Design and Analysis of Impact Attenuator for a Formula Student Car: A Study between Singular and Bi-tubular Tubes of Varying Geometries

A. Rahman, M T A Rahman*, E H A Manaf, A S A Rahman
School of Mechatronic Engineering, Universiti Malaysia Perlis, Pauh Putra Main Campus, 02600 Arau, Perlis, Malaysia.

*Corresponding author: tasyrif@unimap.edu.my

Abstract. The viability of thin-walled energy absorbers as impact attenuators for Formula Student car was examined in this study, specifically the crashworthiness of singular and bi-tubular tubes of varying geometries. 12 designs were lumped into 4 groups, consisting of 3 singular tubes and 9 bi-tubular tubes of varying shapes and dimensions, and they were axially crush-simulated in LS-DYNA. The tubes were set to 50mm long and made of aluminium 6061-T6. The LS-DYNA settings were validated using published experimental data of similar studies. The singular tubes were found to have the highest values of specific energy absorption (SEA), with the singular hexagonal tube design recording the highest value of SEA compared to the other designs. It was also observed that square-shaped geometries were the best in absorbing energy, especially a bi-tubular tube with outer and inner square geometries.

1. Introduction
Many parts of a FSAE racing car has been studied, including impact attenuators [1-6]. The importance of impact attenuator (IA) in reducing the collision’s impact during an accident has been frequently highlighted over the years [7,8], more so for racing/formula cars. A good design of IA is highly critical to absorb crash energy in a controlled manner and thus offer protection. In the Formula SAE (FSAE), this device is one of the most important aspect that will be judged during the tournament. While the FSAE committee has given participating teams options whether to use a standard IA that was officially approved by the committee, or a custom-built one, most teams tend to come up with their novel IA design to reduce cost. Additionally, any customized IA must fulfill the requirements as stated in the FSAE rules [9].

2. CAD Design
In this study, the concept of thin-walled absorbers was applied to produce an IA that meets the FSAE requirements. Figure 1 displays single and bi-tubular tubes of varying geometries investigated in this study, along 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.
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 and inner diameter of 25.4mm. The tubes have also been coded to easily identify them. For Group 1 tubes, the first ‘S’ stands for single, meaning singular tubes whereas the second alphabet stands for the shape of the singular tubes. SH for example means a ‘Singular Hexagonal’ tube. For Groups 2 to 4, the first two letter stand for the shape of the outer tube. OC for example means ‘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. OH IH for example means the inner and outer tubes are both hexagonal in shape.

3. **Finite Element Analysis in LS-DYNA**

The finite element model was set-up as demonstrated in Figure 2. The various tubes in IGES file format were imported into LS-PrePost and the elements (mesh size of 2mm) were generated using _auto-mesher function_. The tubes of 50mm length were placed in between two masses as illustrated in Figure 2. 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 crusher. The set of nodes at the bottom of the tubes were fixed in place, while the mass approaching the tubes was set to be at 7m/s. Next, a total of 490J of impact energy was applied to the model. The dimensions of the masses (i.e. top and bottom plates) were set to 80x80x2 mm.
In this set-up, 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 was set as the master whereas the tubes were set as slaves. This type of configuration is commonly used when the moving mass is a rigid body. To prevent penetration of the bodies, automatic single surface was applied.

4. Measuring Crashworthiness
Equations 1-3, which were based on [12-15], were used to compare the crashworthiness of the tubes. Specific energy absorption (SEA), total energy absorption (TEA), initial peak force (F_{peak}) and mean crush force (F_{mean}) can be expressed using the following equations:

$$TEA = \int_{0}^{\delta} F(\delta) \, d\delta$$  \hspace{1cm} (1)

$$SEA = \frac{TEA}{m}$$  \hspace{1cm} (2)

$$F_{mean} = \frac{TEA}{\delta}$$  \hspace{1cm} (3)

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

5. Results and Discussions
The results from the finite element models for the singular tubes are displayed in Figure 3, while Figures 4-6 illustrate the simulation outputs for the bi-tubular tubes. Comparing the initial peak force for all three tubes in Group 1, SC and SH seem to have the same value for peak force whereas SS has a lower value of approximately 34kN. Lower crushing force means lower deceleration for the rigid body, making it more suitable for the application of impact attenuators in vehicles since humans cannot handle high G-forces [16]. In terms of energy absorption, SC, SH and SS absorbed 479.67J, 483.18J and 482.79J respectively. When looking at the displacement of the models, SS displaced the most at approximately 27mm. As for Group 2 results, there seem to be very minor differences between OC IC, OC IH and OC IS. Likewise, this behaviour was also repeated for the amount of energy absorbed for OC IC, OC IH and OC IS which were 478.5J, 480.23J and 483.46J respectively.
Results

- **Figure 3:** Results for Group 1 (singular tubes)
- **Figure 4:** Results for Group 2 (bi-tubular tubes)

### Force vs Displacement Graph

![Force vs displacement graph](image_url)

Tube collapse with respect to time for respective group.
Results

Figure 5: Results for Group 3

Figure 6: Results for Group 4
The force vs displacements graph for Group 3 however, shows an almost identical results to the one produced by Group 2. The same can also be said for the total energy absorbed for the Group 3 designs which were 479.94J, 483.21J and 485.67J respectively. This may be due to the geometry of group 3 designs which have an outer hexagonal tube, hence resembling the circular tubes in terms of energy absorption.

Finally, Figure 6 demonstrates that all Group 4 designs exhibit lower crushing force value when compared with Groups 2 and 3. Additionally, it is also apparent from Figure 3 that having an outer square tube helps to reduce the initial peak force. Nonetheless, it is interesting to note that tubes in Group 4 also have a larger average of total energy absorbed when compared to the other groups. For instance, the energy absorbed for OS IC, OS IH and OS IS are 482.87J, 481.91J and 487.03J respectively.

6. Conclusions
This study has explored the viability of thin-walled energy absorbers as impact attenuators for Formula SAE racing cars. Singular and bi-tubular tubes of varying geometries made of aluminium 6061-T6 were simulated in LS-Dyna and then compared in terms of the amount of energy absorbed, peak crushing force and specific energy absorption. It was found that the singular tubes were the best in terms of specific energy absorption, with the singular hexagonal tube recording the highest value of SEA out of all the designs.

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, except for the singular hexagonal tube, but they only differ by a small margin.

Overall, this study has demonstrated the capability and suitability of both singular and bi-tubular aluminium tubes as impact attenuators that can be applied in Formula SAE racing cars.

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