

Numerical Investigation of Crash Energy Distribution of Lightweight Vehicle at Medium and High-Speed Impacts

Yogendren Subramani¹, Mohd Norihan Ibrahim^{1*}

¹ Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Parit Raja, Johor, 86400, MALAYSIA

*Corresponding Author: norihan@uthm.edu.my

DOI: <https://doi.org/10.30880/rpmme.2025.06.02.023>

Article Info

Received: 20 June 2025

Accepted: 20 September 2025

Available online: 10 December 2025

Keywords

Crash Energy Distribution,
Lightweight Vehicle, Finite Element
Analysis (FEA), Vehicle
Crashworthiness

Abstract

This study investigates how crash energy is distributed in a lightweight vehicle during frontal collisions at 45 km/h and 90 km/h using Finite Element Analysis (FEA) in ANSYS. As there is an increased demand of fuel efficient and environmentally supporting vehicles, the usage of lightweight materials such as aluminum is on the rise. Although these materials add to functioning and productivity, the problems in accidents emerge. The simulation findings indicated that during medium speeds, light weight vehicles are crashworthy, yet during high speeds severe deformation and concentration of stress undermines structural strength. The paper emphasizes the importance of hybrid materials and advanced design reinforcements aiming at the equilibrium between effectiveness and safety of the occupants.

1. Introduction

The automotive industry is undergoing a significant transformation driven by the urgent need to improve fuel efficiency and reduce environmental impact. This shift has led to a growing interest in lightweight vehicle structures that utilize materials such as aluminum alloys, high-strength steel, and composites to reduce overall vehicle mass while maintaining structural performance [1, 2]. While these materials offer clear advantages in terms of fuel economy and emission reduction, their crash performance particularly under medium and high-speed impacts raises concerns about occupant safety and structural integrity [3].

Crashworthiness, which is defined as the capacity of the vehicle to offer protection to its occupants in case of a crash, is a major design concern that becomes complicated with the introduction of lightweight material. Contrary to traditional materials, such as steel, lightweight materials react a different way in case of dynamic loads, which frequently leads to uncertainties in the deformation patterns and energy absorption behaviors. To address this, computational tools such as Finite Element Analysis (FEA) have become indispensable in modern crash studies. These simulations allow engineers to model, test, and optimize vehicle crash performance in a virtual environment, significantly reducing the cost and time associated with physical crash testing [4].

This research applies ANSYS simulation software to carry out a numerical inquiry of the crash energy arrangements of a low-weight sedan car during the front collision axial direction at two highways 45 km/h (urban speed) and 90 km/h (highway speed). The lessons of this study will seek to determine the structural weaknesses, evaluate material behavior and rendering design advice that will improve the energy absorption and occupant protection without affecting the advantages of light-weighting of the cars [5]

2. Material and Method

This section explaining on the research project conducted by using SolidWorks software to make lightweight vehicle and wall geometric design. The primary goal is to analysis the crash energy distribution in lightweight vehicle at medium (45km/hr) and high-speed (90km/hr) impacts. Ansys software was used to run the simulation.

2.1 Material Selection

Material properties for geometry models are specified in ANSYS Workbench by determining the Engineering Data and selecting the suitable materials. Material selection is critical for accurately depicting the physical properties and behavior of objects during simulation. The wall is built of structural steel, while the vehicle is made of aluminum alloy.

Table.Error! No text of specified style in document. **1 Dimension of lightweight vehicle**

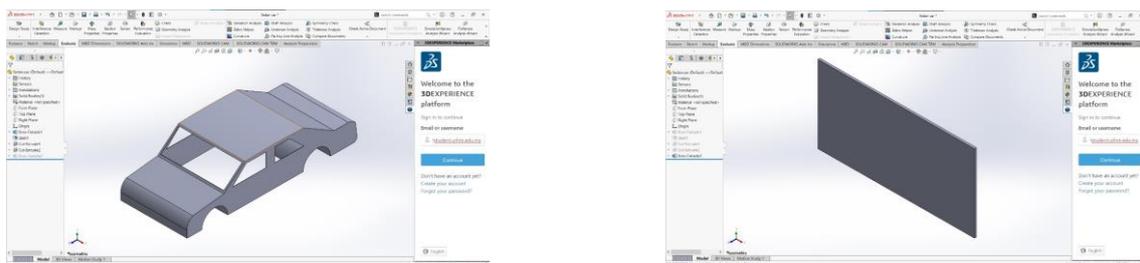
Length	4,150 mm
Width	1,620 mm
Height	1,510 mm
Wheelbase	2,455 mm
Weight	930 kg

Table Error! No text of specified style in document.**2 Dimension of steel wall**

Density	7850 kg/m ³
Yield Strength	250 - 500 MPa
Elastic Modulus	200 GPa
Poisson's Ratio	0.3
Height	2.0 m
Width	4.0m (coverage of the vehicle's width during impact)
Thickness	0.05 m

2.2 Geometry Model

These dimensions are the real-life dimensions which are taken out of company catalogues. With the vehicle, as in the case of the car, the territory of the Competition Commission is limited to the location and parking of the vehicle and not to the running of the car. Due to this, its focus is only on the body of the automobile (its model). The dimensions of the vehicle are meant to make it as realistic as possible, so as to assure realism. derived on real-life car sizes, including the Perodua Bezza 2024 model. The length and width of the wall is determined with the condition that to cover the car body during the impact.



(a)

(b)

Fig.1 Geometry model; (a) vehicle, (b) wall

2.3 Mesh

The meshing process in the finite element simulations is critical in finite element models since it involves breaking down the geometry into discrete elements permitting the approximation of the complex physical systems at the time of impact. In the current case, more mesh density was specifically used in the front-end part of the lightweight sedan model, specifically the crumple zone and the bumper to record the detailed deformation as per the crash conditions. The refinement means that it is more precise in regions most energy is absorbed during the frontal collision at 45km/h and 90km/h.

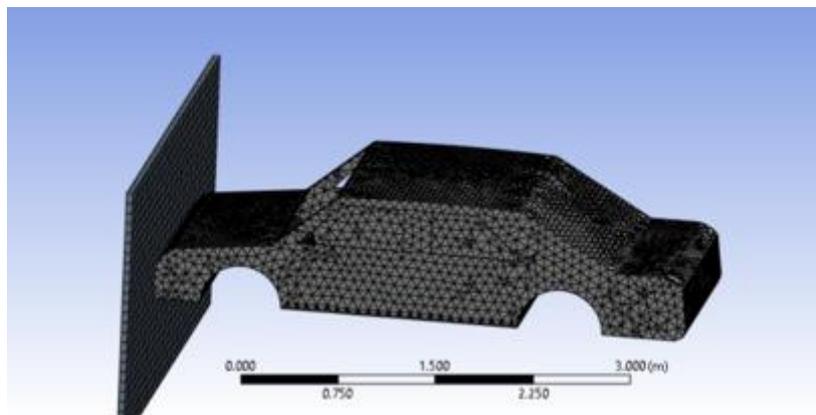


Fig. 2 Final Mesh of wall and vehicle

2.4 Simulation

In the present project, the ANSYS workbench was applied to model the crash behavior of a lightweight vehicle in medium (45 km/h) and high-velocity (90 km/h) frontal impact. It started with importation of a 3D model of a lightweight sedan which was designed using SolidWorks to ANSYS. The material was given in terms of material properties: car structure in aluminum alloys and rigid wall in steel to reflect the behavior as it happens in the real world in the form of crash.

The rigid wall was fixed, and initial velocities (45 km/h and 90 km/h) of the vehicle body on the wall were provided via the Explicit Dynamics module, therewith the boundary conditions implemented. The car was put in motion towards the wall and pretended to be in frontal crash into it. The back or bottom of the wall was supported by a fixed support that recreates an immovable barrier in the real world. In order to carry out the simulation we employed an explicit solver. Time step used was chosen due to convergence needs, and output control was setup so that enough data points would be stored (e.g. deformation, stress, strain). Analysis of crash energy absorption patterns and structural performance was conducted by evaluating the overall deformation, equivalent (von Mises) stress, and equivalent elastic strain with the help of post-processing.

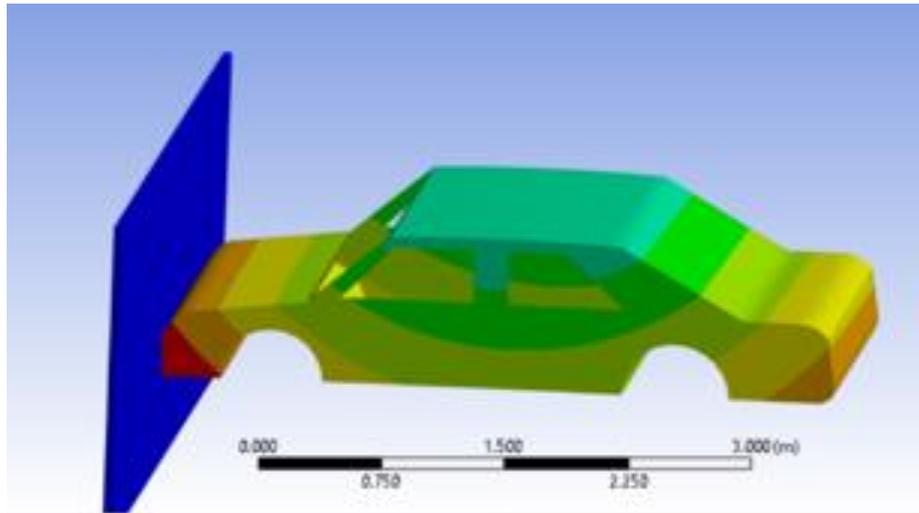
2.5 Solution

In the current analysis, the ANSYS at 45 km/h and 90 km/h was used to simulate the collision of an aluminum alloy lightweight sedan body with a rigid steel wall. The wall was stuck in its place all the way to depict an immovable obstacle in the real world. The simulation involved total deformation of the front-end particularly the crumple zone and the bumper and we followed the deformation on X- axis to examine the behavior of the impact. Analysis of equivalent (von Mises) stress was also conducted in order to determine the propensity of the material to yield or break under crash loads in order to determine the crashworthiness of the lighter weight structure as well.**Error! No text of specified style in document.**

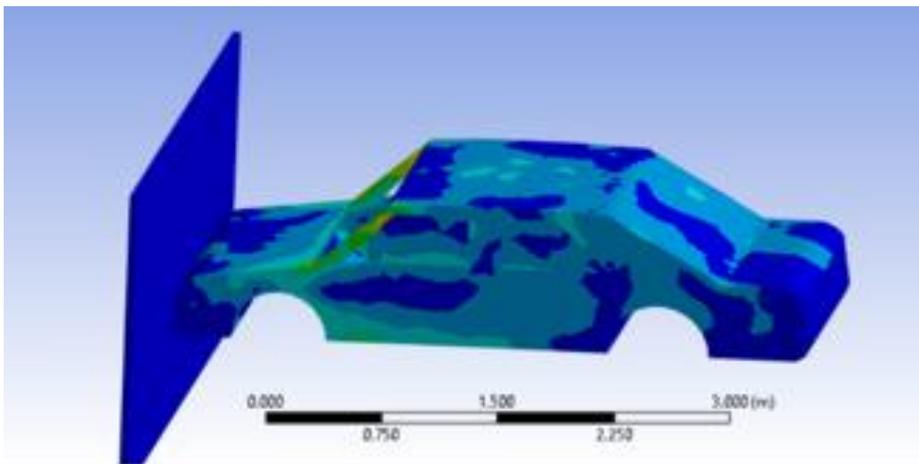
3. Results and Discussion

3.1 Simulation result at 45km/h

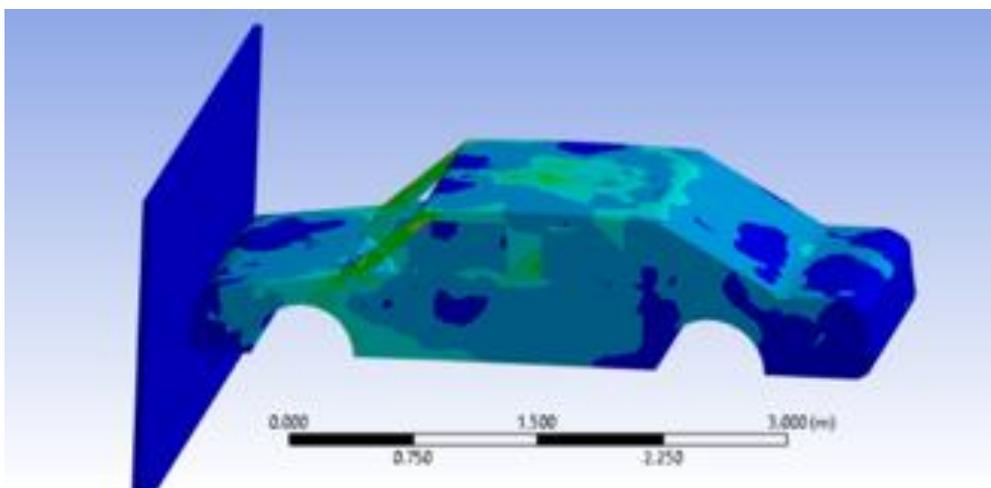
This visualization describes the general deformation of the lightweight sedan in case of its collision with a rigid wall with the velocity of 45 km/h. Summarized deformation map shows that deformation of the vehicle structure, in particular its front-end, is distorted after the impact and the view of the distribution and absorption of energy during the crash event is clear.



(a)

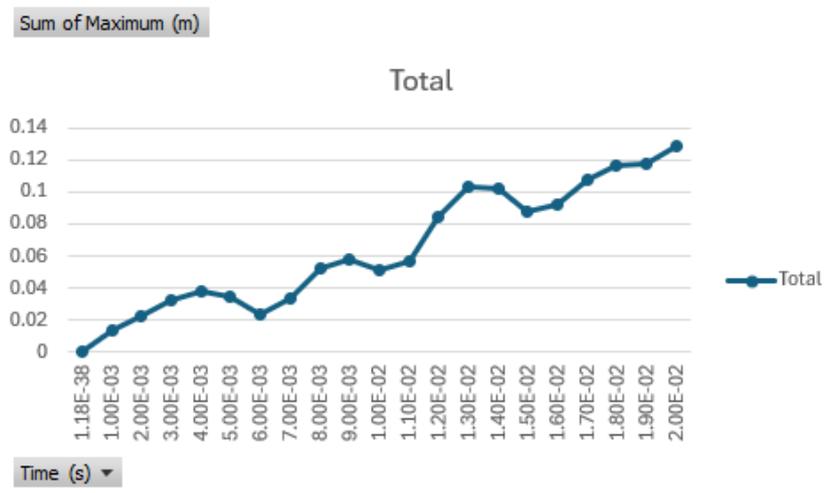


(b)

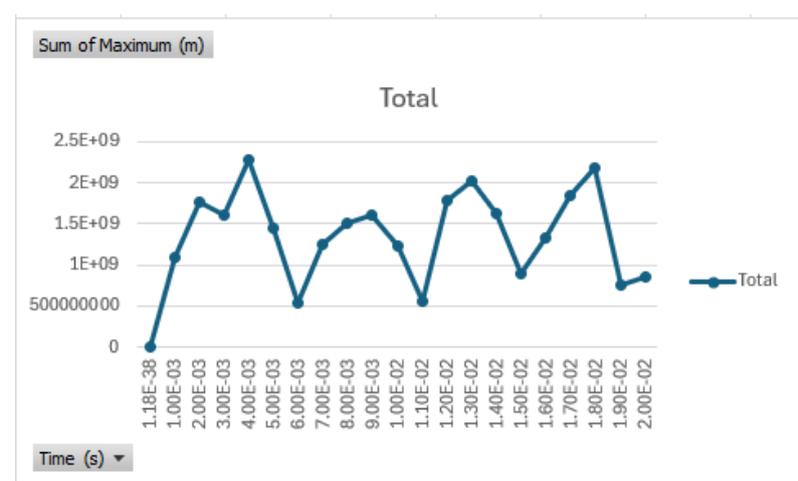


(c)

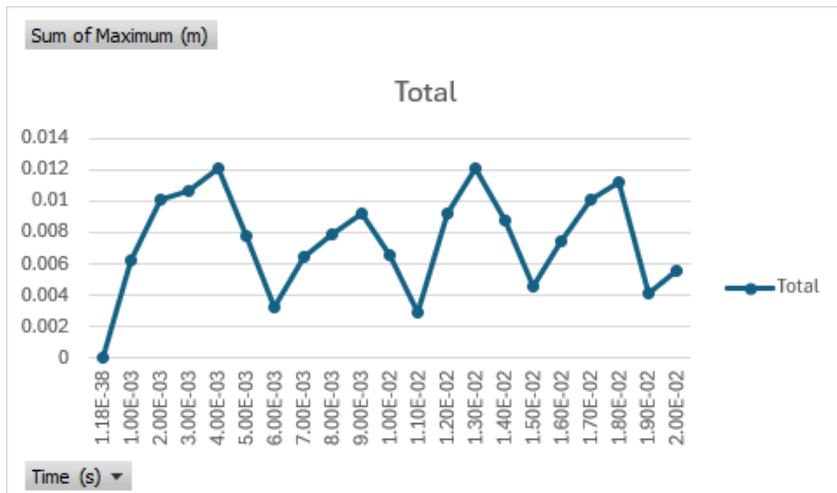
FigError! No text of specified style in document.. 3 Simulation impact at 45 km/h, (a).Profile of Deformation, (b).Equivalent Stress, (c)Equivalent Elastic Strain



(a)



(b)

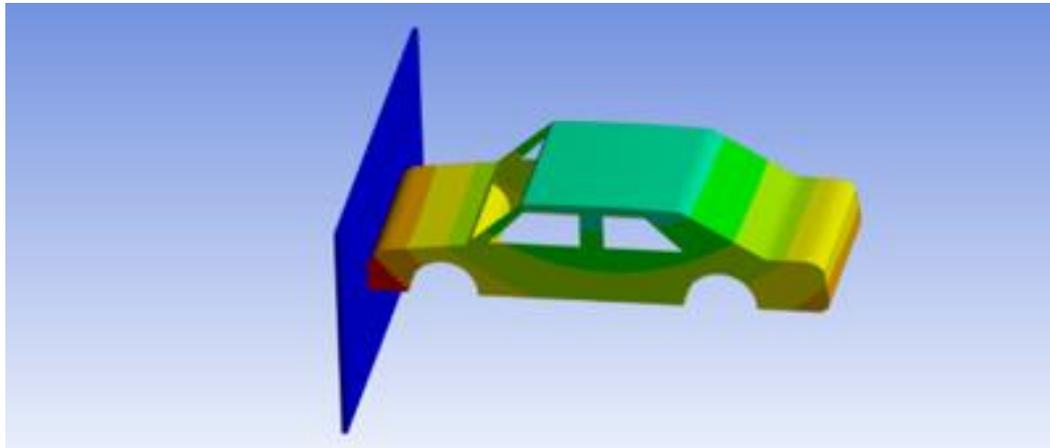


(c)

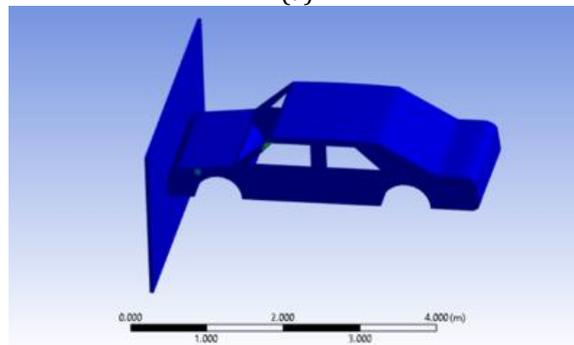
Fig. 4 Simulation impact at 45km/h; (a). Total deformation vs time, (b). Total equivalent stress vs time, (c). Total equivalent elastic strain vs time

3.2 Simulation result at 90km/hr

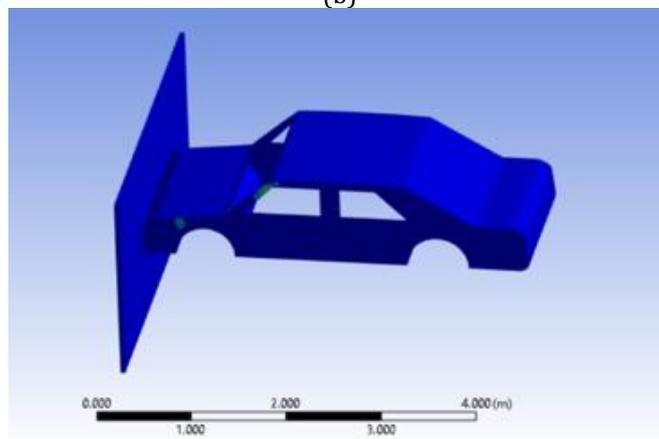
The figure is presented to show overall deformation caused by the collision of the frontal part of the vehicle and a rigid wall at 90 km/h speed. The simulation implies the initial velocity to the whole vehicle body of 90 km/h. This graphical image of total deformation, equivalent stress, and directional displacement gives significant information of how the lightweight car reacts to high-velocity impacts on the structure. The selected velocity makes a huge impact on the level of deformation and its concentration, which can assist in recognizing the importance of stress areas as well as the problem of possible structural characteristic weaknesses in the front-end of the vehicle.



(a)

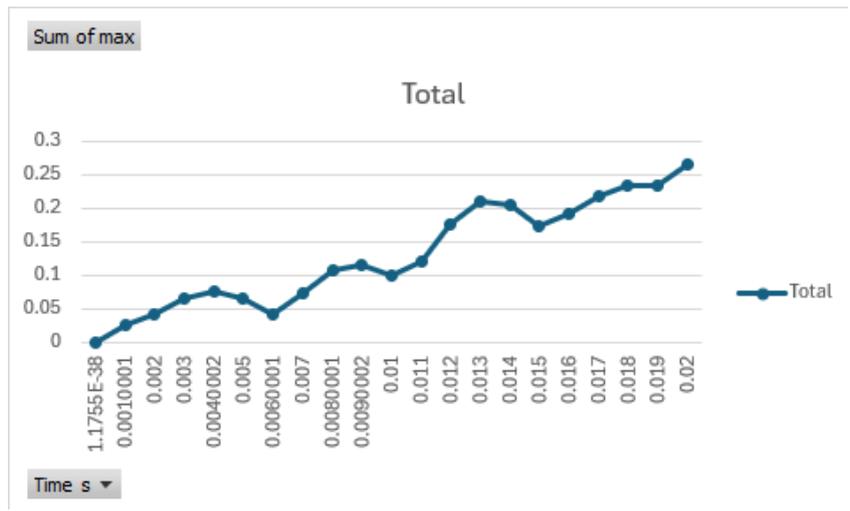


(b)

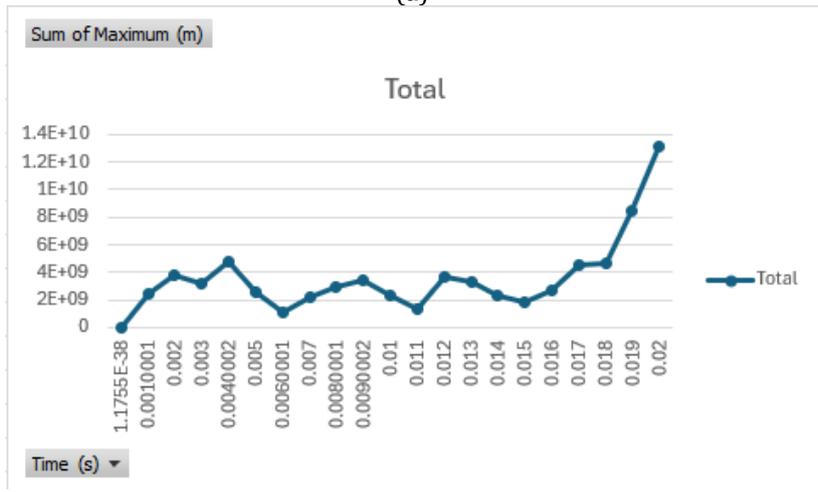


(c)

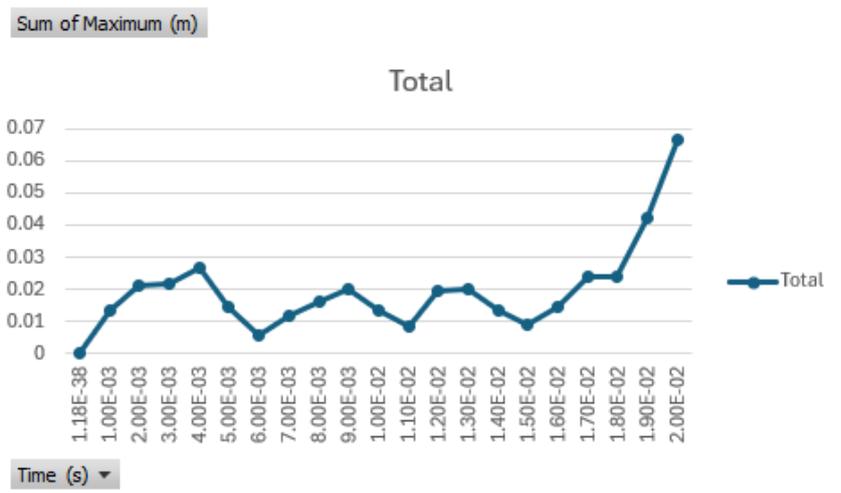
Fig. 5 Impact speed at 90km/h; (a). Deformation, (b). Equivalent Stress, (c). Equivalent Elastic Strain



(a)



(b)



(c)

Fig. 6 Impact speed at 90km/h; (a). Total deformation vs time, (b). Total equivalent stress vs time, (c). Total equivalent elastic strain vs time

3.3 Analysis of deformation profile

In the 45 km/h speed, the car exhibited moderate and minimal deformation where the maximum was approximately 129 mm. The body took the force of the crash fairly and in particular, at the front and the passenger cabin remained viable. The deformation performed at the speed of 90 km/h was considerably worse with its peak of approximately 265 mm. The front part of the car suffered severe damage and the area that got impacted were crucial ones such as the firewall with increased risk to safety. To conclude, the car responded well to mid-speed crashes, however, high-speed collisions greatly damaged it, which indicates that either better material or a better design of lightweight cars is necessary.

3.4 Analysis of equivalent stress

When speed was at 45 km/h, there was a gradual increase in equivalent stress, with the highest value approximated to be 2.18GPa. The stress was predominantly located on the front-end areas such as bumper and crumple zone. This means that the building was able to withstand the force without any serious collapse. The stress levels were considerably higher at the speed of 90 km/h with the highest being 13.17 GPa. Increased stress transferred to further components of the vehicle including the firewall and A-pillars with the increased likelihood of the material failure and severe structural damage. Altogether, the findings indicate that under the crashes of moderate levels, the car can resist them well; however in case of high-speed impacts, extremely high tensions appear, which cause possible cracks or even collapse in the main parts. This indicates the necessity to have better material or reinforcement in high-risk areas.

3.5 Analysis of equivalent elastic strain

At the speed of 45 km/h the elastic strain was developed gradually and it approximately reached 0.0112 (unitless). This indicates that the material bent into non-hazardous elastic strains, i.e. the building was able to restore its initial form without facing permanent deformation in most of the regions. With 90 km/h, the strain became significantly higher with maximum strain of 0.0663 which implies that the material was severely stretched. Such extent of strain implies that some elements of the vehicle could have been over stressed beyond their elastic limit to result into plastic deformation or even possible failure. In short, the car demonstrated recovery strain and control medium speed but under high speed, there was extreme stretching of the material which may cause failure in the system. This brings out the importance of improved material choice and reinforcement of the design at high-impact areas.

4. Conclusion

This study has been able to show why it is worthwhile to analyze crash energy distribution in lightweight vehicles, especially when the category is said to be of medium and high-speed frontal impacts. It was identified through rigorous simulation via ANSYS software that lightweight materials as made of aluminium alloys do possess a far-reaching benefit into weight reduction of vehicles and of course improving fuel consumption, but on the other hand, they carry a greater challenge to uphold structure integrity and the safety of its occupants in event of high energy collision. The simulations revealed that at a medium speed of 45 km/h, the vehicle had a good front-end structure in the absorption of a large amount of impact energy and therefore had negligible cabin intrusion and acceptable levels of deformation. But there was a decrease in energy absorption capacity of the structure at a faster velocity of 90 km/h and heavier concentration of stress and maximum deformation in crucial points, such as firewall and A-pillar, which provided a possibility of reducing the occupant survival space. These results highlight the importance of design reinforcements; hybrid material use or multi-layer crumple zone and structural geometry optimization so that lightweight cars can be designed to have reasonably good crashworthiness in many different speed conditions. Overall, the study can be helpful in achieving the right balance between a lightweight design combined with safety and help car engineers and manufacturers to come up with safer structures of vehicles that impact neither vehicle performance nor the protection of occupants.

Acknowledgement

The authors wish to thank the Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia that has supported on the accomplishment of research activity.

Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Yogendren Subramani;; **data collection:** Yogendren Subramani, Mohd Norihan Ibrahim; **analysis and interpretation of results:** Yogendren Subramani; **draft manuscript preparation:** Yogendren Subramani, Mohd Norihan Ibrahim. All authors reviewed the results and approved the final version of the manuscript.

References

- [1] Busarac, Nina & Dragan Adamović & Nenad Grujović & Fatima Zivic (2022) Lightweight Materials for Automobiles, IOP Conference Series: Materials Science and Engineering, 1271(1), 012010. <https://doi.org/10.1088/1757-899X/1271/1/012010>
- [2] Wu, Dongsheng & Kenny Wei & Arin Mo & Vincent Yan & Ruoxi Wang (2024) Application of lightweight materials in automobiles: A review, Applied and Computational Engineering, 84, 72–99. <https://doi.org/10.54254/2755-2721/84/20240775>
- [3] Idrees, U., Ahmad, S, Alam Shah, I, Talha M, Shehzad R and Amjad M, (2023), *Finite element analysis of car frame frontal crash using lightweight materials*. Journal of Engineering Research, <https://doi.org/10.1016/j.jer.2023.100007>
- [4] Ariffin, N., Kamarudin, K.-A., Abdullah, A. S., & Abd Samad, M. I. (2022) Crash Investigation on Frontal Vehicle Chassis Frame using Finite Element Simulation, Journal of Advanced Research in Applied Sciences and Engineering Technology, 28, 124–134. <https://doi.org/10.37934/araset.28.2.124134>
- [5] Rajesh, R., Babu, A. R., Reddy, C., Maheswari, C. U., & Sakthivelan, N. (2023) Crash analysis of car body structure by using FEM, AIP Conference Proceedings, 2869, 050004.