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Optimizing the layout of nested three-tube structures in quasi-static axial collapse

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ABSTRACT

In this study, energy absorption characteristics of aluminum nested three-tube structures as one of the types of thin-wall energy absorbers were experimentally and numerically examined and some optimal conditions were presented for such structures. In so doing, after determining the type of alloy and stress-strain curves of the tubes, four samples were analyzed under quasi-static collapse. The structures were simulated using finite element software LS-Dyna and the results were compared with data from experimental tests. There was good agreement between experimental and numerical results. After comparing multi-tubular structures with single conventional structures, it was indicated that these structures have a higher capacity to absorb energy. Then, with considering different height and thickness for the structures, the optimal value of these quantities was determined and it was shown that through optimizing three-tube structures, the maximum collapse force can be as low as possible and energy absorption capacity can be hold high. Finally, by optimizing the results with response surface method using Minitab software, samples with optimal performance in the process of collapse were obtained.

1. Introduction

Research on energy absorbers was begun by Alexander in 1960. He did his theoretical investigations based on the assumption of rigid-plastic behavior on thin-wall cylindrical tubes [1]. Abramowics and Jones modified the theory of Alexander and mean crushing force for symmetric folding mode in cylindrical columns [2]. Alavi Nia and Haddad conducted a comparative analysis as experimental and simulation for energy absorption and deformation of thin-wall columns with different sectional geometries such as circular, square, rectangular, hexagonal, triangular, pyramidal and conical [3]. Li et al. investigated the deformation and energy absorption capacity in aluminum tubes under axial and oblique loading [4]. Zamani et al. studied experimentally the cylindrical energy absorbers and found that by increasing the thickness and diameter of the tubes, the crushing force increases [5]. Tang et al. showed that multicellular cylindrical columns have excellent energy absorption properties [6]. In their study, Ying Zhang and Hu Zhang showed that the specific energy absorption of multicellular cylindrical columns is significantly more than single cylindrical tubes [7]. Djamaluddin et al. evaluated aluminum two-tube structures in both empty and foam-filled states under axial and oblique loadings and found that an increase in the loading angle of thin-wall two-tube structures leads to a reduction in specific energy and maximum collapse load [8]. Alavi Nia and Khodabakhsh studied the effect of radial distance among nested cylindrical tubes on mechanical behavior and their energy absorption in simulation and experimental methods [9]. Azarakhsh et al. analyzed the effects of the parameters of a tube including wall thickness, impact velocity, and impactor mass on the dynamic behavior of two-tube structures [10].

Researches about single and nested energy absorbers don't limited to axial loading; a couple of researchers have studied lateral loading of these structures. Morris et al. [11] investigated the behavior of nested tubes subjected to lateral loading at free and constrained boundary conditions. They also studied lateral crushing of circular and non-circular tube systems under quasi-static conditions experimentally and numerically [12], and characteristics of the tubes were analyzed via compression-displacement curves. Olabi et al. investigated optimized design of nested circular and oblong steel tube energy absorbers under lateral impact loading [13,14]. The steel structures were loaded dynamically by a falling impactor at 3–5 m/s velocities; besides, energy absorption characteristics were simulated by LS-Dyna code. Baroutaji et al. [15] studied energy absorption of internally nested tubes subjected to lateral quasi-static and impact loading. They examined three different systems of nested tubes and showed that energy absorption capacity of the structure could be increased by selection of the appropriate system. Furthermore, the effect of various parameters on the collapse mode of the nested tubes was

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Table 1
Geometric 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

considered.

In some studies, the characteristics of energy absorption of thin-walled absorbers have been optimized. Ebrahimi and Vahdatzadeh optimized energy absorption parameters of sandwich cylindrical column with honeycomb core in a multi-objective form [16]. In the study conducted by Abbasi et al. on the columns of the cross-section polygon, the number of corners in order to increase the specific energy and reduce the maximum load was optimized using the multi-objective optimization method [17]. In a multi-objective optimization, Gao et al. optimized columns with elliptical cross-section filled with foam under oblique impact load [18].

Baroutaji et al. had a comprehensive study about energy absorption and multi-objective crashworthiness optimization of circular, oblong and sandwich tubes under lateral quasi-static loading [19–21]. In Ref. [19] the authors used response surface method (RSM) for design of experiments of oblong tube under lateral loading; also they studied the effect of geometric parameters on the collapse behavior of the structures and concluded that the optimum design for flat plate indenter-unconstrained system achieved in the case of the largest and smallest values of the thickness and the diameter, respectively. Baroutaji et al. [20] optimized the circular tube structures under lateral quasi-static loading using RSM method and showed that the specific energy is increased by increasing the thickness and decreasing the diameter of the tubes. Sandwich tubular energy absorbers with foam core under lateral loading were simulated with LS-Dyna code and optimized using RSM method [21]; results of the research showed that energy absorption capacity could be increased with increasing the thickness of the foam and reducing the diameter of the inner tube.

Due to the fact that so far no research has been done on optimizing the properties of the collapse of multi-tubular structures, in this study, after determining the collapse properties of various three-tube structures, geometrical optimization of three-tube structures was done in order to reduce the maximum load and improving specific energy using response surface method.

2. Experimental tests

Experimental tests were performed using the tubes in Iranian market. The geometry of the tubes provided is given in Table 1. Since no information was available on the alloy of the tubes, Quantometery tests were performed on each of the tubes; the results are given in Table 2. According to the results, it is observed that according to [22], all the three tubes are made of aluminum alloy 6101 with the density of 2690 kg/m^3. The method applied to make the tubes is extrusion and after initial tests, it was revealed that the tubes did not have the desired ductility necessary for folding without breaking, so after annealing on the tubes (annealing carried out based on [23] by Azar furnace F11L-1250 at Bu-Ali Sina University), two dumbbells in the axial direction in accordance with ASTM E8-E9 [24] were separated from each tube (Fig. 1) and quasi-static tensile test were done using STM 150 apparatus with the speed of 2 mm/min. The true stress-strain curves of samples are shown in Fig. 2.

Given the curves in Fig. 2, the mechanical properties of tubes 1–3 were extracted and listed in Table 3 (to exactly determine the Young's modulus of the samples, 50 mm short course Extensometer was used).

Then, four samples of three-tube structures shown in Fig. 3 were under quasi-static axial compression tests at 5 mm/min using a STM 150 apparatus in Bu-Ali Sina University, Iran. The specifications of these structures are given in Table 4; h and t, and R represent the height, thickness and average radius of the tubes, respectively and indices 1–3 show the property of the tubes of each structure, from minimum radius to maximum radius. To name the samples, two letters of E. and V. (Experimental Validation) and one number which show the number of the structure have been used.

The results of quasi-static collapse of structures E.V.1 to E.V.4 are listed in Table 5. Furthermore, consecutive deformations of the E.V.4 sample during loading are shown in Fig. 4. The co-axial nested tubes are set on the lower jaw freely; the lower jaw is stationary while the upper jaw moves downward and compresses the specimen quasi-statically. Loading is continued till complete compression of the tubes.

Various steps of the experiments in the research are shown in Fig. 5.

3. Simulation

For simulating the energy absorbers, finite element LS-Dyna software was used. According to Fig. 6, the structures were designed nested and concentric. Upper and lower plates are rigid. According to the tests, the lower plate is fixed and the upper plate comes down only in the axial direction in a quasi-static form. The elements of the tubes have been considered as shell and after considering various sizes for them, for elements 2×2 mm^2, convergence was achieved; however, in smaller sizes, there was no change in the amount of energy absorbed. Static and dynamic coefficients of friction were selected as 0.3 and 0.2, respectively. The mechanical properties of each of the tubes were used in the simulations with regard to the stress-strain curve of Fig. 2 and Table 3.

3.1. Validation of the simulation results

In order to ensure the accuracy of the simulations, the structures tested in Section 2 were first simulated. Load-displacement curves in both experimental and numerical tests are shown in Fig. 7. Given the curves, the amounts of energy absorption, the

Table 2
Weight percentage of the elements in the tubes made by extrusion.

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	B	Others (each)	Others (total)	Al
Percent [22]	**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	√	√	√