Experimental investigation on the folding of axially crushed hexagonal tubes

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Abstract

The objective of this paper is to investigate the folding mechanism of an empty hexagonal tube made of mild steel with respect to the energy absorption. This includes the determination of the plastic wavelength, type of deforming mode and the mean load of the tube subjected to an axial loading. The introduction of chamfer at one end of the tube is also examined and studied. The comparison load-displacement curves between experiment and Finite Element Analysis (FEA) are made. The experimental mean load is also compared with theoretical analysis. The response of the hexagonal tube subjected to axial loading is observed through experiments. The formation of plastic fold length is observed and measured. The mean load and area under the load-displacement curve are calculated to obtain the energy absorption. By introducing the chamfer at one end, the deforming pattern can be determined, i.e. in-out chamfer gives a diamond mode while all-out chamfer gives a concentina mode. The FEA load-displacement curve agrees well with the experiment. However, the predicted mean load is overestimated, while the equivalent circular cylinder underestimates the experimental result.
Keywords: energy absorption, hexagonal tubes, triggering, and crushed.

1 Introduction

Energy absorption systems made of thin-walled circular tubes and tube nests have been given significant attention by researchers for the past few decades. In particular, the initiation progressive axisymmetric and non-axisymmetrical

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folding in tubes has been a subject of intense investigation by many investigators. Alexander [1] was first to present an analysis for the prediction of a mean crushing load, for a tube subjected to axial compression. He managed to obtain an expression for the folding length and the mean crushing load by implementing global energy balance. However, he assumed the tube to be folding into axisymmetric rings, in which the tube wall moves out of its initial position. But in reality there is outward as well as inward movement. This anomaly was first addressed by Reddy and Reid [2] albeit by an over prescribed hinge (four) mechanism. Wierzbicki *et al* [3] presented a more realistic three hinges mechanism in the form of a concentina collapse mode. The mechanism allows for radially inward as well outward folding in a proportion relative to the tube generator. The outer portion of the folding length relative to the total (inward plus outward) length was defined by the eccentricity factor. The mean load deduced was independent of the eccentricity factor, which was indeterminate. Singace *et al* [4] further modified Wierzbicki's analysis enabling the determination of the eccentricity factor, which was in good agreement with the experimental results. The absolute mean crushing load produced by Singace *et al* [4] was similar to that of Wierzbicki *et al* [3] except for an added factor 5.632. These and other analysis are applicable only on the second and subsequent folds. The formation of the first fold is unique and there appears to be no analysis yet to describe it.

Pugsley and Macaulay [5] observed diamond type folding in thinner tubes and derived a semi-empirical expression for the mean load. Horton *et al* [6] reported the findings of an extensive experimental study of quasi-static axial buckling of thin-walled cylindrical tubes, concluding that the buckling mode changed from axisymmetric to non-symmetric patterns if the geometric parameter, radius over wall thickness, t increases. Johnson *et al* [7] developed, a mechanism of inextensional mode of deformation of thin-walled tube under axial loading which involved the stationary and travelling hinges in the diamond mode and derived an expression for the mean crushing load. However, they [7] did not correlate the change of concentina to diamond mode. Tvergaard [8] investigated the influence of buckling pattern localisation, which could cause the transition of diamond mode to axisymmetric mode. The dependence of folding mode on tube geometry has been investigated experimentally by Andrews *et al* [9].

Square, rectangular, hexagonal are more popular than circular tubes in automobile industry. Early investigations [10,11] were concerned with rectangular tubes made of sheet metal and were aimed to understand the behaviour of vehicle body shells. Wierzbicki and Abramowicz [12] formulated kinematically admissible global deformation mechanisms for thin-walled rectangular tubes comprised of flat plates. Reid and Reddy [13], Reid *et al.* [14] and Reddy and Al-Hassani [15] have shown that introducing different fillers like foam or wood increase the overall energy absorption of the tubes. Said [16] presented experimental measurement of elastic half wavelength and plastic fold length during the crushing of rectangular tubes. No work has been found to study the effect of trigger by introducing the chamfer in one end tube. Abramowicz and Wierzbicki [17] developed a mechanism for predicting the crush behaviour of multicorner columns with an arbitrary corner angle. This was applied to find crushing strength of hexagonal tube under axial compression and produce a simple expression for the mean crushing load.

As the hexagonal consists of 6 sides and circular is infinity sides, the correlation may be made by assuming the hexagonal sides as an equivalent circular cylinder. The objective of this paper is to investigate the folding mechanism of empty hexagonal tube made of mild steel with respect to the energy absorption. The effect of triggering with mean load and plastic folding is also examined.

2 Experiment

Axial compression tests were carried out on as-received 170 mm and 200 mm long hexagonal tubes made from the same tube. Longer specimens were labelled as HEX1 to HEX12 and shorter (170 mm long) specimens as HEX170. Some of them were marked with 4 mm grid circles and some chamfered at one end in order to trigger the mode of deformation. Distance of 4 mm is measured from a point of arc intersection to the next point. All the axial compression tests were on specimens in the as-received state only. Tests were carried out on a 200 kN universal testing machine at a loading rate of 10 mm/min.

3 Observations and discussions

This section describes the influence of triggering, the characteristic of load-displacement curves, and the effect of chamfer. This includes the determination of the plastic fold length, mean load and energy absorbed and also compared with the circular tube under axial loading.

3.1 Triggering the mode of deformation

Mode of deformation of hexagonal tube under axial loading can be triggered by introducing the chamfer at one end. Without chamfering, the tube deforms in uncertainty manner, i.e. may deform in concentina or diamond or mixed mode. Experiments have shown that by introducing the chamfer, the mode of collapse can be determined. However, the edge of the tubes under investigations, have to be suitably chamfered. The chamfer was made to half of the original thickness of the tube and with an angle of approximately 45^0 as shown in Figure 1. This results in the axial end forces applied being offset with respect to the centreline of the tube wall. The larger the chamfer is the larger the eccentricity. Experiments have shown that if the chamfering one side only of all end faces (either inner or outer ends), tube collapses into concentina mode.

With external chamfers on all faces (referred to as all-out chamfers), the first buckle was outwards and vice versa. However, if adjacent faces were chamfered on opposites edges (i.e. one on the outside and the other on the inside, referred to as in-out chamfers), the tubes were seen to fold into the diamond mode. In the in-out chamfered tubes, fractures were observed along the corners when the chamfers were extended over the whole face width. By chamfering only over the central region, such corner failures were prevented.

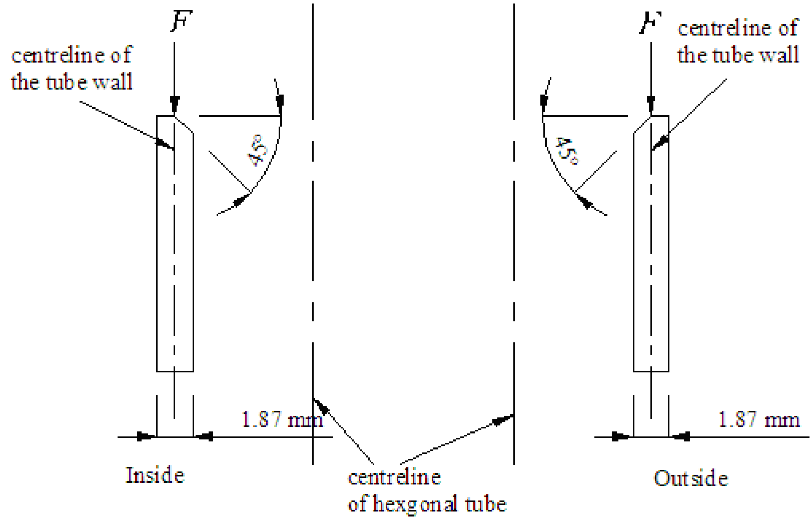

Figure 1: A schematic view of the tube wall, showing the chamfered angle.

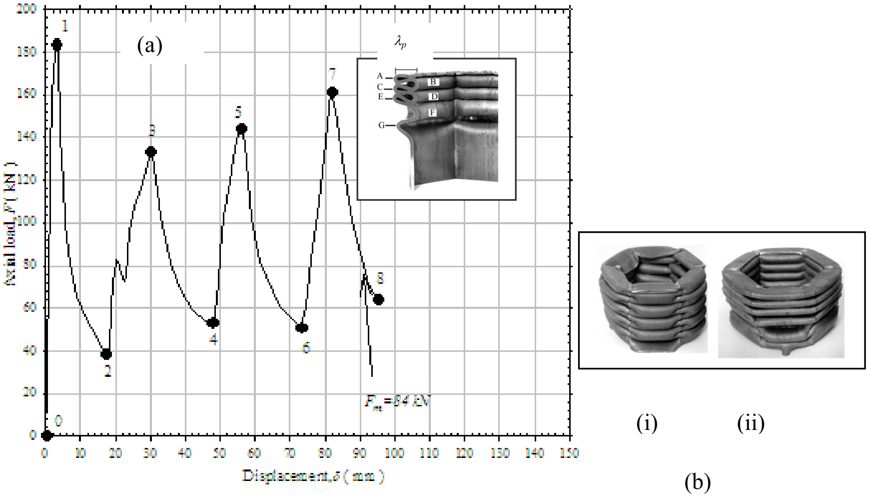

Figure 2: (a) A typical load-displacement curve for a single hexagonal tube (HEX170). Insert: A one-sixth segment of a deformed specimen. (b) Deformed unchamfered tubes (i) Diamond mode (ii) Concentina mode.

3.2 The load-displacement characteristic for unchamfered specimens

Figure 2 shows a typical load-displacement trace for an unchamfered specimen marked as HEX170 and the deformed tubes. A cross-section of the crushed specimen is shown in the inset. During compression, just before the peak load (point 1 in Figure 2a), a series of elastic ripples were noticeable in the sides of the hexagonal tube. It is noticed that, the peak load is 184 kN. Ripples disappeared when the load dropped (point 1 to 2) and were not noticeable afterwards. They reflect the state of buckling and influenced mostly by strain-hardening characteristics of these tubes. At the peak load the tube buckled locally at the top end and initiated a plastic fold. The faces were observed to buckle before the corners collapsed indicating the start of plastic fold. The first fold was followed by a series of load fluctuations. Each cycle in the fluctuations (e.g. 3-5, 5-7 etc) corresponds to a plastic fold that formed in the tube at section labelled as A, B, C, D, E, F and G shown in the inset. The number of peaks in the load-displacement curve indicates the number of folds formed. The mean load during compression was calculated as the ratio of the area under the curve and the displacement is almost the same for all folds. A secondary (minor) load fluctuation was observed between the first and second primary peak only. Such fluctuation was not seen beyond the second peak. A characteristic (plastic-buckling) wavelength can be identified as, λ_p (=2H) as shown in the inset in which mode of deformation seen is of a concentina type, in which all the sides of the tube buckle in phase i.e. inward or outwards simultaneously. The plastic wavelength can be estimated from experiment, as the average length per fold in the deformed specimens. It was found that, λ_p = 33 mm, this also being approximately the displacement difference between two adjacent peaks in the load-displacement characteristic (Figure 2a). A detailed examination of the deformed specimen also indicated that, the first fold was at about 16 mm from top end as shown in the inset. From the calculation, it is noticed that the mean load is about 84 kN. Some specimens exhibited progressive incomplete diamond and concentina type folding patterns in a fold. The diamond type is where in adjacent sides of the tube were buckling out of phase (i.e. one inward and the other outward etc). Incomplete mode is a mixture of half concentina and half diamond in one plastic fold. For example, specimen HEX1 deformed in four incomplete diamond and concentina folds as can be seen from photograph in Figure 2b(i-ii).

In some specimens, concentina fold formation was seen in the initial few folds and then followed by incomplete diamond and concentina folding mechanism was seen. For example in specimen HEX7, Figure 2b(ii), three concentina folds are followed by two folds of incomplete diamond and concentina. None of the specimen was seen to fold in mixed mode. Mixed mode is a complete concentina and diamond folds in the same tube. This concludes that unchamfered specimens exhibit uncertainty of folding mechanisms. A summary of results that includes mean load and plastic fold length for the entire specimen tested is shown in Table 1. This includes the specimens in which triggers are introduced to induce specific mode, i.e. concentina or diamond type of deformation.

3.3 The load-displacement characteristic for chamfered specimens

Figure 3a-b shows typical load-displacement curve for in-out and all-out chamfered hexagonal tubes subjected to axial loading. In-out chamfered specimen exhibits diamond mode, while all-out in concentina mode. The sequence of deformation for the case of all-out chamfers (point 0 to 15) is shown in Figure 4 corresponding to Figure 3b. Point 1 of the same figure indicates the peak load and the initiation of first plastic fold. The peak load shows 165 kN for both in-out and all-out chamfers.

Table 1: Summary of results of hexagonal tubes subjected to axial crushing.

Spec. no.	average λ_p at mid face (mm)	mean Load, F_m (kN)	Energy absorbed W (Nm) at δ=100 mm	Mode of deformation and length of specimen, L
HEX170	33	84	8401	Concentina, L=170 mm (unchamfer)
HEX1	36	84	8376	4 folds incomplete L=200 mm (unchamfer)
HEX2	35	84	8372	4 folds incomplete L=200 mm (unchamfer)
HEX3, 8, 11, 12	36	85	8488	Concentina, L=200 mm (All-out chamfer)
HEX4	-	-	-	Broke halfway, L=200 mm (in-out chamfer)
HEX5	36	86	8592	Concentina, L=200 mm (all-out chamfer)
HEX6	-	-	-	Broke halfway, L=200mm (in-out chamfer)
HEX7	34	85	8477	3 folds Concentina, 2 folds incomplete, L=200mm
HEX10	44	80	7939	Diamond, L=200 mm (in-out chamfer)

This means that insignificant effect on peak load for in-out and all-out chamfers, as the initial compression areas are the same. However, the load fluctuation (amplitude) for in-out chamfer is smaller than all-out chamfer by about 25 kN. Referring to Figure 3b, two secondary peaks (point 3 and 5) exist in load-displacement curve between the first and second primary peak and one between second and third primary peak. But, the secondary peaks were not seen after the third primary peak (point 8). The existing of two secondary peaks may be due to the plastic fold in contact with the top platen. However, the secondary peaks were not seen for the case of in-out chamfered specimen. A summary of results that includes the mean load, and plastic wavelength for all the specimens also is included in Table 1. It shows no significant change on with respect to mean load and plastic folding length for concentina mode for the case of all-out chamfered.

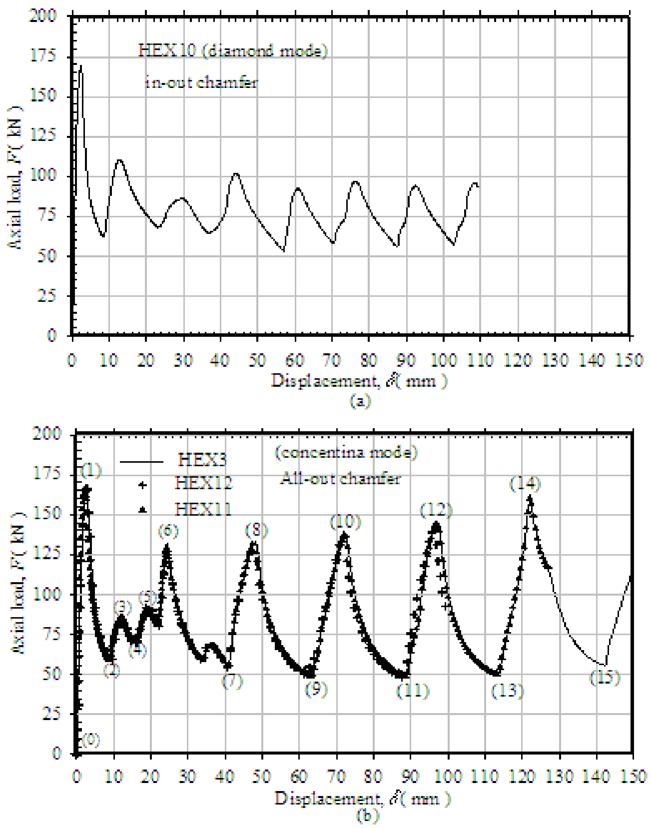

Figure 3: Load-displacement curve of hexagonal chamfered tubes under quasi-static compression (a) In-out chamfer (b) All-out chamfer.

However, in-out chamfer produces diamond mode, which gives the lower mean load, thus gives less energy absorption. Figures 5a-b show the typical cross-sectional views of the deformation patterns of all-out and in-out chamfered specimen crushed under nominally identical conditions. Figure 5a illustrates an all-out chamfered specimen, exhibiting concentina folds, while Figure 5b shows cross-section view of the diamond mode seen in the crushed specimen with in-out chamfers.

3.4 Effect of chamfer

The effect of chamfer is observed for both all-out and in-out chamfer. The significant effect of all-out chamfer is noticed in the load-displacement curve (Figure 3b), which shows the existing of two secondary peaks at point 3 and 5. Figure 3b also show the repeatability of the peaks. No secondary peak has been found in in-out chamfer. The reason of non-existing of the secondary peak has not been explored. However, they also appear in unchamfered tubes but only one secondary peak exists at random. In general, from energy absorption point of view, the all-out chamfered tubes give a higher value of energy absorption.

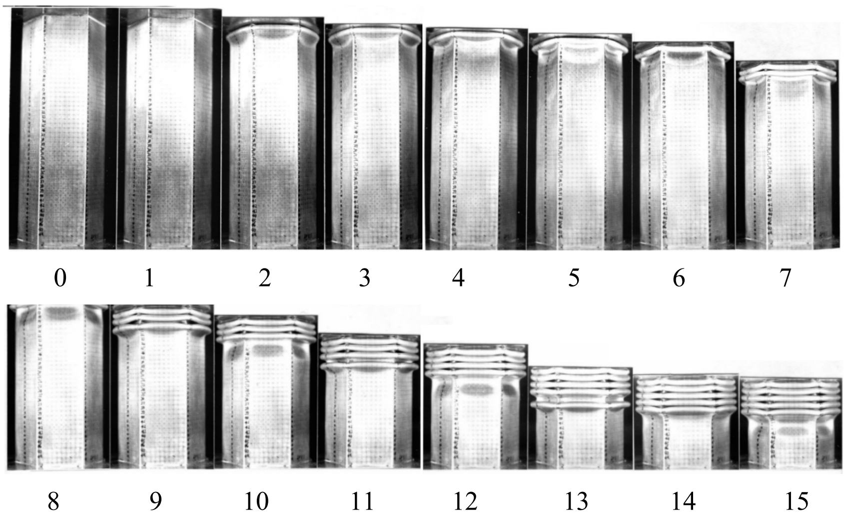

Figure 4: Sequence of deformation of axially crushed tube with all-out chamfer.

Figure 5: Typical cross-sectional views showing deformation pattern.

3.5 Comparison with FEA and equivalent circular cylinder

Figure 6 is the comparison of experimental load-displacement curves and those predicted by FEA [18,19], which are seen to be in good agreement. The FEA mean load is almost the same value with experiment. However the plastic fold length, λ_p(=36 mm) derived from the FEA [18,19] overestimates the experiment by 10%. The prediction of mean loads by various upperbound solutions for equivalent circular cylinder, Alexander [1] and Singace *et al* [4] and for hexagonal tubes, Abramowics and Wierzbicki [17] are also shown in the figure 6. The radius of an equivalent circular cylinder is assumed to be equal side length, *b* of hexagonal tubes. The mean load for the equivalent circular cylinders underestimates the experiment by about 30%. This is not surprising because these solutions underestimate the mean load for the crushing of cylinder by about the same margin. Their plastic fold length, λ_p [4] is also underestimated by about 30%. The mean load predicted by the analysis of Abramowics and Wierzbicki [17] is 105 kN which overestimates the experiment by about 25%.

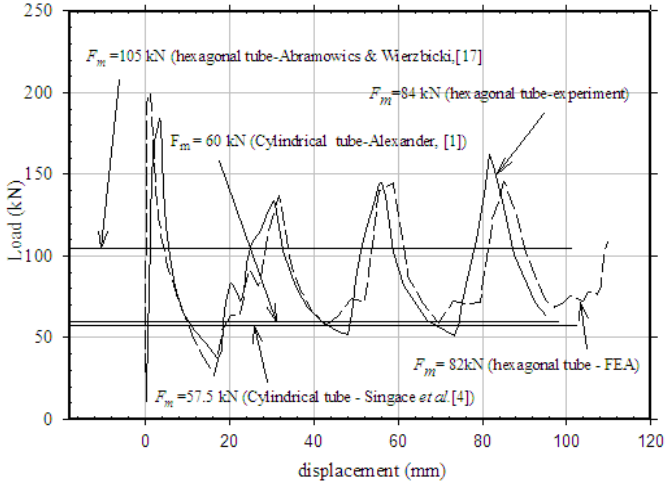

Figure 6: Load-displacement curves for axial compression quasi-static loading and comparison of the mean load, F_m with previous researchers.

4 Conclusion

With chamfering, the tube deforms in certainty manner, i.e. in-out chamfer gives a diamond mode while all-out in concentina mode. However, a slightly higher energy absorption is obtained from concentina mode. It also shows no significant change on with respect to mean load and plastic folding length for concentina mode for the case of all-out chamfered. However, in-out chamfer produces diamond mode, which gives the lower mean load, thus gives less energy absorption. The mean load for equivalent circular cylinder underestimates the experimental result, however FEA give excellent results with experiment.

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