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Bending resistance of thin-walled multi-cell square tubes

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ABSTRACT

The bending resistance of multi-cell square tubes under three-point bending is investigated in this study. Partition plates are introduced in longitudinal direction and cross-section of square tubes to form multi-cell structures. Numerical simulation of the three-point bending test is carried out by nonlinear finite element code and experimental test is conducted to validate the numerical model. Parametric studies are then performed to investigate the influence of the number of cells, load conditions and other geometrical configurations on the bending resistance. Results reveal that the number of partition plates has important influence on the bending resistance of the structure and more partition plates do not necessarily lead to high energy absorption efficiency. The optimum configurations of the structures are found out and some valuable suggestions are offered for multi-cell structures under transverse loading.

1. Introduction

As efficient energy absorbers, thin-walled tubes are widely used in various vehicle engineering fields due to their advantages of light weight, high energy absorption efficiency and cost-effectiveness. Bending collapse of thin-walled tubes is one of the most important energy dissipation mechanisms since transverse impact loading is the most common case in the real accidental crash events. Nevertheless, the bending collapse of thin-walled tubes received relatively less studies when compared to axial crushing. This may be due to the fact that the energy dissipation under axial crushing is about one order of magnitude greater than that of bending collapse.

In past decades, various approaches are developed to further improve the crashworthiness performance of thin-walled tubes under various loading conditions. These methods include introducing grooves [1,2], diaphragms [3] or foam filler [4–9], adopting multi-cell section [10–17] and more recently employing graded thickness [18–23]. Generally, both axial crushing and transverse bending resistance of the tubes can be improved by these methods. For example, foam filler was reported to considerably increase the SEA (specific energy absorption) of square tubes under axial and transverse loading by numerous researchers [4–9]. The diaphragms [3] and multi-cells [10–17] were also found to significantly increase the efficiency of square or circular tubes under axial crushing. However, it is interesting that their effects on the bending resistance of thin-walled tubes received few concerns.

The deformation mechanisms of square tubes under transverse loading are similar as those under axial crushing. In 1983, a classic theory for the bending collapse of rectangular or square tubes was firstly proposed by Kecman [24]. The energy is dissipated by the static and moving plastic hinges and some empirical parameters are given to approximate real conditions. At the same time, Wierzbicki [25] proposed a self-consistent theory based on a superfolding element model to predict crushing force under axial crushing. In 2001, Kim [26] combined the methods of Kecman [24] and Wierzbicki [25] and provided a completely analytical method. The theoretical predictions show better agreement with experiments. Nevertheless, the analysis of bending resistance is much more complicated than that of axial resistance since there are more influencing factors on the responses of the tubes, such as load position, size and shape of the punch, load speed and etc for three-point bending collapse.

Adopting multi-cell was found to be an effective way to increase the axial crush resistance of thin-walled tubes. In this work, the bending resistance of multi-cell square tubes under three-point bending loads is investigated. Partition plates are introduced to square tubes in the longitudinal direction and in cross-section to make the structure show multiple cells in two different ways. Three-point bending test of empty square tube is performed first and numerical simulation of the test is then conducted by using the non-linear explicit finite element code LS-DYNA. The finite element model is validated by the experimental results and then employed for parametric studies. The influences of all kinds of factors are studies, including the configuration of partition plates,

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load position, size of the punch, wall thickness and the load speed. Some interesting conclusions and valuable suggestions are presented for the crashworthiness design of structures under transverse loading.

2. Scheme of parametric studies

The geometry and setup of the three-point bending test are shown in Fig. 1(a). Loaded by a cylinder punch, the square tube is supported by two cylindrical supports. The length of all the square tubes is 250 mm, while the width and thickness of the tubes are 30 mm and 2 mm, respectively. As plotted in Fig. 1(a) and (b), the partition plates are introduced by two different ways: in longitudinal direction and in cross section. Multiple cells are formed in different directions accordingly.

For the partition plates in the longitudinal direction, the number of partition plates is assigned as “C”, while if the partition plates are introduced in the cross-section, two variables “V” and “T” represent the number of partition plates in the vertical and transverse directions, respectively. In the present analysis, the number of partition plates in the longitudinal direction C ranges from 0 to 16, while the maximum value of V and T is 3. The wall thickness H apparently has great influence on the response of the beam and three values 1.5, 2 and 2.5 mm are considered.

The influences of various load conditions are also considered here, including the load position P, load speed S and the radius R of the punch and supports. As shown in Fig. 1(c), three different load positions $P=1$, 2 and 3 are analyzed. The load position is always located in the center of the beams in the literatures. It is necessary to investigate its influence on the response of empty tubes and multi-cell tubes. In addition, five load speeds $S=1$, 5, 10, 15 and 20 m/s and three radii of the cylinders $R=5$, 10 and 15 mm are considered to analyze their effects accordingly. For the sake of concise, the following numbering system is applied, e.g. “C12P1S10” means the case with $C=12$, $P=1$ and $S=10$ m/s.

3. Finite element modeling

The parametric studies of the three-point bending collapse are carried out by using non-liner explicit finite element code LS-DYNA. The post-preprocessor Ls-prepost is used for data post-process and visualization. The finite element model is validated by experimental test in next section and then employed for parametric analyses. Aluminum alloy AA1100-O is employed as structural material of tubes with and without partition plates and the properties of the material is tested and given in next section. Material type 24 (Piecewise linear plasticity material) provided by LS-DYNA is applied to simulate the material. Due to strain rate insensitivity of aluminum alloy, the strain rate effect is neglected in numerical simulations.

The representative finite element models for square tubes with partition plates in longitudinal direction and cross-section are presented in Fig. 2. The formed multi-cell tubes are modeled using SOLID164 eight-node brick element with eight nodes. Reduced one-point integration scheme and hourglass control are adopted for the elements. Two cylindrical supports and the punch are modeled as rigid body using Belytschko-Tsay shell element. To guarantee the calculation accuracy, three elements are employed along the thickness direction. The characteristic size of meshes in the cross-section is 1.0 mm and a sectional view of the meshes is given in Fig. 2. As for the longitudinal direction, the segment adjacent to the punch is modeled with relatively fine mesh size of 2.0 mm while the characteristic size of meshes in other regions is 4.0 mm. The length of the segment with fine meshes is larger than

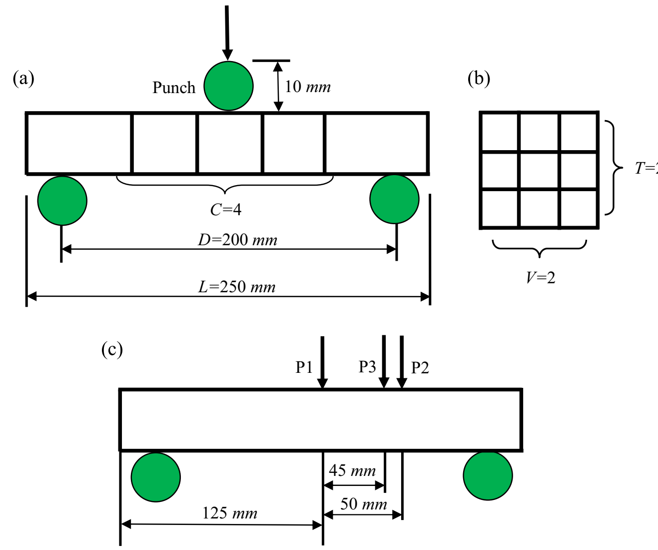

Fig. 1. Geometry for simulation (a) partition plates in longitudinal direction, (b) partition plates in cross-section (c) load position.

50 mm. For the rigid cylindrical supports and the punch, the mesh size is smaller than 1.0 mm. Mesh convergence analysis is performed and the present meshes are found to achieve enough accuracy. An automatic single surface contact algorithm is applied to consider the contact of tube itself. To account for the contact between the punch and tube, and between the supports and tube, the automatic surface to surface contacts are defined. The static and dynamic friction coefficients are set as 0.3 for all contact conditions.

4. Validation of FEM model

To confirm the reliability of the finite element model, three-point bending test of empty square tubes is conducted and the results are compared with the numerical model. The empty square tubes are obtained by cutting of commercial square tubes with the outside width $B=30$ mm, the thickness $H=2$ mm and the length L of the tube is 250 mm. The material of the tubes is aluminum alloy AA1100-O. Uniaxial tensile tests are carried out on a 10 kN capacity Zwick Z010 universal testing machine to obtain the stress–strain curve of the material. The tensile specimens are prepared according to ATSM standard E8M-04. The engineering stress–strain curve of the material is depicted in Fig. 3(b) and the mechanical parameters of it are given here: Young's modulus $E=68$ GPa, initial yield strength $\sigma_y=30.5$ MPa, the ultimate stress $\sigma_u=90.5$ MPa and Poisson's ratio $\upsilon=0.33$.

Three-point bending tests of empty tubes are conducted quasi-statically in Zwick Z010 testing machine with the load velocity of 0.5 mm/s. The experiment setup is shown in Fig. 3(a) and geometry for three-point bending tests is the same as that shown in Fig. 1(a). The span and radius of the two cylindrical supports are 200 and 5 mm, respectively. A cylindrical punch with a radius of 5 mm is used to load the tube in the middle. The tests are displacement controlled with the punch being moved vertically downward to load the specimens. The force responses and deformation pattern of square tube in experiment and numerical simulation are compared in Fig. 3(c). It can be noticed that both the punch force–displacement curves and deformation pattern are almost completely the same in test and simulation. The FEM model can provide very good simulation of the behavior of the tubes under three-point bending collapse. Consequently, the FEM