International Journal of Engineering & Technology, 7 (4.22) (2018) 6-11

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Crushing Behaviour of Filled Tubes Under Static and Dynamic Loading Conditions: A Review

Nurul Izzah AR[1]*, Salwani MS[1], Mohd Shahril M[1]

[1] *Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia*
**Corresponding author E-mail:izzahs78@yahoo.com*

Abstract

Crash box structure is one of the safety requirement that should be considered in vehicle design to ensure safety of the passengers. This paper was developed to summarize the simulation and experimental study that have been conducted regarding the energy absorption capability of a thin-walled tubes. The energy absorption structure can be made of metal or composite thin-walled tubes with variety configurations. These thin-walled structures were filled with foams, honeycomb or composite to enhance the energy absorption capability. A few types of foam-filled and honeycomb-filled with addition of composite to enhance the energy absorption were discussed in this paper. Trigger mechanism with foam-filled was also introduced to increase the energy absorption and protect the passenger during collision. Functionally graded thickness of wall and functionally graded density of foam were introduced in form of simulation study to investigate the effect of the graded configuration to energy absorption capability. In author's opinion, the most promising or more advantages filler among all that have been discussed is functionally graded foam which was recently the investigated using finite element simulation

Keywords: *Foam-filled structure; honeycomb filler; energy absorption capability; crashworthiness.*

1. Introduction

Safety requirements for passenger vehicle have encourages the continuous research in developing an efficient energy absorption devices. The energy absorption devices which is called crash box refer to component that can dissipated energy during collision to reduce damages to the passenger and high cost part in a vehicle[1]. Crash box is designed to be collapsed by absorbing energy from the crash prior to the other parts of the vehicle[2].
Thin-walled tubes subjected to axial loading condition has been used as a crash box as it can dissipate energy excellently. Application of thin-walled structures as crash box have led to existence of undesirable initial peak force and the fluctuation in force-displacement curve when subjected to non-axial loadings[3]. The initial peak force should be sufficiently low and the fluctuation should be in controlled manner to avoid the impact from causing injury to the passenger [4].
One of the approaches that have been examined by the researchers to enhance the crashworthiness and reduce instability of a structure was by filling the tubes with the material that has high energy absorption properties. Instead of having excellent energy absorption behaviour, the filler material should be lightweight enough to maintain the weight of the vehicle. Besides of that, interaction between the wall tube and the foam has increased the energy absorption capability and stabilizing the crushing response of the structure.[5] The addition of foam as filler material have increase the peak strength and energy absorption capacity compared to the sum of the empty tube and the foam separately[6][7]. The foam-filled tubes reduced buckling wavelength of the tube subjected to axial compressive force.
Metal honeycomb is a multi-cellular metal structure that has high value of strength to weight ratio. The commonly used metal honeycomb is aluminium honeycomb. Materials such as aluminium honeycomb and foam have attracted much attention from the researchers due to its properties that fulfil both energy absorption capability and lightweight criteria [4]-[5] [8]. Composite, cork and wood were other types of filler material that was next in line.
Foam can be defined as a lightweight cellular material that can be formed from dispersion of gas bubbles during forming process. It consists of open and closed cell. The compressive strength and energy absorption capability of a closed-cell foam were affected by the entrapped air during forming process [9].Basically, the material properties of foam were related to the relative density of the foam. There are a few types of foam such as metallic, polymeric and biomaterial foam. Type of metallic foam that is commonly used is aluminium foam. Other than that, polyurethane, polystyrene and polyethylene are types of polymeric foam that were chosen for their high strength to weight ratio and energy absorption capability. Balsa wood was biomaterial foam which was investigated for their capability to absorb energy due to dynamic loading condition.
Generally, the stress-strain curve of polymeric foam can be divided into three stages which are linear elasticity, a plateau and densification as in Figure 1.

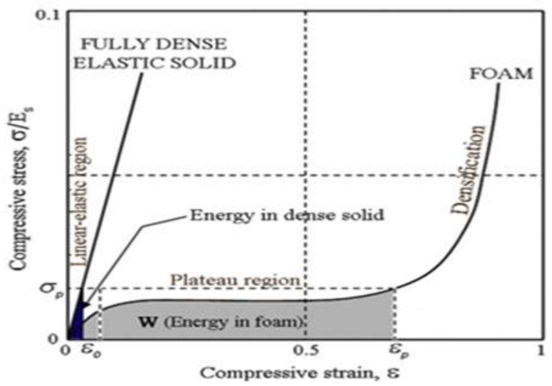

Fig. 1: Stress-strain curve of a foam

The compressive strength increases proportional to the strain rate during the linear-elastic region while the energy absorption indicates by the elongation in plateau region. Densification indicates by the strain hardening region shown that the foam loses its integrity and behaves as a solid material. Density of foam, microstructure and environmental temperature are the factors that influence the behaviour of foam[9]. When foam is subjected to dynamic loading, energy will be dissipated through cell bending, buckling or fracture along the plateau region in the stress-strain curve.

The crash box's performance under various loading conditions has been extensively studied. Due to frontal collision, the crash box experienced an axial impact loading condition. Quasi-static axial loading was conducted to imitate the low velocity frontal collision. Structures under oblique impact loading were also studied due to the real collision context which can be subjected to axial or oblique loads[1][10]. Under oblique loading, the structures may fail in either axial or bending mode[11]. Many researches have been conducted to study the behaviour of these two types of failure mode[1][12][13]. Concertina mode of deformation usually experienced by the thick-walled isotropic metal tubes while the thin-walled tube collapse by diamond mode [14]. The objective of this paper is to present an overview of the energy absorption characteristic of filled thin-walled structure under various loading condition. The main focus of this review paper is on the crashworthiness behavior of foam-filled, honeycomb-filled and composite reinforcement in the metal and composite structure. This paper is structured as follows, in the first section was introducing the thin-walled structure and the application of it in the vehicle design. The second section was focusing on the foam-filled structure which is divided into metal and composite outer tubes with various shapes. Then the third section was discussed on the thin-walled structure filled with honeycomb and the fourth section was describing the multi-tubes configuration of thin-walled tubes which is used to increase the energy absorption capability of the structure. The last section was summarized all the above.

2. Foam-Filled Thin-Walled Structure

In order to reduce or at least maintain weight of the vehicle, thin-walled tubes was filled with foam materials that can enhance the energy absorption of the structure. Instead of energy absorption behaviour of the foam itself, energy dissipation of the foam-filled structure was enhancing by the interaction of the tube wall with the foams. Force-displacement graph of the empty and foam-filled thin-walled structure was shown in Figure 2

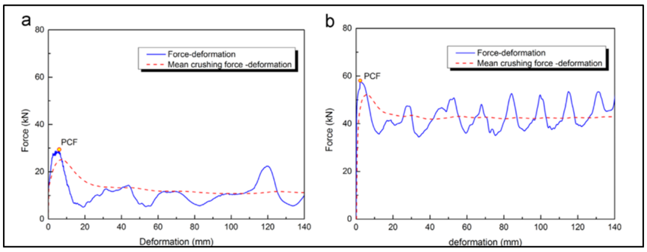

Fig. 2: Axial impact force vs. deformation in thin-walled structure for (a) hollow thin-walled structure and (b) foam-filled thin-walled structure.[15]

Among the materials that have been chosen by the researchers were metallic foam, polymeric foam and composite. These foams stabilize the metal or composite thin-walled structures in order to absorb more energy during crushing process.

2.1. Foam-Filled Metal Thin-Walled Tubes

The most commonly used material for energy absorber is metal thin-walled tubes. Metal thin-walled tubes were chosen because this type of material has high strength to weight ratio, thus the weight of vehicle can be maintained. Shapes of metal thin-walled tubes were summaries in table 1.

Table 1: Shapes of metal thin-walled tubes

Shapes of multi-tubes	Reference
circular tubes	[14],[15],[24][19],[20],[22],[23],[28]
square	[4],[21],[26],[27],[29],[35]
rectangle	[31]

Thinvongpituk et al [16] has compared the characteristic of PU foam-filled steel and aluminium with different density of PU. Mode of deformation for steel changed from concertina to mix mode while vice versa for aluminium. Although the energy absorption values of the foam-filled were increased, but the SEA values were decreased by increasing the density of PU when subjected to impact loading. In the other research, Thinvongpituk and Onsalung [17] has shown the contra results. The authors found that the deformation mode of PU foam-filled has changed to the concertina mode which is a symmetric mode instead of diamond mode during quasi-static loading. Instead of that, they have proved that energy absorption, peak force and mean crushing force of aluminium tube was increased by using the higher density of PU. The same conclusion was reported by Subramaniyan et al [18] in his paper. Besides, the authors investigated on PU composite foam-filled steel tubes. It was found that energy absorption capacity of PU foam-filled tubes was higher than the empty one and energy absorption capacity of PU composite foam-filled tubes were higher than the PU foam-filled tubes by up to 23.2%. An experimental investigations on PU foam-filled square tubes has been conducted by Hussien et al [4] has shown an agreement with Subramaniyan et al[18] study. The mean crushing force and SEA of PU foam-filled were 113% and 40% compared to the hollow tubes. This study also had shown that PU foam-filled showed better crushing behaviour than honeycomb filler.

Zhou [19] has reported on PU foam-filled of magnesium alloy sheet, extrusion and steel under bending load. For the steel beam, the SEA of the foam-filled was 6 times higher compared to the simple beam. As for magnesium extrusion and sheet, the SEA was 1.9 times higher than the empty one. SEA of magnesium sheet was 2 times higher compared to steel sheet for the same density of foam.

Niknejad et al [20] presented theoretical formula to predict crushing force and absorbed energy of PU foam-filled quadrangle tubes by considering the interaction effects between the tube wall and the foam and then conducted an experiment to verify the theoretical analysis. . From the experimental measurement, the formulas have been proven to be used for different materials and size of tubes. To expand the authors' theory, they then performed quasi-static test on PU foam-filled circular aluminium tubes [21]. For the empty tubes, the energy absorption of the larger diameter is less compared to the smaller diameter. While for the foam-filled tubes, the larger diameter tubes gained more energy absorption compared to the smaller one. Mahdi Abedi et al[22] studied on PU foam-filled square and rectangle column subjected to axial loading. Formula to predict the instantaneous folding force, maximum folding force and absorbed energy of the metal column were derived and verified with experimental study.

Movahedi and Linul [23] studied on the crushing behaviour of aluminium foam-filled tubes at 300℃ under axial loading condition. Results of the study showed that energy absorption of the aluminium foam-filled enhanced by 23% compared to the empty tubes. For the same material analysis at room temperature, energy absorption of the empty tubes decreased by 26% and for the aluminium foam-filled tubes decreased by 34% compared to the high temperature analysis. This supported the authors' other study [24] that concluded the energy absorption of the foam-filled tubes were the higher compared to the empty tubes disregard of temperature. The crack propagation of the foam-filled tube was stabilized and reduced by the aluminium foam.

Shahbeyk et al [25] conducted FE analysis to investigate the effect of random distribution of foam density and impactor inclination to the crushing behaviour. Aluminium foam-filled square tubes have been simulated and the results showed that the impactor inclination angle and distribution of density did not affect the crushing behaviour of the columns filled with low-density foam. While for medium-density foam, the small inclination of the impactor changed the deformation behaviour to the unstable global buckling. And for the high-density foam, all columns experience a bending mode of crushing.

Toksoy and Guden [26] studied on the polystyrene foam-filled circular aluminium tubes. Deformation mode of the foam-filled tubes has changed from diamond to concertina which leads to higher energy absorption capacity. Application of polystyrene as filler material has been prolong by Aktay et al [27] who has investigated on crushing response of polystyrene foam-filled aluminium tubes. The foam-filler has reduced the folds' length and increased the number of folds during compression with the increasing of the polystyrene density. This results supported the conclusion made by Toksoy and Guden in their research before[26].

Li et al [28] investigated on foam-filled functionally graded tubes (FGT) subjected to axial loading using numerical analysis. The optimization method showed that the FGT has better energy absorption capacity compared to the uniform tubes. This result showed an agreement with optimization on functionally graded foam-filled tubes made by Yin, Wen Hou and Qing[29]. Figure 3 showed the comparison of deformation mode of the uniform and functionally graded foam-filled tubes. Mohammadiha and Ghariblu [30] supported the statement that ascending density configuration of aluminium foam has increases the energy absorption compared to uniform tubes. Attia et al [31] also agreed that density of foam that range from 8-20% has increased the SEA by 12%. Optimizations model of a FGT that varies axially conducted by Li et al[32] showed the same conclusion as the authors above

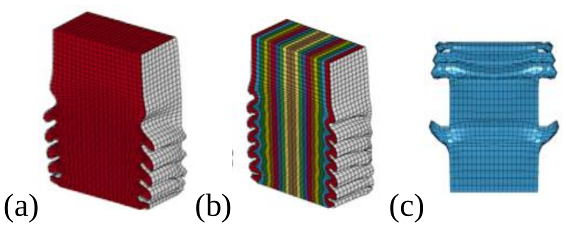

Fig3:. Deformation shape of (a) uniform foam-filled thin-walled structure (b) functionally lateral graded foam-filled thin-walled structure[29] (c) functionally axially graded foam-filled thin-walled structure[32]

Besides, auxetic foam which has negative poison's ratio as a filler in thin-walled tubes was introduced by Mohsenizadeh et al [33]. This new type of foam which can be converted from a conventional foam through certain processes. The investigation results showed that, application of auxetic foam as a filler has increased the SEA by 14% compared to the conventional foam and 23% compared to the empty tubes.

Mirfendereski et al [34] conducted a parametric study on foam-filled tapered rectangular tubes subjected to quasi static and dynamic loading. The authors reported that frusta tubes gained lowest initial peak force under static and dynamic loading.

Darvizeh et al [35] investigated on energy absorption characteristic of circumferentially grooved thick-walled tubes. The circular PU foam-filled tubes increased energy absorption capability by 89% when subjected to quasi static loading and 26% when subjected to dynamic loading. Results from this study was aligned with other study which showed that SEA of PU foam-filled grooved sample was up to 49% higher compared to the empty sample[36]. Besides that, Niknejad and Orojloo has introduced a nested longitudinal grooved section as energy absorbers subjected to lateral compression. For nested system of the same grooved sample, SEA of the foam-filled specimen was 1.74 times of the empty specimen.

Zhu et al. [37] conducted an experimental study on aluminium foam-filled tubes with composite reinforcement. The investigated design succeeded in increasing the SEA by 32% compared to empty aluminium tubes. Unfortunately the peak crushing force was also increased by 148%. This study supported Subramaniyam et al[18] investigation that concluded the existence of composite in the filler material has increased the energy absorption and the peak force of the tubes.

Multi-tubes configurations have been used to enhance the crashworthiness of a structure. However, this types of design usually lost its weight efficiency. Due to that, foam filler was introduced to increase the absorption energy of the design. Table 2 summaries the multi-tubes design

Table 2: Shapes of multi-tubes design

Shapes of multi-tubes	Reference
circular tubes	[14],[15],[24][19],[20],[22],[23],[28]
square	[4],[21],[26],[27],[29],[35]
rectangle	[31]

Li et al [38] has reported on the performance of single and double circular foam-filled tubes subjected to bending load. Aluminium foam-filled has increased the SEA of the double and single tubes by up to 300%. This result was supported by Alavi Nia and Parsapour [39] that investigated on crushing behaviour of square multi-cell. According to the experimental results, SEA and peak load of the square multi-cell tubes were increased by 92% and 79% compared to the simple tubes. The research also showed by simulation that the new proposed multi-cell can increase the SEA and peak load by up to 227% and 298% accordingly. Zhang et al [7] investigation on crashworthiness of aluminium foam-filled square bitubal column also showed an agreement with Li et al [38] and Alavi Nia and Parsapour [39]. Foam-filled bitubal square column has increased by 23% compared to empty bitubal column and 14% compared to sum of empty bitubal and foam-filler.

Although the new profile of square multi-cell proposed by Alavi and Parsapour [39] has shown good performance in energy absorption, but it failed to reduce the initial peak force of the section. The new profile has increased the initial peak force by 455% compared to the simple section. Other than that, they also proposed a new formula to generalize Zhang's formula for un-equal section.

Besides, FE method conducted Zheng et al [15] has shown similar results. The study was conducted to compare the energy absorption characteristic of polygonal column. Crashworthiness results from the numerical simulation showed that the energy absorption of foam-filled tubes increased up to 45% compared the empty tubes for single tubes and 35% for bitubal polygon. Besides, SEA of the foam-filled bitubal was 23% higher than the corresponding single tubes. Other than that, Li et al [3] has compared the crushing behaviour of the ex-situ aluminium foam-filled tubes with different configuration. Results showed that SEA of the corner foam-filled square tubes was the highest which is 103% compared to square hollow tubes. As for the circle tubes, SEA of the foam-filled tubes were lower than the hollow tubes. However, the foam-filled double tubes tend to increase the peak force up to 3 times compared to empty tubes. As in Zhang and Cheng [40]'s research, trigger that has been introduced to the column has succeeded in decreasing the peak force about 46%. They compared the energy absorption characteristic between foam-filled and multi-cell column of a square tubes. Multi-cell column has energy absorption efficiency up to 100% compared to foam-filled column.

Different results found in the research conducted on PU foam-filled circle bitubular tubes made of brass subjected to quasi-static axial loading investigated by Azaraksh [41]. The experimental study showed that SEA of the foam-filled tubes was decreased by 5.1% compared to the empty tubes. While the FE analysis showed the decreasing of the SEA value by 11.5%. This is caused by the additional of the foam filler that makes the tubes loses its weight efficiency. FE analysis and optimization have been conducted on foam-filled single and triple-cell hexagonal columns by Bi et al [42] to verify the tubes that can achieve maximum SEA by considering the tube geometries and foam density. The optimization study showed that the thicker and moderate density of foam have better energy absorption capability.

Dynamic crushing simulation on single and double corrugated tubes has been performed by Kilicaslan[43]. Figure 4 showed one of the foam-filled corrugated tube used in the study. Application of the corrugated tubes led to the progressive deformation which decrease the initial peak force of the tubes. Aluminium foam-filled double corrugated tubes proven to have the best energy absorption capability among all. SEA of the foam-filled double corrugated tubes was 31% better compared to straight tubes.

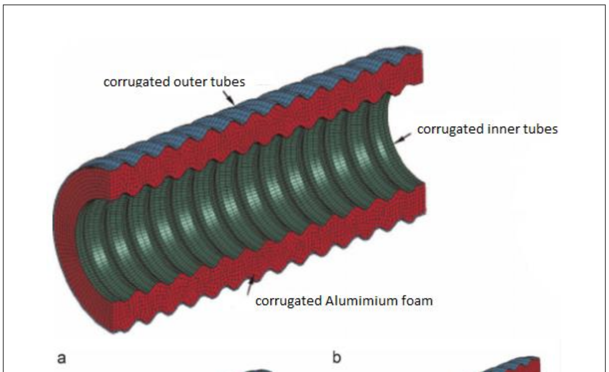

Fig4:. A foam-filled double corrugated tubes [43]

In other study, Yan et al [6] has tested the aluminium foam-filled corrugated tubes as in figure 3 under axial compression. The foam-filled corrugated sandwich panel showed increments in compressive strength and SEA by 211% and 157% respectively. Similar study on PU foam-filled aluminium and composite corrugated core by Ruzaimi[44] proven that energy absorption of aluminium corrugated core was increased by 300% and 50% compared to glass fiber and carbon fiber respectively.

Most of the investigations showed that energy absorbing effect of PU foam-filled structure is better than that of combination of the thin-walled structure and the foam structure. The density of a foam is the most influencing factor that controls the crush and energy absorbing behaviour of the structure. Basically, a higher foam density may exhibit higher energy absorption capacity [45] but increasing the foam density over an optimal value may lead to many serious consequences such as global bending deformation mode, low weight effectiveness, and premature tensile rupture [40,46]

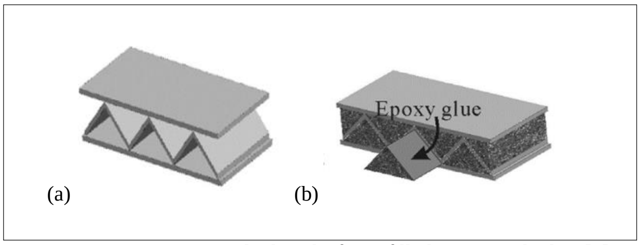

Fig5:.(a)empty corrugated tubes (b) foam-filled corrugated tubes [6]

2.2 Foam-Filled Composite Thin-Walled Tubes

Composite tubes were introduced as a crash box due to strength to weight ratio factor. Empty composite tubes without trigger mechanism generally collapsed in progressive crushing mode. Foam-filled composite tubes stabilized crushing mode but was ineffective in increasing the crushing loads of the composite tubes compared to the sum of the crushing loads of empty composite tube and foam [14].

Yan et al [47] has conducted axial crushing on a PU foam-filled natural flax fabric reinforced epoxy composite tubes. It was found that the foam filled flax/epoxy tubes capable of spreading the deformation. The PU-foam suppressed the fibre fracturing and increased the energy absorption during flattening process. This theory was aligned with Rezaei et al [48]conclusion that stated SEA during splitting of the PU foam-filled circular composite tubes during the axial splitting process showed an increment of 36.8% compared to the empty sample. Sebaey and Mahdi[49]'s investigation on the polyurethane-filled CFRP rectangular tubes has mostly the same conclusion. The CFRP tubes were strengthened with a few inner configurations. The strengthening configuration has increased 25% of the SEA compared to the foam-filled tube without it. Besides, the strengthening configuration increased the peak load from 13% to 75%.

The results were different in experimental study on PU foam-filled CFRP tapered tubes[50]. Foam-filled tapered circle and hexagon shape has shown the value of SEA by 4.3% and 3.1% higher respectively compared to the empty tubes. SEA of the hollow hexagon shape was the highest among all but decreased by 25% for the PU foam-filled tubes. SEA of the PU foam-filled tapered tubes increased by 30% compared to the Al foam filled Al alloy tapered tubes.

Mostly the same results shown by Sun et al [51]. They investigated on the crashworthiness of aluminium foam-filled. As for the empty CFRP tubes, the highest SEA was gained by the highest number of ply tubes with lowest length-to-diameter ratio. For the aluminium foam-filled CFRP tubes, the SEAs were decreased due to mas of the foam filler. Furthermore, lateral expansion of aluminum foam caused circumferential and axial cracks in the foam-filled CFRP tubes. Guden et al [14] also found that the aluminium foam-filled E-glass woven fabric polyester composite tube and thin-walled Al/polyester composite hybrid tubes were ineffective in increasing the crushing loads and SEA values of the empty tubes. But the foam filler stabilizes the crushing process of the tubes.

Trigger has been identified as one of the contributing factors in increasing the energy absorption capability of the energy absorber. Triger is irregularities that is created to reduce force variation in composite tubes by causing a stable crushing on composite tubes. Yan et al [52] investigated on the PU foam-filler effect on a natural flax/epoxy composite tubes with triggering factor. The foam-filler has decreased the peak force and increased SEA of the tubes. The foam-filled composite tubes with a proper design have potential to be lateral energy absorber structure and comparable to aluminium [47]. Although the foam-filled composite tubes was found to be ineffective in increasing the crushing loads over the sum of the crushing loads of empty composite and foam in the progressive crushing region but the foam-filled composite tubes induced a more stable tube crushing trigger and progression [14].

3. Honeycomb-Filled Thin-Walled Structure

Instead of foam, other type of filler that commonly used to enhance the absorption capability of thin-walled tubes was aluminium honeycomb. Aluminium honeycomb is metal structure that has geometry as a honeycomb. Liu et al [53] has conducted a quasi-static and three-point bending test to study the crashworthiness characteristic of weave carbon fiber T300/epoxy prepreg filled with aluminium honeycomb. In quasi-static axial loading, it was found that due to filling, the peak load and SEA was increased by 216% and 400% respectively. While the same specimen subjected to three points bending, the peak load and SEA was increased by 17% and 1% respectively. Increasing in peak load is undesirable in energy absorbers structure. In that case, Zarei Mahmoudabadi and Sadighi [54] studied on foam-filled metal hexagonal honeycomb as a filler. The model was capable in predicted the mean crushing strength and the suggested filler design decreased the ratio of peak load to mean crushing load. A theoretical model has been developed and was verified with the experimental results. Besides, Niknejad et al [55] conducted experimental study on PU foam-filled honeycomb. Results reported that the theoretical prediction of instantaneous folding force showed good agreement with the experimental work

Sun et al.[51] compared performance of empty circular CFRP tubes with the aluminium honeycomb filled CFRP tubes. The study discovered that for honeycomb filled CFRP tubes, SEA and maximum force values were higher than the foam-filled tubes but still lower than the empty tubes. The results were quite similar in Hussien et al [4]'s study which stated that application of aluminium honeycomb as filler has increased the EA and SEA of the empty tubes by 83% and 31%. For improvement purposes, the authors then investigated on combination of PU with honeycomb as filler in square aluminium tubes. Results showed better performance with EA and SEA of the tubes were 334% and 109% respectively compared to the empty square aluminium tubes. The study showed that the crushing velocity influenced the crushing forces of the structure but not the deformation mode. Furthermore, Hao and Du [56] has proposed a bio-inspired honeycomb or bionic design for better energy absorption characteristic. The honeycomb structures with hollow columns contributed in improving the crashworthiness of the structure. FE analysis showed that energy absorption characteristic of the bionic design was better than the conventional design.

Paz et al [57] developed an optimization model using surrogated-based techniques to optimize the square column filled with glass fiber reinforced polyamide honeycomb. The optimization design was succeeded in reducing the peak load by 37% for the same mass and absorbed energy and the SEA was increased by 39.5% for specimens with the same peak load.

The studies showed that a combination of honeycomb with PU structure produced better performance energy absorption structure compared to the structure which only filled with honeycomb or PU.

4. Conclusions

Filled metal and composite thin-walled tubes were significantly efficient in increasing the energy absorption capability of a structure. Instead of energy absorption behaviour of the foam itself, energy dissipation of the foam-filled structure was enhancing by the interaction of the tube wall with the foams. Aluminium honeycomb-filled tubes was reported to be more efficient in term of weight compared to aluminium foam-filled tubes as it has lower density and better strength to weight ratio[46]. Beside the filler, design and configuration of the tubes such as corrugated, sandwich or multi tubes were also proven to be used as energy absorption structure. Instead of that, recently functionally graded wall thickness and functionally graded foam density in axial and radial have been studied by simulation.

Acknowledgement

The author would like to acknowledge the support of the internal grant of Universiti Malaysia Pahang, RDU1803114 and support provided by the Ministry of Higher Education, Malaysia under Fundamental Research Grant Scheme, RDU160140

References

[1] F. Tarlochan, F. Samer, A. M. S. Hamouda, S. Ramesh, and K. Khalid, "Design of thin wall structures for energy absorption applications: Enhancement of crashworthiness due to axial and oblique impact forces," Thin-Walled Struct., vol. 71, pp. 7–17, 2013.

[2] Y. Nakazawa, K. Tamura, M. Yoshida, K. Takagi, and M. Kano, "Development of crash-box for passenger car with high capability for energy absorption," VIII Int. Conf. Comput. Plast., 2005.

[3] R. Lu FangyunLi, Zhibin; Chen, "Comparative analysis of crashworthiness of empty and foam-filled thinwalled," Thin Walled Struct., vol. 124, no. December 2017, pp. 343–349, 2018.

[4] R. D. Hussein, D. Ruan, G. Lu, S. Guillow, and J. W. Yoon, "Crushing response of square aluminium tubes filled with polyurethane foam and aluminium honeycomb," Thin-Walled Struct., vol. 110, no. November 2016, pp. 140–154, 2017.

[5] A. Baroutaji, M. Sajjia, and A. G. Olabi, "On the crashworthiness performance of thin-walled energy absorbers: Recent advances and future developments," Thin-Walled Struct., vol. 118, no. November 2016, pp. 137–163, 2017.

[6] L. L. Yan, B. Yu, B. Han, C. Q. Chen, Q. C. Zhang, and T. J. Lu, "Compressive strength and energy absorption of sandwich panels with aluminum foam-filled corrugated cores," Compos. Sci. Technol., vol. 86, pp. 142–148, 2013.

[7] Y. Zhang, G. Sun, G. Li, Z. Luo, and Q. Li, "Optimization of foam-filled bitubal structures for crashworthiness criteria," J. Mater., vol. 38, pp. 99–109, 2012.

[8] M. Taherishargh, M. Vesenjak, I. V. Belova, L. Krstulović-Opara, G. E. Murch, and T. Fiedler, "In situ manufacturing and mechanical properties of syntactic foam filled tubes," Mater. Des., vol. 99, pp. 356–368, 2016.

[9] U. K. Chakravarty, "An investigation on the dynamic response of polymeric, metallic, and biomaterial foams," Compos. Struct., vol. 92, no. 10, pp. 2339–2344, 2010.

[10] M. Salwani, B. Sahari, A. Ali, and N. Aziz, The Effect of Automotive Side Member Filling on Car Frontal Impact Performance, vol. 6. 2015.

[11] J. Song, "Numerical simulation on windowed tubes subjected to oblique impact loading and a new method for the design of obliquely loaded tubes," Int. J. Impact Eng., vol. 54, pp. 192–205, 2013.

[12] A. G. Jahromi and H. Hatami, "Energy absorption performance on multilayer expanded metal tubes under axial impact," Thin-Walled Struct., vol. 116, no. August 2016, pp. 1–11, 2017.

[13] L. Ying, M. Dai, S. Zhang, H. Ma, and P. Hu, "Multiobjective crashworthiness optimization of thin-walled structures with functionally graded strength under oblique impact loading," Thin-Walled Struct., vol. 117, no. April, pp. 165–177, 2017.

[14] M. Guden, S. Yüksel, A. Taşdemirci, and M. Tanoğlu, "Effect of aluminum closed-cell foam filling on the quasi-static axial crush performance of glass fiber reinforced polyester composite and aluminum/composite hybrid tubes," Compos. Struct., vol. 81, no. 4, pp. 480–490, 2007.

[15] G. Zheng, S. Wu, G. Sun, G. Li, and Q. Li, "Crushing analysis of foam- fi lled single and bitubal polygonal thin-walled tubes," Int. J. Mech. Sci., vol. 87, pp. 226–240, 2014.

[16] S. Thinvongpituk, C., Onsaloong, N. and Poonaya, "Crush Characteristic of Foam-Filled Circular Steel and Aluminum Tubes under Axial Loading," in Proceedings of the World Congress on Engineering 2016, 2016, vol. II.

[17] N. Onsalung, C. Thinvongpituk, and K. Pianthong, "Impact Response of Circular Aluminum Tube Filled with Polyurethane Foam," Mater. Trans., vol. 55, no. 1, pp. 207–215, 2014.

[18] M. S Kanna, Subramaniyan Shahruddin, M. lmran Ghazali, A. M. Ahmad Zaidi, and P. K. Prabagaransd, "Energy Absorption Characteristics of Polyurethane Composite Foam- Filled Tubes Subjected to Quasi-Static Axial Loading S Kanna ~ ubramaniyan '", Shahruddin ~ a h z a n * ? Mohd ~ , lmran ~ h a z a l i ~ l ~ , Ahmad Mujahid Ahmad ~ a i d i ~ Prasath," vol. 315, pp. 872–878, 2013.

[19] P. Zhou, E. Beeh, M. Kriescher, H. E. Friedrich, and G. Kopp, "Experimental comparison of energy absorption characteristics of polyurethane foam-filled magnesium and steel beams in bending," Int. J. Impact Eng., vol. 93, pp. 76–87, 2016.

[20] A. Niknejad, M. M. Abedi, G. H. Liaghat, and M. Z. Nejad, "Absorbed energy by foam-filled quadrangle tubes during the crushing process by considering the interaction effects," Arch. Civ. Mech. Eng., vol. 15, no. 2, pp. 376–391, 2015.

[21] A. Niknejad, S. Ali, and G. Hossein, "Experimental investigation on the lateral compression in the foam-filled circular tubes," Mater. Des., vol. 36, pp. 24–34, 2012.

[22] M. M. Abedi, N. Abbas, G. H. Liaghat, and M. Z. Nejad, "Theoretical and experimental study on empty and foam-filled columns with square and rectangular cross section under axial compression," Int. J. Mech. Sci., vol. 65, pp. 134–146, 2012.

[23] N. Movahedi and E. Linul, "Quasi-static compressive behavior of the ex-situ aluminum-alloy foam-filled tubes under elevated temperature conditions," Mater. Lett., vol. 206, pp. 182–184, 2017.

[24] E. Linul, N. Movahedi, and L. Marsavina, "The temperature effect on the axial quasi-static compressive behavior of ex-situ aluminum foam-filled tubes," Compos. Struct., vol. 180, pp. 709–722, 2017.

[25] S. Shahbeyk, A. Vafai, and N. Petrinic, "Axial crushing of metal foam-filled square columns: Foam density distribution and impactor inclination effects," Thin-Walled Struct., vol. 43, no. 12, pp. 1818–1830, 2005.

[26] A. K. Toksoy and M. Güden, "The strengthening effect of polystyrene foam filling in aluminum thin-walled cylindrical tubes," Thin-Walled Struct., vol. 43, no. 2, pp. 333–350, 2005.

[27] L. Aktay, A.K. Toksoy, and M. Gu¨den, "Quasi-static axial crushing of extruded polystyrene foam-filled thin-walled aluminium tubes:Experimental and numerical analysis," Mater. Des., vol. 27, pp. 556–565, 2006.

[28] G. Li, Z. Zhang, G. Sun, F. Xu, and X. Huang, "Crushing analysis and multiobjective optimization for functionally graded foam- fi lled tubes under multiple load cases," Int. J. Mech. Sci., vol. 89, pp. 439–452, 2014.

[29] H. Yin, G. Wena, S. Hou, and Q. Qing, "Multiobjective crashworthiness optimization of functionally lateral graded foam-filled tubes," Mater. Des., vol. 44, pp. 414–428, 2013.

[30] O. Mohammadiha and H. Ghariblu, "Crush behavior optimization of multi-tubes filled by functionally graded foam," Thin-Walled Struct., vol. 98, pp. 627–639, 2016.

[31] M. S. Attia, S. A. Meguid, and H. Nouraei, "Nonlinear finite element analysis of the crush behaviour of functionally graded foam-filled columns," Finite Elem. Anal. Des., vol. 61, pp. 50–59, 2012.

[32] G. Li, Z. Zhang, G. Sun, F. Xu, and X. Huang, "Crushing analysis and multiobjective optimization for functionally graded foam-filled tubes under multiple load cases," Int. J. Mech. Sci., vol. 89, pp. 439–452, 2014.

[33] S. Mohsenizadeh, R. Alipour, M. Shokri Rad, A. Farokhi Nejad, and Z. Ahmad, "Crashworthiness assessment of auxetic foam-filled tube under quasi-static axial loading," Mater. Des., vol. 88, pp. 258–268, 2015.

[34] L. Mirfendereski and M. Ã. Salimi, "Parametric study and numerical analysis of empty and foam-filled thin-walled tubes under static and dynamic loadings," Int. J. Mech. Sci., vol. 50, pp. 1042–1057, 2008.

[35] A. Darvizeh, A. Meshkinzar, M. Alitavoli, and R. Rajabiehfard, "Low velocity impact of empty and foam filled circumferentially grooved thick-walled circular tubes," Thin Walled Struct., vol. 110, no. February 2016, pp. 97–105, 2017.

[36] A. Niknejad and P. H. Orojloo, "A novel nested system of tubes with special cross-section as the energy absorber," Thin-Walled Struct., vol. 100, pp. 113–123, 2016.

[37] G. Zhu, Z. Wang, X. Huo, A. Cheng, G. Li, and C. Zhou, "Experimental and numerical investigation into axial compressive behaviour of thin-walled structures filled with foams and composite skeleton," Int. J. Mech. Sci., vol. 122, no. January, pp. 104–119, 2017.

[38] Z. Li, Z. Zheng, J. Yu, and L. Guo, "Crashworthiness of foam-filled thin-walled circular tubes under dynamic bending," Mater. Des., vol. 52, pp. 1058–1064, 2013.

[39] A. Alavi Nia and M. Parsapour, "An investigation on the energy absorption characteristics of multi-cell square tubes," Thin-Walled Struct., vol. 68, pp. 26–34, 2013.

[40] X. Z. Ã and G. Cheng, "A comparative study of energy absorption characteristics of foam-filled and multi-cell square columns," vol. 34, pp. 1739–1752, 2007.

[41] S. Azarakhsh, A. Rahi, A. Ghamarian, and H. Motamedi, "Axial crushing analysis of empty and foam-filled brass bitubular cylinder tubes," Thin-Walled Struct., vol. 95, pp. 60–72, 2015.

[42] J. Bi, H. Fang, Q. Wang, and X. Ren, "Modeling and optimization of foam-filled thin-walled columns for crashworthiness designs," Finite Elem. Anal. Des., vol. 46, no. 9, pp. 698–709, 2010.

[43] C. Kiliçaslan, "Numerical crushing analysis of aluminum foam-filled corrugated single- and double-circular tubes subjected to axial impact loading," Thin-Walled Struct., vol. 96, pp. 82–94, 2015.

[44] M. Ruzaimi and M. Rejab, "the Mechanical Properties of Novel Lightweight Structures Based on Corrugated-Cores," University of Liverpool, 2013.

[45] [45] a. . Hanssen, M. Langseth, and O. . Hopperstad, "Optimum design for energy absorption of square aluminium columns with aluminium foam filler," Int. J. Mech. Sci., vol. 43, no. 1, pp. 153–176, 2001.

[46] S. Santosa and T. Wierzbicki, "Crash behavior of box columns filled with aluminum honeycomb or foam," Comput. Struct., vol. 68, no. 4, pp. 343–367, 1998.

[47] [47]L. Yan, N. Chouw, and K. Jayaraman, "Lateral crushing of empty and polyurethane-foam filled natural flax fabric reinforced epoxy composite tubes," Compos. Part B Eng., vol. 63, pp. 15–26, 2014.

[48] B. Rezaei, A. Niknejad, H. Assaee, and G. H. Liaghat, "Axial splitting of empty and foam-filled circular composite tubes – An experimental study," Arch. Civ. Mech. Eng., vol. 15, no. 3, pp. 650–662, 2015.

[49] T. A. Sebaey and E. Mahdi, "Filler strengthening of foam-filled energy absorption devices using CFRP beams," Compos. Struct., vol. 160, pp. 1–7, 2017.

[50] N. Gan, Y. Feng, H. Yin, G. Wen, D. Wang, and X. Huang, "Quasi-static axial crushing experiment study of foam-filled CFRP and aluminum alloy thin-walled structures," Compos. Struct., vol. 157, pp. 303–319, 2016.

[51] G. Sun, S. Li, Q. Liu, G. Li, and Q. Li, "Experimental study on crashworthiness of empty/aluminum foam/honeycomb-filled CFRP tubes," Compos. Struct., vol. 152, pp. 969–993, 2016.

[52] L. Yan, N. Chouw, and K. Jayaraman, "Effect of triggering and polyurethane foam-filler on axial crushing of natural flax/epoxy composite tubes," Mater. Des., vol. 56, pp. 528–541, 2014.

[53] Q. Liu, X. Xu, J. Ma, J. Wang, Y. Shi, and D. Hui, "Lateral crushing and bending responses of CFRP square tube filled with aluminum honeycomb," Compos. Part B Eng., vol. 118, pp. 104–115, 2017.

[54] M. Zarei Mahmoudabadi and M. Sadighi, "A theoretical and experimental study on metal hexagonal honeycomb crushing under quasi-static and low velocity impact loading," Mater. Sci. Eng. A, vol. 528, no. 15, pp. 4958–4966, 2011.

[55] A. Niknejad, G. H. Liaghat, H. M. Naeini, and A. H. Behravesh, "Theoretical and experimental studies of the instantaneous folding force of the polyurethane foam-filled square honeycombs," Mater. Des., vol. 32, no. 1, pp. 69–75, 2011.

[56] P. Hao and J. Du, "Energy absorption characteristics of bio-inspired honeycomb column thinwalled structure under impact loading," J. Mech. Behav. Biomed. Mater., vol. 79, pp. 301–308, 2018.

[57] J. Paz, J. Díaz, L. Romera, and M. Costas, "Crushing analysis and multi-objective crashworthiness optimization of GFRP honeycomb-filled energy absorption devices," Finite Elem. Anal. Des., vol. 91, pp. 30–39, 2014.