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Academic Journal UiTM Pulau Pinang

Volume 3 | 2007 | ISSN 1675-7939

ENGINEERING

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ESTEEM ACADEMIC JOURNAL
UNIVERSITI TEKNOLOGI MARA, Pulau Pinang

ESTEEM Academic Journal is jointly published by the Universiti Teknologi MARA, Pulau Pinang and University Publication Centre (UPENA), Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.

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Academic Journal UiTM Pulau Pinang

Volume 3 | 2007 | ISSN 1675-7939

ENGINEERING

SCIENCE TECHNOLOGY

SOCIAL SCIENCES

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Specific Energy Absorption Study on External Inversion of Metal Tubes

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ABSTRACT

A series of aluminum cylindrical shells are tested under axial impact condition for the numerical solutions validation of the experimental in static response. Mean load from numerical simulation as well as experiment are investigated in order to obtain the specific energy absorption. Comparison with previous researcher also made. As far as this paper concern, good agreement is observed through comparison of experimental results and numerical study.

Keywords: *Cylindrical inversion, mean load, specific energy absorption.*

Introduction

Over the years, many experimental and analytical works has been done to gain more understanding of energy absorption mechanism. These studies are important when involving collision, which cause to the damaged structures. Publics become very aware of the safe design of components and systems that can minimize human suffering. It seems that much more can be done to lessen the potential danger of impact accident (Alghamdi, 2001). Therefore, energy absorption devices are used in all vehicles and moving parts such as road vehicles, railway couches, aircraft, ships, lifts and machinery. So, structural crashworthiness studies have been conducted in order to develop and design such dissipating kinetic energy (Daneshi and Hosseinipour, 2003).

Common example of an impact energy absorbing devices that can be found nowadays is side door impact beams. These structural are mounted on the door panels of passenger car to minimize the impact from side collision. Thus, the impact beams need to perform with large static strength as well as energy absorption capability. Conventionally, it were made from high strength alloy steel that undergone heat treatments. Consequently, it will increase the weight of the car and cause to the fuel deficiency and a lot of gas emission (Tae Seong Lim and Dai Gil Lee, 2002). As far as environmental issues are concerned, the aluminium space frame concept has become more and attractive in designing the vehicles. 25% of the weight reduction can be achieved when aluminium is used as structure structures, compared to conventional steel structures (Galib and Limam , 2004). In addition, aluminium also has potential to be recycled which means it can be reused for other applications.

In order to meet the demand of greater weight saving and crashworthiness protection, structures are designed to withstand an axial compression which is at initial stage appear in the form of thin walled curved shells. It is because by using thin walled shell, they could survive axial loading in a membrane manner rather than through bending (Mahdi et al, 2003). An excellent energy absorbing mechanism can be investigated from the axial folding of metal tubes. This concept of mechanism has been utilized in high volume industrial products such as cars whereby the energy during the crash is absorbed in controlled manner (Hanssen et al., 2001).

Experimental Investigation

Aluminum is used as tube material with 3 m in length, 50.88 mm outside diameter and thickness varied from 1.5 to 1.7 mm. In the pre-cutting process, tubes are cut to be 100 mm length by using handsaw. In the actual tube cutting in order to get required dimension, lathe machine is used. The required length for tube inversion is 90 mm.

Afterwards, the tubes undergo stress relief annealing process by using furnace in order to decrease the effect of strain hardening. The tubes are heated until 360°C for 1 hour and then, the tubes are cooled by room temperature for the next 24 hours. Long time is taken for cooling purpose to prevent distortion from happened. Next, tubes are ready to be compressed.

For the die material, mild steel is chosen with 5 mm fillet radius. The mild steel initial length is 1.5 m with diameter of 103 mm. It has undergone two times cutting process. The first process involved horizontal band saw in order to obtain the initial height of die. Meanwhile the second process involved high precision machine that is Computer Numerical Control (CNC) Okuma LB 15 with indexing of accuracy is $\pm 1\mu$ m. The CNC machine has 2 axes, namely x and z axis with spindle angular speed 65 until 3500 rotation per minute (rpm). G-code is used as program to run this CNC machine.

Instron series 3360 Universal Testing Machine is used to compress tubes over die. The die is placed on the bottom platen of the testing machine. The crosshead speed is set to 0.0833 mm/s. Tubes are compressed until 40% to 60% from the original tube length. The applied load versus the crosshead movement is plotted automatically. Beside, the soft copy of data also can be retrieved from the Instron series 3360 Universal Testing Machine.

Numerical Simulation Details

ABAQUS Student Edition 2004 is employed for numerical analysis tool. ABAQUS Student Edition 2004 has ten main modules i.e. Part module, Property module, Assembly module, Step module, Interaction module, Load module, Mesh module, Job module, Visualization module and Sketch module.

Under Part module, tube length is modeled 90 mm with outside diameter 50.88 mm and 1.5 mm thickness. Die is modeled with 5 mm radius fillet. Both tube and die is revolved 90^0 to represent the whole part since tube and die is symmetrical.

In the Property module, the density of tube and die is set to 2705 kg/m^3 and 7850 kg/m^3, respectively. Comparatively, Young modulus for die is higher than tube that is 2e11 Pa for die and 6.9e10 Pa for tube. The Poisson ratio of tube and die is likely the same, tube is 0.3 and die is 0.26. Both tube and die is categorized as shell and homogenous type.

In the Assembly module, only instance menu involved. This menu combined part tube and part die. Since these parts are created according to the same origin, the instance menu is easily used for combination purpose without any translation needed.

Meanwhile in the Step module, time period for simulation is set to 1 second (s). As far as static simulation is concern, mass scaling with factor of 1e6 is set that will result a large time step.

In the Interaction module, the friction coefficient is set to 0.2, which is result a reasonable agreement with experiment. Types of interaction are chosen as general contact (explicit) with contact domain as all with self. This domain is set by default for surface-to-surface contact and self-contact.

Then, in the Load module, die is constrained either displacement or rotation since die need to be rigid. But tube only constrained displacement in x-axis and z-axis. Next, in the field menu, the magnitude of velocity is install in the y-axis, which is –0.0833 mm/s.

In the Mesh module, the global element size for each part is specified i.e. 0.0021 for tube and 0.01 for die. The nodes of tube are 836 nodes and nodes for the die are 158 nodes.

In the Job module, one menu is used i.e. manager menu. In the job menu, under sub-menu of create, the job is named as Project-1, model name: Model-1 and description as Workshop-1. Afterwards, manager menu is used to write the input and followed by submit the data to the processor.

There are three main menus that are used in the Visualization module, namely plot menu, animate menu and tools menu. Plot menu is used to view the tube and die after the processing is done. In the plot menu, there are about seven sub-menus. They are fast representation, undeformed shape, deformed shape, contours, symbols, material orientations and also history output. Meanwhile in the animate menu, which is used for animation purpose, have three sub-menus i.e. scale factor, time history as well as harmonic. The required graph is plotted by using tools menu, whereby sub-menus manager and create is used.

Results and Discussion

Stages of External Tube Inversion

There are five main stages of external tube inversion observed from experiment as well as numerical simulation. These stages are represents the development of tube. Figure 1 and 2 shows modes of deformation obtained from experiment and numerical simulation, respectively. All these deformation are associated with load-displacement curves as shown in Figure 3.

Result from numerical simulation is more appropriate to be discussed along with modes of deformation since only one peak instead of two peaks occurs in experiment approach. Works from Al-Hassani et al (1972) and Reid and Harrigan (1998) had two peaks in their load-

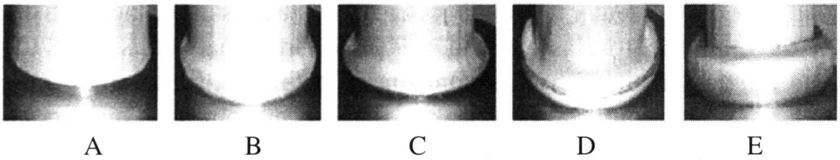

Figure 1: Various Stages of External Tube Inversion under Quasi-static Loading Obtained from Experiment

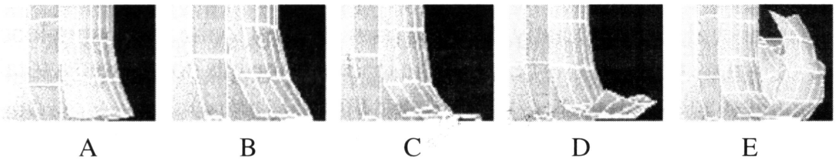

Figure 2: Various Stages of External Tube Inversion under Quasi-static Loading Obtained from Numerical Simulation

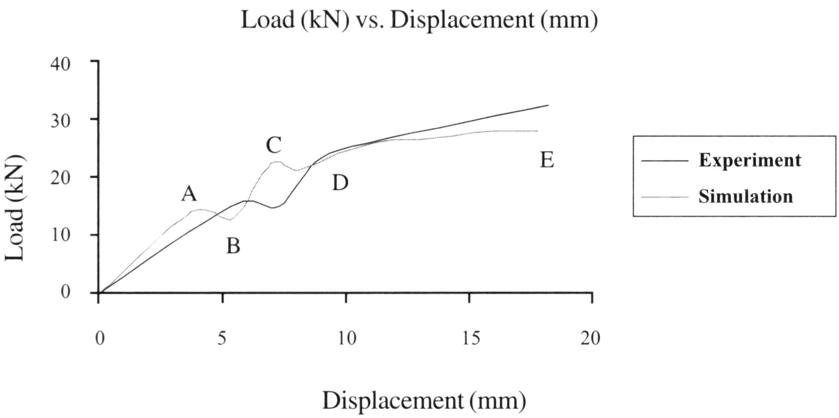

Figure 3: Load-displacement Curves Obtained under Quasi-static Loading from Experiment and Numerical Simulation

displacement curve. The reason why only one peak happens in experiment might be due the sensor in the Instron machine used to compress the tubes does not has good sensitivity in detecting small fall of the load compares with the huge fall of the load as such observed at point B.

Initially, the load rises significantly until first peak is reached at A. Here, the leading tube is in condition just before in contact with die. Al-Hassani et al. (1972) stated that during this initial steep rise in load, the end of the tube appears to be developing into a funnel shape. Then, the load goes down rapidly to point B whereby the tube is in contact with die for the first time. Al-Hassani et al. (1972) reported that at this stage, the load fall accompanied by full conformity to the die. Furthermore, the load rises again until second peak is reached at point C. This second peak is located at higher load compares with first peak. According to Al-Hassani et al. (1972), the load rises again as the tube is pushed around the die and from this point, the leading tube begins to turn inward or to roll up. Next, the load goes down for the second time at point D as the leading tube completes movement of 180° around the die radius (Al-Hassani et al., 1972). Lastly, the load rises steadily to the maximum load as shown by point E. It is because the leading tube has completed a total angular displacement of 270° (Al-Hassani et al., 1972).

By refer to the Figure 3, stage 1 is computes from origin point until point B. Then, stage 2 is in BD region and stage 3 is located in DE region. Reid and Harrigan (1998) classified stage 1 and 2 as unsteady stages. Stage 3 was regarded as steady stage. Different with Reid and Harrigan (1998), Sekhon et al. (2003) divided load-displacement into two phases, namely the unsteady phase and the steady phase. The unsteady or transient phase was regarded as region where the load-displacement curve constantly changes, while during the steady phase, it becomes more or less constant. If interpretation of Sekhon et al. (2003) is taking into account, the unsteady phase is computes from origin point until point D and the steady phase is covering region DE.

Mean Load

Al-Hassani et al. (1972) proposed an equation in order to determine mean load. The equation as follows;

$$P_{mean} = \frac{2\pi R_o t A}{n+1}[B + \frac{2}{\sqrt{3}}\ln(1+\sqrt{\frac{2t}{R_0}})]^{n+1} \qquad (1)$$

By referring to the Table 1, the different of mean load between Al-Hassani et al. (1972) and authors in experiment approach is 8.9%. Then, in comparison between experiment and equation (1) for author works, the mean load difference is smaller i.e. 3.9%. If the same comparison is compute, which is between experiment and equation (1) for Al-Hassani et al. (1972) works, the percentage of difference is 2.3%. Then, the

Table 1: Mean Load from Al-Hassani et al. (1972) And Author Works

Works	Experiment (kN)	Equation (1) (kN)	Simulation (kN)
Al-Hassani et al. (1972)	22.23	21.68	NA
Authors	20.33	19.45	23.04

difference of the mean load between experiment and simulation held by author, the percentage is 11.8%.

Miscow and Al-Qureshi (1997) had conducted external of tube inversion under quasi-static loading for copper tubes and 70:30 brass tubes that were compressed onto 4.76 mm die radius. The approach was experiment and also employed an equation that Miscow and Al-Qureshi (1997) proposed. Table 2 shows the respective results.

When mean load comparison is made between experiment and equation, it is observed that the difference for copper tube is 10.8%. Meanwhile, for the same comparison for 70:30 brass tubes, the difference becomes lower i.e. 3.5%.

Table 2: Mean Load from Miscow and Al-Qureshi (1997) Works

Material	Experiment (kN)	Equation by Miscow and Al-Qureshi (1997)(kN)
Copper tube	40.35	45.23
70:30 Brass tube	53.26	51.37

Sekhon et al. (2003) held quasi-static of external tube inversion for aluminium tubes by employed 5 mm die radius. They were three types of aluminium tubes as tabulated in Table 3. FORGE2 was used as numerical tool.

For specimen INV 381, the difference of the mean load between experiment and simulation is 5.8%. Furthermore, for specimen INV 501, the difference becomes very low i.e. 0.4% but this percentage increase drastically for specimen INV 502 which is 18.0%.

In order to see an overall scenario, Table 4 and Table 5 are created for comparison of the mean load obtained from experiment, the equation (1) and the equation by Miscow and Al-Qureshi (1997) as well as experiment and simulation. From Table 4, the difference of the mean load is range from 2.3% until 10.8%. Meanwhile, for Table 5, the

Table 3: Mean Load from Sekhon et al. (2003) Works

Specimen	Diameter (mm)	Thickness (mm)	Length (mm)	Experiment (kN)	Simulation (kN)
INV 381	37.04	1.12	80	16.57	17.59
INV 501	48.7	1.3	100	24.53	24.42
INV 502	48.92	1.68	100	30.19	36.81

Table 4: Comparison of the Mean Load from Experiment and Equation

Works	Material	Difference (%)
Al-Hassani et al. (1972)	Aluminium	2.3
Miscow and Al-Qureshi	Copper	10.8
(1997)	70:30 Brass	3.5
Authors	Aluminium	3.9

Table 5: Comparison of the Mean Load from Experiment and Simulation

Works	Material	Difference (%)
Sekhon et al. (2003)	Aluminium (INV 381)	5.8
	Aluminium (INV 501)	0.4
	Aluminium (INV 502)	18.0
Authors	Aluminium	11.8

difference is ranging from 0.4% until 18.0%. Both works done by the author is within the range. Thus, an acceptable works has been achieved.

Specific Energy Absorption

Hamada et al. (1999) proposed that specific energy absorption capability, E_s is given by

$$E_S = \frac{P_{mean}}{A\rho} \tag{2}$$

By employed equation (2), specific energy absorption from Al-Hassani et al. (1972), authors-experiment and authors-simulation is 31.394 kJ/kg, 32.433 kJ/kg, and 36.67 kJ/kg, respectively. Figure 4 shows clearly the specific energy absorption for these four cases. It is believed good agreement is observed.

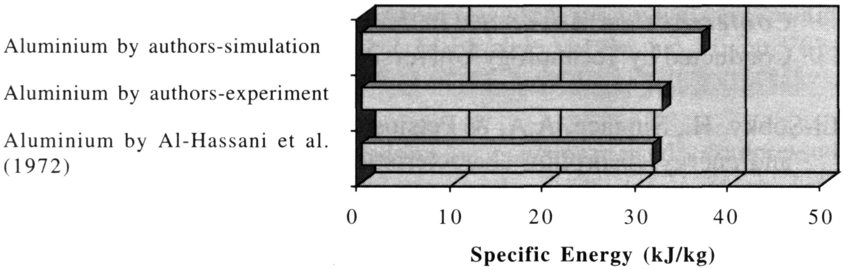

Figure 4: Specific Energy Absorption of Aluminium from Various Works

Concluding Remarks

The inversion of a circular metal tube is an efficient energy absorbing system for a crashworthy system. There are three energy-dissipating mechanisms: tearing, plastic bending and friction. It is has been shown the specific energy absorption of the external inversion of the aluminum metal tubes can also be found by using detailed finite elements model, instead of experiment method only. The results from experiment, numerical simulation as well as from previous researcher shows a good correlation.

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