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Design of Thin-walled Impact Absorbers with Buckling Initiator

Wachirakorn Towicha[1,*], Pattaramon Jongpradist[1]

[1] Department of Mechanical Engineering, Faculty of Engineering, King's Mongkut's University of Technology Thonburi,
126 Pracha Uthit Rd., Bang Mod, Thungkhru, Bangkok 10140, Thailand
[*] Corresponding Author: wachirakorn.to@gmail.com, +6687-675-5214

Abstract

In the design of energy absorber for heavy vehicles, thin-walled members are frequently used as energy absorber to absorb and dissipate impact energy when frontal collision occurs. Buckling initiators can improve the axial crushing performance of such members by the pre-designed buckling of the shell in folding pattern. This research aims to use nonlinear explicit dynamic finite element analysis to investigate characteristics and behaviors of thin-walled hexagonal tubes with different designs of buckling initiators under axial and oblique impact loads. Two initiator types, triangular notch and window-like hole, of single and multiple rows are considered. Locations of the initiators are determined by eigenvalue-based buckling analyses. The use of notch and hole as buckling initiators are shown to advance the crushing performances of thin-walled tubes under dynamics impact. The multiple-row initiator types can remarkably reduce the occurred peak force compared to the members with single-row initiator. A hexagonal absorber with four-row triangular notches is recommended due to advantages in its behaviors under both direct and oblique impact with high specific energy absorption of 10 kJ/kg and crush efficiency of 0.61. The peak force is also diminished by 30 percent.

Keywords*:* Thin-walled member, Hexagonal tube, Buckling initiator, Energy absorber, Axial impact

1. Introduction

Heavy vehicle such as buses and trucks are more inclined to cause severe road accidents due to its high impact energy when collision occurs. Frontal impact is the major origins of accident in such vehicles. To alleviate the severity of crash transferred to the cabin structure and the driver, shock absorber brackets are installed to the front bumper to absorb the crash energy. Thin-walled member is one of the structures commonly adopted because of its light weight and energy absorption efficiency.

Behaviors of thin-walled members under impact and their mechanisms have been investigated by many researchers. Early researches (Abramowicz and Jones [1], Wierzbicki and Abramowicz [2]) experimentally studied folding behaviors of circular and square thin-walled members under applied dynamic axial compression. It was found that there are three possible collapse modes, i.e., symmetric, extensional and mixed modes. Several works [3-5] focused on the energy absorption of different cross-section geometries. Circular and hexagonal tubes generally give the best result among the candidates under various axial impact conditions. Tarlochan et al. [6] extended the study by performing oblique impact on a wide range of cross-sections in which hexagonal cross-section showed the best performance. However, the initial peak forces were extremely high in many cases. Moreover, when the oblique angle was large, global buckling primarily occurred and the energy absorption was considerably diminished. Zhang et al. [7] installed an initiator to a square thin-walled structure resulting in the reduction of the initial peak force up to 30 percent under axial impact due to local buckling at the pre-designed position. The use of multi-cell reinforcement and window-like holes in thin-walled rectangular cross sections were shown to increase the mean crushing force while the initial peak forces were remarkably reduced [8]. Nia et al. [9] performed an oblique impact test on triangular notching of squared tube and concluded that the use of such notching as buckling initiator can increase the specific energy absorption by changing the collapse mode to progressive folding mode.

In this study, the performance of hexagonal thin-walled structure as impact absorber under direct and oblique impact loads are examined by means of nonlinear explicit finite element analysis using two types of initiator; triangular notching on the tube corners and window notching on the tube sides. Effect of using single and multiple row notching on the initial peak forces, mean crushing forces, crushing efficiency and specific energy absorption are studied.

2. Background theories

Typical force-displacement curve of a thin-walled tube due to axial impact is displayed in Fig. 1

The energy absorption, E_{abs}, is computed by the area under the force-displacement curve as

$$E_{abs} = \int_0^d F(x)dx \tag{1}$$

where x is the displacement of the tube, F is the impact load and d is the total displacement.

Specific energy absorption, SEA, is the ratio of the energy absorption to the mass m of thin-walled member or

$$\text{SEA} = \frac{E_{abs}}{m} \tag{2}$$

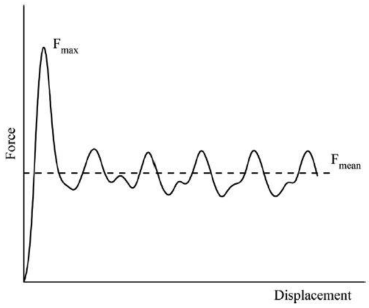


Fig. 1 Typical force-displacement curve of thin-walled member under axial impact [10].

The mean crushing force (F_{mean}) is the average force acting on the member during impact calculated as the energy absorption divided by the total displacement.

$$F_{mean}=\frac{\int_0^d F(x)\,dx}{d} \tag{3}$$

Furthermore, crushing efficiency η is introduced by the ratio of the mean crushing force to the initial peak force, F_{peak}, as

$$\eta=\frac{F_{mean}}{F_{peak}} \tag{4}$$

To utilize a thin-walled member as an energy absorber, higher values of specific energy absorption, mean crushing force and crush efficiency are preferable while the initial peak force is minimized so as to decrease the severity of passenger injury from excessive deceleration.

3. Specimens and loading conditions

In the current study, a regular hexagonal tube with 150 mm perimeter, 1.6 mm thickness and 287.5 mm length, is analyzed. Single-row and multiple-row initiators by using triangular notches on the tube corners and window-like openings on the tube sides are considered. Locations of the notches and openings are determined by either eigenvalue-based buckling analysis or first critical element from axial crush analysis as illustrated in Fig 2a and 2b. Fig. 3 shows different models of hexagonal profile with triangular and window initiators where h_i are the locations of the initiators measured from the top of the member specified in Table. 1. The names of the specimen are designated by three letters, e.g. 10T-C-4. The first label describes the base size of triangular notch or the width of window in millimeter followed by the initiator types (T for triangular notch and W for window type). The second letter defines the patterns of initiator about the hexagonal perimeter (type A, B and C) as shown in Fig. 4. The last letter labels the locations of initiator by using codes listed in Table. 1. The meaning of the codes is explained in the Remark column.

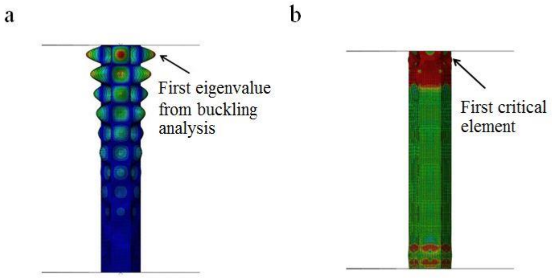


Fig. 2 Locations of notching (a) first eigenmode from buckling analysis (b) first critical element.

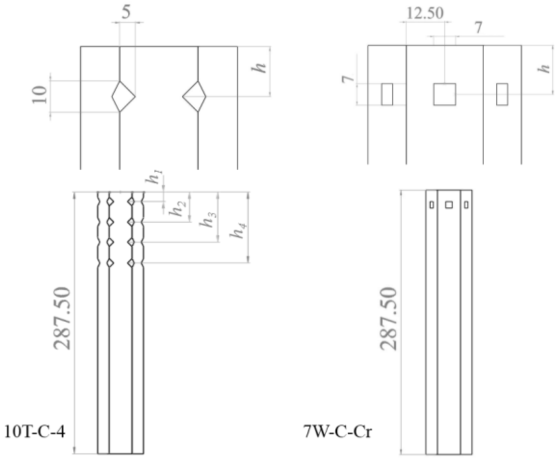


Fig. 3 Hexagonal specimens with triangular and window initiator.

Table.1 Codes for different locations of initiator

Code	No. of row	h_i (mm)	Remark
1	1	10.5	1st buckling mode
Cr	1	16.0	Critical element
Se	1	33.0	Second position of 1st buckling mode
P	1	143.8	Prescribed location
2	2	10.5, 33.0	1st buckling mode
3	3	10.5, 33.0, 55.0	1st buckling mode
4	4	10.5, 33.0, 55.0, 78.0	1st buckling mode

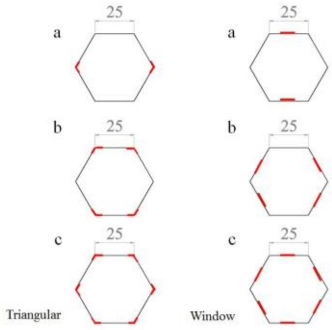


Fig. 4 Patterns of initiator (a) type A- 2 corners/sides, (b) type B- 4 corners/sides, (c) type C- 6 corners/sides.

Fig. 5 depicts some model examples of hexagonal tubes with different patterns of single and multiple rows of initiators. The solid modeling and loading conditions implemented in the finite element analysis are as illustrated in Fig. 6. The base of the thin-walled member is tied to a rigid lower plate. A rigid plate with beveling angle of θ to the hexagonal tube axis is in contact with the top of the tube. The top plate impacts with an initial velocity of 7.5 m/s representing the velocity of pendulum according to the United Nations Economic Commission for Europe Regulation No. 29 for heavy vehicle [11]. The impact angles of interest are $\theta = 0^\circ$, 10° and 15°.

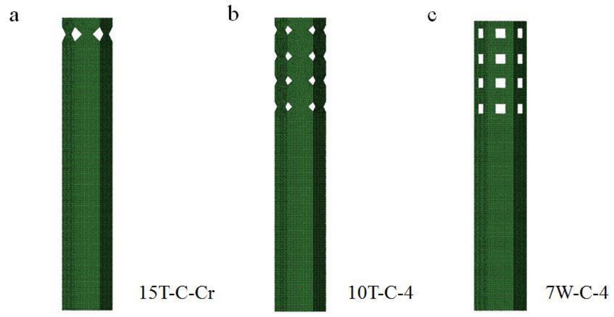


Fig. 5 Examples of hexagonal members with initiators (a) 15T-C-Cr, (b) 10T-C-4, (c) 7W-C-4.

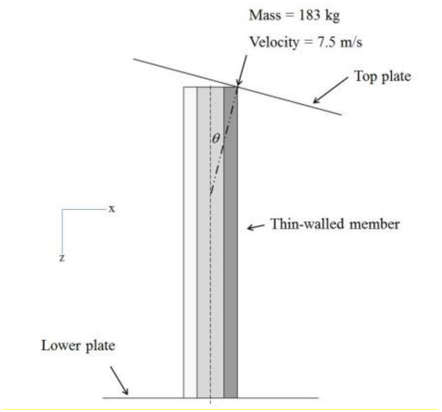


Fig. 6 Model for impact analysis.

4. Finite Element model

Nonlinear explicit dynamic finite element analysis is used in the simulation. The thin-walled members are meshed with 4-node shell elements. Mesh convergence is studied and the proper element size is found to be 1.5 mm. Initial imperfections of 10% are also introduced to the tubes. The top and lower plates are assigned as rigid body. The friction between the contact interactions of the top plate and the specimen is assigned using penalty formulation with the friction coefficient of 0.3. Self-contact of the thin-walled surface is also specified.

The hexagonal tube is made of steel with density of 7860 kg/m^3, Young's modulus 210 GPa, Poisson's ratio 0.3. The yield strength is 312.3 MPa and the ultimate strength is 350 MPa. Results from preliminary finite element analysis are validated to be comparable with experimental data of axial impact tests from Zhang et al. [7].

5. Results and discussions

5.1 Hexagonal tube under direct and oblique loading

First, the regular hexagonal tube is analyzed under axial loading ($\theta = 0^\circ$) and oblique loading ($\theta = 10^\circ$ and 15°). The collapse mode under direct impact (Fig. 7a) and oblique impact of 10° (Fig. 7b) show local buckling at the top part and progressive folding of the thin-walled member which results in specific energy absorption of 5 kJ/kg. The failure behaviors under 15-degree oblique impact is however a global buckling mode (Fig. 7c). The force-displacement curves for the three loadings are depicted in Fig. 7d. The force-displacement curves for direct and 10° are similar, while the global buckling of the 15° oblique load can be readily seen by the sudden drop of resistance force. The crush efficiency of the hexagonal member in the case of direct axial force is 0.5 since the initial peak force under impact is rather high.

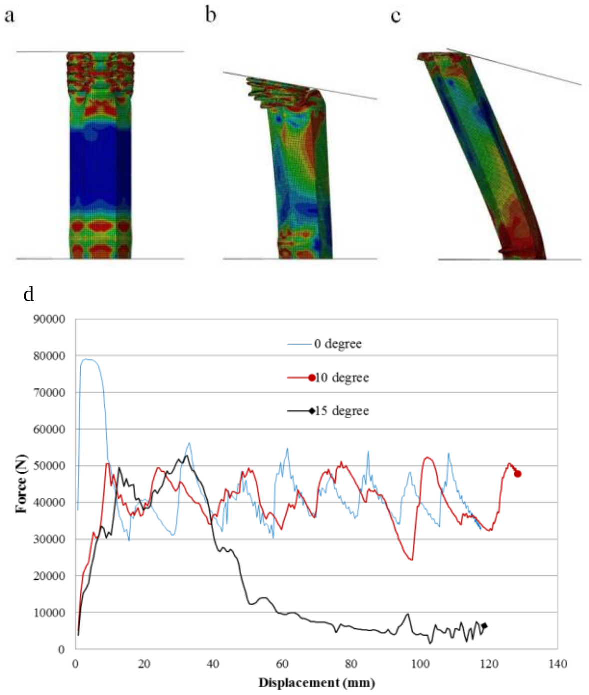


Fig. 7 Deformed shapes of hexagonal tube (a) $\theta = 0^\circ$, (b) $\theta = 10^\circ$, (c) $\theta = 15^\circ$, (d) force-displacement curves.

5.2 Hexagonal tube with single-row initiator

In order to reduce the undesirable initial peak force at the first crushing of hexagonal member under impact load, triangular notches and windows are introduced to the hexagonal models by using different patterns (type A, B, and C in Fig. 4). The initial peak forces, mean crushing forces and crush efficiencies for different models at the critical element and the first buckling mode locations under direct impact are displayed in Fig. 9. It can be observed that single-row initiators can decrease the initial peak force especially in the case of triangular type C (14T-C-1) and window type B (14W-B-1) and window type C (14W-C-1) initiators. The mean crushing forces are not much altered in all models and thus the crush efficiencies generally increase compared with the original hexagonal model. Triangular initiator type C shows the best structural performance with the lowest peak force and the highest crush efficiency. Additionally, initiators can alter the failure modes of the absorber as listed below the model name in Fig. 9 where ‘Sym’ represents symmetric mode and ‘Ext’ is extensional mode.

Fig. 9 Initial peak force, mean crushing force and crush efficiency for tubes with single-row initiators under axial loading

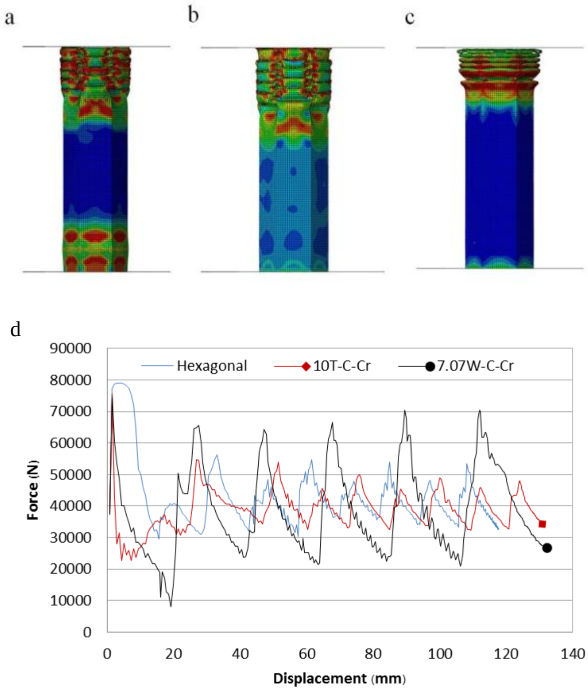


Fig. 10 Deformed shapes of (a) hexagonal tube, (b) 10T-C-Cr, (c) 7W-C-Cr, and (d) Force-displacement curves.

While the original hexagonal tube and triangular notching models give symmetric folding modes as displayed in Fig 10a and 10b, windowed models cause extensional mode under direct axial load (Fig. 10c). The extensional mode of failure often produces higher peaks after the initial peak force as shown in Fig. 10d and therefore should be avoided.

The effect of changing the dimensions of notch initiator is investigated for triangular notch tubes for the base dimensions varying from 10 to 20 mm. From Fig. 11a, it is found that the larger the size of initiator, the lower the initial peak force and the higher the crush efficiency. However, when the notching size is larger than 14 mm, the first folding does not occur at the pre-designed initiator location and the efficiency diminishes. Moreover, results from using the initiator at the location of the first buckling mode and at the critical element location are similar since the two locations are close to each other. When the notch is at an arbitrary prescribed location (15-T-P), the mean crushing force is tremendously low leading to low specific energy absorption. This proves the effectiveness of using the initiator at a proper location.

Fig. 11b depicts the initial peak and mean force under oblique load. Two modes of failure are observed as shown in the figure where ‘Local’ denotes local buckling or folding of the member and ‘Global’ indicates global buckling failure. The 14T-C-Cr and 14T-C-P models fail from global buckling before all the impact energy is absorbed while the other models can absorb the impact energy.

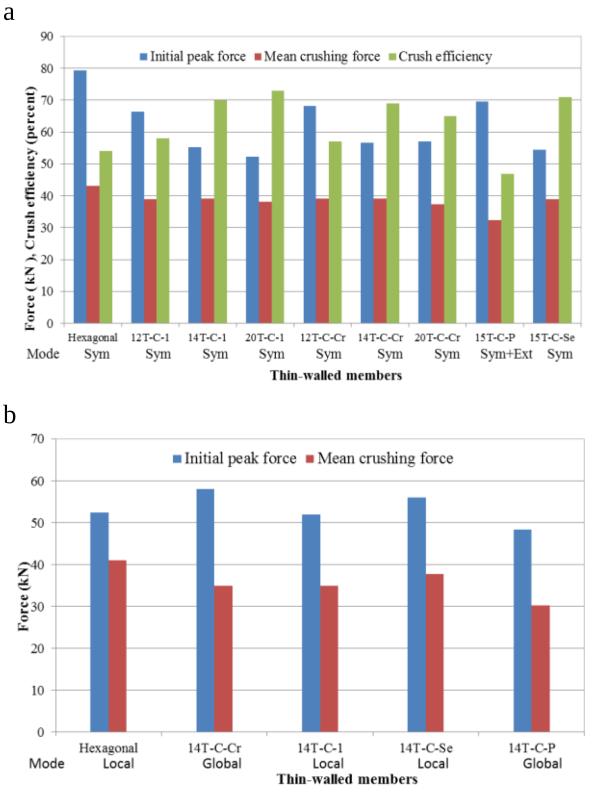


Fig. 11 Parameters for hexagonal tube with single row initiator (a) direct impact (b) oblique loading ($\theta = 10^{\circ}$)

For a single-row initiator tube, the 14T-C-1 model (Triangular notch on all 6 corners at the first buckling location) is recommended because the displacement pattern is in the symmetric mode under direct axial impact. The model can also absorb all crash energy when the tube is subjected to oblique loading at 10 degrees.

5.3 Hexagonal tube with multiple-row initiator

For hexagonal tubes with multiple-row initiator, the initial peak force and the mean crushing force under direct dynamic impact are shown in Fig. 12. Multiple-row initiators can effectively reduce the initial peak forces compared with single-row initiator of the same size. Although the mean crushing forces are generally decreased when the number of row increases, the tubes are able to absorb all impact energy according to ECE-R29 regulation. Fig. 13 demonstrates examples of the final deformed shapes of 10T-C-4, 7W-C-4 and 10T-C-12 models under axial and oblique crushing when all impact energy is absorbed. Though, the hexagonal tube with 12-row triangular notches (10T-C-12) cannot absorb all impact energy since global buckling occurs under oblique load.

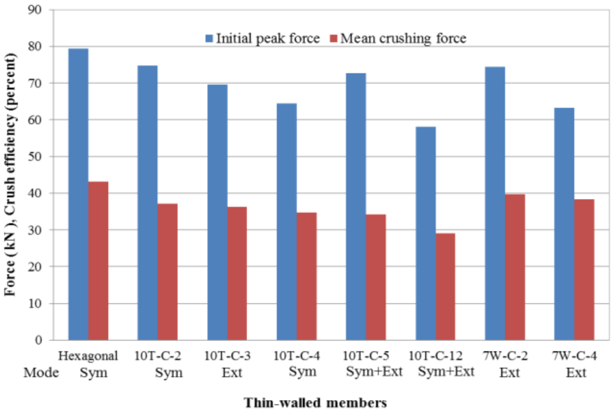
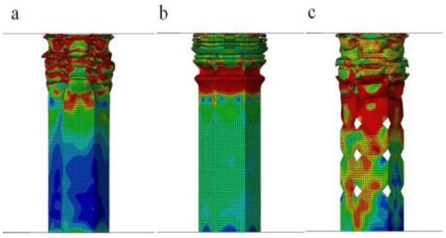
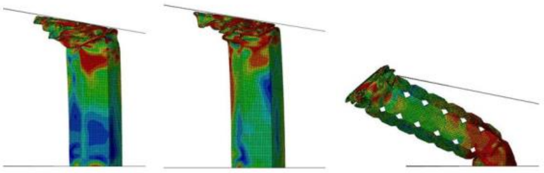


Fig. 12 Parameters for hexagonal tube with multiple-row initiator under direct impact



Direct impact



Oblique impact ($\theta = 10^{\circ}$)

Fig. 13 Deformed shapes of (a) 10T-C-4, (b) 10W-C-4, (c) 10T-C-12 under direct and oblique impact.

The failure modes for multiple-row triangular-notch and window initiators are similar to those with single-row initiators. Multiple-row triangular- notch tubes fold in symmetric modes whereas multiple-row windowed tubes collapse in extensional modes. Nonetheless, when the number of row is greater than 4, some mixed modes are observed when the tube is under axial crush and global buckling occurs under oblique load in which the energy absorption is very low.

Among the hexagonal tubes with multiple-row initiator studied in the current paper, the model with four-row triangular notch (10T-C-4) offers the best performance with initial peak force of 19% lower than that of the original hexagonal tube and crush efficiency of 55% under direct load.

Fig. 14 illustrates the effect of changing the dimensions of initiator for four-row triangular notch hexagonal profile by using the base length of 6 mm, 10 mm and 15 mm. From the graph, the initial peak force of 15T-C-4 model is the lowest where the crush efficiency is as high as 61%. The specific energy absorption is increased to 10 kJ/kg and the peak force is diminished by 30%. Moreover, the model can absorb the energy from a large angle of oblique impact without the occurrence of global buckling due to progressive folding of the tube as shown in Fig. 15.

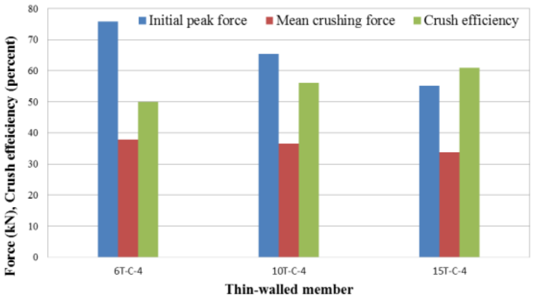


Fig. 14 Effects of changing the size of triangular notch

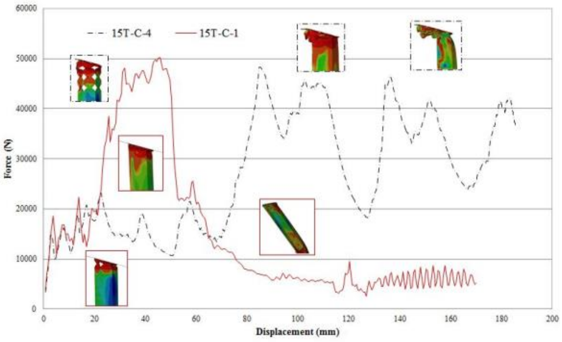


Fig. 15 Force-displacement curves for 10T-C-4 and 15T-C-4 models under oblique loading of $\theta = 15^{\circ}$.

6. Conclusion

Hexagonal thin-walled tubes with triangular-notch or window initiator are shown to be an efficient design of energy absorber under direct and oblique impact.

Hexagonal tubes with triangle notching at all six corners show symmetric collapse mode under axial impact and thus are more preferable than those with window opening which fail in extensional mode that creates secondary peak loads after the first peak under axial loading. The best location for single-row notching is at the first buckling mode location obtained from eigenvalue-based buckling analysis. The recommended design for hexagonal tube with multiple-row initiator is the four-row triangular notching in which the peak force is reduced and the specific energy absorption is increase up to 30 percent compared to hexagonal tube.

7. References

[1] Abramowicz W, Jones N. (1984). Dynamic axial crushing of squared tubes. *International Journal of Impact Engineering2*, pp. 179-208.
[2] Wierzbicki T, Abramowicz W. (1983). On the crushing mechanics of thin walled structures. *Journal of Applied Mechanics50*, pp. 727-34.
[3] Alghamdi A. (2001). Collapsible impact energy absorbers; an over view. *Thin-Walled Structure 39*, pp. 189-213.
[4] Olabi A, Morris E, Hashmi M. (2007). Metallic tube type energy absorpbers: a synopsis. *Thin-walled structure45*, pp. 706-26.
[5] Yuen S, Nurick G. (2008). The energy-absorbing characteristics of tubular structure with geometric and material 1 modifications: an over view. *App 1 Mech Rev* ; 61: 020802-1-15.
[6] Tarlochan F, Samer F, Hamouda A.M.S, Ramesh S, Khalid. (2013). Design of thin wall structures for energy absorption applications: Enhancement of crashworthiness due to axial and oblique impact forces. *Thin-Walled Structures 71*, pp. 7-17.
[7] Zhang X, Su H, Yu T. (2009). Energy absorption of an axially crushed square tube with a buckling initiator. *International Journal of Impact Engineering 36*, pp. 402-417.
[8] Song J, Guo F. (2013). A comparative study on the windowed and multi-cell square tubes under axial and oblique loading. *Thin-Walled Structures 66*, pp. 9-14.
[9] Nia A, Nejad Kh, Badnava H, Farhoudi H.R. (2012). Effects of buckling initiators on mechanical behavior of thin-walled square tubes subjected to oblique loading. *Thin-Walled Strutures 59*, pp. 87-96.
[10] Bandi P, Detwiler D, James P, Tovar A. (2015). Design of progressively folding thin-walled tubular components using compliant mechanism synthesis. *Thin-Walled Structure 95*, pp. 208-220.
[11] Safe Analysis of the New Actors Mega space Cabin According to ECE-R29/02, URL: http://www.dynalook.com/european-conf-2003/safety-analysis-of-the-new-actors_megaspace-cabin,pdf.