IMPACT RESPONSE OF CIRCULAR TUBE WITH MULTIPLE SLOT GEOMETRY

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Abstract
Thin-walled tubes are generally used in various engineering application as an impact energy absorber due to their ease of fabrication and installation, high energy absorption capacity and long stroke. However, the main disadvantage of plain tube is the high initial peak force. So, in this project are about to study and understand the initial peak force or circular aluminium tube when experienced compressive quasi-static force. According to the objective in reducing the high initial peak force, the circular tube has been design with slot and it will be compared with plain circular tube. At the first stage, experimental test was conducted using the INSTRON 3362 which used in the compressive quasi-static test. Then in the second stage, finite element analysis was conducted using ABAQUS software, to stimulate and record the initial peak of crushing force of the aluminium. Aluminium has been selected as the material because it offers advantages compared to other material such as relatively low density, high recyclability, and design flexibility and economic in mass production. There are some parameters that have to be considered; which are the size of the tube, velocity of the crushing force and the number of slot.

Keywords: Thin-walled tube, slot geometry, impact response, finite element analysis

1. Introduction
Since decades, thin walled metal tube has been used as an energy absorbing devices in most automotive vehicles including high- volume industrial products. Huge efforts have been done in investigating the crushing behavior of thin walled tube either through analytical, numerical or experimental methods. In addition, the efforts including to understand and to improve the energy absorption characteristic of them under various load conditions such as axial crushing, dynamic bending or oblique impact and etc.

The term of crashworthiness can be defined as the quality of response of a structure when it is involved in or undergoes an impact. During vehicle collision, it will produce abnormality to the operating condition when subjected to force and deformation to that structure. Basically, this collision phenomenon
occurs with stationary phase, or another vehicle which can cause injuries to the occupant if the force applied exceeds the capability absorption energy of the vehicle structure. Therefore the crashworthiness study has been examined extensively, during the crashworthiness analysis test, the ability of the vehicle structure deforms plastically and decelerations of the load were measured. Crashworthiness is expressed in terms of specific energy absorption $E_{\text{SEA}}$ which may change with the material. Specific energy absorption is the ratio of energy absorbed to the unit mass of the material.

Widely used geometries such as square and circular tubes, frustas and polygons subjected to axial and lateral loadings have been extensively studied for the past five decades. The need to further optimise the structures has prompted researchers to experiment with new geometries, configurations and material combinations.

Introducing patterns to the thin-walled tube, the crushing mode can be altered so that better energy absorbing performance may be achieved. Singace and El-Sobky [11] have developed corrugation pattern on the circular tube and studied the effect of this type of pattern on the crushing behavior of circular tubes. Their results showed that more uniform load–displacement curve and lower initial peak were obtained while the total energy absorption was not improved. J. Song et al [6] have come out with origami pattern. Introducing origami patterns to thin-walled tubes offers two advantages. First, the initial peak force can be reduced and may be controlled. Second, such tubes exhibit much less fluctuation in the force during crushing. In the study, they introduced origami pattern that have square, hexagonal and octagonal cross-sections. There are also groove types of pattern as studied by S.J. Hosseinipour and G.H. Daneshi. [12] For this purpose, the grooves are introduced in the tube to force the plastic deformation to occur at predetermined intervals along the tube. The aims are controlling the buckling mode and predicting energy absorption capacity of the tubes. To do so, circumferential grooves are cut alternately inside and outside of the tubes at predetermined intervals. Compared with the others, they used seamless mild steel tubes of commercial quality which have machined to the required size. Annular grooves have cut alternately inside and outside the tubes surfaces with various distances. To achieve symmetry of deformation, the numbers of grooves have chosen to be odd and the first groove was inside the tube wall. In the study by A Eyvazian, they used aluminum corrugated tubes with various corrugation geometries. They found that introducing corrugations improves the controllability of crushing parameters for these tubes. From previous researches, it can be deduced that a particular structural configuration is most efficient in absorbing the impact energy for a specific load, speed and direction. In the real world, it would be more relevant to design a structure that can efficiently absorb the impact energy over a wide range of conditions while at the same time having lower IPF to reduce occupant injury. Current researches explore the use of trigger mechanism incorporated in structures that aims to induce failure in a desired manner and having impact response which are optimized for a wide range of conditions.

The function of an energy absorber is to absorb kinetic energy upon impact and dissipate it in some other form of energy, ideally in an irreversible manner. Non-recoverable (inelastic) energy can exist in various forms such as plastic deformation, viscous energy and friction or fracture energy. Circular or square sectioned tubes are one of the most commonly used structural elements due to their prevalent occurrence and easy manufacturability. Circular tubes for example, can dissipate elastic and inelastic energy through different modes of deformation, resulting in different energy absorption responses. It is important to study their energy absorption characteristics and mean crushing loads so as to determine their applicability to practical energy absorption situations. [14] Anne-Marie Harte, Norman A. Fleck, Michael F. Ashby (2000) stated that practical energy absorbers have a characteristic load-deflection response. An initial (or subsequent) peak value of load $F_{\text{max}}$ exceeds the average value $F_{\text{av}}$, and leads to an increased acceleration and potential damage to the object. The ‘crush force efficiency’ is a useful measure of the uniformity of collapse
load; for the ideal energy absorber \[16\]. The crush force efficiency is closely related to the structural effectiveness introduced by Puglsey (1960),\[15\]

2. Research Methodology

In this study, the circular tube of aluminium alloy (Al-6063) had been selected as the material. The size of the tube was standard size as it received from the industrial supplier. Table 1 lists to mechanical properties of the aluminum alloys as measured by tensile tests. The specimens were not heat-treated after machining.

Table 1: Properties of Aluminium Alloy AA6063-T5

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2700 kg/m³</td>
</tr>
<tr>
<td>Ultimate tensile strength (UTS)</td>
<td>220 MPa</td>
</tr>
<tr>
<td>Yield strength</td>
<td>180 MPa</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>65 GPa</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Plastic strain at UTS</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
</tr>
</tbody>
</table>

2.1 Specimen

All the specimens were cut from a single continuous tube, and machined in both ends precisely. Specimen was cutting into 250mm in length and undergoes turning process to obtain the flatness and slot making process. The shapes and dimensions of the manufactured specimens are shown in Fig. 1. There are 5 different type of specimen which each type prepared with 3 samples. With the same procedures, all type of specimens applied to the experimental process. The detail of the specimen, show in table 2.

Table 2: Type of specimen

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Type of sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Without slot/plain</td>
</tr>
<tr>
<td>2</td>
<td>2 slot in a row</td>
</tr>
<tr>
<td>3</td>
<td>4 slots in 2 rows</td>
</tr>
<tr>
<td>4</td>
<td>6 slots in 3 rows</td>
</tr>
<tr>
<td>5</td>
<td>4 slot in a row</td>
</tr>
</tbody>
</table>

Figure 1: Cross section of the specimen (a) 2 slot in a row (b) 4 slots in 2 rows (c) 6 slots in 3 rows (d) 4 slot in a row.
For the slot, it starts with 10 mm from the upper surface of the tube. So each tube will have 2 slots each which parallel to each other. It goes same for specimen 1, 2 and 3. But for specimen 4, it will have 4 slots at 10 mm from the top surface.

2.2 Testing procedure
The experiment setup is sketched in Fig. 2. Different quasi-static tests were performed on the corrugated tubes in order to study their behavior when subjected to axial crushing. To achieve accuracy, three samples of each specimen were tested. In each case, the load–displacement curve is provided. The specimens underwent quasi-static axial loading. INSTRON 8502 hydraulic machine equipped with 250 kN load cell was used for quasi-static axial compression tests. The machine is calibrated annually. During the compression tests, the specimens were compressed between the parallel steel plates of the test machine without any additional restraints. Load platens were set parallel to each other before testing. The axes of the die, tube and the testing machine were carefully aligned. To establish quasi-static conditions and to ensure that no dynamic effect was present, all the tubes were compressed at a rate of 5 mm/min until limited crush, which implies complete compaction of the tested tube with a sharp increase in the recorded load. The range of crosshead speed other researchers have applied is between 5 and 10 mm/min [19–21]. In this study, 10 mm/min is chosen to make sure that the tests are within the quasi-static range. The loads and displacements were recorded by an automatic built-in data acquisition system.

![Figure 2: The experiment setup](image)

2.3 Finite element model
To verify the experimental results and investigate the peak forces, a numerical simulation of the axial impact event is performed. The simulation will be carried out using ABAQUS software. The ABAQUS suite of software for finite element analysis (FEA) has the ability to solve a wide variety of simulations. ABAQUS/CAE provides a modeling and visualization environment for ABAQUS analysis products. It offers access to CAD models, advanced meshing and visualization, and an exclusive view towards ABAQUS analysis products. For the test simulation use the nonlinear analytical modeling explicit finite element analysis method with program code apply to simulate the specimen under axial loading condition.
The circular tube was modeled in ABAQUS as a 3D deformable shell. The bottom plate which represents the support and the top plate which represents the impactor were modeled as discrete rigid bodies. Approximately 5000 4-noded linear quadrilateral explicit shell element of type S4R were used for the plain column. For the rigid bodies, 2 4-noded rigid linear quadrilateral elements of type R3D4 were used. For the slotted columns, due to their more complicated geometry, approximately 8000 to 9000 4-noded linear quadrilateral explicit shell elements of type S4R were used. A dynamic explicit solver ABAQUS was used. Time duration of 0.02 s to 0.035 s was specified depending on the speed of the impactor. The contact behavior between the column, support and impactor during collision was set up under the interaction module. The contact property consisted of tangential behavior, which used a ‘penalty’ friction formulation with a coefficient of 0.25. Boundary conditions and impact speeds were specified in the load module. For the impactor, it could only move translationally in the vertical z-direction. U3 set up with -0.18 because the tube will compress into 180mm from its original length and this value based on the experimental analysis when compression test on quasi- static test.

### 2.4 Crush force efficiency (CFE) and Initial Peak Force(IPF)

Later, the data obtained from the experiment and simulations were tabulated and construct force-displacement curve. IPF can be obtained based on the peak value. The ‘crush force efficiency’ is a useful measure of the uniformity of collapse load; for the ideal energy absorber. The crush force efficiency is closely related to the structural effectiveness introduced by Puglsey. Crush force efficiency CFE can be obtained from the below equation:

\[
\eta_c = \frac{F_{\text{mean}}}{F_{\text{peak}}}
\]

It is defined as the ratio of mean load, \(F_{\text{mean}}\) to initial peak force, \(F_{\text{peak}}\). An ideal absorber is said to exhibit a crush force efficiency of 100% which is difficult to achieve in reality.
3.0 Results and Discussion

3.1 Experimental test

Figure 4: The Quasi-static compression test being carried out for plain.

Figure 5: The Quasi-static compression test being carried out for specimen with slot geometry

Based on the Figure 4 above, at the first stage, the deformation of cylinder was in concertina modes. After seven folding, the cylinder undergoes diamond modes deformation. It showed that the cylinder experienced the mixed modes type of deformation. The diamond mode continues until the compression process reach 180 mm. The present of slot lead to the diamond mode collapse because when the load applied the ability to deform increased. For the specimen with slot geometry, all specimen experienced diamond modes from the beginning of compression test until the end. So, concertina modes only occurred for specimen without slot. Collapsing in diamond mode of deformation without experiencing any concertina folds during its axial collapse, leading to the lower amount of energy absorption capacity of this specimen.

3.1 Findings

All the experimental findings are tabulated based on type of specimen. It divided into two groups. The first group is shown in Table 3 and the second group is shown in Table 4. The divisions of the results are based on type of slot that has been design. Based on the objective is to reduce the initial peak value. For the first group, the slot 2, 4, and 6 located parallel to each other while for group two, the difference when 2 and 4 slot slots introduced in a row.
Table 3: First group

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Number of slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Without slot(plain)</td>
</tr>
<tr>
<td>2</td>
<td>2 slot in a row</td>
</tr>
<tr>
<td>3</td>
<td>4 slots in 2 rows</td>
</tr>
<tr>
<td>4</td>
<td>6 slots in 3 rows</td>
</tr>
</tbody>
</table>

Table 4: Second group

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Number of slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Without slot(plain)</td>
</tr>
<tr>
<td>2</td>
<td>2 slots in a row</td>
</tr>
<tr>
<td>3</td>
<td>4 slots in a row</td>
</tr>
</tbody>
</table>

Table 4: Impact performance indices for static loading for the first group

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Number of slots</th>
<th>IPF (N)</th>
<th>$\eta_c$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Without slot(plain)</td>
<td>45587.5</td>
<td>49.35</td>
</tr>
<tr>
<td>2</td>
<td>2 slot in a row</td>
<td>38637.2</td>
<td>50.2</td>
</tr>
<tr>
<td>3</td>
<td>4 slots in 2 rows</td>
<td>36132.03</td>
<td>55.5</td>
</tr>
<tr>
<td>4</td>
<td>6 slots in 3 rows</td>
<td>33824.17</td>
<td>59.2</td>
</tr>
</tbody>
</table>

Figure 6: Static response for specimen in first group

After analyzed the recorded data, it had been observed that the tubular aluminium cylinder with 6 slots in 3 rows recorded the most minimum IPF for the first group. IPF of the circular tube with difference number of slot geometry with constant size of slot showed the decreasing in value. It showed that the present of different slot geometry can reduced the energy absorption of the aluminium tube compared to plain tube. The present of slot help in deformation of the folding, thus it can reduce the force needed to complete the crush. There is reduction in 25.8% of IPF from plain tube to 6 slots in 3 rows.
Table 5: Impact performance indices for static loading for the first group

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Number of slots</th>
<th>IPF (N)</th>
<th>$\eta_c$(%)</th>
</tr>
</thead>
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<tr>
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<tr>
<td>2</td>
<td>2 slots in a row</td>
<td>38637.2</td>
<td>50.2</td>
</tr>
<tr>
<td>3</td>
<td>4 slots in a row</td>
<td>30553.58</td>
<td>81.5</td>
</tr>
</tbody>
</table>

Figure 7: Static response for specimen in second group.

For the second group, the objective is to observe the effect of using slot geometry with two slots and four slots on a row. By introducing four slots, it can be seen that the huge reduction in initial peak force. The plain tube has the highest IPF while tube with 4 slots in a row has the lowest. The development of four slots has increase the collapsibility of the tube. It triggered the deformation of the folding. The crush force efficiency is higher compared to other type of slot geometry. The best CFE was 39.4% better than the plain tube while compare slots in a row and 4 slots in a row, there are 38.4% difference in CFE.

3.2 Finite Element Model

Figure 8: Quasi-static experimental and simulation force-displacement curves for plain tube
Figure 11: Failure modes 2 slots in a rows circular tube by simulation

Figure 9: Failure modes for plain circular tube by simulation

Figure 7 shows the force-displacement curve between simulation and experiment value for plain circular aluminium tube. Simulation show that the IPF slightly higher than the IPF from the experimental result. The difference is due to technical factor during conducting the experimental test. The simulation IPF value is 46808.5 N. There is 2.6% difference. In the simulation, the aluminium tube also experienced mixed modes. At the first stage, it experienced concertina mode before collapsing in diamond mode.

Figure 10: Quasi-static experimental and simulation force-displacement curves for plain tube

Figure 11: Failure modes 2 slots in a rows circular tube by simulation
Figure 10 shows for 2 slots in a row. Simulation values show slightly higher compared to experimental result. The IPF in the simulation is higher than the IPF for experimental. At the displacement 0.05 to 0.1 m, the force difference between experiment and simulation, experiment has higher value than simulation. The pattern of the curve for the tube with 4 slots in 2 rows and 6 slots in 3 rows show the data from the simulation and experiment have not much different. The experiment usually will have lower IPF compared to simulation. It can be seen in Figure 12 and 14.

**Figure 12: Quasi-static experimental and simulation force-displacement curves for 4 slots in 2 rows**

**Figure 13: Failure modes 4 slots in 2 rows circular tube by simulation**

**Figure 14: Quasi-static experimental and simulation force-displacement curves for 6 slots in 3 rows**
Based on the Figure 18, the pattern of the curve shows that the simulation data have higher value than the experiment data. Besides, for specimen with 4 slots in a row, it has the lowest IPF compared with the others. Error could occur especially when conducting experimental test. Size of slot geometry has effect the collapsibility of aluminium tube. Based on the design, the size of slot geometry is 1mm × 5mm. So it was not easy job to produce the slots. Besides, during conducting compression test, the top impactor cannot touch the specimen before the compression test started. If not, the resultant data will be affected. Location of the slots also affects the test. For the first group, each row must have two slots that centered to each either besides to have parallel for specimen that have more than a row of slot.

4.0 Conclusion

Multiobjective crashworthiness optimization has been adopted to solve the problem of maximization of energy absorption and specific energy absorption of aluminum tubes. An impact force constraint has been
used to reduce the vehicle occupant injury. The development of slot geometry can reduce the initial peak force of the axial compression force. So, a study was conducted to study the behavior of slot geometry when it introduced to standard aluminium plain tube. For the plain tube, it experienced a mixed mode which starts with concertina mode then continues folding in diamond mode but after introducing the slot geometry, the collapse mode of tube changed from mixed mode to diamond mode only. Based on the results for the first group, the IPF reduce with increasing number of slot geometry while for the second group, IPF also reduce when more slot introduced in a row. After experimental analysis has been conducted, the results were analyzed in numerical analysis in order to determine the correlation experimental program and numerical analysis. The numerical analysis is one of the platforms to conduct test on circular tube as it provides advantages especially when involving cost factor. Therefore, the present of slot contributed to formation of plastic hinge and results in the diamond modes collapse.

5.0 Recommendation
During conducting the experiment process, the result that we get is actually not the perfect result that we get is actually not the perfect result because some error that occurred. Error also can occur because of the sample and during starting the compression testing.
So to overcome this problem:
1) Provide flatness on the surface of specimen. Lack of flatness can occur during cutting because of equipment that used to cut the specimen. For example, using bend saw either used disc cutter.
2) Slot making process can be improved by using CNC milling machine because the small size of the slot.
3) Operate the compression machine with careful because the impactor is very sensitive.

6.0 References.