1.5 times in the range of these energies determined the formation of the less damaged area. The greater elastic deformation of E-Glass / epoxy composite specimens during the impact determined the less damage onset in the region of 22 J.

When the carbon/epoxy composite specimens were deformed with impact energy of 4 J – 10 J, the abrupt reduction of composite stiffness occurred. This was destined by the damage onset and its displacement.

When the impact energy increased to 28 J, the damage was maximized at the same constant composite stiffness. It has been defined that the significant decrease of impact energy and the obvious asymmetry of impact force − time relationship showed the fiber breakdown.

When analyzing the impact force – displacement relationships of E-glass / epoxy composites it has been determined that the stiffness of E-glass / epoxy composites increased due to increasing impact energy because of great specimen deflection related with significant membrane tensions.

Character of symmetric impact force – time relationships in the range of impact energies equal to 6 J – 16 J was defined. It has been determined that the layer breakdown governed the greatest force restriction when the impact energy was from 22 J to 28 J.

In the case of carbon/epoxy composites when the absorbed amount of energy proportionally increased (from 2 J to 28 J) the damage area increased linearly.

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