

The strain field history during plastic folding of a mild steel tube under axial loading

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Abstract

This paper presents an experimental study on the load-displacement curve and strain histories of a single hexagonal tube under quasi-static axial compression. The result is compared with computer simulation.

The strain gauges are glued on to the outer faces, and both axial and circumferential strains are measured at a sampling rate of 40 readings every one second. The measured strains are examined both as time histories and as deformation fields. The response of hexagonal tube subjected to axial loading is observed through experiments. The FEA strain-displacement curve agrees well with the experiment if the gauges are away from the top of specimen.

Keywords: energy absorption, hexagonal tubes, triggering, and quasi-static.

1 Introduction

Efforts have been made to improve the capability of energy absorption of sheet metal tubes particularly of empty, wood-filled and foam-filled rectangular tubes under static and dynamic crushing. Reid and Reddy [1], Reid et al. [2] and Reddy and Al-Hassani [3] have shown that filling the tubes with foam or wood increases the energy absorbed by inducing a larger overall plastic deformation of the shell wall. Said [4] presented experimental measurement of elastic half wavelength and plastic fold length during the crushing of rectangular tubes. It is noted that the plastic fold length depends on the elastic wavelength, which can also be found from the deformation pattern. Abramowicz and Wierzbicki [5] developed the theory for predicting crush behaviour for multicorner columns with an arbitrary corner angle. This was applied to find the crushing strength of



the hexagonal tube under axial compression to produce a simple expression for the mean crushing: $F_m/M_o = 80.92 (b/t)^{0.4}$.

The strain histories play an important role in determining the energy absorption. Avalle and Belingardi [6] experimentally obtained the strain histories for a circular tube under axial loading. The present study is an experimental measurement of deforming material by fitting the strain gauges in the outer faces of a mild steel hexagonal tube. The study includes strain histories and the load-displacement characteristics during plastic folding of the tube under axial loading. The FEA results presented by Said [7,8] are also compared.

2 Experiment

The mechanical properties of a single hexagonal tube material were determined from tensile tests on coupons, instrumented with electrical resistance strain gauges. It gave Young's Modulus, $E = 212$ GPa, yield stress, $\sigma_y = 435$ MPa, ultimate stress, $\sigma_{ult} = 453$ MPa.

Tubes made of mild steel, with a side length of 40 mm and wall thickness of 1.87 mm were used in this study. Axial compression tests were carried out on as-received 170 mm or 200 mm long hexagonal tubes. Some of them were chamfered at one end in order to trigger the mode of deformation. All the specimens were compressed axially between the platens of an Instron Universal Testing machine at a crosshead speed of 20 mm/min.

One specimen was fitted with 68 electrical strain gauges. The gauges, which are electrical resistance strain gauges with a maximum plastic strain of 15% and 2 mm gauge length (type YFLA-2, Tokyo Sokki Kenkyujo Co.), were glued on to the outer faces of the specimen using epoxy resin adhesive (type AE10). The locations of these gauges on one face of the hexagonal tube are shown in Figure 1. For identification purposes, the gauges were designated as An-xy and Cn-xy for axial and circumferential strains, respectively, n representing face identification (1 to 6). x is the horizontal (circumferential) coordinate measured from the centre line of the face and y is the vertical coordinate measured from the top end. For example, the gauge number A1-0021 is the axial strain gauge located on the centre line on face 1 at 21 mm from the top end. Each dot represents two strain gauges; one in the axial and the other in the circumferential direction. The arrangement of gauges was such that the axial and circumferential strains over a length of 60 mm (equal to 2 folds lengths) and across the face could be monitored. Each set (axial and circumferential) of gauges were fitted at identical locations but on different faces for logistical reasons. All these gauges were connected individually to a solartron data logger (along with the signals from the load and displacement transducers) at a sampling rate of 40 readings every one second, this translating to taking a reading in each gauge every 1.7 seconds. The data were captured at every 5 kN or every 0.5 mm displacement, whichever occurred first. The strains gauge signals were then processed by means of a personal computer.

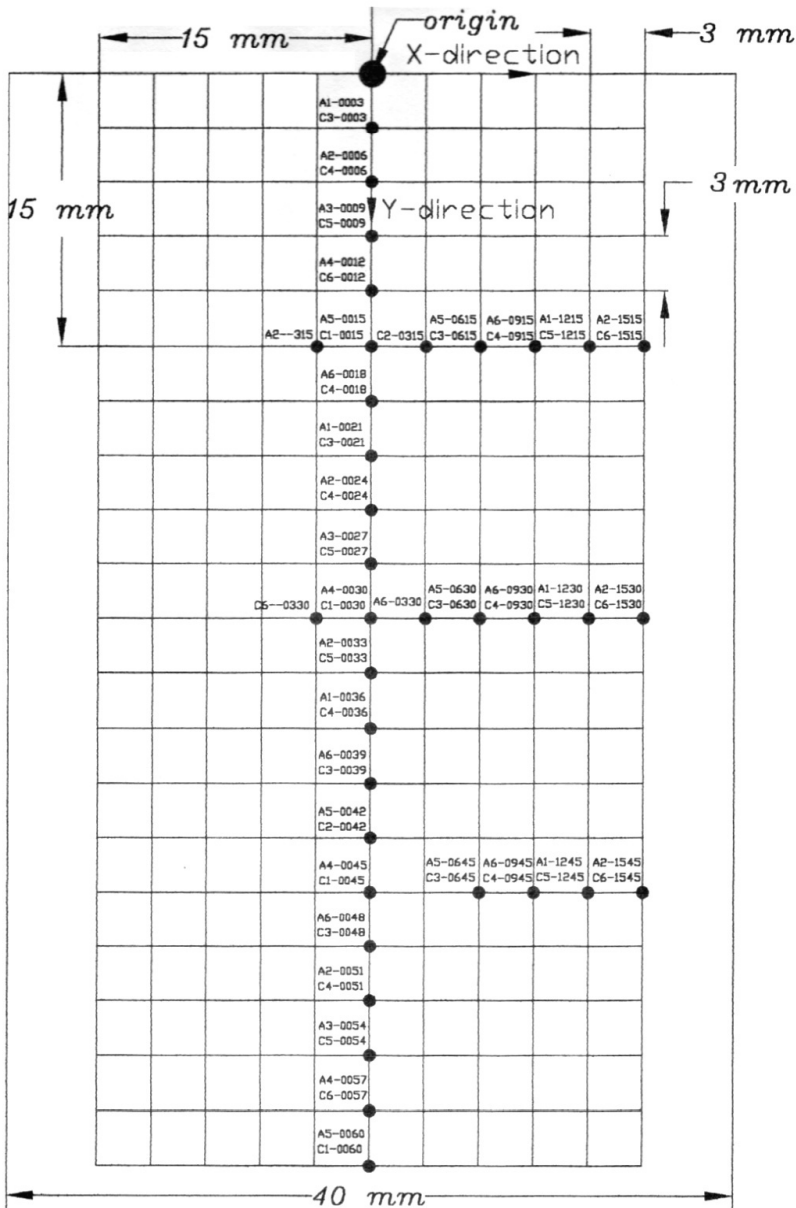


Figure 1: Locations of the strain gauges on a hexagonal tube are indicated by dots. A and C indicate the axial and circumferential orientation of the gauge axis.

3 Observations and discussion

This section describes the circumferential strain-displacement curves and the strain histories in the axial and circumferential direction, at a number of predetermined locations during compression.

Figures 2 and 3 show the plots of the axial and circumferential strain, respectively against the crosshead displacement along with the load trace. All axial strain gauges except gauges no. A1-0003 and A2-0006 show negative compressive of strains, which vary almost linearly up to the collapse load (see Figure 2a-i). The tensile strain in gauges A1-0003 and A2-0006 is likely to be due to the axial bending in this end zone, right at the beginning of compression. With continued compression and associated bending in this end zone, the outputs of gauge A1-0003 and A2-0006 have saturated. The gauges peeled off very early in the deformation.

Figure 2b shows that the strain in the gauge A3-0009 changes from compression (after the peak load at $\delta=3$ mm) to tension and then it drops to zero value, while strain in the gauge A4-0012 also drops but only to ε at about -0.6% after $\delta=3$ mm. Strain in gauge A5-0015 continues to increase to about 2.4% . The strain readings for gauges no. A6-0018, A1-0021, A2-0024, and A3-0027 are shown in Figure 2c. It shows that all gauges experience compressive strains as deformation continues. Gauge A1-0021 indicates an 11% strain at about 6 mm crosshead travel.

At a compression of 13 mm, the top end region of the tube was folded flat and was in contact with the top platen. This obviously damaged gauges in this region (about 9 mm length). When the compression reached 41 mm, all gauges in the zone of 41 mm from top end of the hexagonal tube were damaged as two plastic folds occurred.

Figure 3a-i shows the strain against displacement for circumferential gauges. Load variations are also shown in (a) and (e). All gauges show the positive strains, before reaching the peak load indicating hoop stretching right from the beginning of compression until it reaches the peak load. It can also be seen that the strains are in proportion with the axial strain, the ratio being about 0.3 to the Poisson's ratio, ν (C6-0057 and A5-0060). Figures 4a-c illustrate the graphs of axial strain against the position along the tube at various movements of the crosshead. All axial gauges were located on the central lines of the faces of the tube. Initially, under compression, all gauges along the tube show negative strains except the gauge located at 3 mm (i.e. A1-0003) and 6 mm (A2-0006) from the top of specimen. A sudden, negative decrease of strain occurs in the gauges located at 15mm and 18 mm (Figure 4a) when the crosshead travels up to 3 mm. This indicates that the specimen starts to buckle at the top specimen adjacent to the crosshead.

As the compression continues up to 8 mm, the strain increases until a maximum of -11% strain is reached in the gauge located at 21 mm from the top end of the specimen. The rest of the gauges along the tube show a constant strain (Figure 4b). The gauges located at 30mm, 33, 36, 39, 42, and 45 mm begin to show a positive reading as the crosshead moves up to 18 mm, which is shown in



Figure 4c. The highest strain values in Figure 4b and 4c are associated with the formation plastic hinge and located at 20 mm from the top specimen. It means that the plastic fold length is 40 mm. However, it is higher by 10% compared with the measured value.

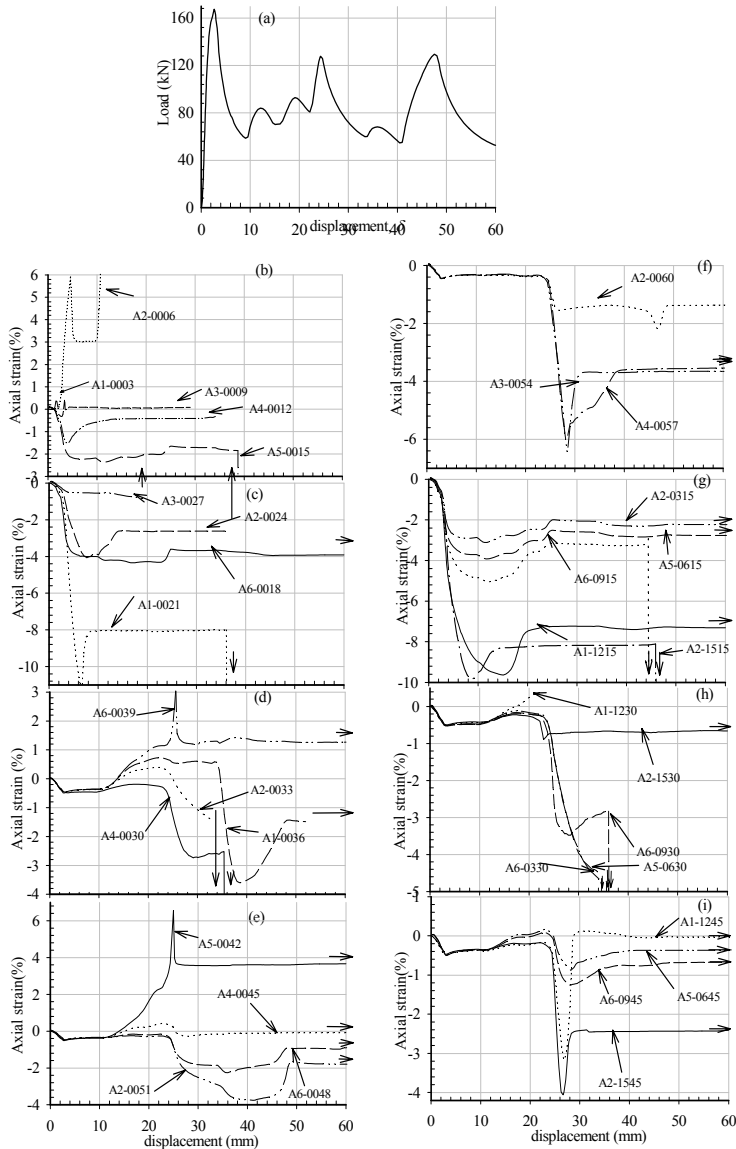


Figure 2: (a) Load against displacement. (b)–(i) Graphs of axial strain in different gauges against displacement.

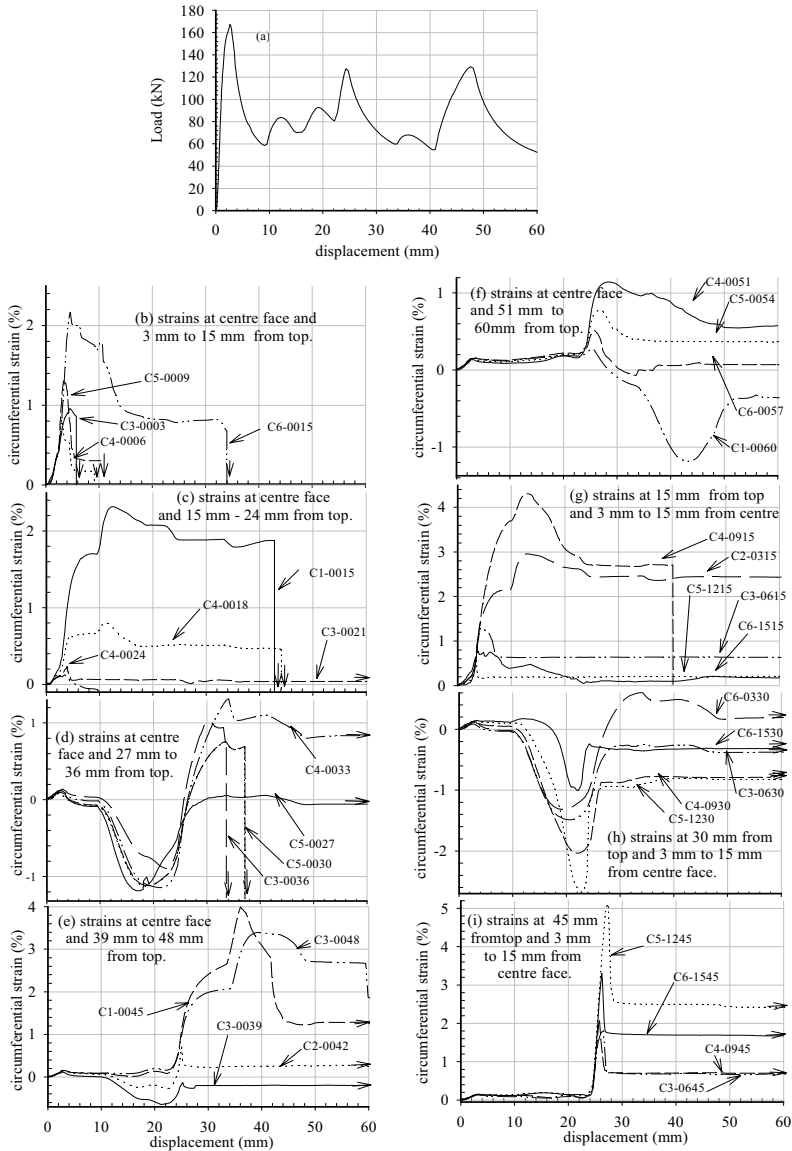


Figure 3: (a) Graph of load against displacement. (b)–(i) Graphs of circumferential strain in different gauges against displacement.

Typical measured strain histories at two different locations (15 mm and 60 mm away from the top end and mid-face) are compared with the corresponding strains computed by the FEA [7] in Figure 5. The curves shown are up to the displacement of 35 mm and beyond this displacement, the comparison between FEA and the experimental results is not appropriate due to the saturation of the strain gauge.

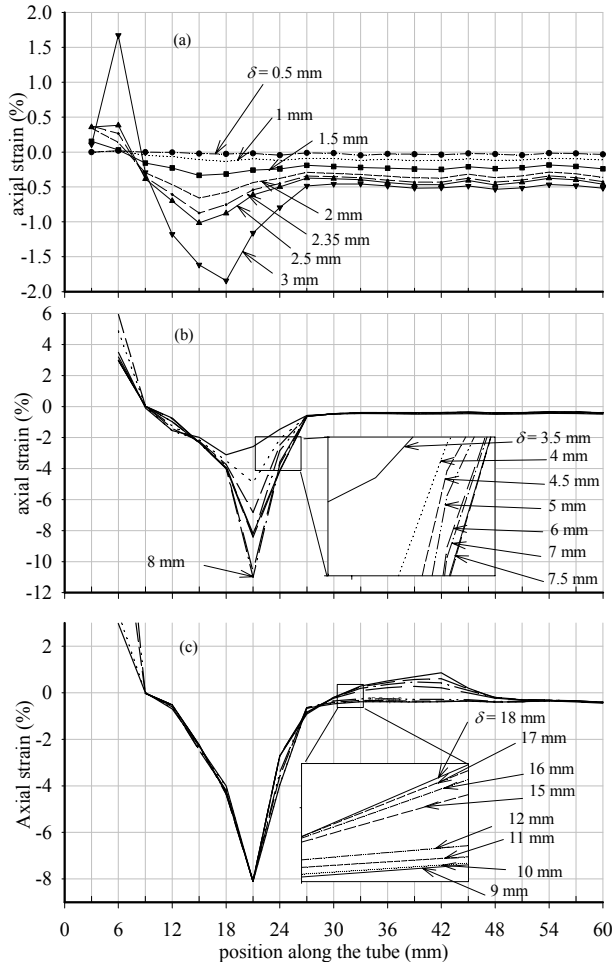


Figure 4: Graphs of axial strain against position along the tube in the mid face at various movements of the crosshead. (a) Compressed from 0.5 mm–3 mm. (b) Compressed from 4–8 mm: Inset is the close-up view. (c) Compressed from 9–18 mm: Inset is the close-up view.

Axial and circumferential strains 15 mm away from the top end are shown in Figures 5a and Figure 5b, respectively. The deviation between the predicted and the measured axial strains gradually increases and while the strain gauge output saturates a displacement of about 5 mm, the predicted strains increased monotonically. For the case of circumferential strain curves, the deviation fluctuates between 40% (at $\delta=5$ mm), 10% ($\delta=15$ mm), 30% ($\delta=20$ mm) and then (after $\delta=23$ mm) gradually increases. The measured strains saturate and even show a decrease after $\delta=12$ mm.

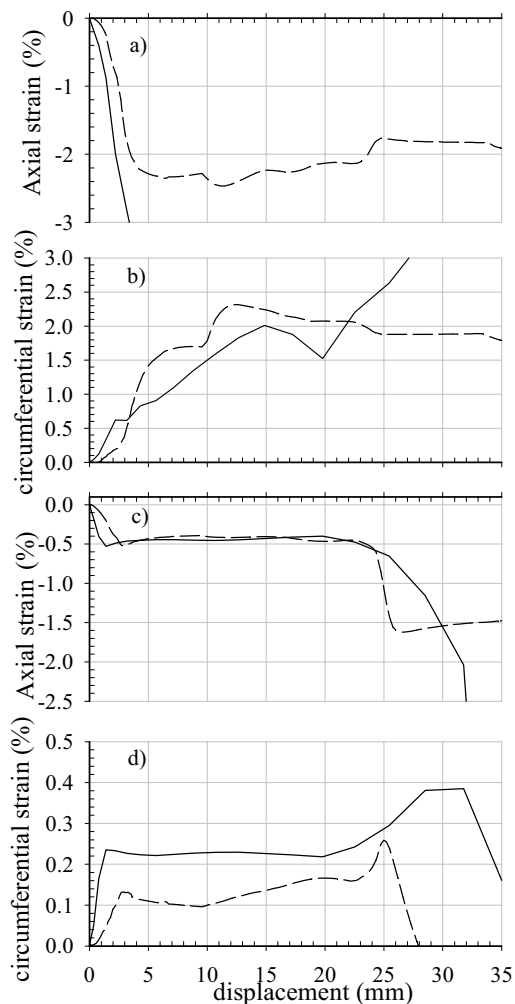


Figure 5: Strain-displacement curves, FEA (solid lines) and experiment (dashed lines). (a) and (b) Axial and circumferential strains at a distance of 15 mm from the top end. (c) and (d) Axial and circumferential strains at a distance of 60 mm from the top end.

The axial strains at 60 mm from the end (Figure 5c) are in good agreement. However, the circumferential strains (Figure 5d) and the predicted strain curve are overestimated by about 50%, but the form of variation is the same. The loads versus strain variations are also plotted in Figures 6.

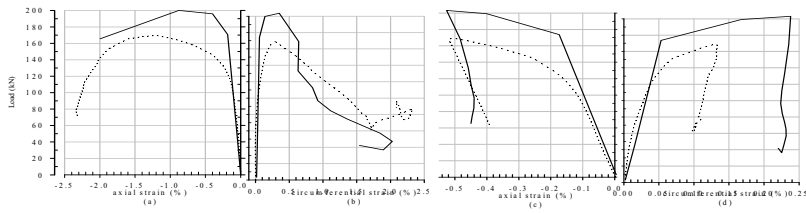


Figure 6: Typical load-strain curves, FEA (solid lines) and experiment (dotted lines) at mid-face. (a) (b) Axial and circumferential strain at 15 mm. (c) and (d) Axial and circumferential strain at 60 mm.

4 Conclusion

A single hexagonal tube under quasi-static loading has experimentally studied. The result has been compared with FEA. It can be seen that the strain curves and the form of the experimental curves are in agreement with the FEA at locations away from the end. The comparison between the FEA and the experimental results for gauges close to the end is not appropriate due to the saturation of the strain gauge.

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