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A novel multi-cell tubal structure with circular corners for crashworthiness

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ABSTRACT

Multi-cell structures have proven to own excellent energy absorbing capability and lightweight effect in the automotive and aerospace industries. The cross-sectional configuration of the multi-cell structure has a significant effect on crashworthiness. Unlike existing multi-cell tubes, a new type of five-cell profile with four circular elements at the corners (C5C) was proposed in this study. To investigate the crashworthiness of the new C5C tube, finite element (FE) models were first established by using the nonlinear finite element code LS-DYNA and validated with experimental results. Following that, the comparison of the C5C tube and other multi-cell tubes with the same mass was conducted to quantify the relative merits of the C5C tube. Then, a detailed study was performed to analyze the effect of the corner-cell size and wall thickness. Finally, the optimization design was carried out to seek the optimal structure. The results showed that the new multi-cell structure can absorb much more crash energy than other four types of tubes. Moreover, the energy absorption of this new multi-cell tube C5C was affected by the corner-cell size and wall thickness significantly. A proper corner-cell size and slightly thicker internal ribs were recommended. In addition, the multi-objective particle swarm optimization (MOPSO) algorithm and radial basis function (RBF) surrogate model can optimize the structure effectively. The outcomes of the present study will facilitate the design of multi-cell structures with better crashworthiness.

1. Introduction

To address the urgent environmental problems, light-weighting has been a key target in the automotive industry [1]. The mass reduction of the vehicles is beneficial to the reduction of fuel consumption and carbon dioxide emission. On the other hand, the study by Evans [2] showed that the mortality rate of occupants in the lighter vehicle tends to be at higher risk than that in the heavier vehicle in the frontal two-car collision accident. Although the effect of the vehicle mass on safety is very complicated, there is no doubt that the mass is a key factor directly related to the secondary safety performance of the vehicle. This is because that the greater velocity change of a lighter car would lead to more severe injuries of occupants during the collision [3]. Thus, effective crash energy absorption of the vehicle is also very important to reduce the kinetic energy transmitting to the occupants. Thin-walled structures featured by exceptional performance in energy absorption and light-weighting, have been extensively used in front side rails [4,5].

A number of experimental and theoretical studies have been performed to investigate various single- cell structures, such as circular [6], square [7] and hat shaped tubes [8,9], subjected to static and dynamic loads. Alexander [10] developed a simple yet very practical theoretical model to evaluate the average crush force and energy absorption of a metal tube under axial compression. Based on Alexander's work, Wierzbicki et al. [11] presented a self-consistent theory named Super Folding Element (SFE) theory to capture the axial crush behavior of a square thin-walled structure. According to this theory, a model consisting of trapezoidal, toroidal, conical and cylindrical surfaces with moving hinge lines was developed. Later, Lee and Wierzbicki [12] studied the effect of the material distribution on the crash energy absorption for the square extruded tubes. They found that more material at the corner led to more crash energy absorption. Zhang et al. [13] investigated square tubes with graded thicknesses with more material at the corner, and found a 30~35% increase in energy absorption efficiency. Sun et al. [14] presented square tubes with an axial functionally graded thickness (AFGT) and a lateral functionally graded thickness (LFGT), and derived analytical solutions for their mean crush forces. In addition, Yamashita et al.[15] compared the single-cell tubes with different cross-sections. They found that the energy absorption increased with the increase in the number of corners of the cross-section, and that circular tubes could absorb more crash energy than square ones.

In fact, the phenomenon that the crashworthiness of the tubes with curved surfaces is better than that of their counterparts with the flat surface corners has been verified by many studies. Jones [16] studied

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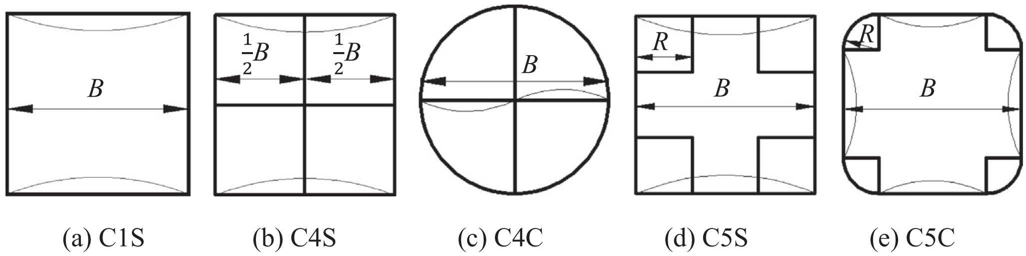

Fig. 1. Cross-sectional configurations of different thin-walled structures.

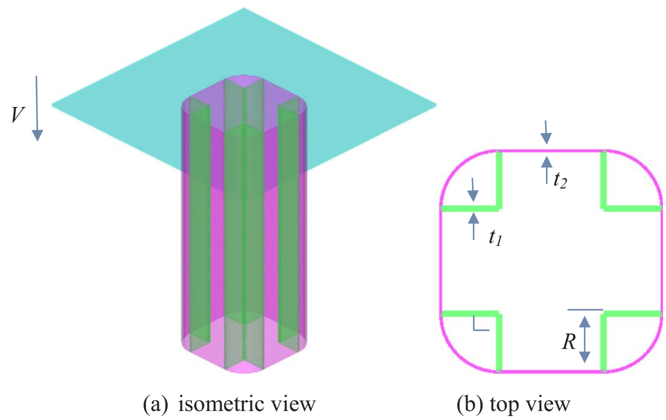

Fig. 2. Schematic of the FE model.

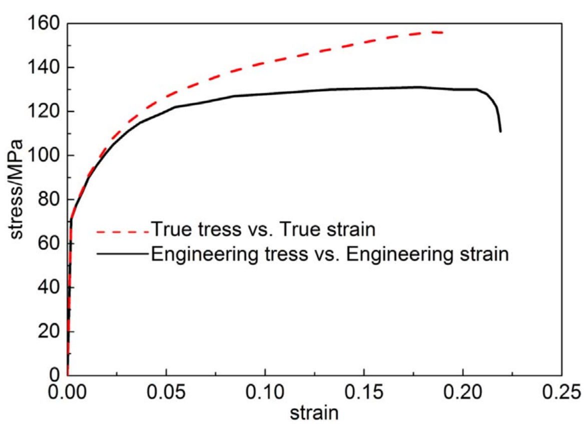

Fig. 3. Stress–strain curves of AA6061 O [40].

the energy absorption of various cross sections, and found that an axially crushed circular tube was the most effective structure. Tang et al. [17] compared the energy absorption of a cylindrical multi-cell tube and a square multi-cell tube, and found that the cylindrical multi-cell tube was more efficient in energy absorption. Xiang et al. [18] conducted an in-depth analysis and comparison on the energy absorption of polygonal tubes. They found that the effectiveness of energy absorption of a polygonal tube could be improved by increasing the number of the tube sides, and the circular tube possessed the best energy absorption performance as it could be regarded as a polygonal tube with an infinite number of sides. Sun et al. [19] studied square and criss-cross tubes in crashworthiness with the same weight, and found the criss-cross tube with curved surface exhibited the best energy absorption. Excellent energy absorption of circular tubes or tubes with curved surfaces can be explained by using the Super Folding Element theory of Wierzbicki [11]. Severe deformation of square tubes only occurs at the zones near corners and bending flange lines. Most of the material of the square tube undergoes rigid motion during the crushing process. On the other hand, for the tubes with a curved surface, not only bending deformation takes place along bending hinge lines but also membrane deformation occurs for a large portion of the material. Thus, the energy absorption of a circular tube is higher than that of a square tube.

Multi-cell thin-walled structures have been studied by so many researchers because their energy absorption is better than that of conventional single-cell tubes [20–24]. Zhang et al. [25] studied the energy absorption of the square tube with nine square cells by theoretical and numerical methods. Then, they compared the multi-cell tubes and foam-filled tubes, and found that the former ones had a better energy absorption capacity [26]. Najafi et al. [27] studied the square tubes with different multi-cells, multi-corner configurations, and compared their differences in energy absorption. Pirmohammad et al. [28] compared the crush behaviors of multi-cell structures consisting of two straight columns with the same shape of cross-section connected together by several ribs. Mahmoodi et al. [29] investigated the crashworthiness behavior of tapered multi-cell tubes theoretically and numerically. They found that the increase in the taper angle and the number of cells in the cross section would improve the crashworthiness of the structure. Sun and his coauthors [30] investigated the effect of the number of cells and topological configurations of multi-cell structures on their crashworthiness. Then, they explored the crushing behavior of multi-cell tubes with laterally variable thickness(LVT), and found that the LVT multi-cell structures were better energy absorbers than the uniform counterparts [31,32]. Hou et al. [33] optimized multi-cell tubes using the response surface method to enhance their energy absorption. More recently, Fang et al. [34] developed a topology optimization technique for optimizing multi-cell tubes for axial crushing, which does not require pre-defined sectional configurations, therefore a series of novel multi-cell topologies were obtained.

Square or rectangular profiles are commonly used in many vehicular crash structures [35,36]. One of the reasons is that they can be easily

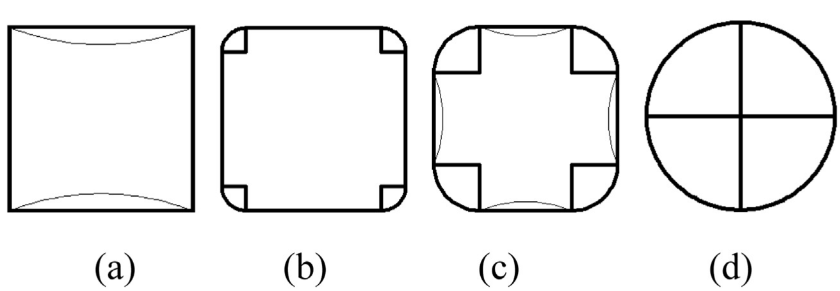

Fig. 4. New multi-cell tubes: (a) $R = 0$; (b) $R = B/8$; (c) $R = B/4$; (d) $R = B/2$.