Comparative large deformations studies on circular tubes
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ABSTRACT
This paper describes the large deformation phenomenon and compares the plastic energy absorption of tubes, for the different phenomenon. Experiments were conducted on circular aluminum tubes having typical external diameter of 25.5 mm and thickness 2 mm. Generally the tube lengths were 100mm. Also 50mm lengths were chosen to see the length effect on the deformation phenomenon. Numerical analysis was performed to simulate the different phenomenon. A good agreement was observed between experimental data and numerical simulation. The force-stroke curves of different deformation modes are discussed in detail. Various characteristics associated with large deformation are explored and discussed. Based on these experimental studies, best energy absorption phenomenon is found.

Keywords: Large deformations, fixtures, energy absorption, plastic deformation, force-stroke

1. Introduction
Energy absorbing devices are employed in vehicles to reduce the potential danger of impact accidents. Large deformation associated with energy absorption of shell structures of common shapes includes circular tubes, square tubes, frusta, cones, honeycombs, and sandwich plates etc. Common modes of deformation are inversion, axial crushing, curling, tearing, lateral indentation, tube flattening, buckling, tube expansion and contraction etc. Circular tubes had been of great interest for researcher for its good energy absorption characteristics. Alghamadi have given an overview on energy absorption by the tubes in 2001. Nia and Hamedani, 2010 studied the axial crushing on various section shapes including circular shapes. They found that the energy absorbed per unit mass is maximum for circular tube. The common modes of deformation such as lateral and axial compression, indentation and inversion were reviewed for metallic tubes by A.G. Olabi et al., 2007. Their advantage and disadvantage were discussed.

Lateral compression of a tube is studied in details by Reid and Reddy, 1978-79 and they presented a series of paper in this. A study of the crushing of tubes by two indenters was done by G. Lu et al., in 1993. They observed that the force increases with displacement in a nonlinear fashion. They also observed that the force increases with the length of the tube and for short tubes, there exists a sort of collapse load corresponding to a sudden change of slope. But for long ones, it is difficult to locate the collapse load on the curve. Tube inversion under axial loading was studied by Al-Hassani et al., in 1972. They found that the splitting mode is a special case of tube inversion where the die radius is large enough to cause splitting instead of inversion. In 1972, Ezra and Fay identified the combined modes of axial splitting and subsequent curling of the split ends of the tubes as an efficient means of energy dissipation in
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the absorber. The absorbed energy is dissipated in tearing of the metal of the tube into strips. Axisymmetric collapse mode for the tubes had been studied by Alexander in 1960. Guillow et al., 2001 did detailed experimental analysis for axial compression for thin walled circular tubes. Jialing Yang et al., 2010 studied the energy absorption of expansion tubes under axial compression by a conical–cylindrical die. Based on their experimental and numerical results, characteristics of driving force (F)–stroke (H) curves in different deformation modes were discussed in detail. Effects of tube dimensions and semi-angle of the die on steady-state force and energy absorption efficiency are also presented.

In this paper, the aluminum tubes of 100mm length as base length is chosen for experiment. The thickness for all the tubes is 2mm. Different fixtures were made to execute the different large deformations phenomenon on the tube. The affected length (L) is measured for each tube undergoing large deformations. The deformations of different phenomenon are plotted in terms of force displacement graphs experimentally and numerically. The energy absorption per unit mass is extracted from these graphs and compared. The deformations phenomenon could be decided based on this experiment for better energy absorption.

2. Experiments

2.1 Experimental setup

The experimental setup for this study has three main components i.e. system to apply compression force to the model through fixture, model and fixtures. The Instron system having maximum capacity up to 4 ton was used for applying force and recording F-H graphs. In the system, the load cell is kept below the top stud. Top stud is fixed in place. The bottom ram of system moves up and down with maximum ram stroke up to +/- 125 mm. The system is hydraulically operated and can operate at quasi static and at transient load conditions. During the experiment, the ram on which bottom fixture is kept, was moved up, in speed of 10mm/min to ensure the quasi static condition. The alignment of test tube and its fixture is assured with machine axis. The test setup is shown in Figure 1. Aluminum tubes of 25.5 mm outer diameter (Do) and thicknesses (T) of 2mm were machined from commercially available tubes in the length of 100mm and 50mm. Samples are shown in Figure 2.

![Test setup](image)

**Figure 1:** Test setup
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Figure 2: Test samples

Variations in length were kept to study its effect on few deformation phenomenons. The fixture has top and bottom parts. Top fixture is attached to load cell stud of Instron system. It can be flat plate, simple pushing rod for inversion or notched vertical plate etc. This fixture is stationary and butt against the model and restraint test sample for upward movement. Similarly the bottom fixture could be flat plate, conical entry fixture, Conical tip expansion fixture, angles and geometrical shaped fixture for curl in, various curvature curl out and tear fixture etc as per the deformation phenomenon. These fixtures are fixed to moving ram of the system, through which upward force is applied. These fixtures are made of steel material and can be treated as rigid. To reduce the friction between tubes and fixture, say for tube expansion, contraction and curl in, and curl out experiments etc, Kluber Isoflex NBU15 grease was used. The testing was done to maximum displacement to get the large deformation phenomenon fully developed.

2.1 Material properties

The tubes were made by machining in workshop, by commercially available aluminum tubes. The tensile testing was done on test pieces, prepared from the tubes, to the specifications of ASTM. From the test, the yield strength obtained was 157.92MPa, while tensile strength was 182MPa at 7% elongation. The fixture were made of steel, having 0.2% proof stress of 800 MPa, and an elastic modulus, E, of 210 GPa, which is much greater than that of the tubes. Hence the fixture can be regarded as rigid.

3. Experimental results

The experimental photographs are shown in Figure 3. In these Figures the left to right columns illustrates the phenomenon, fixture, samples during and after the loadings. It is emphasized here that the experiments were conducted keeping in mind that it should fulfill to generate the deformation phenomenon first, continue the phenomenon by increasing the stroke till any other phenomenon like buckling, tearing etc is not observed. Stop the stroke once the other phenomenon is observed other than the intended one. Hence we suppose that

1. Large deformation phenomenon is generated fully in experiments
2. The specific energy is calculated with experimental data, for the distance of the tube undergone the phenomenon.

The large deformation graph can be divided broadly into three stages as illustrated below.
1. Initiation stage- This is the stage where deformation process starts. In this stage the stiffness of tube play important role. The applied force has to overcome this stiffness to march further. This stage can be smooth or perturbed in nature. Except contraction and expansion, other phenomenon has smooth starts.

2. Transition stage- This is the stage where the nature of contact between fixture and tube may change or tube specific deformation characteristics starts like tearing, buckling etc.

3. Stabilization- In this stage the process is fully stabilized. Graph nature is also smooth. The experimental observations are discussed as follows.

Refer Figure 3 for experimental photographs and Figure 4 for typical F-H graphs for large deformations phenomenon, subsequently discussed. The photographs and graphs are covered under “a” to “r” sub category.

3.1 Bending
The bending takes place with increasing load constantly till it buckle at load application point. After that the load decreases constantly. The top and bottom fixture were of 5mm width. The support length to sample was kept 100mm. The bend zone is formed by compression of top notched fixture, followed by bending. The zone is widened to 38mm at the middle and bending effected length in both the side is 25mm approximately. Also scoring marks of 7mm length in each side were noticed on tube at support location. It means, tube had slide freely by 14mm while bending process.

Refer Figure 4a for typical F-H graph of this phenomenon.

3.2 Contraction

In the process of contraction, tube reaches to the end of conical entry (10 degree) portion of fixture, after which transition takes place to the straight portion (dia~22mm). The contact state changes in this transition. Once tube crosses this stage, tube is stabilized in deformation phenomenon. Perturbation is noticed in initiation stage as marked in Figure 4b. Afterwards also repeated ripples are noticed in data due disturbance into hydraulic system of the instrument.

3.3 Buckling

When tube of 100mm length was compressed between two flat plates, they performed the Euler (global) bending mode to the progressive buckling. The force increased steadily till the bending starts. Afterwards it diminishes fast as collapse mechanics is set as shown in Figure 4c. The buckling usually started at 1/3 location from the top.

3.4 Crushing

The smaller tube of length 50mm when pressed between two platens, it starts folding from top and bottom and ultimately making folds at 90 degree towards inside. The respective F-H graph is shown in Figure 4d, wherein after 1st peak, few smaller peaks can be noted which are generated while making folds.

3.5 Expansion

The expansion is done with the solid fixture having 10 degree conical angle at the tip, with straight cylindrical portion (dia~24 mm). The expansion is started with initial perturbation as marked in respective F-H graph in Figure 4e, until it does not cross the junction of conical and straight portion of the fixture.

3.6 Flattening

Flattening experiment is done on tube in single (Figure 4f), tube inside tube (Figure 4g) and tubes kept in parallel (Figure 4h). The deformation graph rises initially to overcome the circumferential bending strength of tube and with further displacement, it starts yielding from two sides and as well from top and bottom, shaping into Figure ∞. Once the top and bottom portion start touching each other, forces rises. If a tube is kept inside the tube, the F-H graph has step at the point where outer tube touches the inner tube and the bending strength of inner tube is also start count for resistance. Refer Figure 4g wherein step is encircled. It is also observed that the force required in parallel tubes arrangement is double of single tube as shown in Figure 4h, and hence result of one tube can be linearly extrapolated for more
numbers of tubes.

3.7 Curl inside (Geometry)

The geometrical fixture is shown in Figure 3 i, which is made with the groove with central guide to facilitate curling inside. Groove internal diameter is kept 26.5 mm, so that the tube of 25.5 mm outer diameter could glide inside the groove. In this process the force rises constantly with steep angle to overcome tube circumferential bending strength, initially. Further displacement lead to an incubation stage where tube adjust itself to glide into outer curvature of the fixture geometry. Further force causes it to glide towards inside and adopt the inner curvature which causes rise in the force again as shown in F-H graph in Figure 4 i. This phenomenon offers a good energy absorption in the process.

3.8 Curl inside (Angle)

This is another means to curl in the tubes. Refer Figure 3 j for angled fixture whose angle at the centre is maintained to 127 degree. The central depth is kept 12mm. It offers initially high force as shown in Figure 4 j. This force is greater for short tube as compare to long tube. Force then drop once circumferential bending strength is overcome and again increases as material from upper portion are forced towards tip and folds are made subsequently. This also offers a great energy absorption capability.

3.9 Inversion

To prepare the tube for this experiment, tips were folded progressively at one end by hand beating. A solid rod plunger with screw end arrangement was used with top & bottom washer, to push the tube inside as shown in Figure 3 k. The phenomenon could be initiated and stabilized by pushing tube inside by 10mm. After 10mm stroke, tearing in the tube was noticed. The F-H graph is shown in Figure 4 k for this phenomenon.

3.10 Curl out

This deformation takes place in smoother way as tube glides through small radius curvature (6mm radius) of the fixture shown in Figure 3 l. The force steadily rises as shown in its graph in Figure 4 l, for flaring followed by fold inside.

3.11 Tearing

Tearing is a case of curl out which takes place in larger radius curvature (radius 10mm). Due to this large radius, the tearing takes place. Once tearing start, the graph falls rapidly as shown in Figure 4 m.

3.12 Indenting

Indenting is another phenomenon for energy absorption. Experiments were carried out on single shorter (Figure 4 n) and longer tube (Figure 4 o) as well longer tubes kept in parallel (Figure 4 p). Bulge out is noticed for indent on single side of longer tube as compared to shorter tube as shown in Figure 4 o. This is because the adjacent support is obtained by indented portion of longer tube while it is not in the case of shorter tube. The effort in loner tube kept in parallel is double of single tube (Figure 4 p), hence here too linear interpolation can be done for increased numbers of tubes. The experiment for both side indents was carried
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for shorter and longer tubes. The overall effort was more for longer tube, as shown in Figure 4 r as compared to shorter tube (Figure 4 q)

Figure 4: Force “F” (Y axis in kN) – Stroke “H” (X axis in mm) graphs of large deformations

3.13 Finite Element simulation

Finite element simulation was used to simulate the experimental process. The Altair product HyperMesh was used for FE model building. Aluminum models were presented with shell elements at mid plane surface as shown in Figure 5. Top and bottom fixtures were modeled
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with rigid material property. The LsDyna was used as solver. It offers wide variety of material modeling and provides lot of contact algorithm. The materials *MAT_RIGID (Mat-20) was used for fixtures and *MAT_PIECEWISE_LINEAR_PLASTICITY (Mat-24) was used for tube samples. The *CONTACT_SURFACE_TO_SURFACE was used to define contacts between disjoint parts. Also self contact of model was defined through single surface contact. Coulomb friction was used to define the coefficient of friction between interfaces. The post processing was done with LS-PREPOST.

4. Discussion

4.1 Experiment repeatability

Many samples of similar physical dimensions were tested and F-H graph extracted for different large deformations phenomenon. The repetitions of experiments were ensured by superimposing this experimental result as shown in Figure 6, for bending as an example. Good agreement between samples were obtained for the different large deformation phenomenon, which shows that the experiment do not have any variation on any parameters.

4.2 Energy graph comparison

The energy absorption in different stages of deformations was compared for experimental and numerical simulation. Results matched well, for example, indent in single side as shown in Figure 7. This shows that the numerical simulations taking material properties from the test, its geometrical representations and boundary conditions are perfectly all right.

4.3 Specific energy capacity (ω) of different deformation phenomenon

The samples specifications and their specific energy (energy/wt) are enlisted in Table I, for different large deformations. A bar chart has been drawn and shown in Figure 8 for specific energy content in vertical axis and deformation phenomenon in horizontal axis. It is observed that variation in energy is less, for a particular deformation phenomenon from sample to sample.

Figure 5: FE models before (left) and after deformation (right)
From the bar chart, it is evident that the curl in through geometrical fixtures and angled fixture absorb the maximum energy as compared to others. This is then followed by inversion, curl out, tear, crush, contraction and expansion. The least energy absorption phenomenon is both side indenting.

4.4 Flattening and bending offered almost same amount of energy absorptions, but these are the phenomenon with less energy absorbers.

4.5 The specific energy may vary by varying the parameters of fixtures and tubes. For example the interference value in tube contraction and expansion phenomenon, curvatures in curl out, curl in and tearing phenomenon. Researcher had been doing these kinds of parametric studies. Here the optimum value fixtures taken and generated the large deformations for comparison on phenomenon.
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4.6 In practicality the flattening, bending is easiest to achieve and curl in is the most difficult process to perform. In the curl in process, the tube mostly locally buckles at upper and lower fixture end. If the energy to be absorbed more in initial condition with smaller stroke then curl in kind of phenomenon could be used.

Table 1: Samples and their specific energy capacity for different large deformation phenomenon

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<tr>
<th>Phenomenon</th>
<th>Sample</th>
<th>OD (mm)</th>
<th>Thickness ’T’ (mm)</th>
<th>Affected Length(mm)</th>
<th>Effective w(kg)</th>
<th>Energy(kJ)</th>
<th>Specific Energy/(kJ/kg)</th>
<th>Ref(Fig3) &amp; (D) category</th>
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Figure 8: Specific energy of samples (S1, 2, 3 etc) for large deformations phenomenon

4.7 Curl in (angle), crushing and buckling phenomenon shows steep initial graph with higher force value, as compared to others, as shown in Figure 9. Hence this phenomenon
can be used, wherever a large amount of force to be absorbed initially.

4.8 Contraction and expansion had much initial perturbation in F-H graph as shown in Figure 4 b and Figure 4 e. This is due to changed in contact condition and fixture profile changed in both the phenomenon.

4.9 If energy has to be absorbed in steps with time interval, in an increased fashion, then the flattening to the tube inside the tubes can be the option as shown in Figure 3 g and Figure 4 g. Multiple tubes can be used as per the desired steps, intervals and for the amount of energy to be absorbed.

4.10 If energy to be absorbed in multiple amounts, energy absorbing objects (tubes) can be kept in parallel. For example, as shown in Figure 3h and Figure 4 h. The amounts of energy absorbed by two long parallel tubes for single side indent is double that of single tube.

4.11 Axial crushing has 8 to 10 times more energy absorption then flattening.

4.12 Indenting in single side get support at bottom and that is why it absorbs more energy as compared to both side indenting. The longer tube has more material support from adjacent of indent and hence it absorbs more energy than shorter tube initially. Hence it has bulge out F-H graph as shown in Figure 4 o.

4.13 In indenting process, once the shorter tube start yielding, it doesn’t have material adjacent to indent to get support and hence its slope declines after some time. The shorter tube ends become oval in shape.

4.14 For longer duration energy absorption with longer stroke could be achieved by expansion, contraction, and curl out and also with tearing

5. Conclusion
The large deformations on aluminum tubes of similar physical properties were studied. The experimental and numerical approach was adopted for the study. The different state of deformations and its F-H graphs were presented and compared. The large deformation energy absorption, deformation behavior’s studies were done. The best energy absorber phenomenon and their practicality were also discussed. It was found that curl in phenomenon have maximum energy absorption while both side indent has the least.

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