

Design and Finite Element Analysis of Lightweight Composite Automotive Body Under Frontal and Rear Impact Conditions

Kamatam Munna Kiran¹, Dr. S. Solomon Raj²

¹Student M.E(CAD/CAM), Department of Mechanical Engineering, Chaitanya Bharathi Institute of Technology, Hyderabad.

²Associate Professor, Department of Mechanical Engineering, Chaitanya Bharathi Institute of Technology, Hyderabad.

Abstract — The increasing demand for lightweight, safe, and fuel-efficient vehicles has driven structural optimisation of automotive body frames. A passenger vehicle body shell was designed in SolidWorks and analysed in ANSYS Workbench 2024 R1 under frontal and rear impact at 60, 80, and 100 km/h using five material configurations: ABS, structural steel, Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), and a hybrid CFRP+GFRP laminate. Performance metrics — total deformation, equivalent stress, equivalent strain, and factor of safety (FOS) were extracted for each scenario. Modal analysis extracted the first six natural frequencies and mode shapes. Results show CFRP achieves superior crashworthiness (FOS > 2.40 at all speeds) and highest natural frequencies (86.38–153.62 Hz), while the hybrid composite nearly replicates CFRP performance at reduced cost. ABS is structurally unsuitable and steel approaches failure at 100 km/h. The hybrid CFRP+GFRP laminate is the optimal lightweight alternative to conventional steel for passenger car body shell applications.

Keywords— Crashworthiness; CFRP; GFRP; Hybrid Composite; ANSYS Workbench; FEA; Modal Analysis; Automotive Body Shell; Factor of Safety; Lightweight Materials.

I. INTRODUCTION

The automotive industry faces increasing pressure to develop vehicles that are simultaneously lightweight, fuel-efficient, and crashworthy. Conventional steel body structures contribute significantly to overall vehicle mass, adversely affecting fuel economy and emissions. Advanced composite materials such as CFRP and GFRP have emerged as promising alternatives owing to their superior specific stiffness and strength.

The car body shell must withstand high-energy impact loads during frontal and rear collisions while protecting occupants. Evaluation of crashworthiness through total deformation, equivalent stress, strain, and factor of safety is essential during the design stage.

FEA using ANSYS Workbench provides an efficient means to simulate crash behaviour without physical testing cost. Modal analysis characterises the dynamic response by extracting natural frequencies and mode shapes, helping avoid resonance. This paper evaluates five material configurations — ABS, steel, CFRP, GFRP, and hybrid CFRP+GFRP — under frontal and rear impact at 60, 80, and 100 km/h, and under free vibration conditions.

II. LITERATURE REVIEW

Venkatesh and Suresh [1] performed frontal crash FEA of a passenger car body and reported significant stress concentrations at front rail junctions. Obradovic et al. [2] showed composite energy-absorbing structures reduce peak crush force by 40% vs. steel. Hickey and Xiao [3] validated an FE crash model against experimental barrier test data.

Mohamed and Hashim [4] compared CFRP, aluminium, and steel for automotive hoods, reporting 60% mass reduction with CFRP at maintained stiffness. Sellitto and Riccio [5] confirmed composite laminates meet pedestrian safety criteria. Han and Chi [6] linked vibration modes to structural noise, guiding NVH improvement.

Abid and Rizmin [7] showed CFRP configurations achieve lower HIC values during pedestrian impact. Yan and Xu [8] highlighted hybrid laminates as a cost-effective automotive strategy. Karthikeyan et al. [9] found CFRP bumpers absorbed 35% more energy than steel. Patil et al. [10] confirmed CFRP structural integrity at higher impact speeds using ANSYS explicit dynamics.

III. METHODOLOGY

1. Material Selection

The five materials were selected for comparative analysis: Steel, Acrylonitrile Butadiene Styrene (ABS), Glass Fiber Reinforced Polymer (GFRP), Carbon Fiber Reinforced Polymer (CFRP), and a Hybrid Composite consisting of 0.4 mm CFRP and 0.4 mm GFRP.

Steel was selected as the conventional automotive material due to its high strength and stiffness. ABS was considered as a lightweight polymer with good manufacturability but relatively lower structural strength. GFRP was chosen because of its low density, corrosion resistance, and satisfactory mechanical properties. CFRP was included owing to its excellent specific strength, stiffness, and superior energy absorption capability. The Hybrid Composite was developed to combine the advantages of CFRP and GFRP, providing an optimum balance between structural performance, weight reduction, and manufacturing cost.

Table I. Material Properties

Material	E (GPa)	ρ (kg/m ³)	Yield strength (MPa)
ABS	2.3	1050	50
Steel	200	7850	250
GFRP	24	1900	283.8
CFRP	70	1600	600

2. CAD Design (SolidWorks)

The car body shell was modelled in SolidWorks by importing a side-view reference image as a sketch template (Fig. 1) and tracing it to generate the 2D profile. The Extrude Boss/Base feature produced the 3D solid (Fig. 2), followed by the Shell feature at 0.8 mm uniform thickness to replicate thin-walled panel construction.

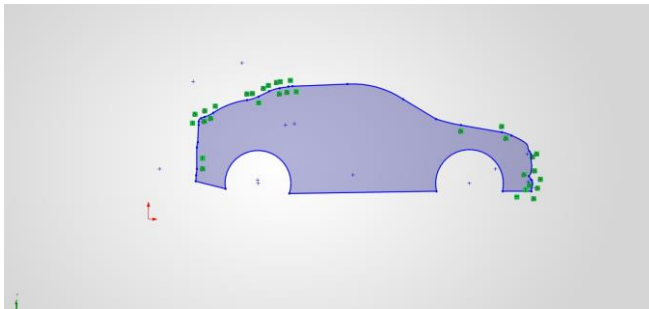


Fig. 1: 2D Car Body Profile Sketch (SolidWorks)

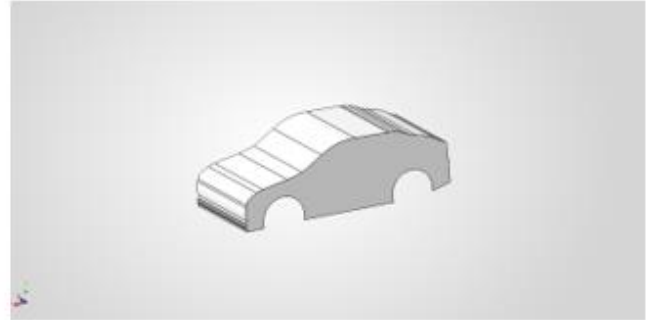


Fig. 2: 3D Car Body Shell Model (SolidWorks)

3. FEA Setup (ANSYS Workbench)

The STEP file was imported into ANSYS Workbench Static Structural and Modal modules (Fig. 3). Tetrahedral elements with mesh refinement at impact zones were applied. Impact forces for a vehicle at 60, 80, 100 km/h (333,556,925 kN) were applied as pressure loads on the frontal and rear faces and the the four wheels of the vehicle body was fixed.

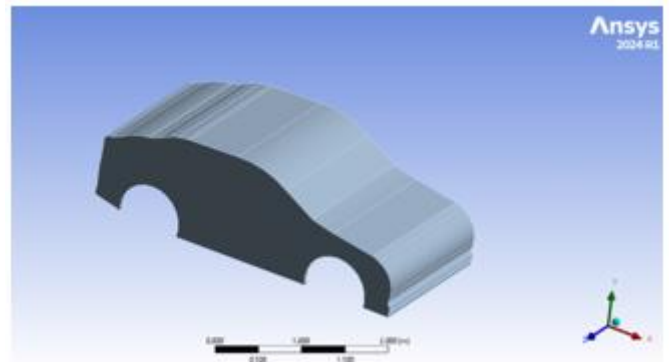


Fig. 3: Car Body Model Imported into ANSYS Workbench

IV. RESULTS AND DISCUSSION

1. Frontal Impact Analysis

Frontal impact simulations were carried out by applying an impact load at the front section of the vehicle body while constraining the four wheels of the vehicle body. The analyses were performed at three different impact velocities to evaluate the crashworthiness of each material. ABS (Fig. 4) exhibited catastrophically high deformation at all velocities and the FOS consistently below 1.0, confirming structural failure at every test speed. CFRP (Fig. 5) delivered the best single-material performance with lowest deformation and FOS above 2.40 at all speeds. The hybrid CFRP+GFRP model (Fig. 6) closely replicated CFRP. GFRP (Fig. 7) maintained FOS marginally above 1.0 in most scenarios. Steel showed low deformation but

FOS approached 1.0 at 100 km/h. Table II and Table III show the values of deformation and factory of safety of all speeds and materials.

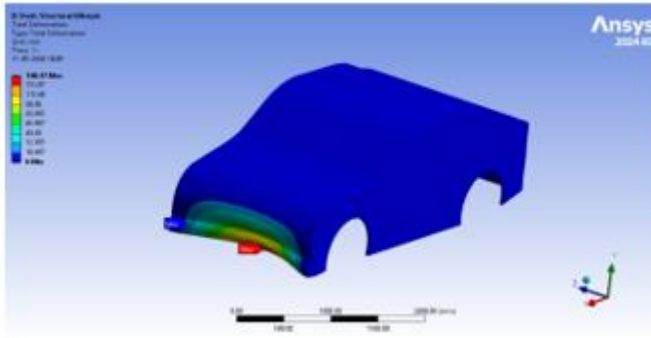


Fig. 4: Total Deformation of ABS material at 60km/h for front impact analysis (Max 148.47 mm)

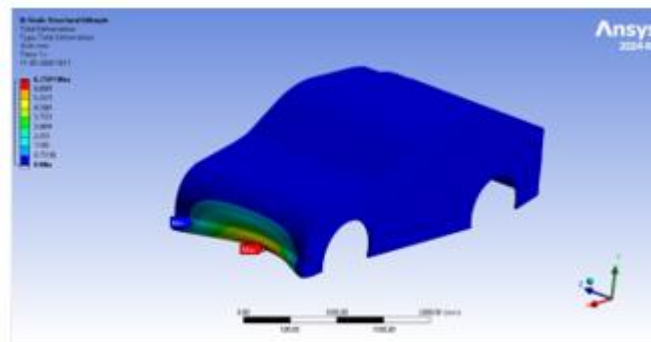


Fig. 5: Total Deformation of CFRP material at 60km/h for front impact analysis (Max 6.76 mm)

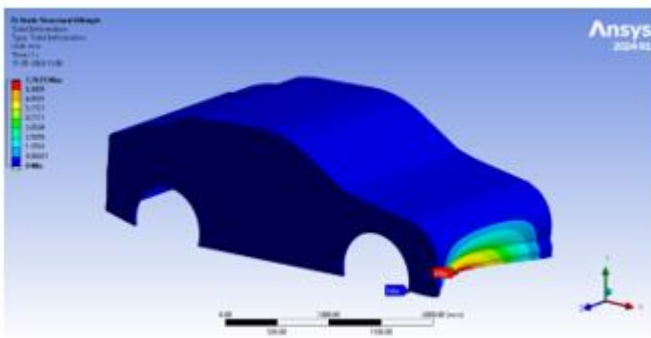


Fig. 6: Total Deformation of Hybrid material at 60km/h for front impact analysis (Max 7.76 mm)

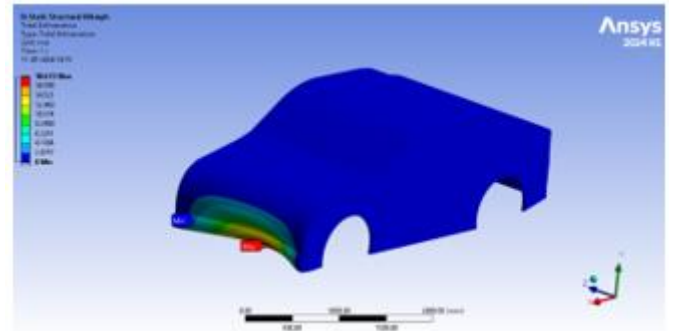


Fig. 7: Total Deformation of GFRP at 60 km/h of Front Impact analysis

Table II . Frontal Impact Analysis Deformation (mm)

Speed km/h	ABS	Steel	CFRP	GFRP	Hybrid
60	342.47	5.53	6.76	44.80	7.76
80	456.30	7.37	9.01	59.73	9.68
100	570.63	9.21	11.26	74.66	12.10

Table III. Frontal Impact Analysis Factory of Safety (Fos)

Speed km/h	ABS	Steel	CFRP	GFRP	Hybrid
60	0.32	2.0	2.41	1.20	2.39
80	0.24	1.50	2.41	1.20	2.39
100	0.20	1.00	2.40	1.19	2.39

2. Rear Impact Analysis

Rear impact analysis was performed by constraining the four wheels of the vehicle body and applying impact loading at the rear portion.

The rear impact analysis exhibited trends similar to those observed in the frontal impact study, with increased damage severity at an impact speed of 100 km/h. The ABS model (Fig. 8) experienced the highest deformation of 579.63 mm and the lowest factor of safety (FOS) of 0.20, indicating complete structural failure. Steel maintained a low deformation of 9.26 mm; however, its FOS decreased to 1.00, placing the structure at the failure threshold. In contrast, the CFRP model (Fig. 9)

demonstrated the best rear impact performance, with a deformation of 26.45 mm and the highest FOS of 2.40.

The hybrid CFRP+GFRP model (Figs. 10–11) exhibited comparable performance, recording a deformation of 26.77 mm and an FOS of 2.39, closely matching the CFRP results. GFRP provided moderate crashworthiness with an FOS of 1.19. The complete rear impact analysis results are presented in Table IV.

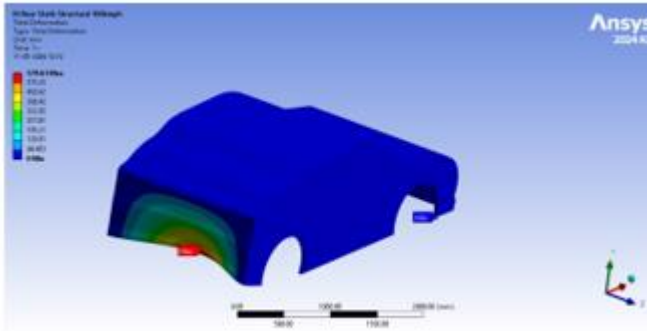


Fig. 8: Total Deformation of ABS material at 100km/h for rear impact analysis (Max 579.63 mm)

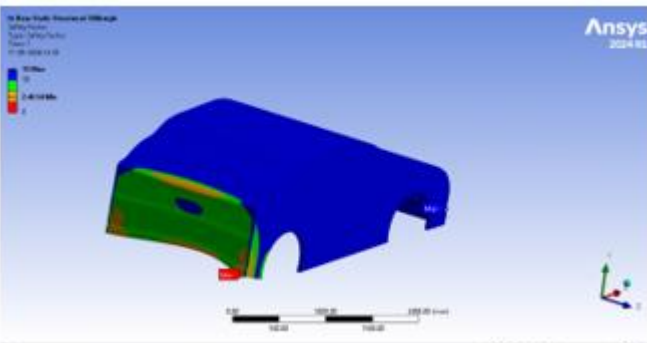


Fig. 9: Total Deformation of CFRP material at 100km/h for rear impact analysis (Max 26.45 mm)

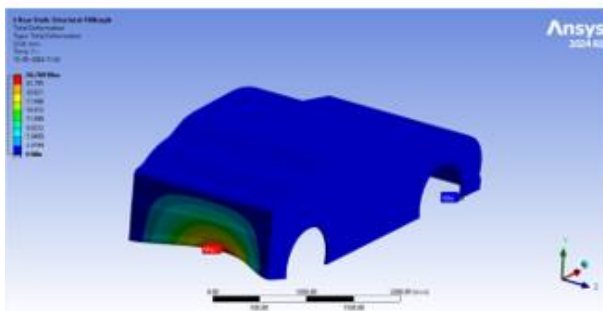


Fig. 10: Total Deformation of Hybrid material at 100km/h for rear impact analysis (Max 26.77 mm)

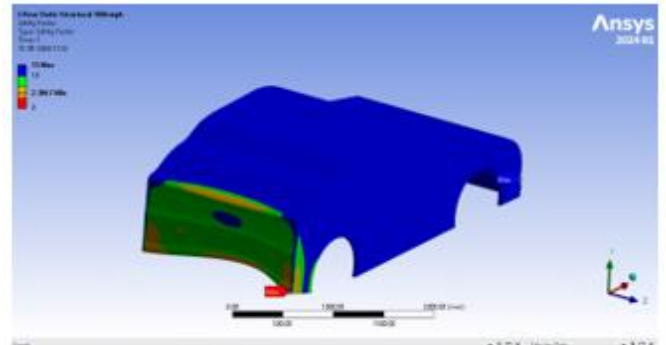


Fig. 11: Safety Factor of Hybrid material at 100km/h for rear impact analysis (Min FOS 2.39)

Table IV. Rear Impact Results at 100 km/h

Parameter	ABS	Steel	CFRP	GFRP	Hybrid
Deformation (mm)	579.63	9.26	26.45	73.27	26.77
Stress (MPa)	247.86	249.6	249.65	251.13	251.3
Strain	0.077	0.001	0.0035	0.0101	0.003
FOS	0.20	1.00	2.40	1.19	2.39

3. Modal Analysis

The modal analysis results indicate that the CFRP model exhibited the highest natural frequencies, ranging from 86.38 to 153.62 Hz, owing to its superior stiffness-to-weight ratio. The hybrid composite demonstrated comparable dynamic performance, with natural frequencies ranging from 86.07 to 153.38 Hz. The steel model ranked third, with frequencies between 65.92 and 117.23 Hz, followed by GFRP (47.26–84.44 Hz) and ABS (22.90–40.53 Hz). The complete modal analysis results for all materials are summarized in Table V.

Table V. Natural Frequencies of First Six Modes (Hz)

Mode	ABS	Steel	CFRP	GFRP	Hybrid
1	22.90	65.92	86.38	47.26	86.07
2	23.71	68.51	89.78	49.35	89.58
3	26.02	75.01	98.30	53.92	97.85
4	27.23	79.23	103.82	57.65	103.28

5	33.73	98.23	128.72	71.51	128.28
6	40.53	117.23	153.62	84.44	153.38

V. CONCLUSION

This study investigated the crashworthiness and dynamic stability of a passenger car body shell under frontal and rear impact conditions at 60, 80, and 100 km/h using five material configurations: ABS, steel, CFRP, GFRP, and a hybrid CFRP+GFRP composite. The simulation results demonstrated that ABS is unsuitable for structural automotive applications due to excessive deformation and factor of safety (FOS) values below the acceptable limit under high-speed impacts. Steel exhibited high structural stiffness and low deformation; however, its high density increases vehicle weight, reducing fuel efficiency, while the FOS approached the failure threshold at 100 km/h. GFRP provided moderate crash performance with FOS values slightly above the safe limit but lower stiffness and energy absorption than CFRP-based designs.

Among the evaluated materials, CFRP delivered the best overall crashworthiness and dynamic performance, exhibiting the lowest deformation, the highest factor of safety, and the highest natural frequencies because of its superior stiffness-to-weight ratio. However, its widespread application is constrained by high material and manufacturing costs. The hybrid CFRP+GFRP composite demonstrated performance closely matching that of pure CFRP while offering improved cost-effectiveness. It maintained a factor of safety greater than 2.38 under the 100 km/h rear impact condition and exhibited natural frequencies comparable to CFRP. Therefore, The hybrid model represents the most suitable lightweight alternative to conventional steel, offering a balanced trade-off of safety, stiffness, weight reduction, and cost-effectiveness.

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