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Crushing and theoretical analysis of multi-cell thin-walled triangular tubes under lateral loading

TrongNhan Tran[a,b,*]

[a] Division of Computational Mechatronics, Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[b] Faculty of Electrical & Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam

A R T I C L E I N F O

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A B S T R A C T

This paper investigates the lateral crushing behavior of multi-cell thin-walled triangular tubes using experiments. More crushing modes are found in the lateral compression experiments of the multi-cell triangular tubes. The average crushing force, P_a, is governed by the plastic hinge lines. Based on experiments and the improved simplified super folding element (ISSFE) theory, theoretical models are proposed to predict average crushing force (P_a) in each stage. The formula of P_a is a function of flow stress of material, wall thickness, and length of tube. The results show that the theoretical solutions agree well with the experiment data.

1. Introduction

Crushing behaviors of multi-cell thin-walled tubes, especially in cases of axial and oblique loading, have received enormous investigations due to the promising applications in energy absorber. Numerous literatures published are concerned with their experimental study, theoretical analysis and numerical investigation. Chen and Wierzbicki [1] was one of the firsts to investigate the multi-cell thin-walled tube. They have simplified the super folding element (SFE) theory [2] to study the crushing performance of the multi-cell tubes with right-corner angle element. Zhang et al. [3] also adopted the model of [1] to derive a theoretical solution for calculating the mean crushing force of multi-cell square tubes under the dynamic loading. Kim [4] used Chen and Wierzbicki's mode to study multi-cell tubes with four square elements at the corner. The method of [1] was also applied by Hanssen et al. [5] to predict the mean crushing force of complex aluminum extrusion. Najafi and Rais-Rohani [6] extended the SFE theory to investigate the crushing characteristics of multi-cell tubes with two different types of three-flange elements. An equation of closed form for prediction of the mean crushing force was also proposed. Alavi Nia et al. [7] carried out an investigation on the energy absorption characteristics of multi-cell square tubes. Sun et al. [8] investigated crushing mechanism of the hierarchical lattice structure under axial loading. Then Tran et al. [9,10] extended simplified super folding element (SSFE) theory to investigate the crushing characteristic of multi-cell tubes with different types of angle element.

Concerning lateral crushing, Gupta et al. [11–13] studied the deformation and energy absorbing behaviors of rectangular and square tubes under lateral compression through experiments and simulations. They figured out that the square tube absorbs more energy as compared to the rectangular tube of equal cross-sectional area, and the tube sections collapsed due to the formation of two sets of plastic hinges. Maduliat et al. [14] revealed the collapse behavior and energy absorption capability of hollow steel tubes under large deformation due to lateral impact load. In their work, analytical solutions for the collapse curve and in-plane rotation capacity was developed, and then used to simulate the large deformation behavior and energy absorption. Tran [15] investigated the crushing behavior of multi-cell tubes and the energy absorption in case lateral crushing was estimated through the bending and membrane energy. Additionally, the energy absorption behaviors of the hollow and nested tubes were also addressed by Baroutaji et al. [16–18], Eyvazian et al. [19], Wang et al. [20], Tran et al. [21], and Morris et al. [22,23] in lateral loading.

Most of the above studies, however, emphasized axial crushing of the multi-cell tubes or lateral crushing of the hollow and nested tubes. The study on lateral crushing of the multi-cell thin-walled tubes is therefore quite rare. In this work, lateral crushing behaviors of multi-cell triangular tubes are investigated through experiment and theoretical analyses. To apply the SSFE theory to lateral loading, this theory will be improved and also added hypotheses. Based on the improved simplified super folding element (ISSFE) theory and experiment, theoretical expressions for each stage are proposed to predict the average crushing forces.

* Correspondence address: Division of Computational Mechatronics, Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City, Vietnam.
E-mail address: trantrongnhan@tdt.edu.vn.

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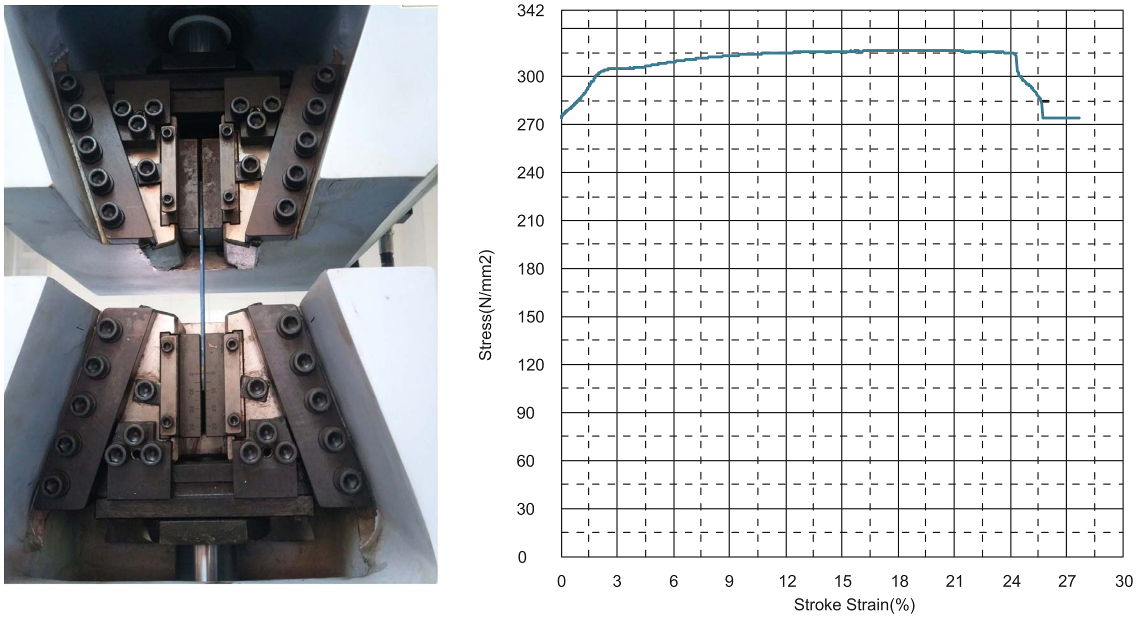

(a) (b)

Fig. 1. a) Tensile test; b) Typical stress-strain diagram.

2. Material properties and experimental setup

To find out the material properties, the specimen was carried out on UH-F500kNI SHIMADZU universal testing machine, as indicated in Fig. 1(a). Specimens were cut the same tubes made of steel plate CT3 as used for performing the lateral crushing tests. The engineering stress strain curve, used to determine the material properties, is recorded and shown in Fig. 1(b). The yield and ultimate stresses of this materials are $\sigma_y = 218$ MPa and $\sigma_u = 316$ MPa, respectively.

Cross beam of an automotive bumper is generally subjected to the lateral crushing. Potential of using the multi-cell triangular structure as a new cross beam of automobile bumper is one of its functions. However, the investigation of the multi-cell triangular tubes under the lateral crushing is too infrequent. A new system of thin-walled triangular specimens with special cross-section is therefore presented in this research work (Fig. 2). To manufacture specimens of the multi-cell thin-walled triangular tubes, the component parts of tube are firstly cut from the steel plate. The outer wall is bent in the shape of equilateral triangle. Finally, they are welded together. The tubes' specifications are depicted in Table 1. Crushing behaviors of triangular tubes in Fig. 2 were then studied in this article and experiments were performed on the same device at a loading rate of 5 mm/min. The specimens were freely placed between the upper and lower platen of the test machine. The upper platen moved downward and together with the apex of the tube after the impinging instant. The lateral compression process continued until the sides of the deforming tubes got in contact with each other. The load-displacement curves were recorded over the whole lateral crushing process with the automatic chart recorder of the machine. The deformed profiles of the specimens were taken at different stages of compression by camera.

The typical progressive lateral collapse modes of the multi-cell triangular tube type I and II at different stages are displayed in Figs. 3 and 4, respectively. In spite of being the multi-cell triangular tubes, their lateral collapse behaviors are different from each other. This difference is due to structure of tube. Regarding the tube type I, the decline in force is dramatically larger after the elastic deformation phase. Then, rotations at plastic hinge lines control the deformation plateau before this process repeats. The formation of the second process is demonstrated by new moving plastic hinge lines developed on the horizontal side of tubes. The process of tube type II is basically similar to that of tube type I. The corresponding load–displacement curves are shown in Fig. 5, respectively. The load–displacement curves of all the profiles show that the crushing load first reaches an initial peak, then drops rapidly and then slightly declines before rising again as a result of the new plastic hinge lines' formation. However, the load-displacement of tube type II is different to that of tube type I. Shape of the load-displacement curve in second stage in which crushing force is greater is similar to that in first stage (Fig. 5b). Different stages of the lateral crushing at which crushing behavior recorded are marked on the corresponding load-displacement curves. Fig. 5 also shows that although the tube continued to deform under lateral crushing but the crushing force does not change much or decreases slightly in plateau region. In this plateau region, the area under the curve represents the ideal energy absorption zone. The average crushing force, P_a, in each stage is therefore defined as the equivalent constant force with a corresponding amount of stroke.

As shown in Figs. 3–5, their deformation processes corresponding to the load-displacement. To investigate the crushing mechanism occurring during lateral crushing of multi-cell triangular tubes, it is convenient to roughly divide the deformation process into two principal stages: designated as stage A and stage B (Fig. 5). Deformation patterns of these tubes in Figs. 3 and 4 are hence used to raise the theoretical analysis of the crushing forces.

3. Lateral crushing analysis

The analysis of the dissipated energy in bending and membrane for lateral crushing can be found in previous literature [15]. Therefore, the equilibrium of the work and energy is also expressed via the principle virtual work in case of tube under lateral crushing. By expanding this principle, the external energy work for a crushing equals to the total energy absorbed during crushing, E_t, including bending and membrane energy, E_b and E_m. That is

$$P_a \delta = E_t = E_b + E_m \quad (1)$$

where P_a is the average crushing force. δ is the distance of the crushing.

To apply the SSFE theory to lateral loading case, an improved approach is used in the following derivation. In this approach, instead of creating a model consisting of triangular elements with plastic hinge