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# Crashworthiness analysis and design of multi-cell hexagonal columns under multiple loading cases

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ABSTRACT

Multi-cell thin-walled structures have proven fairly effective in energy absorption and have been extensively used in vehicle engineering. However, the effects of multi-cell configurations and oblique loads on the crashworthiness performance have been under studied. This paper aims to investigate the crash behaviors of different multi-cell hexagonal cross-sectional columns under axial and oblique loads comprehensively. The modeling results are first validated by comparing with the theoretical and experimental data. It is found that for the same cell number, the number of corners plays a significant role in enhancing energy absorption. Second, a multicriteria decision-making method, namely complex proportional assessment (COPRAS), is used to select the best possible sectional configuration under multiple loading angles. Finally, the Kriging modeling technique and multiobjective particle optimization (MOPSO) algorithm are employed to optimize the dimensions of such a cross-sectional configuration. The results exhibit that an optimized multi-cell sectional tube is more competent in crashworthiness for multiple load cases (MLC).



## 1. Introduction

With increased customer demand and government regulation, more and more attention has been recently drawn to improvement of structural crashworthiness for reducing occupant fatalities and injuries. On the other hand, growing concern in fuel consumption and environment sustainability pushes the vehicle structures lighter and lighter. As a result, thin-walled structures, especially the multi-cell columns are widely used as an energy absorber in vehicle structures. To date, substantial studies [1–8] have been conducted with differently shaped mono-cell hollow and filled tubes. It has been shown that foam-filled tubes are more efficient in energy absorption than the hollow columns.

Nevertheless, Zhang and Cheng [9] pointed out that the multi-cell columns with different configurational sizes could absorb about 50–100% more energy than the foam-filled columns with the same weight. Besides, the state-of-the-art extrusion process allows to fabricate multi-celled tubes in a single piece of component straightforward nowadays, making fabrication of arbitrary cross-sectional members relatively easily without increasing too much cost [10]. Over years, considerable studies have been conducted on the energy absorption of multi-cell tubes by using analytical, numerical and experimental methods. For example, Bai et al. [11] proposed a new analytical model to predict the mean crushing strength of hexagonal multi-cell thin-wall structures under quasi-static crushing, which was validated by the experimental test and literature data. Chen and Wierzbicki [12] derived a theoretical formula for calculating the mean crushing force of foam-filled double-cell and triple-cell columns, which agreed with the simulation results well. Kim [10] proposed some new multi-cell configurations with four square cells at corners and found that energy absorption of these columns can be improved substantially over the conventional column. Zhang and Zhang [13] studied the crash behaviors of different multi-cell sections under axial load and improved the Chen and Wierzbicki's formula of mean crushing load. Alavi Nia and Parsapour [14] investigated the crashworthiness of single cell and multi-cell tubes, and showed that adding partitions at corners does help improve the crash behaviors. They also revised Zhang et al.'s formula so that it could be applied to the tubes with unequal cell size. Najafi and Rais-Rohani [15] studied the energy absorption characteristics of thin wall tubes with different multi-cell and multi-corner configurations

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under axial quasi-static loading condition. These aforementioned multi-cell tubal structures have well exhibited their superior abilities in absorbing crash energy under axial loading.

On the other hand, a vehicle rarely encounters a completely axial load, but rather likely experiences in oblique loading in real life crashing events. In practical design of vehicle, the bumper system requires to endure as large as 30° loading angle to the longitudinal axis [16]. For this reason, crashworthiness design should take into account the oblique loading. In this regard, Song and Guo [17] compared the crash behaviors of windowed and multi-cell square tubes with the same weight under axial and oblique loading conditions. The results indicated that the multi-cell and windowed columns perform better at the axial loading angle but even worse at small oblique angles than conventional tubes. Tran et al. [18] extended the analytical solutions from pure axial quasi-static to dynamic oblique loading conditions, by proposing an oblique impacting coefficient and taking into account the inertia effect, which were validated by the numerical results. Li et al. [19] numerically studied the crash behaviors of functionally graded foam-filled tubes in comparison with the uniform foam-filled counterparts under oblique loads. They revealed that impact angle affects the crashworthiness drastically and needs to be considered in optimization. Reyes et al. [16,20,21] studied the crashworthiness of foam-filled aluminum tubes under quasi-static oblique loads; and they confirmed that the mean and peak loads decrease with the impact angles as more severe bending reduces loading bearing capacity.

While there have been some studies available on the crashworthiness of multi-cell tubes, few has systematically compared the energy absorption of different cross-sectional configurations. Further, it remains to be clarified how a loading angle affects the energy absorption of multi-cell hexagonal tubes, and how the multi-cell configurations can be optimized for better absorbing energy under oblique loads?

The rest of this paper is organized as follows. Section 2 introduces the numerical modeling techniques and validation, followed by crashworthiness comparison of different multi-cell tubes in Section 3. Section 4 describes the optimization of multi-cell tubes and Section 5 draws some conclusions.

## 2. Numerical analysis

### 2.1. Finite element (FE) model

Alavi Nia and Parsapour [22] compared the energy absorption of multi-cell thin-wall tubes made of aluminum with triangular, square, hexagonal and octagonal sections subjected to quasi-static loading. They found that the hexagonal column absorbs more energy than the other sectional configurations. From their studies, the hexagonal thin-walled tube is a comparatively better choice for design of vehicular components. For example, Honda employed complex hexagonal extruded cross-section members for the front side rail of its new hybrid passenger car, namely Insight [23]. Therefore, this study focuses on the crashworthiness of different multi-cell hexagonal tubes, as shown in the schematic of cross-sections in Fig. 1. Besides, the one singly-walled tube (Fig. 1a) and two doubly-walled tubes (Fig. 1b and e), and four multi-cell tubes (Fig. 1c, d, f and g) were constructed by connecting the outer and inner walls through six ribs with different configurations. As such, seven different cross-sectional configurations were considered for the comparative study: i.e. (a) S1: single tube; (b) S2: bitubal tube I; (c) S3: corner ribs connecting the outer and inner walls, (d) S4: middle ribs connecting the outer and inner walls, (e) S5: bitubal tube II; (f) S6: ribs connecting the outer corners with the middle inner walls; (g) S7: ribs connecting the middle outer walls with the inner corners. These seven columns with the same outer side width of $B=36$ mm, inner side width of $C=18$ mm (if any) and axial length of $L=180$ mm are assigned with different wall thicknesses to maintain the same mass (Fig. 1).

The commercial explicit non-linear dynamic finite element analysis (FEA) code LS-DYNA was employed to simulate the crash behaviors of the above mentioned multi-cell hexagonal columns under different loading angles. As shown in Fig. 2, the finite element (FE) model was comprised of the differently sectional tubes, the striker with mass of 600 kg and the base used to constrain the bottom end of the tube. At different loading cases, the striker with different incident angles $\theta$ impacted on the top end of the tube at an initial velocity of $v=15$ m/s. The outer, inner and rib walls of the multi-cell columns were modeled using the Belytschko–Lin–Tsay reduced integration shell elements with five integration points across the thickness. The reduced integration technique and hourglass control were employed to avoid volumetric locking and spurious zero energy deformation modes, respectively. The mesh size of 1.5 mm was selected for tube specimens based on a mesh convergence study. "Automatic node to surface" algorithm was employed to simulate the interfaces between the tube and striker as well as between the tube and rigid base. Meanwhile, the contacts between the column walls, with and without ribs and inner walls, were modeled with "Automatic single surface" contact to avoid interpenetration during crushing. The value of Coulomb friction coefficient for all the contact surfaces was set at 0.15 [13].

The material of multi-cell columns is aluminum extrusion AA6061 with the following mechanical properties [13]: the density $=2700$ kg/m$^3$, Poisson's ratio $=0.33$, Young's modulus $=68$ GPa, initial yield stress $=71$ MPa, ultimate stress $=130.7$ MPa and the power law exponent of 0.18. The constitutive behavior of the thin-walled structure was based on an elastoplastic material model 123 in LS-DYNA with piecewise linear plastic hardening. The engineering stress–strain curve of the material is shown in Fig. 3 [13].

### 2.2. Validation of FE model

The numerical results of single-wall tube (S1) under axial quasi-static impact can be validated using a close-form formula of the mean crushing force, which was developed based on the super folding element method as calculated by [13]

$$F_{avg-S1-static}=\frac{136.037}{k}\sigma_0 B^{0.2} t^{1.8} \tag{1}$$

where $\sigma_0$ denotes the flow stress of tube material, and $t$ is the wall thickness of the tube. The coefficient $k$ is given as the ratio of the effective crush distance to initial length, and is identified as 0.79 for single wall tube in this validation study [13].

In addition, the theoretical formulae [24] of the mean crushing force for single tube S1 and multi-cell tube S4 were employed to validate the effectiveness of the FE model under dynamic loading conditions.

$$F_{avg-S1-Dynamic}=\lambda\frac{136.037}{k}\sigma_0 B^{0.2} t^{1.8} \tag{2}$$

$$F_{avg-S4-Dynamic}=\lambda\frac{42.45}{k}\sigma_0 B^{0.5} t^{1.5} \tag{3}$$

According to Hou et al. [25], the strain rate does not have much influences on aluminum alloy and can be neglected. Therefore the dynamic coefficient $\lambda$ is introduced to consider the inertia effect, which is set as 1.1 here [26–28]. The coefficient $k$ is identified to the effective folding length obtained from the simulation for correlation analysis, which is given as 0.66 here for multi-cell