External inversion of aluminium tubes under static and dynamic compression

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KEYWORDS

Inversion,
Quasi-static,
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LS-Dyna,
Impact,
Compression.

ABSTRACT

Inversion of metal tubes has been acquired for many years to act as affect energy absorbers. Metal tubes turned inside-out or outside-in and tears via pressing them axially onto machine die. Experiments to find out about the exterior inversion ability of aluminium round tubes beneath quasi-static and dynamic axial conditions had been conducted. Also, FEM evaluation has been achieved and the equal is compared with experimental results.

1. Introduction

Thin-walled aluminium tubes are widely used as energy-absorbing materials for absorbing kinetic energy during collisions. They absorb energy by undergoing large plastic deformation or crack propagation. Aluminium tubes as dynamic energy absorbers are well received [1]. This paper is focused on the energy absorption capabilities of circular aluminium tubes through external inversion.

Impact energy absorbers (IEAs) come in the form of metallic circular tubes. This is due to their simplicity, along with the easy availability of a wide range of geometrical and material combinations. Besides, they can adopt various modes of deformation, depending on their geometry and loading conditions, therefore providing many different combinations of operating loads and strokes. Numerous analyses and experiments have been done in the past attempting to predict and quantify the capabilities of circular tubes as IEAs.

Crashworthiness is the ability of a structure to protect its occupants or objects during an impact. This is commonly tested when investigating the safety of protective structures, aircraft, and vehicles. Depending on the nature of the impact and the vehicle or structural components involved, different criteria are used to determine the crashworthiness of the structure strain rate is the rate of change in strain (deformation) of a material with respect to time. The effects of impact loads result in higher strain rates on the material. Collisions between objects giving rise to suddenly acting loads are common in everyday life. Collisions are either accidental or intentional whether they are desirable or not such impacts and collisions can and will result in loss of limb, life, and property as well as undesirable short and long-term effects. It is possible to try and reduce the possibility of unwanted collisions but impossible to prevent them. Therefore one of the means of reducing damage to or loss of life or property during collision is to include impact energy absorbers in the system.

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2. Materials and Methods

2.1 Die

The die was formed by turning mild steel (EN8) rod of diameter 105mm in a lathe machine. A die of a radius of approximately 4mm was obtained from the following calculation.

$$\text{Die radius (R)} = \frac{\sqrt{tr_o}}{2}$$

r_o = 25.3 mm; t = 1.6 mm

Therefore, $R_d = \frac{\sqrt{25.3*1.6}}{2}$ = 3.45mm

Hoop stress is given by $= \frac{\text{change in diameter}}{\text{original diameter}}$

Table 1
Material properties of specimen.

Material	Property	Value
Aluminium 6063 (as received)	Density	2.7 g/cc
	Modulus of Elasticity	69.5 GPa
	Yield strength	200 MPa
	Vickers Hardness Number	59.6
Aluminium 6063 (half Hardened)	Density	2.7 g/cc
	Modulus of Elasticity	69.5 GPa
	Yield strength	176.58 MPa
	Vickers Hardness Number	54

Final radius (R_d + hoop stress) = 3.18+0.167 = 3.34mm

Hence, approximately the radius of die 4mm was selected,

Vickers hardness test was conducted on the machined die to evaluate the hardness of the material which was found to be 229 VHN. Figure 1 gives the details of die geometry.

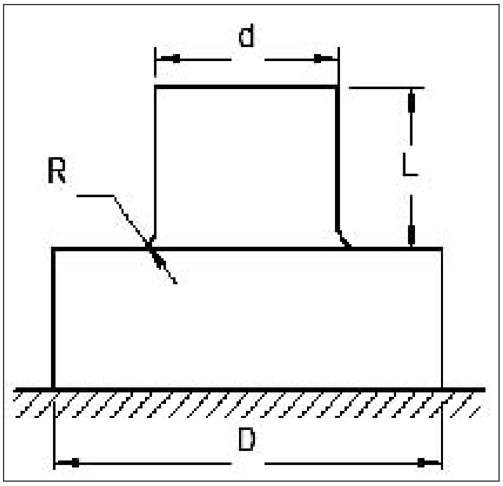

Fig. 1. Die geometry.

2.2 Specimen

Specimens of circular aluminium tubes were cut to a length of 140mm from the stock as received from the market. The ends of the tube were finished to close flat surfaces by turning the tubes in the lathe machine and the ends were finally grounded. The tubes received had a higher hardness value (59.6 VHN). Hence, the tubes were subjected to half hardening process by heating them to 230ºC, soaking for the same temperature for half an hour, and furnace cooling the specimens. By half hardening process, obtained a hardness of 51-54 VHN. Table 1 gives the material properties of the specimen.

3. Experiments

3.1 Ring compression test

For Finite element analysis, a measure of flow stress is required. Large strains leading to considerable strain-hardening during inversion and the use of the conventional yield model, i.e., offset stress at 0.2% strain is not justifiable in a rigid perfectly plastic material model. Many previous investigators used ultimate yield stress which is the other extreme [2]. It has been found that the flow stress derived from Vicker's hardness test (a third of the hardness number is the flow stress in kgf/mm^2 at 7% strain), a good measure for use of the above analysis.

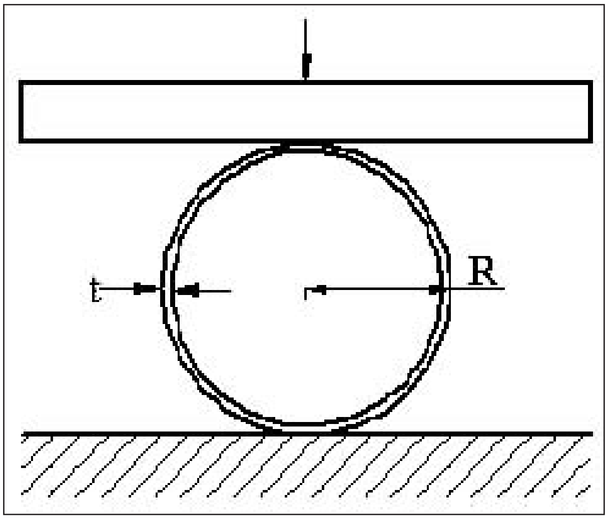

Fig. 2. schematic of ring compression.

Another way to obtain a weighted value flow stress is from a tube compression test in which an identical tube is compressed between flat plates Figure 2. This produces a load-compression curve typically as shown in Figure 3. The collapse load, P_c obtained at the intersection of the forward and backward extensions of elastic and plastic parts of the curve provides yield stress as [8]

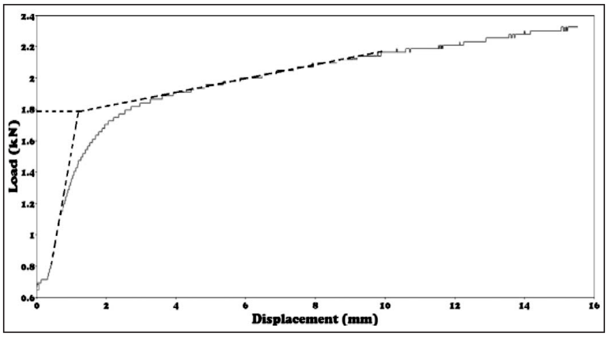

Fig. 3. Load – displacement curve under ring compression.

$$\sigma o = \frac{Pc * \mathrm{Ro}}{t^2 * l}$$

The yield stress of tube for a collapse load of 1.78 kN is 176 MPa.

3.2 Quasi-Static inversion

The quasi-static compression tests were performed on the Electronic Universal Testing Machine model UTES-40. The machine consists of two parallel rigid steel plates. The upper crosshead is fixed, while a computer-controlled hydraulic device controls the movement of the lower crosshead, with a manual override. The required experimental parameters such as the crosshead speed, maximum load or displacement, and data sampling rate are fed into the computer before the start of each test. All experimental data acquired are stored in the computer, allowing for easy future access.

Uni-directional, quasi-static compression tests were carried out on metal tubes using an electronic universal testing machine of 400 kN capacity (UTES-40) at a impression rate of 3 mm per minute. Figure 4 shows the schematic representation of the test set-up. All the specimens were axially compressed. It consists of a die with a radius ‘R’ resting on a rigid bottom beam and shows a tube which has been introduced on to a die shank. The middle cross head pressed the tube on to the die at a constant compression rate in the quasi-static test and inverted tubes were shown in Figure 5.

3.3 Deformation of tube

A typical load-displacement curve of aluminium tubes is shown in Figure 6 [4]. It is observed that the load rises steeply until a maximum is reached. During this initial steep rise in load, the

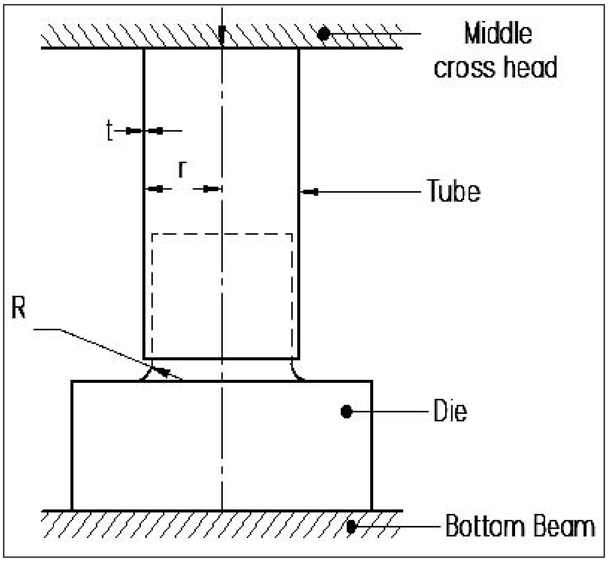

Fig. 4. Quasi-static test setup.

Fig. 5. Inverted tube.

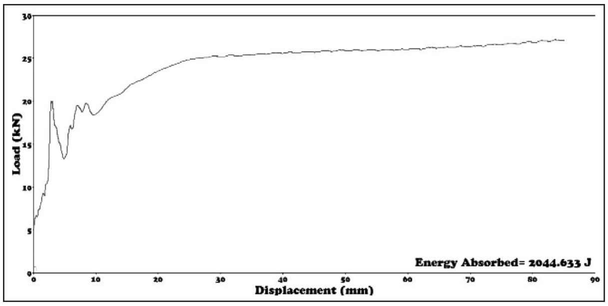

Fig. 6. load-displacement curve for quasi static test.

Table 2
Results of quasi-static compression.

Specimen No.	VHN	Mass (g)	EA (J)	SEA (kJ/kg)
1	52.9	94.9	2044.63	21.54
2	52.38	95.2	2048.97	21.52
3	52.38	95.4	2314.22	24.26
4	52.38	95.5	2347.10	24.58
5	52.38	95.3	2221.69	23.31
Average			**2195.32**	**23.04**

Table 3
Results of dynamic inversion.

Speci-men No.	(VHN)	Drop Height (m)	Inverted Mass (g)	EA (J)	SEA (kJ/kg)
1	51.9	1.5	35.62	666.51	18.71
2	52.2	2	43.46	861.23	19.81
3	52.4	2.5	56.04	1125.99	20.09
4	52.2	2.75	53.31	1210.72	22.71
5	52.6	3	56.84	1322.44	23.26
6	52.4	3.25	66.39	1432.62	21.57

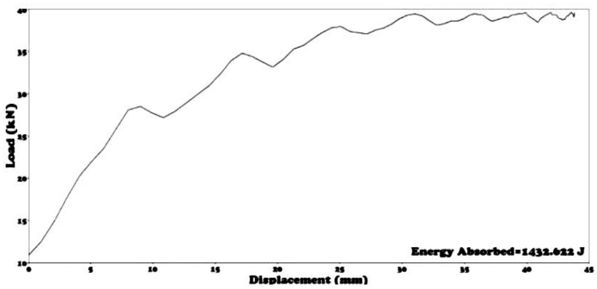

Fig. 7. Load-displacement curve of dynamic inversion of height 3.25m.

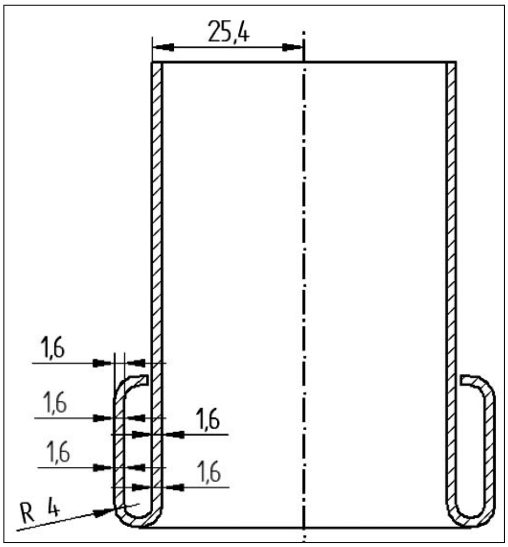

Fig. 8. Sectional view of inverted.

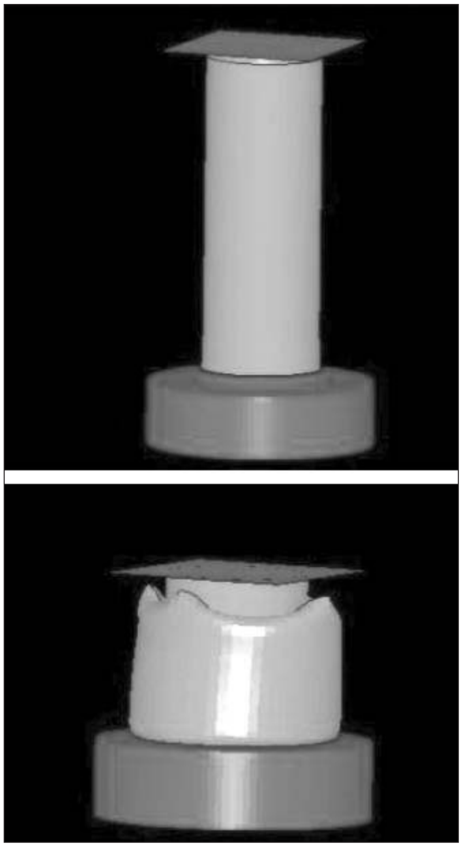

Fig. 9. FEA simulation.

end of the tube appears to be developing into a funnel shape. When the radius is fully formed on the tube, the load again rises as the tube is pushed around the die. A second peak is then reached and from this point, the radius end of the tube begins to turn outward. A shallow trough in the Load-displacement curve is noted as the tube tip completes a movement of 180^o around the die radius and the load rises steadily to the maximum steady-state load when the tube tip has completed a total angular displacement of 270^o[5].

3.4 Dynamic Inversion

The half-hardened Aluminium tubes were externally inverted dynamically under a drop hammer, indigenously design and developed at Vemana Institute of Technology. The dynamic test was conducted for different velocities of the drop mass.

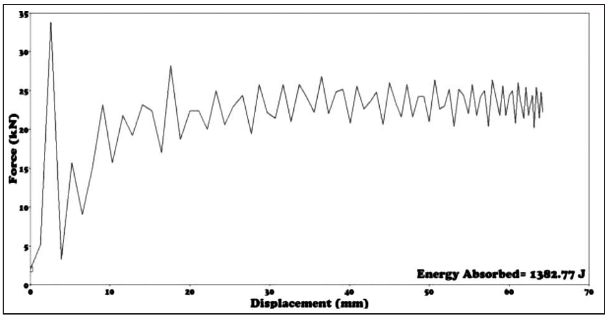

Fig. 10. Comparison of quasi-static, dynamic and FEA results.

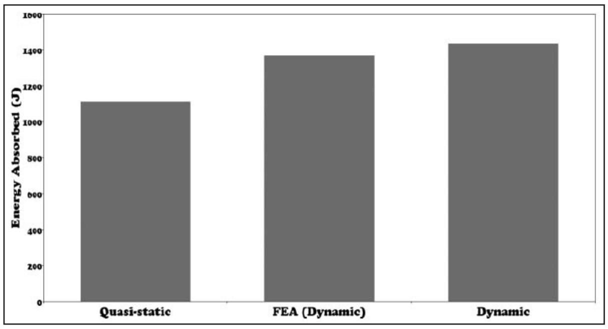

Fig. 11. Comparison chart.

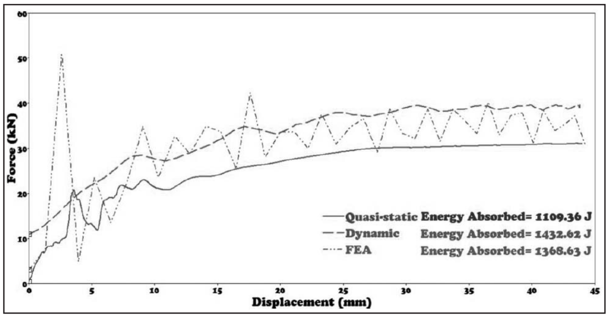

Fig. 12. Comparison of results of quasi-static, FEA and dynamic compressions.

The drop mass was comprising a mass of 45kgs and the maximum mass that can be held by drop hammer was 120kgs. In each case the drop mass was lifted to the required height and allowed to impinge on the free end of the tube, thereby pushing it over the die. The velocity of the drop mass can be varied by varying the height of the drop mass. Load-displacement curve of aluminium tubes is shown in Figure 7. The inverted tube sectional view is shown in Figure 8 (all dimensions are in mm). The data of voltage versus time plot was obtained from Digital Signal Oscilloscope (DSO) for further process of the data.

3.5 Finite element analysis

The model is discretized using a 4- 4-noded shell element in Hypermesh [7]. The inversion mode of deformation was analyzed using LS-Dyna. The material code employed for the tube is MAT24 (Elasto-Plastic material). Figure 9 shows the simulation under dynamic loading conditions. Figure 10 shows the load-displacement curve obtained in finite element analysis [7].

The energy absorbed by dynamic compression is more when compared to quasi-static compression [6]. The experimental results and finite element analysis shows consistency in energy absorption. Figure 11 and Figure 12 shows the comparison between static, dynamic and finite element analysis.

4. Conclusions

Invert tube experiments are interesting to observe and have good educational value. A series of quasi-static and dynamic axial compression tests were carried out on a set of thin-walled aluminium tubes designed to collapse into the invert mode. In the quasi-static test, the tubes are axially compressed at a compression rate of 3 mm/min on a universal testing machine (UTES-40). The dynamic test is conducted in drop weight apparatus for different heights and the tubes are axially compressed. The energy absorbed is found to be more in the dynamic test when compared to the quasi-static test [10].

The computed results of dynamic testing are further compared with finite element analysis to validate the computational model. The experimental results are in good agreement with the Finite Element Analysis.

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