DOI: 10.24425/amm.2020.132789

P. KACZYŃSKI[1], J. KARLIŃSKI[1], M. HAWRYLUK[1*]

EXPERIMENTAL AND NUMERICAL STUDIES OF THE BEHAVIOR AND ENERGY ABSORPTION OF FOAM-FILLED CIRCULAR TUBES

Following paper is focused on experimental and numerical studies of the behavior and energy absorption for both: quasi-static and dynamic axial crushing of thin-walled cylindrical tubes filled with foam. The experiments were conducted on single walled and double walled tubes. Unfilled profiles were compared with tubes filled with various density polyurethane foam. All experiments were done in order to possibility of the safety of the elements absorbing collision energy which can applied in car body. The dynamic nonlinear simulations were carried out by means of PAM-CRASH™ explicit code, which is dedicated calculation package to modelling of crush. Computational crushing force, plastic hinges locations and specimens post-crushed geometry found to be convergent with the real experiments results. Conducted experiments allowed to draw conclusion, that crashworthiness ability is directly proportional to foam density. The investigation of the experimental data revealed, that double walled tubes have greater energy absorbing ability. A proposed investigation enable to analyze and chosen of optimal parameters of these elements, which can use in automotive industry as an absorption energy components.

Keywords: numerical simulation; single and double-walled tubes; polyurethane foam; energy absorption; dynamic axial crush

1. Introduction

The use of thin-walled tubular structures as an energy absorbing elements designed to improve passive safety, especially in automotive industry, has been studied over three decades. The great majority of research works is focused on the influence of the structure material mechanical properties, absorber geometry and specific deformation mode on specimen crashworthiness parameters. The comprehensive review of existing experiments results can be found in articles [1-3].

Much attention is recently paid to the thin-walled structures filled with cellular materials. Papers concerning polyurethane foam, aluminum foam, honeycomb structures, etc. can be easily found [4-13]. For example in paper [5] was investigated the axial crush of the polyurethane foam-filled aluminum cylindrical tubes with shallow spherical caps (combined thin-walled structures). Non-linear dynamic finite element analyses were carried out to simulate the quasi-static tests, for which obtained satisfactory agreements. Also was analyzed an influence of important parameters such as semi-apical angle, length of cylindrical and spherical caps, diameter and density of foam filler. While in work [8] authors were developed the metamodels in were constructed to predict the crashworthiness criteria of specific energy absorption and peak crushing force under multiple load cases. Work [10] showed the results of a pioneering investigating for the newly developed polymer-aluminum alloy hybrid foams as fillers of thin-walled square tubes, as an alternative to the conventional closed-cell aluminum foams. The reason for this state is mechanical properties of cellular materials, which can undergo large deformation and remain in low state of stress at the same time. The densification level corresponding to the yield stress is in the range of 60-90% [14-17]. In work [15] was shown that the maximum of the efficiency identifies the condition For optimal energy absorption of the foam, while the maximum stress reaches a value limited through other design considerations. Next by using the efficiency diagram method, the authors were developed the synthetic diagrams, which were useful to characterize the material, what supporting the design of energy absorbing components. In paper [16] was present research concerned of the mechanical properties of a variety of hybrid foams with both, particulate and interpenetrating microstructures. Based on the experimental and numerical results, which were agreement, showed that the hybrid foam concept provides the opportunity to design lightweight cellular bodies with effective mechanical properties in a wide range. The main improvements resulting from simultaneous use of energy absorbing structures and cellular materials are:

[1] WROCLAW UNIVERSITY OF SCIENCE AND TECHNOLOGY, 6 ŁUKASIEWICZA STR., 50-371, WROCŁAW, POLAND

* Corresponding author: marek.hawryluk@pwr.edu.pl

interaction effect between filler and tube wall and compression of the filler during crushing process. Mentioned features provide significant improvements to the crushing process [18].

The positive effect of filling cylindrical tubes with low-density polyurethane material has been initially studied by Thornton [19]. A considerable specimen strengthening effect was observed and empirical formula for the mean crushing load was derived. Research focused on the impact of the cellular material filling on the crushing behaviour of steel square tubes under quasi-static and dynamic conditions was performed by Reid [20]. The following conclusion was drawn: the mean crushing load and the plastic folding wavelength depend on the foam density. Similar effect has been noticed by Abramowicz and Wierzbicki [4]. General method allowing researchers to predict the crushing characteristics of foam-filled columns was developed by mentioned authors. Thereafter, the behaviour of aluminium thin-walled cylindrical tubes filled with polystyrene foam were analysed by Toksoy and Güden [21]. Analysed specimens deformation modes were: axisymmetric (concertina) or diamond. While more and more experimental results are published in papers and databases, the new, precise data supporting optimal structure design are needed.

The main objective of following paper was to study the energy absorption and behaviour of circular single-walled and double-walled foam-filled tubes subjected to dynamic, axial crushing. Unfilled profiles were compared with tubes filled with various density polyurethane in the respect of their crashworthiness and value of crushing force. The dynamic non-linear simulations were carried out by means of PAM-CRASH™ explicit code.

2. Test procedure and material properties

Two types of profiles were used in this study: single-walled and double-walled specimens (Fig. 1). Single-walled tubes were cut out from commercial mild steel tubing (R35) 60 mm in diameter and 1.0 mm thick. In case of double-walled specimens outer material remained the same, while inner profile was cut out from aluminium solid drawn tube (PA38) 30 mm in diameter and 1.0 mm thick. The D/t ratio of steel and aluminium tubes amounted correspondingly to: 60 and 30. Total length of single-walled and double-walled specimens amounted 200 mm. Dimensions were selected in accordance to previous results [22], which showed that for these ratios, steel tubes should deform in diamond mode and aluminium tubes should collapse in axisymmetric (concertina) mode. The yield stress and ultimate strength of R35 steel were determined respectively as 366 and 482 MPa. Following parameters in case of PA38 aluminium amounted to: 231 and 243 MPa.

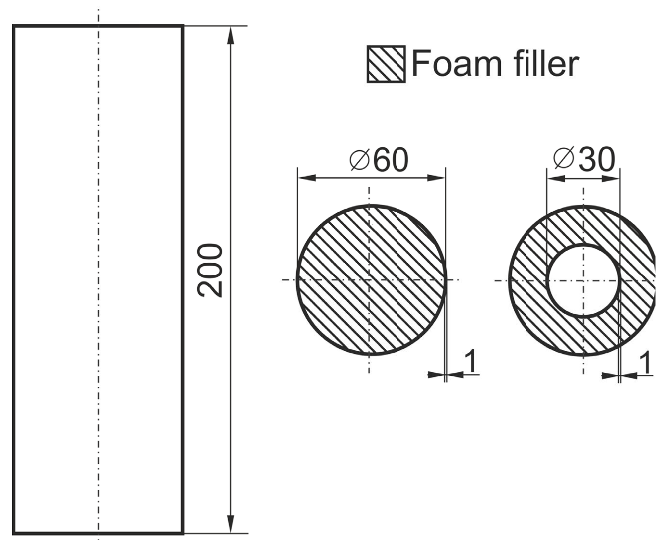

Fig. 1. Geometry of tested specimens

The polyurethane foam (ISO foam RR 3040) was used to fill the tubes. After the mass of foam reagents required to obtain given density was poured into a tube, its ends were sealed to prevent the expanding foam from free discharge. Descripted methodology allowed to obtain average densities of polyurethane foam used as filler at the level between 50 and 240 kg/m^3. Next step of specimens preparation was facing them in order to obtain flat ends normal to specimen longitudinal axis.

3. Preliminary experimental results

The mechanical characteristics (stress-strain curves) of foams with different initial densities were obtained by axial compression tests of cubic specimens with dimensions of 30×30 ×30 mm. Polyurethane foam quasi-static stress-strain compression curve is depicted in Fig. 2. The mechanical properties is characterized to some extent by horizontal plateau stress σ_f, which depends on the foam density. It was evaluated by the authors of following paper as average stress at 0.5 strain.

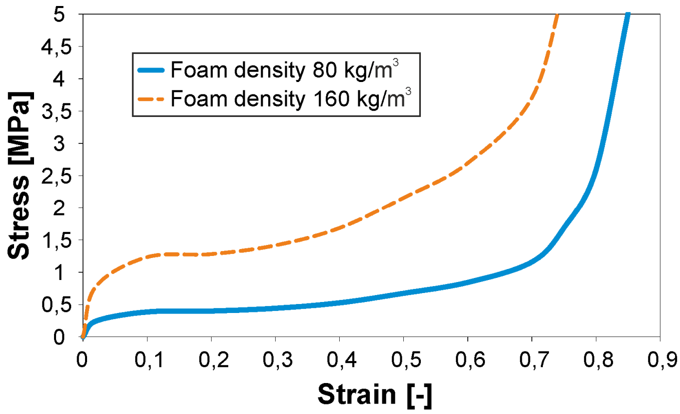

Fig. 2. Stress-strain curve of used polyurethane foam

3.1. Experimental tests set-up

The impact testing system (ITS) (Fig. 3) consisted of: gravity drop hammer, laser-grating-photoelectron (LGP) recording system for crushing distance monitoring and data acquisition system. A hammer ram mass amounted to 206 kg.

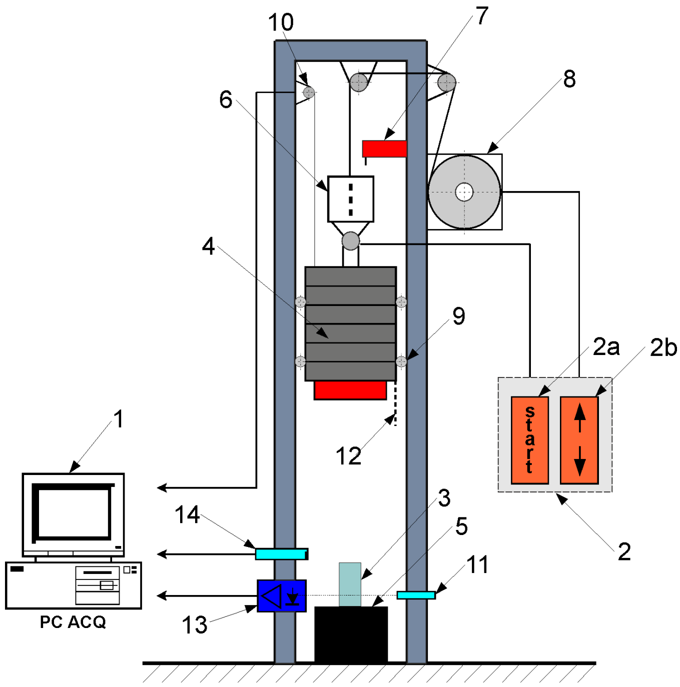

Fig. 3. Dynamic crushing test stand: 1 – PC data acquisition system, 2 – operator panel, 2a – electromagnet release button; 2b – position adjustment buttons, 3 – specimen, 4 – Tup weights, 5 – anvil, 6 – electromagnet, 7 – limit switch, 8 – power winch, 9 – rolling bearing, 10 – rate generator, 11 – laser transmitter, 12 – grating, 13 – photodiode circuit, 14 – distance release switch

Its bottom surface as well as upper anvil surface were polished in order to decrease the friction coefficient. The ram was mounted in a 4,5 m high tower at specific height corresponding to 6.24 m/s impact velinetic energy of approximately 4 kJ. The ram was being released by means of electromagnetic hook. The grating was fixed to the moving element – the ram. Two laser emitters as well as the special photodiode circuit was fastened to the stationary element – lower part of the drop tower frame. While impact tests were being conducted the signal generated by laser transmitter, after optical pattern transition, was being measured by photodiode with amplifier and subsequently stored in a PC by National Instruments data acquisition system. The data sample rate was established as 100 kHz per channel (10 µs per channel). Detailed description of the data acquisition system can be found in papers [23,24].

3.2. Axial crushing parameters

Several fundamental descriptors of crushing process, defined on the basis of load-displacement curves, are analyzed in the next part of this paper. They were used to evaluate specimens crashworthiness efficiency.

- **$P_{\max}$ (maximum load):**

  The first load value peak. It is associated to the force level required to initiate crushing process. After reaching this value first plastic fold is created and deformation process is started.

- **P_m (mean crushing force):**

$$P_m = \frac{1}{\delta_f}\int_0^{\delta_f} P(\delta)\,d\delta = \frac{W}{\delta_f} \tag{1}$$

  where: W – total energy dissipated by the specimen, δ_f – specimen upper part maximum displacement.

- **δ_{rel} (relative crushing distance):**

$$\delta_{rel} = \frac{\delta_f}{l_0} \tag{2}$$

  where: l_0 – initial length of the specimen.

- **W_s (specific energy absorption):**

  This was another important parameter used for specimens evaluation. The reason for using it was necessity to take specimen total mass into consideration. It was defined as the quotient of the total energy absorbed to the specimen mass:

$$W_s = \frac{W}{m} = \frac{P_m \cdot \delta_f}{l_0} \tag{3}$$

where: m – specimen total mass.

4. Experimental results and discussion

Representative pictures of crushed specimens are depicted in Fig. 4. Specimens cross-sections are depicted in Fig. 5. Two main deformation modes were identified: diamond (asymmetric) and concertina (axisymmetric). The deformation mode is

Fig. 4. Typical collapse modes of single-walled and double-walled tubes: a – diamond (asymmetric), b – concertina (axisymmetric), c – mixed

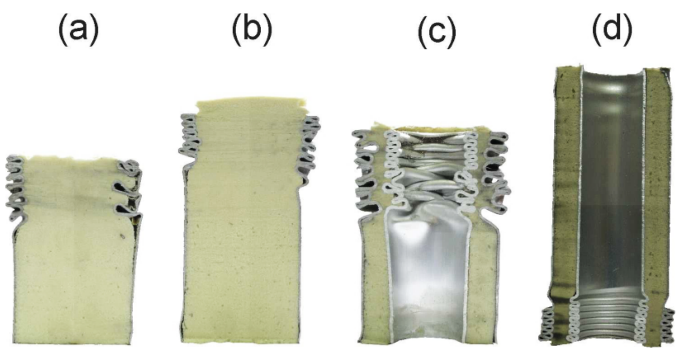

Fig. 5. Typical section view of post-crash specimens: a) single-wall 50 kg/m^3 foam density, b) single-wall 120 kg/m^3 foam density, c) double-wall 50 kg/m^3 foam density, d) double-wall 120 kg/m^3 foam density

an effective indicator of energy efficiency, which result from interdependence of plastic folds formation and energy dissipation mechanism. The first mode occurred in case of empty and low density foam-filled specimens (Fig. 4a). The second mode (Fig. 4b) occurred for specimen with foam density $\rho > 80$ kg/m^3. Mixed deformation mode, e.g. two diamond folds, and four concertina folds, occurred for the filler density range 50-80 kg/m^3 (Fig. 4c). The axisymmetric mode of deformation guarantee progressive collapse, so it is preferred despite the fact, it has lower energy absorption ability.

The force-displacement curves of single-walled and double-walled specimens are depicted in Fig. 6. These function diagrams are characterized by a high force peak value followed by force value oscillations. Oscillatory course of the force function result from the specimen progressive buckling mechanism, i.e. formation of plastic folds (diamond or concertina). Moreover, the double-walled specimens with greater stiffness were characterized by higher force initial peak (Fig. 6b). It was most likely caused by simultaneous occurrence of inner and outer profiles force value peaks.

4.1. Mean crushing force

The influence of average foam density on mean crushing force P_m for single-walled and double-walled specimens is depicted in Fig. 7. Investigated parameters are directly proportional – value of the force increases with the foam density. Slope of a curve is almost identical in the case of the single-walled and double-walled specimens.

4.2. Relative crushing distance

The influence of average foam density on relative crushing distance for single-walled and double-walled specimens is depicted in Fig. 8. In both cases linear dependency can be observed. The calculated relative crushing distance decreases with the foam density. Because potential energy of the hammer used in all experiments was constant, lower relative crushing distance means higher energy absorption ability. In case of single-walled specimens investigated parameter decreased from 60% to 40% (for higher foam densities). The reduction of relative crushing distance is strictly connected to the behaviour of the filling material. Metal parts of the filled samples were shifted to the lower strain values. During progressive buckling some material was locked between the plastic folds (Fig. 5c). This region of the foam was in high stress state preventing the folds to contact each other. This was another cause of relative crushing distance decrease.

Foam density increase cause simultaneous decrease of the crushing distance and increase of the mean crushing force. This result in crashworthiness parameter increase. Experimental work

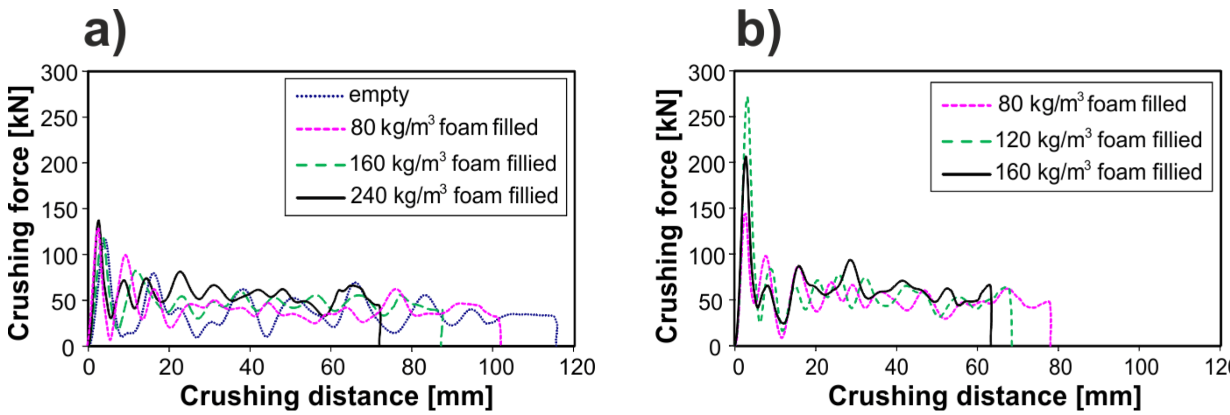

Fig. 6. The specimens crushing force as a function of crushing distance: a) single-walled specimens, b) double-walled specimens

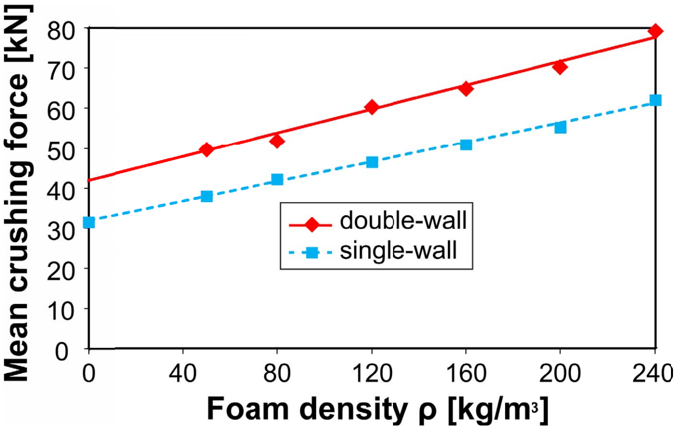

Fig. 7. The influence of foam density on mean crushing force

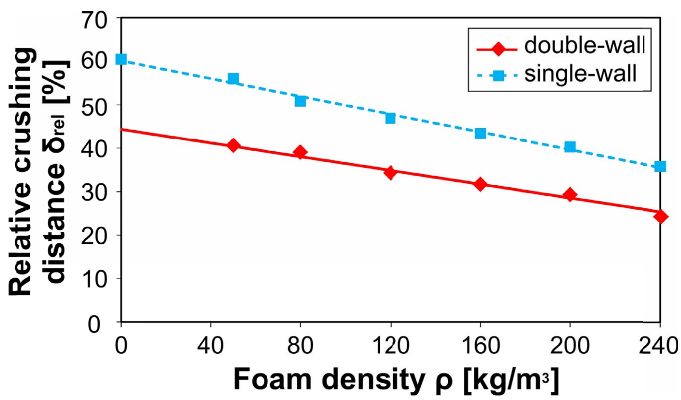

Fig. 8. Relative crushing distance as a function of foam density

focused on square aluminium solid drawn tubes filled with aluminium foam was conducted by Hanssen et al. [7]. They obtained similar reduction of the relative crushing distance.

4.3. Specific energy absorption

The influence of average foam density on the specific energy absorption was investigated. The results of experiment is briefly depicted in Fig. 9. The specific energy absorption increases by 20% in case of single-walled specimens filled with various density foam (50-240 kg/m$_3$). Similar effect was observed in case of double-walled specimens. They have higher specific energy absorption, even in case of global buckling which makes their usage as energy absorbers worth considering.

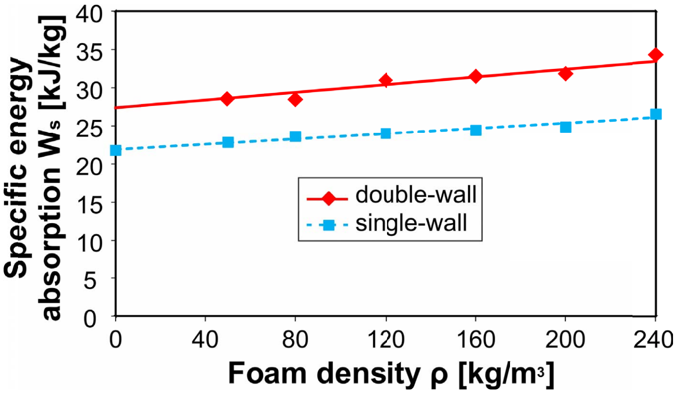

Fig. 9. Specific energy absorption as a function of foam density

4.4. Comparison with quasi-static tests

Quasi-static tests were carried out using MTS 810 universal testing machine. Tests were being conducted at movable cross-head constant speed of 10 mm/min. Tested specimens had been lubricated and placed between machine's platens in order to minimize losses caused by friction. Axial force and displacement were being digitally recorded using PC based data acquisition system.

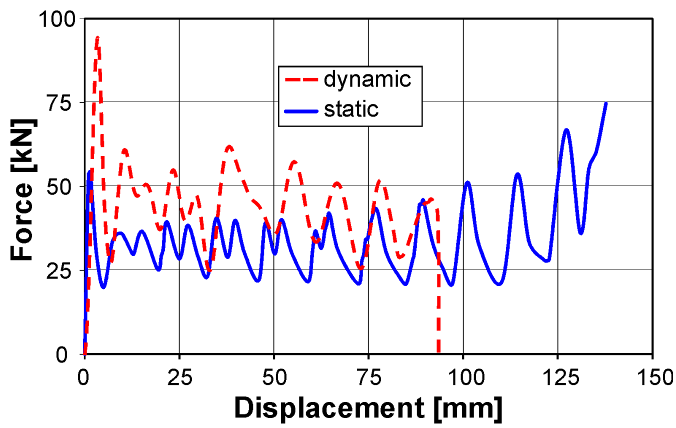

Fig. 10. Comparison of dynamic and static crushing forces for single-walled tubes, foam density 120 kg/m^3

The dynamic and static experiment results found to be similar. In both cases progressive deformation modes occurred. The value of force in case of dynamic crushing was usually higher (Fig. 10). During analysis of mean crushing force analogous situation was observed. Values were bigger in case of the dynamic tests, because of the internal forces and strain-rate hardening (Fig. 11).

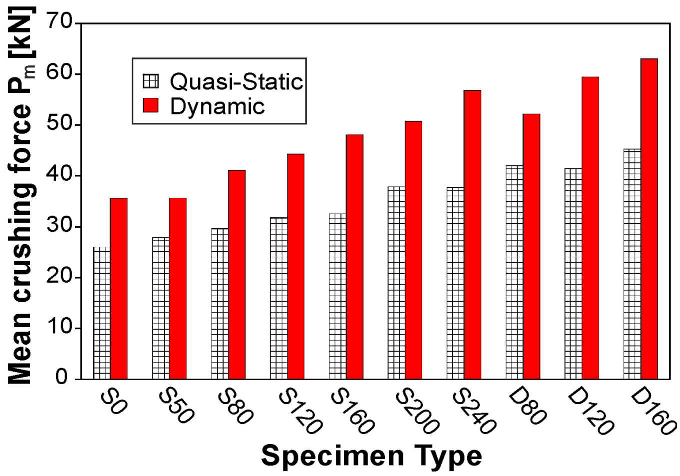

Fig. 11. Comparison of static and dynamic crushing force

4.5. Numerical simulations

The dynamic non-linear simulations were carried out by means of PAM-CRASH™ explicit code. The finite model was created by means of mesh generating module of I-DEAS™ system. Thin shell finite elements were used to digitize the solid drawn tubes. Digitization of foam was carried using 8-node solid elements [25,26]. The possibility of large foam deformation occurrence was reason for using solid elements selective reduced integration rule (with 8 deviatoric strain integration points and 1 volumetric strain integration points). The interaction between the specimen upper surface and the hammer ram was defined with the use of surface contact. Friction coefficient equal 0.25 was assumed in order to prevent specimen upper end from slipping out of ram lower surface. Self-contact of thin-shell elements was assumed frictionless. Mechanical properties of materials used during numerical simulations are presented in Table 1.

TABLE 1

The mechanical properties of the materials used in numerical simulation

Mechanical properties	Materials			
	Alfapoor RR3040	Alfapoor RR3040	Steel R35	Aluminum PA38
Density [kg/m^3]	80	160	7860	2700
Young's modulus [MPa]	6.28	21.17	$2.06 \cdot 10^5$	$6.90 \cdot 10^3$
Poisson's ratio	—	—	0.29	0.33
Yield stress [MPa]	—	—	366	231
Crushing strength of foam [MPa]	0.49	1.50	—	—

The numerical simulations were being stopped when the kinetic energy of hammer ram achieved the value of 0. The time step size equalled $3 \cdot 10^{-7}$ s. All simulations was being executed using Pentium Pc 3 Gh. Average simulation time was 14-20 h. Examples of numerical specimens deformation modes are depicted in fig 12.

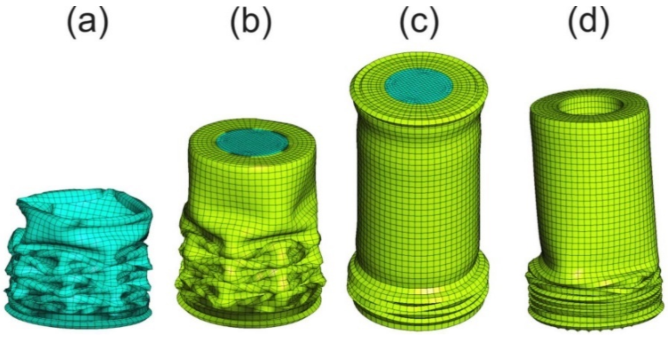

Fig. 12. Obtained deformation modes of tubes: a) empty, b) single-wall 80 kg/m^3 foam density, c) single-wall 160 kg/m^3 foam density, d) double-wall 80 kg/m^3 foam density

The results obtained by numerical simulations were carefully compared with real experiment in order to evaluate crashworthiness, deformation mode and crushing force predictions accuracy.

Fig. 13. Comparison of post-crash geometry of 160 kg/m^3 foam filled tubes: a) single-wall, b) double-wall

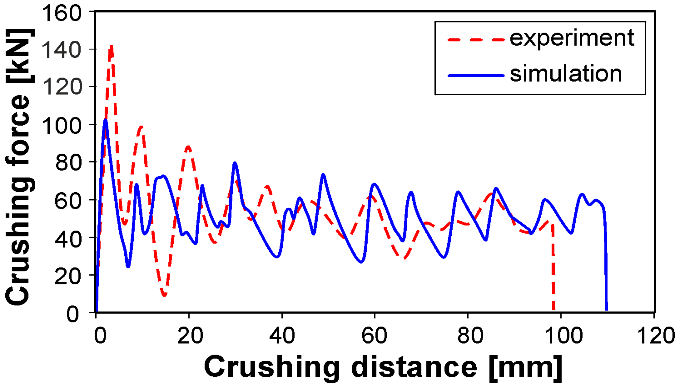

Fig. 14. Diagram of crushing force of double-wall specimens filled with 80 kg/m^3 foam

4.6. Comparison of numerical and experimental analysis

Comparison of the axial shortening and mean crushing force for single-walled and double-walled tubes is presented in Table 2.

Comparison of deformation modes obtained by experimental and numerical analysis are depicted in Fig. 13. Presented results clearly indicates convergence between them. In both cases, the tubes were progressively crushed by forming plastic folds on specimen both ends.

The comparison of crushing forces as a function of crushing displacement for experimental and numerical analysis is depicted in Fig. 14. The first load peak of the load was about 30% smaller in case of numerical simulation.

This fact could be explained by constant numerical model thickness of 1.0 mm (real thickness of solid drawn tubes varied from 1.05 to 1.20 mm). After the formation of first plastic fold, the value of crushing force oscillates around constant asymptotic value. This value can be defined as the tube mean crushing force characteristic P_m. Characteristics depicted in Fig. 14 seems to be convergent and the result presented in table 2 shows, that the value of mean crushing force was similar in both cases.

5. Summary

Dynamic axial crushing behaviour and crashworthiness of circular tubes (both single-walled and double-walled) filled with various density polyurethane foam were studied. Progressive buckling were observed for both: statically and dynamically crushed tubes. Two main collapse modes were identified: diamond (asymmetric) and concertina (axisymmetric).

Crashworthiness was studied in terms of collapse mode and foam density. The results clearly shows that the mean crushing force increase with an increase of the foam filler density.

TABLE 2

Comparison of experimental and numerical tests

Specimen	Foam density [kg/m^3]	Impact energy [J]	Axial displacement			Mean crushing force		
			Experiment [mm]	Simulation [mm]	Rel. error [%]	Experiment [mm]	Simulation [mm]	Rel. error [%]
R	0	4154	115	123	7.0	33.0	34.5	4.5
R80	80	4118	102	110	7.8	41.0	39.2	–4.4
R160	160	4121	87	87	0.0	48.1	48.0	–0.2
RR80	80	4134	78	84	7.7	49.7	52.2	5.0
RR160	160	4124	63	67	6.0	63.0	65.5	4.0

Further investigation of double-walled specimens revealed that they are able to absorb more energy than single-walled tubes. The described phenomenon results mainly from the presence of inner profile. Foam filler presence has minor influence.

The conducted finite element method simulations were compared to the experimental data in order to verify and validate the proposed numerical model. The numerical model developed during project realisation allows to predict behaviour of single-walled and double-walled tubes filled with foam. It also enables to specify following features: value of crushing force and mean crushing force, length of plastic wave and folding mode. Based on the above results, design of foam-filled energy absorbing elements can be efficiently analysed and optimised only with the use of numerical model. It consist of shell elements and cellular solid elements.

The general conclusion is that one can control the crashworthiness efficiency using foam fillers density in circular single-walled and double-walled aluminium tubes. However the efficiency improvements caused by the use of polyurethane foam is relatively small and causes the increase of mean crushing force which authors of this paper see as main disadvantage. Good accuracy of conducted FEA of dynamic crushing process gives opportunity to use presented method for virtual experiments. It allows to optimize tubes geometry and different fillers usage in order to mass minimization without decreasing of absorbed energy.

REFERENCE

[1] A.A.A. Alghamdi, Collapsible Impact Energy Absorbers: An Overview, Thin-Walled Struct. **39** (2), 189-213 (2001).

[2] N. Jones, Structural Impact, Cambridge University Press, United Kingdom (2012).

[3] S.R. Reid, Plastic Deformation Mechanisms in Axially Compressed Metal Tubes Used as Impact Energy Absorbers, lnternational Journal of Mechanical Sciences **35** (12), 1035-1052 (1993).

[4] W. Abramowicz, T. Wierzbicki, Axial Crushing of Foam-Filled Columns, International Journal of Mechanical Sciences **30** (3-4), 263-271 (1998).

[5] S. Mingming, W. Han, H. Hai, Axial and radial compressive properties of alumina-aluminum matrix syntactic foam filled thin-walled tubes, Composite Structures 226, UNSP, 111197, (2019).

[6] Y. Ru-yang, Hao Zhen-yu, et al., Experimental and theoretical investigations on axial crushing of aluminum foam-filled grooved tube, Composite Structures 226, UNSP, 111229, (2019).

[7] A.G. Hanssen, M. Langseth, O.S. Hopperstad, Static and Dynamic Crushing of Circular Aluminum Extrusions with Aluminum Foam Filler, International Journal of Impact Engineering **24** (5), 475-507 (2000).

[8] D. Fauzan, A. Shahrum, Optimisation and validation of full and half foam filled double circular tube under multiple load cases, International Journal of Crashworthiness **24** (4), 389-398 (2019).

[9] N. Abba, E. Seyed Ahmad, Foam-Filled Columns with Rectangular Cross-Section During the Flattening Process: Theory and Experiment, Iranian Journal of Science and Technology-Transactions of Mechanical Engineering **43** (1), 783-795 (2019).

[10] I. Duarte, L. Krstulovic-Opara, et al., Axial crush performance of polymer-aluminium alloy hybrid foam filled tubes, Thin-Walled Structures **138**, 124-136 (2019).

[11] M. Jahani, H. Beheshti, M. Heidari-Rarani, Effects of Geometry, Triggering and Foam-Filling on Crashworthiness Behaviour of a Cylindrical Composite Crash Box, International Journal of Automotive and Mechanical Engineering **16** (2), 6568-6587 (2019).

[12] Y. Wang, X. Zhai, Dynamic Crushing Behaviors of Aluminum Foam Filled Energy Absorption Connectors, International Journal of Steel Structures **19** (1), 241-254 (2019).

[13] D. Fauzan, Review: deformation and optimisation crashworthiness method for foam filled structures, Latin American Journal of Solids and Structures **16** (7), UNSP e213. (2019).

[14] M.R. Ashby, The Mechanical Properties of Cellular Solids, Metallurgical Transactions **14**A (9), 1755-1769 (1983).

[15] M. Avalle, G. Belingardi, R. Montanini, Characterization of Polymeric Structural Foams under Compressive Impact Loading by Means of Energy-Absorption Diagram, International Journal of Impact Egineering **25** (5), 455-472 (2001).

[16] L.J. Gibson, M.F. Ashby, Cellular Solids: Structure and Properties, Cambridge University Press, New York, Second Ed. (1997).

[17] J. Hohe, C. Beckmann, W. Boehme, An experimental and numerical survey into the potential of hybrid foams, Mechanics of Materials **136**, UNSP 103063, (2019).

[18] H.W. Song, Z.J. Fan, G. Yu, Q.C. Wang, A. Tobota, Partition Energy Absorption of Axially Crushed Aluminum Foam-Filled Hat Sections, International Journal Solids and Structures **42** (9-10), 2575-2600 (2005).

[19] P.H. Thornton, Energy Absorption by Foam Filled Structures (1980).

[20] S.R. Reid, T.Y. Reddy, M.D. Gray, Static and Dynamic Axial Crushing of Foam-Filled Sheet Metal Tubes, lntemational Journal of Mechanical Sciences **28** (5), 295-322 (1986).

[21] A.K. Toksoy, M. Güden, The Strengthening Effect of Polystyrene Foam Filling in Aluminum Thin-Walled Cylindrical Tubes, Thin-Walled Struct. **43** (2), 333-350 (2005).

[22] K.R.F. Andrews, G.L England, E. Ghani, Classification of the Axial Collapse of Cylindrical Tubes under Quasi-Static Loading, International Journal of Mechanical Sciences **25** (9-10): 687-696. (1983).

[23] P. Zając, M. Struś, S. Polak, Z. Gronostajski, A. Tobota, Z. Niechajowicz, J. Gronostajski, P. Wiewiórski, Measurement System of Crash-Test Experiments, Archives of Civil and Mechanical Engineering **4** (1), 5-23 (2004).

[24] A. Tobota, W. Olchowik, M. Domański, P. Wiewiórski, Measuring System for Investigations of Cash-Test Deformation of Samples, in Proceedings of the Technical Diagnostic of Systems and Devices National Scientific Conf. (2003).

[25] J. Karlinski, A. Iluk, Explicit Integration of Equations of Motion in Nonlinear Constructions Dynamics, in Proceedings of the Computer Aided Engineering International Scientific Conf. 2000.

[26] J. Karlinski, A. Iluk, Numerical Techniques of Resolving the Nonlinear Dynamics Problems, in Proceedings of the Computer Aided Engineering International Scientific Conf. 2000.