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Lateral crushing behaviour and theoretical prediction of thin-walled rectangular and square tubes

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ABSTRACT

One of the important topics in impact engineering was lateral crushing behaviour of thin-walled tube. In this study, crushing behaviours of rectangular and square tubes are investigated through lateral crushing testing and theoretical analysis. The average crushing force of the rectangular tube is smaller than that of the square tube. These two types of tubes have identical crushing mechanism, including two crushing stages. Plastic models are built based on the observed crushing behaviour. Theoretical solution for each stage is developed to predict the average crushing force of rectangular and square tubes.

1. Introduction

Thin-walled tubes are frequently used as energy-absorbing components in vehicle design because of their relatively cheap price and weight efficiency. Their crushing behaviour under different loading conditions has been obtained considerable attentions in [1–7] due to the fact that thin-walled tubes have comparatively high energy absorbing capacity. Gupta and Khullar [8] carried out the investigation of the lateral compression on single rectangular and square cross sections. They showed that hinges are first formed at the middle of the vertical arms and later on at the four corners of the tube. Gupta et al. [9] investigated the deformation and energy absorbing behaviour of rectangular and square tubes of aluminum and mild steel under lateral compression through experiments and simulations. They figured out that between the square and rectangular tubes of equal cross-sectional area, the square tube absorbs more energy as compared to the rectangular tube, and the tube section collapsed due to the formation of two sets of plastic hinges. Gupta and Ray [10,11] studied the behaviour of empty and foam filled aluminum tubes in different sizes of square tube under lateral loading. Analysis of the compression process was based on the formation of the stationary and rolling plastic hinges.

Abdewi et al. [12] investigated the effects of corrugation geometry on crushing behaviour, energy absorption, and failure mechanism of composite tubes under axial and lateral compressive loadings. However, no effect of corrugation geometry was observed for lateral crushing in their work. The effects of geometrical discontinuities on energy absorption characteristics of tubular structures subjected to lateral crushing was reported by Rouzegar et al. [13]. McShane et al. [14] investigated the dynamic compressive response of the inclined strut. They proposed three classes of collapse mode in which a three-hinge plastic buckling mode of wavelength equal to the strut length, similar to quasi-static mode. Maduliat et al. [15] revealed the collapse behaviour 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 model the large deformation behaviour and energy absorption. The energy absorption behaviour and crashworthiness optimisation of short length circular tubes was addressed by Baroutaji et al. [16] in quasi-static lateral loading.

Even though a number of work have been carried out on lateral crushing of single tube, theoretical prediction of average crushing force for rectangular and square tubes are rare in this loading condition. In this work, lateral crushing behaviours of rectangular and square tubes are investigated through experiment and theoretical analyses. Plastic models are proposed based on the observed deformation. Based on plastic models, theoretical equation for each stage is built to predict the average crushing force of two types of tubes.

2. Experimental setup

2.1. Material properties

Tensile test specimens were prepared by cutting the same tubes as used for performing the lateral crushing tests. The uniaxial

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Nomenclature

P	average crushing force	M_p	fully plastic bending moment
δ	crushing length	λ, η	length ratio
E_r	energy dissipated by the plastic hinge with rotation	α, β, θ	rotation angle
E_m	energy dissipated by the plastic hinge with movement	h, b	size of tube
r	radius of the plastic hinge	L_a	arc length at dynamic plastic hinge
S	traveling distance of the dynamic plastic hinge	h_c	calculated height in stage B

tensile tests were conducted on the universal testing machine. The engineering tensile-stress strain curve of one representative CT33 steel specimen used to determine the materials properties is shown in Fig. 1. The mean values of the elastic modulus, yield strength, and the ultimate tensile strength over all the tensile specimens are listed in Table 1.

2.2. Experiment

Lateral crushing behaviours of tubes in Fig. 2 are firstly investigated in this article. Specimens of 85 mm length are to be fabricated from steel plates. The tubes' specifications are depicted in Table 2. A UH-F500kNI SHIMADZU universal testing machine is used for compressing the specimens. At first, the upper platen was moving downward at the velocity of 3 mm/min. The lateral compression process continued until the top and bottom horizontal sides of the deforming specimens got in contact with each other. The force-stroke curves were recorded over the whole lateral crushing process.

Fig. 3 shows the typical progressive lateral crushing modes of a rectangular tube specimen (labeled I1-) and a square tube specimen (labeled I2-) at different stages of lateral crushing. It can be seen that the deformation processes of the rectangular and square tubes are similar in both stages. After the elastic deformation phase, the force drops sharply due to the plastic buckling. Then rotations of dynamic plastic hinges controlled the deformation plateau before this process repeats. The formation of the second process is demonstrated by new dynamic plastic hinges developed in the horizontal side of the tubes. The corresponding force–stroke curves are shown in Fig. 4 respectively. The force–stroke 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 formation of new plastic hinges. Different stages of lateral compression at which crushing behaviour were recorded are marked on the corresponding force–stroke curves. Additionally the effective crushing distances were about 0.787h and 0.84h for rectangular and square tube, respectively. Figs. 3 and 4 show that although the tube continued to deform under lateral crushing but the average crushing force, P, does not change much. The average crushing force in each stage is therefore defined as the equivalent constant force with a corresponding amount of stroke. Thus, the calculated heights of the two types of tubes in stage B are equivalent to 60.3% of the effective crushing distance.

Table 1
Mean values of material properties from the tensile tests.

Property	CT33
E (GPa)	205.7
σ_y (Mpa)	218
σ_u (Mpa)	316

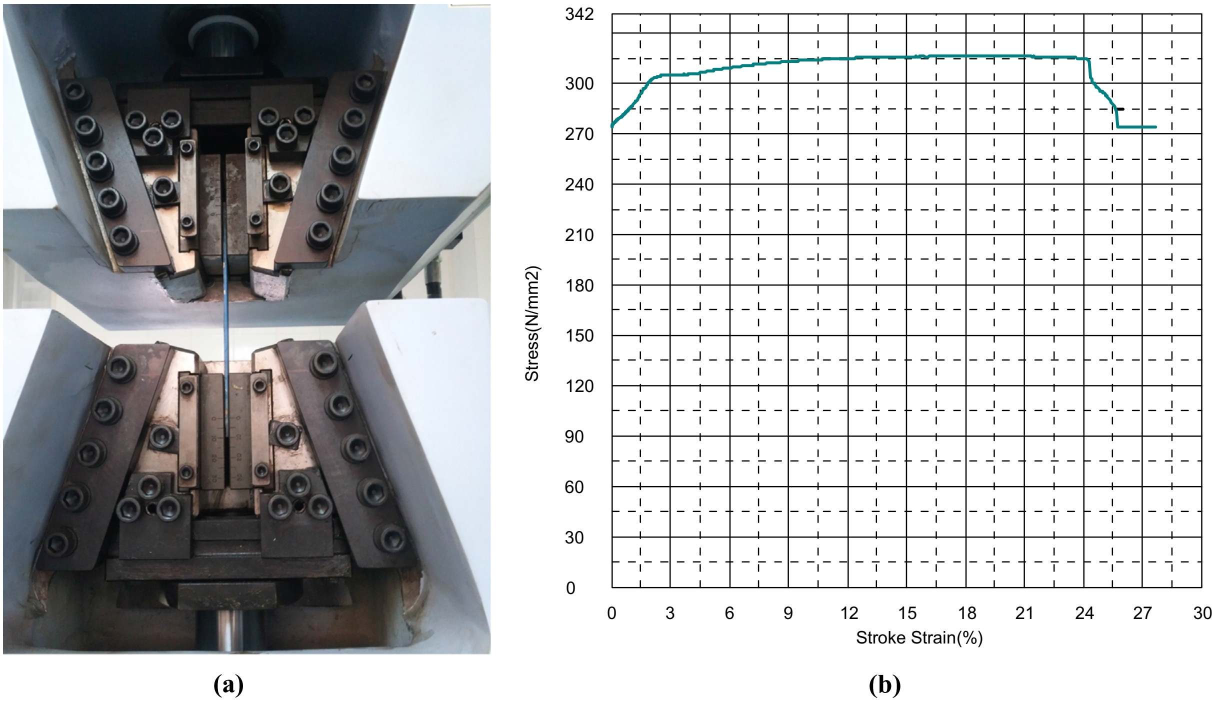

Fig. 1. a) Tensile test; b) Typical stress-strain diagram.