ICIC Express Letters
Part B: Applications
Volume **8**, Number **11**, November **2017**

ICIC International ©2017 ISSN 2185-2766
pp. 1497–1504

DYNAMIC AXIAL CRUSHING OF METALLIC TUBES WITH WALL-SUPPORTING STIFFENERS

Naveed Ahmed[1], Pu Xue[1], Muhammad Kamran[1] and Ammara Mustafa[2]

[1]School of Aeronautics
Northwestern Polytechnical University
No. 127, West Youyi Road, Xi'an 710072, P. R. China
naveedahmed@mail.nwpu.edu.cn; p.xue@nwpu.edu.cn; kamranm470@yahoo.com

[2]Department of Mechanical Engineering
College of Electrical and Mechanical Engineering
National University of Sciences and Technology
H-12, Islamabad 44000, Pakistan
Ammara.mustafa16@me.ceme.edu.pk

Received May 2017; accepted August 2017

Abstract. *Multi-cell thin walled columns are highly efficient in energy absorption under dynamic axial compression. In this study, the semi-circular and wavy shaped longitudinal stiffeners are placed around the circumference of the tube in order to provide support and strength, forming multi-cell feature in the structure. Then, numerical approach is employed to crush these configurations in the axial direction under dynamic loading. The effect of the variation of the semi-circular and wavy stiffeners arrangement is studied by changing the shape, position and quantity of the stiffeners, attached to the single and the bi-tubular metallic tubes' configurations. Number of configurations can be classified by the number of the employed curved stiffened shells. The mass in each configuration is maintained as the same by adjusting the thicknesses of the tubes and the stiffeners. Energy absorption parameters for all of the configurations are compared with published experimental literature of standard single tube and the tube with cross straight stiffeners. Deformation modes and energy absorption characteristics are evaluated and discussed for all of the proposed configurations. Results indicate that the performance of the semi-circular shaped stiffeners is superior to the wavy-shaped stiffeners in tailoring and optimizing the energy parameters.*
Keywords: Dynamic axial crushing, Wall supporting stiffeners, Metallic tubes, Energy absorption, Finite element modeling, Wavy stiffeners, Bi-tubular tubes

1. **Introduction.** Many applications in engineering, in particular, aerospace and automobile industries need the structural designs to be capable of energy absorption to minimize human injuries. Over the past three decades, exploration of structural designs with enhanced energy absorption capabilities has been research interest [1]. Thin-walled metal tubes are one such structure which are mostly employed as an energy absorbing devices under axial crushing due to efficient energy absorption characteristics along with low cost and ease of manufacturing. Theoretical, numerical and experimental evaluations of energy absorption characteristics of metal columns with various cross-sections like circular [2], square and hexagonal [3] have been studied under axial impact loadings, which absorb the energy by deforming themselves in different kinds of deformation modes like locally deformed concertina mode, diamond mode, mixed mode or globally deformed Euler buckling mode under axial crushing, depending on the geometry, material parameters and boundary conditions [4].

Several modification to thin-walled tubes such as filling tubes with different cellular materials or structures including metallic foams [5,6], multi-tube usage [7] and generating corrugated/grooved surfaces on the tubes [8] has been attempted and found to be effective for increasing energy absorption capacity and structural safety. Theoretical predictions of the mean crushing load for the single-cell, double-cell and triple-cell square sections under axial loading proved that multi-cell tubes absorb higher energy as compared to single-cell columns [9]. The multi-cell choice is based on the observation that the SEA of a square tube decreases with b/t, means that with the same height and wall thickness but different widths, the one with a small width will have a higher SEA than that of the one with a large width. A 50% gain in SEA is achieved when a square tube is divided in multi-cells of 3×3 cells [10]. A similar observations of energy absorption improvement in the multi-corner tubes under the axial crushing was reported by Yuen et al. [11] and Najafi and Rohani [12] using both analytical and numerical approaches. Circular tubes with single, double, triple and quadruple cells also revealed the same characteristics under the axial compression [13].

To improve the performance of crashworthiness in thin walled cylinders, researchers used bi-tubular configuration. It is shown that the square sectional bi-tubes with parallel and diamond arrangements, showed that the absorbed energy of bi-tubes is more than the summation of the absorbed energy of inner and outer tubes loaded separately [14]. A bi-sectional bi-tubular metal thin-walled structure consisting of an outer circular tube and an inner tube with different polygonal sections such as triangle, square or hexagon shows that bi-tubular structures with hexagonal inner tube have more energy absorption capability than the other bi-tube combinations [15]. The energy absorption is also affected by the length differences of bi-tubal structures [14].

Though researchers have done series of numerical and experimental work on the energy absorption of multi-cell single and bi-tubular tubes' structures, curved stiffeners supporting the walls of the circular tubes are rarely studied. In this study, a new stiffened-tube concept is presented where the walls of a circular tube are stiffened with semi-circular and wavy shaped stiffeners in a single and later extended to a bi-tubular arrangement. The numbers of stiffeners are placed in ascending order in the proposed configurations till the circumference of the outer tube is almost filled with stiffeners. A dynamic axial crushing of such structures is performed numerically to find out the performance of the proposed configurations for energy absorption characteristics. Results are compared among different configurations along with two selected experimental configurations [13] of a single tube and a single tube with cross-stiffeners. In this paper's organization, Section 2 describes the proposed structural configurations. The energy absorption indicators are defined in Section 3. The crushing response of the proposed configurations and the results of their energy absorption are discussed in Section 4. Section 5 concludes the work.

2. **Proposed Configurations.** A series of structural configurations consisting of an outer tube of diameter D, length L, semi-circular stiffener's radius R_s and thickness t for single tube configurations while with additional parameters of inner tube diameter d and wavy stiffeners' radii $R_1 = R_2 = R_3$ for bi-tubular configurations is shown in Figure 1. The configurations can be separated in five groups of semi-circular wall stiffened single tube system (STS), wavy wall stiffened single tube system (WS-STS), semi-circular wall stiffened bi-tubular tube system (BTS), wavy wall stiffened bi-tubular tube system and reference configurations as shown in Figures 1(b)-1(f), respectively. The proposed configurations nomenclature is defined as SαA-STS/BTS where Sα shows the number of wall stiffeners, and A is the type of stiffener; WS is used for wavy stiffeners while semi-circular stiffeners are not designated by any symbol being the default configuration and STS/BTS describes single tube system/bi-tubular tube system. The reference configurations for comparison are named as ST-CS-Rn where ST shows single tube, CS means cross-stiffeners and Rn defines the reference number of the configuration. In total, thirteen configurations are proposed including two reference configurations and one single wavy tube (SWT).

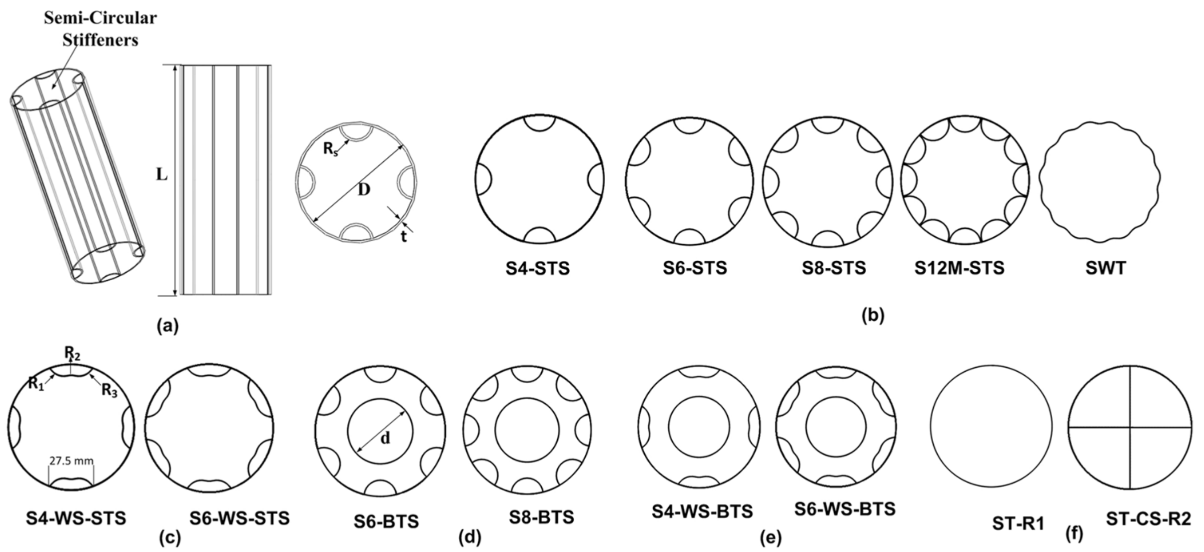

Figure 1. (a) Schematic of the proposed configuration; S4-STS (b) STS configurations; (c) WS-STS configurations; (d) BTS tubes' configurations; (e) WS-BTS configurations; (f) reference configurations

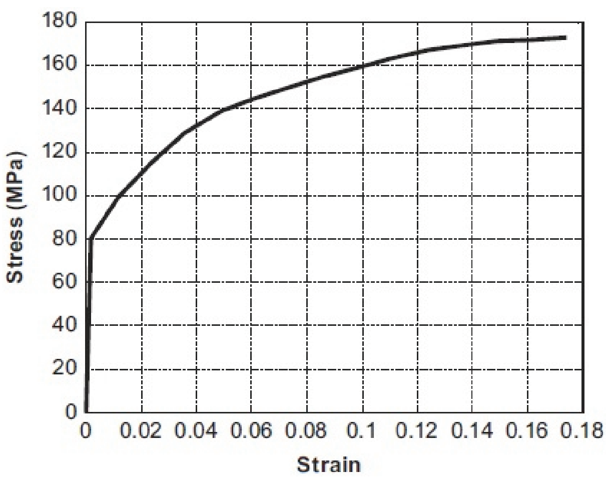

Figure 2. Stress-strain curve for AA 6060 T4 [16]

The proposed configurations including stiffeners, in this study are all metallic. The tube and stiffeners' material is extruded aluminum AA 6060-T4 [16] with Young's modulus of 68.21 MPa, yield strength of 80 MPa, ultimate strength of 173 MPa and Poisson's ratio of 0.3. The stress-strain curve of the selected material is shown in Figure 2. The structural information of the proposed configurations is listed in Table 1 where the thicknesses of each configuration are adjusted to keep the mass in each configuration as the same.

3. **Crashworthiness Energy Absorption Indicators.** The energy absorption can be described with following defined indicators which can be determined from the load-displacement curve as follows.

Energy Absorption (EA): The area under the force-displacement curve during axial crushing is the energy absorption and can be calculated as:

$$EA = \int F d\delta \tag{1}$$

where F is the crushing force and δ is the crushing distance.

Table 1. Geometry parameters of proposed configurations

Configuration	L (mm)	D (mm)	d (mm)	t (mm)	R_s (mm)	$R_1 = R_2 = R_3$ (mm)
S4-STS	200	80	–	1.73	8	–
S6-STS	200	80	–	1.5	8	–
S8-STS	200	80	–	1.32	8	–
S12M-STS	200	80	–	1.07	8	–
SWT	200	80	–	2.4	8	–
S4-WS-STS	200	80	–	1.7	–	10
S6-WS-STS	200	80	–	1.45	–	10
S6-BTS	200	80	40	1.2	8	–
S8-BTS	200	80	40	1.07	8	–
S4-WS-BTS	200	80	40	1.3	–	10
S6-WS-BTS	200	80	40	1.15	–	10
ST-R1	200	80	–	2.55	–	–
ST-CS-R2	200	80	–	1.55	–	–

Specific Energy Absorption (SEA): It is the energy absorbed per unit mass (m) of thin-walled member and can be computed as:

$$SEA = \int Fd\delta \Big/ m \tag{2}$$

Mean Crush Force (MCF): It is obtained by dividing the energy absorbed (EA) by crushing distance δ as:

$$MCF = {}^{EA}/_{\delta} \tag{3}$$

Crush Force Efficiency (CFE): It is the ratio of the mean crushing force to the peak crushing force (PCF). For an ideal energy absorber, the CFE is 100% and it can be calculated as:

$$CFE = {}^{MCF}/_{PCF} \tag{4}$$

4. **Performance of the Proposed Models.**

4.1. **FE modeling and validation.**

Abaqus/Explicit is used to simulate the dynamic axial compression of proposed circular tubes' configurations by applying a constant velocity of 10 m/s. The material model is defined as per the stress-strain curve shown in Figure 2. The structural configuration is placed between two rigid plates in such a way that the lower plate is fixed in all directions, while the upper one can only move in the loading direction. The shell S4R element is used for tube configurations while upper and lower plates are modeled by using discrete rigid element. General contact is defined to the whole model with a friction coefficient of 0.2. The element size is set as 2 mm after sensitivity analyses. The final crushed distance is adjusted at 70% of the initial height of the tube used as a reference for the evaluation of all energy absorption characteristics. An experimental study [13] is selected for validation in which the experimental dynamic axial behavior of a bi-tubular tube with cross stiffeners was presented. For validation, the geometry, material properties and boundary conditions are kept exactly the same as reported in the referred work. Figure 3(a) shows the comparison of force-displacement curve and Figure 3(b) shows the deformation pattern as observed by Zhang et al. [13] and determined in this study. A maximum difference of 16.6% (also observed by Zhang himself) is observed for MCF, in comparison to Zhang et al.'s model, validating the numerical approach of the present work.

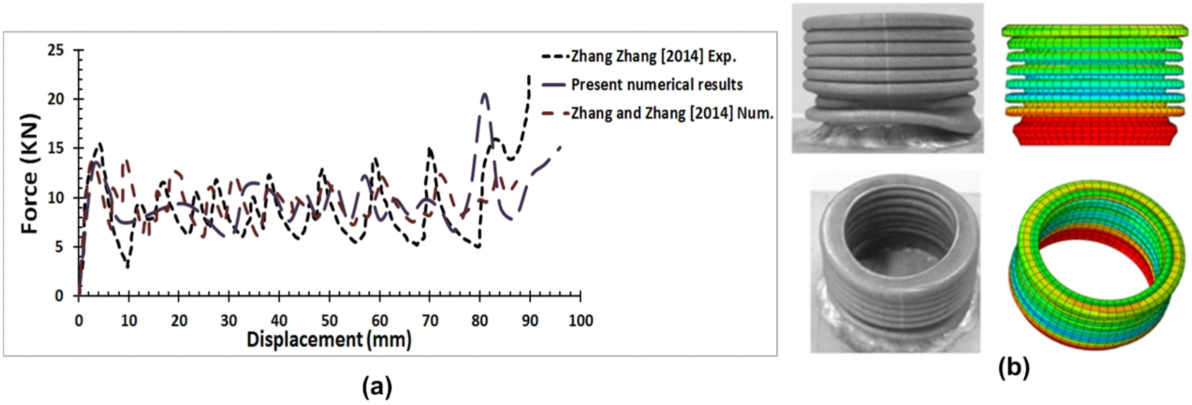

Figure 3. FE model validation (a) force displacement curves, (b) deformation modes

4.2. **Results and discussion.** Deformation plots for the proposed configurations are shown in Figure 4. Most of the configurations showed an axisymmetric mode at start in deformation modes, later converted to diamond or mixed modes. Axisymmetric modes are preferable as they guarantee the progressive collapse despite having less energy absorption. The details of the number of lobes and their type in a specific configuration are compiled in Table 2 where Diam, Axi and Mix show diamond, axisymmetric and mixed mode respectively. The single tube system with semi-circular stiffeners generally showed diamond modes after the first axisymmetric mode such as S4-STS, S6-STS, with the exception of all diamond modes in higher intensity stiffened configurations such as S8-STS, S12M, STS. The wavy stiffeners stiffened tubes showed a diamond or mixed mode after the initial axisymmetric lobe formation. The bi-tubular configurations such as S6-BTS, S8-BTS, S4-WS-BTS and S6-WS-BTS showed mixed modes in majority of the configurations. In general, it can be said that the stiffener shape and geometry have a considerable effect on mode shape ultimately defining the energy absorption in a specific configuration. Single wavy tube showed 5 axisymmetric modes but because of very low energy absorption indication, it is discarded in further discussion.

The energy absorption characteristic for a configuration can be determined from the force displacement curve using Equations (1)-(4). The force displacement curves for STS system along with reference configurations are shown in Figure 5(a) while a comparison of force displacement curves for STS and BTS systems is drawn in Figure 5(b). Figure 5(c)

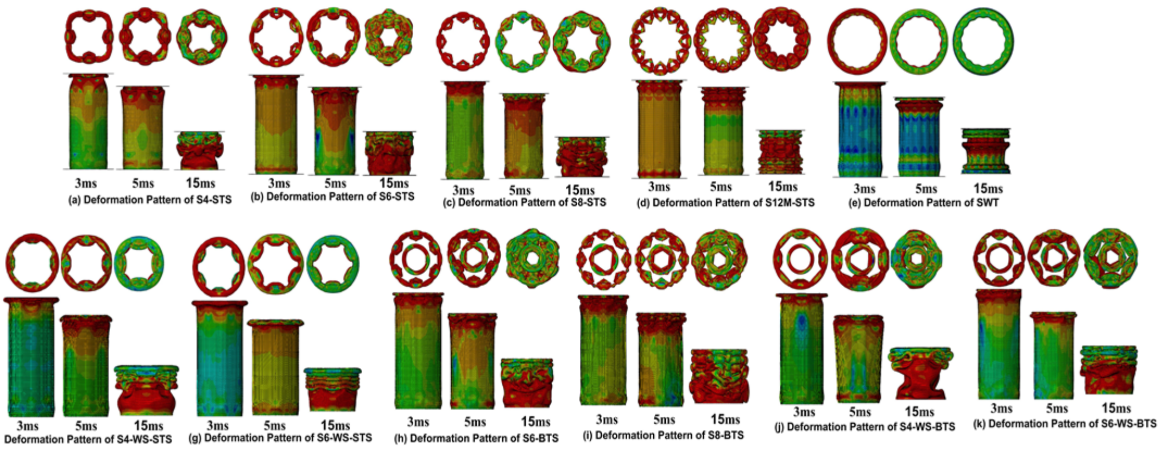

Figure 4. Deformation modes: (a) S4-STS, (b) S6-STS, (c) S8-STS, (d) S12M-STS, (e) SWT, (f) S4-WS-STS, (g) S6-WS-STS, (h) S6-BTS, (i) S8-BTS, (j) S4-WS-BTS, (k) S6-WS-BTS

Table 2. Energy absorption indicators

Configuration	Mass (kg)	EA (KJ)	PCF (KN)	MCF (KN)	CFE	Mode of Deformation
S4-STS	0.345	9.45	86.1	67.5	0.71	1 Axi, 2 Diam
S6-STS	0.345	9.43	92.6	67.4	0.728	1 Axi, 3 Diam
S8-STS	0.345	11.23	99.2	80.5	0.81	3 Diamond
S12M-STS	0.345	11.17	99.3	82.14	0.827	7 Diamond
SWT	0.345	6.13	78.3	43.8	0.56	5 Axi
S4-WS-STS	0.345	8.03	83.6	57.3	0.685	1 Axi, 4 Diam
S6-WS-STS	0.345	7.88	86.8	78.8	0.65	1 Axi, 5 Diam
S6-BTS	0.345	8.6	82	61.5	0.75	1 Axi, 4 Mix
S8-BTS	0.345	9.5	89	67.8	0.76	2 Diam, 2 Mix
S4-WS-BTS	0.345	6.65	78.5	47	0.6	1 Axi, 2 Mix
S6-WS-BTS	0.345	7.2	78	51.3	0.66	1 Axi, 2 Mix
ST-R1	0.345	6.4	74.3	46.2	0.62	4 Axi, 1 Dia
ST-CS-R2	0.345	9.29	91.8	66.3	0.72	1 Axi, 3 Diam

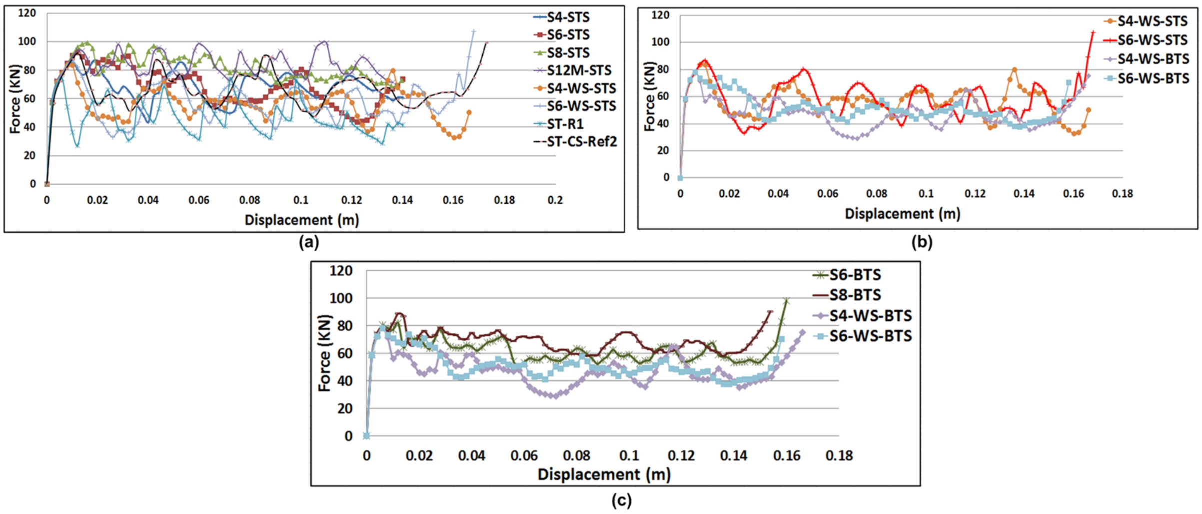

Figure 5. Force displacement curves comparison (a) Semi-circular and wavy stiffeners, (b) WS-STS and WS-BTS configurations, (c) STS and BTS semi-circular and WS-configurations

shows semi-circular and wavy stiffened BTS systems comparison. In STS configurations in Figure 5(a), the increasing number of semi-circular stiffeners shows an increase in energy absorption, the highest being in S8-STS and S12M-STS. The wavelength of folders also gets reduced reducing the sudden transitions in the graph. The wavy stiffened tubes showed comparatively less PCF values with lesser EA though S6-WS-STS shows much better results in comparison to S6-STS.

Figure 5(b) shows that STS is performing better than BTS while BTS is especially helpful in reducing the PCF at the cost of less EA and MCF. The performance of semi-circular stiffened tubes is better than wavy stiffened tube which is clear from Figure 5(c) because of the mixed mode failure probability in the former. The energy absorption indicators of all of the configurations are tabulated in Table 2 including EA, PCF, MCF, CFE and mode of deformation along with constant mass of each configuration. The highest energy absorption noted in S8-STS with an increase of 17.3% in comparison to ST-CS-R2 but with high peak force, about 7.55 higher than ST-CS-R2. The MCF was 19.2% higher in S12M-STS than ST-CS-R2. The S12M-STS also showed the CFE value increase of 11.1%. S6-WS-STS showed the best performance among the wavy stiffened configurations. BTS systems showed their effectiveness in reducing the PCF value with CFE being in the range of 0.6-0.68.

5. **Conclusion.** The wall strengthening and supporting concept is employed in this study by stiffening the metallic tube with semi-circular and wavy shaped supports. A number of configurations are numerically studied to see their shape, geometry and arrangement effects. The wall-stiffened thin-walled tubes show improved performance compared with the cross-wall stiffeners. EA, MCF increase with a value of 17.3% and 19.2%, respectively, for S12M-STS. The stiffeners' shape and geometry affect the axial deformation. Wavy shaped stiffened tubes show diamond and mixed modes while semi-circular stiffeners show a shorter wavelength with increased number of folds with diamond deformation mode shapes and increased energy absorption parameters. STS performs superior at the cost of high PCF values while BTS systems show lower PCF at the cost of low EA and MCF, showing predominantly mixed modes. The performance greatly depends on the arrangement of stiffeners as the number of stiffeners increases around the perimeter, and larger area is stiffened giving increased energy absorption and uniform deformation. It can be seen that the superior energy absorption is because of increasing number of cells while keeping the same weight. By making an optimization study of the arrangement of the stiffeners shape and number across the perimeter, further energy absorption along with reduced PCF is possible.

Acknowledgment. This work is partially supported by the financial supports from National Natural Science Foundation of China under Grants 11472226 and 11672248.

REFERENCES

[1] N. Jones, *Structural Impact*, 2nd Edition, Cambridge University Press, New York, 2012.
[2] S. R. Guillow, G. X. Lu and R. H. Grzebieta, Quasi-static axial compression of thin-walled circular aluminum tubes, *International Journal of Mechanical Sciences*, vol.43, pp.2103-2123, 2001.
[3] W. Abramowicz and N. Jones, Dynamic progressive buckling of circular and square tubes, *International Journal of Impact Engineering*, vol.4, no.4, pp.243-270, 1986.
[4] M. S. Zahran, P. Xue and M. S. Esa, Novel approach for design of 3D-multi-cell thin-walled circular tube to improve the energy absorption characteristics under axial impact loading, *Int. J. Crashworthiness*, 2016.
[5] D. G. Manmohan, Deformation, energy absorption and crushing behavior of single, double and multi-wall foam filled square and circular tubes, *Thin-Walled Structures*, vol.90, pp.1-11, 2015.
[6] C. Qi and S. Yang, Crashworthiness and lightweight optimization of thin-walled conical tubes subjected to an oblique impact, *Int. J. Crashworthiness*, vol.19, no.4, pp.334-351, 2014.
[7] A. A. Nia and M. Parsapour, Comparative analysis of energy absorption capacity of simple and multi-cell thin walled tubes with triangular, square, hexagonal and octagonal sections, *Thin-Walled Structures*, vol.74, pp.155-165, 2014.
[8] D. H. Chen and S. Ozaki, Numerical study of axially crushed cylindrical tubes with corrugated surface, *Thin-Walled Structures*, vol.47, no.11, pp.1387-1396, 2009.
[9] W. Chen and T. Wierzbicki, Relative merits of single-cell, multi-cell and foam-filled thin-walled structures in energy absorption, *Thin-Walled Structures*, vol.39, pp.287-306, 2001.
[10] X. Zhang, G. Cheng and H. Zhang, Theoretical prediction and numerical simulation of multi-cell square thin-walled structures, *Thin-Walled Structures*, vol.44, no.11, pp.1185-1191, 2006.
[11] S. Yuen, C. Kim, G. N. Nurick and R. A. Starke, The energy absorption characteristics of double-cell tubular profiles, *Lat. Am. J. Solids Struct.*, vol.5, pp.289-317, 2008.
[12] A. Najafi and M. R. Rohani, Mechanics of axial plastic collapse in multi-corner crush tubes, *Thin-Walled Structures*, vol.49, pp.1-12, 2011.
[13] X. Zhang, H. Zhang and Z. Wen, Experimental and numerical studies on the crush resistance of aluminum honeycombs with various cell configurations, *International Journal of Impact Engineering*, vol.66, pp.48-59, 2014.

[14] M. H. Kashani, S. Alavijeh, H. Akbarshahi and M. Shakeri, Bi-tubular square tubes with different arrangements under quasi-static axial compression loading, *Materials and Design*, vol.51, pp.1095-1103, 2013.

[15] K. Vinayagar and A. Kumar, Crashworthiness analysis of double section bi-tubular thin-walled structures, *Thin-Walled Structures*, vol.112, pp.184-193, 2017.

[16] Z. Tang, L. Shutian and Z. Zhang, Analysis of energy absorption characteristics of cylindrical multi-cell column, *Thin-Walled Structures*, vol.62, pp.75-84, 2013.