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Experimental investigation on energy absorption of auxetic foam-filled thin-walled square tubes under quasi-static loading

S. Mohsenizadeh*, R. Alipour, A. Farokhi Nejad, M. Shokri Rad, Z. Ahmad

Dept. of Applied Mechanics & Design, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor Bahru, 81310, Malaysia

Abstract

Auxetic materials are modern class of materials that have recently been gaining popularity within the research community due to their enhanced mechanical properties. Unlike conventional materials, they exhibit a negative Poisson's ratio when subjected to a uniaxial loading. This present research experimentally investigates the crush response and energy absorption performances of auxetic foam-filled square tubes under axial loading. For comparison, the crush response and energy absorption of empty and conventional foam-filled square tubes have also been examined with respect to deformation modes and force displacement curve. Standard compression tests were conducted on a series number of thin-walled tube samples. An additional compression test on conventional and auxetic foam has also been conducted to observe the behavior of foam itself. It is evident that the auxetic foam-filled square tubes are superior to empty and conventional foam-filled square tubes in terms of energy absorption capacity. It shows that such tube is preferable as an impact energy absorber due to their ability to withstand axial loads effectively. Furthermore, it is found that the load capacity increases as the crush length increases. The primary outcome of this study is design information for the use of auxetic foam-filled square tubes as energy absorbers where impact loading is expected particularly in crashworthiness applications.

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* Corresponding author. Tel.: +60-111-766-9204
E-mail address: stc_saba@yahoo.com

1. Introduction

Thin-walled tubular structures have been prevalently used as energy absorbers in crashworthiness applications such as automotive and aerospace industries to decrease human fatality and damage of vehicle components. The advantages of thin-walled structures rise from their excellent energy absorption capacity, lightweight and ease of production. The primary studies of energy absorbers were focused on steel tubes for their low costs and high ductility [1-5]. As the increasing importance of lightweight, the application of aluminum tubes has received increasingly interest for years [2, 6]. In comparison with empty thin-walled aluminum tubes, foam-filled tubes (FFT) are able to absorb greater energy without increasing considerable total weight [7-9].

To better perceive crushing behavior of FFT, several studies have been conducted using numerical, analytical and experimental methods. Reid and Reddy [10] implemented a series of experiments on the impact behavior of squared FFT subjected to quasi-static and dynamic loadings. Ahmad and Thambiratnam [11] and Ahmad et al. [12] found out 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. Sun et al. [13] investigated the energy absorption of functionally graded foam-filled (FGF) square thin-walled structures in comparison with the uniform foam-filled (UF) square tubes. It is found that the crashworthiness of FGF-filled tube is greater than that of UF-filled tube. In their study, the density of the filled foams of FGF-filled tubes was varied along the axial direction of the tube.

In a few recent decades, auxetic materials (e.g. auxetic foam) have been introduced and used in structures due to negative Poisson's ratio (NPR), which means they get constricted laterally under uniaxial compression and expand when stretched longitudinally [14, 15]. This unique ability can be applied to manufacture auxetic reinforcement in the thin-walled structures with formation the extra absorbent layers along the impact load transmission path. Most of the previous works on FFT just focused on conventional FFT, whereas the effect of using auxetic foam-filler material on the energy absorption parameters of thin-walled tubes has not been investigated to date.

This paper aims at addressing the issue of energy absorption of FFT by considering the effect of using auxetic foam-filler in aluminum square thin-walled tube. Three types of thin-walled tubes; empty tube, conventional FFT and auxetic FFT under quasi-static loading have experimentally been studied. In order to compare the crashworthiness of these structures, the energy absorption capacity (EA) and specific energy absorption (SEA) were investigated. In addition the fabrication process of auxetic foam has also been described briefly in this paper.

2. Fabrication process of auxetic foam

The auxetic material fabricated and used in this research is a type of polyurethane foam. This material was fabricated via mixing an appropriate weight ratio of two liquid chemical compositions; Polyol and Isocyanate. A previous study showed that the stiffness of the foam depends on the value weight ratios [16]. After mixing the components, the mixture was poured into a mold. The mold was then capped and held at room temperature for more than two hours.

A new modification method was used to simplify the volumetric compression step of the specimens. This method also contributes to fabrication of isotropic auxetic specimens with more complex shapes. The facilities employed in this process are hydraulic oil pump, specially-designed thick wall cylinder, special aluminum mold, and oven. To avoid oil penetration, the foam specimens were covered with plastic cover and silicate glue. Subsequently, specimens were compressed by applying oil pressure in a thick wall cylinder. Finally, the specimens need to be heated to the softening temperature and cool down at the room temperature. After finishing the process of fabrication, compression test and high speed camera were used to determine the Poisson's ratio of materials.

3. Experimental procedure

3.1. Geometry and material

Five samples for each tube: empty, conventional FFT and auxetic FFT were tested in this present study. Fig. 1 shows the configurations of the tubes used in the experimental tests.

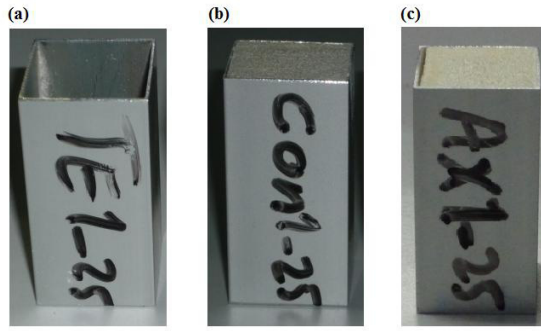


Fig. 1. Tube configuration; (a) empty tube, (b) conventional FFT, (c) auxetic FFT

The tubes were made from 1 mm thick aluminium sheets with a square cross section 25x25 mm and 50 mm height in consideration of simplicity and cost-effectiveness. The mechanical properties of the aluminium and foams were determined by using standard tensile and compression tests, respectively which are shown in Table 1.

Table 1. Mechanical properties of the materials

Type of materials	Young's Modulus	Poisson's Ratio	Initial Yield Stress
Aluminium	56 GPa	0.33	115 MPa
Conventional Foam	5.2 MPa	0.01	0.48 MPa
Auxetic Foam	9.6 MPa	-0.26	0.62 MPa



Fig. 2. Loading process of samples

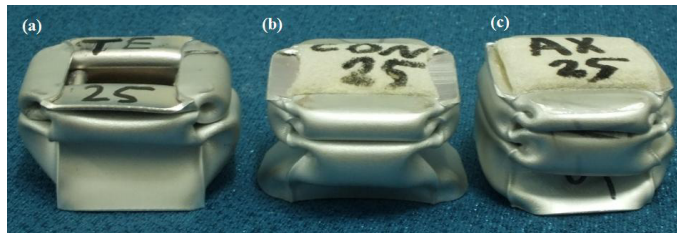


Fig. 3. The deformation modes; (a) empty tube, (b) conventional FFT, (c) auxetic FFT

3.2. Experiments

Quasi-static compression test on the samples was done by using a universal testing machine as shown in Fig. 2. The loading rate was set to 1.5 mm/min. The samples were compressed up to 30 mm crush length. The deformation modes of different specimens are shown in Fig. 3.

3.3. Crashworthiness indicators used in this study

In order to investigate the crashworthiness performance of the tubes, it is necessary to define the crashworthiness indicators. Energy absorption indicators namely Energy absorption capacity (EA) and specific energy absorption (SEA) are used to calculate energy absorption capability. The energy absorption can be calculated as follows [17].

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

where d is the crushing distance and F denotes the crushing force. In particular, the area under the load displacement curve is equal to energy absorption capacity.

The SEA is one of the most important factors in the design of crashworthy structures especially where the weight efficiency and safety are the main concerns. The specific energy absorption is defined as the energy absorbed per unit mass of the structure which is expressed by Eq.2 [18].

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

where m is the mass of the structure. It means that a greater SEA leads to a better capacity of energy absorption with respect to the mass of the structure.

4. Results and discussion

The load–displacement curve for quasi-static compression tests are shown in Fig. 4. The EA of each tube was determined by integrating the area under the experimental load–displacement curve [19] and depicted in Fig. 5(a). The SEA is determined by dividing EA by the mass of material involved in the deformation as shown in Fig. 5(b).

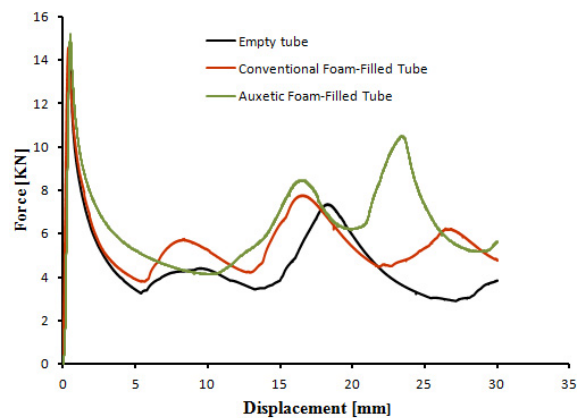


Fig. 4. Load–displacement curves

From Fig. 5(a), it is evident that each tube has a different level of energy absorption ability. The EA of the conventional FFT is about 1.23 times higher than ones of the empty tube. The EA of the auxetic FFT is 14.3% higher than that of the conventional FFT and 41.3% than that of the empty tubes. Surprisingly, the initial peak load of the auxetic FFT is slightly higher than that of the empty tube and conventional FFT which is undesirable in crashworthiness applications. However, this initial onset load effect may be compromised with a greater energy absorption capacity obtained. This is due to the NPR of auxetic material which made the extra absorbent layers along the impact load transmission path.

In Fig. 5(b), it is noted that as a conventional FFT changes to an auxetic FFT, its SEA increases at around 14%. It can also be highlighted that conventional FFT has 23% greater SEA than empty tubes. It means that despite increasing the weight of structure in auxetic FFT, better capacity of energy absorption for this tube is obtained. The possible reason for this trend is that the NPR materials can exhibit slow decay of stress according to Saint-Venant's principle.

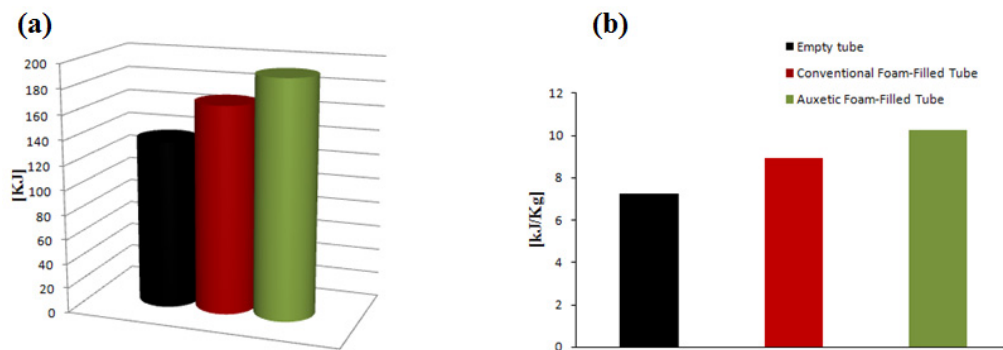


Fig. 5. (a) Energy absorption capacity of tubes, (b) SEA of tubes

5. Conclusion

In this paper, the energy absorption behavior of aluminum square tubes namely empty tube, conventional FFT and auxetic FFT was experimentally studied under quasi-static loading condition. A comparison of the results showed that an auxetic FFT has greater EA in comparison with other tubes. Overall, the auxetic FFT exhibit 41.3% and 14.3% increment in EA than empty tubes and conventional FFT, respectively. On the other hand, despite increase in the total weight of structure of auxetic FFT, its SEA increases remarkably. The present outcome of this paper may be received high interest for those engineers who require the safety and weight efficiency in their designs.

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