Crashworthiness Analysis of Bi-Tubular Aluminium Tubes with Varying Shapes in LS-Dyna

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Abstract. The viability of thin-walled energy absorbers as impacts attenuators for Formula SAE racing cars was studied. The crashworthiness of bi-tubular tubes of varying geometries were explored. 9 designs grouped into 3 batches, were axially crush simulated in LS-Dyna. The tubes were set to 50mm long and made of aluminium 6061-T6. A convergence study was conducted, and the tubes were simulated using a meshing size of 1.5mm. The crushing energy applied is 490J. The LS-Dyna settings used were validated using experimental data from previous studies. It was found that the tube with an outer hexagon shape and an inner square shape had the best SEA. It was also observed that square-shaped geometries were the best in absorbing energy, with the most amount of energy being absorbed by a bi-tubular tube with outer and inner square geometries. Tubes with hexagonal geometries absorbed slightly less energy compared to tubes with square geometries, but they only differ by a small margin.

1. Introduction
The past century of human civilization has seen remarkable developments in the automotive industry generally in the engineering sector. Vehicles such as Koenigsegg Agera R and Bugatti Veyron are the pinnacles of speed machines and are exemplary of the extensive applications of engineering. However, with great power comes greater risk. In accordance with the laws of physics, the greater the velocity of a mass, the higher the kinetic energy the body has. In the event of a car crash, all of that energy would be transferred to the vehicle, and more critically, to the occupant of the vehicle, heightening the chances of severe injury. This is where impact attenuators (IA) come into play. They are devices that reduce the damage done to the vehicles and its occupants by absorbing the energy and deforming or redirecting the impact entirely thus safeguarding the occupants. This device is vital in racing competitions such as Formula SAE (FSAE). The impact attenuator acts as an energy absorber, absorbing the kinetic energy of the impact. The FSAE committee has given participating teams two options, whether to use a standard impact attenuator officially approved by the committee, or custom-make one. The custom-made one however must fulfil the requirements as stated in the rules [1].

Many parts of a FSAE racing car has been studied, including impact attenuators [2-7]. In a study of impact attenuator for racing vehicles, J. Wang et al experimented with the use of composite in impact attenuators for FSAE [8]. The basic structure chosen for the makeup of the IA was a half-corrugated beam. The structure was modelled in LS-DYNA and axial crushing of the model was studied. Material model 54 was chosen to simulate the fiber reinforced composite makeup of the IA. The rigid hammer responsible for the axial crushing was modelled using MAT_RIGID. Overall, the damage on the composite thin wall utilised shell 163 to reduce computation time. LS-OPT was then utilised to optimise the structure through Response Surface Methodology (RSM). They found that by increasing the diameter of the corrugated beams on the impact attenuator (IA), specific energy absorption (SEA) increased whilst increasing the height of the IA decreased SEA.
2. Cad Design

In the design of an impact attenuator, many different geometries and materials can be utilised to produce the desired part. Materials such as epoxy reinforced fibre and aluminium honeycomb sandwiches have been used in the makeup of an IA, proving that the possibilities are endless in the design and manufacture of IA’s. In this study, the concept of thin-walled absorbers was applied to produce an IA that meets the FSAE requirements. Single and bi-tubular tubes of varying geometries were investigated. The different geometries of the tubes are presented in Figure 1, together with their respective codes. The outer and inner diameters of the tubes were set to 38.1mm and 25.4mm respectively. The wall thickness of all the tubes were set to 1mm and the lengths were set to 50mm. The geometries were drawn in Solidworks 2017 and were saved as IGES files to be further processed in LS-DYNA.

![Figure 1: Varying tube geometries with their respective codes](image)

The dimensions of the tubes were based off commonly available sizes on the market. All the tubes have the same outer diameter of 38.1mm or 1.5inches and inner diameter of 25.4mm or 1inch. The tubes have also been coded to easily identify them. The first two letters stand for the shape of the outer tube. OC for example stands for ‘outer circle’, meaning that the outer tube is circular. The next set of letters dictate the shape of the inner tube. IS for example means ‘inner square’ meaning the inner tube is square in shape. So, OH IH for example means the inner and outer tubes are both hexagonal in shape.

3. Simulation Validation

Before proceeding with the simulation on the different tube designs, the simulation configurations must first be validated to ensure that the results tally up with real life results. Based on research done in [9], the authors compared both experimental and simulation results on the axial crushing of empty aluminium tubes. They found that the major trends were well capture, but the difference is as high as 29%. Using that as a basis, a recreation of the setup was done, and the results were compared with the experimental results in [9]. The force versus displacement graph for both are shown in Figure 2.
Comparing the peak force for both the simulation and experiment, the percentage error is approximately 2.4%.

4. Finite Element Analysis In Ls-Dyna

The finite element model was set up as in Figure 6. The various tubes in IGES file format were imported into LS-PrePost and meshed using auto mesher with mesh size of 2mm. The tubes of 50mm length were placed in between two masses as in Figure 3. Both the top and bottom masses are rigid solid sections. The bottom mass acts as a supporting platform for the axial crushing whereas the top plate acts as the crater. The set of nodes at the bottom of the tubes were fixed in place and the mass is set to approach the tubes at 7m/s. 490J of energy was applied. The dimensions of the masses were set to 80x80x2 mm.

In this setup, the tubes are made from aluminium 6061-T6. Material model 24, piecewise linear plasticity, was chosen to represent the material since it is an elasto-plastic material with strain-rate dependency. The properties of the 6061-T6 used were obtained from ASM International [10-11]. For the stationary and moving masses, MAT_RIGID was used since the masses are considered as rigid bodies in this simulation. In this study, the contact between the tubes and the moving mass is described by CONTACT AUTOMATIC NODE TO SURFACE. The moving mass is set as the master whereas the tubes were set as slaves. According to recommendations, this type of contact is suitable when the
master part, in this case the moving mass is a rigid body. To prevent penetration of the bodies, automatic single surface was used.

5. Measuring Crashworthiness
Comparing how capable the tubes are in terms of absorbing energy without some sort of standard measurement would be like comparing apples to oranges. Thus, based on [12-15], a few parameters such as specific energy absorption (SEA), total energy absorption (TEA), initial peak force (Fpeak) and mean crush force (Fmean) can be used to compare the crashworthiness of the tubes. The parameters are expressed as the following equations

\[ TEA = \int_0^\delta F(\delta) \, d\delta \]  
\[ SEA = \frac{TEA}{m} \]  
\[ F_{\text{mean}} = \frac{TEA}{\delta} \]

where \( \delta \) is the displacement and \( m \) is the mass of the tube. For initial peak force \( F_{\text{peak}} \), it is the highest value on the force versus displacement graph.

6. Results And Discussions

6.1. Group 1 Results

![Figure 4: Force vs displacement graph for group 1 tubes](image)

![Figure 5: Group 1 tube collapse](image)
6.2. Group 2 Results

![Figure 6](image1.png)

**Figure 6**: Force vs displacement graph for group 2 tubes

![Figure 7](image2.png)

**Figure 7**: Group 2 tube collapse

6.3. Group 3 Results

![Figure 8](image3.png)

**Figure 8**: Force vs displacement graph for group 3 tubes
Figure 9: Group 3 tube collapse

The finite element analysis results for bi-tubular tubes with cylindrical outer tubes; OC IC, OC IH and OC IS are presented in Figure 4. The collapse progression of the tubes is shown in Figure 5. Looking at the force vs displacement graph, there seem to be little difference between OC IC, OC IH and OC IS. The same applies to the amount of energy absorbed for OC IC, OC IH and OC IC which are 478.5J, 480.23J and 483.46J respectively.

The finite element analysis results for bi-tubular tubes with hexagonal outer tubes are presented in Figure 6. Figure 7 shows the collapse of group 3 tubes with the progression of time. Similar to group 1 results, the force vs displacements graphs are almost identical. The same could be said for the total energy absorbed for group 2 designs which are 479.94J, 483.21J and 485.67J respectively. This may be due to the geometry of group 2 designs which have an outer hexagonal tube, behaving similar to circular tubes in terms of energy absorption.

The finite element analysis results for bi-tubular tubes with square outer tubes are presented in Figure 8. The collapse of the tubes with the progression of time is shown in Figure 9. An interesting observation to note in Figure 8 is the lower crushing force value for all group 3 designs compared to groups 1 and 2. The tubes in group 3 also has a larger average of total energy absorbed compared to the other groups. The energy absorbed for OS IC, OS IH and OS IS are 482.87J, 481.91J and 487.03J respectively.

7. Conclusions
This study has explored the viability of thin-walled energy absorbers as impact attenuators for Formula SAE racing cars. Bi-tubular tubes of varying geometries made of aluminium 6061-T6 were simulated in LS-Dyna. It was found that the bi-tubular tube with an outer hexagonal tube and an inner square tube was the best in terms of specific energy absorption. It was also observed that square-shaped geometries were the best in absorbing energy, with the most amount of energy being absorbed by a bi-tubular tube with outer and inner square geometries. Tubes with hexagonal geometries absorbed slightly less energy compared to tubes with square geometries, but they only differ by a small margin. It can be concluded that bi-tubular aluminium tubes could be used as impacts attenuators especially in vehicles such as Formula SAE racing cars.

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