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Finite element analysis and crashworthiness evaluation of a multi-stage aluminium alloy 6061-T6 impact attenuator for Formula SAE

Aditia Pratama*, Zainal Abadi, Delima Yanti Sari, and Wanda Afnison

Department of Mechanical Engineering, Faculty of Engineering, Universitas Negeri Padang, **Indonesia**

*Corresponding Author: aditiaprt0903@gmail.com

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Abstract: Formula SAE regulations require every prototype vehicle to be equipped with an impact attenuator as a passive safety system capable of absorbing a minimum frontal impact energy of 7,350 J at an impact velocity of 7 m/s for a vehicle with a mass of approximately 300 kg. This study aims to design an impact attenuator that satisfies the Formula SAE requirements to improve vehicle crashworthiness. Three design variations were analyzed using Finite Element Analysis (FEA) with LS-DYNA to evaluate energy absorption, impact force, acceleration/deceleration, and displacement. The accuracy of the numerical model was validated using previously published experimental data before analyzing the effect of thickness variation in each stage of the impact attenuator. The simulation results show that the optimum design is capable of absorbing impact energy above the minimum requirement of 7,350 J, exhibits a high Crash Force Efficiency (CFE), produces acceleration within the prescribed safety limits, and provides controlled deformation during the impact process. The results indicate that the proposed impact attenuator design satisfies the Formula SAE safety requirements and has the potential to be applied to prototype vehicles to improve safety performance during frontal collisions.

Keywords: AA6061-T6 aluminium alloy; Crashworthiness; Energy absorption; Finite Element Analysis (FEA); Formula SAE; Impact attenuator

1. Introduction

The rapid development of electric vehicles has driven increasing research and development of prototype vehicles in academic environments, including Formula SAE competitions, where safety is regarded as one of the primary requirements in the vehicle design process (Belingardi & Obradovic, 2010; Kaya & Özyurt, 2022; SAE International, 2024). In the design of single-seat prototype vehicles, driver safety is the highest priority and is strictly regulated by the Formula SAE Rules (SAE International, 2024). One of the most important passive safety systems is the impact attenuator, an energy-absorbing structure installed at the front of the vehicle to reduce the kinetic energy generated during a frontal collision before the load is transmitted to the Front Bulkhead and the primary vehicle structure (Arora & Venkatachalam, 2022; Belingardi & Obradovic, 2010; Boria, 2010). According to the Formula SAE Rules 2025, the impact attenuator must be capable of absorbing a minimum kinetic energy of 7,350 J during a frontal impact involving a 300 kg vehicle traveling at an impact velocity of 7 m/s (SAE International, 2024). In addition to energy absorption capacity, deceleration characteristics are also critical parameters for evaluating crashworthiness, as they are directly related to the level of driver protection during frontal collisions (Belingardi & Obradovic, 2010; Hermawan et al., 2025; Kaya & Özyurt, 2022).

Crashworthiness is the ability of a vehicle structure to absorb impact energy through controlled plastic deformation, thereby reducing the deceleration experienced by the driver and improving safety during collisions (Abramowicz & Jones, 1986; Boria, 2010; Jones, 2011). In thin-walled structures, the desired energy absorption mechanism is progressive plastic collapse, as it provides a more stable distribution of impact forces than global deformation or sudden structural failure (catastrophic collapse) (Abramowicz & Jones, 1986; Reid & Harrigan, 1998). Therefore, the impact attenuator should be designed to produce stable progressive deformation, allowing the impact energy to be absorbed effectively without increasing the load transmitted to the primary vehicle structure.

Various studies have evaluated different impact attenuator concepts to improve the crashworthiness performance of Formula SAE vehicles. Geometric optimisation of impact attenuators has been reported to enhance energy absorption capacity while controlling the deceleration characteristics during frontal collisions (Belingardi & Obradovic, 2010; Boria, 2010). Design developments involving variations in cross-sectional geometry, grooves, holes, and varying wall thickness have also demonstrated improvements in crash force efficiency and specific energy absorption (Kaya & Özyurt, 2022). In addition, the use of honeycomb structures, composite materials, and multi-stage or stepped-thickness configurations has been investigated through both numerical and experimental approaches to improve energy absorption efficiency and deformation stability during impact (Belingardi & Obradovic, 2010; Hermawan et al., 2025; Vettorello et al., 2020; Xie et al., 2023). Despite these developments, studies specifically evaluating the influence of thickness distribution configuration at each stage (multi-stage thickness configuration) as the primary design parameter on crashworthiness response remain very limited.

Studies investigating the influence of thickness distribution configuration at each stage (multi-stage thickness configuration) as the primary design parameter on crashworthiness response remain relatively limited, particularly those that comprehensively evaluate energy absorption, peak deceleration, average deceleration, crush distance, and crash force efficiency in accordance with the Formula SAE Rules 2025. However, the thickness distribution at each stage has the potential to control the sequence of plastic deformation (progressive collapse), thereby improving energy absorption efficiency while reducing the deceleration characteristics during frontal collisions. Therefore, a dedicated investigation is required to evaluate the effect of a multi-stage thickness configuration on the crashworthiness performance of an impact attenuator.

This study aims to evaluate the effect of thickness distribution configuration in a multi-stage impact attenuator made of Aluminium Alloy 6061-T6 on crashworthiness performance using Finite Element Analysis (FEA) based on explicit dynamic analysis in ANSYS LS-DYNA. Aluminium Alloy 6061-T6 was selected because of its high strength-to-weight ratio, good corrosion resistance, and plastic deformation characteristics that are suitable for energy-absorbing structural applications (ASM Handbook Committee, 1990). FEA has been widely employed in crashworthiness analysis because it can accurately predict the deformation behaviour of thin-walled structures, stress distribution, and impact response (Athafarras et al., 2022; Prasetya et al., 2021; Rogala & Gajewski, 2023). Unlike previous studies, which primarily focused on optimising geometric shapes or local structural features, this study considers the thickness distribution configuration between stages as the primary design variable to evaluate its influence on crashworthiness response. Three thickness configurations were analysed and compared to identify the design that provides the best balance between energy absorption, deceleration characteristics, and structural efficiency while satisfying the requirements of the Formula SAE Rules 2025.

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2. Methods

A numerical approach using FEA was employed in this study to design and evaluate the crashworthiness performance of the impact attenuator structure. The research procedure consisted of a literature review, geometric design, three-dimensional modelling, numerical simulation, and result analysis and evaluation. The simulations were performed using the LS-DYNA explicit dynamic solver to predict the structural response under frontal impact conditions. This approach has been widely applied in crashworthiness analysis because it can accurately represent nonlinear deformation behaviour, energy absorption, and impact force distribution during the collision process (Athafarras et al., 2022; Prasetya et al., 2021; Segade et al., 2016).

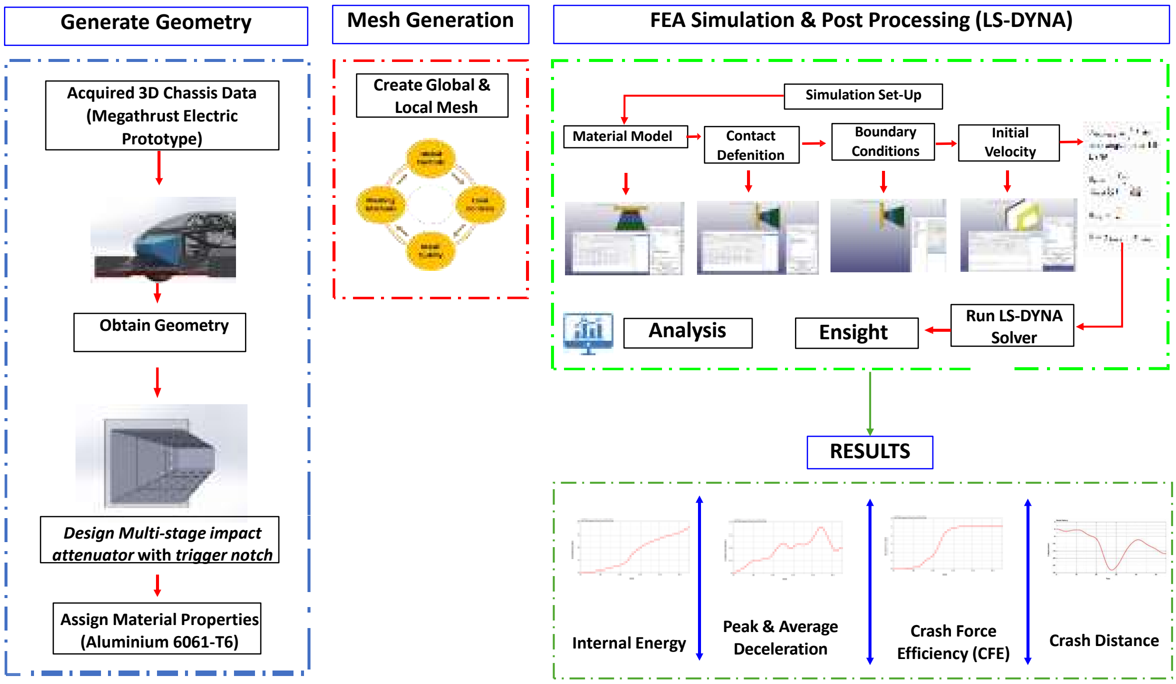

Figure 1. Flowchart of the research methodology

Figure 1 illustrates the research methodology employing an explicit dynamic FEA approach to evaluate the crashworthiness of the impact attenuator structure. The research procedure consisted of a literature review, three-dimensional geometric design, mesh generation, application of boundary conditions, numerical simulation, and post-processing to obtain the parameters of energy absorption, peak and average deceleration, crush distance, and crash force efficiency. All numerical simulations were performed using ANSYS LS-DYNA student version, which has been widely employed in impact analysis because it can accurately represent nonlinear material behaviour, complex contact interactions, and plastic deformation in thin-walled structures (Athafarras et al., 2022; Prasetya et al., 2021). This numerical approach was used to evaluate the structural response under frontal impact conditions and to assess its compliance with the requirements of the Formula SAE Rules, particularly in terms of energy absorption capability and deceleration characteristics, which were used as the primary parameters for crashworthiness evaluation (Belingardi & Obradovic, 2010; SAE International, 2024).

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Table 1. Material properties of Aluminium Alloy 6061-T6

Property	Value	Unit
Density	2.70	g/cm³
Young's Modulus	68.9	Gpa
Poisson's Ratio	0.33	-
Yield Strength	276	MPa
Ultimate Tensile Strength	310	MPa

The impact attenuator was designed with a truncated prism geometry using Aluminium Alloy 6061-T6. This material was selected because of its high strength-to-weight ratio and plastic deformation characteristics, which make it suitable for energy-absorbing structural applications. The material properties used in the numerical simulations are presented in Table 1 and were obtained from the standard data provided in the ASM Handbook (ASM Handbook Committee, 1990).

2.1 Geometry model

The impact attenuator was designed as a thin-walled shell structure with dimensions adapted to the front bulkhead area of the Megathrust vehicle. The design adopted a multi-stage configuration combined with trigger notches to initiate progressive plastic deformation, thereby improving energy absorption efficiency during frontal impact (Rogala & Gajewski, 2023; Rooppakhun et al., 2015; Xie et al., 2023). The geometry of each stage and the overall impact attenuator configuration are illustrated in Figure 2, while the thickness variation of each stage investigated in this study is presented in Table 2.

(a)
(b)
(c)
(d)

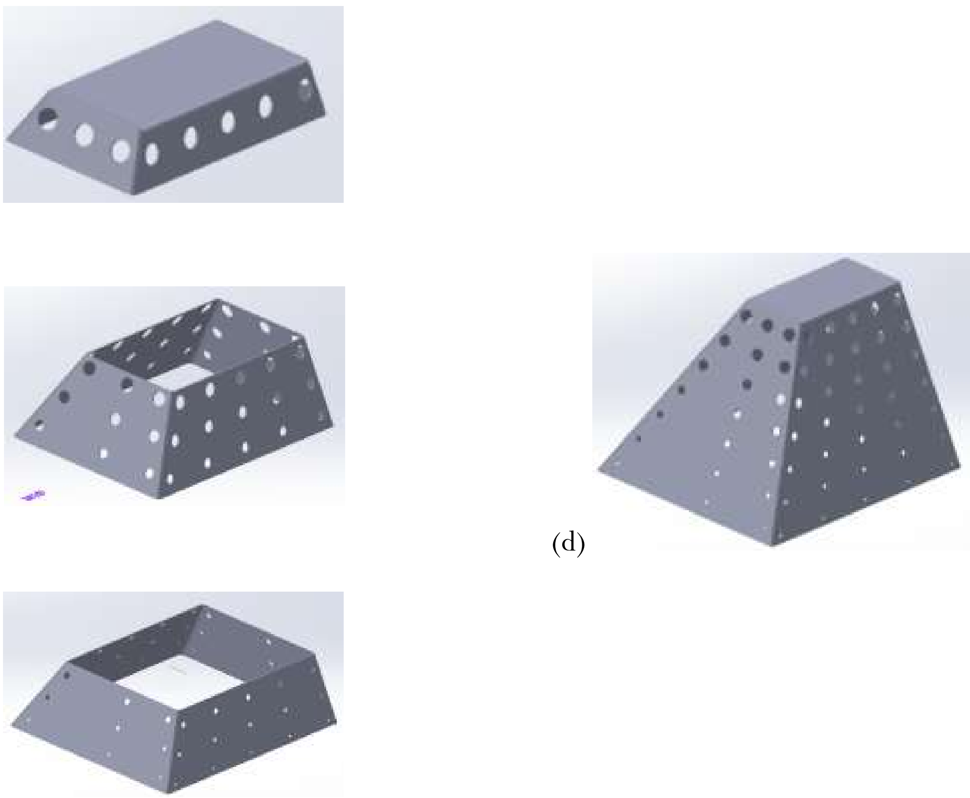

Figure 2. Geometry of the multi-stage impact attenuator with trigger notches: (a) Stage 1, (b) Stage 2, (c) Stage 3, and (d) overall impact attenuator model

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Figure 2 illustrates the geometry of each stage comprising the impact attenuator, together with the assembled impact attenuator model. The model consists of three stages arranged in a multi-stage configuration and is equipped with trigger notches at the front of the structure. Table 2 presents the thickness variations of each impact attenuator stage investigated in this study. Three thickness configurations were applied to evaluate the effect of thickness variation on the structural response through numerical simulations.

Table 2. Thickness configurations of each stage of the impact attenuator model

Variasi	Stage 1 (mm)	Stage 2 (mm)	Stage 3 (mm)
Variation 1	0.7	0.9	2
Variation 2	0.7	1.1	2.7
Variation 3	0.9	1.5	2

2.2 Simulation parameters and setup

The impact attenuator model was analysed using FEA with LS-DYNA to evaluate the structural response under frontal impact conditions. The simulation parameters, including loading conditions, material properties, and boundary conditions, are presented in Table 3. The simulation setup, comprising the initial velocity, impact direction, and contact definitions between components, is illustrated in Figure 3.

Table 3. Simulation parameters

Parameter	Value / Setting
Analysis type	Explicit dynamic (Crash / Impact)
Material model	MAT_024 Piecewise Linear Plasticity
Material model (Rigid body)	MAT_RIGID
Element type (dominant)	Shell (Belytschko-Tsay)
Shell element size	2 – 4 mm
Mesh quality (angle)	0.35 (max), 0.25 (min)
Solid element size	8 mm
Contact algorithm	CONTACT_AUTOMATIC_SURFACE_TO_SURFACE
Contact tied	CONTACT_TIED_NODES_TO_SURFACE_OFFSET
Friction coefficient	Static 0.3, Dynamic 0.2
Impact velocity	7 m/s
Mass of vehicle	300 kg
Termination time	55 s
Hourglass control	IHQ = 4, QM = 0.10
Output database	D3PLOT, GLSTAT, MATSUM, RCFORC

Table 3 summarises the principal parameters used in the numerical simulations, including the impact velocity, impactor mass, boundary conditions, simulation time, and element size. All parameters were kept consistent across all model configurations.

Figure 3 illustrates the configuration of the frontal impact simulation used in this study. The simulation begins by assigning an initial velocity to the impact attenuator, as shown in Figure 3(a). Subsequently, the model moves toward the rigid wall along the prescribed impact direction, as illustrated in Figure 3(b). The contact definition between the impact attenuator and the rigid wall during the simulation is shown in Figure 3(c).

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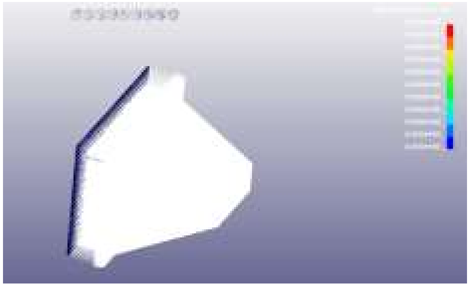
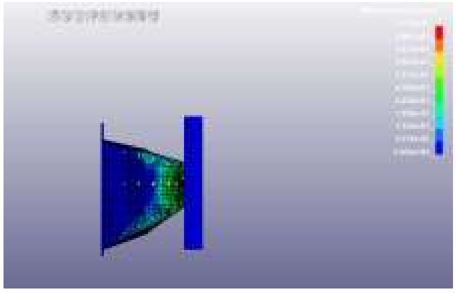


(a)



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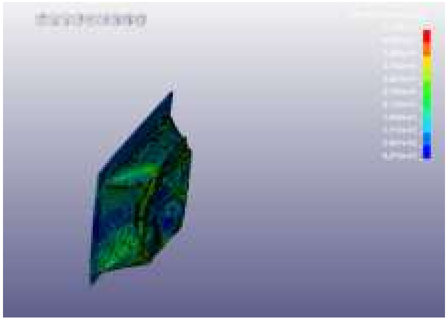

(c)

Figure 3. Configuration of the frontal impact simulation in LS-DYNA: (a) initial configuration of the impact attenuator, (b) frontal impact of the impact attenuator against the rigid wall, and (c) contact interaction between the impact attenuator and the rigid wall during impact

2.3 Meshing

Mesh type and mesh density play a critical role in numerical simulations, as the mesh is an essential component of the simulation process. The impact attenuator model was discretised using shell elements with a mesh size of 2–4 mm. A mesh independence study was conducted to determine the mesh size that provides converged results with efficient computational cost. Based on the results of the mesh independence study, the final model consisted of 28.609 elements. The mesh configuration of the simulation model is illustrated in Figure 4.

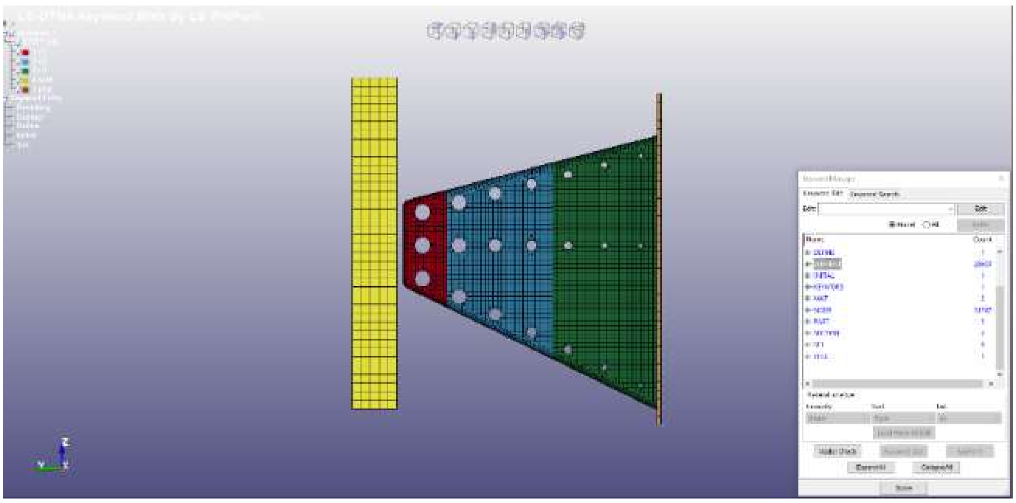

Figure 4. Finite element mesh model of the impact attenuator

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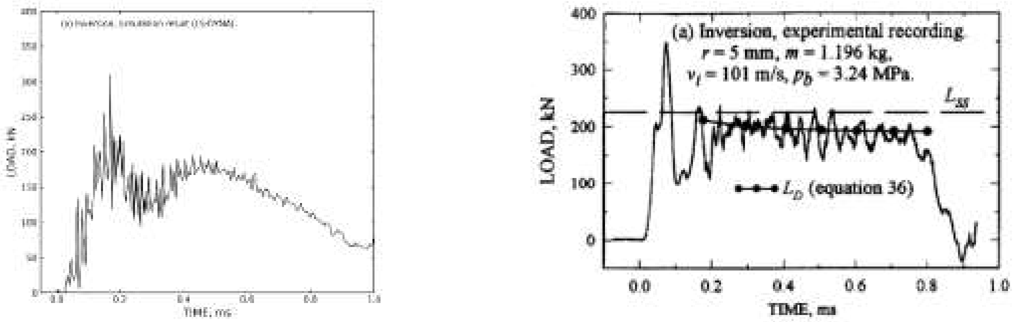
2.4 Validation and regulatory compliance

2.4.1 Validation

The numerical model was validated by comparing the force–time curve obtained from the LS-DYNA simulation with previously published experimental data (Reid & Harrigan, 1998). The comparison was conducted to evaluate the agreement between the numerical model and the structural response observed during impact loading based on the characteristics of the force–time curve, including the peak force, transient phase, and steady-state load. The comparison between the simulation results and the experimental data is presented in Figure 5.



(a) (b)

Figure 5. Comparison of the force–time curves obtained from (a) the LS-DYNA simulation and (b) the experimental data (Reid & Harrigan, 1998)

Table 4. Comparison between the simulation results and the experimental data

Parameter	Experiment	Simulation	Error (%)
Peak force (kN)	350	310	11.43
Steady-state load (kN)	220	176	20

As summarised in Table 4, the LS-DYNA simulation predicted a peak force of 310 kN, whereas the experimental data showed a value of 350 kN, resulting in a relative error of 11.43%. For the steady-state load, the simulation predicted a value of 176 kN, while the experimental data indicated a value of approximately 220 kN, corresponding to a relative error of 20.00%. These results indicate that the numerical model provides a good prediction of the peak force but underestimates the steady-state load compared with the experimental results.

Nevertheless, the force–time curve obtained from the simulation in Figure 5(a) exhibits characteristics similar to those of the experimental curve shown in Figure 5(b). Both curves demonstrate the occurrence of a peak force during the initial stage of impact, followed by a decrease in force towards a relatively stable steady-state load region throughout the inversion process. The similarity in the response patterns indicates that the numerical model is capable of representing the primary deformation mechanism occurring during the impact process (Reid & Harrigan, 1998).

The discrepancy in the steady-state load is likely attributable to the simplifications adopted in the numerical model, including the assumptions regarding material properties, contact and friction conditions, and the idealised boundary conditions employed in the explicit simulation. These factors primarily affect the structural response after the transient phase, resulting in a greater deviation in the steady-state load region than in the peak force (Athafarras et al., 2022; Prasetya et al., 2021). Overall,

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the numerical model is capable of reproducing the principal characteristics of the force–time curve and predicting the peak force with a relative error of 11.43%. Therefore, the validated model was used to evaluate the effect of the multi-stage thickness configuration on the crashworthiness response of the impact attenuator in this study.

2.4.2 Compliance with Formula SAE rules

The performance of the impact attenuator was evaluated based on the requirements specified in the Formula SAE Rules, including energy absorption, peak deceleration, average deceleration, and crush distance. The acceptance limits for each parameter are presented in Table 5 and were used as the evaluation criteria for the numerical simulation results (SAE International, 2024).

Table 5. Impact attenuator requirements specified in the Formula SAE Rules

Parameter	Formula SAE Requirement
Absorbed Energy	≥ 7,350 J
Peak Deceleration	< 20 g
Average Deceleration	< 40 g
Crush Distance	< 150 mm

The performance of the impact attenuator was evaluated based on the requirements specified in the Formula SAE Rules 2025, including energy absorption, peak deceleration, average deceleration, and crush distance. The acceptance limits for each parameter are presented in Table 5 and were used as the evaluation criteria for the numerical simulation results. These parameters were selected because they represent the ability of the structure to absorb impact energy, control the deceleration response, and limit deformation during the impact process (Belingardi & Obradovic, 2010; SAE International, 2024).

3. Results and discussion

Numerical simulations using LS-DYNA were conducted on three impact attenuator design variations to evaluate the effect of stage thickness variation on the structural performance. The evaluation was performed based on the parameters of energy absorption, peak deceleration, average deceleration, crush distance, and Crash Force Efficiency (CFE) in accordance with the requirements of the Formula SAE Rules 2025.

3.1 Energy absorption performance

Energy absorption is a primary parameter for evaluating the performance of an impact attenuator, as it reflects the effectiveness of the structure in dissipating impact energy in accordance with the requirements of the Formula SAE Rules 2025 (SAE International, 2024). The internal energy curves for the three design variations are presented in Figure 6, while the energy absorption values of each model are summarised in Table 6.

Table 6. Comparison of the energy absorption values for the three impact attenuator design variations

Model Variation	Internal Energy (J)	Compliance
Variation 1	17,024.1	Pass
Variation 2	25,266.5	Pass
Variation 3	17,797.5	Pass

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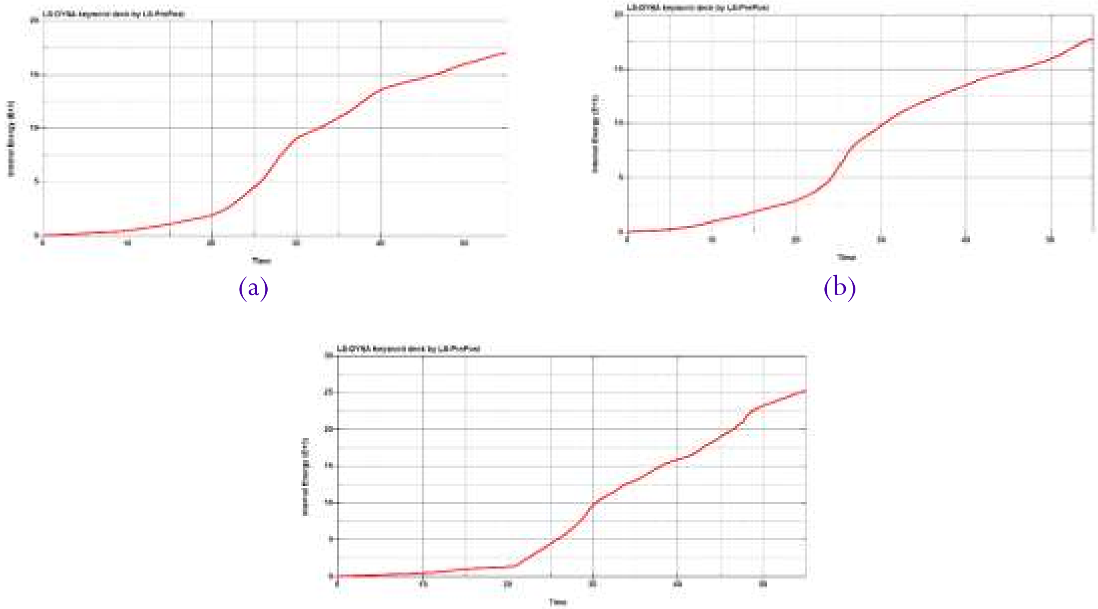

(a) (b)

(c)

Figure 6. Internal energy–time curves for the three impact attenuator design variations: (a) Variation 1, (b) Variation 2, and (c) Variation 3

Based on the numerical simulation results, Variation 2 achieved the highest energy absorption of 25,266.5 J, followed by Variation 3 with 17,797.5 J and Variation 1 with 17,024.1 J. All three design variations satisfied the minimum energy absorption requirement of 7,350 J specified in the Formula SAE Rules 2025, and therefore all designs achieved PASS status. The higher energy absorption obtained by Variation 2 indicates that its stage thickness configuration promoted more effective plastic deformation during the impact process, thereby enabling the structure to absorb impact energy more efficiently (Kaya & Özyurt, 2022; Prasetya et al., 2021). The internal energy curves shown in Figure 6 exhibit a continuous increase throughout the impact event without any abrupt decrease. This behaviour indicates that the impact energy was absorbed progressively through a mechanism of progressive plastic deformation, thereby preventing catastrophic collapse during the impact process. This deformation mechanism is a key characteristic of energy-absorbing structures designed to enhance crashworthiness through controlled deformation (Abramowicz & Jones, 1986; Belingardi & Obradovic, 2010; Reid & Harrigan, 1998).

3.2 Deceleration characteristics

Peak deceleration and average deceleration are key parameters for evaluating the impact response of an impact attenuator, as they are directly related to the inertial forces experienced by the driver during the impact event. These parameters were used to evaluate the deceleration characteristics throughout the impact process. The resultant acceleration curves for the three design variations are presented in Figure 7, while the values of peak deceleration and average deceleration are summarised in Table 7.

Table 7. Peak deceleration and average deceleration values for the three impact attenuator design variations

Model Variation	Peak deceleration (g)	Average deceleration (g)	Compliance
Variation 1	76.68	29.06	Not Pass
Variation 2	51.50	19.89	Not Pass
Variation 3	37.93	15.09	Pass

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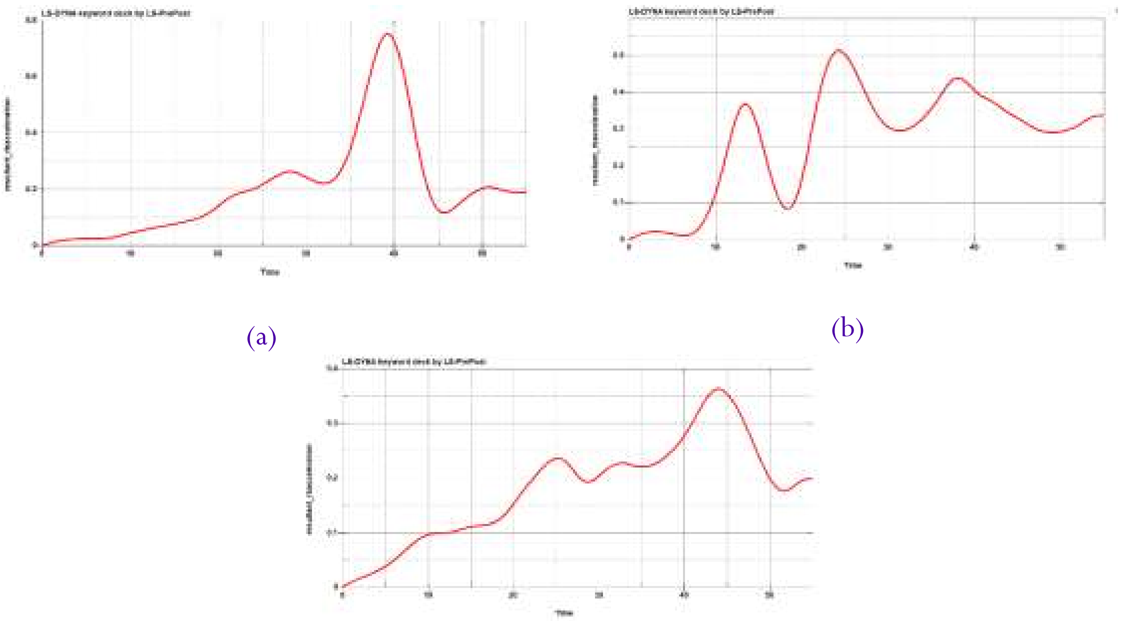
The reduction in deceleration indicates that the multi-stage configuration promotes more progressive deformation during the impact process, resulting in a more controlled distribution of the impact forces (Hermawan et al., 2025; Rooppakhun et al., 2015). Although Variation 2 exhibited a higher energy absorption capacity, Variation 3 provided a better balance between energy absorption capability and deceleration characteristics, thereby demonstrating a more balanced crashworthiness performance (Belingardi & Obradovic, 2010; Kaya & Özyurt, 2022).



(a) (b) (c)

Figure 7. Resultant acceleration–time curves for the three impact attenuator design variations: (a) Variation 1, (b) Variation 2, and (c) Variation 3

Based on the numerical simulation results, Variation 3 produced the lowest peak deceleration of 37.93 g and an average deceleration of 15.09 g, followed by Variation 2 with 51.50 g and 19.89 g, respectively, and Variation 1 with 76.68 g and 29.06 g. These results indicate that the multi-stage thickness configuration adopted in Variation 3 produced a lower deceleration response than the other two design variations.

3.3 Crush distance

Crush distance is a parameter used to evaluate the axial deformation of the impact attenuator during the impact process. The Y-displacement–time curves for the three design variations are presented in Figure 8, while the crush distance values for each model are summarised in Table 8.

Table 8. Crush distance values for the three impact attenuator design variations

Model Variation	Crush distance (mm)	Compliance
Variation 1	28	Pass
Variation 2	13	Pass
Variation 3	29	Pass

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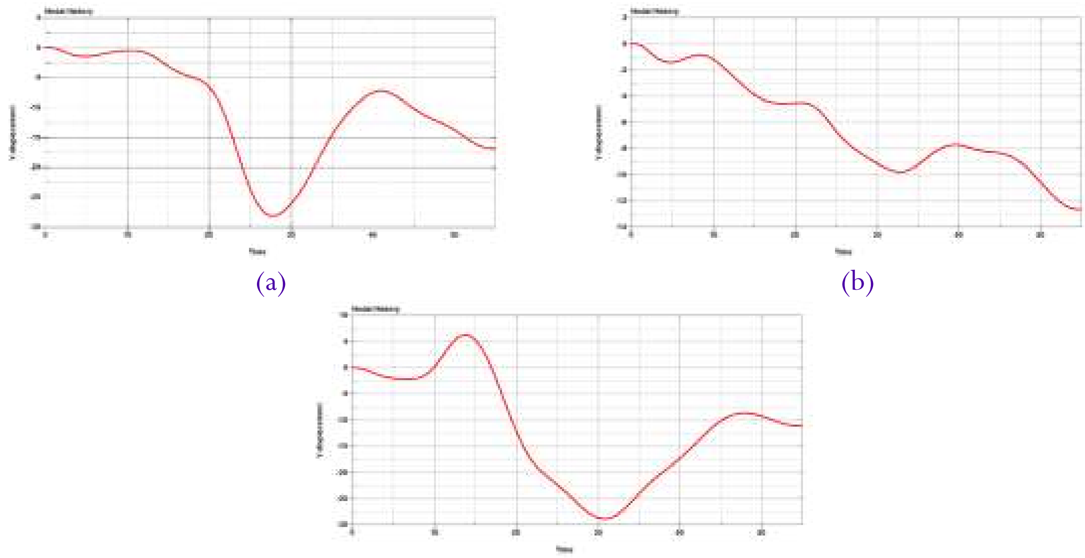
The differences in crush distance among the design variations indicate that the multi-stage thickness configuration influences the structural deformation characteristics. Variation 2 produced the smallest crush distance, whereas Variation 3 exhibited the greatest axial deformation. When considered together with the results presented in Sections 3.1 and 3.2, Variation 3 provided a better balance between energy absorption capability, deceleration characteristics, and structural deformation than the other design variations (Kaya & Özyurt, 2022).



(a) (b) (c)

Figure 8. Axial displacement (Y-displacement)–time curves for the three impact attenuator design variations: (a) Variation 1, (b) Variation 2, and (c) Variation 3

Based on the simulation results, the crush distance values were 28 mm, 13 mm, and 29 mm for Variation 1, Variation 2, and Variation 3, respectively. All design variations satisfied the requirements specified in the Formula SAE Rules, with crush distance values below the maximum allowable limit of 150 mm (SAE International, 2024). These results indicate that the structural deformation remained within the permissible limit, thereby ensuring that the integrity of the survival cell was maintained throughout the impact event (Belingardi & Obradovic, 2010).

3.4 Crash Force Efficiency (CFE)

Crash Force Efficiency (CFE) was used to evaluate the efficiency of impact force distribution during the deformation process of the impact attenuator. A CFE value approaching 1 indicates a more uniform force distribution, resulting in a more effective energy absorption process (Rooppakhun et al., 2015; Xie et al., 2023). The impact force–time curves for the three design variations are presented in Figure 9, while the peak force, average force, and CFE values are summarised in Table 9.

Table 9. Hasil evaluasi Crash Force Efficiency (CFE) pada setiap variasi desain impact attenuator

Variasi Model	Peak Force (N)	Average Force (N)	CFE
Variasi 1	4.940	5.050	0.97
Variasi 2	3.650	3.928	0.92
Variasi 3	5.000	5.210	0.95

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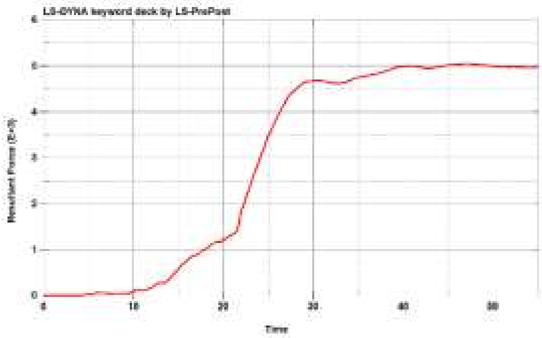
Overall, considering the energy absorption capability, deceleration characteristics, crush distance, and Crash Force Efficiency (CFE), Variation 3 demonstrated a better overall performance balance than the other design variations. These findings indicate that the implementation of a multi-stage thickness configuration contributes to improving the crashworthiness of the impact attenuator structure, consistent with previous studies on thin-walled aluminium structures (Reid & Harrigan, 1998; Rogala & Gajewski, 2023).



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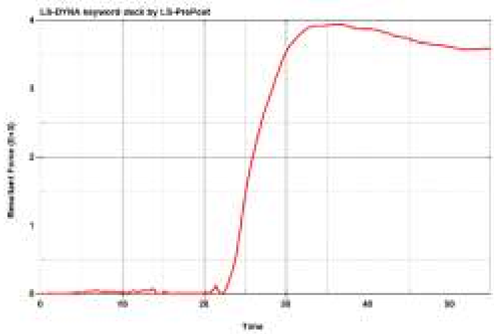

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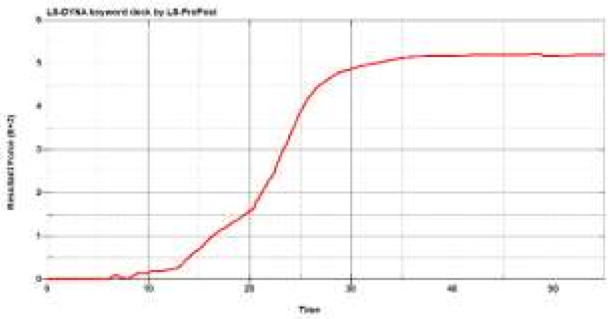

(c)

Figure 9 Kurva gaya tumbukan (impact force) terhadap waktu pada setiap variasi desain impact attenuator. (a) Variasi 1, (b) Variasi 2, dan (c) Variasi 3

Based on the simulation results, the CFE values obtained were 0.97, 0.92, and 0.95 for Variation 1, Variation 2, and Variation 3, respectively. All design variations achieved CFE values above 0.90, indicating that the impact force distribution remained relatively stable throughout the deformation process. Variation 1 exhibited the highest CFE value, whereas Variation 3 maintained a high CFE while exhibiting lower deceleration and structural deformation characteristics than the other design variations.

4. Conclusion

This study successfully developed an Aluminium Alloy 6061-T6 impact attenuator design based on a multi-stage configuration in accordance with the safety requirements of the Formula SAE Rules. Numerical analysis using Finite Element Analysis (FEA) based on LS-DYNA was conducted to evaluate energy absorption capability, deceleration characteristics, crush distance, and Crash Force Efficiency (CFE) as the primary parameters for crashworthiness assessment. The simulation results demonstrated that all design variations absorbed energy exceeding the minimum requirement of 7,350 J specified by the Formula SAE Rules. Variation 2 achieved the highest energy absorption capacity, whereas Variation

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3 exhibited the lowest deceleration characteristics, with a peak deceleration of 37.93 g and an average deceleration of 15.09 g. Furthermore, all design variations produced crush distance values below the maximum allowable limit of 150 mm and CFE values above 0.90, indicating that the impact force was distributed efficiently throughout the deformation process.

Based on the overall evaluation of the crashworthiness parameters, Variation 3 demonstrated a better overall performance balance than the other design variations. The multi-stage thickness configuration combined with trigger notches promoted more progressive deformation, thereby providing a favourable compromise between energy absorption capability, deceleration characteristics, structural deformation, and force distribution efficiency. These findings suggest that this design approach has the potential to serve as a reference for the development of impact attenuators for prototype vehicles designed in accordance with the Formula SAE Rules. Future research is recommended to conduct experimental validation through impact testing, such as quasi-static crush tests or dynamic impact tests, to verify the accuracy of the numerical simulation results and to evaluate the design performance under testing conditions that more closely represent real-world applications.

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Author's declaration

Author contribution

Aditia Pratama: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – Original Draft. **Zainal Abadi**: Methodology, Supervision, Data curation, Visualization, Writing – Review & Editing. **Delima Yanti Sari**: Validation, Formal analysis, Investigation, Writing – Review & Editing. **Wanda Affnison**: Conceptualization, Data curation, Visualization, Writing – Review & Editing.

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Data availability

The simulation data and LS-DYNA input files generated during this study are available from the corresponding author upon reasonable request.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical clearance

Not Applicable

AI statements

The translation of this manuscript was assisted by ChatGPT, while grammar checking and language refinement were performed using Grammarly to improve the readability and linguistic quality of the manuscript. No sentences, figures, or tables presented in this manuscript were generated by artificial intelligence. The authors take full responsibility for the content of the manuscript.

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