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Energy absorption and optimization design of multi-cell tubes subjected to lateral indentation

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ABSTRACT

The local indentation of thin-walled beams is a key mechanism for the collapse of beams under lateral loads. The indentation behavior of multi-cell tubes is investigated in this work. Quasi-static experimental tests are conducted first for multi-cell tubes with three different sections. The deformed shapes and force responses are obtained by indenting the tubes resting on a rigid surface. Numerical simulations are then performed to analyze the static and dynamic responses of the tubes, and the accuracy of the numerical model is validated by the experimental results. The crushing force responses and deformation characteristics of the multi-cell sections are analyzed in detail and the energy absorption performances of them are evaluated. Results reveal that the cross-sectional shapes of the tubes have great influence on their deformation process and crushing force responses. Moreover, to further increase the energy absorption efficiency, sequential response surface method (SRSM) is employed to achieve the optimal designs of the multi-cell sections. Results show that the energy absorption performances of the sections are greatly improved by the SRSM optimization.

1. Introduction

Thin-walled structural components are widely used as energy absorbers [1,2] in the vehicle industry. The excellent crashworthiness performance of the absorbers can effectively avoid injuries and guarantee the safety of the occupants in accidental impact. The energy absorption performances of various components [3–6] have been extensively investigated during the past decades. For the purpose of improving energy absorption efficiency, adopting multi-cell sections has been demonstrated as an effective approach. Numerous studies [7–14] have been conducted on the crashworthiness of multi-cell structures subjected to axial, oblique and lateral loads.

Bending collapse is one of the typical energy dissipation mechanisms of thin-walled beams under lateral loading. Comprehensive studies on the energy absorption of rectangular tubes subjected to pure bending were carried out by Kecman [15], Wierzbicki et al. [16] and Kim and Reid [17], and theoretical models were established. However, the response of thin-walled beams under three-point bending is significantly different from those under pure bending. The local indentation beneath the punch head makes some difficulty in predicting the force response. This phenomenon was observed in the recent studies on bending collapse of single or multi-cell square tubes [12–14]. An illustration of such indentation mode of a multi-cell tube under three-point bending is shown in Fig. 1. The punch head indents into the multi-cell tube and the deformation mechanisms include both local indentation and global bending collapse. In order to analyze the bending collapse of multi-cell tubes with a local indentation, it is necessary to investigate the local indentation characteristics alone first. However, there are only few studies on the local indentation behavior of thin-walled tubes.

Besides bending collapse, lateral crushing is another important energy dissipation process of thin-walled beams. The energy absorption of thin-walled structures compressed laterally by two rigid planes has been studied extensively [3,18–23]. However, there is relatively less investigation concerned with the local compression or indentation behaviors of them under transverse loads. In 1971, Morris and Calladine [24] conducted an experimental and analytical investigation on the indentation of a cylindrical shell subjected to two opposite radial loads. In 1989, the deformation behavior of a laterally compressed tube resting on a flat base was investigated by Gupta and Sinha [25]. Recently, basing on experimental and numerical investigations, a theoretical model for local indentation of rectangle section tubes was proposed by Huang et al. [26]. There are still no related studies on the local indentation behaviors of multi-cell tubes and the energy absorption characteristics of them are still not clear.

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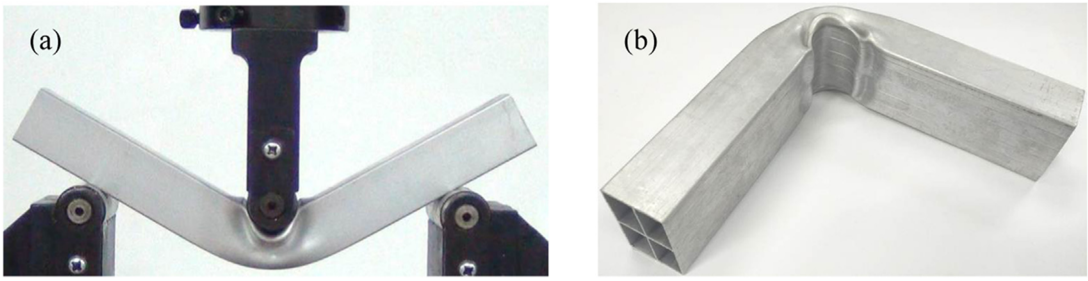

Fig. 1. (a) Three-point bending test of a multi-cell tube and (b) Deformed shapes.

In these two decades, surrogate-based methods have been widely applied to solve the crashworthiness optimization problems [27–32] in order to further improve the energy absorption efficiency of absorbers. For instance, structural optimization was performed for square tubes under three-point bending [29], multi-cell tubes subjected to axial loading [30,31], and tapered tubes subjected to oblique impact loads [32]. Generally, all these optimization studies considerably improved the energy absorption efficiency of related structures. Recently, introducing thickness variables in the cross-section [33–36] has been demonstrated to be an effective way to extend the design domain and achieve a better design of thin-walled structures. Consequently, the energy absorption performance of multi-cell tubes under local indentation can definitely be improved by varying the wall thickness in their sections.

In this paper, the local indentation characteristics, energy absorption performance and structural optimization of multi-cell tubes are analyzed. Quasi-static experimental tests are carried out first for multi-cell tubes with three different sections. Numerical simulations are then performed to analyze the static and dynamic responses of the tubes. The crushing force response and deformation characteristics are analyzed in detail and energy absorption performances are evaluated. Moreover, to further increase the energy absorption efficiency, sequential response surface method (SRSM) is employed to achieve the optimal designs of the multi-cell tubes under indentation loads.

2. Experimental test setup

Rectangular multi-cell tubes with three different cross-sectional shapes are prepared for the indentation tests. The structural material of tubes is aluminum alloy AA6063-O. The sectional shapes and the dimensions of the specimens are exhibited in Fig. 2. As indicated in the figure, the three sections include a double-cell, a quadruple-cell, and a diagonal quadruple-cell section tube. All these sections have two symmetric planes in the cross-section, which is expected to show better performance during loading. They are named as Cell-2, Cell-4, and Cell-4D respectively, and two repetitions are tested for each section. The length of specimens is 150 mm and the outside sectional dimension (width × height) of Cell-2, Cell-4 and Cell-4D are 38 mm × 25 mm, 43 mm × 28 mm, and 40 mm × 30 mm, respectively. The specimens are commercial products produced by the metal extrusion process. There are several shallow grooves on the flanges of Cell-2 and Cell-4. As the depth of the grooves is very small (about 0.1 mm), the influence of the grooves is expected to be small. The wall thickness in the section of the multi-cell tubes is not uniform and the thicknesses are indicated in Fig. 2. For Cell-2, the wall thicknesses of the upper flange, bottom flange, outside web plates and inside web plates are 1.32, 1.12, 1.18 and 1.23 mm, respectively. For Cell-4, the thicknesses of outside plates, horizontal rib, and vertical rib are 0.93, 0.82 and 0.90 mm, respectively. With regard to Cell-4D, the wall thickness of outside plates is 1.24 mm. The thickness of the two upper diagonal plates is 1.30 mm while that of the two lower diagonal plates is 1.00 mm.

The engineering stress-strain curves of the material AA6063-O are obtained for each multi-cell section by uniaxial tensile tests, which were

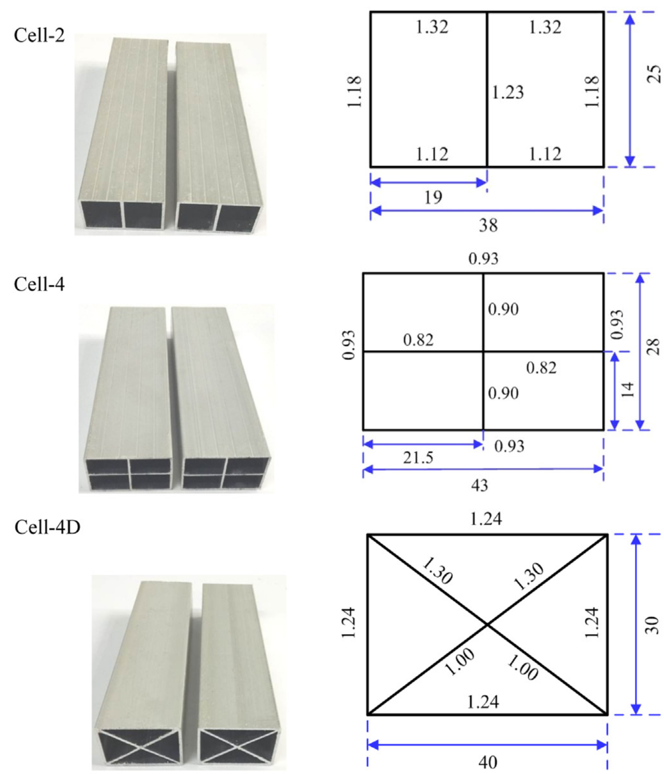

Fig. 2. Specimens for experimental tests and cross-sectional dimensions (units: mm).

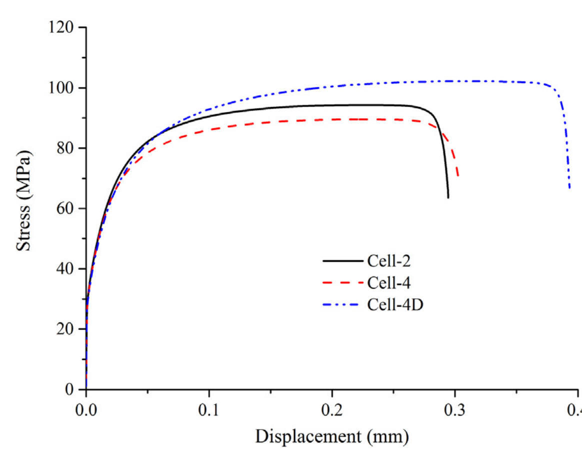

Fig. 3. The engineering tensile stress-strain curves of AA6063-O.

carried out in a 10 kN capacity Zwick Z010 universal material machine. Standard tensile tests are performed according to the principles in ASTM E8M-04 [37]. The engineering stress-strain curves are presented