INTERNATIONAL JOURNAL OF AUTOMOTIVE
SCIENCE AND TECHNOLOGY
2017, VOL. 1, NO:2, 1-7
www.dergipark.gov.tr/ijastech

Investigation of the Effect of Corrugated Structure on Crashing Performance in Thin-Walled Circular Crash Boxes

Murat Altın[a], Serdar Halis[a], H. Serdar Yücesu[a]

[1] *Automotive Engineering Department, Faculty of Technology, Gazi University, Ankara, Turkey*

Abstract

Crash boxes are fasteners that are used in automobiles and have the ability to absorb energy emerged during impact. These parts can have different geometric properties. Within the scope of this study, corrugations of 1 mm, 3 mm, 5 mm in diameter were formed on the crash boxes. They are designed to have 0°, 2° and 4° taper angles. Each crash box has a wall thickness of 2 mm. The crash boxes designed were subjected to a velocity of 17 m/s with a mass deformation of 500 kg and crashing performances were investigated. As a result, the corrugation size was found to have influence on crashworthiness performance.

Keywords: Corrugated, Thin-walled tubes, Specific energy absorption, Crush force efficiency, Finite element method

* Corresponding author
Murat ALTIN
maltin@gazi.edu.tr
Adress: Automotive Engineering Department, Faculty of Technology, Gazi Universit, Ankara, Turkey
Tel: 0312 202 86 63
Fax: 0312 202 89 47

Manuscript Received 30.03.2017
Revised 10.07.2017
Accepted 29.07.2017

1. Introduction

Crash boxes used in automobiles and placed on the front bumper are fasteners with the ability to absorb kinetic energy, which occurs as deformation in frontal crashes. If impact forces acting on crash boxes are not sufficiently damped during an accident, these forces are directly transmitted to the passenger compartment in the vehicle. This situation will result in both fatal injuries to the passengers in the vehicle and a high amount of financial damage in the vehicle. Crash boxes are used in automobiles to minimize this damage that occurs. There are various studies for crash boxes. In some of these studies, the geometry [1-4], taper angle [5-8], single-cell or multi-cell [9-12] and corrugated shape [13-16] of the crash box are used as variable parameters in order to increase the energy damping capacity of crash boxes. In addition to these studies, the information on the extensive literature search is given in Table 1.

Jusuf et al. [1] investigated the numerical and experimental analysis of different cross-sections of compares to single-walled and double-walled columns under dynamic loading. They found that energy absorption capacity is improved by incorporating the internal ribs in multi-cell tubes. Kashani et al. [2] performed finite element analyses and experimental on the bitubular square tubes with parallel and diamond configurations under quasi-static axial compression loading. They found that the energy absorbed by bitubal tubes exceeds the sum of the energy absorbed by inner and outer tubes when loaded separately. Mamalis et al. [5], have focused on the axial crushing of square frusta tubes with four tapered sides. They found deformation charactereistic of such elements are similar to those of tubes. Nagel and Thambiratnam [6], compared the energy absorption response of straight and tapered thin-walled rectangular tubes under quasi-static and dynamic axial as well as off-axial dynamic impact loading. They found that the advantages of using tapered tubes for energy absorption under oblique impact loading. Experimental studied were carried out by Salehghaffari et al. [9] and development a two new design concept to energy absorption characteristic of circular metal tubes under quasi-static loading condition. They found that the significant efficiency of the presented design methods in improving energy absorption characteristic and collapse modes of circular tubes under axial loading. Nia and Parsapour [10] investigated experimental and numerical the energy absorption characteristics of multi-cell square tubes different sized cells and found that multi-cell square section absorb 227% higher energy capacity than of other section. Chen and Ozaki [13], studied the crushing behavior of cylindrical tubes subjected to under axial loading. They show that the deformation modes corresponding to corrugations can be classified into asymmetric and axisymmetric modes. Kılıçaslan [14], performed numerical simulation for determining energy absorption and crushing characteristics of empty and foam-filled corrugated single and double circular tubes. The result indicated that the foam-filled corrugated tubes have progressive and decreased peak crush force.

Table 1. Studies conducted on the crash boxes

References	Load type		Taper Angle		Cell Structure		Corrugation		Analysis Method		Filled		Geometry						
	Quasi-static	Dynamic	Straight	Angle	Single-cell	Multi-cell	Non-corrugated	Corrugated	Finite Element	Experimental	Empty	Foam	Circular	Square	Rectangular	Hexagonal	Triangular	Conical	Elliptical
[10] Nia and Parsapour (2013)	X		X			X	X		X	X	X			X					
[12] Tang et al. (2013)	X		X			X	X		X		X		X	X		X	X		
[13] Chen and Ozaki (2009)	X		X		X			X	X		X		X						
[14] Kılıçaslan (2015)	X		X		X			X	X			X	X						
[16] Eyvazian et al. (2014)	X		X		X			X		X	X		X						
[19] Attia et al. (2012)	X		X		X		X		X	X	X	X			X				
[20] Bi et al. (2010)	X		X		X	X	X		X			X				X			
[21] Djamaluddin et al. (2014)	X	X	X		X		X		X		X	X	X						
[22] Gao et al. (2016)	X		X		X		X		X		X	X	X	X	X				X
[23] Goel (2015)	X	X	X		X	X	X		X			X	X	X					
[24] Hou et al. (2011)	X			X	X		X		X			X						X	
[25] Aktay et al. (2006)	X		X		X		X		X	X	X	X	X						
[26] Ghamarian et al. (2011)	X		X	X	X				X		X	X	X					X	
[27] Hong et al. (2014)	X		X			X	X			X	X						X		
[28] Abdewi et al. (2008)	X		X		X	X	X	X		X	X		X						
[29] Elgalai et al. (2004)	X		X		X			X		X	X		X						
[30] Mahdi et al. (2003)	X			X	X		X			X	X							X	
[31] Acar et al. (2011)	X			X	X			X	X		X							X	
[32] Hosseinipour & Daneshi (2002)	X		X		X			X		X	X		X						
[33] Mokhtarnezhad et al. (2009)	X		X		X			X	X	X	X		X						
[34] Rezvani & Nouri (2014)	X			X	X			X	X	X	X							X	
[35] Wei et al. (2016)	X		X		X			X	X	X	X		X						
[36] Wu et al. (2016)	X		X		X			X	X	X	X		X						
[37] Yang et al. (2017)	X		X		X		X		X	X	X		X						
[38] Zhang and Huh (2009)	X		X		X			X	X		X			X					
[39] Qi and Yang (2014)	X		X	X	X		X		X		X	X	X					X	
[40] Murat et al. (2017)	X		X		X	X	X		X	X	X	X	X	X					

In this study, different sizes of corrugations were formed on the crash boxes used as passive safety system components in automobiles and the effects of these corrugations on crashing performance were examined.

2. Problem description

Representative geometric drawings of crash boxes to be used in the study are given in Fig. 1 and Fig. 2. The crash boxes were selected with circular cross section and the base diameter was determined as 90 mm and the height as 180 mm. The crash boxes designed are deformed by a speed of 17 m/s with a load of 500 kg (See Fig. 3)

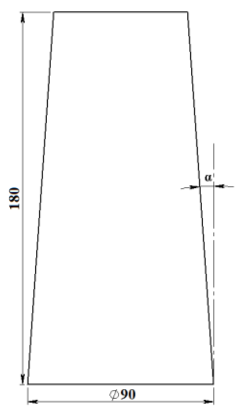

Fig. 1. The geometry of the crash box (withought corrugated) having circular cross-section.

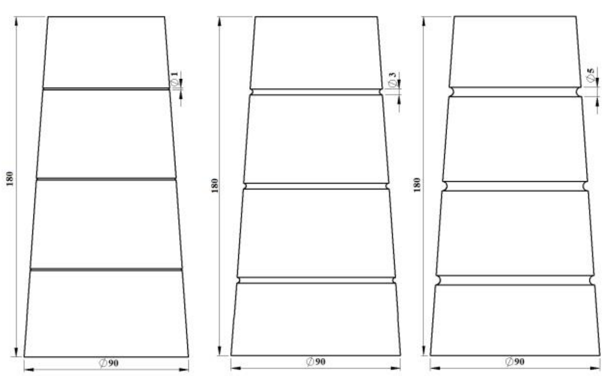

Fig. 2. The geometry of the thin walled tube (with corrugated) having circular cross- section.

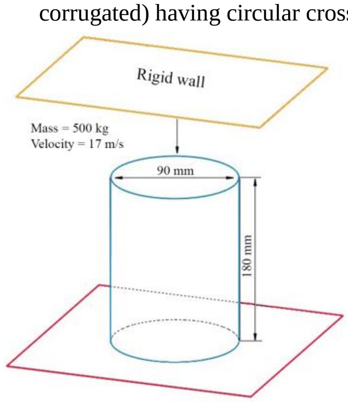

Fig. 3. The crash box impacted with a rigid wall.

3. Definitions

The parameters needed for characterising the crashworthiness performance of the crash boxes can be described as follows [17]:

3.1. Total energy absorption

The total energy absorbed, $E_{absorbed}$, in crushing the structure is equal to the area under the load-displacemenet curve. The total energy absorbed may be calculated by;

$$E_{absorbed} = \int_0^{\delta_{\max}} F d\delta \tag{1}$$

where F is the resultant impact force and δ is the displacement of the crushed structure.

3.2. Peak crush force

The peak crush force, F_{max}, is the highest load required to cause significiant permanent deformation in the axial direction during the crush.

3.3. Mean crush force (F_{mean})

Mean crush force which is obtained by following equation,

$$F_{mean} = \frac{E_{absorbed}}{\delta_{\max}} \tag{2}$$

F_{mean} is defined as the total energy absorption divided by the maximum crush displacement.

3.4. Specific energy absorption (SEA)

Specific energy absorption (SEA) which is defined as the total absorbed crash energy per unit of the crushed structure mass *(m)*.

$$SEA = \frac{E_{absorbed}}{m} \tag{3}$$

3.5. Crush force efficiency (CFE)

The crush force efficiency is defined as the ratio of the mean crush force to the peak crush force:

$$CFE = \frac{F_{mean}}{F_{\max}} \tag{4}$$

4. Finite Element Simulation

The numerical simulations of these models are performed in the explicit nonlinear FE code LS-DYNA. The finite element model was constructed as a shell element with a dimension of 2×2 network structure (See Fig. 4). The sidewall of circular tube was modeled with Belytschko-Tsay 4-node shell element with five integration points through the thickness. The material models used are the “Material type 20 rigid material” for the rigid wall and the “Material type 24 elasto-plastic material.” For Material type 24, the plastic region is included with true stress true strain curve. The self-contact between the tube and the rigid wall are defined by using this type of contact. The static and dynamic frictional coefficients defined in these contacts are taken as 0.2 and 0.3, respectively.

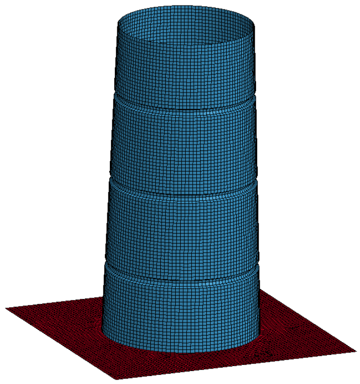

Fig. 4. Finite element mesh of the corrugated crash box

Table 2 shows the True effective stress-true effective plastic strain values for the aluminum mild steel with density 7850 kg/m^3, young's modulus E = 210 GPa, poisson's ratio v = 0.33 [18].

Table 2. True effective stress-true effective plastic strain values for aluminum.

σ_t [MPa]	331	247	290	427	450	469	501	524	533
ε_p	0	0.018	0.037	0.056	0.075	0.093	0.138	0.180	0.230

4.1. Validation of the numerical models

In order to assure the accuracy of the FEA model, the present numerical model has to be validated by existent numerical models for axial crushing of conical tubes. In order to validate the numerical simulation results, circular tube has been modeled and compared to experimental result. The crash box was selected as Al 6082-T5 with a length of 180 mm, a diameter of 90 mm and a wall thickness of 2 mm. The tests were carried out on the INSTRON 600 LX servo hydraulic testing device with a compression capacity of 600 kN.

The deformation rate to be applied to the crashing force during compression was determined as 2 mm/min. The crash box was deformed by 80 mm for a total of 40 minutes under this compression rate. As a result of the tests and the finite elements analysis, the load-displacement curves of the crash box are obtained as given in Figure 5. As shown in Figure 5, the experimental results and the finite elements analysis results are very close to each other. Besides, deformation views of crash boxes are given within 80 mm in Figure 6.

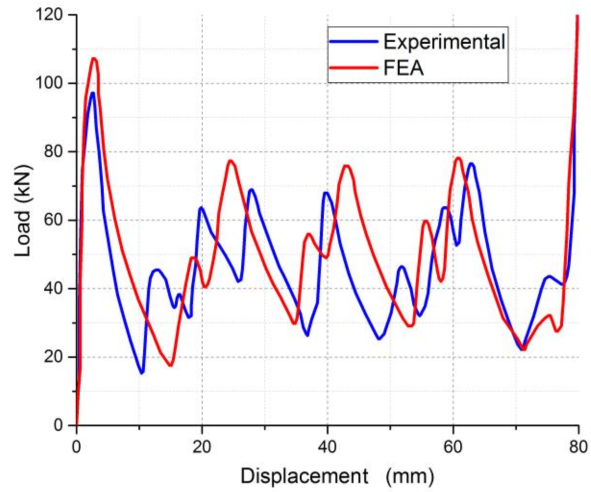

Fig. 5. Experimental and simulation load-displacement curves of crash boxes

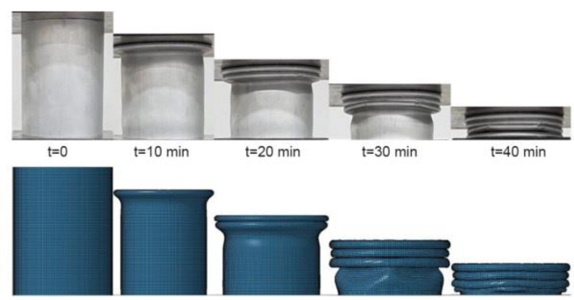

Fig. 6. Deformation of collapse models circular tube from the experimental and numerical results.

5. Result and Discussion

In this section, first the crash performances of different types of cross-section geometry are evaluated and compared to each other. Then, the effect of corrugated size and the different taper angle are explored. The crash performances of different corrugated width size are evaluated by using the metrics defined in Section 2. The wall thickness is set to 2.0 mm, and the taper angle is set to 0°, 2° and 4° (for tapered tubes). The abbreviated symbols given in Table 3 are used to identify different types of models (see Fig. 1). In model descriptions, 'CS***' is used to define the corrugation width and 'TA***' is used to define the taper angle. For instance, CS1.0TA4.0 is the model with corrugated circular geometry that has 1.0 mm corrugation width and 4 taper angle. The CFE and SEA results for different corrugation size configurations are presented in Table 3, Fig. 7 and Fig. 8.

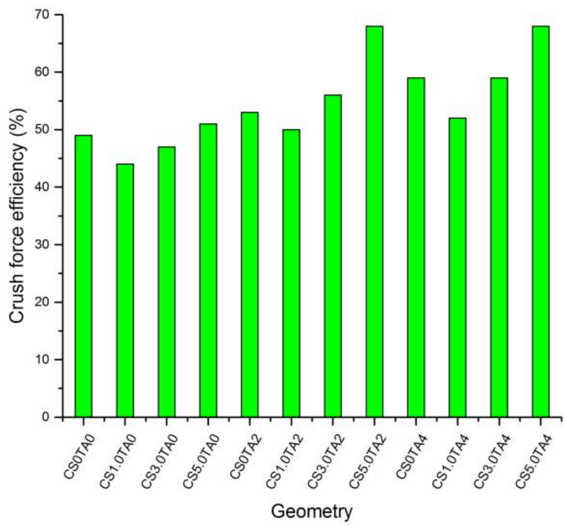

Fig. 7. Crush force efficiency for geometries

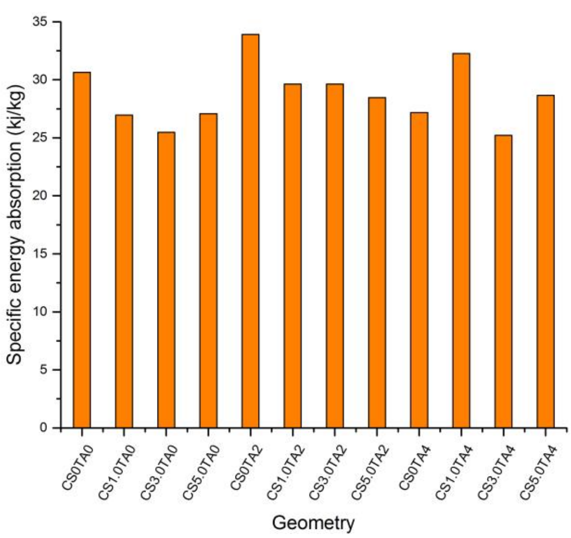

Fig. 8. Specific energy absorption for geometries.

It shows that, it can be inferred that the corrugated width 5.0 mm design having the best CFE performance (CS5.0TA2.0) has a CFE value of 0.69, and this value is 63.7% larger than the corrugation width 1.0 mm design having the worst performance (CS1.0TA0 design) with a CFE value of 0.44. The deformation shaper of the CS5.0TA2.0 crash box are show in Fig. 9. Similarly, the non-corrugated design having the best SEA performance (CS0TA2.0) has a SEA value of 33.91 kj/kg, and this value is 74.3% larger than the corrugation size 3.0 design having the worst performance (CS3.0TA4.0 design) with a SEA value of 25.21 kj/kg.

Table 3. The effect of corrugated width size on the crash performance circular crash boxes energy absorber models. *The numbers with bold fonts shows the maximum value observed in the corresponding column.*

Geometry	Displacement (mm)	Energy (kJ)	Peak Crash Force (kN)	Mean Crush Force (kN)	CFE (%)	SEA (kj/kg)	Taper Angle
CS0TA0	120	8.421	143.17	70.18	49	30.6	0
CS1.0TA0	120	7.457	140.32	62.14	44	26.9	0
CS3.0TA0	120	6.558	116.21	54.65	47	25.4	0
CS5.0TA0	120	6.923	112.56	57.69	51	27.0	0
CS0TA2	120	8.090	125.39	67.42	54	**33.9**	2
CS1.0TA2	120	8.299	137.16	69.16	50	29.6	2
CS3.0TA2	120	7.020	104.39	58.50	56	29.6	2
CS5.0TA2	120	7.422	89.65	61.85	**69**	28.4	2
CS0TA4	120	7.767	108.20	64.73	60	27.1	4
CS1.0TA4	120	7.790	124.40	64.92	52	32.2	4
CS3.0TA4	120	6.702	93.87	55.85	59	25.1	4
CS5.0TA4	120	7.058	85.89	58.82	68	28.6	4

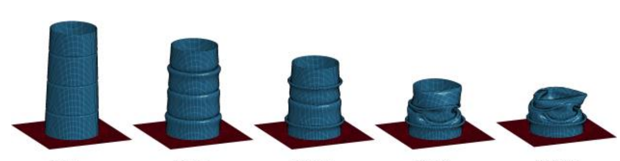

Fig. 9. Deformation photos of CS5.0TA2.0 crash box

6. Conclusion

The crashworthiness performance of corrugated circular tubes under impact loading are investigated with numerical simulation in this paper by using an explicit nonlinear finite element code LS-DYNA. The crashworthiness assessment was based on the crush force efficiency (CFE), and the specific energy absorption (SEA).

- All the specimens showed very good energy absorption capacity.

- Highest SEA values (33.9 kj/kg) were found for corrugated width 0 and taper angle 2° (CS0TA2) configurations.
- Highest CFE values (69%) were found for corrugated width 5.0 mm and taper angle 2° (CS5.0TA2) configurations.
- CFE value increased when taper angle increase from 0° to 4°.
- When the taper angle of absorber increase, the absorbed energy also increases for all models.
- It is possible to control the compressive stress in a cylindrical tube during impact loading by introducing corrugations on the tube surface.
- The initial peak load of CS5.0TA4 crash box is 59.9% less than the CS0TA0 samples and the CS5.0TA4 crash box are convenient shock absorber for structures which are sensitive to deceleration level.

The initial peak load can be controlled with the corrugeted width and initial peak load is reduced by increasing of the corrugeted width size.

References

[1] Jusuf, A., Dirgantara, T., Gunawan, L. and Putra, I. S., (2015). "Crashworthiness analysis of multi-cell prismatic structures", International Journal of Impact Engineering, 78:34-50.
[2] Kashani, M. H., Alavijeh, H. S., Akbarshahi, H. and Shakeri, M., (2013). "Bitubular square tubes with different arrangements under quasi-static axial compression loading", Materials and Design, 51:1095-11030.
[3] Zhang, Z., Liu, S. and Tang, Z., (2010). "Crashworthiness investigation of kagome honeycomb sandwich cylindrical column under axial crushing loads", Thin-Walled Structures, 48:9-18.
[4] Zhang, X. and Zhang, H., (2012). "Experimental and numerical investigation on crush resistance of polygonal columns and angle elements", Thin-Walled Structures, 57:25-36.
[5] Mamalis, A. G., Manolakos, D. E., Ioannidis, M. B., Kostazos, P. K. and Hassiotis, G., (2010). "Finite element simulation of the axial collapse of thin-wall square frusta", International Journal of Crashworthiness, 6:2, 155-164.
[6] Nagel, G. M. and Thambiratnam, D. P., (2005). "Computer simulation and energy absorption of tapered thin-walled rectangular tubes", Thin-Walled Structures, 43:1225-1242.
[7] Rezvani, M. J. and Nouri, M. D., (2015). "Analytical Model for Energy Absorption and Plastic Collapse of Thin-Walled Grooved Frusta Tubes", Mechanics of Advanced Materials and Structures, 22:5, 338-348.
[8] Zhang, X., Zhang, H. and Wen, Z., (2015). "Axial crushing of tapered circular tubes with graded thickness", International Journal of Mechanical Sciences, 92:12-23.
[9] Salehghaffari, S., Tajdari, M., Panahi, M. and Mokhtarnezhad, F., (2010). "Attempts to improve energy absorption characteristics of circular metal tubes subjected to axial loading", Thin-Walled Structures, 48:379-390.
[10] Nia, A. A. and Parsapour, M., (2013). "An investigation on the energy absorption characteristics of multi-cell square tubes", Thin-Walled Structures, 68:26-34.
[11] Song, J. and Guo, F., (2013). "A comparative study on the windowed and multi-cell square tubes under axial and oblique loading", Thin-Walled Structures, 66:9-14.
[12] Tang, Z., Liu, S. and Zhang, Z., (2013). "Analysis of energy absorption characteristics of cylindrical multi-cell columns", Thin-Walled Structures, 62:75-84.
[13] Chen, D. H. and Ozaki, S., (2009). "Numerical study of axially crushed cylindrical tubes with corrugated surface", Thin-Walled Structures, 47:1387-1396.
[14] Kılıçaslan, C., (2015). "Numerical crushing analysis of aluminum foam-filled corrugated single- and double-circular tubes subjected to axial impact loading", Thin-Walled Structures, 96:82-94.
[15] Ghasemnejad, H., Hadavinia, H., Marchant, D. and Aboutorabi, A., (2009). "Energy absorption of thin-walled corrugated crash box in axial crushing", Structural Durability and Health Monitoring, 98:1, 1-17.
[16] Eyvazian, A., Habibi, M. K., Hamouda, A. M. and Hedayati, R., (2014). "Axial crushing behavior and energy absorption efficiency of corrugated tubes", Materials and Design, 54:1028-1038.
[17] Jin, S. Y. and Altenhof, W., (2007). "Comparison of the load/displacement and energy absorption performance of round and square AA6061-T6 extrusions under a cutting deformation mode", International Journal of Crashworthiness, 12:3, 265-278.
[18] Wang, B. and Lu, G., (2002). "Mushrooming of circular tubes under dynamic axial loading", Thin-Walled Structures, 40:167–82.
[19] Attia, M. S., Meguid, S. A. and Nouraei, H., (2012). "Nonlinear finite element analysis of the crush behaviour of functionally graded foam-filled columns", Finite Elements in Analysis and Design, 61:50-59.
[20] Bi, J., Fang, H., Wang, Q. and Ren, X., (2010). "Modeling and optimization of foam-filled thin-walled columns for crashworthiness designs", Finite Elements in Analysis and Design, 46:698-709.
[21] Djamaluddin, F., Abdullah, S., Ariffin, A. K. and Nopiah, Z. M., (2014). "Multi objective optimization of foam-filled circular tubes for quasi-static and dynamic responses", Latin American Journal of Solids and Structures, 12:1126-1143.
[22] Gao, Q., Wang, L., Wang, Y. and Wang, C., (2016). "Crushing analysis and multi objective crashworthiness

optimization of foam-filled ellipse tubes under oblique impact loading", Thin-Walled Structures, 100:105-112.
[23] Goel, M. D., (2015). "Deformation, energy absorption and crushing behavior of single-, double- and multi-wall foam filled square and circular tubes", Thin-Walled Structures, 90:1-11.
[24] Hou, S., Han, X., Sun, G., Long, S., Li, W., Yang, X. and Li, Q., (2011). "Multiobjective optimization for tapered circular tubes", Thin-Walled Structures, 49:855-863.
[25] Aktay, L., Toksoy, A. K. and Güden, M., (2006). "Quasi-static axial crushing of extruded polystyrene foam-filled thin-walled aluminum tubes: Experimental and numerical analysis", Materials and Design, 27:556-565.
[26] Ghamarian, A., Zarei, H. R. and Abadi, M. T., (2011). "Experimental and numerical crashworthiness investigation of empty and foam-filled end-capped conical tubes", Thin-Walled Structures, 49:1312-1319.
[27] Hong, W., Fan, H., Xia, Z., Jin, F. and Zhou, Q., (2014). "Axial crushing behaviors of multi-cell tubes with triangular lattices", International Journal of Impact Engineering, 63:106-117.
[28] Abdewi, E. F., Sulaiman, S., Hamouda, A. M. S. and Mahdi, E., (2008). "Quasi-static axial and lateral crushing of radial corrugated composite tubes", Thin-Walled Structures, 46:320-332.
[29] Elgalai, A. M., Mahdi, E., Hamouda, A. M. S. and Sahari, B. S., (2004). "Crushing response of composite corrugated tubes to quasi-static axial loading", Composite Structures, 66:665-671.
[30] Mahdi, E., Hamouda, A. M. S., Sahari, B. B. and Khalid, Y. A., (2003). "Experimental quasi-static axial crushing of cone-tube-cone composite system", Composites Part B: Engineering, 34:285-302.
[31] Acar, E., Guler, M. A., Gerçeker, B., Cerit, M. E. and Bayram B., (2011). "Multi-objective crashworthiness optimization of tapered thin-walled tubes with axisymmetric indentations", Thin-Walled Structures, 49:94-105.
[32] Hosseinipour, S. J. and Daneshi, G. H., (2003). "Energy absorbtion and mean crushing load of thin-walled grooved tubes under axial compression", Thin-Walled Structures, 41:31-46.
[33] Mokhtarnezhad, F., Salehghaffari, S. and Tajdari, M., (2009). "Improving the crashworthiness characteristics of cylindrical tubes subjected to axial compression by cutting wide grooves from their outer surface", International Journal of Crashworthiness, 14:6, 601-611.
[34] Rezvani, M. J. and Nouri, M. D., (2014). "Axial crumpling of aluminum frusta tubes with induced axisymmetric folding patterns", Arabian Journal for Science and Engineering, 39:2179-2190.
[35] Wei, Y., Yang, Z., Yan, H., Guo, Y., Wu, X. and Huang, C., (2016). "Proactive regulation of axial crushing behavior of thin-walled circular tube by gradient grooves", International Journal of Mechanical Sciences, 108-109:49-60.
[36] Wu, S., Li, G., Sun, G., Wu, X. and Li, Q., (2016). "Crashworthiness analysis and optimization of sinusoidal corrugation tube", Thin-Walled Structures, 105:121-134.
[37] Yang, Z., Yu, Y., Wei, Y. and Huang, C., (2017). "Crushing behavior of a thin-walled circular tube with internal gradient grooves fabricated by SLM 3D printing", Thin-Walled Structures, 111:1-8.
[38] Zhang, X. and Huh, H., (2009). "Energy absorption of longitudinally grooved square tubes under axial compression", Thin-Walled Structures, 47:1469-1477.
[39] Qi, C. and Yang, S., (2014). "Crashworthiness and lightweight optimisation of thin-walled conical tubes subjected to an oblique impact", International Journal of Crashworthiness, 19:4, 334-351."
[40] Altin, M., Guler, M. S. and Mert, S. K., (2017). "The effect of percent foam fill ratio on the energy absorption capacity of axially compressed thin-walled multi-cell square and circular tubes", International Journal of Mechanical Sciences, 131-132: 368-379.