Thin-Walled Structures 82 (2014) 183–195

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Theoretical prediction and crashworthiness optimization of multi-cell triangular tubes

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ARTICLE INFO

Article history:
Received 2 January 2014
Received in revised form
13 March 2014
Accepted 26 March 2014
Available online 17 May 2014

Keywords:
Crashworthiness
Multiobjective optimization
Triangular tube
Multi-cell
Energy absorption
Impact loading

ABSTRACT

The triangular tubes with multi-cell were first studied on the aspects of theoretical prediction and crashworthiness optimization design under the impact loading. The tubes' profiles were divided into 2-, 3-, T-shapes, 4-, and 6-panel angle elements. The Simplified Super Folding Element theory was utilized to estimate the energy dissipation of angle elements. Based on the estimation, theoretical expressions of the mean crushing force were developed for three types of tubes under dynamic loading. When taking the inertia effects into account, the dynamic enhancement coefficient was also considered. In the process of multiobjective crashworthiness optimization, Deb and Gupta method was utilized to find out the knee points from the Pareto solutions space. Finally, the theoretical prediction showed an excellent coincidence with the numerical optimal results, and also validated the efficiency of the crashworthiness optimization design method based on surrogate models.
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1. Introduction

Thin-walled extrusions have been extensively applied in vehicle crashworthiness components to absorb impact energy in the past three decades. The tests and the theoretical expressions of square and circular tubes under axial quasi-static and dynamic loading cases were first described by Wierzbicki and Abramowicz [1] and Abramowicz and Jones [2]. From then on, DiPaolo et al. [3,4], Guillow et al. [5], Ullah [6] Zhang and Zhang [7], Alavi Nia and Parsapour [8] also did many researches on these aspects. Beside square and circular tubes, several other profiles were also studied on their quasi-static or dynamic responses, such as triangular tubes [9–12], hexagonal tubes [13], etc. The structural collapse modes of triangular and square tubes are different from those of circular tubes. Nevertheless, the crushing curves of force–displacement of triangular and square tubes are similar to those of circular tubes. The crushing curves of force–displacement of all the profiles show that the crushing force first reaches an initial peak, then drops down and then fluctuates around a value of the mean crushing force. The extensional deformation has more dominant effect on the crushing responses while the quasi-inextensional mode occurs normally [14].

According to studies by Wierzbicki and Abramowicz [1], the number of "angle" elements on cross-section of tube decided, to a certain extent, the effectiveness of energy absorption. As a matter of fact, it is necessary to design thin-walled multi-cell tubes for weight-efficient energy absorption. Chen and Wierzbicki [15] examined the axial crushing resistance of single-cell, double-cell and triple-cell hollow tubes, and the respective foam-filled tubes under the quasi-static axial loading. The Simplified Super Folding Element (SSFE) theory was applied to simplify SFE theory, and three extensional triangular elements and three stationary hinge lines were comprised instead of the kinematically admissible model of SFE [1]. The average folding wavelength and the theoretical expression of the mean crushing force were deduced by dividing the cross-sectional tube into distinct panel section and angle element, assuming that the roles of each panel and of angle element were at the same level. The work of Chen and Wierzbicki [15] showed that the multi-cell tube could increase the specific energy absorption SEA by approximately 15%, compared to the respective hollow tube. Kim [16] used Chen and Wierzbicki's model [15] to study multi-cell tubes with four square elements at the corner. The SEA of new multi-cell tube was reported to increase by 190%, compared to conventional square tube. Zhang et al. [17] also applied SSFE theory to derive a theoretical expression of the mean

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http://dx.doi.org/10.1016/j.tws.2014.03.019
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crush force of multi-cell square tubes under the dynamic impact loading. In Zhang's work, the cross-section of tube was divided into three basic angle elements, and the study also came to the contribution that plastic energy of each element type was dissipated through membrane action. It was assumed from the theoretical expression that the average wavelength for the dissimilar folds developed at corners. Thereafter, the *SSFE* theory was also adopted by Zhang et al. [18] to predict the mean crushing force of 3-panel angle element. At the same time, the SFE theory was extended by Najafi and Rais-Rohani [19] to explore the crushing characteristics of multi-cell tubes with two different types of three-panel elements. A closed form expression of mean crushing force was also put forward by Najafi and Rais-Rohani [19].

Dynamic progressive buckling of thin-walled multi-cell tubes under axial impact loadings was studied by Jensen et al. [20] and Karagiozova and Jone [21]. Then, the structural dynamic progressive buckling under the axial loading was summarized by Karagiozova and Alves [22] from a phenomenological point of view. Consequently, the desirable energy-dissipating mechanism was a stable and progressive folding deformation pattern for the structural deformation. On the other hand, the global bending on a structure was an undesirable energy-dissipating mechanism mode. At the beginning, multi-cell tubes were mostly employed from the aspects of theoretical researches, such as by Kim [16] and Najafi and Rais-Rohani [19], Nowadays, either FE solutions [23] or surrogate models [13,24–26] developed appeared in the search field of multi-cell tubes under the impact loading. However, there is seldom a combination study of theory, numeric and optimal method for thin-walled multi-cell tubes.

Above all, the axial crushing of tube types I, II, III was studied on both theoretical prediction and numerical optimization design in this paper. Based on the SSFE theory, theoretical expressions of the mean crushing force for the three types were derived. All the profiles studies in this paper were divided into 2-, 3-, T-shape, 4 and 6-panel angle elements. In order to obtain the optimal profiles under the crashworthiness criterion, dynamic finite element analysis code ANSYS/LS-DYNA was executed to simulate tubes and to obtain the numerical results at the design sampling points. The multiobjective optimization design was utilized to obtain the optimal configurations. Finally, the theoretical expressions are employed to validate the numerical optimal solutions.

2. Theoretics

2.1. Theoretical prediction of multi-cell triangular tube

The SSFE theory was applied to solve the axial collapse of triangular multi-cell thin-walled tubes. In the SSFE theory, the wall thickness was assumed to be constant and the variation of wavelength $2H$ for different lobes was ignored. To analyze energy dissipation over the collapse of a fold, the triangular multi-cell thin-walled tubes were divided into several basic elements: the 2-, 3-, 4- and 6-panel angle element as shown in Fig. 1.

Based on the principle of global equilibrium for shells, the internal and external energy dissipations are of equal rate ($\dot{E}_{ext} = \dot{E}_{\mathrm{int}}$). The external energy work for a complete single fold is equal to the sum of dissipated bending and membrane energy. That is

$$P_m 2H = \frac{1}{\eta}(E_b + E_m) \quad (1)$$

where P_m, $2H$, E_b and E_m respectively denote the mean crushing force, the length of the fold, the bending energy and the membrane energy, and η is the effective crushing distance coefficient. The panel of folding element after deformation is not completely flattened as shown in Fig. 2. Hence, the available crushing displacement is smaller than $2H$. In this study, the value of η was taken as 0.7 since it was found between 0.7 and 0.8 [1].

2.1.1. The bending energy of tube

The SSFE theory was applied to calculate the dissipated energy in bending of each panel. Only three extensional and compressional triangular elements and three stationary hinge lines were used in SSFE theory, which was different from SFE theory. In SFE theory, a model was built with trapezoidal, toroidal, conical and cylindrical surfaces of moving hinge lines.

In the work of Chen and Wierzbicki [15], the energy dissipation for bending of each panel E_b was estimated by summing up the energy dissipation at three stationary hinge lines. Then

$$E_b^f = \sum_{i=1}^{4} M_0 \alpha_i b \quad (2)$$

where $M_0 = \sigma_0 t^2/4$ is the fully plastic bending moment of the panel, b is the sectional breadth and α denotes the rotation angle at the stationary hinge lines.

In this case, the panel was supposed to completely flatten after the deformation of the wavelength $2H$. Consequently, the four rotation angles α at three stationary hinge lines were $\pi/2$ one by one (as shown in Fig. 2). By applying Eq. (2), the bending energy at

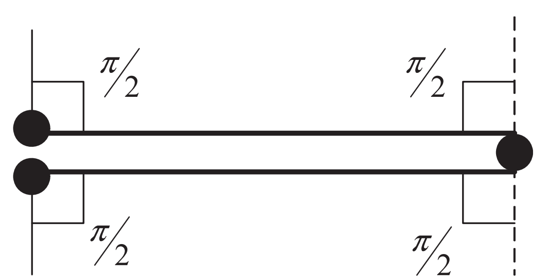

Fig. 2. Bending hinge lines and rotation angles on basic folding.

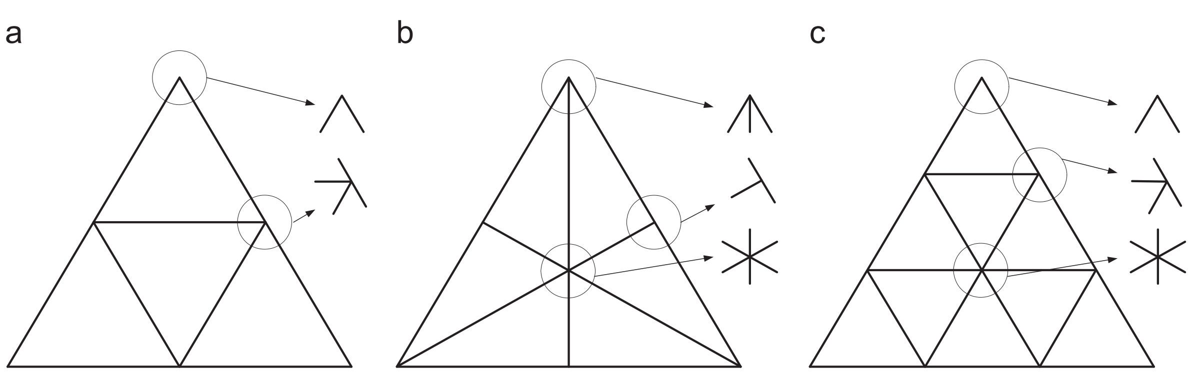

Fig. 1. Cross-sectional geometry of triangular multi-cell tube and typical angle element. (a) Tube type I (b) Tube type II and (c) Tube type III.

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