

Full length article

Theoretical development and numerical investigation on energy absorption behavior of tapered multi-cell tubes

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ARTICLE INFO

Article history:

Received 27 October 2015

Received in revised form

17 January 2016

Accepted 19 January 2016

Available online 3 February 2016

Keywords:

Tapered multi-cell tube

Transition wall thickness

Energy absorption

ABSTRACT

In this study, the crashworthiness behavior of the tapered multi-cell tubes is theoretically and numerically investigated. The side wall tapering and the cross section dividing into the cells are used in order to improve the energy absorption of the thin walled structure. In order to estimate the non-constant mean crush load of the tapered multi-cell tubes, incorporating the theoretical relations on the energy absorption of the simple multi-cell and tapered single-cell tubes, in conjunction with numerical results, would lead to the development of the analytical formula. The analytical formula is based on the mean crush load calculation of the equivalent segmented simple multi-cell tubes. In order to prepare a realistic finite element model, the elastic–plastic–damage material assumption is introduced into the numerical simulation. The numerical predictions of the mean crush load are consisted with experimental data in literature. The results reveal that the increase of the taper angle, the wall thickness and the number of cells in the cross section would enrich the crashworthiness capacity of the structure. The results indicate that the crashworthiness improvement rate of the structure with number of cells in the cross section is decreased in such a way that the variation of the energy absorption efficiency in the thin walled structure with the 8×8 , 9×9 and 10×10 cells in the cross section would be negligible. The transition wall thickness in which the crashworthiness of the tapered multi-cell structure transits from thin to thick walled behavior are determined.

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1. Introduction

The increase in the number of vehicles riding through the highways would lead to the numerous accidents in the world. While the front side of a vehicle would suddenly stop due to a collision, the other parts of the vehicle would tend to move with high accelerations which would lead to high compressive load on body and structure. In order to protect the human from intensive deformations of passenger compartment, the kinematic accident energy would be absorbed through the folding of the thin-walled structures in crush zone.

Although, there are enormous numerical and experimental studies in order to characterize the energy absorption behavior of the thin-walled structure in literature, but the presentation of the analytical solution is limited to a few available researches. The analytical procedure leading to a simple formula for the mean crush load prediction enables one to conceptually design the structures and the framework of the experimental studies. In order to predict the collapse of the thin-walled circular cylinder under axial loading, Alexander [1] presented an approximate theory using the upper band technique in the limit analysis. Assuming the

collapse of thin-walled structure in the form of a “concertina” with straight-sided convolutions, the mean axial load would be predicted by yield strength of material, thickness and mean diameter of cylindrical shell. Abramowicz and Wierzbicki [2] derived a formulation for the folding of the multi-corner perfect plastic sheet metal columns with arbitrary angle using the super folding element theory. In order to calculate the mean crush load, Chen and Wierzbicki [3] developed a theory for the multi-cell thin-walled structure with the linear hardening material assumption. The results reveal that application of the multi-cell structures improves the energy absorption characteristic in comparison with those in single-cell structures.

Duo to the impact of the cross section on the energy absorption of the thin walled structure, there are some innovative sections in order to enrich the crashworthiness characteristic of the structures. Kim [4] proposed a multi-cell tube with four square elements at the corner. Fan et al. [5] and Reddy et al. [6] proposed the simple thin walled structure with extra stable corners in the cross section. They investigated about the multi-cornered thin-walled structure capacity made of square, hexagonal, octagonal, 12-edge and 16-edge sections. Tabacu [7] studied the axial crushing of the

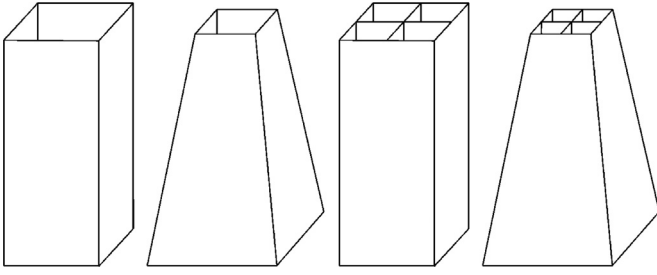


Fig. 1. The schematic view of the (a) Simple single-cell tube. (b) Tapered single-cell tube. (c) Simple multi-cell tube. (d) Tapered multi-cell tube.

simple circular structures with the rectangular insert. He developed a formula in order to predict the mean crush load of the structure. Tang et al. [8] and Alavi Nia and Parsapour [9] presented comparative studies about the crashworthiness behavior of simple multi-cell thin walled tubes with different cross section. Zhang et al. [10,11] developed a theoretical solution for the mean crushing force prediction of the multi-cell sections using super folding element theory. Conducting the numerical simulations of the dynamic energy absorption, an enhancement coefficient was introduced so as to account for the inertia effects.

The advantages of the crashworthiness behavior of the tapered tubes in comparison with the simple ones were addressed in literature [12]. In Fig. 1 the schematic view of the simple single-cell, the tapered single-cell, simple multi-cell and tapered multi-cell tubes are presented. Nagel [12] presented a parametric study on the energy absorption of the simple tapered tubes using numerical simulation. The analysis indicated that the energy absorption response of the tapered tubes would be controlled by wall thickness and taper angle. Mirfendereski et al. [13] showed that the increase of the taper angle would lead to the reduction of the peak load in axial crushing. Qi et al. [14] numerically compared the crashworthiness efficiency of the simple single-cell, the tapered single-cell, simple multi-cell and tapered multi-cell tubes subjected to oblique loading. The numerical analyses were limited to the structures with 2×2 cells in the cross section. The results revealed that the last tube is more efficient than the other aforementioned structures. Zhang et al. [15] proposed a new circular tapered single-cell tube with a gradient wall thickness in order to improve the energy absorption efficiency.

While the energy absorption characteristic of the tapered thin-walled tubes is proved to be more efficient than the simple ones, the lack of analytical solution is obvious in literature. Unlike the simple thin-walled tubes, the mean crush load of the tapered thin walled tubes is not constant with subsequent folding of the structure. In order to have an accurate prediction of the energy absorption, the nature of section variation during the subsequent folding should be account for the last structure. Reid and Reddy [16] presented the rarely available analytical formulation in order to predict the mean crush force in tapered single-cell structure. Dividing the length of tapered thin-walled tube into finite segments of simple tubes leads to an analytical framework for calculating the non-constant mean crush load of the structure subjected to axial compression.

In present study, the energy absorption behavior of the tapered multi-cell section tube is analytically and numerically investigated. The analytical formula for the prediction of the non-constant mean crush load in the thin-walled structure is presented utilizing the equivalent segmented simple tube concept in conjunction with the super folding element theory. The enhancement factor of the formula is determined using the numerical simulation results. A comparative study about the effects of the wall thickness, taper angle and the number of cells in the cross section on the crashworthiness behavior of the structure is conducted.

2. The mean crush load

In this section, the mean crush load of the simple single-cell tubes would be introduced. The formulations of the simple multi-cell square cross-section tubes and tapered single-cell tubes are combined in order to extract a simple formula for predicting non-constant mean crush load of the tapered multi-cell tubes.

The mean crush load of the simple square section tubes is calculated as follows [2]:

$$P_m = 9.56 \sigma_0 t^{\frac{5}{3}} c^{\frac{1}{3}} \quad (1)$$

where t and c are the thickness and the side lengths of the cross section. In order to improve, it is suggested that the constant coefficient, 9.56, is replaced with 13.06 [2]. σ_0 is the yield stress in perfect plastic material model. The nonlinear strain hardening of plasticity would be considered as follows [17]:

$$\sigma_0 = \sqrt{\frac{\sigma_y \sigma_u}{1+n}} \quad (2)$$

where σ_y and σ_u are the yield stress and the ultimate stress respectively, and n indicates the power of nonlinear strain hardening in the material model.

According to the energy conservation principle, the external work of mean crush load, P_m , is equal to the bending and membrane dissipated energies (defining as $W_{bending}$ and $W_{membrane}$ respectively) during the folding process, as shown in Fig. 2,

$$2HP_mk = W_{bending} + W_{membrane} \quad (3)$$

where H is the half of crush distance and k is a constant coefficient accounting for the effective crush distance [10]. The fact is that the complete folding of thin-walled structure would not always occur in reality. In order to modify the theoretical relations for mean crush load prediction, an enhancement coefficient, k , is defined. The parameter would be determined using either the numerical simulation results or experimental observations. For instance, the k parameter for the crumpling of the simple single-cell square cross section tubes is suggested between 0.7 and 0.75 [2].

Applying the upper band technique in the limit analysis of each folding process, the dissipated bending energy is calculated by the summation of the energy loss in three plastic hinges as schematically illustrated in Fig. 3.

$$W_{bending} = \sum_{i=1}^3 M_0 \theta_i L \quad (4)$$

in which M_0 represents the required bending moment for folding process

$$M_0 = \frac{1}{4} \sigma_0 t^2 \quad (5)$$

and, θ_i and L are the fold angle and the perimeter of the folding cross section respectively. In complete folding with the $2H$

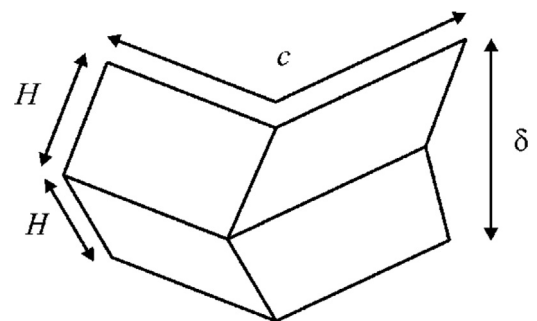


Fig. 2. The super folding element.

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