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On design of multi-cell thin-wall structures for crashworthiness

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ABSTRACT

Multi-cell thin-wall structures have drawn increasing attention and been widely applied in automotive and aerospace industries for their significant advantages in high energy absorption and lightweight. The number of cells and the topological configurations of the multi-cell thin-wall structures have a significant effect on the crashworthiness. In order to investigate the effect of the number of cells and the topological configurations of multi-cell structures on their crashworthiness characteristics, this paper first sets up the simulation models of multi-cell tubes and verifies their accuracy with the quasi-static and dynamic impact experiments. Second, it compares the energy absorption characteristics of the multi-cell structures with different numbers of cells and topological configurations under dynamic impact condition using finite element analysis (FEA). The results show that the mean crushing force (MFC) and specific energy absorption (SEA) increase with the increase in the number of cells of the multi-cell tubes, among which the five-cell tube has the best energy absorption characteristics. Third, a parametric study is carried out to investigate the effects of wall thickness and topology configurations on the crashworthiness of five-cell tubes. Finally, the multiobjective Non-dominated Sorting Genetic Algorithm (NSGA-II) is used to further optimize the five-cell tube for maximizing specific energy absorption and minimizing peak crushing force (PCF). The optimal five-cell tube has excellent crashworthiness and is a potential energy absorber.

1. Introduction

As a typical class of energy absorbers, thin-walled structures have been widely used in crashworthiness applications such as automotive industry to protect passengers from severe injury for their excellent energy absorption capacity and lightweight. The early investigation of energy absorbers have mainly focuses on steel tubes for their low costs and high ductility [1]. As the increasing importance of lightweight, the use of aluminum tubes has become more and more predominant in the recent years [2]. Over the past decades, substantial efforts have been devoted to investigation into the crushing behaviors of the thin-walled structures through analytical and experimental methods. For example, Alexander [3] first derived an analytical solution to calculate the axial mean crushing force for circular tubes. Wierzbicki and Abramowicz [4] proposed the close-form formulas to predict the axial crush response of aluminum thin-walled tubes. The analytical predictions were validated experimentally by Abramowicz and Jones [5,6] and Langseth and Hopperstad [7].

The crashworthiness structures are expected to absorb maximum energy with minimum mass. To achieve a lightweight design, multi-cell configuration of thin-wall structures has exhibited superior capacity of energy absorption with proper weight efficiency. Comprehensive studies have been conducted theoretically, numerically and experimentally to investigate the crushing behavior of the multi-cell structures. Chen and Wierzbicki [8] investigated analytically the behavior of single-cell, double-cell and triple-cell aluminum tubes. They adopted a so-called Super Folding Element theory [4,9] to develop an analytical solution for mean crushing force of multi-cell sections. Based on the Chen and Wierzbicki's work [8], Zhang and Chen [10] derived an analytical solution for the mean crushing force of multi-cell rectangular tubes with four to nine identical rectangular cells. In their model, they analyzed the energy absorption of square multi-cell tubes by dividing the cross-section into three basic angular elements and assumed an average wavelength for the dissimilar folds. Lately they found that the crisscross part was the most efficient component for energy absorption. In addition, they compared the energy absorption efficiency of multi-cell tubes with that of foam-filled tubes and identified that the performance of multi-cell tubes is substantially better [11]. Najafi and Rais-Rohani [12] also adopted the super folding element theory to study the energy absorption characteristics of multi-cell and multi-corner tubes with different sectional configurations and derived an analytical formula for calculating the mean crushing force of multi-cell and multi-corner tubes. Alavi Nia and Parsapour [13] applied Zhang et al.'s formula [10] for predicting mean crushing force of the square tubes with nonuniform cells. Kim [14] proposed a new

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extruded multi-cell profile through adding four square corner elements to the tube, which increased the specific energy absorption (SEA) by 190% over the conventional square tube. Tang et al. [15] further showed that by introducing more corners into the structure, the energy absorption can be further increased. Song and Guo [16] conducted a comparative study on the performance of windowed and multi-celled square tubes with the same weight under axial and oblique loading. These studies showed that SEA of multi-cells is significantly higher than that of single-cell.

The combination of analytical and experimental investigations into multi-cell structures has been recently gaining comprehensive attention. Krolak et al. [17] explored experimentally the stability and load-bearing capacity of multi-cell tubes. Their experiments showed that the multi-cell tube with a sectional area approximately 15% smaller than that of single-cell column has seven times higher buckling stress and 1.9 times bigger load bearing capacity. Zhang et al. [18] studied experimentally, analytically and numerically the deformation behavior and energy absorption characteristics of circular multi-cell tubes with double, triple and quadruple cells. In their analytical models, a constituent element method was proposed and employed to predict the mean crushing force of the circular multi-cell tubes. In addition, Zhang et al. [19] conducted the experimental investigations and theoretical analyses of multi-cell square tubes with different sections. Hong et al. [20] proposed multi-cell tubes with triangular and Kagome lattices, and carried out quasi-static axial compression tests to reveal the progressive collapse mode and folding mechanism of multi-cell lattice tubes. It is noted that the above experiments largely focused on the crushing behavior of multi-cell tubes under quasi-static axial compression.

Although multi-cell tubes are capable of enhancing energy absorption, the degree of energy absorption was found to be highly dependent on the cross-sectional configuration of tube. To further improve their energy absorption capability, various optimization techniques have been extensively adopted in recent years [21–23]. For example, Hou et al. [21] combined multiobjective optimization design (MOD) technique with response surface method (RSM) to maximize the energy absorption and minimize the peak force of multi-cell tubes. Qi et al. [22] integrated particle swarm optimization (PSO) with surrogate models to conduct a crashworthiness optimization for tapered multi-cell square tubes, showing that the optimal designs differed under different load angles; and the weighting factors for different load cases are critical in the design. In summary, the researches mentioned above have mainly focused on some special topological configuration of multi-cell thin-walled tube. In fact, the sectional topologies can have significant effects on the crashworthiness of multi-cell thin-walled tube. To the author's best knowledge, however, there are few reports available to compare the different topological configurations for enhancing crashworthiness.

This paper aims to investigate the energy absorption characteristics of multi-cell structures under impact loads. Three representative topological configurations are considered to compare the multi-cell tubes with different cross-sectional configurations. The quasi-static axial crush and dynamic crash experiments are carried out to validate finite element (FE) models of multi-cell tubes. A comprehensive comparison of the multi-cell tubes with different sectional topologies is first conducted to investigate the effect of multiply-connected cells on their corresponding energy absorption characteristics. Then, a parametric study is carried out to explore the effects of the size of corner-cell, location of connecting flange and wall thickness of the five-cell tube on their crashworthiness. Finally, the five-cell configuration is optimized to achieve the maximum specific energy absorption (SEA) and minimum peak crushing force (PCF). Through which, the Pareto fronts for the two conflicting objectives (SEA and PCF) are obtained, which provides us with a set of design schemes in line with different requirements.

2. Crashworthiness criteria

Generally, energy absorption (EA), specific energy absorption (SEA), mean crushing force (MCF), the peak force (PCF) (Fig. 1), the crash load efficiency (CLE) are extensively used to measure the crashworthiness characteristics of thin-walled structures. Taking the axial impact as an example, the energy absorption of a structure is determined by integrating the crashing force with respect to displacement x as:

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

where d denotes deformation distance and F is the axial impact force. A typical axial crushing force–deformation curve of a thin-walled structure is illustrated in Fig. 1. The mean crushing force (MCF) for a given deformation can be calculated as:

$$MCF(d)=\frac{E(d)}{d} \tag{2}$$

The specific energy absorption (SEA) is considered a more critical criterion to measure energy absorption capability of unit material, defined as the ratio of absorbed energy to the structural mass M:

$$SEA=\frac{E_{total}}{M} \tag{3}$$

Obviously, a higher SEA value indicates higher capacity of energy absorption.

The crash load efficiency (CLE) can be calculated as the ratio of the mean crushing force MCF to the peak crushing force PCF as shown in Fig. 1:

$$CLE=\frac{MCF}{PCF} \tag{4}$$

As an energy absorber, the highest CLE is preferred [24].

3. Cross-sectional configurations of multi-cell thin-wall structures

In this study, three representative multiply-connected topologies are considered for comparison of the energy absorption characteristics of the multi-cell structures, as shown in Fig. 2. The

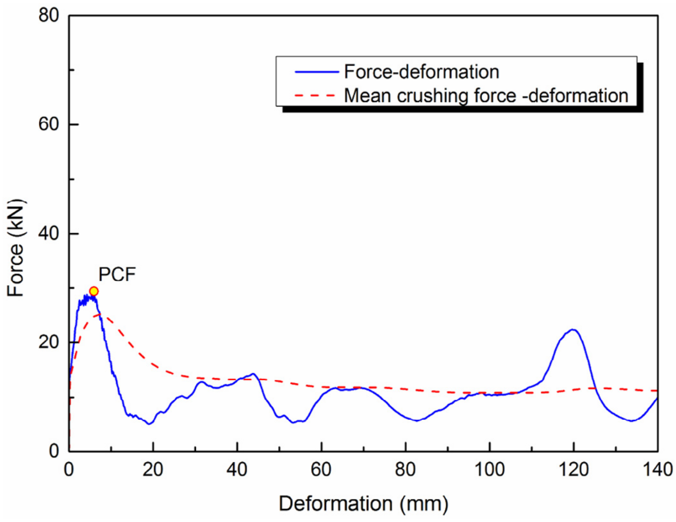

Fig. 1. Axial crushing force *vs.* deformation for a typical thin-walled structure.