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Topological configuration analysis and design for foam filled multi-cell tubes

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ABSTRACT

Foam filled multi-cell tubes have attracted much attention recently because of their exceptional advantages in energy absorption characteristics and lightweight. The study aims to explore the effects of cross-sectional configurations, including topological distribution of empty and foam-filler in the multi-cell tube, on the crashworthiness; and further optimizing the wall thickness and foam density. First, the coupled finite element method (FEM) and element free Galerkin method (EFGM) were adopted to model the foam filled multi-cell tubes. Second, the multi-criteria decision making method, namely COPRAS (complex proportional assessment), was used to rank the energy absorption characteristics of the considered foam filled multi-cell tubes with different topological configurations. The results show that the five-cell tube with four cells in the corners filled with forms was the best choice compared with the other topological configurations for the given design domain. Finally, the discrete optimization based on successive orthogonal arrays was employed to conduct the topological design of foam filled multi-cell tubes for maximizing the specific energy absorption (*SEA*) under the constraint of the global peak crushing force (*GPCF*). The results showed that the *SEA* of the optimized design is about 6.15% higher than the best choice from COPRAS analysis within the *GPCF* constraint, which demonstrated that the proposed approaches can be an effective tool for crashworthiness topology optimization of foam filled multi-cell tubes.

1. Introduction

Thin-walled tube, as one of the most common energy absorbing structures, has been extensively used in vehicles for their exceptional advantages in crashworthiness and lightweight [1–3]. Through comprehensive studies over the past three decades, the crashworthiness potential of traditional mono-cell tube has been somewhat pushed to its limits [4]. For further improving the energy absorption capacity, while realizing lightweight design, multi-cell tubes have become more and more attractive due to their significant benefits in efficiency of energy absorption. In this regard, Zheng et al. [5] first proposed the laterally variable thickness (LVT) multi-cell tubes and derived the analytical models for the mean crushing force and energy dissipation of the LVT multi-cell tubes with regard to the thickness gradient. Tang et al. [6] proposed a novel cylindrical multi-cell structure; and investigated the energy absorption characteristics under axial impact loading numerically. The parametric studies showed that the wall thickness and the number of cells have considerable effects on energy absorption. Nia et al. [7] systematically studied 12 kinds of different topological configurations and discovered that the multi-cell tubes showed a dramatic improvement over the conventional mono-cell columns. Zhang and Zhang [8,9] explored circular and square multi-cell tubes with different sections; and the results indicated that the energy absorption efficiencies of multi-cell tubes are significantly higher than those of the simple tubes. Sun et al. [10,11] optimized the multi-cell tubes and further improved the crashworthiness. Mahmoodi et al. [12] investigated crashworthiness of the tapered multi-cell tubes and explored several different ways to improve the energy absorption of multi-cell tubes. Wu et al. [13] explored the crashworthiness of several different configurations of multi-cell structures and reported that the energy absorption of five-cell tube was the best compared with the other tubes. More recently, Tran [14,15] explored the crushing analysis of square and triangular multi-cell tubes under lateral loading and developed theoretical formulas to predict the crushing behaviors of multi-cell tubes. Zhang et al. [16] studied a new type of embedded multi-cell tube under axial crushing and they found that the specific energy absorption of such structures can be improved notably.

In addition to these empty multi-cell tubes, aluminum foam, one of common lightweight cellular materials, has been recently used as filler in thin-walled hollow structures to enhance the capacity of energy

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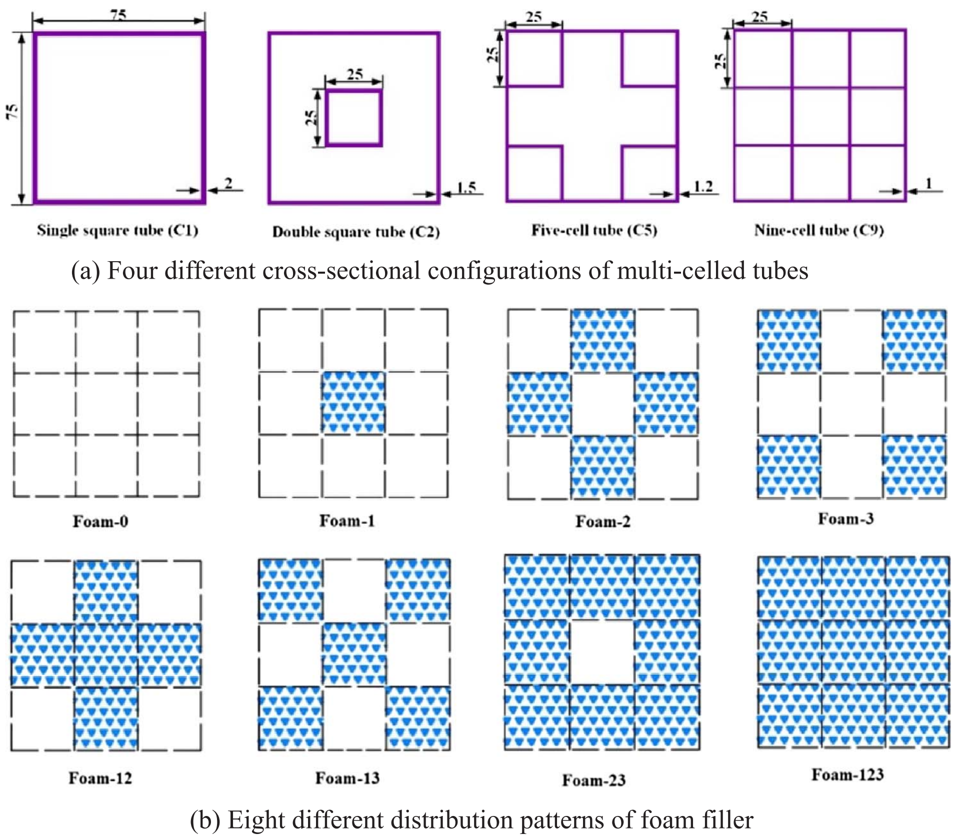

Fig. 1. The topological configurations of multi-celled tubes and distribution of foam filler.

absorption [17–20]. In this regard, Hanssen et al. [21,22] studied the crashworthiness of a series of foam filled thin-walled structures and developed theoretical formulas to predict the mean crushing forces under the quasi-static and dynamic loading. Their research revealed that the energy absorption of foam filled tubes is even higher than the sum of the energy absorption of empty tube alone and filler alone, attribute to the interaction between tube wall and foam. Gao et al. [23] investigated a novel foam-filled ellipse tube using nonlinear finite element (FE) analysis under multiple loading angles and divulged that the energy absorption of foam filled ellipse tube was superior to the other structures concerned in their study. Duarte et al. [24] explored the dynamic and quasi-static bending behavior of foam filled tubes experimentally; and found that the presence of the foam-filler in thin-walled tube has higher load carrying capacity under three-point bending loading, thereby increasing the energy absorption capacity. Li et al. [25] found that foam-filled double circular tube exhibited excellent energy absorption characteristics under bending collapse loading. Fang et al. [18,26] demonstrated that the functionally-graded foam filled tubes have better performance in crashworthiness than the uniform foam filler.

From these abovementioned studies, it appears that the multi-cell and foam filling are two main approaches to improving the energy absorption of thin-walled structures. The energy absorption will be further improved if combining them. The recent studies have demonstrated its advantages. For example, Zheng et al. [27] systematically studied the energy absorption characteristics of foam-filled bitubal polygonal tubes; and they demonstrated that the foam-filled bitubal circular tube was of better crashworthiness characteristics in comparison with other configurations. Goel [28] assessed the crashworthiness of single, double and multi-celled square and circular tubes with and without aluminum foam core. It was found that the concentric tube configuration and foam filler affected the deformation and energy absorption; and by changing the configuration of the tube and foam filling, better performance can be achieved. Altin et al. [29] studied 26 different types of multi-cell tubes (with or without foam filler) through the FE analysis. They revealed that different foam filling methods have great influence on the performance of the structures. The above researches evidently indicated that the energy absorption capacity of foam filled multi-cell tubes can be greatly influenced by cross-sectional configurations and distribution of foam filler. For this reason, it appears necessary to seek the optimal design parameters for foam filled multi-cell tubes. In this regard, the researchers have been undertaken on the optimization of foam filled multi-cell tubes. For instance, Yin et al. [30,31] optimized the foam-filled multi-cell thin-walled structures under axial and lateral impacts to improve energy absorption. Their results showed that the foam filled multi-cell tube with nine cells had the best crashworthiness. Later, Yin et al. [32] carried out multi-objective optimization for foam-filled bionic thin-walled structure; and they found that the crashworthiness of foam-filled bionic structure was better than that of the traditional structures. Gao et al. [33] optimized foam-filled double ellipse tube to achieve a better crashworthiness performance. From the optimization results, they found that the optimal foam filled double ellipse tube outperformed the other structures concerned.

Nevertheless, the above studies on crushing behavior of foam filled multi-cell structures were mainly concentrated on some specific structures with pre-defined cross-sectional configurations and/or the distribution of foam filler. As a matter of fact, the cross-sectional configuration of multi-cell tube and distribution of foam filler may have a distinctive effect on the crashworthiness. Thus, it raises a fundamental question in how to devise a sectional configuration for foam filled multi-cell tube to maximize crashworthiness. To address this issue, this study first investigated the crashworthiness of foam filled multi-cell tubes with different cross-sectional configurations and distribution of foam filler under axial crushing load. Second, a discrete optimization method based on successive orthogonal arrays [34–36] was presented to optimize the topological configuration of filler materials within multi-cells for maximizing specific energy absorption (*SEA*) under the