ISSN (Print) : 0974-6846
Indian Journal of Science and Technology, *Vol 9(33), DOI: 10.17485/ijst/2016/v9i33/101344, September 2016* ISSN (Online) : 0974-5645

Quasi Static Axial Crushing of Foam Filled Thin Walled Circular Tubes

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Abstract

Objective: Thin walled circular tubes are used in many practical situations to absorb impact energy, the axial impact of these thin-walled tubes absorb deformation energy at nearly constant load resulting in high energy absorption. This paper investigates the dynamic progressive buckling response of empty and foam filled tubes under quasi static loading conditions and validation of results using non linear finite element code LS-DYNA. **Method/Analysis:** In the experimental study, aluminium 6063-T5 thin walled circular tubes are integrated with low density polyurethane foam and quasi static loading is conducted on both empty and foam filled tubes to determine the buckling response and deformation shape under impact. The load-displacement graph obtained is used to determine the energy absorbed by the thin walled structure. The numerical analysis of a similar loading condition is simulated using LS-DYNA and a systematic comparison between the finite element model and experimental deformed shapes, load-displacement, number of folds, energy absorption is done. **Findings:** The integration of low density foam in empty aluminium tube increased the energy absorption by 1.4% with an additional stability in the deformation and satisfactory agreements were achieved between the finite element model and experimental deformed shapes, load-displacement, number of folds, energy absorption with an error less than 15%. **Applications/Improvements:** One potential application of polyurethane foams is that it can be used as reinforcement in energy absorbing structures, hence an understanding of the response of the system in different loading condition is necessary to improve the crashworthiness. The experimental results are correlated to FEM to reduce the time spend on experimental testing.

Keywords: Dynamic Progressive Buckling, Energy Absorption, Foam Filled Tubes, Finite Element Method, LS-DYNA

1. Introduction

Thin-walled tubes have been widely used in the energy absorbing structures of cars, trains and ships to improve its structural crashworthiness. These columnar structures crush with almost constant load when subjected to compressive loads, resulting in relatively high energy absorption efficiency.

There has been considerable interest in the recent years to improve the specific energy absorption of these structures by the introduction of a filler material. In[1] pointed out that filling the columnar structure with foam like material increases the crushing load higher than the sum of the crushing loads of tube (alone) and foam (alone) due to the interaction effect between them. In[2] studied the effect of filling thin walled columns with aluminium foam and it was noted that the interaction at the foam wall interface decreases the folding length, and therefore increases the crushing force and the number of lobes. Early research using polyurethane as a filler material showed that there is significant increase in the energy absorption and force during crushing. In[3] investigated the crushing behaviour of polyurethane foam-filled thin-walled metal tubes, at quasi-static and dynamic conditions and it was concluded that tube wall interacts with the foam filler deformation resulting in tendency for axis symmetric mode of deformation. In[4] conducted a study which pointed out that high density foam were weight effective as a structural

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reinforcement, but not as an energy absorber, medium density foam improved the energy absorption, however, weight effectively changing the metal thickness or the section size is a better alternative. Low density foam proved to be weight ineffective as an energy absorber in typical automotive structures. In[5] studied the experimental and numerical crushing response on polystyrene foam filled thin walled tubes and found satisfactory agreements between the experimental and numerical models. In[6] presented a procedure to run quasi static axial crushing using explicit dynamics. In[7] studied the bonding of the foam to the thin walls of the tube and concluded that the bonding increased the specific energy absorption of the tube. In[8] investigated the effect of low density polyurethane foams as filler in the axial crushing of sheet metal tubes and concluded that foam filling stabilizes the deformation of thin-walled tubes.

In this study the effect of foam filling on thin walled circular Al-tubes under quasi static loading condition is studied[9]. The axial impact of circular tubes with low velocities (up to tens of metres per second for metal tubes) is taken as quasi-static, and the influence of inertia forces is, ignored. This is a reasonable simplification when the striking mass is much larger than the mass of a tube. Low density rigid polyurethane is used as foam filler in the Al-tubes. Rigid polyurethane is generally used in automobile crash absorbing structures and in insulations.

2. Materials and Properties

2.1 Tube-Material

The extruded, thin walled, round aluminium tube of alloy 6063-T5 has a outer diameter of 38.2 mm with a thickness of 1.6 mm. They are tensile tested according to ASTM B-557, the properties of the alloy is given as follows. The stress strain curve obtained from the tensile test is given in Figure 1.

- Density - 2700 Kg/m^3
- Young's Modulus - 68 GPa
- Poisson's Ratio - 0.33
- 0.2% Proof Stress - 144.48 MPa
- Ultimate Stress - 171.4MPa

2.2 Filler-Foam Material

The rigid polyurethane foam of density 40 kg/m^3 used in this study is a mixture of two chemical substances; i.e.,

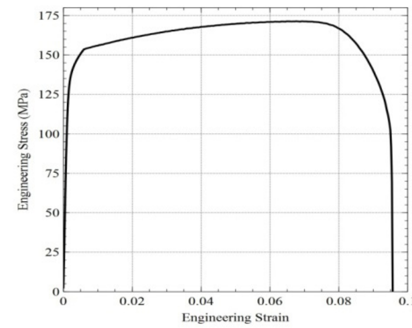

Figure 1. Tensile stress strain curve of Al tube material.

Polyol and Isocyanate. They were mixed in a ratio of 1:1 in liquid form and stirred to produce Polyurethane foam. A cubic sample of size 50x50x50 mm^3 is cut out to perform uniaxial compression testing on the foam according to ASTM D1621 standard, the stress strain curve is shown in the Figure 2. These curves show typical elastomeric foam compression behaviour, composing of three distinct deformation regions: Elastic, plateau and densification. The properties of the Polyurethane foam is summarized as follows.

- Density - 40 kg/m^3
- $E_{elastic}$ - 10.282 MPa

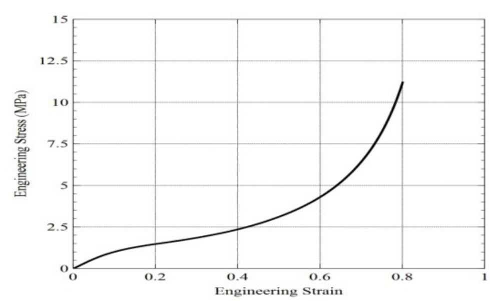

Figure 2. Uniaxial compression stress strain curves for polyurethane foam.

3. Experimental Testing

The produced Polyurethane foam is allowed to expand in the Al tube so that the foam gets bonded to the walls of the Al tube. The foam filled and empty aluminium tubes are then cut to a length of 150 mm to maintain a L/D ratio of 4. Quasi static compression tests were conducted on a fully computer controlled Schmadsu universal testing machine. The compression tests on empty and foam filled Al tubes of length 150 mm was performed at 3.06 mmsec^{-1}

corresponding to a deformation rate of 0.02^{-1} sec Figure 3. The load displacement curve for empty and foam filled tube obtained is given in Figure 4.

Figure 3. Quasi static compression test setup, sample held between two flat rigid compression plates.

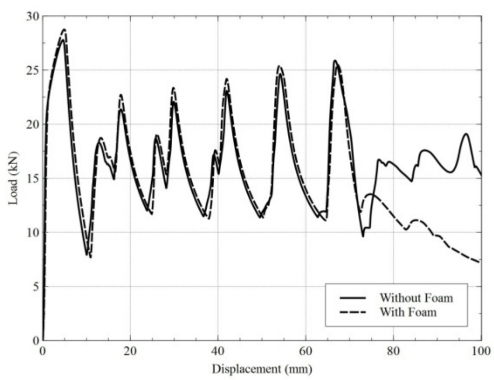

Figure 4. Load displacement curve for empty and foam filled tubes.

The max peak force attained in the empty tube is 27.77 KN and for the foam filled tube a max of 28.75 KN is obtained. Clearly, foam filled tubes absorb 0.98 KN more peak force than the empty tubes. After 75 mm the load taken by the foam filled tube suddenly decreases this is due to the eulerian buckling. The Energy absorbed by the foam filled tube is 1.4% more than the empty tube.

4. Finite Element Modelling

The explicit dynamics non-linear finite element code LS-DYNA is used to numerically simulate the quasi static axial compression. The finite model is created with mesh generator programme HYPERMESH 11.0. The thin wall tube is modelled with Belytschko-Tsay-4-node quadrilateral thin shell element with 3 integration points along the thickness to capture the progressive buckling of the tube and the foam was modelled with 8 node solid elements. The mesh size is kept as 3 mm. The two flat compression plates are represented by constraining all degree of freedom of the nodes which are in contact with the stationary plate and the moving plate is represented by a planar rigid wall to which the velocity is assigned. The movement of the rigid wall was fully determined by the movement of an artificial "node" located at the rigid body centre of gravity.

MAT_24 Mat_Piecewise_Linear_Plasticity is used to capture the plastic deformation of the aluminium tube. The effective plastic strain and the corresponding plastic stress values which are obtained from the true stress vs. true strain of the Al tube is entered into the material card to capture accurate deformation after the yield point.

MAT-57 Mat Low Density_Foam is used to define the polyurethane foam. The density, young's modulus and stress-strain curve obtained in the compression is used to define the material card.

Foams modelled with brick elements may undergo extremely large deformation under the loading condition which may lead to negative volume errors. A contact card *CONTACT_INTERIOR was assigned to prevent negative volume error in foams. To prevent the penetration between the walls of the tube during compression a self contact card * CONTACT_AUTOMATIC_SINGLE_SURFACE is assigned to the components.

Since explicit dynamic solvers are stable only when the time steps is sufficiently small, running a quasi static analysis which is relatively slow with large number of time steps would take large durations of computational time. A procedure to run quasi static analysis on explicit dynamic software was given by, scaling down the mass of the material and scaling up the loading rate. Scaling down the mass results in smaller stable time steps and to limit large number of time steps the loading rate is accelerated. Two type of tests need to be performed to verify the quasi static process. First, the total kinetic energy has to be very small compared to the total internal energy over the period of the crushing process. Secondly, the crushing force-displacement response must be independent from the applied velocity. Figure 5 shows the internal energy

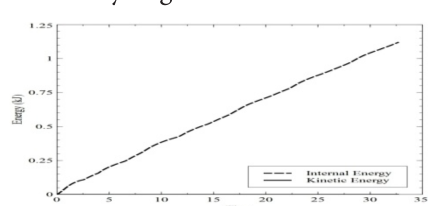

Figure 5. Kinetic energy and Internal energy history plot.

and kinetic energy history plots, it is seen that the kinetic energy is relatively smaller than the internal energy during the entire period of crushing.

5. Results and Discussions

5.1 Empty Aluminium Tube

The load displacement curves for the experimental empty aluminium tube under quasi static compression is compared with the theoretical FEM result as shown in Figure 6 and the values of peak load, average load and the energy absorption is compared with the FEM values as shown in Table 1.

The number of folds produced is 5 in both the experimental and FEA simulation as shown in the deformation history in Figure 7.

Table 1. Comparison of experimental and FEM results for empty Al-tube

Parameter	Experimental	FEM	Error (%)
Peak Load	27.77 kN	28.50 kN	2.6
Average Load	16.31 kN	16.01 kN	1.8
Energy Absorption	1.35 kJ	1.31 kJ	3

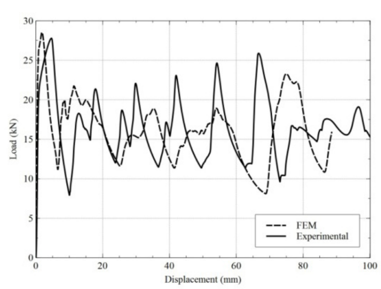

Figure 6. Comparison of experimental and FEM load-displacement for empty Al-tube.

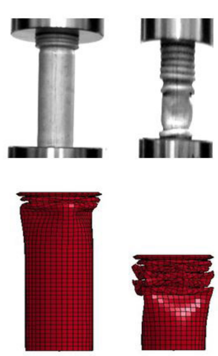

Figure 7. Deformation history of empty Al-tube at 15 % and 100% deformation (Experimental and FEA).

5.2 Foam Filled Aluminium Tubes

The load displacement curves for the experimental foam filled aluminium tube under quasi static compression is compared with the theoretical FEM result and shown in Figure 8 and the values of peak load, average load and the energy absorption is compared with the FEM values as shown in Table 2. It can be seen that there is satisfactory agreement in the peak loads and average loads.

Table 2. Comparison of experimental and FEM results for foam filled Al-tube

Parameter	Experimental	FEM	Error (%)
Peak Load	28.74 kN	30.60 kN	6.4
Average Load	16.33 kN	18.76 kN	14.8
Energy Absorption	1.37 kJ	1.57 kJ	14.5

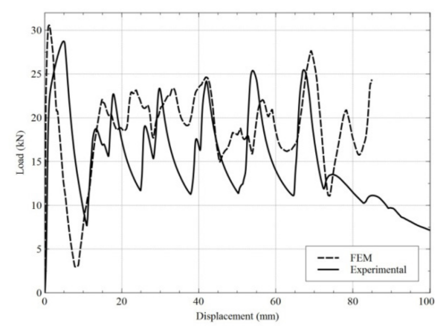

Figure 8. Comparison of experimental and FEM load-displacement for foam filled Al-tube.

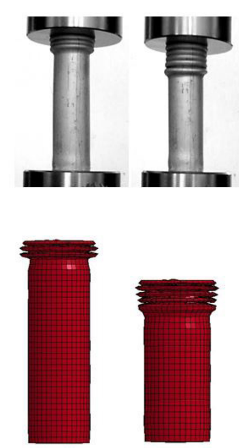

Figure 9. Deformation history of foam filled Al-Tube at 15 % and 100% deformation (Experimental and FEA).

It is also seen that the addition of foam filler stabilizes the deformation and considerably reduces the fold length.

The number of folds produced is 5 in both the experimental and FEA simulation as shown in the deformation history in Figure 9.

6. Conclusion

The quasi-static crushing behavior of polyurethane foam-filled Al tubes was investigated experimentally and numerically. The numerical solutions were carried out using the explicit finite element code LS-DYNA and in general satisfactory agreements were found between the experimental and FEM values in terms of Peak force, Average Force, Energy absorbed, folds formed. Although addition of low density foams does not increase the energy absorption significantly they stabilize the deformation.

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