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Mechanical behavior of nested multi-tubular structures under quasi-static axial load

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ABSTRACT

In this paper, parameters affecting the collapse of nested multi-tubular thin-walled aluminum structures as one of the energy absorbers have been studied experimentally and using simulation techniques. In empirical studies, after annealing and determining the mechanical properties of 6101 aluminum, the properties of four different combinations of nested four-tabular structures located as equi-axed within each other were examined under quasi-static compression. Simulations and parametric investigations were done using finite element LS-Dyna software which had a good consistency with the experimental results. Simulations showed that multi-tabular structures have better performance for absorbing impact energy compared to single-tube structures with the same thickness, height and mass. It was also observed that the increase in the number of tubes from 1 to 2, 3, 4 and 5 leads to an increase in specific energy as 37%, 66%, 105%, and 88%, respectively as well as the increase in the crash force efficiency as 62%, 96%, 154% and 185%, respectively. In this study, the effects of thickness and the mean diameter of tubes on the characteristics of the collapse of structures were also investigated.

1. Introduction

Todays, thin-walled energy absorbers which cause a waste of energy through plastic deformation have numerous applications. These types of absorbers are highly used in reducing injuries and damages caused by collision. The more the amount of deformation of absorber, the higher the level of energy absorbing for them will be. It should be noted that high level of absorbed energy is not only criteria for designing absorbers but the stability of the rate of absorbing energy and minimizing force required for the initial buckling and other factors are also important and effective [1–4]. Guden and Kavi investigated wrinkling and folding of single circular tubes and hexagonal and square boxes which were a combination of circular aluminum tubes in two states of hollow and filled with aluminum foam under uniaxial quasi-static loading by experimental method [5]. Their results showed that using a combination of empty or foam-filled aluminum multi-tubes results in considerable increase of energy absorption capacity of the structure. Olabi et al. studied experimentally and numerically an arrangement of nested circular tubes which had suffered lateral dissipation by dynamic loading [6]. In experiments the impactor had a velocity between 3 and 5 m/s, and numerical simulations carried out with LS-Dyna code. They concluded that nested tubes are more efficient than singular tube when loaded laterally. In a study by Alavi Nia and Haddad on different types of absorbers, circular section had maximum capability for absorbing energy and was the most suitable section [7]. The important results of their experimental tests and numerical simulations are as follow: the circular and the triangular section tubes have the most and the least specific energy absorption, respectively; the circular tubes have the greatest peak load and the tapered ones have the minimum peak load among the investigated sections; and finally, the difference between the peak and average loads is considerable for frusta and tapered structures and this value is less for frusta tubes. Li et al. evaluated deformation and capacity of energy absorption in aluminum tubes subjected to axial and oblique loading and observed new modes of deformation [8]. They investigated the behavior of singular empty, single foam-filled and bi-tubular foam-filled sandwich structures and showed that twisting folding, expansion folding and symmetric folding are common deformation modes of the tubes. Furthermore, they found that specific energy absorption of the tubular sandwich structure is more than the empty tubes. Jandaghi Shahi and Marzbanrad studied experimentally and analytically collapse behavior of thin-walled aluminum structures with circular section and variable wall thickness under quasi-static axial load. They showed that absorbing energy and maximum force during the collapse of thin-walled structures can be improved by changing the thickness [9]. They found good agreement between experimental results and analytical predictions; and concluded that there is better control on collapse

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Table 1.
Geometry specifications of the tubes.

	Thickness (mm)	Average radius (mm)
Pipes (1)	1.23	19.95
Pipes (2)	1.12	21.85
Pipes (3)	2.17	28.88
Pipes (4)	2.03	41.34
Pipes (5)	2.70	62.50

process with Taylor-made- tubes (TMT) because of variation of the material and thickness along the tube length. Besides, it was shown that TMT structures have greater specific energy absorption and less amount of peak load. Xiong Zhang and Hui Zhang examined multicellular circular columns with different levels in experimental, theoretical and simulation studies [10]. In experiments the structures with various sections subjected to axial quasi-static loading; and in theoretical study based on constituent element method they predicted the collapse resistance of the multicellular structure. It was found that specific energy absorption of multicellular circular columns was significantly more than single cylindrical tubes. In a laboratory research, Sharifi et al. tested compound double tubes under quasi-static axial load [11]. They showed that the collapse mode of both of the tubes are the same, as like as two apart tubes if there was not interaction between the tubes due to sufficient gap. Furthermore, they found that deformation length of bi-tubular structures is less than single tubes, and an increase in height of one of the tubes results in decrease of the peak load of the structure. Energy absorption and collapse behavior of single, double, triple, and multilayer structures for circular and square sections in both modes of empty and foam-filled was investigated by Dass Goel [12]. In his simulations, he showed that compared to single columns, energy absorption in binary and ternary columns are more for both rectangular and circular sections. In a comparison between the concentric circle tubes and concentric square columns, it was found that circular columns are better at energy absorption. In an experimental and numerical work, Alavi Nia and Khodabakhsh showed that compared to single tubes, nested double tube absorbents have greater capacity to absorb energy when subjected to axial loading [13]. They studied the effect of tubes distance and finally proposed an optimum distance for maximizing the absorbed energy. Baroutaji et al. [14] studied the behavior of the internally nested tubes subjected to lateral dynamic and quasi-static loading and investigated the effects of various parameters on the energy absorption of the tubes. In a creative design they investigated the behavior of three different arrangements of nested circular tubes, and carried out a comprehensive numerical study about the effective parameters on collapse of nested tubes.

Many researchers have studied crushing and energy absorption characteristics of the non-circular sections with and without foam filling [15–22]. Zhang and Zhang [17] investigated crush resistance of polygonal columns and angle elements subjected to axial loading both experimentally and numerically. Energy absorption characteristics of multi-cell square tubes under axial compression

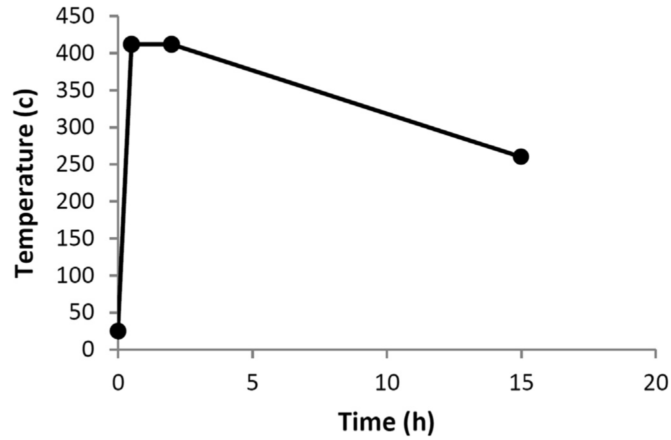

Fig. 1. The process of heating and cooling aluminum tubes to enhance ductility.

are investigated in references [18,19]. Bai et al. [20] studied analytically, experimentally and numerically the crushing behavior of hexagonal multi-cell thin-walled structures. Crashworthiness optimization of multi-cell triangular tubes using surface response method is carried out by Tran et al. [21]. Khan et al. [22] investigated the crushing of frusta tubes and proposed a curved folding model with non-constant length. Their theoretical model was in good agreement with experimental data.

There are some other types of energy absorption mechanisms; inward or outward inversion, extension and tearing are some cases studied in [23,24].

Most of the researches about nested tubes abovementioned are about bi-tubular structures; and in the case of three tubular structures the loading is laterally. Therefore, there is not a comprehensive study on energy absorption behavior of multi-tubular structures subjected to axial loading. Hence, mechanical behavior of nested three to five tubular energy absorbents is investigated by the authors.

In this study, after determining the effect of annealing on the characteristics of the energy absorption of tubes, the mechanical behavior of several tubular structures with different numbers of tubes were studied both experimentally and numerically. Also, the effect of the number of tubes and the effect of their height, thickness, and diameter on the characteristics of energy absorption were analyzed as well.

2. Experiments

In order to perform empirical experiments, tubes with geometry specifications provided in Table 1 were prepared. Of each tube, one sample went under Quanto test. Quanto test results showed a 6101 aluminum alloy in accordance with the standard ASM [25] with high confidence (alloy density of 2690 kg per cubic meter). Weight percentage of aluminum alloy 6101 [14] and Quanto test results are given in Table 2.

Given that in the study the greatest amount of flexibility was

Table 2.
Weight percentage of the elements in the prepared tubes (prepared using extrusion method).

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	B	Others (each)	Others (total)	Al
Percent [14]	0.3 To 0.7	0.5 Max	0.1 Max	0.03 Max	0.35 To 0.8	0.03 Max	0.1 Max	0.06 Max	0.03 Max	0.1 Max	Rem
TUBE 1	0.42	0.1	0.02	Trace	0.51	Trace	0.01	< 0.001	✓	✓	✓
TUBE 2	0.42	0.1	0.02	Trace	0.51	Trace	0.01	< 0.001	✓	✓	✓
TUBE 3	0.32	0.2	0.02	trace	0.5	Trace	0.02	< 0.001	✓	✓	✓
TUBE 4	0.41	0.13	0.01	Trace	0.5	Trace	0.01	< 0.001	✓	✓	✓
TUBE 5	0.36	0.7	0.15	0.07	0.26	0.03	0.1	< 0.001	✓	✓	✓