Experimental and Numerical Study of In-Plane Loading of Thin-Walled Tubes with Different Section Shapes and Wall Thickness

Sajjad Dehghanpour*
Department of Mechanical Engineering, Tuyserkan Branch, Islamic Azad University, Tuyserkan, Iran
Email: sajjaddehghanpour@yahoo.com
*Corresponding author

Ali Alavi Nia
Department of Mechanical Engineering, Bu-Ali Sina University, Hamedan, Iran
Email: alavi1338@yahoo.com

Received: 26 December 2021, Revised: 20 April 2022, Accepted: 23 April 2022

Abstract: In this paper, deformations and energy absorption capacities of thin-walled tubes with different section geometries (circle, square, rectangle, hexagon and triangle) under quasi-static in-plane loading are investigated. The tubes have the same material properties, mass, volume, lengths and average section area and the loading conditions are similar for all of the specimens. In order to investigate the behaviour of the tubes, more than 100 tests are carried out and numerical simulations are performed. The numerical results are in good agreement with experimental data and show that the section geometry has an important effect on energy absorption capacity so that the circular and square sections have the least and the most capability of energy absorption, respectively. Furthermore, for a specific tube, the absorbed energy increases with the wall thickness. The first peak load in load-displacement curves has the greatest and the smallest values for rectangular and circular sections, respectively.

Keywords: Energy Absorption, In-Plane Loading, Peak Load, Quasi-Static, Thin-Walled Tube

How to cite this paper: Sajjad Dehghanpour, and Ali Alavi Nia, "Experimental and Numerical Study of In-Plane Loading of Thin-Walled Tubes with Different Section Shapes and Wall Thickness" , Int J of Advanced Design and Manufacturing Technology, Vol. 15/No. 3, 2022, pp. 89-97.
DOI: 10.30486/admt.2022.1948255.1330.

Biographical notes: Ali Alavi Nia is Professor at Bu-Ali Sina University, Hamedan, Iran. He received his PhD in Mechanical Engineering from Tarbiat Modarres University, in 2003. His current researches include Impact mechanic and Energy absorption in thin–walled structures. **Sajjad Dehghanpour** is Assistant Professor of Mechanical Engineering at IAU, Tuyserkan Branch. He received his PhD in Mechanical Engineering at Department of Mechanic Engineering Islamic Azad University, Qazvin Branch, Iran in 2020. His current researches include Impact mechanic and Energy absorption in thin–walled structures.

 © 2022 IAU, Majlesi Branch

1 INTRODUCTION

Analysis of thin-walled structures is one of the important subjects in mechanics of impact. Aluminium thin-walled tubes are of interest due to their low density and high resistance to corrosion properties and are used in automobile industries extensively. During designing such structures, studying of their collapse behaviour and energy absorption capacity would be necessary and this is the reason for considerable researches about axial and lateral loading of them during recent decades.

Collapse and deformation of thin-walled structures when are subjected to axial and/or lateral loads, occur in the form of folding and crushing due to initiation and movement of plastic hinges. Such a failure mechanism dissipates energy in the form of plastic deformations. The geometry, dimensions and loading type have considerable effects on the behaviour of these structures especially on energy absorption capacity of them.

Mutchler studied numerically in-plane loading and energy absorption of aluminium tubes which are con-strained between two rigid plates [1]. Deruntz and Hodge investigated the behaviour of tubes using finite element method and assumed that the deformed contour consists of four circular arcs which maintain their original radius and plastic deformation occurs in the hinges only [2]. Reid and Reddy studied compression of tubes with lateral constraints and investigated the effect of these constraints theoretically [3]. They carried out experiments on thin-walled structures with a circular section and different lengths and studied the effect of length on the energy absorption capacity [4]. Sinha and Chitara studied in-plane loading of square section tubes both experimentally and numerically and obtained the collapse load of these structures [5]. Kecman investigated the behaviour of rectangular section tubes under in-plane loading using FEM and compared the results with experimental data [6]. Gupta and Khullar studied construction of basic plastic hinges and showed that the hinges are formed at first at the middle of vertical arms and then at the four corners of the section [7]. Gupta and Sekhon investigated the effect of in-plane loads on square and rectangular section tubes both experimentally and numerically and studied the effects of thickness, geometry and friction [8]. Gupta et al. [9] studied also the in-plane loading of thin-walled structures with circular section and proposed an analytical model for prediction of deformations of tubes and compared them with experimental data. Morris et al. [10] investigated in-plane loading of compound tubes and show that in-creasing number of tubes result in increase of absorbed energy; furthermore, the vertical and oblique constraints affect this property. Kheirikhah et al. [11] studied experimentally and numerically the energy absorption, crushing length, and deformation of thin-walled circular compo-site tubes under a quasi-static axial loading. Dehghanpour and Rahmani investigated the lateral col-lapse of square and rectangular composite tubes experimentally and numerically [12]. Dehghanpour and Rahmani investigated the crushing length, deformations and energy absorption of thin walled square and rectangular composite tubes which were reinforced with Aluminium and SMA wires and without wire, under a quasi-static lateral load, both experimentally and numerically [13]. Dehghanpour et al [14] studied the energy absorption of metal-matrix composite in compound tubes and investigated the energy absorption in two systems with the same weight.

As a result of review in the accessible literatures, it is found that there is no work on deformations and energy absorption capacities of Aluminium thin-walled tubes with different section geometries (circle, square, rectangle, hexagon and triangle) under quasi-static in-plane loading. In this paper, the results of experimental and numerical studies about in-plane loading of thin-walled tubes with different sections and various thicknesses are presented and energy absorption capacity and load-displacement curves of them are compared.

2 EXPERIMENTS

2.1. Specimens Specifications

Since there were not available the tubes with predefined dimensions, they were made manually. In this procedure due to welding process effects it may be some unwanted changes in properties which are diminished by slowly cooling and grinding of weld line. Aluminium alloys due to their low density and high strength are used as energy absorbers material. AL3003-H 12 alloy plates in three thicknesses 1, 1.5 and 3 mm are used to make the specimens.

Tension test: In order to determine mechanical properties of plates, tension test is carried out based on ASTM 8M-98 by using INSTRON 8305 apparatus. Results of this test are presented in Table I. The stress-strain curve for one of the samples is shown in “Fig. l”.

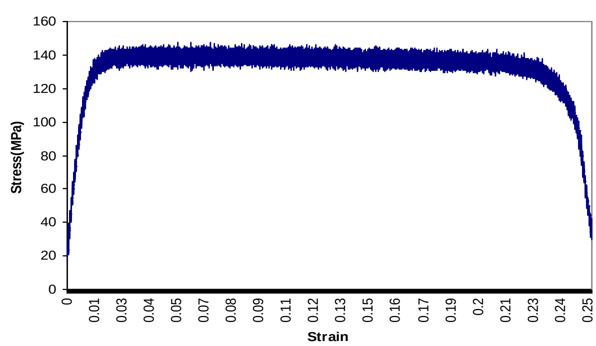


Fig. 1 Stress-strain curve in tension test for one of the samples.

© 2022 IAU, Majlesi Branch

Based on data presented in “Table 1”, the yield and ultimate strengths of the plates are obtained equal to 130 and 138.47 MPa, respectively.

Table 1 Tension test results for the material of the samples

Thickness of Specimen (mm)	Elongation at (mm) Break	Stress at 0.2% Yield (MPa)	Ultimate Strength (MPa)
1	6.5	132	140
1	7.33	129	135
1	6.77	130.5	138
1.5	6.9	129.53	131.89
1.5	7.1	127.21	134
1.5	7.1	131	147.8
3	6.8	128.7	139
3	6.85	131	138.6
3	7.1	130.6	142

Chemical compositions: The samples are made from three plates with different thicknesses. In order to determine material compositions of the plates, three 3 x 3 cm specimens are tested and the results are listed in “Table 2”. Comparing these data with standard hand books verifies that the materials or the plates are AL3003-H 12.

Table 2 Chemical compositions of the specimens' materials

Composition	Percentage (1 mm thickness plate)	Percentage (1.5 mm thickness plate)	Percentage (3 mm thickness plate)
Al	97.82	97.81	97.80
Si	0.41	0.38	0.39
Zn	0.048	0.047	0.046
Mn	1.03	1.06	1.05
Sn	0.00015	0.00017	0.00018
Fe	0.52	0.55	0.53
Cu	0.17	0.15	0.18
	99.99815	99.99717	99.9961

Preparing the samples: After cutting the plates, the bending process was carried out using numerical control machine, then the edges of parts were welded and finally the grinding operation were done and samples cooled at moderate rate. Some of the prepared specimens are shown in “Fig. 2”.

Coding the specimens: For identification of the samples and simpler referring them, proper codes were assigned to the samples. Each sample has a code consisting a letter which is abbreviation of the section name and a decimal number which shows the size of section. For the rectangular sections letters "a" and "b" refer to the longer and the shorter dimensions of the rectangle, respectively and the last letter shows the edge which the loading is exerted. For example, Ra57b38a refers to a specimen with rectangular section which its dimensions are 57× 38 mm and is loaded in a direction normal to its longer edge. These codes are listed in “Table 3”.

Fig. 2 Prepared specimens with various section geometries.

Table 3 Specifications and codes of the first group of specimens

No.	Specimen Section shape	Specimen Code	Section Dimensions (mm)
1	Circle	C60.47	Diameter 60.47
2	Triangular	T63.3	Edge 63.3
3	Hexagonal	H31.66	Edge 31.6
4	Rectangular	Ra57b38a Ra57b38b	Cross section 57×38
5	Square	S47.5	Edge 47.1

Specimens' dimensions: The specimens (and test) are arranged in two groups. In the first group which is used to investigate the effect of section geometry on the energy absorption capacity and the first peak load in load-deflection curve, there are five types of sections with the same length and thickness of 100 and 1.5 mm, respectively. Section shapes are circle, triangle, hexagon, rectangle and square. These types have the same material, volume, length, section area and thickness; and their specifications and codes are listed in “Table 3”.

The second group of specimens is designed to study the effect of the wall thicknesses of the tubes on the 'energy absorption capacity and the peak load in load-detection curve. Since the net area of section for all of the specimens should be the same, change in specimen thickness results in change in its diameter or edges. In order to provide the possibility of comparison between the two groups, the second group specimens have the same length as the first group. The specification and codes of the second group specimens are presented in “Table 4”.

© 2022 IAU, Majlesi Branch

Table 4 Specifications and codes of the second group of specimens

No	Specimen Section shape	Specimen Code	Section Dimensions (mm)	
			Diameter	Thickness
1	Circle		Diameter	Thickness
		C90.7	90.7	1
		C60.47	60.47	1.5
		C30.29	30.29	3
2	Rectangular		Cross section	Thickness
		Ra85.5b57a	85.5×57	1
		Ra57b38a	57×38	1.5
		Ra28.5b19a	28.5×19	3
3	Square		Edge	Thickness
		S71.25	71.25	1
		S47.5	47.5	1.5
		S23.75	23.75	3

2.2. Quasi-Static Tests

Test procedure: Quasi-static compression tests are carried out using Instron 8305 apparatus (“Fig. 3”).

Fig. 3 Instron 8305 apparatus.

This machine has two jaws which the upper one is stationary and the lower one can move with a predefined velocity in a specific distance. The load is exerted by hydraulic system up to 600 KN. The specimen is set between jaws and the load- displacement curve is plotted during deformation. The rate of loading for all of tests is 100 mm/s.

2.3. Test Results Related to The Effect of Section Geometry

In this section, results of tests related to the effect of section shape on the energy absorption and the first peak load are presented and the optimum shape of the section is determined.

In these tests, the specimens listed in “Table 3” are located on the lower jaw and a rigid steel plate over it. The compressive loading is done at a velocity of 100 mm/s. Three tests with the same conditions are carried out for each case and the values of the maximum force (the first peak load) and the maximum displacement (crushing distance) are determined from the load-displacement curve. The value of the absorbed energy is calculated from the area under load-displacement curve and the mean force value is calculated by dividing the absorbed energy to the displacement. Figure 4 shows different specimens during the test and after complete deformation.

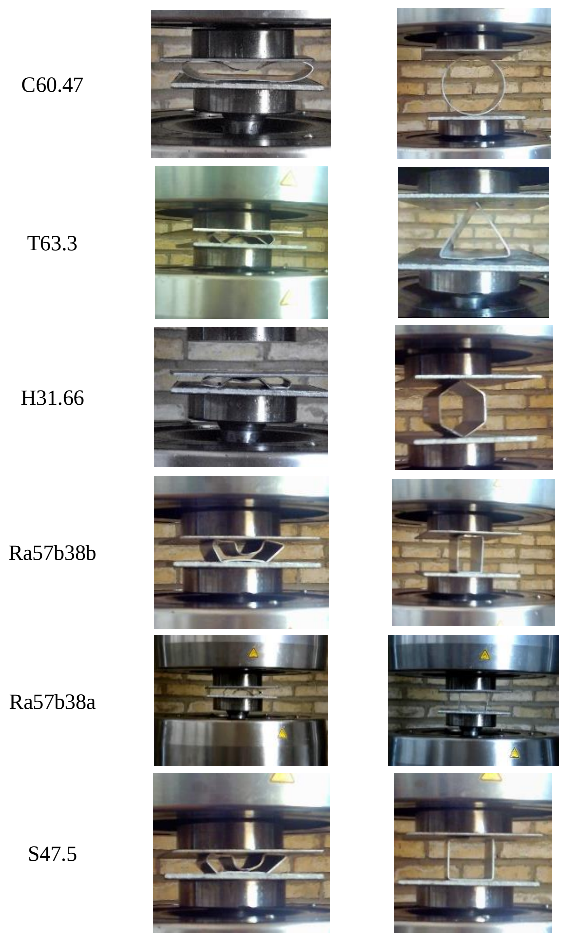


Fig. 4 Test set up for different specimens (right: at the beginning of loading, left: at the end of loading).

The most important parameters in these tests are the maximum displacement (crushing length), Wmax, the absorbed energy, E, the peak load, Fmax and the mean force, Fmean. The values of these parameters for all of tested specimens are listed in “Table 5”. It should be explained that since there is no edge for circular section, its load-displacement curve has no a peak before

© 2022 IAU, Majlesi Branch

continuous deformation and therefore in this case, the mean force is greater than the first peak load.

Table 5 Values of the important parameters measured from tests on different specimens

Specimen code	Crushing Length (mm)	Max force (N)	Mean force (N)	Absorbed energy (J)
C60.47-1	50	1535	1642.8	82.14
C60.47-2	47	1540	1707.65	80.26
C60.47-3	46	1528	1763.47	81.12
T63.3-1	34.6	11715	3410.40	118
T63.3-2	36	11692	3361.4	121
T63.3-3	35.2	11704	3323.86	117
H31.66-1	50	5671	2200	110
H31.66-2	49.8	5598	2329.31	116
H31.66-3	51.3	5682	2241.71	115
Ra57b38a-1	29	17920	6206.89	180
Ra57b38a-2	32	17754	5687.5	182
Ra57b38a-3	31	17810	5967.74	185
Ra57b38b-1	39	13110	3205.12	125
Ra57b38b-2	38	12996	3236.84	123
Ra57b38b-3	42	13000	2833.33	119
S47.5-1	42	14958	4476.19	188
S47.5-2	40	15217	4675	187
S47.5-3	41	15026	4609.75	189

2.4. Test Results Related to The Effect of Wall Thickness

In these series of tests, the length and the net section area are taken constant but the thickness is changed. The tests are carried out on three section geometries consisting circular, rectangular and square. Selection of these sections is due to their performance in the previous tests so that the circular and square sections showed the best and the worth capability in energy absorption, respectively. Tests are carried out on the specimens listed in “Table 4”. For each case, three tests are done and the load-displacement curves are plotted. The values of the desired parameters are measured and listed in “Table 6”.

3 NUMERICAL SIMULATIONS

Since the experimental studies are heavy expense and involve difficulties, and due to complexity of analytical works in the field of plastic deformations, the researcher’s tendency is toward using numerical soft wares. LS-DYNA software due to its capabilities in modeling impact loads and high deformation processes has an extensive application in this field.

In this research, besides the experimental tests the numerical simulation is done using LS-DYNA 970. Three dimensional simulations are carried out for modeling in-plane loading of thin-walled tubes with different section geometries. Tubes dimensions are as the same as tested specimens (as are listed in “Tables 3 and 4”). The upper surface is stationary and the lower one is moved toward it with a velocity of 100 mm/s. The boundary conditions are as like as those in tests. Material properties are taken from tension tests. Proper contacts between the tubes' elements and the end plates and between the tubes' elements with each other are defined. The finite element model of the square section tube during loading is shown in “Fig. 5”.

Table 6 Values of the important parameters measured from tests on different specimens

Specimen section shape	Crushing Length (mm)	Max force (N)	Mean force (N)	Absorbed energy (J)
Circle	47.66	1534.33	1704.64	81.17
Triangular	35.26	11703.6	3365.22	118.66
Hexagonal	50.36	5650.33	2257	113.66
Rectangular(a)	30.66	17828	5954.04	182.33
Rectangular(b)	39.66	13035.33	3091.76	122.3
Square	41	15067	4586.98	188

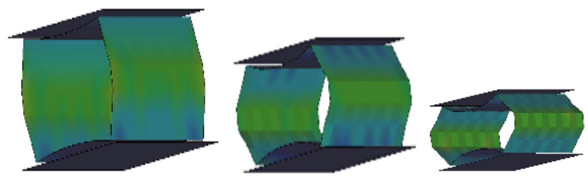


Fig. 5 Finite element model of the square section tube during loading.

3.1. Numerical Results Related to The Effect of Section Geometry

The results of numerical simulations of quasi-static loading of tubes with different section geometries are listed in “Table 7”. Furthermore, the simulated specimens before and at the end of loading process are shown in “Fig. 6”.

Table 7 Comparison of the absorbed energy and the maximum and average loads at in-plane

Specimen section shape	Crushing Length (mm)	Max force (N)	Mean force (N)	Absorbed energy (J)
Circle	49	1440	1538.77	75.4
Triangular	35	11400	3085.7	108
Hexagonal	49	5150	2122.44	104
Rectangular(b)	38	12600	2921.05	111
Rectangular(a)	30	16900	5966.66	179
Square	42	13700	4357.14	183

3.2. Numerical Results Related to The Effect of Tube Wall Thickness

In this section, the results of simulations conducted to investigate the effect of the tube wall thickness on energy absorption capacity and the maximum and

© 2022 IAU, Majlesi Branch

average forces are presented. The change in thickness is so that the net area of the tube section stays constant. Three sections including circular, rectangular and square in three different I, 1.5 and 3 mm thicknesses are chosen to simulate as in experiments. The results of these simulations are presented in “Table 8”.

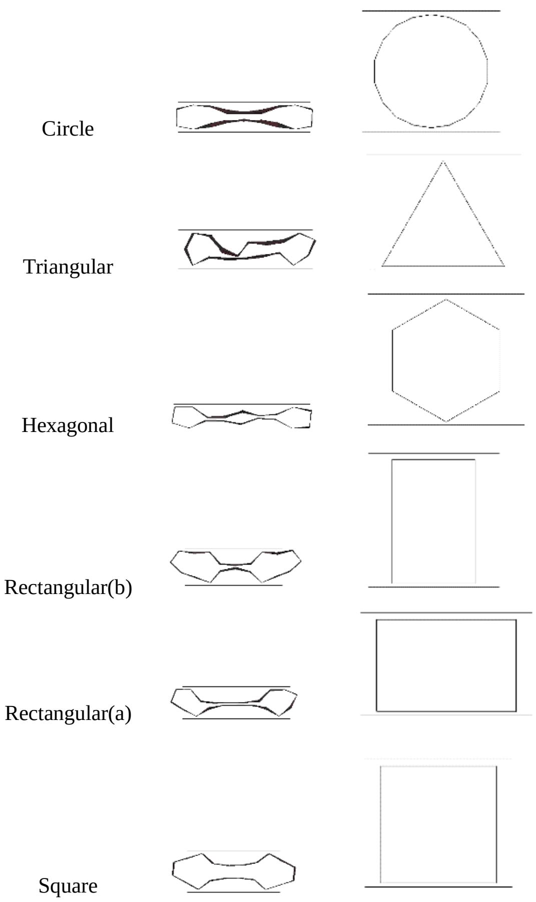


Fig. 6 Deformation of tubes with different section geometries subjected to in-plane loading right: before loading left: at the end of loading.

4 COMPARISONS BETWEEN THE NUMERICAL AND EXPERIMENTAL RESULTS

The results of the simulations are compared with the experimental data and differences are calculated and presented in “Table 9”.

4.1. Comparison of the Results Related to The Effect of Section Geometry

Absorbed energy: As it is clear from “Table 9”, the square section tube has the greatest capability of energy absorption and the tube with rectangular section which is loaded across its longer edge is placed after it. Also the least energy absorption belongs to the circular section tube.

Table 8 Comparison of the absorbed energy and the maximum and average loads at in-plane loading of tubes with different wall thicknesses

Specimen section shape	Thickness (mm)	Crushing Length (mm)	Max force (N)	Mean force (N)	Absorbed energy (J)
Circle	1	77	371	431.16	33.2
Circle	1.5	49	1440	1538.77	75.4
Circle	3	24	10800	10833.33	260
Rectangular (a)	1	46	4680	1300	59.8
Rectangular (a)	1.5	30	16900	5966.66	179
Rectangular (a)	3	11	70200	38636.36	425
Square	1	58	3660	1134.48	65.8
Square	1.5	42	13700	4357.14	183
Square	3	18	62400	25555.5	460

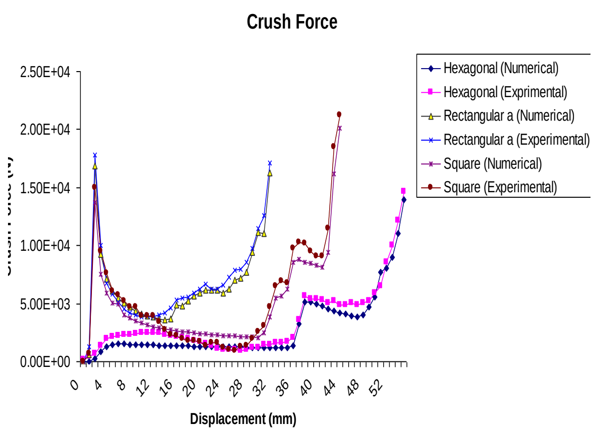
Table 9 Comparison between the numerical and experimental results for the absorbed energy

Specimen section shape	Specimen Code	Max Force (N) (Numerical)	Max Force (N) (Experimental)	Difference (%)
Circle	C 60.47 in	1440	1534.33	6.14
Hexagonal	Poly 31.6 in	5150	5650.33	8.85
Triangular	Tri 63.3 in	11400	11703.6	2.59
Rectangular (b)	Reca57b38inb	12600	13035.33	3.33
Rectangular (a)	Reca57b38ina	16900	17827	5.19
Square	Squ 47.5 in	13700	15067	9.07

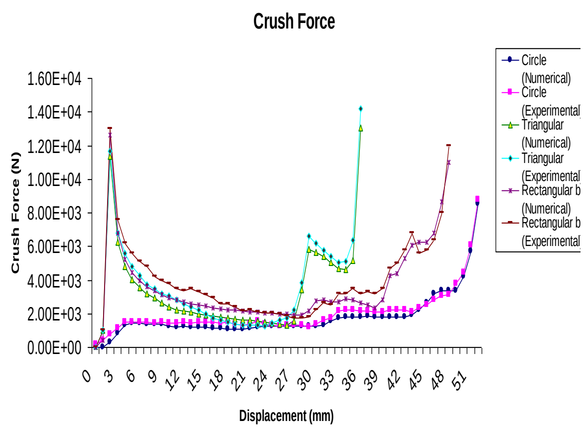
Table 9 shows that changing the section shape changes the absorbed energy capacity so that the least capacity belongs to the circular section which has no edges. In hexagonal and triangular sections, the energy absorption increases but due to non-perpendicular edges this capacity is not the most. For the rectangular section, the closer the aspect ratio to unity the greater the absorbed energy and the maximum value belongs to square section.

© 2022 IAU, Majlesi Branch

The load-displacement curves for hexagonal, square and rectangular (which is loaded across its longer edge) section tubes obtained from experiments and simulations are compared in Fig. (7- a).



(a)



(b)

Fig. 7 Comparison between load-displacement curves obtained from tests and simulations: (a): (upper): hexagonal, square and rectangular (which is loaded across its longer edge) section tubes, and (b): (lower): circular, triangular and rectangular (which is loaded across its shorter edge) section tubes.

The same curves for the circular, triangular and rectangular (which is loaded across its shorter edge) section tubes are presented in "Fig. (7-b)". Deformations of the tubes from tests and simulations during loading at the same times are shown and compared in "Fig. 8". The peak load: The peak load is the most dangerous load during impact which is recognized with the first peak in the load- displacement curve and it is interested to reduce its value. Comparison of this load for the investigated sections of "Table 9" shows that the least and the greatest loads are related to the tubes with circular and rectangular section which is loaded across its longer edge, respectively.

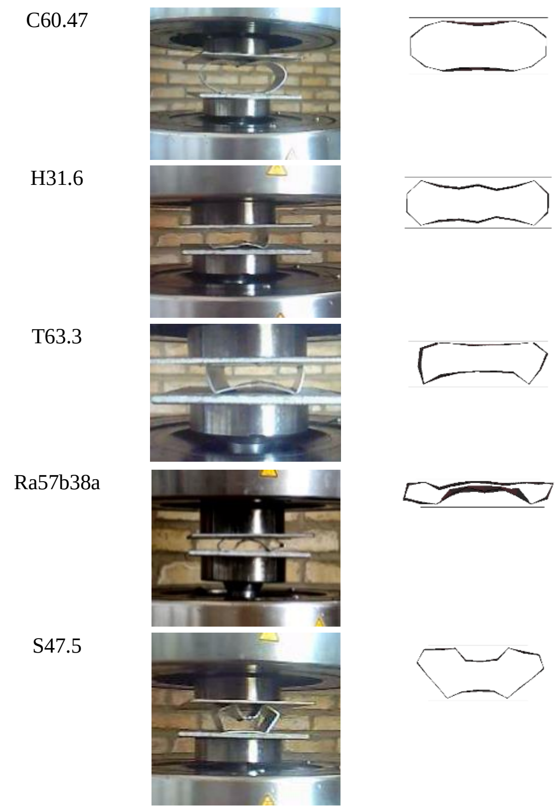


Fig. 8 Deformations of tubes with different section geometries during in-plane loading (right: simulation, left: experiment).

This shows that the section geometry has a great effect on the peak load. The circular section tube due to easy formation of plastic hinge lines needs smaller force for initiation of collapse, whereas in square and rectangular section tubes and due to perpendicular edges, this force is greater. For better comparison of the peak load, the load-displacement curves for tubes with different section shapes are presented in "Fig. 9".

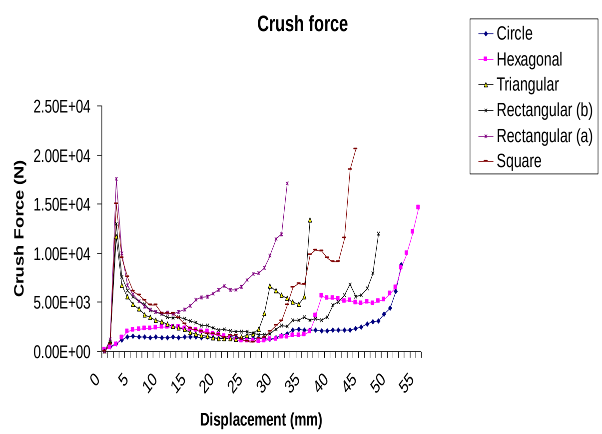


Fig. 9 Comparison between the load-displacement curves for tubes with different section shapes.

© 2022 IAU, Majlesi Branch

As it is seen from "Table 9 and Fig. 9", the section shape and in turn the angle between the edges of the section has an important effect on the peak load and when this angle is 90 degrees the peak load is greater. For the circular section, since there is no edge, the peak load is the least. For the triangular and hexagonal sections, this load increases considerably compared with the circular section but is smaller than for the square and rectangular sections. Results show that for the rectangular section, the less the height of the section along the load direction, the greater the peak load so that for the rectangular sections which are loaded across their longer and shorter edges, the peak loads are maximum and minimum, respectively and for square section the peak load is between these extremes .

4.2. Comparison of the Results Related to The Effect of Wall Thickness

Absorbed energy: As it is seen form "Table 10", increase in wall thickness results in increase of absorbed energy. Although increasing the thickness do not change the number of plastic hinge lines during collapse, but due to increase of the average force which is directly proportional to thickness, the absorbed energy which is calculated from multiplying the average force by displacement increases. The curves of energy-displacement for the tubes with rectangular sections with different thicknesses are compared in "Fig. 10".

Table 10 Experimental and numerical values of the absorbed energy and the peak load for

Section shape	Thickness (mm)	Specimen Code	Max Force (N) (Numerical)	Max Force (N) (Experimental)	Difference (%)
Circle	1	C 90.7	371	409.73	9.45
Circle	1.5	C 60.47	1440	1534.33	6.14
Circle	3	C 30.23	10800	10011.66	-7.84
Rectangular(a)	1	Ra85b57a	4680	5166.33	9.41
Rectangular(a)	1.5	Ra57b38a	16900	17828	5.2
Rectangular(a)	3	Ra28.5b19a	70200	77126	8.98
Square	1	S 71.25	3660	3790	3.43
Square	1.5	S 47.5	13700	15067	9.07
Square	3	S 23.7	62400	67504.16	7.58

The peak load: "Table 10" shows that increasing the thickness increases the peak load value considerably. This is due to the more bending moment needed to create plastic hinges in thicker sections. The changes in the peak load with the change in thickness are shown in "Fig. 11".

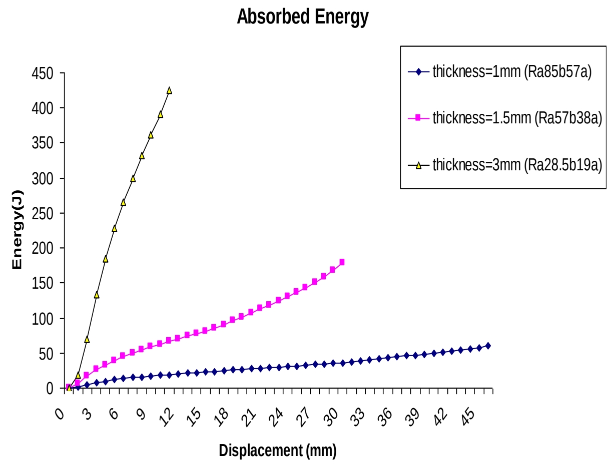


Fig. 10 Energy-displacement curves for the rectangular section tubes with different thicknesses.

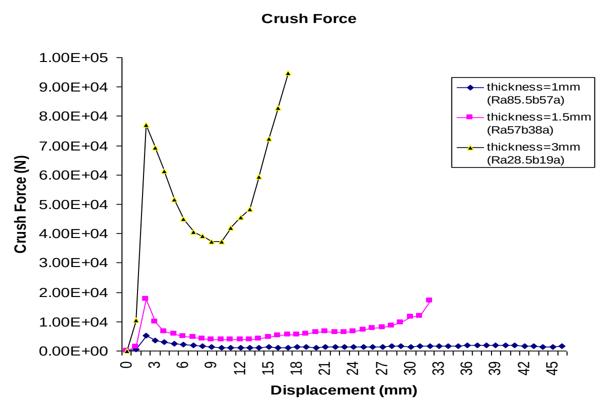


Fig. 11 Comparison of the load-displacement curves for rectangular sections with different thicknesses.

5 CONCLUSIONS

In this research the effects of section geometry and thickness of thin-walled tubes on energy absorption capacity and the value of the peak load are studied both experimentally and numerically. The important results are as follow:

- The section geometry has a considerable effect on energy absorption capacity, so that changing the section shape from circle to hexagon, triangle, rectangle and square increases energy absorption capacity, respectively.
- For the tubes with rectangular section, the smaller the height of specimen during in-plane loading, the greater the absorbed energy, in other words loading across the longer edge of rectangle increases the absorbed energy with respect to loading across the shorter edge.
- The angle between edges of the sections has an important role on the peak load; if the edges are perpendicular to each other results in increase of the peak load. Due to no edge in circular section the peak

© 2022 IAU, Majlesi Branch

load is the least and for the hexagonal and triangular sections, this load is greater compared with the circular one and smaller with respect to square and rectangular sections.

- For the rectangular sections, the lower the height (the edge parallel to load direction) of the section, the greater the peak load, hence if it is loaded across the longer edge the peak load will have greater value.
- For circular section tubes, the larger the diameter/thickness ratio the lower the absorbed energy.
- For the square and rectangular sections. increasing the thickness results in increase of absorbed energy.
- For the tested specimens, increase in thickness increases the peak load.
- Changing the thickness of the investigated tubes, do not affect the order of energy absorption capacity and the peak and the average loads.
- Numerical results are in good agreement with the experimental data.

REFERENCES

[1] Mutchler, L. D., Energy Absorption of Aluminum Tubing, Trans, ASME, 1. App. Mech, Vol. 27, 1960, pp. 740-743.

[2] Deruntz Jr, J. A, Hodge Jr, P. G., Crushing of a Tube Between Rigid Plates, J. Appl. Mech., Vol. 30, 1963, pp. 391-398.

[3] Reid, S. R., Reddy, T. Y., Effect of Strain Hardening on The Lateral Compression of Tubes Between Rigid Plates, Inl. J. Sol ids Struc, Vol. 14, No. 3, 1978, pp. 213-225.

[4] Reddy, T. Y., Reid, S. R., Lateral Compression of Tubes and Tube-System with Side Constrains, Int. 1. Mech. Sci. Vol. 21, No. 3, 1979, pp. 187-199.

[5] Sinha, D. K., Chitkara, N. R, Plastic Collapse of Square Rings, Int. J. Solid Struc, Vol. 18, No. 9, 1982, pp. 819-826.

[6] Kecman, D., Bending Collapse of Rectangular and Square Section Tubes, Int. J. Mech. Sci, Vol. 25, No. (9-10), 1983, pp. 623-636.

[7] Gupta, N. K, Khullar, A., Collapse of Square and Rectangular Tubes in Transverse Loading, Arch. Appl. Mech, Vol. 63, No. 7, 1993, pp. 479-490.

[8] Gupta, N. K., Sekhon, G. S., and Gupta, P. K., A Study of Lateral Collapse of Square and Rectangular Metallic Tubes, Thin-Walled Struc, Vol. 39, No. 9, 2001, pp. 745-772.

[9] Gupta, N. K., Sekhon, G. S., and Gupta, P. K., Study of Lateral Compression of Round Metallic Tubes, Thin-Walled, Vol. 43, No. 6, 2005, pp. 895-922.

[10] Morris, E., Olabi, A. G., and Hashmi, M. S. J., Analysis of Nested Tube Type Energy Absorbers with Different Indenters and Exterior Constraints, Thin-Walled Struc, Vol. 44, No. 8, 2006, pp. 872-885.

[11] Kheirikhah, M. M., Dehghanpour, S., and Rahmani, M., Quasi-Static Axial Compression of thin-walled Circular Composite Tubes, Journal of Structural Engineering and Geo-Techniques, Vol. 6, No. 1, 2016, pp. 9-13.

[12] Dehghanpour, S., Rahmani, M., Experimental and Numerical Study of Lateral Collapse of Square and Rectangular Composite Tubes, Proceedings of the World Congress on Mechanical, Chemical, and Material Engineering, Barcelona, Spain, July 2015, pp. 352.

[13] Dehghanpour, S., Rahmani, M., Experimental and Numerical Study of Lateral Loadings on the Composite Tubes with SMA and Aluminum Wires and Without Wire, ADMT Journal, Vol. 14, No. 22021, pp. 15-22.

[14] Dehghanpour, S., Hosseini Safari, K., Barati, F., and Attar, M. M., Comparative Analysis of Energy Absorption Capacity of Single and Nested Metal Matrix Composite Tubes Under Quasi-Static Lateral and Axial Loading, Journal of Solid Mechanics,Vol. 13, No. 2, 2021, pp. 134-143.

© 2022 IAU, Majlesi Branch