COMPOSITE-POLYMER MATERIALS FOR ENERGY-ABSORBING STRUCTURES

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Abstract

On the basis of the results obtained from our own experimental investigations of energy- absorbing elements, the influence of the given factors on absorbed energy (WEA) was determined. The objects of the research were the samples made of epoxy composites reinforced with glass fibres formed in roving, roving stripes and glass mat as well as with carbon fibres formed in roving and carbon roving stripes. To investigate the capability of hitting energy absorption of the samples in the shape of tubes, the truncate cones and in the shape of a thin cuboid were taken under consideration. The sample in the shape of tubes, wavy coats and thin cuboids with angle 45° (on one edge), play the role of the initiator of progressive destruction process. The composites matrix was taken into account during investigations: epoxy, the vinyl-esters, polyetheretherketones, reinforced with carbon and glass fibres with different structures of the samples. The influence of the sample geometry and the orientation of the layers in carbon / epoxide and the aramid / the epoxide composites on the WEA absorption value were presented in the papers.

The comparison of the structures made from single elements with relevant structures of four elements shows that absorbed energy is accumulating. In this case the relative absorbed energy remains at the similar level.

Keywords: *energy absorption structures, safety, composites, numerical simulation, energy absorption investigations*

1. Introduction

The particular elements of energy-absorbing structures should be made from thin-walled elements, because they must destroy themselves with comparatively small strength in order to not overload the construction. The thin-walled elements are subjected to buckling and violent destruction. To protect the thin plates (compressed in the plane of the plate) before buckling, the light porous materials are located among the plates or they are formed in the shape of the tube, wavy plates and cross section-shaped elements.

The Authors of [1-4] investigated the influence of the kind of the material and the structure on the energy absorption capability of the samples in the round, square and rectangular section shapes. The influence of the geometry of the sample and the orientation of layers was examined too. The results of the investigations of the influence of layers orientation as well as the geometry of the sample in carbon / epoxide and the aramid / the epoxide composites on the WEA absorption value were presented in the papers [5, 6].

The samples reinforced with aramid fibres showed WEA growth for fibres orientation of angles [15 °~ 45 °], however WEA decrease for angles [45 °~ 75 °] was observed.

The results of investigations confirmed that the carbon fibres reinforced structures absorb more energy, when the fibres orientation is the same as loads.

However, the paper [7] showed that the composite which has layers [0 °] does not have the high energy absorption capability because the lack of the fibre reinforced layer structure [90 °] allows the fast growth of the longitudinal cracks, which cause the destruction at the lower force.

The phenomenon was confirmed in the experiment during which the tube with the fibres arranged parallel to the axis was compressed with an external sliding ring causing greater destruction force because of ring limitations creating longitudinal cracks leading to the bending method of destruction.

The polymer composites, metals as well as their alloys are used in most cases to create energy-absorbing structures.

The energy-absorbing capabilities of different materials are shown in Fig. 1.

WEA - the relative absorption energy – is the amount of absorbed energy by the sample divided by mass of destroyed part of the sample.

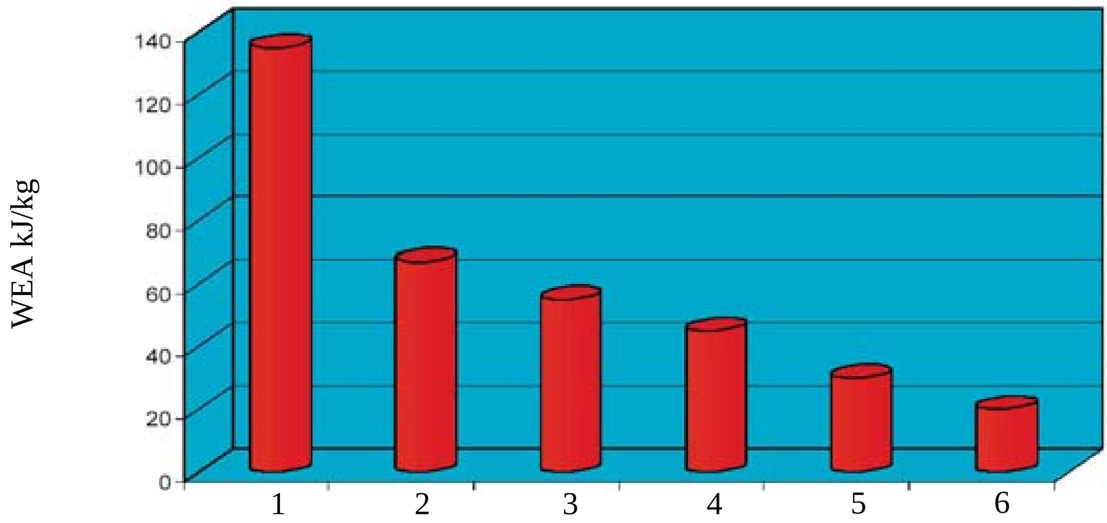

Fig. 1. Relative absorbed energy (WEA) depending on kind of the materials:
1 - carbon/PEEK, 2 -carbon/epoxide, 3 - glass/epoxide, 4 - short glass fibres epoxide, 5 - steel, 6 - aluminium. [8]

2 The object of investigations

The objects of the research were the samples made of epoxy composites (E-53) reinforced with glass fibres formed in roving (STR-012-350-110) with weight 350g/m^2, roving stripes (ES-10-400-0-60) and glass mat with weight 316 g/m^2 as well as with carbon fibres formed in roving (TENAX HTA 5131) and carbon roving stripes (TENAX HTS 5631).

To investigate the capability of hitting energy absorption of the sample in the shape of tubes (with internal diameter Dw = 49.3 mm) as well as the truncate cones with half top angles α = 5, 10, 15 and 20 [°], and wall thickness t = 1.2 – 9 [mm] as well as in the shape of a thin cuboid were taken. The sample in the shape of tubes, wavy coats and thin cuboids with angle 45° (on one edge) play the role of the initiator of progressive destruction process. Samples in the shape of truncate cones do not require the initiator, because the beginning of destruction starts from smaller cone diameter.

The composites matrix was taken into account during investigations: epoxy, the vinyl-esters, polyetheretherketones, reinforced with carbon and glass fibres with following structures of the samples: $[0_n]$; $[90_n]$; $[(0/90)_T]_{n;}$ $[90/0_n/90]$; $[\pm15/0_n/\pm15]$; $[\pm30/0_n/\pm30]$; $[(\pm45)_T/0_n/(\pm45)_T]$; $[(0/90)_T/0_n/(0/90)_T]$; $[(\pm45)_T/(0/90)_T/(\pm45)_T]$; where ~~it~~ the layer [0 °] indicates the composite with the solid fibres simultaneously to axis of samples; [90 °] – with the fibres perpendicularly to the axis of the sample; $[(0/90)_T]$– fabric reinforced layer. The middle layers of the sample, usually had fibres arranged parallel to the axis of the specimen. The composite samples reinforced with glass matting were considered too.

The experimental investigations were conducted on standard testing machine INSTRON 8802, in a temperature 20 ° C and moisture 55%. The investigations were performed with the loading speed (traverses speed of machine) equal 40 mm/min. The relation of the destructive force to deformation (the shortening of the sample) received during the investigations were recorded automatically. Moreover, in the work [13] the characteristic dimensions of the samples and influence of the shape of energy-absorbing structures elements on WEA are given [2].

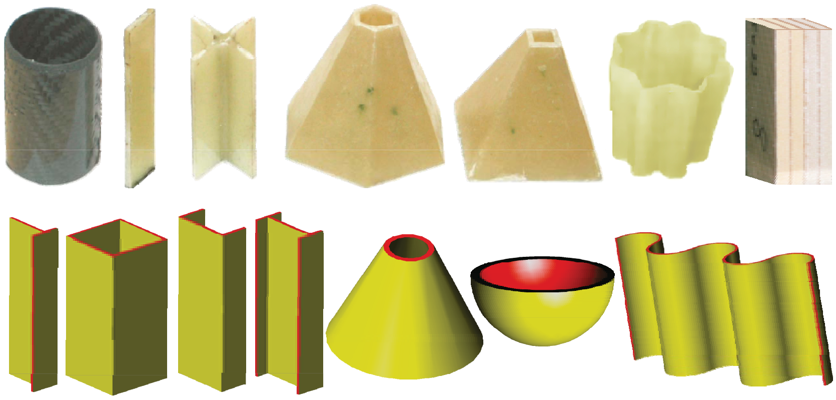

Fig. 2. The shapes of the samples applied in investigations

The energy absorption (WEA) was calculated by numerical integration as the field under the graph. The integration step (the length of the range Δl) was constant and resulted from the testing frequency. The number of ranges was 2251 for each graph.

3. The influence of the kind of the composite matrix on WEA

The epoxy, vinyl-ester and polyetheretherketone composites with carbon, glass and aramid reinforcement in different shapes (solid fibres, fabrics and mat) were taken into account during the investigation [10 and 11].

On the basis of the investigations presented in Fig. 3 we can conclude that the highest WEA is presented by the composites with the polyetheretherketone (PEEK) matrix, slightly lower WEA is presented by the composites with vinyl-ester matrix and considerably lower WEA is presented by the composites with epoxy matrix.

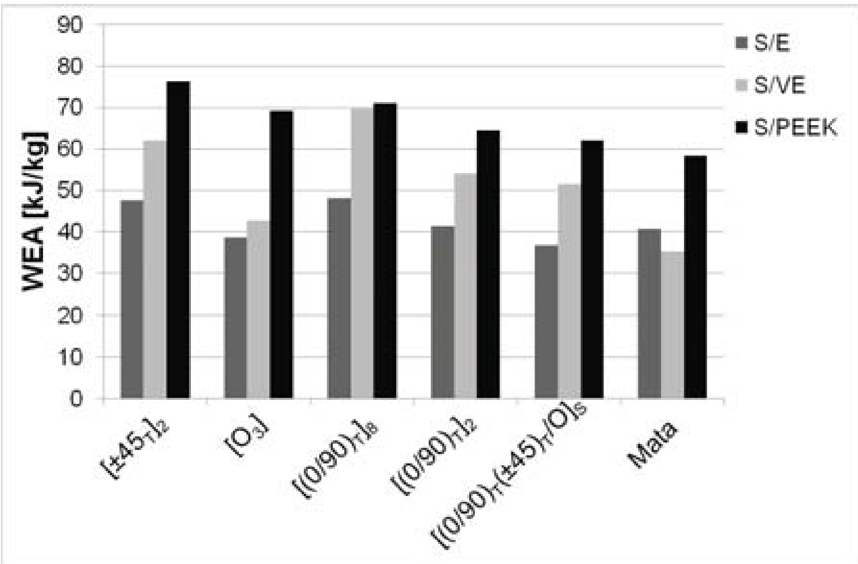

Fig. 3. The influence of the kind of the composite matrix on WEA for different glass fibre reinforced structures

The mechanical properties of the composite matrix show the resistance to cracking. The investigations showed that the more fragile the matrix is the lower resistance to cracking occurs, therefore the elements are destroyed at a smaller force and WEA is lower. The composite with the thermoplastic matrix (PEEK) reinforced with carbon fibres is the most resistant to cracking among the analysed composites.

4. The influence of the kind of composites reinforcements on WEA

The results presented in Table 1 and in Figure 4 are taken from the work [10 and 12].

Tab. 1. The comparison of WEA for different kinds of epoxy composites reinforcements

The shapes of the samples	Structures	Carbon roving	Carbon fabric	Glass roving	Glass fabric	Aramid fabric
Plane	$[0]_8$	62.4	-	40.2	-	-
	$[(\pm 45)_T]$	-	65.1	-	47.8	47.9
	$[(0/90)_T]_{10}$	-	67.7	-	41.3	48.1
	$[0/90_T/(\pm 45)_T/0]_S$	-	60.8	-	36.8	47.4
Tubes	$[0]_8$	62.4	-	41.9	-	-
	$[\pm 15/0_2]_S$	71.3	-	47.5	-	-
	$[\pm 30/0_2\ ]_S$	62.1	-	32.6	-	-
	$[\pm 45/0_2]_S$	56.8	-	53.4	-	-
	$[90/0_2]_S$	75.1	-	48.6	-	-
	$[(0/90)_T/0_2]_S$	-	87.4	-	64.2	57.5

From the results shown in Tab. 1 and Fig. 4 we can conclude that the carbon fibre reinforced composites present the highest capability of hitting energy absorption, however the aramid fibre reinforced composites present the smallest one. This phenomenon can be explained by the mechanical properties of fibres. Carbon fibres present a very high resistance to compressing and cutting. During the progressive destruction the composites are subjected to cutting and bending of the layers. Aramid fibres have a very low resistance to compressing but they have a high resistance to stretching (R_m = 1300 MPa).

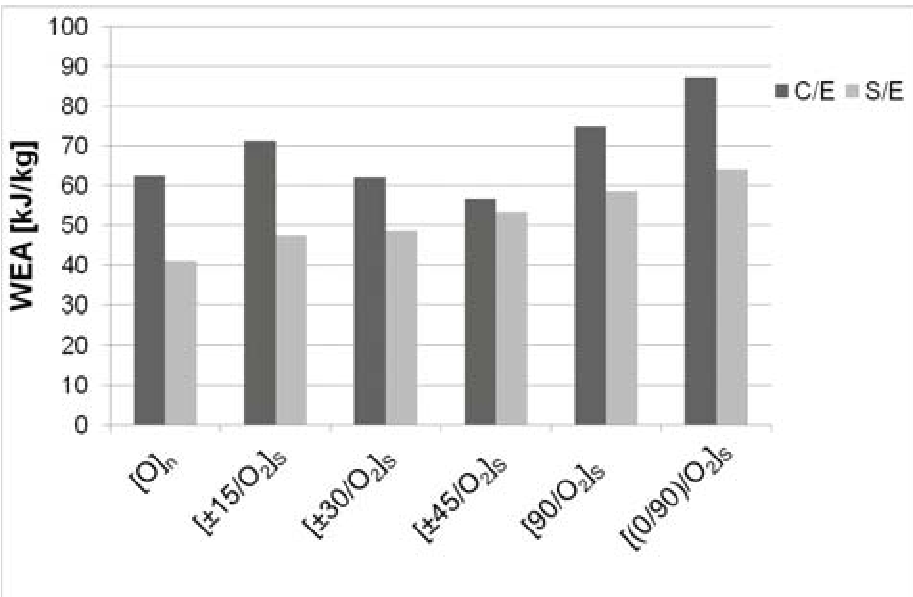

Fig. 4. The influence of epoxy composite structures reinforced with glass stripes of roving on WEA

5. The influence of the composite structure on WEA

The influence of the fibres orientation in the energy absorbing element on WEA is the same as a resistance to bending and cutting. The highest WEA was received for the element of the structure $[(0/90)_T/0_n/(0/90)_T]$, in which the surface layers of the reinforcement were made from the fabric, while the central layer was made from solid–fibres arranged parallel to the direction of the compressing force. The structures of composites [0]n and [90]n show lower energy absorption capability because they have a lower resistance to the occurring and growth. The results of the investigations are presented in Fig. 5 and 6.

The samples of the structure $[(0/90)_T/0_n/(0/90)_T]$ which central layer is reinforced with solid fibbers showed the highest hitting energy absorption capability.

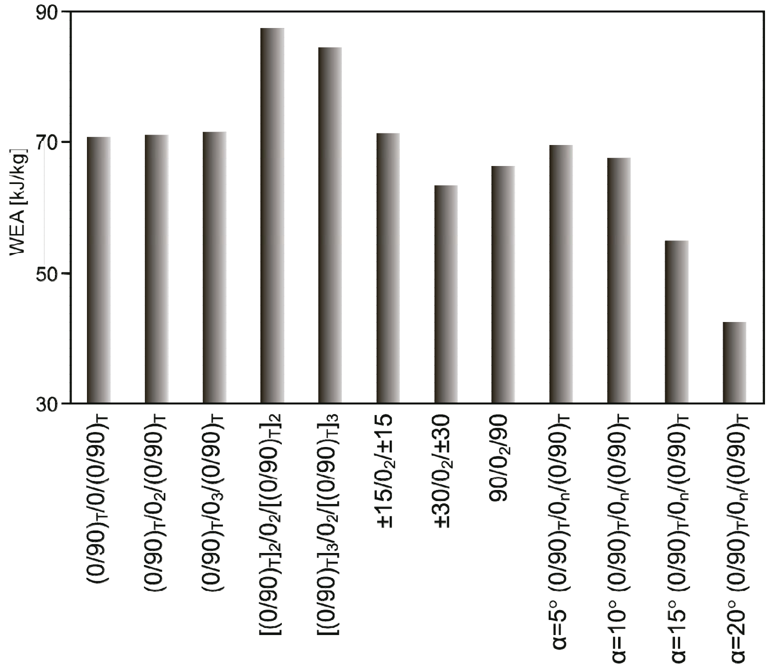

Fig. 5. The relation of the energy absorption capability to the carbon/epoxide composite structure

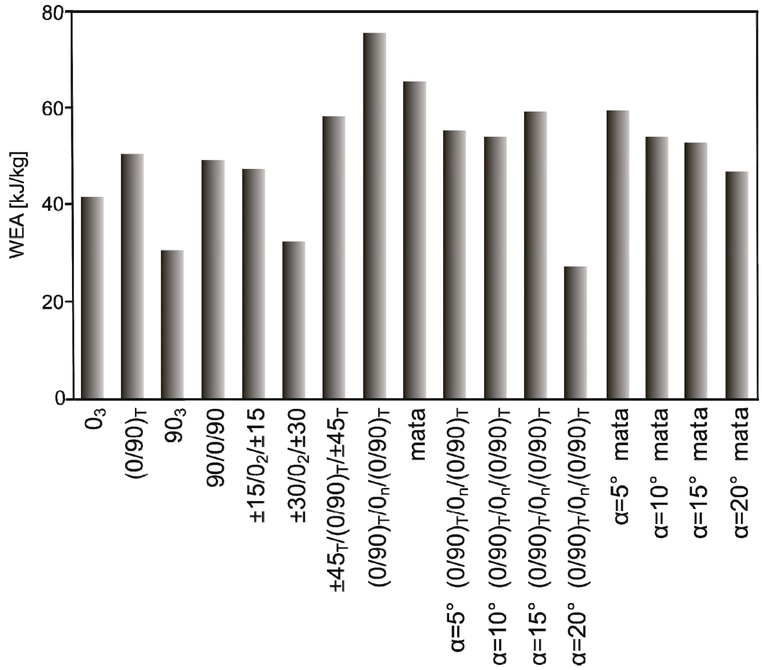

Fig. 6. The relation of the energy absorption capability to the glass/epoxide composite structure

6. The influence of the shape of the energy absorbing element on WEA

The samples in the shape of thin cuboids, tubes, truncate cones with the cross section, wavy coat and spheres were taken into account during the investigation [13]. To evaluate the influence of the energy absorbing element shape of the on the quantity of the absorbed energy the equal elements thickness (2.5mm) was considered because the energy absorption capability depends on thickness which is shown for example in Fig.7.

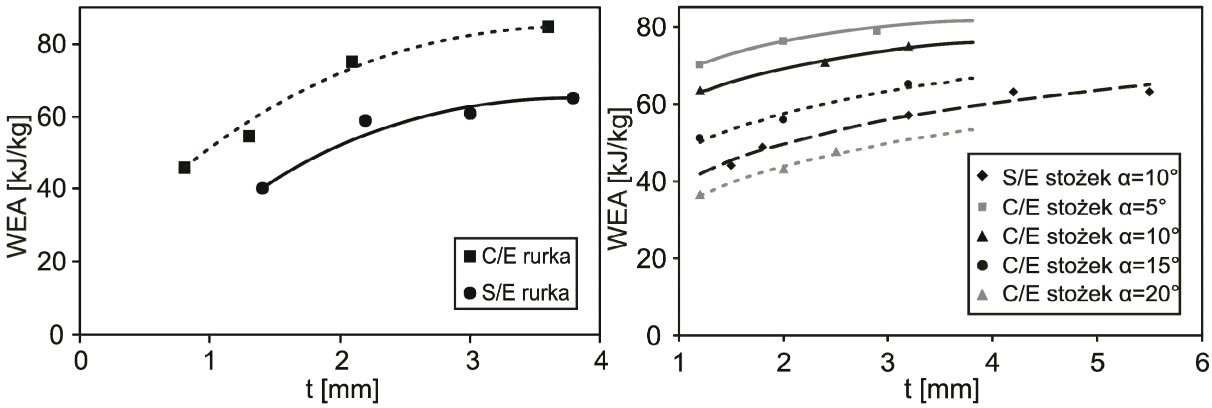

Fig. 7. The influence of the wall thickness of the tube and the truncate cone on the energy absorption capability

The results of the investigations are compared in Table 2 and Figure 8.

Tab. 2. The comparison of WEA for different shapes of energy absorbing elements

Kind of composite: S-glass, C-carbon, E-epoxy	Structure	Plane samples	Tube samples	Trancate cones	Wavy shells	Cuboid shells
S/E	mat	40.8	63.5	55.3 (5°) 44.8 (20°)	38.8	11.8
S/E	$[(0/90)_T]_S$	41.3	44.2	51.1 (5°) 35.8 (20°)		24.3
S/E	$[(\pm45)_T]_n$	47.8	53.4	56.5 (5°) 38.3 (20°)		-
C/E	$[\pm45/0_2]_S$	65.1	58.4	-	-	-
C/E	$[(0/90)_T]_S$		75.1	-	-	-

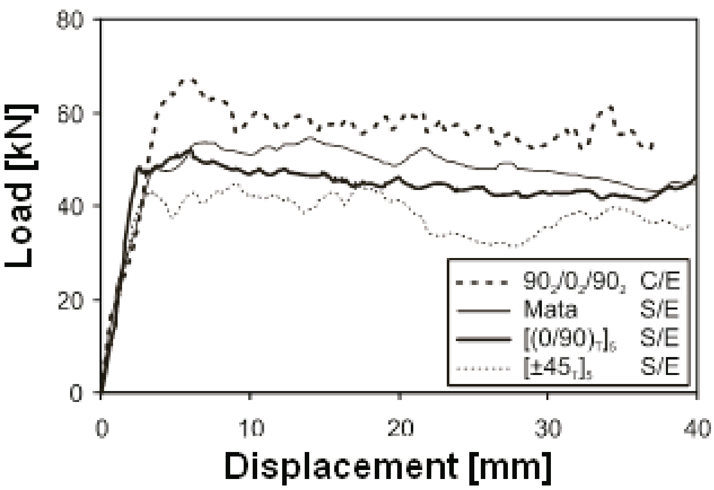

Fig. 8. The relation P-Δl of chosen structures of the samples in the shapes of tubes

From the data presented in Table 2 and Figure 10 and 11 we can conclude that the higher WEA is presented by energy absorbing elements in the shape of the tube with the ring section, lower by the truncate cones, wavy coats, and the lowest is presented by spheres. The lowest WEA of the element in the sphere shape is caused by a specific destruction mechanism. The wall brittle fragmentation and the cracking of the fibres do not occur during the destruction, but the wall of the sphere is bending to the inside with the permanent deformation.

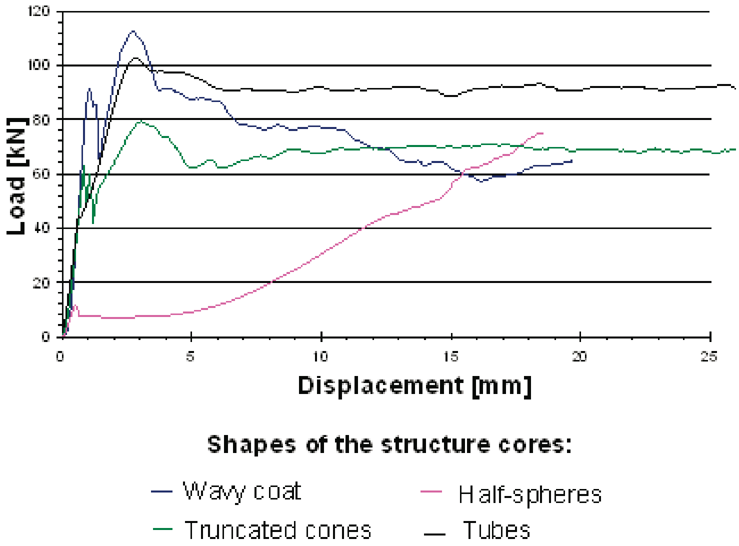

Fig. 9. The comparison of the relations P-Δl for different shapes of S/E mat elements

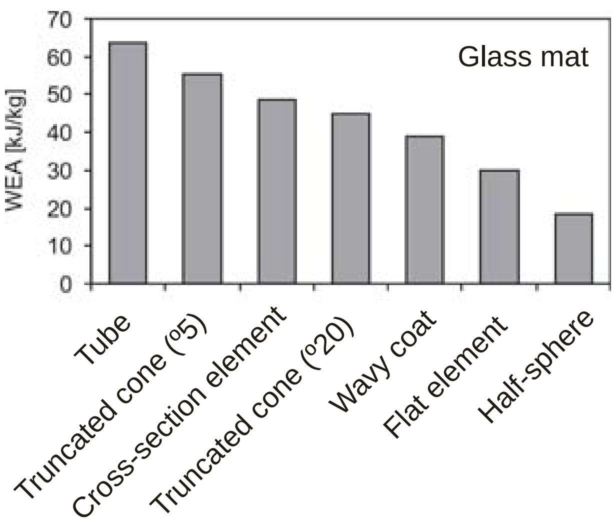

Fig. 10. The relation of WEA to the shape of the epoxy glass mat reinforced element

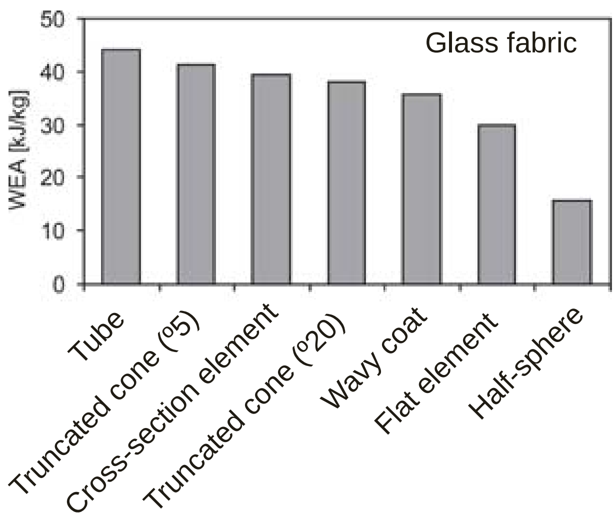

Fig. 11. The relation of WEA to the shape of the epoxy glass fabric reinforced element

7. The influence of filling the tubes with foam materials on WEA

The samples in the shape of tubes with the internal diameter ø 40mm and ø20mm and the length 50mm [14] were considered during the investigation. In order to examine the influence of the thickness on the destructive mechanism and the WEA value, the thicknesses of the tubes walls taken into account were as follows: 1.0; 1.5; 2.0; 2.5; 3.0 and 4.0mm, they are described in the work [14]. Two materials were used to fill the tubes: foamed polyvinyl chloride (PCW) (PCHW-1-115) and foamed aluminium (ALPORAS) containing: ~97% Al, ~1.5% Ca, ~1.5% Ti.

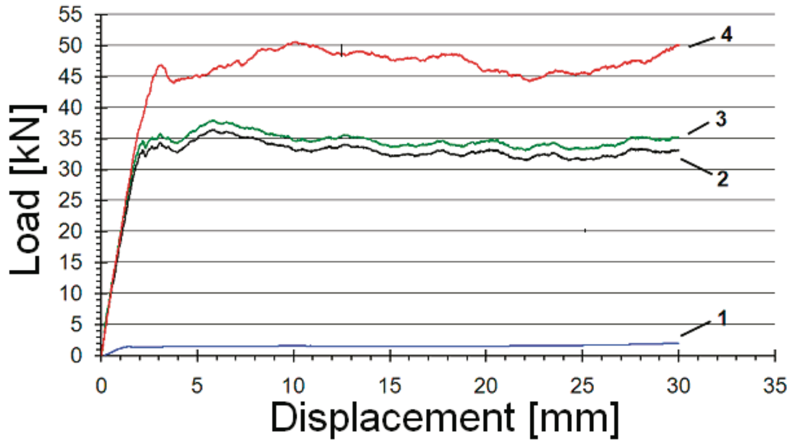

Fig. 12. Relation Pnisz – Δl of S/E sample with the diameter ø40mm and the wall thickness 3.0mm: 1) foamed PCW, 2) S/E sample without filling, 3) the algebraical sum of the ordinates from graphs 1 and 2, 4) S/E sample foamed PCW

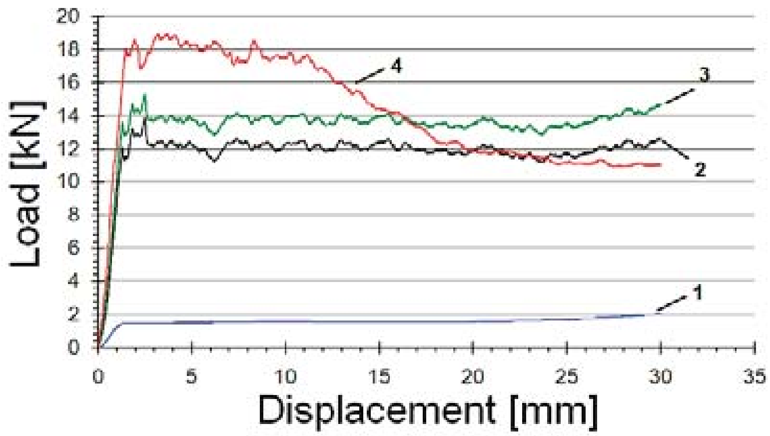

Fig. 13. Relation Pnisz – Δl of S/E sample with the diameter ø40mm and the wall thickness 1.0mm: 1) foamed PCW, 2) S/E sample without filling, 3) the algebraical sum of the ordinates from graphs 1 and 2, 4) S/E sample foamed PCW

On the basis of the investigations experiential results we can conclude two mechanisms of the samples destruction. The first occurs at a small wall thickness (the thickness which i.e. equal or smaller than 1mm), the second occurs at t>2mm. During the compressing of the tubes filled with foamed materials their swaging occurs, which produce the pressure on the inner surface of the tubes. It results in arising of circumferential stress on the surface of the external tube. They have greater influence on the tube destruction than stresses caused by the compressing force and they contribute to the early samples destruction. It is confirmed by the falls of destruction force in the relation Pnisz – Δl shown in Fig. 13, however there is no fall of the force in the case of t the tube of 1mm thickness without filling. For the tube wall thickness larger then 2mm, the tubes filling causes the significant WEA growth, which is greater then WEA sum of the foamed material and the tube without filling. This effect can be seen in Fig. 12. The filling of the tubes made from S/E composite causes greater WEA increase than in the case of those made from C/E composite, what is caused by greater destructive deformations of glass fibre reinforced epoxy composites.

In the energy absorbing investigations the filling the tubes with the foamed materials increases WEA when the wall thickness is larger than approximately 1mm. In such a case the additional tube loading produced by the pressure of the foamed material is absorbed by the enlarged tube section. However, the tubes with the thickness smaller than 1mm destroy themselves by the additional circumferential stresses. The influence of the filled tubes destruction mechanism causes EA increase. During the destruction the wall is curved onto the external edge of the tube. However, in the case of the tube without filling a part of the wall thickness is curved outside –Fig. 14.

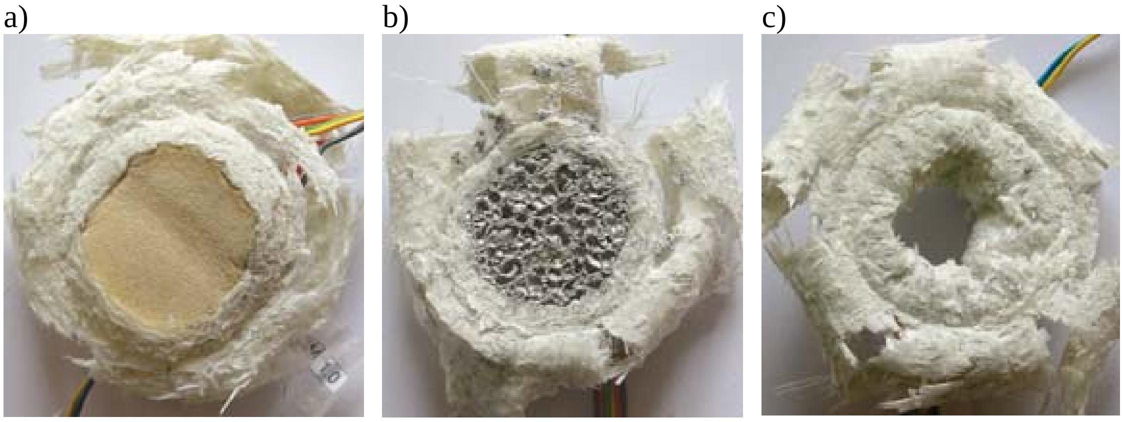

Fig. 14. The pictures of the destroyed S/E samples with the wall thickness 1.0mm: a) filled with foamed PCW, b) filled with foamed Al, c) without filling

8. WEA comparison of elements and fragments of energy absorbing structures

The energy absorbing structures in the shape of coats are mostly made from the composites with the sandwich type of structure, where the cones can be: the arrangement of tubes, truncate cones, shaped profiles, thin wavy coats, structures in the shape of honeycomb or they can be filled with the foamed material.

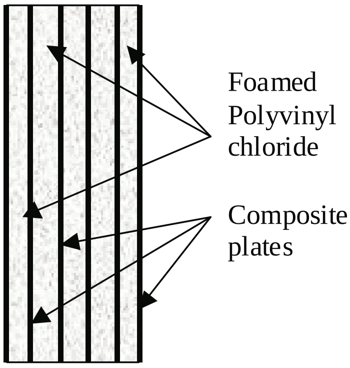

Fig. 15. The sandwich structure with the cone filled with the porous material

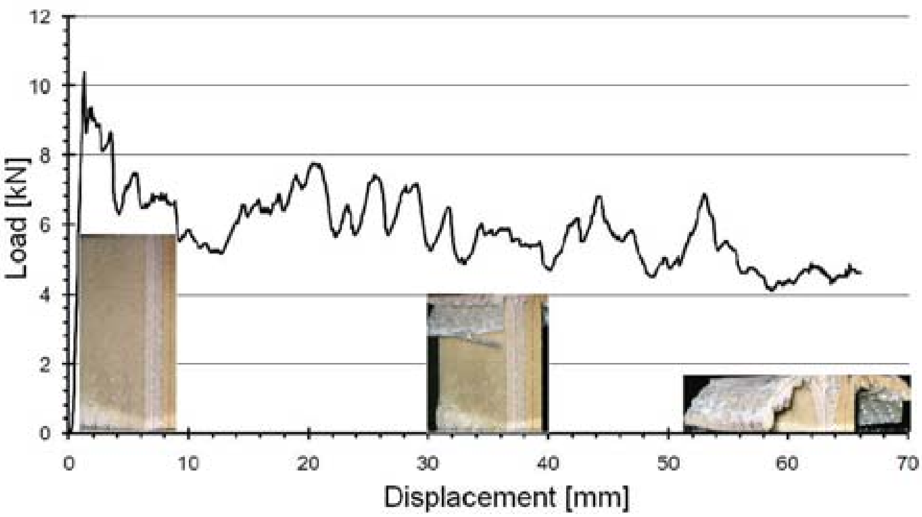

Fig. 16. The relation of crush load to displacement for the sandwich structure with thin-walled composite sections reinforced with glass mat [(0/90)T]n

From the results presented in the paper [15] we can state that the sandwich type structures with the thin wall plates made from the composite reinforced with the fabric of structure [(0/90T]n showed a greater hitting energy absorption capability then the plates reinforced with the fabric of structure [(±45)T]n. the relative energy absorption for this type of structures is up to 20kJ/kg. The fragment of the sandwich type structure and the result of the test are shown in Fig. 15 and 16.
The examined part of the sandwich type of the structure consisted of two thin plates made from the glass fabrics reinforced epoxy composite and the core in the shape of four tubes [15]. The tubes of the length 50mm and diameter 40mm were made from the glass mat reinforced epoxy composite. In order to make a comparison, there were also performed the compressing tests for a single glass/epoxyd mat tube filled with the foamed material and for the structure of four tubes without filling. The test with the foamed material in the shape of the cylinder was also done.

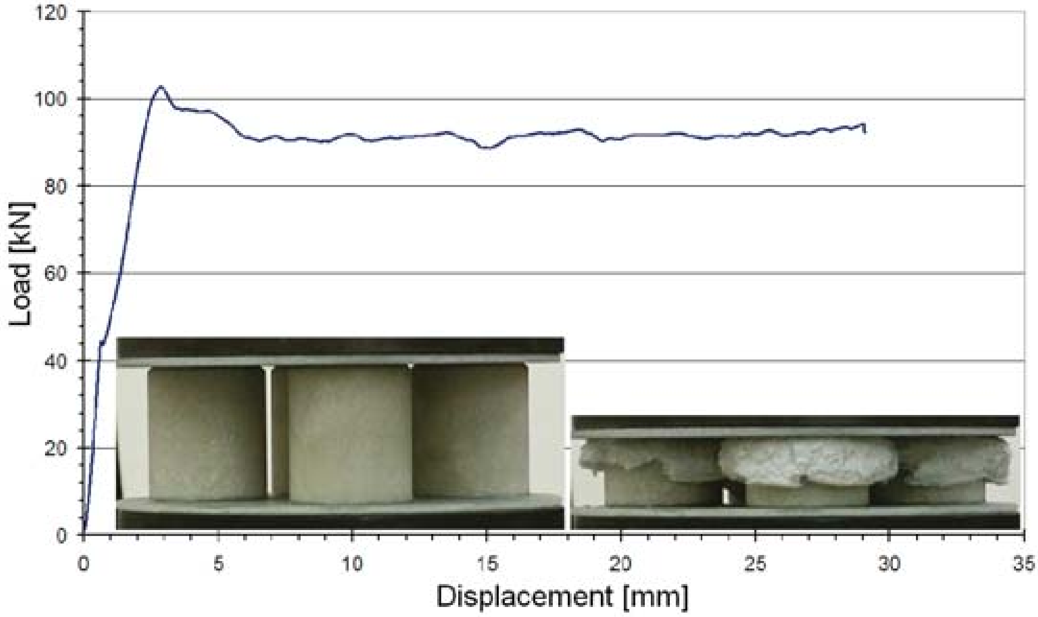

Fig. 17. The relation of crush load to displacement for the sandwich structure with the core of four tubes with the initiator, without filling material

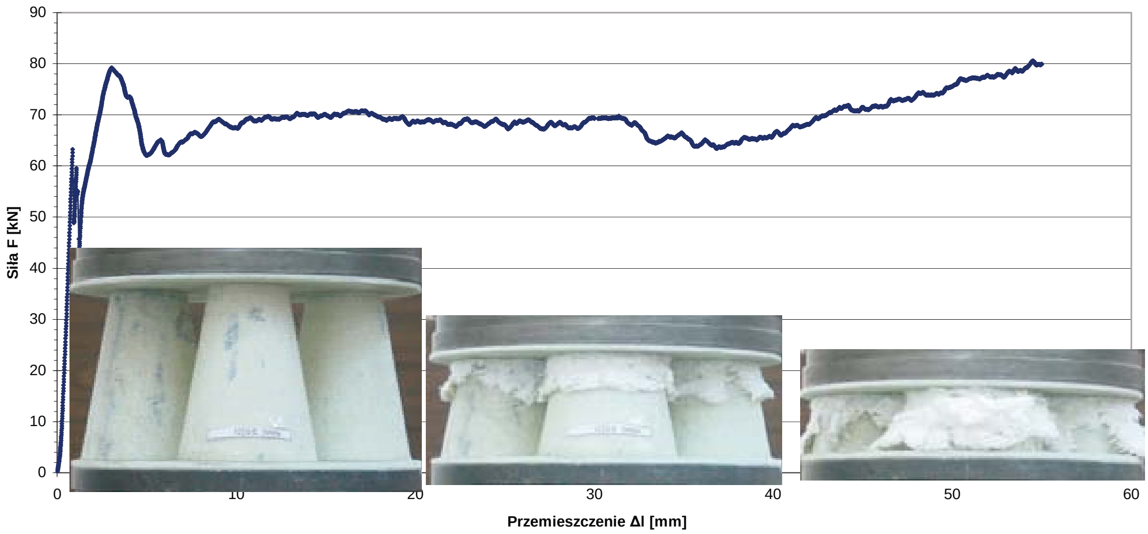

Fig. 18. The relation of crush load to displacement for the sandwich structure with the core of four truncate cones

Among different shapes of the shapes used in energy absorbing structures there are also cores in the shape of spheres.

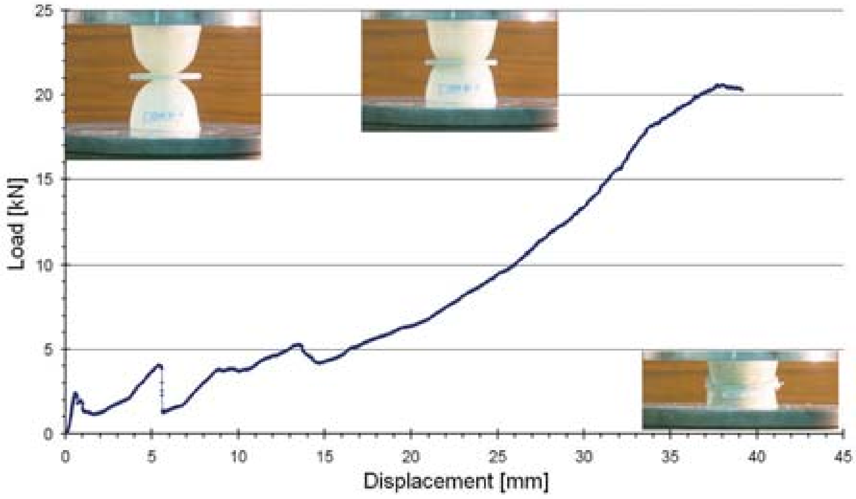

Fig. 19. The relation of crush load to displacement for the sandwich structure with the core of two spheres welded together with their tops to the common plate

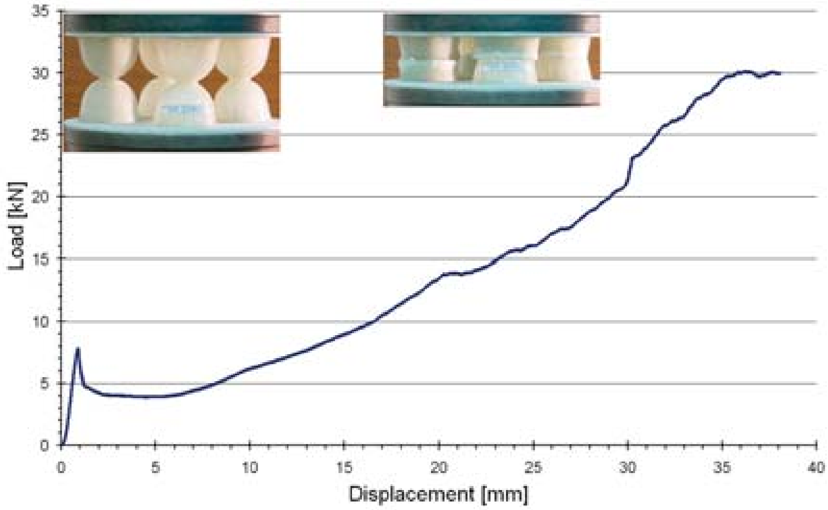

Fig. 20. The relation of crush load to displacement for the sandwich structure with the core of two spheres welded in pairs with their tops

In further part of the test there was also examined the structure which core was made from the fragments of glass mat/epoxy wavy coats attached to the plates along their opposite edges. It was compared to a single wavy coat.

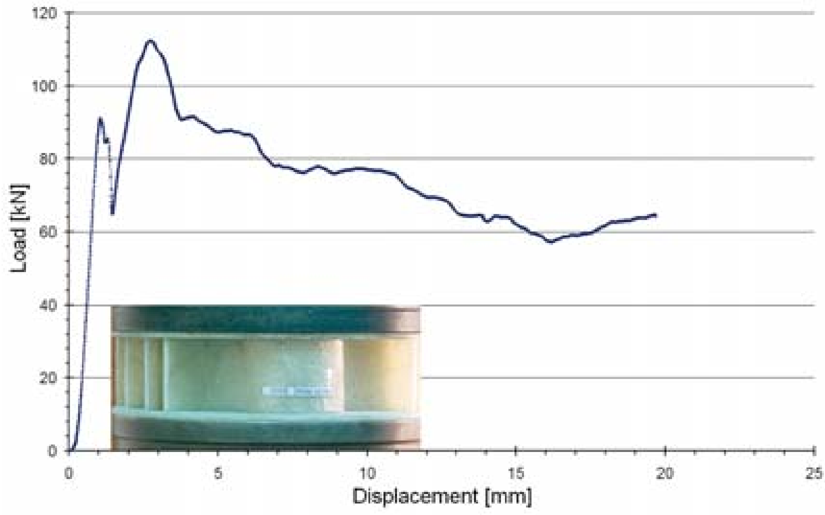

Fig. 21. The relation of crush load to displacement for the sandwich structure with the core of four wavy coats – Tab.7

From the examined wavy coat structure of the total length 800mm WEA equal 1.44 kJ was obtained, however in the case of a single sample of the length 160mm -0.15 kJ. For the wavy coat structures we can assume approximately that the rule of WEA addition of single samples is confirmed.

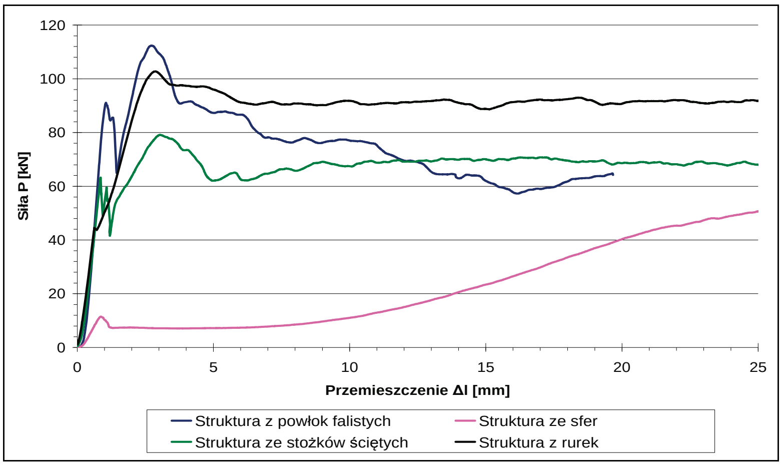

Fig. 22. The comparison of energy absorption capability for different types of sandwich structures

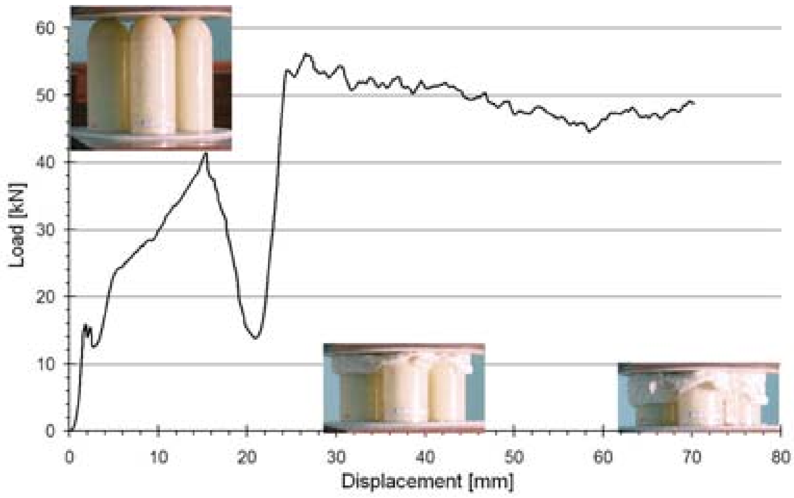

Fig. 23. The relation of crush load to displacement for the sandwich structure with the core of the four glass tubes structure with the glass mat sphere

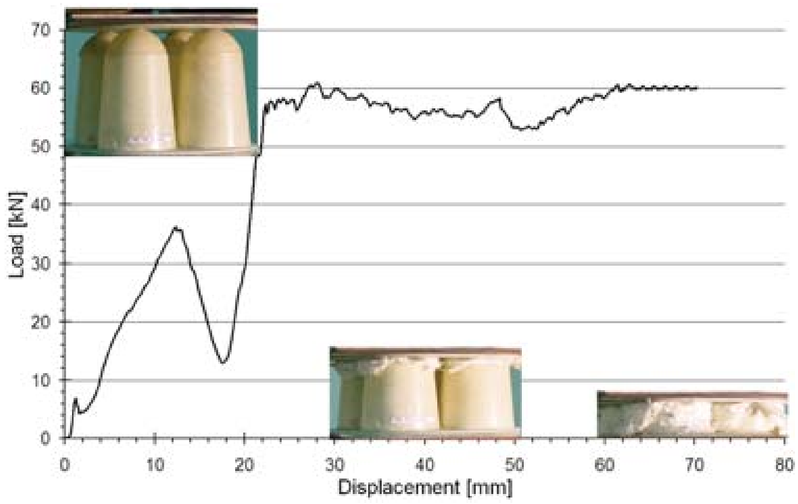

Fig. 24. The relation of crush load to displacement for the sandwich structure with the core of the four glass cones structure with the glass mat sphere

The above graphs show that the connection of the tube and the sphere with the use of epoxy resin is clearly marked on the relevant curves. Their initial part is the same as for the spheres destruction. The process of the second part is the same as for the progressive destruction respectively tubes or cones. The destruction at the place of connection, in the graph you can see the rapid fall of destruction force and then its steep increase. The connection weakens the whole sample resistance. The crushed sphere is bent to the inside of the tube or cone, and then it cuts down the weld and under the slight loading it is bent to the inside of the sample. Next, the rapid growth of the force is caused by the progressive destruction of the tube or cone despite the lack of the initiator. In the initial phase of the tubes (cones) destruction there is no significant peak of the force.

9. Conclusions

Polymer composites because of their high mechanical properties related to the mass have a wide application in the energy absorbing cars and airplanes construction. The kind of the composite as well as the components from the composite is made from have an influence on the value of absorbed energy – the carbon fibres reinforced epoxy composites show WEA greater than 20% than the glass fibres reinforced composites.

For the examined composites and structures there is a synonymous WEA growth occurring together with the wall thickness growth. It can be used in the structures demanding higher hitting energy absorption. Circumferentially orientated fibres in the specimen have main influence on the decrease of the number of translayer cracking as well as on and their length, what causes the increase of absorbed energy. The samples of the structure [(0/90)T/0n/(0/90)T] reinforced with the continuous fibres showed the greatest hitting energy absorption capability during the investigation. WEA grows together with the growth of the wall thickness because the bending stiffness grows and during the destruction of the element, the layers bending destruction mechanism dominates.

The largest WEA is shown by the elements in the shape of tubes, a little lower by truncate cones, and the flat ones in the shape of thin cuboid with the wavy section and the smallest (lowest) WEA is presented by the elements in the shape of the sphere.

Lower WEA of the elements in the truncate cones is caused by the fact that the component of the compressing force operates along the element wall. WEA of cones decreases together with the growth of the half-angle of the cone. In the first phase of progressive destruction, the elements in the shape of half-sphere destroy themselves under small load through the destructive bending of the whole wall thickness into the inside the half-sphere. In further phase the destructive force grows gradually because the destroyed sections are longer. The change of the relations P-Δl elements in the shape of spheres, which grows at the time of destructive causes smaller peaks of acceleration, therefore the smaller overloading in relation to the elements in the shape of tubes. The foamed material used as filling of the sample increases the absorption energy, however because of the higher element mass it decreases WEA.

The comparison of the structures made from single elements with relevant structures of four elements shows that absorbed energy is accumulating. In this case the relative absorbed energy remains at the similar level.

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