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AXIAL CRUSHING ANALYSIS OF AUXETIC FOAM-FILLED THIN-WALLED CIRCULAR TUBE

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ABSTRACT

Auxetic materials are new class of materials that have recently been gaining popularity within the research community as an effective candidate to enhance energy absorption due to their enhanced mechanical properties. Unlike normal materials, they exhibit a negative Poisson's ratio when subjected to uniaxial loading. This paper treats crush response and energy absorption performance of auxetic foam-filled circular tubes when subjected to uniaxial quasi-static loading. For comparison, energy absorption capacity, specific energy absorption, deformation modes and load–displacement curves of empty and conventional foam-filled circular tubes were quantified. Quasi-static compression tests were conducted on all empty and foam-filled thin-walled samples. It is found that crush response and energy absorption performance of auxetic foam-filled circular tube is superior to empty and conventional foam-filled circular tubes. The primary outcome of this study is the design information for the use of auxetic foam-filled circular tubes as energy absorbers where impact loading is expected particularly in crashworthiness applications.

Keywords: Auxetic foam, Negative Poisson's ratio, Thin-walled tub, Energy absorption, Axial loading

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1. INTRODUCTION

Increased requirements in vehicle safety and interests on crashworthiness have led to exhaustive studies into crush responses and energy absorption characteristics of various thin-walled structures with the different materials and geometrical shapes by using experimental, analytical and numerical methods. Thin-walled structures have been frequently utilized as preferable energy-absorption devices with high crashworthiness capacity and desirable deformation modes in the crashworthiness applications such as automotive and aerospace industries owing to their high resistance to weight ratio. Generally, thin-walled tubes are very effective components to absorb and dissipate kinetic energy during crushing process when subjected to different loading conditions. Therefore, they have been received extensive attention by numerous researchers. Over the past few decades, numerous studies have been carried out on different types of energy absorber systems such as prismatic tubes in order to better perceive of crushing behavior, deformation and energy absorption of thin-walled structures.

The first systematic study on the collapse of cylindrical tube under axial loads was carried out by Alexander in 1960. In another major study, the quasi-static axial collapse of cylindrical tube was experimentally investigated (Andrews et al., 1983) in order to study deformation modes of cylindrical tubes with respect to tube length to diameter and wall thickness to diameter ratios. Wierzbicki and Abramowicz (1983) proposed a simple formula to predict the axial crush response of thin walled columns under dynamic and static loading conditions. Abramowicz and Jones (1984) analyzed crushing response of circular and square tubes under dynamic axial loading. In an analysis of mean crushing force on square cross-section aluminum tube under static and dynamic loading tests,Langseth and Hopperstad (1996) reported that mean crushing force in dynamic mode is lower than static one.

During the past 30 years, a considerable amount of literature has been published on optimization and improvement the crush analysis of thin-walled structure. More recently, Nia and Hamedani (2010) investigated the energy absorption capacity of thin-walled structures with various geometric shapes. In their research, crushing behavior of circular, rectangular, square, triangular, pyramidal, hexagonal and conical was compered both experimentally and numerical. They found that, cylindrical and triangular tubes are stood at the top and down energy absorber devices per-unit mass respectively. In terms of predicting and controlling the collapse mode of thin-walled structures numerous studies have been conducted due to enhanced energy dissipating devisees (Mozafari et al., 2017). Eyvazian et al. (2014) performed a series of experimental tests on aluminum corrugated tubes with different geometries and directions in order to examine the effect of corrugating in crashworthiness performance. They reported that corrugated tubes can be considered as reliable energy absorbers owing to uniform crush responses without high initial peak loads and predictable collapse mode.

A number of researchers have reported the effect of polyurethane and metallic foams as a filler of thin-walled tubes to enhance their crashworthiness performance. To better perceive crushing behavior of foam-filled structure, several studies have been conducted using numerical, analytical and experimental methods. In a study which set out to determine the effect of using polyurethane foam inside thin-walled tubes, Thornton (1980) found that specific energy absorption of foam-filled tube remarkably increased in compared with unfilled tube. It was not weight effective when compared with the thickening of empty tube wall. In an another investigation into the crushing response of low density polyurethane foam-filled sheet metal tubes, Lampinen and Jeryan (1982) pointed out that using foam filler stabilizes the deformation of thin-walled tubes. Reid and Reddy (1986) implemented a series of experiments on the impact behavior of squared foam-filled tube subjected to quasi-static and dynamic loadings. The effect of foam filer density in crushing response of extruded polystyrene foam in aluminum tubes was experimentally and numerically investigated by Aktay et al. (2006). Authors reported that with increasing foam filler density, the number of folds formed in foam-filled tubes rose both in diamond and concertina mode of deformation. Furthermore, some studies have focused on the performance of polyurethane and metallic foams as a filler in thin-walled tubes under oblique loading, Ahmad and Thambiratnam (2009) and Ahmad et al. (2010) discovered that using foam-filler materials in thin-walled tube assist to improve crushing stability and collapse mode of a structure, resulting in great crashworthiness performance in both axial and off-axis loading.

Auxetic material, which is a new generation of foam material with negative Poisson's ratio has gained popularity as a filler in thin-walled tubes owing to considerable capabilities such as better fracture toughness, increased strength, superior energy dissipation and absorption and improved damping and indentation resistance compared with conventional foam with positive Poisson's ratio (Mohsenizadeh et al., 2016; Mohsenizadeh et al., 2015; Rad et al., 2017). In crushing analysis of auxetic foam-filled square aluminum tube under quasi-static axial loading, Mohsenizadeh et al. (2015) reported that energy absorption and specific energy absorption of auxetic foam-filled tube remarkably increased in compression with conventional one in spite of increase in the total weight of structure. The main objective of this present study is to evaluate the effects of using auxetic foam inside thin-walled circular tubes for enhancing the crashworthiness performance in comparison with conventional foam-filled and empty tubes.

2. FABRICATION AND EXPERIMENTAL PROCEDURE

Fabrication method of auxetic foam and experimental procedure are described in this section. In addition, material specification of sample has been detailed.

2.1 Foam preparation

A native conventional polymeric closed-cell foam with a density of 45 kg m^{-3} was used to fabricate auxetic foam. Converting process involved 3 stages: compression, heating, cooling and relaxation. To transform conventional cell-structures into re-entrant ones, conventional foam was cut into cubic sample (with dimensions: 90mm X 90mm X 90mm) using a foam cutter then the resized foam was placed in an aluminum mold to compress the foam in three dimensions in order to buckle the cell ribs as depicted in Fig. 1(b). Compressed foam was then placed in the preheated oven at 175°C for 45 min to preserve the new configuration. Heating time and heating temperature determine with respect to density and types of foam (e.g. open or closed-cell). The final step of converting process was to cool down of samples at the ambient temperature. The fabrication auxeticity method as displayed in Fig. 1.

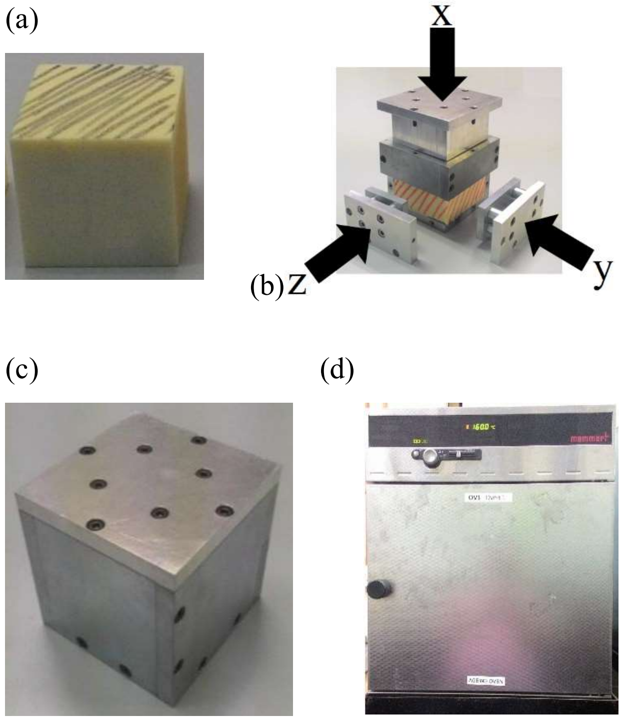

Fig.1. Different steps of converting process; (a) sizing foam sample, (b) applying volumetric compression, (c) molding for heating and (d) heating process

2.1. Material specification

The structure considered in this study was a circular cross-section aluminum tube made from 1 mm thickness for ease and affordability. The outside diameter and length of the samples were 38 mm and 80 mm, respectively. Fig. 2 shows the empty tube (ET), conventional foam filled tube (CFFT) and auxetic foam filled tubed (AFFT). The specifications of aluminum tube, conventional and auxetic foams are enlisted in Table 1.

Table 1. Mechanical properties of the materials

Type of materials	Young's Modulus	Poisson's Ratio	Initial Yield Stress
Aluminum	68.2 GPa	0.33	80 MPa
Conventional Foam	4.2 GPa	0.015	0.22 MPa
Auxetic Foam	4.4 GPa	-0.32	0.63 MPa

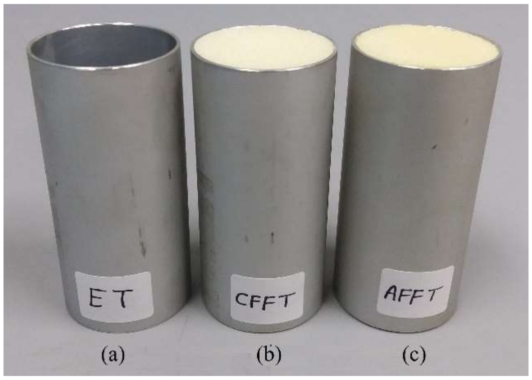

Fig.2. Tube configuration; (a) ET, (b) CFFT and (c) AFFT.

2.2 Experimental procedure

Crush response and energy absorption capacity of ET, CFFT and AFFT under quasi-static axial loading were experimentally examined using an INSTRON universal testing machine as shown in Fig. 3. 50 kN load cell was used to increase the result accuracy. The compressive loading rate was set to 3 mm/min and the samples compressed up to 60 percent of their original length. Each test includes 5 samples in which the average data was used for the crashworthiness assessment.

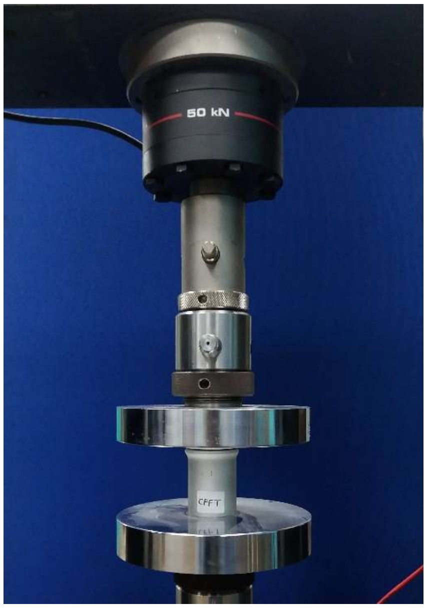

Fig.3. Quasi-static test set-up

3. CRASHWORTHINESS PERFORMANCE

Energy absorption (EA), specific energy absorption (SEA), mean crush force (P_m) and crush force efficiency (CFE) are crashworthiness indicators which are used to evaluate the crashworthy performance. In other words, these indicators evaluate the influence of geometrical characteristic and material under crushing forces in order to design a controllable crushing pattern for maximizing energy absorption and allowable peak forces during the collapse. During axial crushing, the EA can be expressed as:

$$EA = \int_0^d F(x)dx \qquad (1)$$

Where *F* is the axial crushing force and *d* denotes the axial crushing distance. SEA is the most characteristic of energy absorbers that used to reflect the efficiency of energy absorption per unit mass, mathematically as:

$$SEA = \frac{EA}{m} \qquad (2)$$

Where *m* is the mass of structure. For a given energy absorption, higher SEA presents the better energy absorption of structure in terms of its weight.

4. CRUSH RESPONSE AND ENERGY ABSORPTION PERFORMANCES

The main purpose of this study is to investigate the crush response and global behavior of auxetic foam-filled circular tube under quasi-static axial loading. For comparison, the crush response of ET and CFFT were also examined with respect to deformation profile and force displacement curve. As mentioned earlier, each experimental test includes 5 samples, hence the average data has been used for the crashworthiness evaluation. Fig. 4 shows the deformation profiles of ET, CFFT and AFFT. It can be observed that, there were no significant differences between the deformation profiles of unfilled, conventional and auxetic foam-filled circular tubes.

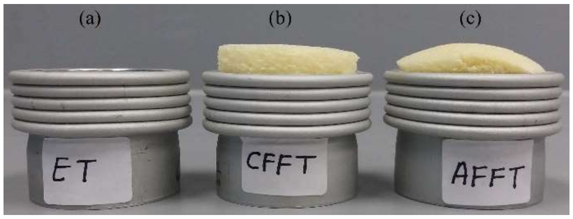

Fig.4. Deformation modes; (a) ET, (b) CFFT, (c) AFFT

Fig. 5 plots the axial crushing load vs displacement for the samples (ET, CFFT and AFFT) from experimental test. Moreover, the value of all crashworthiness indicators used in this research is enlisted in Table 2.

Table 2. Experimental results from axially compressed samples

Samples	EA (J)	SEA (kJ/kg)	P_{max} (kN)
ET	517	18.73	25.95
CFFT	603	19.37	26.85
AFFT	723	20.08	29.08

From Fig. 6(a) and Table 2, it is apparent that the EA of AFFT is greater than that of ET and CFFT. It can be attributed to the toughness of auxetic foam which is an important mechanical property since specifies the maximum EA of the foam per unitvolume when impacted. Material toughness can be measured by integrating the area under stress–strain curve. Auxeticity procedure leads to increase the toughness of foam during conversion process. Hence, enhanced toughness of auxetic foam filler causes greater area under crushing force vs displacement curve which improves the EA capacity of structure. It is interesting to note that the EA of the AFFT is 16.6% higher than that of the CFFST and 28.5% than that of the ET.

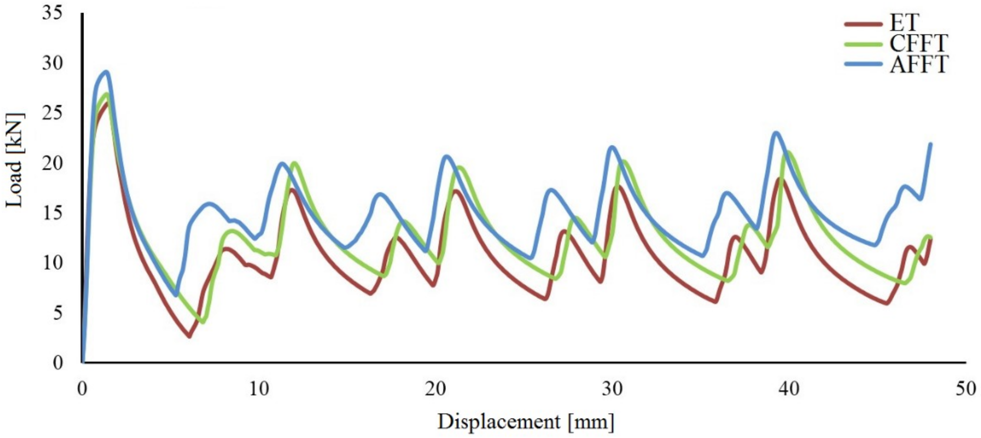

Fig.5. Load–displacement curves of ET, CFFT and AFFT.

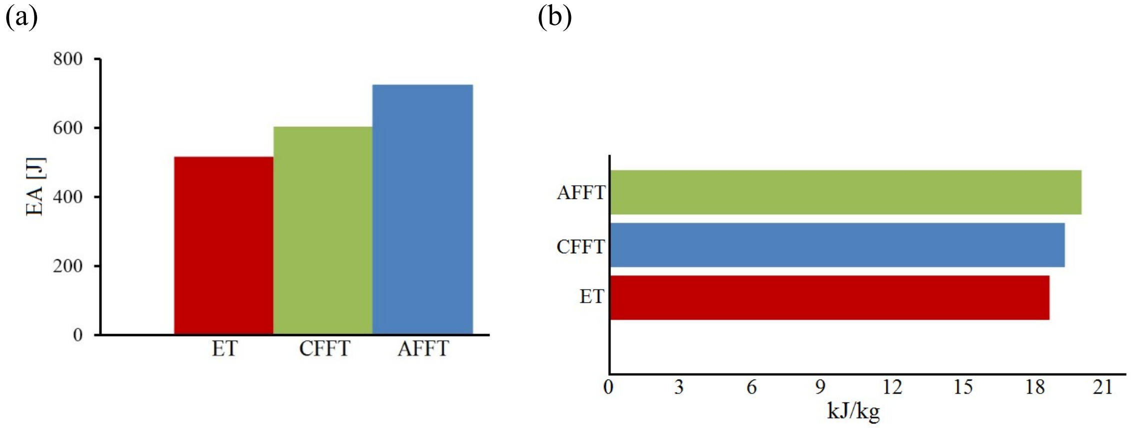

Fig.6. Comparison between experimental values of (a) EA and (b) SEA of samples

It can been seen from the data in Table 2 that the initial P_{max} of the AFFT is slightly higher than that of the CFFT and ET which is surprisingly undesirable in crashworthiness applications. Nevertheless, this initial onset load effect may be compromised with a greater energy absorption capacity obtained. This may be due to the NPR of auxetic material which made the extra absorbent layers along the impact load transmission path. Considering the higher strength of tube than foams, the study of P_{max}may not singly enough and second peak load in crushing force *vs* displacement curves can assist to better evaluate the crashworthiness ability.

The result of the SEA is shown in Fig. 6(b). It is noteworthy that as a CFFT changes to an AFFT, its SEA increases at around 3.5%. It can also be highlighted that AFFT has 6.7% greater SEA than EST. It means that despite of increasing the weight of structure in AFFT better capacity of energy absorption for this tube can be obtained. By using auxetic foam, the structure becomes heavier which is inevitable due to densification process during converting conventional foam into the auxetic foam. Although increasing density is the predominant effect of auxeticity phenomenon, the main influence of increasing energy absorption capacity is due to the changing of microstructure during the converting process from conventional into the auxetic. This microstructural variation leads to obtain the NPR. Previous studies showed that in parallel of increasing in NPR, the indentation resistance and toughness are enhanced remarkably (Critchley et al., 2013; Lakes., 1987). The former causes to increase the initial peak loads and the latter leads to enhance energy absorption capacity.

5. CONCLUSION

In this paper, the axial crushing behavior and EA of aluminum circular tubes namely ET, CFFT and AFFT under quasi-static axial loading was experimentally investigated. The results showed that the AFFT has greater EA in comparison with the ET and CFFT. Generally, the AFFT exhibit 28.5% and 16.6% increment in EA than ET and CFFT, respectively. On the other hand, despite of the increase in the total weight of the structure of the AFFT, its SEA increases remarkably. No significant differences were found between the deformation profiles of all tubes. Above all, it is evident that a foam core with a negative Poisson's ratio has a significant influence in crashworthiness applications.

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REFERENCES

Abramowicz W., and Jones N. (1984). Dynamic axial crushing of circular tubes. International Journal of Impact Engineering, 2(3), 263-281.

Ahmad Z., and Thambiratnam, D P. (2009). Dynamic computer simulation and energy absorption of foam-filled conical tubes under axial impact loading. Computers & Structures, 87(3), 186-197.

Ahmad Z., Thambiratnam, D P., and Tan, A C C. (2010). Dynamic energy absorption characteristics of foam-filled conical tubes under oblique impact loading. International Journal of Impact Engineering, 37(5), 475-488.

Aktay L., Toksoy A K, and Güden M. (2006). Quasi-static axial crushing of extruded polystyrene foam-filled thin-walled aluminum tubes: experimental and numerical analysis. Materials & design, 27(7), 556-565.

Alexander J M. (1960). An approximate analysis of the collapse of thin cylindrical shells under axial loading. The Quarterly Journal of Mechanics and Applied Mathematics, 13(1), 10-15.

Andrews K R F., England, G L., and Ghani E. (1983). Classification of the axial collapse of cylindrical tubes under quasi-static loading. International Journal of Mechanical Sciences, 25(9-10), 687-696.

Critchley R., Corni, I., Wharton, J. A., Walsh, F. C., Wood, R. J., and Stokes, K. R. (2013). A review of the manufacture, mechanical properties and potential applications of auxetic foams. physica status solidi (b), 250(10), 1963-1982.

Eyvazian A., Habibi, M K., Hamouda, A M., and Hedayati R. (2014). Axial crushing behavior and energy absorption efficiency of corrugated tubes. Materials & Design (1980-2015), 54, 1028-1038.

Lakes R. (1987). Foam structures with a negative Poisson's ratio. Science, 235, 1038-1041.

Lampinen, B E., and Jeryan, R A. (1982). Effectiveness of polyurethane foam in energy absorbing structures (No. 820494). SAE Technical Paper.

Langseth M., and Hopperstad, O S. (1996). Static and dynamic axial crushing of square thin-walled aluminium extrusions. International Journal of Impact Engineering, 18(7-8), 949-968.

Mohsenizadeh S., Alipour R., Ahmad Z., and Alias A. (2016). Influence of auxetic foam in quasi-static axial crushing. International Journal of Materials Research, 107(10), 916-924.

Mohsenizadeh S., Alipour R., Nejad A F., Rad M S., and Ahmad Z. (2015). Experimental investigation on energy absorption of auxetic foam-filled thin-walled square tubes under quasi-static loading. Procedia Manufacturing, 2, 331-336.

Mohsenizadeh S., Alipour R., Rad M S., Nejad A F., and Ahmad Z. (2015). Crashworthiness assessment of auxetic foam-filled tube under quasi-static axial loading. Materials & Design, 88, 258-268.

Mozafari H., Eyvazian A., Hamouda A M., Crupi V., Epasto G., and Gugliemino E. (2017). Numerical and experimental investigation of corrugated tubes under lateral compression. International Journal of Crashworthiness, 1-13.

Nia A A., andHamedani J H. (2010). Comparative analysis of energy absorption and deformations of thin walled tubes with various section geometries. Thin-Walled Structures, 48(12), 946-954.

Prawoto Y. (2012). Seeing auxetic materials from the mechanics point of view: a structural review on the negative Poisson's ratio. Computational Materials Science, 58, 140-153.

Rad M S., Mohsenizadeh S., and Ahmad Z. (2017). Finite element approach and mathematical formulation of viscoelastic auxetic honeycomb structures for impact mitigation. Journal of Engineering Science and Technology, 12(2), 471-490.

Reid S R., Reddy T Y., and Gray M D. (1986). Static and dynamic axial crushing of foam-filled sheet metal tubes. International Journal of Mechanical Sciences, 28(5), 295-322.

Thornton P H. (1980). Energy absorption by foam filled structures (No. 800081). SAE Technical Paper.

Wierzbicki T., and Abramowicz W. (1983). On the crushing mechanics of thin-walled structures. Journal of Applied mechanics, 50(4a), 727-734.

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