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Crushing analysis and multiobjective optimization design for rectangular unequal triple-cell tubes subjected to axial loading

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ABSTRACT

Multi-cell thin-walled tubes have proven to be better in energy absorption than plain square tubes subjected to axial compression. Therefore, square multi-cell structures have been extensively utilized as energy absorbers in automobiles. This paper provides an investigation on the crashworthiness of rectangular single-, double- and triple-cell columns under axial loading and an optimization design of rectangular unequal triple-cell tubes. First, a theoretical solution is derived for the mean crushing force (MCF) of tubes with unequal triple-cell configuration. Second, quasi-static crushing experiments and finite element analyses (FEA) are conducted on single-, double- and unequal triple-cell columns. Theoretical predictions compare well with experimental and numerical data, and all results show that the triple-cell tubes exhibit the best crashworthiness among all the samples. Third, in order to study effects of wall thickness distribution and the layout of internal ribs on crashing behavior, multiobjective optimization design is implemented combining Radial Basis Function (RBF) model with Non-dominant sorting Genetic Algorithm II (NSGA-II). The optimal solution obtained from Pareto frontier indicates that unequal triple-cell tube with appropriate thickness distribution and arrangement of internal ribs is superior in energy absorption to initial design.

1. Introduction

Thin-walled metal tubes have been widely used in vehicles serving as energy absorbers in the process of crash. For instance, crash boxes in automotive body-in-white (BIW) are always metal thin-walled structures that can absorb kinetic energy through plastic deformation when collision occurs. Recently, a great number of studies have been carried out to explore the crashworthiness of metal tubes under axial load [1–4]. Among all research directions, structural investigation has caught the attention of many scholars, and as a result a wide range of sectional configurations have been investigated aiming to find out structures with better energy absorbing ability and lower weight, for instance, the circular, square, polygonal tubes and their tapered variations [5–10].

Square metal tubes are one of the most commonly used among all kinds of sectional configurations. To improve the crashworthiness of square tubes, numerous studies have been carried out exploring square structures that have been divided axially into several cells by adding internal ribs. For example, Chen and Wierzbichi investigated square double-cell and triple-cell tubes and summarized formulae for predicting mean crushing force (MCF) [11]. Zhang et al. studied square multi-cell columns numerically and proposed a more convenient formula to predict MCF of multi-cell tubes [12]. Hou and Li investigated square tubes of single-, double-, triple- and quadruple-cell in aspect of crashworthiness. Single- and multi-objective optimizations were performed in terms of sectional width and wall thickness in Hou and Li's study. It was found that sectional width and wall thickness could affect crashing performance notably [13]. Zhang et al. studied crashing behaviors of multi-cell tubes and used constitutive element method to predict the crush resistance [14]. Previous studies have shown that multi-cell square tubes are more efficient in energy absorption than plain square columns and worth paying great efforts.

It should be noted that most multi-cell tubes were fabricated with uniform wall thicknesses and cell layouts, indicating that these thin-walled columns did not take full advantage of their material and structural advantages for the best crashworthiness. There have been some publications dealing with this issue to some extent. For example, Alavinia and Parsapour explored 3×3 square tubes of unequal-celled section and revised Zhang's [12] formula for predicting MCF of unequal multi-cell tubes [15]. It was found that unequal multi-cell tubes are

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superior to their uniform counterparts in terms of energy absorption. Nevertheless, many problems remain unsolved, for instance, how different thicknesses distribution and arrangements of cells lead to different crashworthiness outcomes. Therefore, there is still a need to further design multi-cell tubes for better crashing performance. To address this complicated design issue, optimization design technique needs to be employed to present an optimal solution. A number of researchers have applied multiobjective optimization technique in current crashworthiness design and acquired reasonable conclusions, e.g. Sun et al. [16], Gu et al. [17], Hou et al. [18], and Costas et al. [19]. According to these earlier studies, it can be noted that the optimization method has proven accurate and less time-consuming in non-linear design tasks.

This paper offers a study on crashworthiness of three different rectangular columns under axial loading and optimization design of rectangular unequal triple-cell tubes. In this paper, rectangular tubes are all made of aluminum alloy with single-cell, double-cell and unequal triple-cell sections. Firstly, an improved formula for predicting axial MCF of rectangular unequal-cell tubes is derivated based on Alavinia's [15] formula. The finite element analysis (FEA) models for tubes with three kinds of different sections are then constructed by FEA code LS-DYNA. Results obtained from quasi-static simulations are verified against data from experiments and predictions. Thirdly, a system methodology, including design of experiments (DOE), radial basis function (RBF) and Non-dominated sorting genetic algorithm II (NSGA-II), is applied to conduct multiobjective optimization design. In optimization procedure, thicknesses of each plate and the arrangement of internal ribs are considered as variables. The optimal solution obtained from Pareto sets is finally validated with numerical data.

2. Evaluation criteria

To evaluate the crashworthiness quantitatively, several criteria are first introduced in this study, namely peak crushing force (PCF), mean crushing force (MCF), crushing force efficiency (CFE), energy absorption (EA) and specific energy absorption (SEA). The PCF is the first maximal value in a Force-Displacement curve. The MCF is obtained mathematically as:

$$MCF = \frac{1}{d}\int_0^d F(\delta)d\delta \tag{1}$$

where d denotes total crushing deformation; $F(\delta)$ is the instantaneous crushing force. Crushing force efficiency is a ratio of the average crushing force to the initial peak force:

$$CFE = \frac{MCF}{PCF} \tag{2}$$

The energy absorption is the total energy dissipated in plastic deformation. The specific energy absorption is defined as a ratio of the energy absorption to the weight of the tube.

$$SEA = \frac{EA}{W} \tag{3}$$

where W is the mass of specimen. Generally, when a vehicle collision occurs, MCF and PCF need to be low for occupant protection while high SEA is desirable for good energy absorption.

3. Theoretical solutions

3.1. Background

It can be achieved to calculate MCF by using analytical methods [21,22] and there have been several theoretical solutions for predicting MCF of square tubes under axial load. Wierzbicki et al. [21,22] proposed a formula for calculating MCF as:

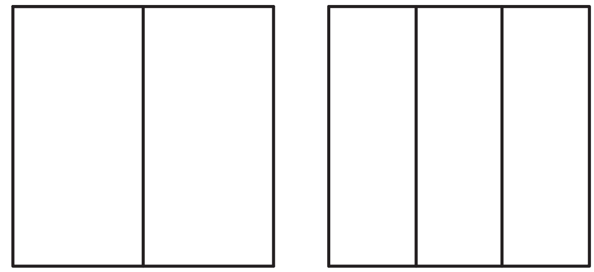

Fig. 1. Double-cell and triple-cell sections studied by Chen and Wierzbicki [11].

$$MCF = 13.06\sigma_0 b^{\frac{1}{3}} t^{\frac{5}{3}} \tag{4}$$

Where σ_0 is the flow stress of the material, t denotes the wall thickness and b means the sectional width. The flow stress σ_0 is not a constant value because of the strain hardening effects of the material. In this paper, σ_0 is obtained as the average of the yield strength σ_y and the ultimate strength σ_u of the material [14].

Chen and Wierzbicki [11] used a simplified method to apply the Super Folding Element theory [20] to predict MCF of double-cell and triple-cell tubes, as shown in Fig. 1. The formula can be written in Eq. (5).

$$MCF = \frac{2}{3}\sigma_0 t\sqrt{\pi N A} \tag{5}$$

where A is area of the section and N means the number of contributing flange.

Zhang et al. [12] proposed a formula (Eq. (6)) for predicting MCF by calculating energy absorbed through deformation of three kinds of elements, namely corner, cross and T-shape elements (Fig. 2):

$$MCF = \sigma_0 t\sqrt{(N_c + 4N_o + 2N_T)\pi L_c t} \tag{6}$$

where N_c, N_o and N_T are amounts of corner elements, crisscross elements and T-shape elements respectively, and L_c means the total length of all flanges.

Alavinia et al. [15] improved Zhang's formula to calculate MCF of unequal multi-cell structure. Parameters involving Z_c, Z_o and Z_T were introduced as the ratios of the lengths of corner, crisscross and T-shape elements in equal multi-cell section to the lengths of these elements in unequal multi-cell section (Fig. 3).

Ratios are defined as

$$Z_c = \frac{S_c}{P_c},\ Z_o = \frac{S_o}{P_o},\ Z_T = \frac{S_T}{P_T} \tag{7}$$

Eq. (8) is the revised version of Eq. (6), therefore, MCF of unequal multi-cell tubes is calculated by Eq. (8).

$$MCF = \sigma_0 t\sqrt{\left(\left(\frac{3a}{L}\right)N_c + 6\left(\frac{L-a}{L}\right)N_o + 2N_T\right)\pi L_c t} \tag{8}$$

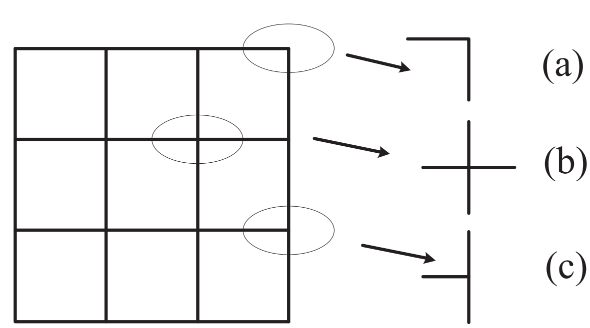

Fig. 2. (a) Corner element, (b) Crisscross element, (c) T-shape element [12].