International Journal of Mechanical Sciences 107 (2016) 58–68

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Crush resistance of square tubes with various thickness configurations

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ARTICLE INFO

Article history:
Received 29 September 2015
Received in revised form
1 January 2016
Accepted 3 January 2016
Available online 11 January 2016

Keywords:
Crush resistance
Corner element
Square tube
Energy absorption
Experiment

ABSTRACT

The crush resistance of corner elements with various thickness configurations is investigated in this paper. Experimental study and numerical analyses are performed for square tubes with uniform and nonuniform wall thickness. The variation of wall thickness is found to have great influence on both deformation mode and force responses of the tubes. Two theoretical methods are proposed to predict the mean crushing force of the corner elements with nonuniform wall thickness. One is based on data fitting with average wall thickness and another is a newly proposed analytical model. Both methods can give satisfactory predictions for crush resistance of corner elements developing inextensional mode.

1. Introduction

Square or rectangular tubes are efficient energy absorbing components that widely applied in the transportation industry. Numerous efforts [1–11] have been made in the past decades to explore the deformation mechanisms of them or improve the crashworthiness performance of them under various load conditions. Under axial loading, the deformation mode of a square tube is determined by the basic folding corner elements in the structure. The corner elements generally develop two progressive collapse modes: extensional mode and inextensional mode, or mixed mode of these two. Extensional mode is always developed for tubes (corner elements) with small ratio of width to thickness and inextensional mode is the most commonly encountered collapse mode of square tubes.

Although empty square or rectangular tubes are efficient in absorbing energy, thin-walled tubes with multi-cell section [12–17] were found to have very much higher specific energy absorption than single-cell tubes under axial crushing. As the increasing in the applications of multi-cell sections in the industry, more studies on multi-cell sections are necessitated. As we know, the crush resistance of a multi-cell section should be obtained by summing up the contribution of every constituent element. However, the constituent elements can be multifarious. For example, they could be constituted by plates with different wall thicknesses. A series of theoretical work on the crush resistance of constituent elements has been conducted by Zhang and Zhang [18–21]. Nevertheless, all these elements consist of plates with uniform thickness. In fact, constituent elements with different wall thickness in different plates are quite common. Commercial hexagonal honeycomb, which has double thickness in two of the six cell walls, is an example. When elements are constituted by plates with different thickness, the deformation behavior may be quite different and new theoretical model is required to predict its crush resistance.

The square tubes with various thickness configurations are investigated in the present work. The purpose of this paper is twofold: first, the crush resistance of the simplest right angle corner elements with various thickness configurations is analyzed; second, theoretical methods are proposed to predict the mean crushing force of them. The paper is organized as follows: in Section 2, experimental study on the axial crushing of square tubes is introduced first. Information about specimen preparation and material properties is offered. Numerical simulation of the test is then performed by using finite element code LS-DYNA and the finite element modeling is given in Section 3. Experimental and numerical results are presented in Section 4. Discussions on the results are then made in Section 5. Numerical analyses by employing the validated finite element model are also conducted in this section. The influence of thickness on crush resistance of square tubes is addressed. In Section 6, theoretical methods are offered to predict the mean crushing force of corner elements and square tubes. Finally, Section 7 summarizes the present work.

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http://dx.doi.org/10.1016/j.ijmecsci.2016.01.003
0020-7403/

2. Specimen preparation and material properties

As shown in Fig. 1(a), a group of square aluminum tubes is prepared for the axial crushing test. The specimens are obtained by cutting of aluminum alloy AA6061O blocks. Wire cut Electrical Discharge Machining (WEDM) technique is applied to cut the blocks and the process precision is ± 20 μm. The length L and the width C of the specimens are kept constant to be 126 and 36 mm, respectively. The sectional dimensions of the square section are illustrated in Fig. 1(b). The same thickness is assigned to the opposite plates of the tubes. The wall thicknesses t_1 and t_2 of the tubes are listed in Table 1. The thicknesses are ranging from 0.8 to 2.4 mm with an interval of 0.4 mm. All the tubes are welded to a thick aluminum plate in the bottom to clamp the column during the test. The axial crushing tests are performed quasi-statically by using a 100 kN capacity universal materials testing machine. The testing is displacement controlled and the loading speed is 1.0 mm/s.

By using the standard tensile specimens as specified in ASTM E8M-04 [22], a 10 kN capacity Zwick Z010 universal tensile tester is employed to measure the stress–strain relation of the structural material AA6061 O. Fig. 2 presents the tensile engineering stress–strain curve. The mechanical properties of the material are given here: Young's modulus $E=68.9$ GPa, Poisson's ratio $\nu=0.33$, material density $\rho=2730$ kg/m^3, initial yield stress $\sigma_y=62.8$ MPa and the ultimate stress $\sigma_u=115.0$ MPa.

3. Finite element modeling

The commercial explicit dynamics finite element code LS-DYNA is employed to simulate the behavior of the specimens under axial loading. A representative finite element model is shown in Fig. 3. Due to symmetry property of the tubes, a quarter of the structure (one corner element) is established and symmetric boundary constraints are imposed on the symmetry planes. The bottom of the tubes is fixed and a rigid plane is employed to crush the structure from the top. The tube is discretized by 6804 eight-node brick elements with one point integration and 9520 nodes. Elasto-plastic material model #24 in LS-DYNA [23] is adopted to model the aluminum alloy material AA6061 O. Strain rate effect is neglected in the numerical model, since aluminum alloy is strain rate insensitive. The characteristic size of the meshes is set to smaller than 1.5 mm in the width and length direction, while the element size must be much smaller in the thickness direction to guarantee the simulation accuracy. Three elements are adopted in the thickness direction after a mesh convergence analysis. Two types of contacts: automatic single-surface contact and node-to-surface contact are employed to simulate the contact of the tube itself and that between the rigid plane and the tube. The friction coefficient between all the contact interfaces is set to 0.3. Initial imperfections have to be introduced in the structure to induce the same deformation as experiment. In the present model, indentation triggers are introduced in the wall plates of the square tubes in accordance with experiment. The triggers for inextensional and extensional mode are also given in Fig. 3. The depth of the indentation is 0.2 mm and the position of the triggers is located at a certain distance λ below the top, which is also determined by experiment. The distance λ is given in Table 2 for each specimen. For simulation of quasi-static loading by explicit finite element method, the loading rate has to be increased to accelerate the analysis. The load velocity of the rigid plane is increased up to 1 m/s in the present analysis and the principles proposed by Santosa et al. [24] are followed, just as quasi-static simulation done in Ref. [14].

Table 1
Experimental results for axial crushing of square tubes with various wall thicknesses.

Test #	t_1 (mm)	t_2 (mm)	δ (mm)	E (J)	P_m (kN)	P_{max} (kN)
1	0.8	0.8	83.1	210.7	2.54	7.32
2	0.8	1.2	92.9	296.1	3.19	9.80
3	0.8	1.6	96.0	465.5	4.85	12.28
4	0.8	2.0	96.1	681.3	7.09	16.14
5	1.2	1.2	90.2	490.6	5.44	13.35
6	1.2	1.6	89.2	597.7	6.70	17.15
7	1.2	2.0	90.5	956.0	10.57	20.42
8	1.2	2.4	92.3	1146.6	12.42	24.38
9	1.6	1.6	88.0	820.8	9.32	21.18
10	1.6	2.0	86.3	1031.9	11.96	24.14
11	1.6	2.4	94.2	1537.1	16.32	28.08
12	2.0	2.0	80.6	1229.2	15.24	30.26
13	2.0	2.4	85.0	1745.1	20.53	36.61
14	2.4	2.4	88.8	2187.0	24.62	38.67

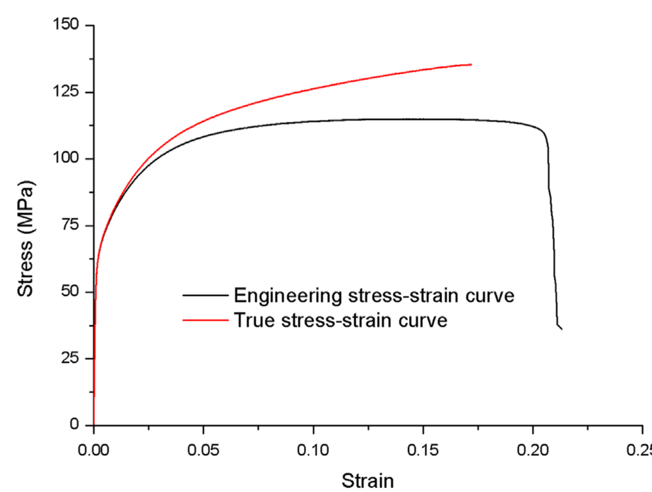

Fig. 2. Engineering and true stress–strain curves of AA6061 O.

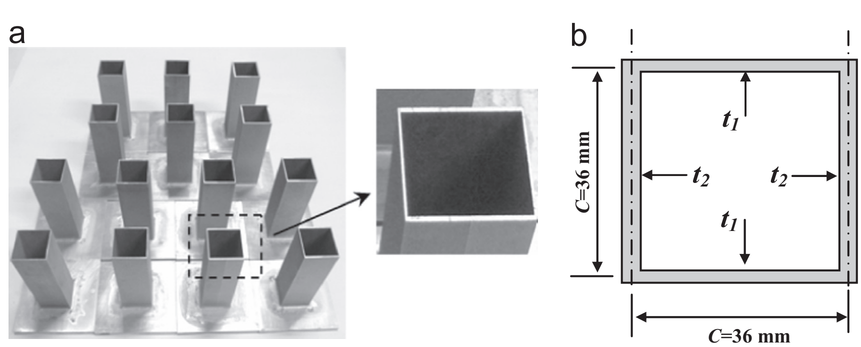

Fig. 1. (a) Square specimens with various wall thickness configurations and (b) Dimensions of square specimens.