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Static axial crush performance of unfilled and elastomer-filled composite tubes

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Abstract. The paper presents the results of the experimental static axial crush performance of unfilled and filled composite tubes. Composites are widely used as materials for energy absorbing structures because of their low density and a very high absorbed energy in relation to the mass ratio. Foamed materials are used in order to additionally increase their efficiency, because of stabilizing the progressive crush. It was proved by many authors that various foamed materials positively influence the energy absorption. In this work authors took effort to evaluate a very different material as a filler of common composite elements – elastomers. Elastomers are materials characterised by very high crush strains and viscoelastic properties. The tube shaped specimens made of epoxy composite, reinforced with carbon or glass fabrics were filled with elastomers of 40; 60; 70 and 90° ShA hardnesses. The influence of the elastomer hardness and the filling degree on the energy absorption factor (EA) was evaluated. The degree of filling the specimens with elastomers is determined by a different size of the elastomer perforation. Elastomers have a negative impact on the energy absorbed by the composite tubes.

Key words: mechanical properties; absorbed energy; polymer composites; elastomers; experimental mechanics.

1. Introduction

The modern crashworthy structures have to be as light as possible and are to absorb the impact energy in the most plastic, progressive and safe way for passengers or protected substances in general and still have to be very light. Composites are commonly used as materials for energy absorbing structures due to their low density and very high absorbed energy with respect to the mass ratio. In most cases foamed materials are used, to increase additionally their efficiency. The advantage of filling the tubes with the foamed materials results from the tendency of the stable (progressive) crush induced by the lack of local buckling of tube walls. Many papers present investigations of filling composite energy absorbing structures with foamed materials [1–7]. In most cases it is clearly seen that foamed material positively influence the performance of the composites. This paper deals with experimental investigations of the influence of filling the tubes with elastomers. Elastomers show a viscoelastic state and are characterised by very high failure strains. Especially, if their hardness is of 40° ShA range and during tension they are destroyed at the deformation larger than 200 per cent [8]. Elastomers are widely used in damper constructions. The absorbed energy is partly accumulated in an elastic way and partly is transferred into heat. The part of dissipated energy corresponds to the inner area of a hysteresis loop. The literature study shows no articles about using the elastomers to improve crashworthiness of composites.

The influence of the elastomer hardness on their mechanical properties determined from our own research [9], are compared in Table 1. The elastomers of greater hardness have the higher compression and tension strength. The elastic modulus and shear modulus also increase. However, the Poisson's ratio, which can be assumed as 0.5, slightly depends on the hardness.

Table 1
Hardness influence on mechanical properties of the elastomers [9]

Properties determined from investigations	Hardness in °ShA			
	40	60	70	90
Tension strength for given ε [MPa]	1.95 ($\varepsilon = 2.5$)	7.8 ($\varepsilon = 2.5$)	9.0 ($\varepsilon = 2.5$)	12.7
Compression strength for given ε [MPa]	2.5 ($\varepsilon = 0.5$)	4.5 ($\varepsilon = 0.5$)	6.0 ($\varepsilon = 0.5$)	14.6
Normal modulus in phase (E_1) [MPa]	21.4	28.5	36.6	73.5
Out of phase component (E_2) [MPa]	0.783	1.18	1.92	3.7
Shear modulus [MPa]	7.13	9.5	12.2	24.5
Poisson's ratio	0.493	0.497	0.498	0.498

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2. Object of investigation

The objects of the interest is the crush performance of the specimens in the shape of tubes made of epoxy composites reinforced with carbon fabrics (C/E) and glass fabrics (G/E) with elastomer fillers. The scheme of an example specimen is shown in Fig. 1. Two groups of specimens were prepared for the investigations. The first group consisted of the tubes filled with the elastomers of different hardness and different degree of filling of the inner specimen volume. The second group was composed of the empty composite tubes.

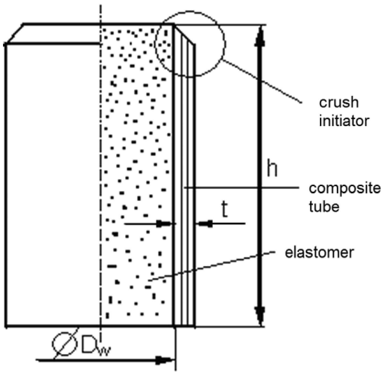

Fig. 1. Shape of the specimens used in the investigations

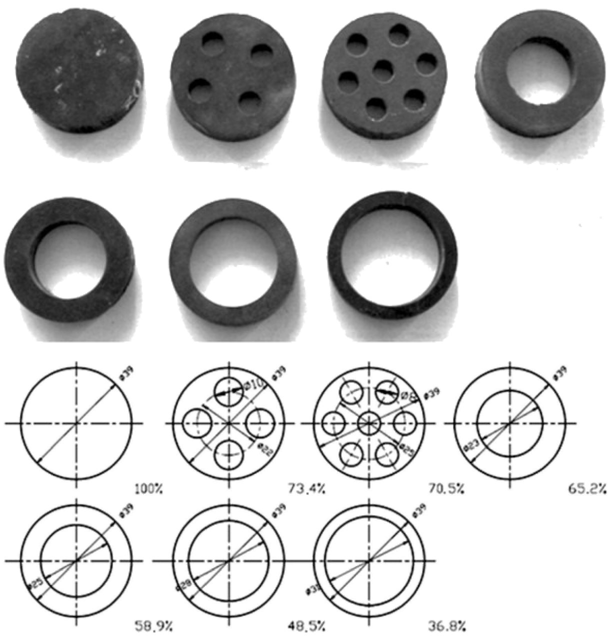

Fig. 2. The perforations of the elastomer fillings

The tubes were made of epoxy resin SARZYNA E-53 reinforced with the glass fabric STR-012-350-110 of 350 g/m^2 weight and with the carbon fabric TENAX HTA. The tubes had ø40 mm diameter and were 50 mm high. In order to investigate the influence of thickness on the failure mechanism and EA values, the wall thicknesses were equal to 1.0; 2.0; 3.0 mm in case of C/E composites and 2.0 mm in case of G/E tubes. The composite tubes were manufactured with the use of a hand lamination method described in [10]. To ensure more accurate results, the specimens were sorted so that the constant thickness along the circumference of each specimen was assured.

The elastomers of 40°; 60°; 70° and 90° hardness in Shore's A scale (°ShA) were manufactured from nitrile rubber, stearin, age-registor, soot, softening agent, sulphur and organic accelerator. A different degree of filling the tubes was evaluated. The degree of filling the specimens with elastomers is determined by the percentage filling of the inner volume of the tube with elastomer of the different size of perforation. The number of the holes in elastomer and their diameters constituted the perforation shape. The outer diameter of the perforated elastomers was equal to the inner diameter of the given specimen. The perforations of the elastomer fillings are presented in Fig. 2.

3. Experimental method and results of investigations

The energy absorbing tests were performed on the universal testing machine Instron 8802. The specimens were placed between two flat plates and were compressed at the constant loading rate equal to 40 mm/min. The machine recorded the displacement of the compressing head and the crush force. The maximal shortening of the specimens was equal to 30 mm. On the basis of these data the graphs of crush force in the function of the specimen shortening were outlined. The energy absorbed by the specimens (EA) was calculated by the numerical integration of the field under the graph load – displacement from the following formula:

$$\mathrm{EA} = \int_0^{l_1} P dl, \tag{1}$$

where l_1 is shortening of the specimen. The obtained EA value corresponds to the area below the curve until catastrophic crush occurs (crack along the side surface of the tube) or until reaching the 30 mm shortening.

The energy absorption performance of the composite-elastomer hybrid specimens was determined from the experimental results compared in Table 2 and 3. Table 2 compares C/E tubes of 1.0, 2.0 and 3.0 mm wall thicknesses. In Table 3 G/E of 2 mm wall thickness is presented. The last column contains EA values. Specimens with 0% filling degree are tubes without any elastomer inside. They have been bolded and are used as reference specimens in the EA calculation.

The influence of the tube wall thickness of polymer composites on EA is increasing for all examined cases of the tube filling degree and the elastomer hardness (Table 2). It results from the tubes crushing by the layer bending, as the bending strength depends on the thickness in square.

Table 2
Results of tests for C/E tubes filled with elastomers

Composite	Tube wall thickness	Filling degree	Maximum force	Specimen shortening	Elastomer hardness	EA	Composite	Tube wall thickness	Filling degree	Maximum force	Specimen shortening	Elastomer hardness	EA
	[mm]	[%]	[kN]	[mm]	[°ShA]	**[kJ]**		[mm]	[%]	[kN]	[mm]	[°ShA]	**[kJ]**
C/E	1	100	30.3	3.6	40	0.05	C/E	2	100	74.9	4.3	70	0.14
C/E	1	73.4	22.0	11.1	40	0.19	C/E	2	73.4	53.4	13.1	70	0.51
C/E	1	70.5	25.9	14.2	40	0.25	C/E	2	70.5	53.5	14.1	70	0.55
C/E	1	65.2	20.7	17.7	40	0.30	C/E	2	65.2	51.1	16.2	70	0.60
C/E	1	58.9	19.9	20.1	40	0.33	C/E	2	58.9	43.1	19.5	70	0.72
C/E	1	48.5	19.6	28.1	40	0.44	C/E	2	48.5	46.4	26.6	70	0.88
C/E	1	36.8	15.9	30.0	40	0.42	C/E	2	36.8	38.9	30.0	70	0.97
C/E	***1***	***0***	***15.93***	***30.0***	***no***	***0.41***	C/E	2	100	68.0	2.6	90	0.16
C/E	1	100	30.3	3.4	60	0.04	C/E	2	65.2	67.8	15.0	90	0.61
C/E	1	73.4	27.4	10.9	60	0.22	C/E	2	58.9	63.7	18.1	90	0.75
C/E	1	70.5	26.6	15.0	60	0.30	C/E	2	36.8	47.6	19.6	90	0.73
C/E	1	48.5	21.4	22.0	60	0.41	C/E						
C/E	1	36.8	19.2	29.6	60	0.47	C/E	3	100	82.7	4.0	40	0.07
C/E	1	100	36.2	4.4	70	0.08	C/E	3	73.4	93.5	8.9	40	0.44
C/E	1	65.2	26.6	14.5	70	0.29	C/E	3	70.5	93.2	12.4	40	0.59
C/E	1	58.9	22.3	18.8	70	0.35	C/E	3	65.2	87.9	17.7	40	0.85
C/E	1	48.5	19.6	22.0	70	0.37	C/E	3	65.2	87.6	17.5	40	0.87
C/E	1	36.8	17.8	30.0	70	0.47	C/E	3	58.9	80.7	21.7	40	1.13
C/E	1	100	49.4	3.2	90	0.08	C/E	3	36.8	70.7	28.2	40	1.17
C/E	1	65.2	30.1	13.7	90	0.29	C/E	***3***	***0***	***49.9***	***30.0***	***no***	***1.11***
C/E	1	58.9	26.8	15.1	90	0.31	C/E	3	100	113.4	2.3	60	0.12
C/E	1	36.8	19.9	14.3	90	0.23	C/E	3	73.4	94.8	9.6	60	0.49
							C/E	3	70.5	90.0	12.3	60	0.63
C/E	2	100	68.0	4.6	40	0.41	C/E	3	65.2	68.7	17.4	60	0.83
C/E	2	73.4	62.2	10.5	40	0.16	C/E	3	58.9	70.4	22.6	60	1.06
C/E	2	70.5	60.1	12.4	40	0.38	C/E	3	48.5	71.6	26.8	60	1.27
C/E	2	65.2	60.9	17.6	40	0.46	C/E	3	36.8	63.0	29.9	60	1.33
C/E	2	58.9	55.9	23.0	40	0.65	C/E	3	100	120.0	2.4	70	0.18
C/E	2	48.5	64.8	26.8	40	0.76	C/E	3	73.4	83.1	10.8	70	0.59
C/E	2	36.8	54.6	29.2	40	0.91	C/E	3	70.5	77.5	12.6	70	0.62
C/E	***2***	***0***	***32.94***	***30.0***	***no***	***0.94***	C/E	3	65.2	79.8	19.0	70	0.93
C/E	2	100	84.6	3.4	60		C/E	3	58.9	63.1	23.2	70	1.18
C/E	2	73.4	55.0	10.9	60	0.09	C/E	3	48.5	67.8	26.1	70	1.27
C/E	2	70.5	53.5	14.7	60	0.39	C/E	3	36.8	66.0	30.0	70	1.47
C/E	2	65.2	46.1	17.3	60	0.54	C/E	3	100	124.3	2.6	90	0.13
C/E	2	58.9	46.1	25.6	60	0.57	C/E	3	73.4	84.4	7.8	90	0.47
C/E	2	48.5	44.0	26.4	60	0.70	C/E	3	70.5	87.8	11.8	90	0.72
C/E	2	36.8	40.2	30.0	60	0.90	C/E	3	65.2	75.6	15.8	90	0.80
						0.96	C/E	3	36.8	53.6	13.0	90	0.84

Figures 3 and 4 include four diagrams each, illustrating crush performance of 2 mm thick tubes made of CE and G/E composites respectively. Each diagram contains several curves described by the percentage number of filling degree and is dedicated for elastomers of different hardnesses (40°; 60°; 70° and 90° in Shore's A scale). Hardnesses of elastomers are pointed in the right bottom corner of the diagrams.

Filling the C/E and G/E composite tubes with elastomers causes the increase of the maximum crush force. Along with the increase of the tubes filling degree, the tube crush displacements highly decrease, which influences directly the total EA value decrease.

The EA comparison of carbon/epoxy and glass/epoxy-elastomer hybrid tubes is presented in four diagrams, in Fig. 5. The C/E composite tubes filled with elastomers show greater EA than the analogical tubes made of G/E composite because the C/E composite compression strength is significantly greater. This effect was shown in the tests of C/E and G/E of equal wall thicknesses. However, the EA value was slightly influenced by the hardnesses of elastomers (40°, 60° and 70° ShA) which filled the tubes. In case of 90° ShA elastomer filled tubes strong scattering of the EA results can be observed. This is due to very short crushing distance (about 2–4 mm) caused by pressure of very stiff and incompressible filling material and catastrophic character of crush.

Table 3
Results of tests for G/E tubes filled with elastomers

Composite	Tube wall thickness	Filling degree	Maximum force	Specimen shortening	Elastomer hardness	**EA**	Composite	Tube wall thickness	Filling degree	Maximum force	Specimen shortening	Elastomer hardness	**EA**
	[mm]	[%]	[kN]	[mm]	[°ShA]	**[kJ]**		[mm]	[%]	[kN]	[mm]	[°ShA]	**[kJ]**
G/E	2	100	62.0	4.3	40	0.12	G/E	2	100	58.9	0.14	70	0.14
G/E	2	73.4	55.0	11.1	40	0.34	G/E	2	73.4	56.0	0.50	70	0.50
G/E	2	70.5	57.1	14.6	40	0.45	G/E	2	70.5	55.5	0.47	70	0.47
G/E	2	65.2	58.3	18.2	40	0.57	G/E	2	65.2	54.3	0.60	70	0.60
G/E	2	58.9	43.4	20.8	40	0.63	G/E	2	58.9	48.6	0.69	70	0.69
G/E	2	48.5	53.9	26.6	40	0.84	G/E	2	48.5	48.0	0.85	70	0.85
G/E	2	36.8	53.8	28.7	40	0.83	G/E	2	36.8	39.7	0.84	70	0.84
G/E	***2***	***0***	***27.3***	***30.0***	***no***	***0.68***	G/E	2	100	60.2	2.6	90	0.14
G/E	2	100	55.1	2.3	60	0.06	G/E	2	65.2	60.7	15.6	90	0.67
G/E	2	73.4	53.0	10.9	60	0.36	G/E	2	58.9	60.4	17.5	90	0.67
G/E	2	70.5	54.5	15.3	60	0.50	G/E	2	48.5	39.8	18.7	90	0.65
G/E	2	65.2	57.3	18.2	60	0.62	G/E	2	36.8	46.1	17.3	90	0.60
G/E	2	58.9	43.4	20.8	60	0.63							
G/E	2	48.5	53.9	26.6	60	0.84							
G/E	2	36.8	40.9	30.0	60	0.85							

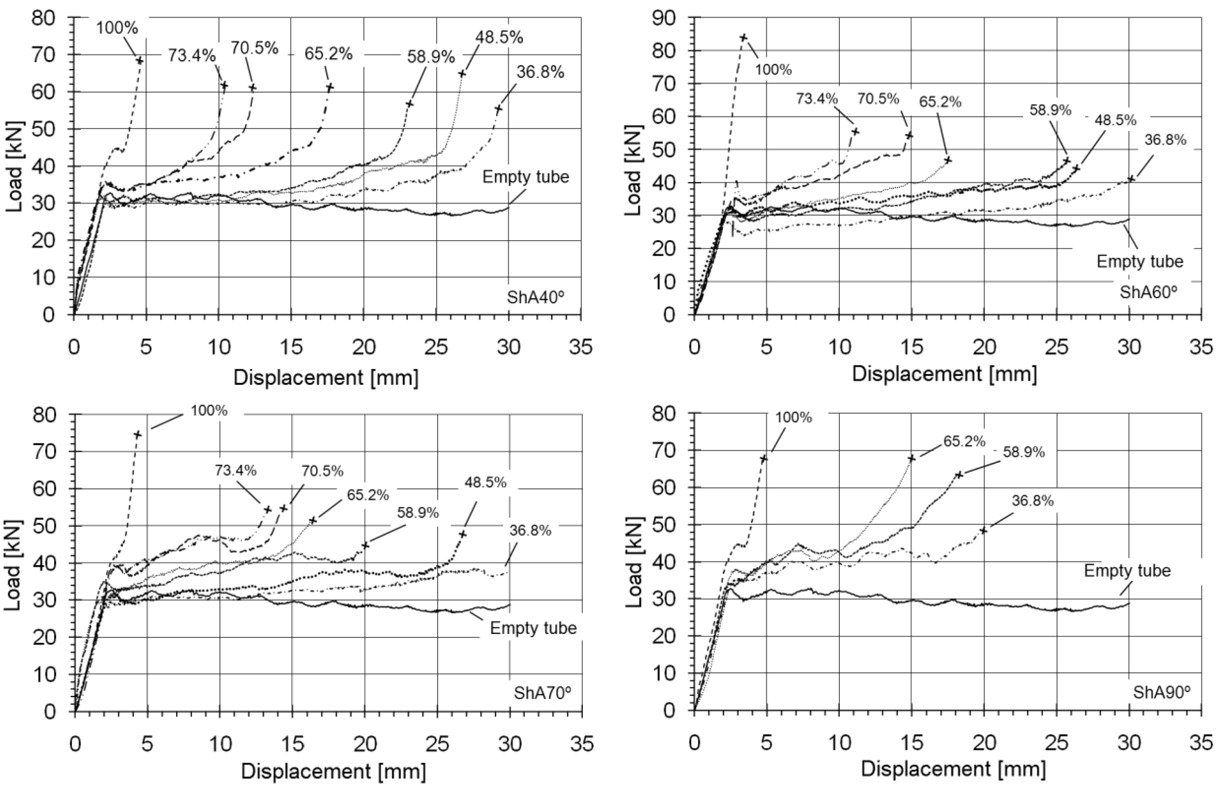

Fig. 3. Dependence load-displacement of C/E composites filled with elastomer of different degree and different hardness. X denotes catastrophic crush of specimens

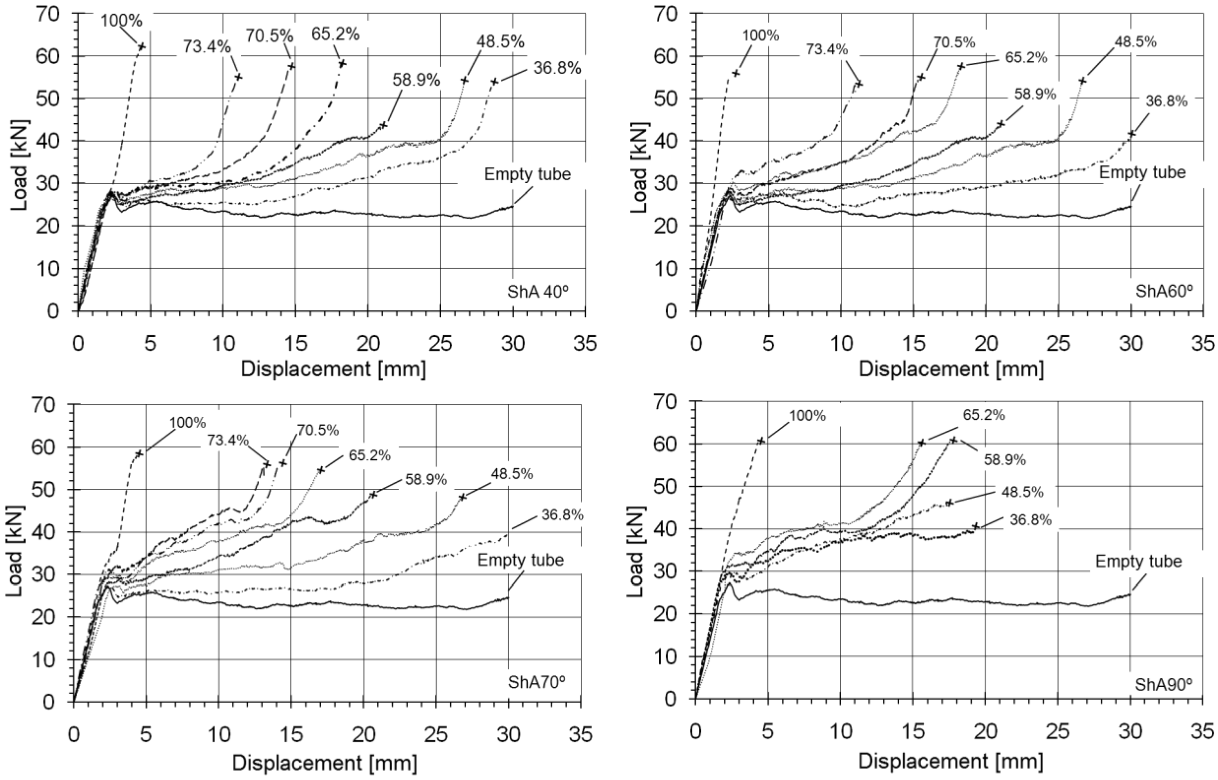

Fig. 4. Dependence load-displacement of G/E composites filled with elastomer of different degree and different hardness. X denotes catastrophic crush of specimens

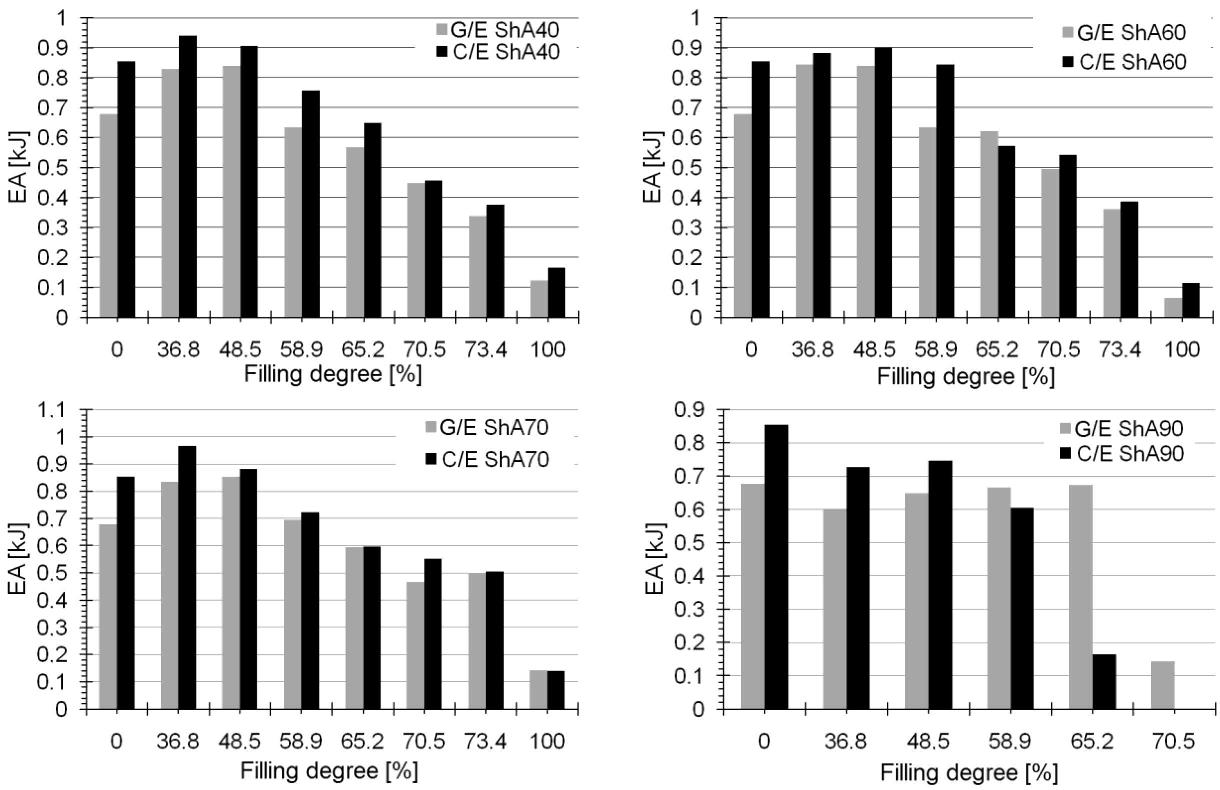

Fig. 5. Comparison of EA for filled C/E and G/E composite tubes with 2 mm wall thickness for different degrees of filling and hardnesses

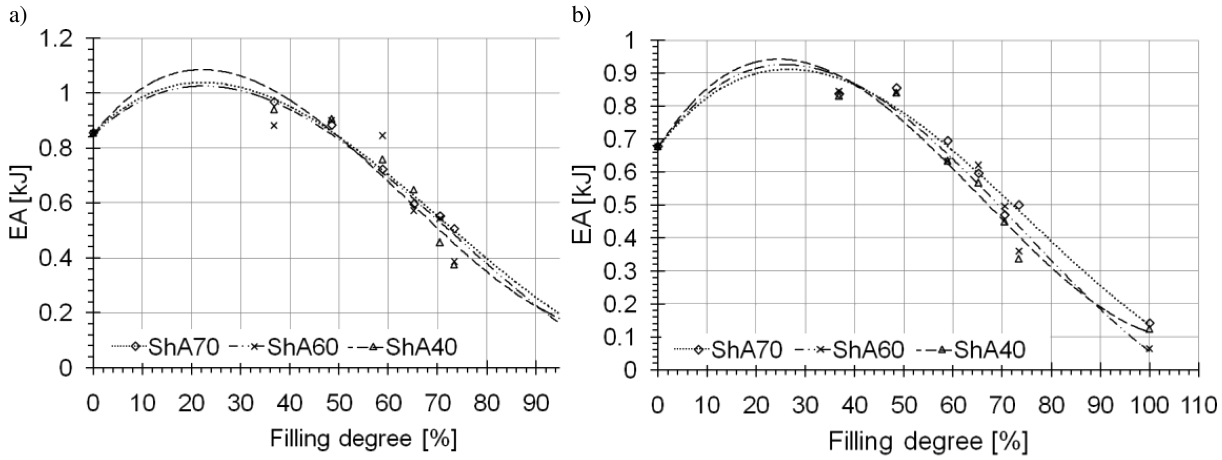

Fig. 6. Influence of degree and hardness on EA of the tubes made of a) C/E and b) G/E composites of 2 mm wall thickness

The points presented in Fig. 6a and b indicate the experimental results for C/E and G/E and the solid lines arose as the result of describing the points with polynomials obtained by the least squares method. The approximations of the dependence degree of the filling on the absorbed energy value show that EA increases to the filling degree of about 22 per cent, however, EA significantly decreases when it is over 22 per cent. This effect occurs due to the circumferential stresses caused by the pressure inside the tube induced by the compression of incompressible elastomers. The circumferential stresses cause the tubes crush, that is shown in the zoom in Fig. 7.

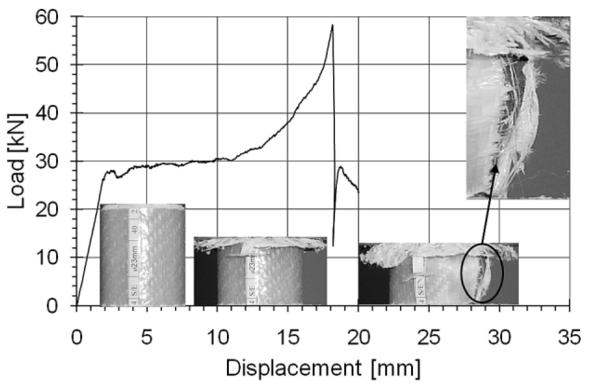

Fig. 7. Dependence load-displacement of G/E specimen of 2.0 mm wall thickness, 65.2% filling with elastomer of 40^o hardness

Elastomer filled composites show the crush mechanism very differently comparing to unfilled tubes, which are crushed by the layers bending mode. In the first phase when load increases the filled specimen is crushed by the layers bending mode as in the case of an empty tube (cf. thumbnails in Fig. 7). The ultimate crush occurs by crack along the side surface of the tube. In the case of 100% filled tubes a crack appears for about 2–4 mm of displacement (tube shortening), depending on the filler hardness. Generally, as the hardness increases the crack occurs faster and shortening of the tube is small as shown in Fig. 8. As filling degree decreases, shortening is more significant and layers bend simultaneously outside the tubes and inside the perforations in the elastomers (if possible). In some points of the crush progress inside present bend layers divide from the tube. In Figs. 9 and 10 separated inner fragments are presented next to the main tube.

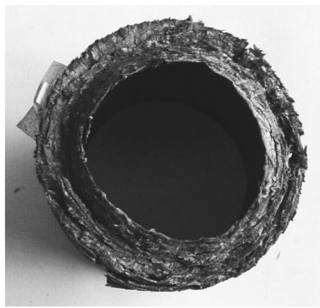

Fig. 8. C/E tube 100% filled with elastomer of 70°ShA

Fig. 9. C/E tube 73.4% filled with elastomer of 60°ShA

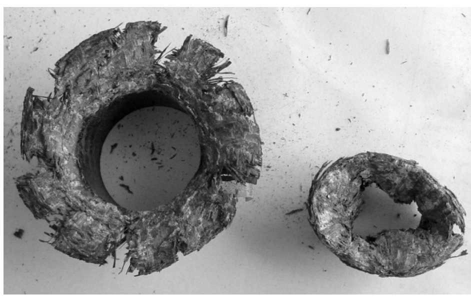

Fig. 10. C/E tube 36.8% filled with elastomer of 90°ShA

4. Conclusions

Taking into consideration the results of experimental investigations of the G/E and C/E tubes filled with elastomers it can be concluded that:

- Filling the tubes with elastomers causes different effects depending on the tube filling degree. The approximations of results show that EA increases to the degree of filling about 22 per cent, however over this degree EA significantly decreases, that can be easily seen from the presented test results in Fig. 6 a) and b);
- EA of specimens filled with elastomers increases significantly along with the tube wall thickness growth, similarly as in the case of the specimens without filling;
- The energy absorption studies confirmed that hardness insignificantly influences EA;
- Taking into account the same degrees of filling the tubes with elastomers, EA was proved to be greater for the tubes made of C/E composites than in the case of the tubes made of G/E composites. This is due to the greater strength of C/E composites.

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