International Journal of Impact Engineering 000 (2017) 1–11

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Large deformation of tubes under oblique lateral crushing

X.M. Xiang[a,b], G. Lu[a,*], Z.-X. Li[c], Y. Lv[d]

[a] *Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, Vic 3122, Australia*
[b] *Tianjin Key Laboratory of Civil Structure Protection and Reinforcement, Tianjin Chengjian University, Tianjin 300384, China*
[c] *Key Laboratory of Coast Civil Structure Safety of Ministry of Education, Tianjin University, Tianjin 300072, China*
[d] *School of Civil Engineering, Tianjin Chengjian University, Tianjin 300384, China*

ARTICLE INFO

Article History:

Keywords:
Tube crushing
Energy absorption
Oblique compression
Plastic hinges
Travelling hinges

ABSTRACT

This paper presents a detailed investigation of short tubes under combined lateral compression and shearing by applying two parallel rigid platens in an oblique manner. The tubes were placed between the two parallel platens. The relative directions of the two platens were 0°, 15°, 30°, 45°, 60° and 75°, respectively; a value of 0° corresponds to pure compression while a 90° would be for pure shearing. Quasi-static tests were conducted by an INSTRON machine and the force-displacement curves were obtained. A finite element (FE) analysis was performed, which revealed more detailed deformation mechanisms. Subsequently, an analytical model is established for rigid, perfectly plastic material, which invokes stationary and travelling plastic hinges. The analytical results are in agreement with those obtained from the experiments and the FE analysis. The dynamic effect was also considered in the FE analysis.

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1. Introduction

Rings and short tubes are common components used as energy absorption structures. Analytical and experimental studies of two-dimensional deformations of rings/short tubes and their systems under in-plane loads were reviewed by Lu and Yu [1]. Ring compressed by two point loads was analysed using the equivalent structure technique [2,3]. Several other loadings have been also studied, for example, ring pulled by two point loads [4]; built-in semi-circular arch under point loads [5]; tubes under general lateral constraint of various degrees compressed with cylindrical indenters [6]; arrays of parallel, thin-walled circular tubes compressed between parallel flat plates [7]; triangular arrays of metal rings/tubes subjected to compression along the axis of symmetry and oblique compression [8]. Gupta et al. [9,10] have investigated experimental and computational study of round, rectangular and square tubes made of aluminium and mild steel and subjected to quasi-static transverse loading. They found that specimens of lower diameters have higher energy absorbing capacity and mean collapse load when their thickness are equal [9], and the square tube absorbs more energy as compared with the rectangular tube with equal cross-sectional area [10].

When a short tube is idealised as being rigid-perfectly-plastic, its plastic deformation is concentrated at one or a few cross-sections which are termed as plastic hinges. The magnitude of the applied bending moment reaches the fully plastic bending moment of the cross-section. The plastic hinges are important features of plastic deformation, which are inherent in more complex structures [1].

For a short tube under compression between two flat platens, two typical idealised modes were proposed by previous researchers [11,12]. de Runtz and Hodge's [11] mode has four stationary plastic hinges and is more appropriate for mild steel, which has an upper and lower yield point, while Burton and Craig's [12] mode involves flattening of the tube at the moving contact point. Both modes have the same force diagram for the undeformed segment and hence lead to the same force-deflection curve. However, this predicted force is lower than experimental results because of the strain hardening effect in two implications, as pointed out by Reid and Reddy [13]: 1) the plastic bending moment resistance increases as deformation proceeds; 2) plastic deformation takes place over a zone instead of being confined within a localised plastic hinge - i.e. the hinge has a certain length. The latter effect leads to a change in load through significant change in geometry and hence moment arm length. A simple way of estimating the strain-hardening effect is to evaluate the average strain involved in the deformation zone and then incorporate this into an enhancement of bending moment resistance [14]. It gives a better predication, but still lower than the experimental results, especially when deflection is large. This is because the plastic hinges are still very localised and the geometry is basically the same as previously assumed. Reid and Reddy [13] investigated this problem and proposed a Plastica theory, which replaced the concentrated hinges with an arc whose length varies with the deflection. The governing

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[*] Corresponding author.
E-mail address: glu@swin.edu.au (G. Lu).

http://dx.doi.org/10.1016/j.ijimpeng.2017.01.020
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Please cite this article as: X.M. Xiang et al., Large deformation of tubes under oblique lateral crushing, International Journal of Impact Engineering (2017), http://dx.doi.org/10.1016/j.ijimpeng.2017.01.020

equation including the length of the plastic deformation segment was given by Frisch-Fay [15]. This essentially revealed that the effective moment arm length reduces with increasing deflection, as well as the enhancement of plastic bending moment.

Almost all of the previous relevant work has been concerned with lateral compressive behaviour of a tube under two platens. In our recent work on sandwich beams with tubes being core [16], the behaviour of a short tube under shearing forces was investigated by means of finite element analysis, followed by an analytical model based on an idealized rigid-perfectly-plastic material. In this paper, large deformation of short mild steel tubes compressed obliquely by two parallel flat platens is investigated, which involves both compression in the initial radial direction and shearing. Two cases were considered: the tube was placed freely in contact with the platens with inherent friction in-between, or it was fully fixed to the platens at contacts by screws. Quasi-static experiments were conducted first, followed by detailed finite element analyses. Based on the observed deformation mechanisms, idealized modes of deformation are proposed and analytical solutions obtained.

2. Experiments

2.1. Specimens and experimental set-up

Two different sets of experiments were conducted, separately. In the first group of tests (Group 1), the tubes were made of mild steel with width $L = 49$ mm, inner diameter $D = 47.9$ mm and thickness $t = 1.48$ mm. The tensile stress-strain curve was obtained and is shown in Fig. 1. The tubes were merely placed between two inclined parallel platens (Fig. 2) and the cross-head moved vertically; the total vertical load at the cross-head was measured by the load cell in the Instron machine. To maintain symmetry, two tubes were crushed in each test and the measured total vertical force was assumed to be equally applied to the tubes. As the cross-head moved vertically, each of the tube was crushed in the diametrical direction as well as some shearing from the frictional forces. A tri-axial Kistler load cell was also placed beneath one tube in order to measure the three force components. The angle of the two parallel faces, α, was 0°, 30° and 45°, respectively.

In the second group of tests (Group 2), which were actually conducted before Group 1, the tubes were also made of mild steel, but with width $L = 50$ mm, inner diameter $D = 80$ mm and thickness $t = 3$ mm. Its tensile stress-strain curve obtained is also given in Fig. 1. Instead of being freely placed in-between the two platens as in Group 1, they were fixed to the two flat parallel faces. The angle of the two parallel faces α was 0°, 15°, 30°, 45°, 60° and 75° respectively (Fig. 3). In this group, only the total vertical load and displacement were measured from the universal testing machine.

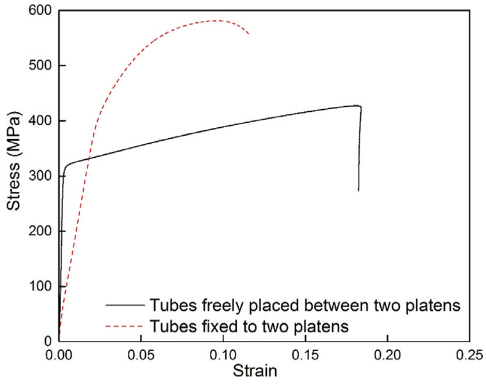

Fig. 1. True stress-strain curves of tubes in the two groups.

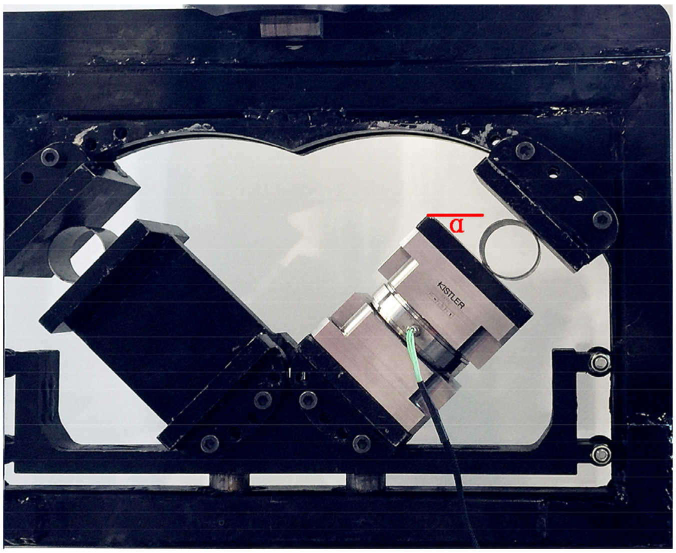

Fig. 2. Specimen in group one - tube placed between the platens: $\alpha = 45°$.

2.2. Experimental results

For Group 1 of tests with frictional contact, Fig. 4 shows the deformation process of a tube placed between two platens with a tilt angle of 45°. The vertical force (F_V) applied by the indenter was obtained from the machine, and the normal force (F_N) and shear force (F_S) applied on the tube were measured from the triaxial load cell. Fig. 5(a) and (c) plot the vertical forces (F_V) and shear force (F_S) against the vertical displacement (δ_V) of the indenter respectively, and Fig. 5(b) plots normal force (F_N) against the normal displacement (δ_N) for three values of α: 0°, 30° and 45°. When $\alpha = 0°$, the case corresponds to the conventional lateral compression of a tube previously studied extensively and the normal force is the measured vertical force (Fig. 5(a) and (b)) while the shearing force vanishes (not plotted in Fig. 5(c) and (d)). The vertical and normal force-displacement curves exhibit general characteristics of compressing a tube. The force increases in the initial elastic stage and then an almost plateau stage is achieved, with the force increasing slightly. Finally, the force increases significantly when the tube becomes fully crushed.

The measured shear force, which is the frictional force, increases over a long range of displacement and so does the ratio of the frictional force over the normal force (see Fig. 5(d)). This could be due to the fact the contact area between the tube and platen became large as the tube walls bended at the contact. The ratio of up to 8% at the end of the deformation indicates that the friction coefficient between the tube and the platen, μ, was 0.08 approximately.

For Group 2 of tests, where the specimens were secured to the platens via screws, Fig. 6 shows the deformation process of tubes fixed to the platens with a tilt angle of 15° and 30°, respectively. The vertical force (F_V)-displacement (δ_V) curves of the six specimens were obtained from the experiments (see Fig. 7). Curves for cases of $\alpha = 0°$ and 15° are almost the same, and for the case of $\alpha = 30°$, the force in the plateau stage is reduced largely and its value is about half of that in the cases of $\alpha = 0°$ and 15°. The area under the curve corresponds to the energy absorbed. Again, when $\alpha = 0°$ the case corresponds to the conventional lateral compression of a tube. As the value of α increases, the magnitude of the vertical force decreases and the maximum displacement increases. This group of specimens may also be regarded as a special case of Group 1 when the frictional coefficient between the tube and the platen is infinite.

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