Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 5, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

Carbon Fiber Impact Attenuator: A Comprehensive Design and Analysis Approach

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Abstract

In the high-stakes world of Formula One competition, accidents are a sad reality. The primary causes of these accidents are violent overtaking, high speeds, and environmental factors. All of these causes result in accidents, such as a car colliding head-on with barricades, two automobiles colliding, a car skidding on a wet track, etc. Driver safety must be improved, and accidents of this nature must be avoided. One such safety elements that needed to be considered when designing the racing vehicles is the impact attenuator. This research paper presents a comprehensive approach to the design and analysis of an optimized custom Step Impact Attenuator tailored to meet the stringent requirements set forth by the FSAE regulations. The research paper proposes the development of a carbon fiber step impact attenuator design specifically engineered for FSAE applications. The research methodology involved analytical quantitative research, leveraging computer simulations to iteratively optimize the design. Detailed crash simulations were performed in ABAQUS, enabling the analysis of force-displacement curves, energy absorption capabilities, and anti-intrusion plate displacement. The proposed solution offers enhanced driver safety through superior energy absorption capabilities, achieving 12.024 kJ of energy absorption while maintaining an anti-intrusion plate displacement within permissible limits. This approach demonstrates the potential of advanced composite materials and computational simulation techniques in developing more effective safety systems for high-performance racing vehicles.

Keywords: Step Impact Attenuator, Carbon Fiber, Anti-Intrusion Plate, Crash Simulation, ABAQUS, FSAE

INTRODUCTION

Following the success of Formula One competition, Society of Automotive Engineers (SAE) came up with a new competition named Formula Student Association Event (FSAE) for the engineering students to increase the enthusiasm among the engineering students and to get hands on experience on manufacturing a physical car on their own and compete. FSAE challenges university students from different domains like Mechanical, Electronics, Computer Science, etc. to conceive, design, fabricate, develop and compete with small, formula-style race cars.

Accidents are an unfortunate reality in high stakes world of Formula One (F1) and the main reasons for these accidents are high speeds, harsh overtaking, environmental conditions, etc. All these reasons lead to accidents which includes head on collision of the car with barricades, collision of two

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Received Date: January 16, 2025
Accepted Date: March 18, 2025
Published Date: July 24, 2025

Citation: Vinayak H. Khatawate, Hari Vasudevan, Bhavik Kapadia, Krisha Vora, Mann Dave, Prathamesh Desai. Carbon Fiber Impact Attenuator: A Comprehensive Design and Analysis Approach. Journal of Polymer & Composites. 2025; 13(Special Issue 5): S452–S468p.

cars with each other, skidding due to wet track etc. In order to ensure the driver's safety in case of high-speed crashes, the FIA (International Automobile Federation) came up with certain solutions to increase the safety of the drivers and to prevent these kinds of accidents. Impact Attenuator (IA) is one of the components which is made mandatory while designing the F1 vehicle, and are designed to absorb the race car's kinetic energy and limit the decelerations acting on the human body. It is used to decelerate impacting vehicles slowly to a stop and huge amount of impact energy is transferred in the deformation of impact attenuator structure.

PRINCIPLE OF OPERATIONS

FSAE Impact Attenuator is same as that of Crumple Zone used in Passenger vehicles. The Crumple Zone in a passenger vehicle is a structure which is designed to absorb or redistribute the energy during collision of the vehicle. The crumple zone is typically situated in front and rear of the vehicle. This safety feature is now a standard for passenger vehicles.

The primary principles of operation of Impact Attenuator are:

1. Energy Absorption through controlled deformation – IA is made of deformable materials like Aluminum honeycomb, Foam or Plastics. The IA itself gets deformed by absorbing the kinetic energy of the vehicle.
2. Progressive Loading – IA is designed for Progressive loading which means initial stages are designed for absorbing low energies and later stages are designed for absorbing high energies.
3. Compact and Light Weight – IA must be designed such that it is compact and lightweight to enhance the vehicle packaging and to reduce overall weight of the vehicle.
4. Structural Integrity – Although IA is designed to get deform, yet it should be structurally strong enough to restrict the penetration of sharp objects into the vehicle cockpit.
5. Compliance with the competition rules – The IA must be in compliance with the competition rules and regulations, which guides for compact design of IA and its minimum energy absorption capacity.

The Impact Attenuator for an FSAE car must comply with the specific rules set by the competition. According to the Formula Bharat 2025 rulebook [1], the Impact Attenuator (IA) must be:

- Attached to the front of the vehicle.
- The minimum dimension of IA is 100mm x 200mm x 200mm.
- The above-mentioned volume must me positioned within 350mm from the ground.
- IA must not penetrate through the Front Bulkhead.
- It must be designed with closed front section.
- Con not be wider or higher than Anti Intrusion Plate (AIP).
- Decelerate the vehicle at a rate not exceeding 20 g average and 40 g peak.
- The energy absorbed in this event must meet or exceed 7350 J.

FSAE Standard Impact Attenuator meets all design requirements such as minimum and maximum dimensions, crush force characteristics, and attachment specifications to the vehicle's front bulkhead. The front part of FSAE vehicle is shown in Figure 1.

The use of a standardized design ensures that all vehicles have a minimum level of frontal impact protection and helps prevent more severe injuries to drivers in the event of a crash. It is typically made of Aluminum honeycomb or foam materials that progressively crush and deform upon impact, absorbing the kinetic energy and decelerating the vehicle in a controlled manner. It is easily available and is pre-tested so it does not require further testing and its crushing behavior is relatively predictable which means the further crumple zone of the chassis can be designed effectively. It also saves the cost of testing which can be utilized for other critical components. The FSAE standard IA is shown in Figure 2.

Journal of Polymer & Composites
Volume 13, Special Issue 5
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

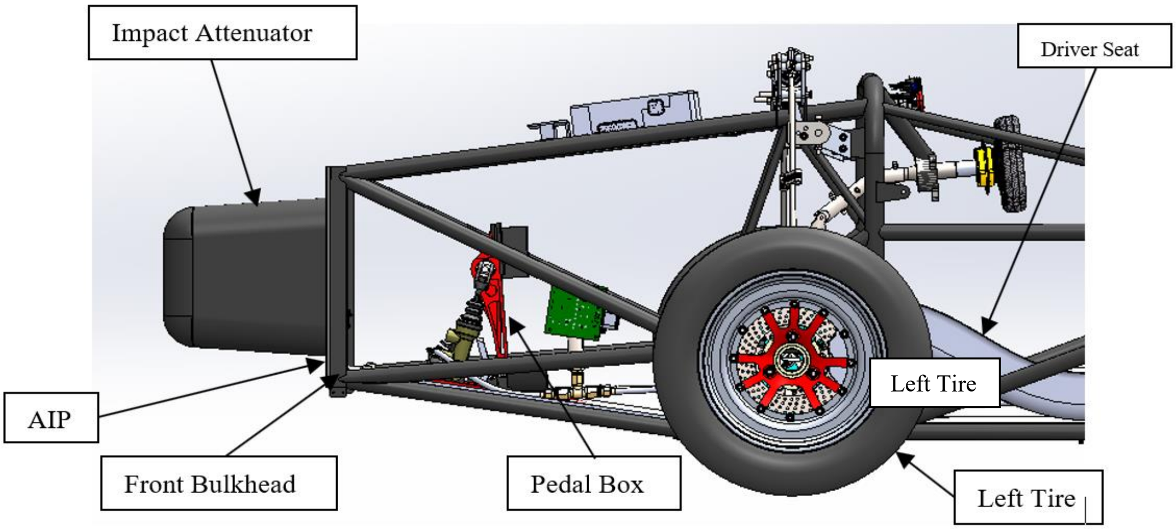


Figure 1. Schematic of Front Part of FSAE Vehicle

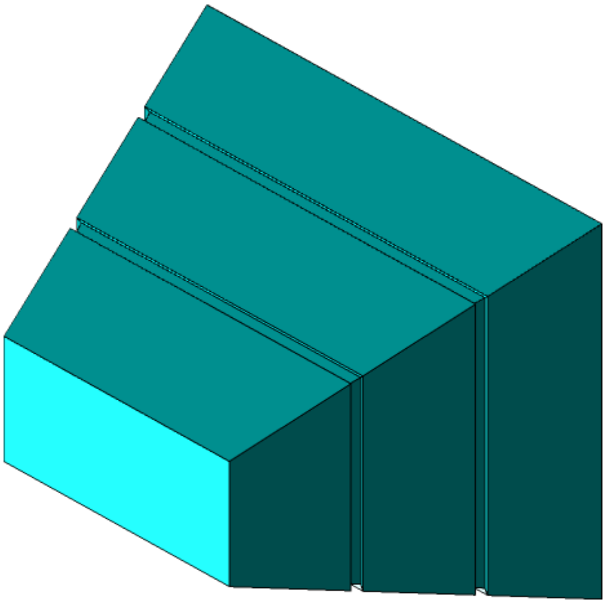


Figure 2. FSAE Standard Impact Attenuator (Foam).

On the other hand, Standard IA does not have a scope of weight reduction which is an important factor to improve top speed of the car in dynamic events. It is also tested for minimum energy absorption requirement so there is no scope to improve driver safety in case of higher energy impact crashes. The objectives of the present paper are to outline a comprehensive approach to designing and analyzing an optimized custom Step Impact Attenuator, specifically engineered to meet the rigorous standards of FSAE regulations.

LITERATURE REVIEW

A literature review is essential for the design and analysis of an impact attenuator for a student FSAE vehicle as it helps identify existing designs, materials, and methods used in similar applications. It provides insights into best practices, potential challenges, and compliance with FSAE regulations, ensuring an informed and efficient approach to achieving an optimized design.

Parth Thakar et.al., [2], compared various materials such as aluminum, aluminum honeycomb, carbon fiber reinforced plastic (CFRP), and glass fiber in terms of cost, weight, availability, strength and ease of manufacture. They chose CFRP despite its greater cost and manufacturing difficulty, because of its high strength to weight ratio and availability. SolidWorks was used to simulate the impact attenuator iterations, while ABAQUS software was used for explicit dynamics analysis. Finally, a square frustrum was chosen on the basis of energy absorption and deceleration performance. Validation was done by performing drop test and results were compared with software analysis. The custom CFRP impact attenuator achieved a 30% weight reduction & 37.8% higher energy absorption compared to standard FSAE impact attenuator while meeting FSAE requirements.

The researchers Emre et. al.,[3] chose expanded polypropylene (EPP) foam with 100 g/l density to create a lightweight impact attenuator design. The EPP foam material impact attenuator was validated through finite element simulations to make sure that model satisfied FSAE requirements. It was 10 % lighter than standard FSAE impact attenuator. The final simulation results showed that EPP foam impact attenuator was meeting FSAE requirements, absorbing 7420 J and decelerating the vehicle at an average of less than 20g and a peak of 30g.

Giovanni Belingardi et al. [4] conducted finite element simulations using Hypermesh software. The model incorporated two types of materials: steel S275JR UNI EN 10025 (Fe430) and 6082T6 aluminum alloy. The results for both materials were comparable, but the IA design featured a shell-like structure with punched holes, which acted as triggers. This design approach reduced the weight of the structure while improving crush behavior by lowering the initial peak collapse force. Crash tests were performed under face-to-face direct collision conditions.

Kush Soni [5] examined a range of core structures and materials, such as Aluminum sheets, Aluminum honeycomb, steel-Aluminum alloy conical-shaped impact attenuators, along with various cans and bottles. Finally, author selected tins made of Aluminum alloy with compressive strength of 180.995 N/mm2 as material of IA. Different layers of tin were created in step form using Aluminum plates. Adhesives such as Araldite and Meta Set Bondtite were used to attach tins with Aluminum plates. Tins were welded from one side to prevent axial distortion and to increase strength. Aluminum 6061 plate with a 4 mm thickness was utilized for anti-intrusion plates due to its reduced weight in comparison to 1.5 mm solid steel plate. Testing of attenuators was done on UTM machine under compressive load. Following the UTM results, a two-layer design with an energy absorption of 9490 J was ultimately chosen. The first layer contained 12 tins, and the second layer had 6 tins above it, all enclosed in a 2 mm-thick Aluminum shell.

The utilization of aluminum alloy cans from beverage containers was investigated by Laksmana W P et al [6-7]. A number of consequences on attenuators were identified using non-linear FEA. The investigation took into account the cans' thickness and impact velocity. They discovered that cans with a thickness of 1 mm could absorb twice as much energy as cans with a thickness of 0.5 mm [8].

Sean Jenson and Muhammad Ali [9] investigated the possibility of increasing an axial crush tube member's energy absorption efficiency by causing folding in the outer tube structure. The ABAQUS/Explicit dynamic modeling environment was used in their study's numerical methodology. Partial cuts were carefully positioned at predetermined intervals along the tube's circumference to allow for the controlled folding mechanism. Energy-deformation stroke graphs, deformation patterns, and crushing force were among the metrics that were the focus of the investigation. The results showed an 11.1% improvement in energy absorption and a 29.2% increase in response forces.

Based on the reviewed literature, it is concluded that carbon fiber offers the best results due to its lightweight properties and its proven ability to enhance the impact performance of an attenuator by reducing deceleration. The aim of current study is to design a carbon fiber step impact attenuator that achieves a higher power-to-weight ratio.

DESIGN OF STEP IMPACT ATTENUATOR

As stated in section-3, the material of Step Impact Attenuator was finalized as Carbon Fibre and shape as Square Frustum. The designing and analysis of IA is done by changing the dimension of the IA and by iterating the number of Steps to be used. This is an Iterative process as a permutation combination of different dimensions and steps will result in different energy absorption and variable weight of the Step IA. So, it is necessary to fix either the dimension or number of steps in order to get proper data by analysis. The solid model of step IA has been created using SolidWorks software. Three CAD models of IA were developed, which undergone simulation tests and one model was finalized as shown in Figure 3.

CRASH ANALYSIS OF STEP IMPACT ATTENUATOR

The process of simulating a crash impact scenario on computer software and analyzing the impact on the vehicle or component under examination is known as crash simulation. Car manufacturers typically utilize crash tests or crash simulations to assess the vehicle's structural integrity, passenger safety, and the impact on specific components in the event of a collision.

Crash testing was required to determine the overall energy absorbed by the Impact Attenuator. The construction of the component is intended to deform in the event of an accident and absorb most of the energy rather than transmit it to the vehicle for the protection of the passengers. Also, it helps to determine the displacement of the 'Anti-Intrusion Plate' which prevents sharp objects from entering the vehicle.

Numerous programs, such as ABAQUS, LS-Dyna, etc., can carry out crash analyses. Of these, ABAQUS [10] was selected for the study due to its characteristics, which include an interactive easy-to-use user interface, the ability to rapidly modify parameters for multiple iterations.

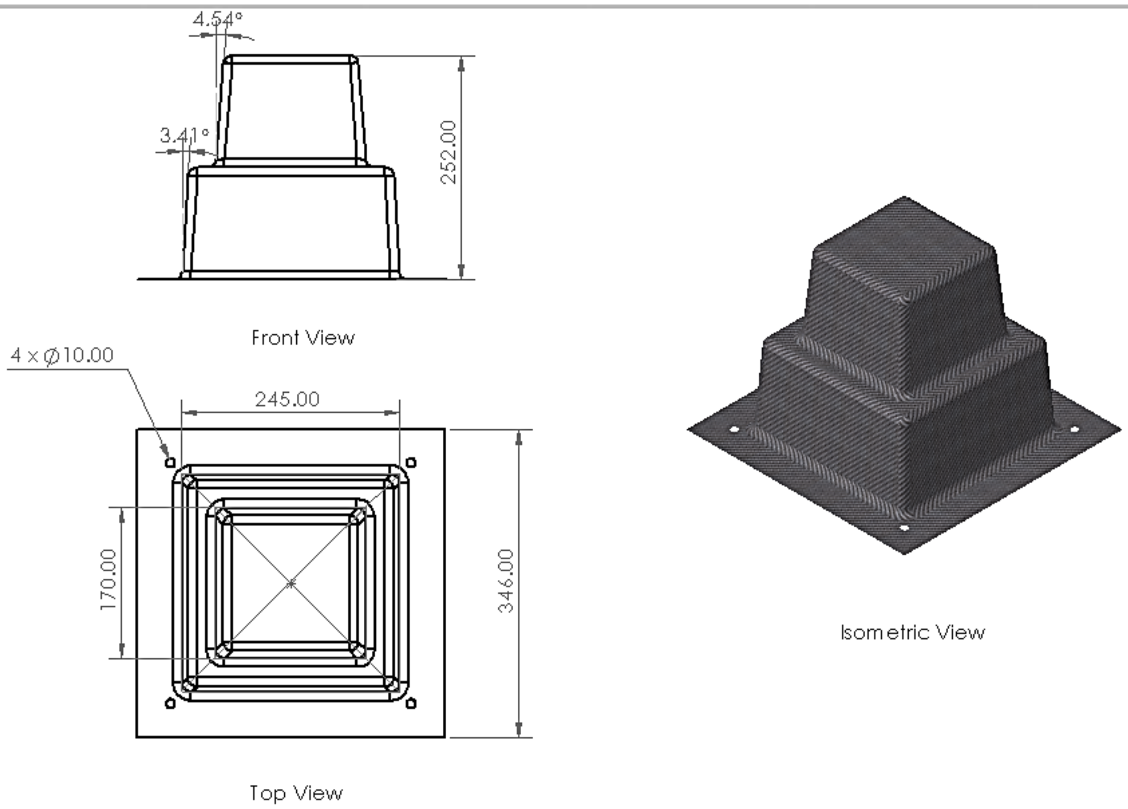


Figure 3. The Finalized Design of Step Impact Attenuator

Procedure for Crash Simulation

Importing CAD Model

Step IA and AIP were imported from SolidWorks and Rigid wall was designed in ABAQUS. AIP is an extruded model, while Step IA is a surface model. The 600 × 600 mm rigid wall was of the 3D, Discrete Rigid, and Planar type. Since the wall was rigid, it doesn't require thickness. The Wall would not deform throughout the analysis because it is discretely rigid. A reference point is created at the wall's center to specify its material properties and measure the energy absorbed during Step IA. The solid model of Anti Intrusion Plate, Step Impact Attenuator and Wall is shown in Figures 4, 5 and 6 respectively.

Creating Material and assigning it to the Components

Creating Material

As Step IA is made of Composite material, it requires creating composite material whereas, AIP is made of Aluminum.

a. Carbon Fiber Properties:

Set TYPE=LAMINA to define an Orthotropic Material in Plane Stress.

b. Aluminum:

Set TYPE=ISOTROPIC (default) to define Isotropic behavior.

Assigning to Components

Composite components are manufactured using the Layup process. For Step IA, Layup with Conventional Shell was chosen to assign materials with varying orientations. The Layup consists of four carbon fiber layers, each with a thickness of 0.25mm/ply, enabling precise control of material properties within the composite structure.

Material assignment for AIP involves creating a 'SECTION' to define homogeneity throughout the component, followed by using the 'ASSIGN SECTION' command to apply it. Material assignment for the wall is unnecessary as it is discrete rigid and non-deformable. However, a 300 kg mass is assigned at the reference point.

Assembling all the Components for the Setup

The assembly is arranged with the origin at the rear face of Step IA. The wall is positioned 257mm from the origin, as Step IA is 252mm long with a 5mm gap from the wall. Step IA and AIP are in contact with each other as shown in Figures 7 and 8.

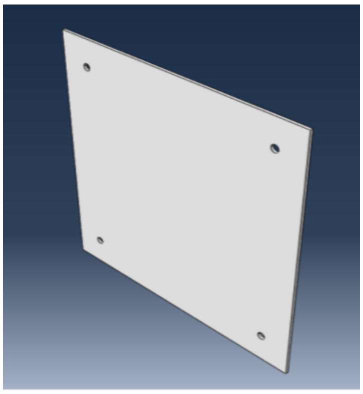


Figure 4. Anti Intrusion Plate.

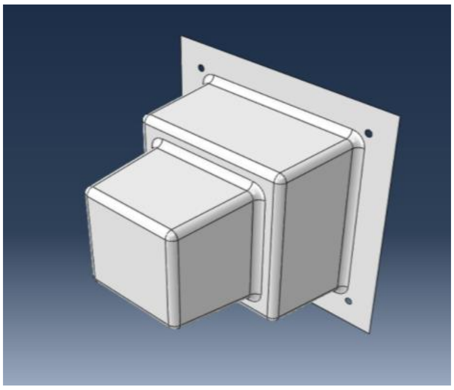


Figure 5. Step Impact Attenuator (AIP).

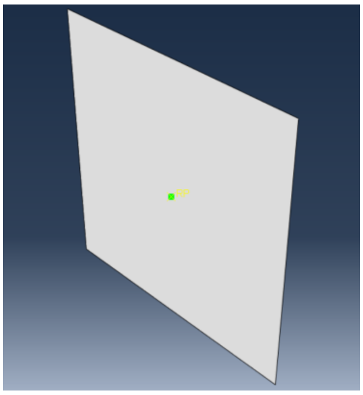


Figure 6. Wall.

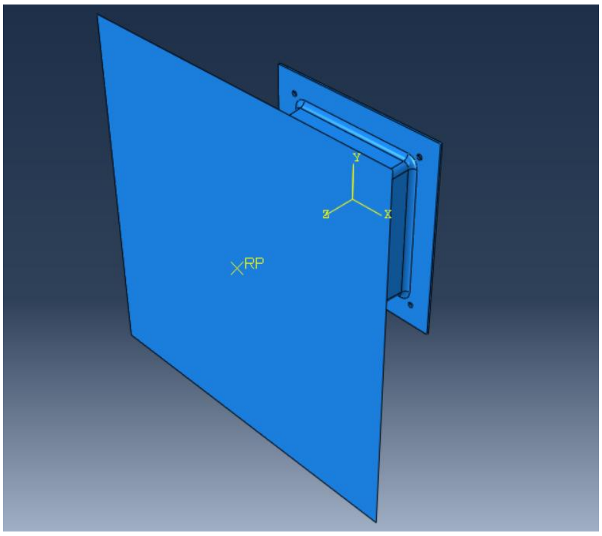


Figure 7. Isometric View of Assembly.

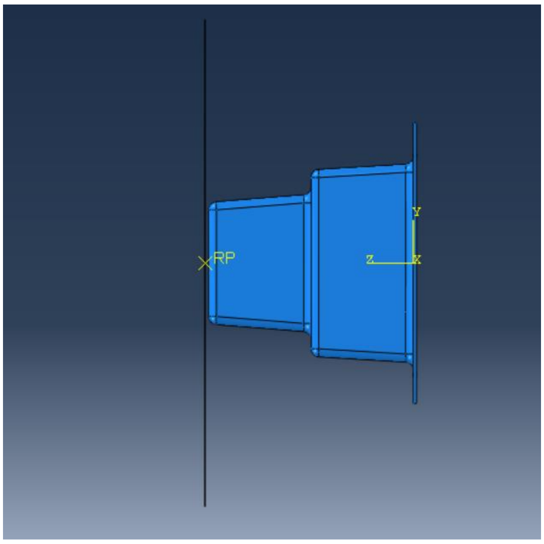


Figure 8. Side View of Assembly.

Setting Time step for Analysis and Interaction between components

The STEP option defines the total analysis time, while the STEP parameter controls convergence. The analysis is set as Dynamic and Explicit to capture stress and displacement under dynamic conditions and efficiently handle large models with contact. Nlgeom is set to 'On' to account for geometric nonlinearity, and the STEP time is 0.036s, based on the calculations.

Speed of the Wall = 7 m/s = 7000 mm/s.
Total distance to be travelled by the wall is 257 mm (Length of Step IA + 5mm gap).

By the equation:

$$Velcity = \frac{Displacement}{Time}\ Time = \frac{252}{7000}\frac{mm}{mm/s}$$

$$Time = 0.036714\ s$$

Based on these calculations, the analysis time step assigned was 0.036s. The Interaction Parameter sets the Coefficient of friction between components. The tangential behavior was defined with a coefficient of 0.6 (assumed value), which is then assigned to the components. Generally, the coefficient of friction for the wet road is between 0.4-05 and for the dry road, it is between 0.7-0.8. Considering the average coefficient of friction of two conditions, which comes around 0.6.

Applying Boundary Conditions

For the analysis, there three boundary conditions were applied.

- *Fixed Support to Step IA and AIP* – The corners and the mounting point holes of Step IA and AIP were fixed with all the linear and rotational degree of freedom to zero as shown in Figure 9.
- *Displacement* – The edges of the wall were restricted to all the three rotational degree of freedom and are also restricted in linear displacement of X and Y axis (fig.10). Which means the Wall is allowed to move in Z direction only.
- *Velocity* – The reference point of the wall was given a velocity of 7000 mm/s in Z direction and all the other velocities were set to 0 mm/s.

Meshing of Components

Each component was meshed based on the required data resolution. Components like Step IA and AIP were fine-meshed to capture detailed force and displacement data. As the wall used was rigid, that does not deform, a course meshing was used to optimize computational efficiency.

A QUAD mesh type was selected because the components are primarily cubic or cuboidal, with minimal curvature except for the fillets in Step IA. The QUAD mesh efficiently adapts to these geometries. Figures. 11, 12 and 13 shows meshing of step IA, AIP and rigid wall respectively.

Job Setup
The solving process begins with the following steps:

- *Writing Data Input* - The input data required for the analysis were collected.
- *Data Check* - The collected data was analyzed to identify any errors in the process, ensuring the analysis is not interrupted due to issues during solving.
- *Final Submission* - Once the data was verified and confirmed to be accurate, the analysis started and runs from 0 seconds to 0.036 seconds.

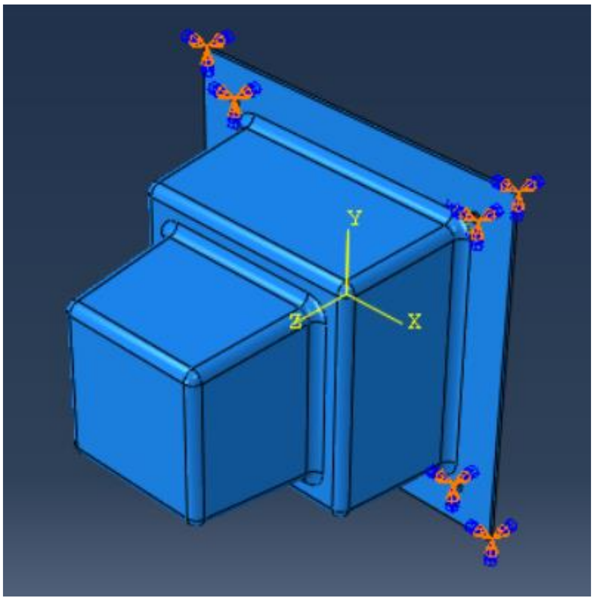


Figure 9. Fixed Support.

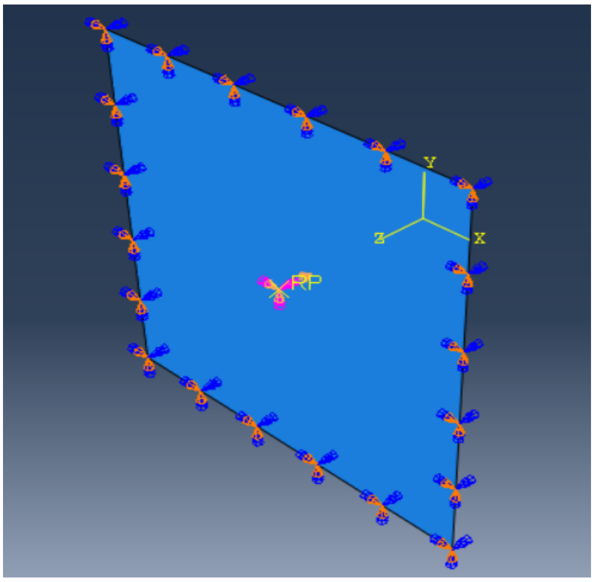


Figure 10. Velocity and Displacement Conditions.

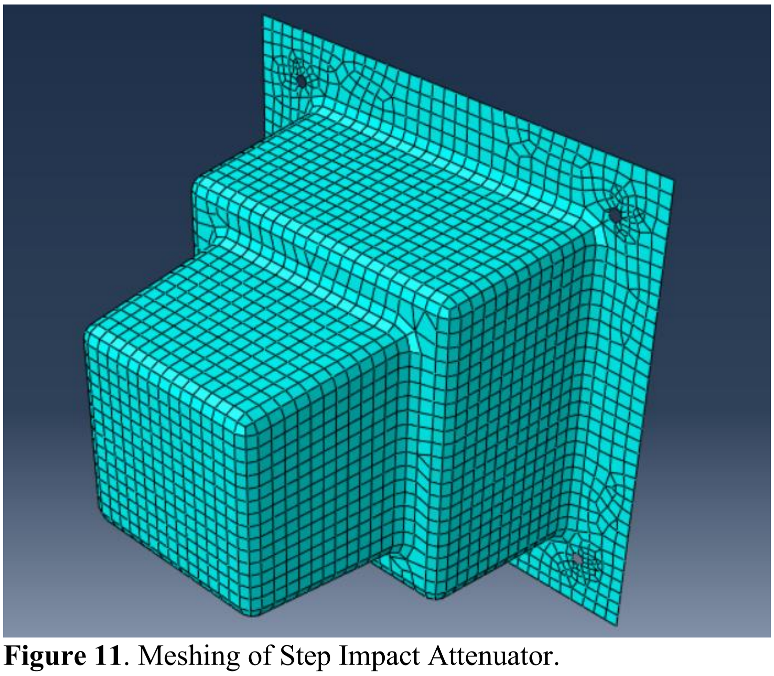


Figure 11. Meshing of Step Impact Attenuator.

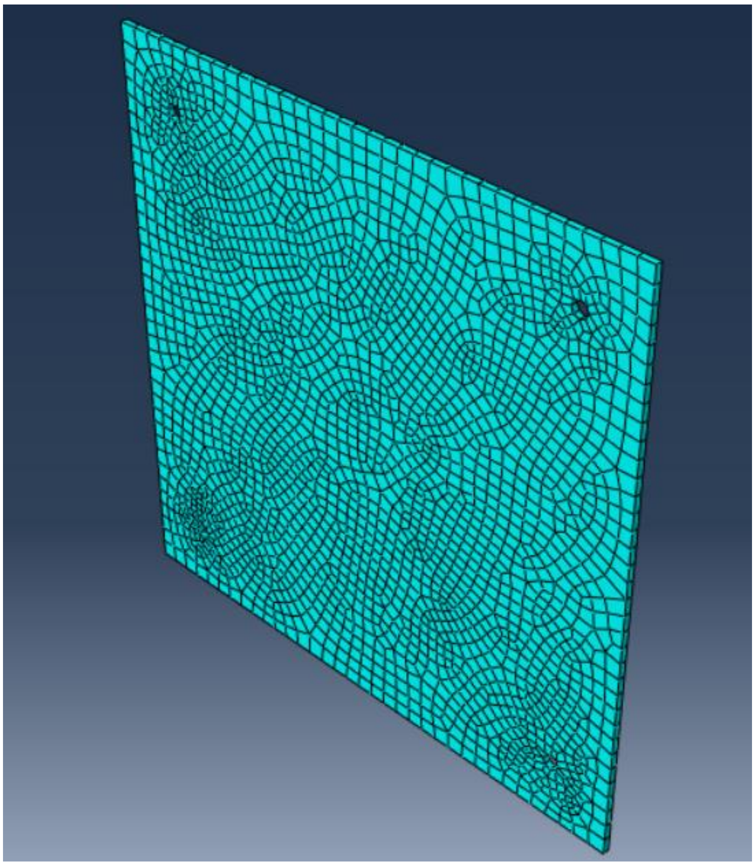


Figure 12. Meshing of Anti Intrusion Plate.

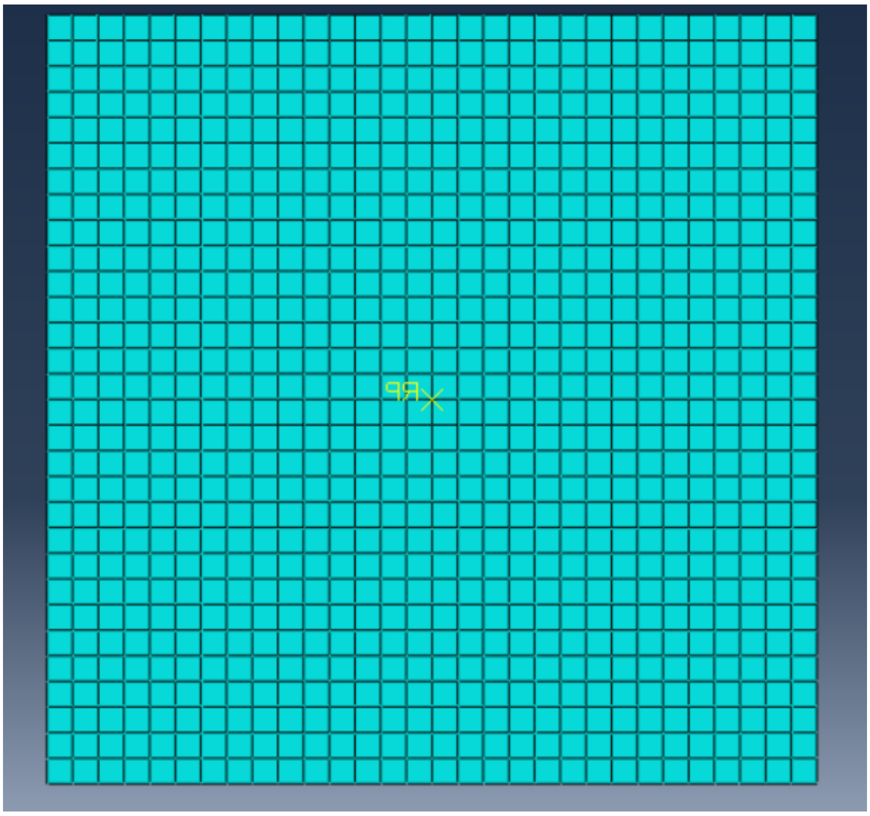


Figure 13. Meshing of Rigid Wall.

RESULTS AND DISCUSSIONS

This is the post-processing stage of the analysis, where the data is interpreted by plotting various graphs, such as Force vs. Time and Displacement vs. Time, integrating them, and determining the final results. Figures 14 and 15 respectively shows initial and final deformation of Step IA.

Force vs Time Graph

The graph of Force vs Time for the step IA is shown in Figure 16. The reference point located at the center on the wall, serving as the first point of impact, is used for plotting the values. The Force data extracted from the graph was then used as input to calculate the energy absorption. Only the reaction force along the Z-axis is plotted, as the energy absorption is required in this direction.

Displacement vs Time Graph

Figure 17 show the plot of displacement vs Time for Step IA to determine the final displacement after crushing. To plot the values, a section view of Step IA was taken, and the front most point along the Z-axis was selected. Only the displacement along the Z-axis is used for plotting the graph. The displacement data extracted from the graph was used as input into Excel spread sheet to calculate the energy absorption.

Determination of Anti Intrusion Plate Displacement

To determine the displacement of the AIP, the same procedure is followed as for the Displacement vs. Time graph of Step IA. However, instead of selecting the front most point of Step IA, the rearmost point of the AIP is selected in the section view. After plotting the graph, the data is extracted, and the maximum displacement value represents the maximum displacement of the AIP.

Energy Absorption by step IA

The force and displacement values extracted from the graphs (Figures 16 and 17) were entered into Excel spread sheet programe, where the total energy absorbed and the maximum displacement of the AIP are calculated.

$$Energy\ Absorbed\ by\ IA = (F_2 - F_1) \times (\frac{x_2+x_1}{2})$$

Where F_1, F_2 are the Forces and x_1, x_2 are the Displacements

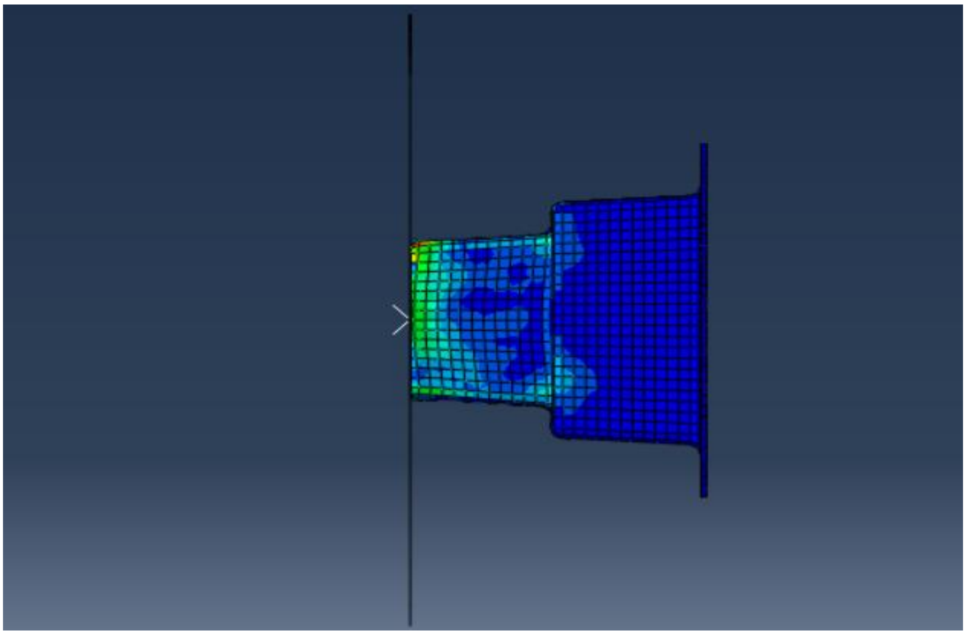
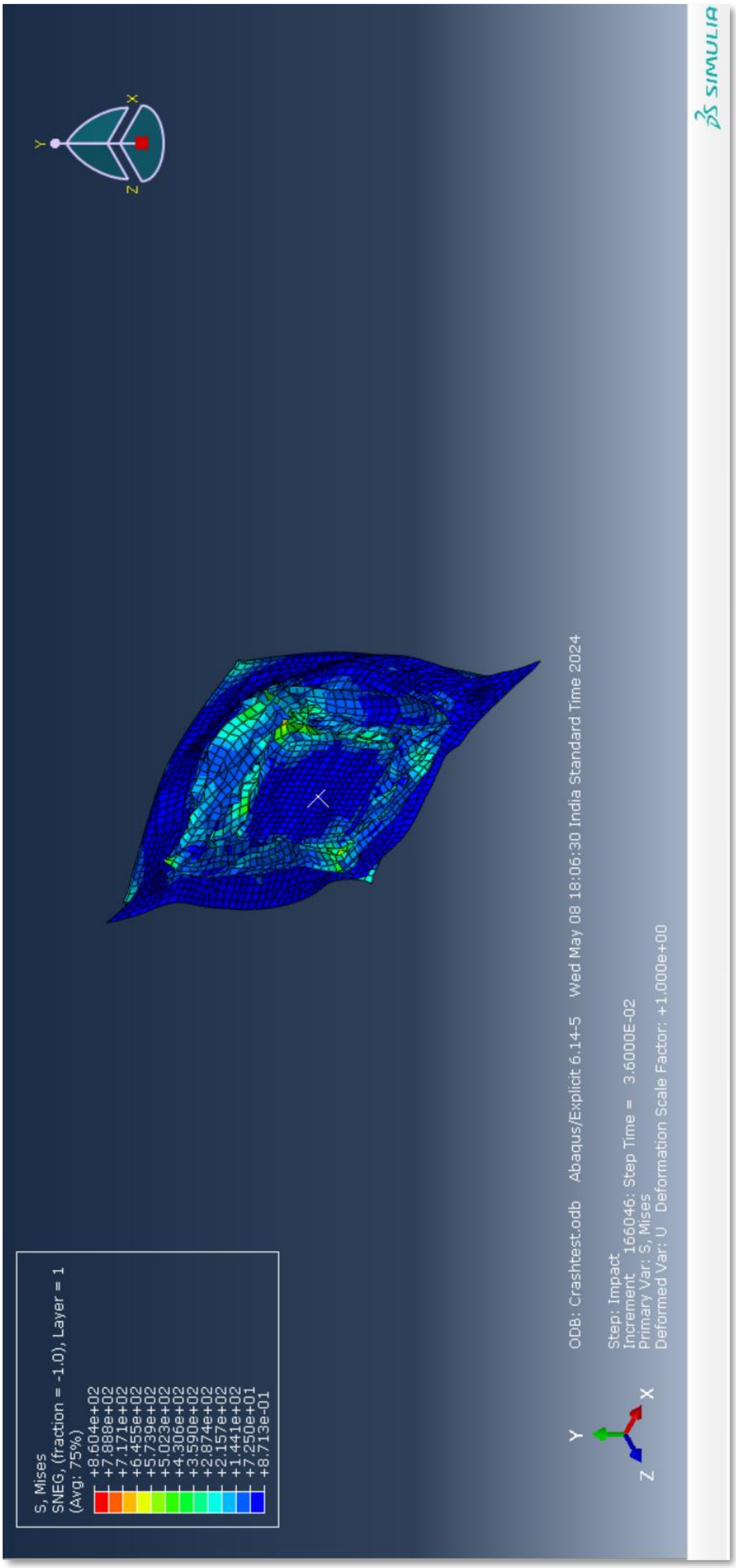


Figure 14. Initial Deformation of Step Impact Attenuator.



Figures 15. Final Deformation of Step Impact Attenuator.

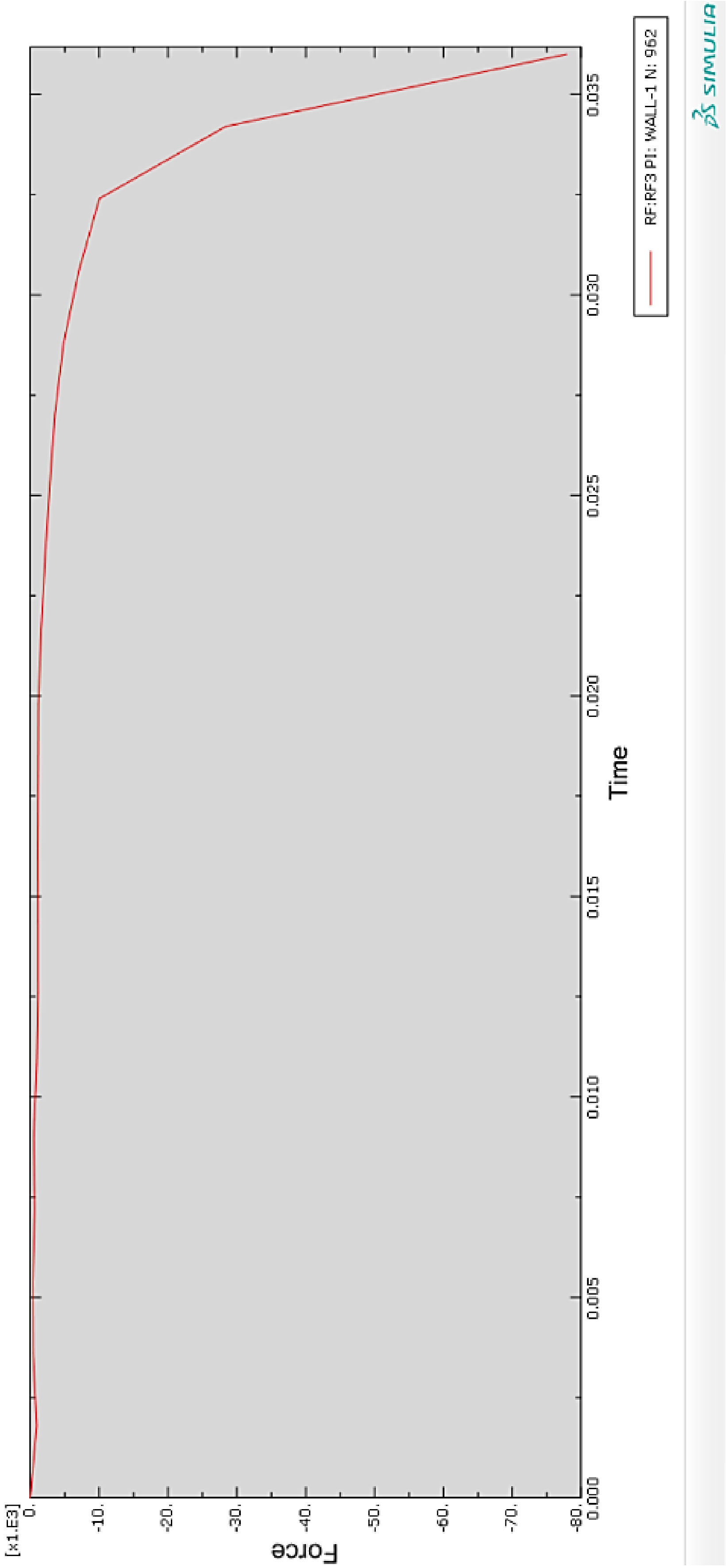


Figure 16. Force vs Time Graph.

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

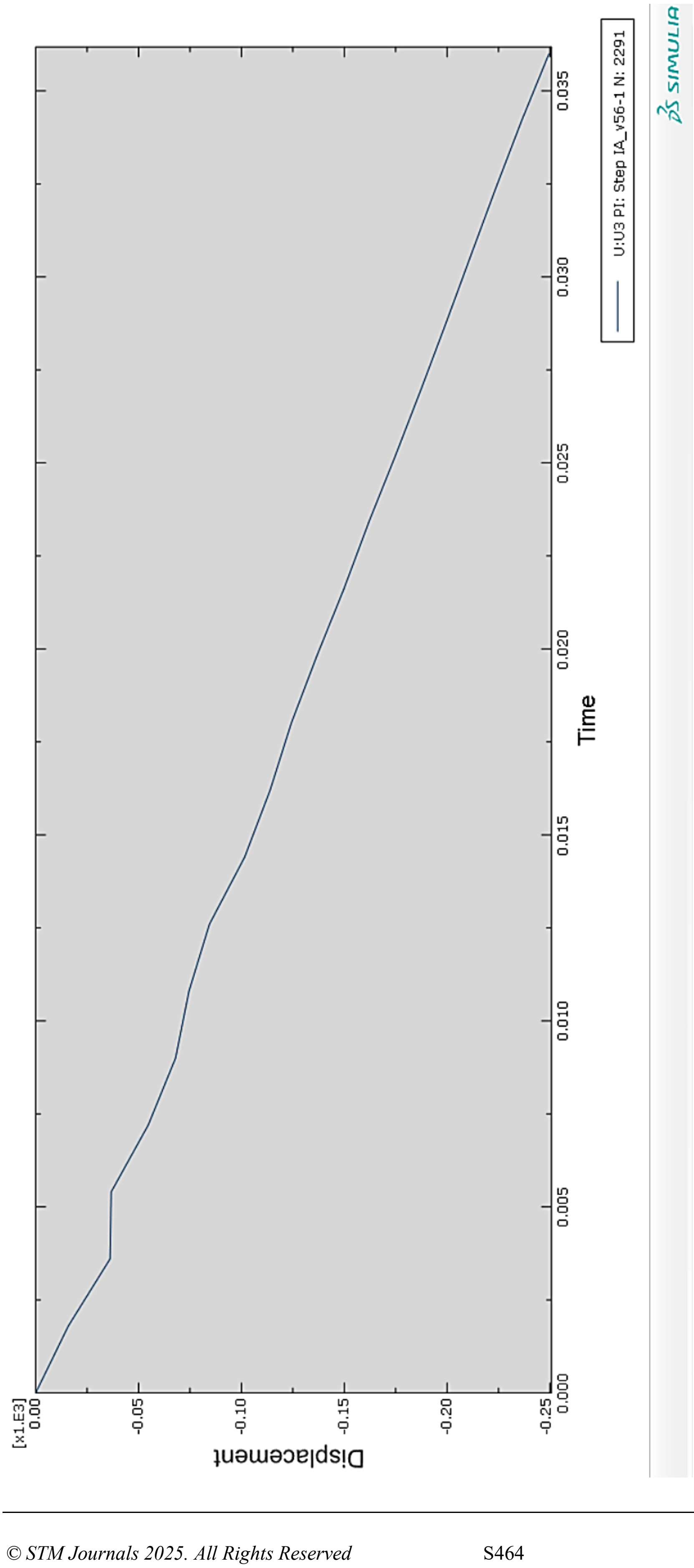


Figure 17. Displacement vs Time Graph.

The Force vs Displacement plot is shown in Figure 18. Negative signs of force magnitudes indicate that there is absorption of energy by the IA. The displacements were also initially negative, as Step IA moved in the negative Z direction. However, for calculation purposes, these negative values were converted to positive. Table 1 tabulates the magnitudes of force, displacement and energy absorbed by the step IA. From the table it is evident that the maximum force value is **-77914 N** (Negative sign implies compressive force), **249.56 mm** is the maximum displacement of the reference point on the step IA. The maximum energy absorbed was **12024 J** i.e. **12.024 KJ**, and the maximum AIP displacement was **18 mm**.

Three models of IAs were analysed to select optimum energy absorbing IA and these models are shown in Table-2. The energy absorbed by the model-1, 2 and 3 respectively are 10.15KJ, 21.17KJ and 12.024KJ. As the energy absorbed by model-1 was less than model-2 and 3, it was not considered for the crash test. For the model-2, energy absorption is 21.17KJ, which is more than the energy absorption by model-3, this is because, in mosel-3, fillets of 10mm radius were introduced on the edges, which gave the load path and there is decrease in the absorption of energy. However, the AIP displacement of the model-2 is 27mm, which is more than the model-3 of displacement 18.07mm. For the safety of driver, the limiting value of the displacement must be within 25.4mm [1]. The model-3 was selected as it displaces within the permissible value.

Average and Peak Deceleration

As per the rulebook [1] the Average and Peak deceleration of vehicle after the crash must be less than 20g and 40g, and the intent of this rule is that average deceleration of up to 20g ensures that the energy absorbed is gradual and there is no sudden spike in the energy absorption which helps protect the driver. As the magnitude of Average and Peak deceleration obtained were 26.48g and 2.39g respectively, which are within the permissible limit, the safety of vehicle and driver is ensured.

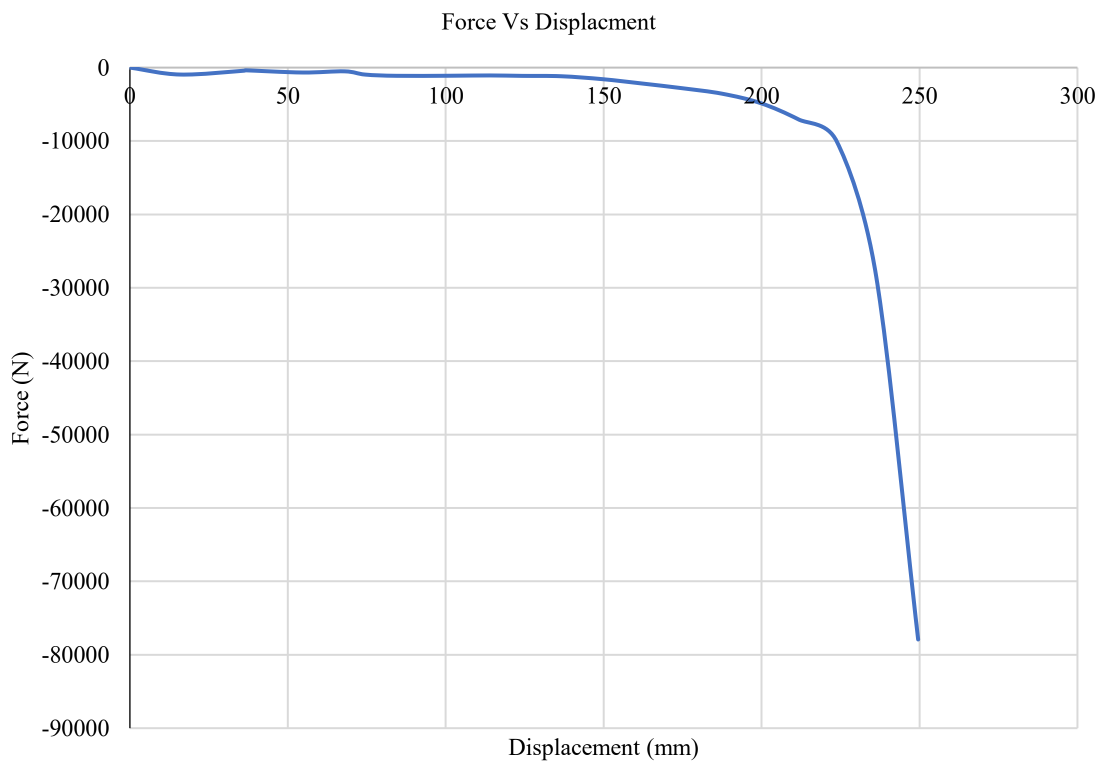


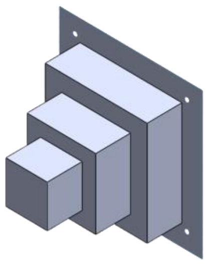
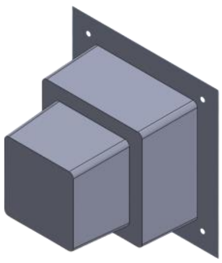
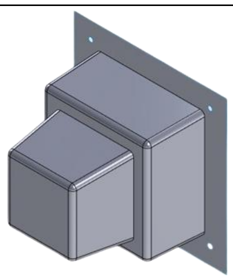
Figure 18. Force vs Displacement Graph.

Journal of Polymer & Composites
Volume 13, Special Issue 5
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

Table 1. Force, Displacement, Energy of Step Impact Attenuator.

Force (N)	Displacement (+) mm	Energy (J)	AIP Displacement (mm)
0	0	0.00	0.00
-944.657	15.8799	-7.50	0.00
-420.33	36.1351	13.64	0.00
-369.28	36.6855	1.86	0.28
-666.348	54.7112	-13.58	1.95
-507.281	67.9968	9.76	3.28
-948.766	74.5236	-31.46	2.24
-1118.4	84.479	-13.49	1.30
-1104.67	101.573	1.28	1.56
-1066.53	113.957	4.11	2.36
-1123.31	124.243	-6.76	2.69
-1176.08	136.618	-6.88	2.30
-1577.94	149.756	-57.54	2.05
-2153.68	161.913	-89.72	3.08
-2812.04	174.932	-110.88	5.14
-3556.62	187.514	-134.94	4.22
-4845.04	199.755	-249.48	5.48
-7062.47	211.728	-456.22	6.00
-10046.6	223.79	-649.82	7.30
-28411.9	236.271	-4224.58	9.85
-77914	249.566	-12024.98	18.07

Table 2. Comparison of various IA under study.

Impact Attenuator	Specification	Energy Absorption	AIP Displacement
 Model-1	4 layers of CF	10.15 KJ	22.5 mm
 Model-2	4 layers of CF 6 degree draft	21.17KJ	27 mm
 Model-3	4 layers of CF 10mm fillet 6 degree draft	12.024 KJ	18.07 mm

$Acceleration = Deceleration = \frac{Force}{Mass}$

a. Peak Deceleration
$Maximum\ Force = 77914$ N $Mass = 300$ kg
$Peak\ Deceleration = \frac{77914}{300} = 259.71\ \mathrm{m}/s^2$
$Peak\ Deceleration = 26.48$ g

b. Average Deceleration
$Average\ Force = 7039.33$ N $Mass = 300$ kg
$Average\ Deceleration = \frac{7039.33}{300} = 23.46\ \mathrm{m}/s^2$
$Average\ Deceleration = 2.39$ g

CONCLUSION

In conclusion, the design and analysis of an effective impact attenuator is crucial for ensuring the safety of drivers in motorsports events, particularly in the context of the Formula Student Association Event (FSAE) competitions. Through an extensive literature review, various impact attenuator designs were explored, each offering unique advantages and trade-offs in terms of energy absorption capabilities, weight, and manufacturing considerations. After carefully evaluating the different options, a carbon fibre step impact attenuator design was proposed, combining the benefits of both the square frustum and stepped aluminum tin configurations reported in the literature. This design leverages the exceptional strength-to-weight ratio and controlled deformation characteristics of carbon fiber composites, while incorporating a stepped geometry to facilitate progressive and efficient energy dissipation during an impact event.

The design process involved an iterative approach, where multiple iterations were modelled using SolidWorks CAD software, and their performance was evaluated through crash simulations conducted in ABAQUS explicit dynamics software. The simulations provided valuable insights into the energy absorption characteristics, deceleration profiles, and anti-intrusion plate (AIP) displacements for each design iteration. The final design, a two-step carbon fiber impact attenuator with a 6° draft angle and 10mm fillets, demonstrated promising results during the simulations. It achieved an impressive energy absorption of 12.02 KJ while maintaining the AIP displacement within the permissible limits of 25.4mm, ensuring the prevention of sharp object intrusion into the vehicle cockpit.

Overall, the design, analysis of the carbon fiber step impact attenuator demonstrated the potential for enhancing driver safety in motorsports events while adhering to FSAE regulations. The iterative design process, coupled with rigorous simulations, ensured that the final product met the necessary performance criteria and energy absorption requirements.

This study serves as a testament to the importance of continuous innovation and the pursuit of advanced materials and designs in the field of motorsports safety. By embracing cutting-edge technologies and leveraging computational tools, Engineers can develop more effective impact protection systems, setting new standards for driver safety in high-stakes racing competitions worldwide.

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