

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

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Abstract. The use and the combination of new, high efficient materials for crashworthiness is of great interest nowadays. Foamed materials are commonly used to increase efficiency of composite materials. Based on the results obtained by Brachos and Douglas, it can be concluded that the sum of the energy absorption capabilities of the foamed filling and unfilled composite tubes is smaller than the energy absorbed by the tubes filled with the same filling. The paper presents the results of the experimental investigations into the influence of filling the tubes with different materials on the impact energy absorption capability. The tube shaped specimens made of epoxy composite, reinforced with carbon or glass fabrics were filled with foamed aluminium or foamed poly(vinyl chloride). It was proved that the foamed materials increase the energy absorption and the absorbed energy of the tubes filled with foams is greater than the sum of the energy absorbed by the composite tube without filling and the foamed material itself investigated separately, when the wall thickness is more than 2 mm. The investigations of the filled tubes with the thickness of walls equal to 1 mm showed lower absorbed energy values because the crushing force had decreased during the crush. The investigations were executed to show what are the effects of filling composite energy absorbing elements in the shape of tubes with foamed materials. Additionally, influence of tube wall thickness and crush mechanism were studied.

Key words: mechanical properties, absorbed energy, polymer composites, foamed materials, 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. Composites are widely used as materials for energy absorbing elements, mainly due to their very high absorbed energy with respect to the mass ratio. Worldwide studies are carried out to increase the performance of composite structures by using additional materials. The advantage of filling composite tubes with the foamed materials results from the tendency of the stable (progressive) crush induced by the lack of local buckling of tube walls. This problem was studied by Brachos and Douglas in [1]. Based on the results obtained by them, it can be concluded that the sum of the energy absorption capabilities of the foamed filling and unfilled tubes is smaller than the energy absorbed by the tubes filled with the same filling.

The investigations of glass fibre reinforced polyester tubes and the hybrid aluminium – composite tubes, filled with foamed aluminium, on absorbed energy are presented in the paper [2]. The influence of different density filling: 0.27 g/cm^3 , 0.35 g/cm^3 , 0.43 g/cm^3 of closed-cell foamed Al on the static axial load was studied. The hybrid and composite tubes with and without filling were examined. The filling of the tubes causes the absorbed energy (EA) growth, but it was found to be ineffective in increasing the crushing loads of the composite tubes over the sum of the crushing loads of empty composite tubes and foams. The Specific Absorbed Energy (SEA) decreased. However, a foam filling stabilized

the composite progressive crushing mode. The foam filling of hybrid tubes however resulted in axial splitting of the outer composite tube due to the resistance imposed by the foam filler to Al tube inward folding and hence it was ineffective in increasing a crushing load, and SAE values over those of empty hybrid tubes.

The experimental research under an axial compression load of hybrid tubes made of aluminium wrapped with an epoxy composite reinforced with glass fibres was presented in the paper [3]. The tubes without filling and filled with foamed epoxy resin were investigated. The composite fibre orientation was $\pm 45^\circ$ or $\pm 75^\circ$ in relation to the specimen axis. The circular and square cross sections were tested. The maximum failure force as well as absorbed EA and SEA were obtained.

The energy absorption investigations of composite square cross-section tubes with aluminium and polyurethane foams during an axial compression test are described in the paper [4]. The failure mechanisms in the macroscopic scale were examined and analysed. The behaviour and the contribution of filling materials to the tubes crashworthiness were investigated, in order to determine the functional and financial efficiency. The main advantages of aluminium foam in comparison to the polyurethane foam was: greater energy/mass and energy/volume absorbing ratio, better stabilization of the tube. Metal foams absorb the crash energy in a completely plastic way, converting it into heat, while polymeric foams behave elastoplastically, retransferring a large amount of kinetic energy back to the crashing system. The main compensations of

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polyurethane foam are: lower price and it is easily processed as it is a softer and less dense material.

The paper [5] describes both the studies on the sense of using the energy absorbing elements in the shape of cones filled with the foamed materials and their application in the protective vehicle constructions in order to improve their capability to absorb an impact energy, thereby increasing the passengers' safety during accidents. The effect of the additional energy absorbing structure was studied for the specimens of the different tube wall thickness and different density of the foamed material. The experiment analysis showed that the additional energy absorbing structures are economically cost-effective as well as they increase the energy absorption capability of the structure, hence the passengers' safety level is also improved.

The results of the investigations of a sandwich hybrid structure made of the composite beams and applied in a rail wagon structure were described in the paper [6]. The absorbed energy was determined during the axial compression tests. The system response and the shield failure mechanism were defined. Both the type of the failure and the energy absorption character of the compressed elements of the structure were analysed taking into account the mechanical and constructional parameters. The influence of different kinds of initiators on EA was also examined in the work, moreover, the paper [7] presents the experimental investigations into the energy absorbing structures. The comparison of the impact energy absorbing capability of sandwich structures with foamed PVC filling and the thin-walled structures with the core made of wavy coats was executed. The specimens were made of epoxy resin reinforced with glass mat, glass fabric and carbon fabric.

2. Object of investigation

The objects of the interest was performance of the specimens in the shape of tubes made of epoxy composites reinforced with carbon fabrics (C/E) and glass fabrics (G/E) filled with foamed material insertions. The scheme of example specimen is shown in Fig. 1.

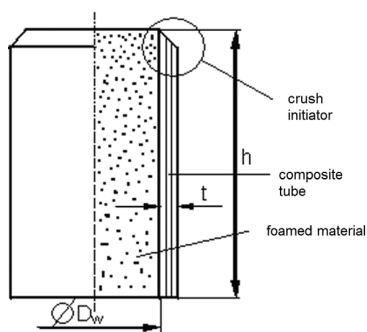


Fig. 1. Shape of the specimens used in the investigations

The tubes were made of the epoxy resin SARZYNA E-53 reinforced with the glass fabric STR-012-350-110 of 350 g/m² 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: 1.2; 2.0; 3.0 mm for G/E and: 1.2; 2.0; 3.0 for C/E. The composite tubes were manufactured with the use of a hand lamination method described in [9]. To ensure more accurate results, the specimens were sorted so that the constant thickness along the circumference of each specimen was assured. The mean value of each specimen wall thickness did not differ more than 10% from the nominal value.

The following kinds of foams were used as fillers: foamed poly(vinyl chloride) PCHW-1-115 (foamed PVC) and foamed aluminium named ALPORAS composed of ~97% Al, ~1.5% Ca, ~1.5% Ti (foamed Al). In the paper [8] both elastic and strength moduli of foamed poly(vinyl chloride) (PCHW-1-115) were investigated for different load cases.

Three groups of specimens were prepared for the investigations. The cylindrical specimens made of foamed aluminium were stuck into the tubes of the first group with the use of epoxy resin. The diameter of the specimens was equal to the inner diameter of the given specimen. The cylinders made of foamed poly(vinyl chloride) were stuck into the tubes of the second group in the same manner. The third group consisted of the composite tubes without filling.

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. EA was calculated from the following formula:

$$EA = \int_0^{l_1} Pdl, \quad (1)$$

where l_1 is shortening of the specimen.

The investigation results for tubes made of G/E and C/E composites of different tube thicknesses and filled with foamed Al or foamed PVC are presented in Table 1. The results were averaged from three the most representative tests performed on the specimens of the same kind.

Figures 2–5 present the crushing load analysis for G/E and S/E specimens of different wall thicknesses filled with examined foams compared to empty tubes and foamed materials investigated separately. Each graph includes four curves. The curve no.1 represents crushing load of foamed material (PVC in Figs. 2 and 5 or Al in Figs. 3 and 5). The curve no. 2 is for a composite without filling (G/E in Figs. 2 and 3 or C/E in Figs. 4 and 5). The dependence number 3 is the algebraic sum of ordinates from the graphs 1 and 2, and finally 4 is a composite specimen filled with a given foam.

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Table 1
 Investigation results for tubes made of G/E and C/E composites of different tube thickness and filled with foamed Al or foamed PVC

Composite	Foamed material	Tube wall thickness	Tube mass	Total weight	EA	SEA	ΔEA	ΔSEA
		[mm]	[g]	[g]	[kJ]	[kJ/kg]	[%]	[%]
G/E	No filling	1.2	12.7	12.7	0.35	27.56	-	-
G/E	No filling	2.0	18.8	18.8	0.53	28.19	-	-
G/E	No filling	3.0	32.1	32.1	0.97	30.22	-	-
G/E	Al	1.2	12.6	26.3	0.44	16.73	25.7	-39.3
G/E	Al	2.0	19.4	33.1	0.75	22.66	41.5	-19.6
G/E	Al	3.0	32.7	46.4	1.36	29.31	40.2	-3.0
G/E	PVC	1.2	12.7	19.5	0.42	21.59	20.0	-21.6
G/E	PVC	2.0	19.4	26.2	0.75	28.68	41.5	1.7
G/E	PVC	3.0	32.5	39.3	1.34	34.14	38.1	13.0
C/E	No filling	1.8	17.5	17.5	0.81	46.29	-	-
C/E	No filling	2.8	21.2	21.2	0.94	44.34	-	-
C/E	No filling	4.0	32.1	32.1	1.55	48.29	-	-
C/E	Al	1.8	17.9	31.6	0.89	28.16	9.9	-39.2
C/E	Al	2.8	22.6	36.3	1.30	35.81	38.3	-19.2
C/E	Al	4.0	33.5	47.2	1.90	40.25	22.6	-16.6
C/E	PVC	1.8	18.0	24.8	0.87	35.15	7.4	-24.1
C/E	PVC	2.8	21.9	28.7	1.25	43.63	33.0	-1.6
C/E	PVC	4.0	33.5	40.3	1.87	46.46	20.6	-3.8
	Foamed Al	-			0.041	5.5		
	Foamed PVC	-			0.046	11.3		

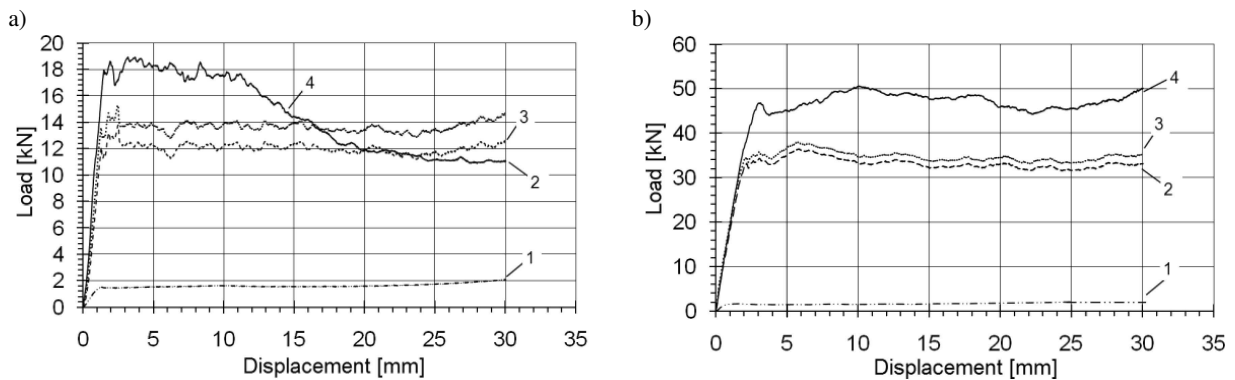


Fig. 2. Load-displacement dependence for G/E specimen of a) 1.2 and b) 3.0 mm wall thickness and foamed PVC material examined together and separately

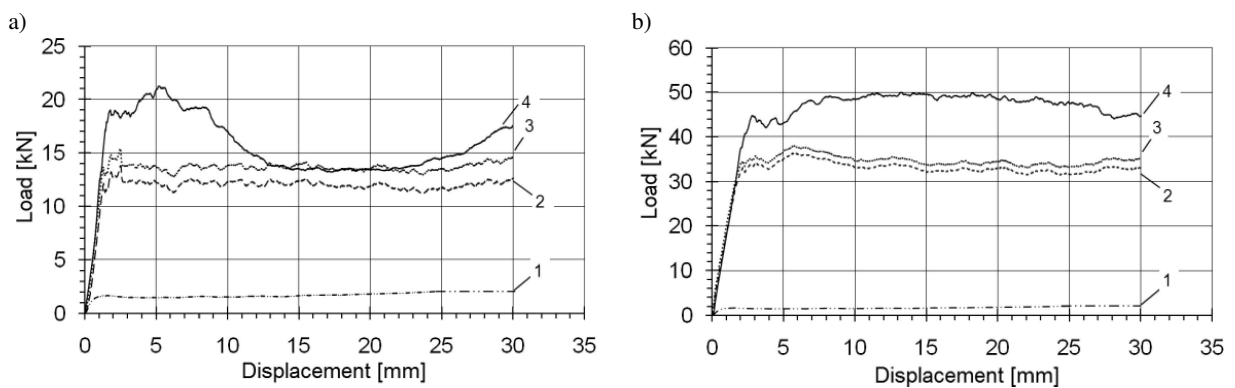


Fig. 3. Load-displacement dependence for G/E specimen of a) 1.2 and b) 2.8 mm wall thickness and foamed Al material examined together and separately

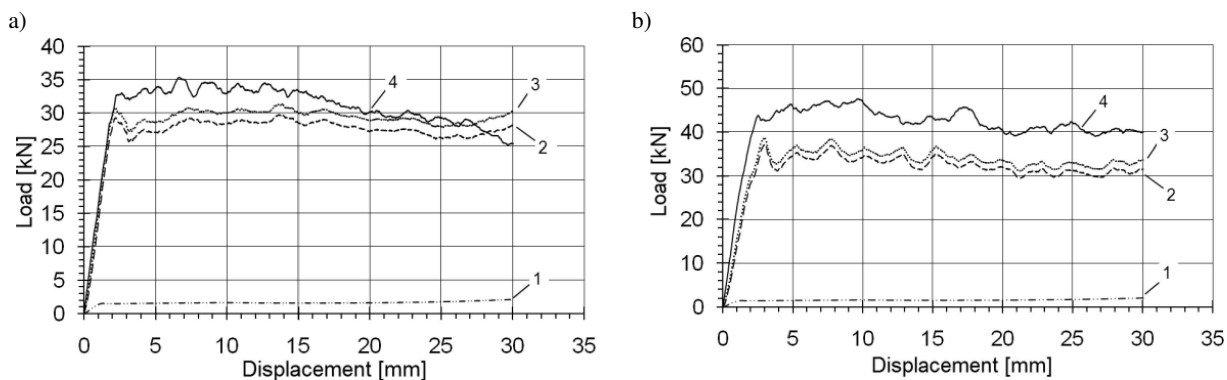


Fig. 4. Load-displacement dependence for C/E specimen of a) 1.8 and b) 2.8 mm wall thickness and foamed PVC material examined together and separately

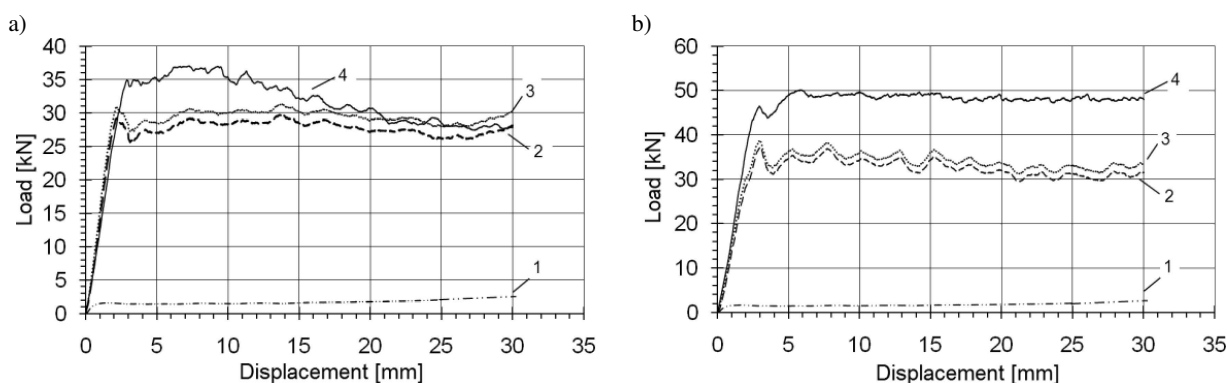


Fig. 5. Load-displacement dependence for C/E specimen of a) 1.8 and b) 2.8 mm wall thickness and foamed Al material examined together and separately

When the wall thickness is over 2 mm, the tubes filling causes a significant EA increase. This effect is illustrated in Figs. 2–5b) – curve 4. It can be concluded that the sum of the energy absorption capabilities of the foamed filling and unfilled tubes is smaller than the energy absorbed by the tubes filled with the same filling. These observations are similar to the results presented in [1]. However, at the small wall thickness (less than 2 mm), the second failure pattern occurs. During the compression of the tubes filled with foamed materials, their swelling occurs producing the pressure on the inner surface of the tubes. It results in the circumferential stresses arising on the tube outside surface. These stresses lead to the premature specimen crush. It is confirmed by the decreases of the failure force in the relationships presented in Figs. 2–5a) – curve 4. However, there is no force decrease for the tube of small thickness without filling, as shown in Figs. 2–5a) in curve 2. These curves show the flat progress of the load for the specimens without filling materials.

The energy absorption performance of the composite-foam material hybrid was determined from the experimental results compared in Table 1. Absorbed Energy and Specific Absorbed energy were analysed. Last columns contain EA and SEA per cent difference in relation to unfilled specimens with corresponding wall thicknesses. On the two last bottom lines EA and SEA of foamed materials are presented.

Both foam materials increase the EA capacity of the investigated composites. The foam filling of G/E composite tubes

causes greater EA increase than in the case of C/E composite tubes. Thick C/E tubes gain about 20.6–38.3%, while thick G/E tubes – 38.1–41.5%. It is caused by larger failure strains of epoxy composites reinforced with glass fibres although the tension strength of C/E composites (circumferential stresses) is larger than the strength of G/E composites. The EA increase of the thin tubes is significantly smaller (especially C/E).

The foamed Al improves absorbed energy better than foamed PVC, which is clearly seen in the case of carbon/epoxy tubes with small thicknesses, where the energy growth difference is about 34% per cent. The foamed Al has greater elastic modulus, therefore its stiffness is greater than in the case of foamed PVC, which results in lower pressure on the tube inner surface as well as in the lower circumferential stresses. In the case of the thicker tubes the EA growth difference is not so significant and it is contained within the range of 0 to 16%.

While the EA of filled tubes increases, SEA decreases because of the mass of additional filling materials. The foamed Al is heavier so the SEA decrease is higher than in the case of foamed PVC. SEA of the thinner tubes suffers the most.

All the examined specimens were crushed by the layers bending mode. The specimens without filling were crushed by the layers bending into inside and outside of the tube. However, the specimens filled with the foamed materials were crushed by the tube wall bending into outside only. Figures 6 and 7 present the photos of the crushed specimens with different filling configuration – G/E and C/E respectively.

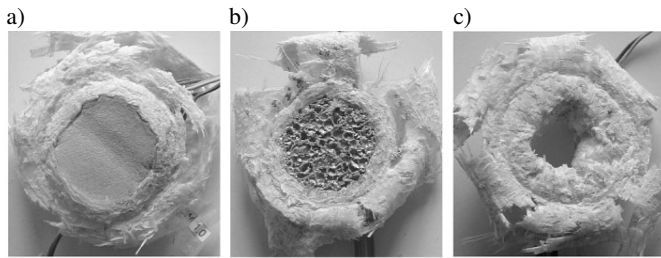


Fig. 6. Photos of the crushed G/E specimens: a) filled with foamed PVC, b) filled with foamed Al, c) without filling

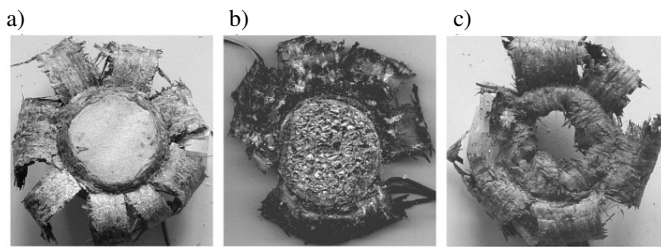


Fig. 7. Photos of the crushed C/E specimens: a) filled with foamed PVC, b) filled with foamed Al, c) without filling

Papers [10, 11] show cases where the catastrophic crush of the specimen occurred. In [12] authors describe the role of the crush initiator and the specimen shape in the progressive crush. When the catastrophic crush occurs, it causes the entire specimen to lose its energy absorbing features. The energy absorbed EA is very low because only a small part of the whole volume of the specimen is crushed. Our studies show that the catastrophic crush is more likely to appear in the case of a glass mat reinforcement and very thin-walled specimens. In the case of fabric reinforced specimens, in the shape of tubes, in which the fabric fibres lie circumferentially, the catastrophic crush is less likely to be present and refers mainly to tubes with wall thicknesses less than 2 mm, also when the specimen has some defects. The results for specimens which crushed catastrophically are not included in this work.

4. Conclusions

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

- In the energy absorbing tests, filling the tubes with foamed materials increases EA, when the wall thickness is over 2 mm, however the tubes of the thickness below 2 mm are destroyed by the additional circumferential stresses. Load decreases during the crush progression and consequently, the EA growth is significantly lower.
- The C/E composite tubes are more sensitive to additional circumferential stresses originated from the pressure of foamed materials due to smaller failure strains than in the case of epoxy composites reinforced with glass fibres. Foamed Al improves absorbed energy better than foamed PVC. The kind of the filler slightly influences EA despite significantly different mechanical properties of foamed materials (foamed Al and PVC) which were used to fill the

tubes. In the case of the thicker tubes the growth differences is contained within the range of 0 to 16%.

- The influence of wall thickness of filled tubes on EA is significant. For the examined C/E and G/E specimens filled with foamed Al or PVC, the EA increases 2–3 times at the wall thickness growth within the range 1 mm to above 2 mm. This occurs due to additional circumferential stresses, caused by a compressed foamed material, which are more significant in the case of thinner tubes.
- The influence of filling the tubes with foamed materials is significant. However, the foamed materials increase total mass of the filled specimens which leads to SEA decrease.
- Generally, both filled and unfilled energy absorbing elements crushed in progressive way by layer bending and defragmentation.

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