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Quasi-static crushing behaviors and plastic analysis of thin-walled triangular tubes

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ABSTRACT

To study the collapse mechanism and energy absorbing ability in lateral compression, metallic isosceles triangular tubes were designed and fabricated, with the base angle varying from 30°, 45°, 60° to 75°. According to the experiments, it is found that three typical crushing modes and two critical base angles characterize the lateral crushing behaviors of the isosceles triangular tubes. Tubes with base angle smaller than 45.6° are crushed without obvious fold. Tubes with base angle greater than 72.6° have side-wall contact at the buckling center before forming a new shortened triangle and being folded. With the base angle between these two critical values, tubes behave the same as the equilateral triangular tube. Triangular tubes have unified energy absorbing mechanism, including six plastic hinges and one traveling plastic hinge. The mean crushing force of the tube was well predicted based on plastic analysis, supplying criterion for material selection in designing anti-impact structures.

1. Introduction

Crushing behaviors of thin-walled structures have received extensive attention [1–5] for their applications in energy absorbers, such as blast-resistant walls, protective doors, and anti-crash bumpers. Crushing behaviors of collapsible cellular energy-absorption devices with circular and elliptical cross-section were investigated by Mahdi and Hamouda [6]. Hou et al. [7,8] suggested a multi-objective optimization method for the crashworthiness design of thin-walled tubes.

Hong et al. [9,10] and Fan et al. [11] revealed the plastic deformation and energy absorption of triangular tubes in axial compression experiments. However, performances of these tubes under lateral crushing are rarely reported. Rejab and Cantwell [12] revealed that triangular corrugated-core sandwich panels would take on a trapezium shape in crushing. Gupta et al. [13] presented experimental and computational investigations on the lateral crushing behaviors of rectangular and square metallic cells, which collapsed around two sets of plastic hinges. Abdewi et al. [14] studied the lateral crushing behaviors of radial corrugated composite cells. McShane et al. [15] studied the dynamic buckling of inclined struts and built a three-hinge plastic buckling model.

In this paper, experiments and plastic analyses were carried out to investigate the deforming and energy absorbing behaviors of laterally compressed triangular tubes, which would be applied to construct an expedient impact-resistant wall.

2. Experiments

In experiments, isosceles triangular tubes with base angle, θ, varying from 30°, 45°, 60° to 75° were designed and fabricated, as shown in Fig. 1. All specimens were made of mild steel Q235, whose mechanical constants were acquired through tensile experiment, as shown in Fig. 2. The thickness of the cell wall, t, is 3 mm. The tube length, b, is 50 mm. The length of the base line, B is 90 mm. Lateral compression experiments were carried out on a 600 kN universal testing machine at loading rates of 2.5 mm/min and 5.0 mm/min. The sample was freely placed between the built-in loading plates of the test machine, as shown in Fig. 1. Test results are plotted in Figs. 3 to 6 and summarized in Table 1.

In lateral compression, triangular tubes have three typical plastic deformation plateaus, named as stage A, stage B and stage C. After each peak value, the load drops due to elastic or plastic buckling, accompanying the formation or development of plastic hinges. The mean crushing

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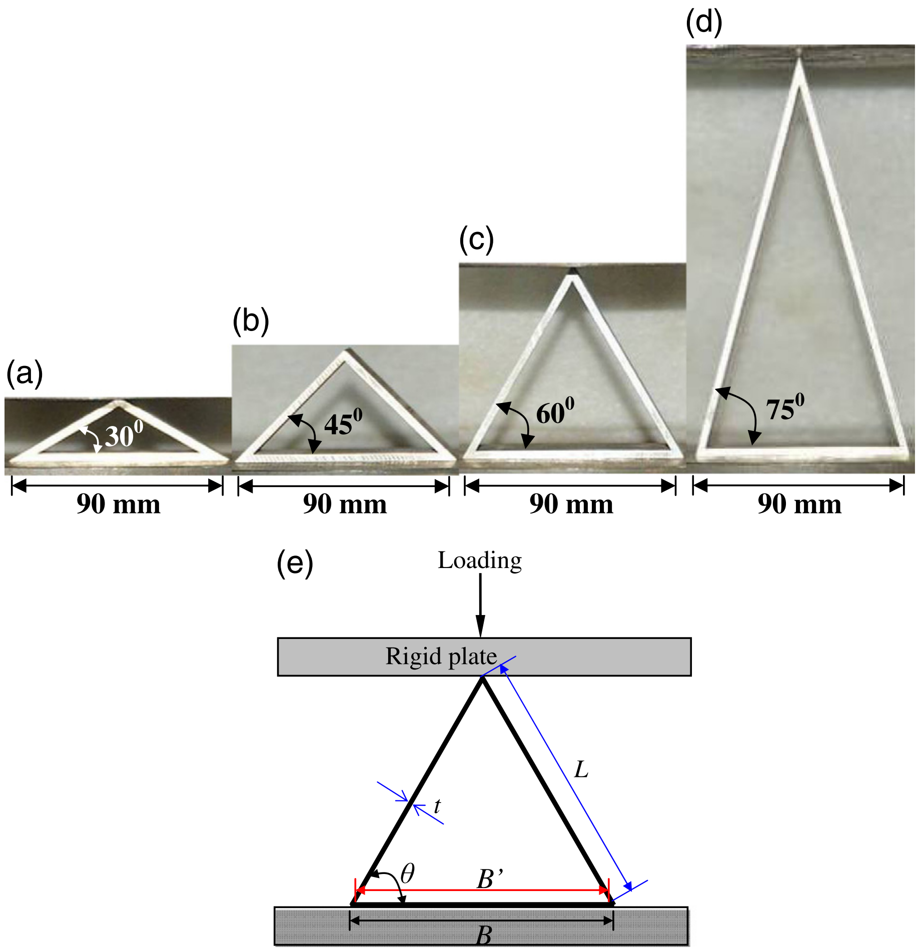

Fig. 1. Isosceles triangular tubes with base angles of (a) 30°, (b) 45°, (c) 60° and (d) 75° and (e) the sketch map of lateral compression.

force of each plateau gradually increases from stage A, stage B to stage C, leading to excellent energy absorption.

The deformation curves are different in stage C. In Fig. 3, stage C of tube I1 is very short, even disappears for I1-1, while its stress is rather great, about twice of the initial peak strength. In Figs. 4 and 5, deformations of I2 and I3 are similar. In Fig. 6, stage C of I4-3 can be further divided into three sub-stages, C_1, C_2 and C_3, just like stage A, stage B and stage C of I3, the equilateral triangular tube.

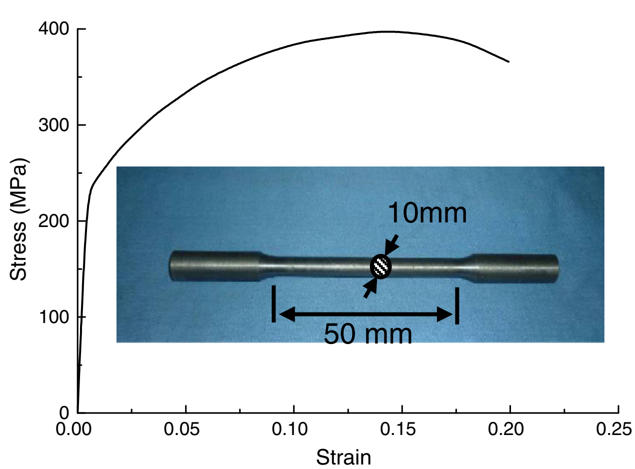

Fig. 2. Stress-strain curve of Q235 steel.

Crushing modes of isosceles triangular tubes are illustrated in Fig. 7. Their deformation modes are identical in stage A, while different in stage B and stage C. Three typical crushing styles are found. Tube I1 has no obvious fold. I2 and I3 have similar folding modes. There is instability or contact between the side walls of I4 before being folded. After that it behaves as I2 and I3.

3. Strength

For tubes failed by strength yielding, the initial peak load, $P_{\max}$, is predicted by

$$P_{\max} = 2\sin\theta\sigma_y tb, \tag{1}$$

where the yield strength, σ_y, is 235 MPa. For tubes failed by elastic buckling, the load is

$$P_{\max} = 2\sin\theta\frac{\pi^2 EI}{(\mu L)^2} = \frac{2\pi^2 Ebt^3\sin\theta\cos^2\theta}{3(\mu B)^2} \tag{2}$$

with $L = B/(2\cos\theta)$, second moment of area $I = bt^3/12$, Young's modulus $E = 210$ GPa and constraint coefficient $\mu = 0.7$ for strut with one end pin-jointed and the other built-in [16]. A critical angle, θ_c, is suggested by Eqs. (1) and (2) as

$$\theta_c = \arccos\left(\frac{\sqrt{3}\mu B}{\pi t}\sqrt{\frac{\sigma_y}{E}}\right) \tag{3}$$