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Original Article

Design and Optimization of Body in White of a Four-Wheel Vehicle

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Abstract *- The Body in White (BIW) is an important component in an automobile, which should have structural integrity to bear various loads and stresses during the working of vehicle operation. This paper demonstrates a BIW chassis analysis of a Bolero vehicle using the Finite Element (FE) method to evaluate its performance under various loading and boundary conditions. The study focuses on structural and crashworthiness to ensure sufficient protection for passengers in vehicles during accidents.*

A geometrical model of the BIW chassis was developed using CATIA software, and analyses were carried out using Ansys Workbench. The deformations and stresses developed during side and frontal impacts were analysed. The materials considered for the BIW structure are CP Steel, Duralumin, and a combination of both. A parametric study on weight optimization was conducted by varying the thickness of the structural members according to allowable stresses and deformations to ensure structural integrity and performance.

The results for the vehicle weight reduction are presented by using a combination of Duralumin (dominating in reinforcement parts) and CP Steel (in remaining areas). The combined material structure is analysed for deformation and stress levels in static structural, side crash, and frontal impact scenarios, and the results are compared with both materials individually. The combination of Duralumin for reinforcement and CP Steel for other structural members is analyzed, as well as the optimal thickness for the required design criteria.

Keywords *- BIW, Crashworthiness, FE analysis, Parametric study, Weight optimization.*

1. Introduction

The "Body in White" (BIW) is a key stage in car manufacturing where the vehicle's sheet metal components are assembled using welding, riveting, and adhesives before painting. This phase is crucial as it establishes the vehicle's structural integrity, safety, and quality. Mastering BIW can significantly enhance vehicle performance, manufacturing efficiency, and cost-effectiveness [1] & [2].

Traditionally, BIW focused on creating a strong, rigid structure to handle driving stresses and protect passengers in a collision. Nowadays, there is a greater emphasis on reducing the weight of the BIW to improve fuel efficiency and lower emissions while maintaining safety and durability. Environmental regulations, high fuel costs, and consumer demand for efficient vehicles drive this shift.

Optimizing BIW involves balancing material selection, design, manufacturing processes, and cost. Each factor critically influences the final BIW characteristics and overall vehicle performance. For example, choosing the right materials can affect the BIW's weight, strength, and cost, while its design impacts aerodynamics, crashworthiness, and manufacturability [3].

Material choice is vital for BIW optimization. Although steel has traditionally been used for its strength and affordability, new materials like high-strength steel, aluminium, magnesium, and composites offer benefits such as reduced weight and improved strength [5]. These materials, however, introduce new manufacturing and cost challenges.

Advanced Computer-Aided Engineering (CAE) tools help in BIW design optimization by simulating and analysing various design alternatives. These tools enable engineers to assess different design parameters, such as geometry, material properties, and joining methods, to find the best design that meets performance criteria while minimizing weight and cost [6]. New manufacturing technologies like laser welding, adhesive bonding, and 3D printing also enhance precision and flexibility but require investment in new equipment and workforce training (22&23). Balancing these factors with cost

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considerations ensures that the BIW is efficient, sustainable, and cost-effective. The research gap is observed in the necessity of analysis for various modes of loading conditions on BIW with various materials combinations and geometry. This paper focuses on the FE analysis for three modes of operation on BIW and carries out a parametric study by optimizing the BIW using various geometric cross-sections (24).

2. Methodology

2.1. Modelling

"Body in White" is a stage in automotive manufacturing where a car's sheet metal components are welded together before final assembly. The Mahindra Bolero, a popular SUV [4],, is considered the primary reference foranalyzing the modeld. The BIW structure model was developed using Mahindra Bolero's specifications. This work aims to reduce weight by maintaining the necessary strength and stiffness. This balance is required to maintain the vehicle's safety and performance with better fuel efficiency. The model was created using CATIA software, as shown in Figure 1.

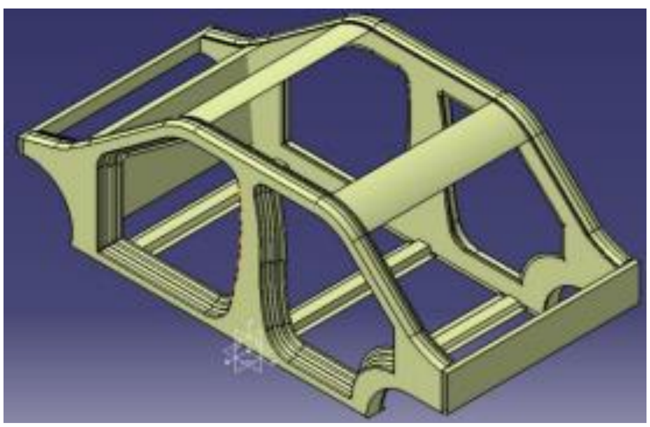

Fig. 1 Geometric model of BIW structure

2.2. Material Selection

The selection of materials for Body in White (BIW) is crucial for a vehicle's performance, efficiency, and safety steel, particularly mild steel, is mostly used for BIW due to its strength, durability, economy, and sound structure. However, the lighter materials requirement is becoming essential for more fuel-efficient vehicles is increased and the limitations of mild steel can be eliminated. This shift from heavier to light material usage has driven the automotive industry to use modern materials such as high-strength steel, magnesium, aluminium, and composites, with better strength-to-weight ratios that have new manufacturing and cost challenges [16].

2.2.1. C P Steel

Complex Phase (CP) steels, similar to TRIP steels but having less retained austenite, feature fine precipitates and a high volume of hard phases within a fine ferrite microstructure. These steels are precipitation-hardened using vanadium, titanium, and/or niobium to achieve high strengths of 800 MPa and above. The CP steels have less alloy content and better weldability than TRIP steels with low cost.

Table. 1 Material properties of CP steel

Property	Value
Density (kg/m^3)	7850
Young's modulus (MPa)	2.1 x 10^5
Poisons ratio	0.33
Tensile strength (MPa)	800 .12

2.2.2. Duralumin

Duralumin is an aluminium alloy developed by the German company Dürener Metallwerke AG in the early 20th century. It combines aluminium, copper, and sometimes manganese and magnesium to develop a lightweight, stronger material. Its inception revolutionized the aircraft industry by significantly decreasing weight without losing strength or durability. Duralumin has high tensile strength, machinability, and corrosion resistance.

Table. 2 Material properties of Duralumin

Property	Value
Density (kg/m^3)	2800
Young's modulus (MPa)	7.6 x 10^4
Poisons ratio	0.33
Tensile strength (MPa)	730
Compressive strength (MPa)	460

2.3. Regulatory Standards

2.3.1. Initial Design

In Body-in-White (BIW) design, vehicle dimensions are crucial in determining the overall structure and layout. The Mahindra Bolero, having a length of 3995 mm and a width of 1745 mm, is considered for the model. The structure dimensions should accommodate interior space to provide essential components like power trains and safety systems with stability and handling. The BIW structure design must maintain the vehicle's aesthetic and performance goals.

2.3.2. Crash-Worthiness Standards

The Bharat New Car Assessment Program (Bharat NCAP) is followed to enhance automotive safety standards in India by insisting manufacturers follow safety as a priority in their designs [15]. This initiative involves rigorous testing of vehicles, providing consumers with clear safety ratings to make informed choices, and driving automakers to invest in advanced safety technologies.

The result will be improved vehicle safety, reduced road accidents, and a more competitive and innovative automotive industry [17]. The standards to be followed as per Bharat NCAP for the four-wheel vehicle manufacturers are as mentioned below for front and side impact testing.

- 64 KMPH Front impact test
- 50 KMPH Side impact test
- 29 KMPH optional Pole impact test
- 40 KMPH child and adult pedestrian impact tests.

2.4. FE Analysis

2.4.1. Static Structural Analysis using Ansys

A parametric study is used to explore how changes in design variables affect performance. In the present work, the analysis has been carried out by considering thickness as a varying parameter. This process considers the design for the optimization of the structure.

In static structural analysis, the bending and torsional stiffness are focused. Bending stiffness evaluates the structure behaviour in resisting deformation under transverse loading of the components like beams and shafts. Torsional stiffness estimates the behaviour of the structure under applied torques in the components like the drive shaft and frame. To ensure the structure's safety and reliability, FE analysis can be implemented to predict the structure's behaviour under actual working conditions and refine the design. The Modal analysis is also performed to understand natural frequencies and mode shapes for the pitching, rolling, and steering motions of the vehicle.

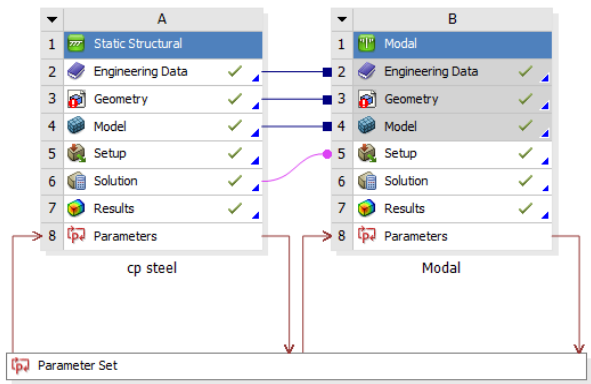

Fig. 2 Preprocessing in Ansys Workbench

Table 3. Boundary conditions for static structural analysis

Type of Motion	Front End	Rear End	Loads
Rotation about X (Pitching) Bending	Rotation about X is free The remaining DOFs are constrained	Rotation about X and translation about Y is free. The remaining DOFs are constrained.	A pair of 10 kN forces parallel to the Z axis (moment about X axis)
Rotation about Z (Steering)	Rotation about Z is free The remaining DOFs are constrained	Rotation about Z and translation about X is free. The remaining DOFs are constrained.	2000 Nm moment is applied about the Z axis
Rotation about Y (Rolling)	Rotation about Y is free The remaining DOFs are constrained	Rotation about Y and translation about X is free. The remaining DOFs are constrained.	2000 Nm moment is applied to the Y axis.

2.4.2. Explicit Dynamic Analysis

This explicit dynamic analysis mainly focuses on side crash and frontal crash analysis.

Side Crash Analysis

Explicit dynamic crash analysis is performed by using Ansys to simulate a collision, where a point mass traveling at 50 km/h impacts a stationary car for about 0.01 second intervals. The boundary conditions are considered to reflect the impact velocity and observe the main indicators like equivalent stress and total deformation during the simulation. This analysis helps to assess the car's structural integrity and safety during a collision, providing valuable data for design improvements and enhancing vehicle safety.

Frontal Crash Analysis

An explicit dynamic analysis is performed to simulate a frontal crash, where a car traveling at 65 km/h impacts a stationary vehicle over 0.01 seconds. The boundary conditions are set with the stationary car's base fixed, and the specified velocity is applied to the moving car. During the simulation, key metrics like equivalent stress, average stress, and total deformation are observed to assess the vehicle's structural integrity and safety. The results help refine the design and improve overall vehicle safety.

Table. 4 Explicit analysis settings

Definition	**Side crash**	**Frontal crash**
Pre Stress Environment	Non-available	Non-available
Pressure Initialization	From Deformed State	From Deformed State
Input Type	Velocity	Velocity

Define By	Components	Components
Coordinate System	Global Coordinate System	Global Coordinate System
X Component	13888.9 mm/s	0 mm/s
Y Component	0 mm/s	18055.6 mm/s
Z Component	0 mm/s	0 mm/s

3. Results and Discussions

3.1. Variation of Weight with Change in Thickness

It is considered varying thicknesses from 2 mm to 0.8 mm for CP Steel, Duralumin, and a combination of both to the Body-in-White (BIW) structure, leading to notable changes in weight. The modifications in thickness have resulted in a variation in the overall weight of the structure; the variation of mass according to thickness change is tabulated in Table 5.

3.2. Static Structural Analysis

3.2.1. Pitching (Rotation about X)

The static structural analysis has been done for CP Steel, Duralumin, and a combination of both under rotation about X axis with the loading conditions mentioned in Table 3. The maximum deformation and maximum stress plots in pitching for the combination of metals with 2 mm thickness are shown in Figures 3 and 4. The parametric study in Ansys software is conducted, and the results of total deformation and maximum stress are represented in Table 6 and shown in Figures 5 and 6, respectively.

Table. 5 Variation of mass with varying thickness

Thickness (mm)	Mass in kg		
	Cp steel	Duralumin	Combination of CP steel and Duralumin
2.0	315.864	112.665	257.101
1.8	284.278	101.398	231.391
1.5	236.898	84.499	192.825
1.2	189.518	67.599	154.260
1.0	157.932	56.334	128.550
0.8	126.346	45.066	102.840

Table. 6 Total deformation and maximum stress for pitching

Material	CP Steel		Duralumin		Combination of both	
t (mm)	Deformation (mm)	Stress (MPa)	Deformation (mm)	Stress (MPa)	Deformation (mm)	Stress (MPa)
2.0	0.878	22.701	2.389	22.859	1.049	24.947
1.8	1.186	28.029	3.227	28.221	1.407	30.397
1.5	2.006	40.339	5.456	40.609	2.349	42.671
1.2	3.839	62.941	10.439	63.352	4.424	64.393
1.0	6.545	90.541	17.794	91.121	7.450	89.972
0.8	12.603	141.365	34.255	142.256	14.151	135.364

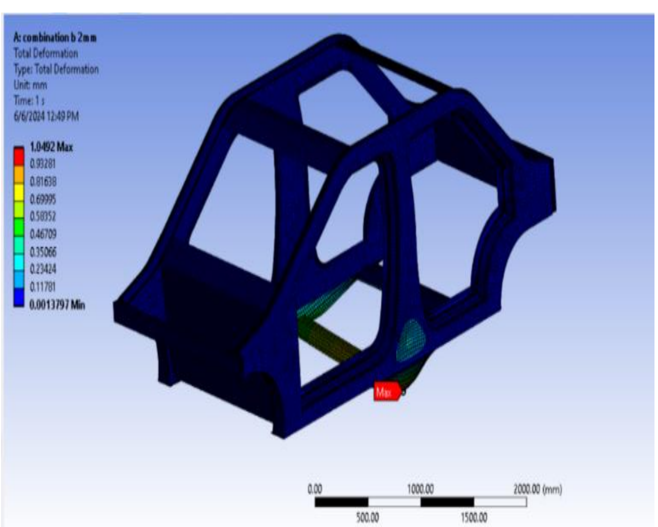

Fig. 3 Deformation in pitching for the combination of metals 2mm thick

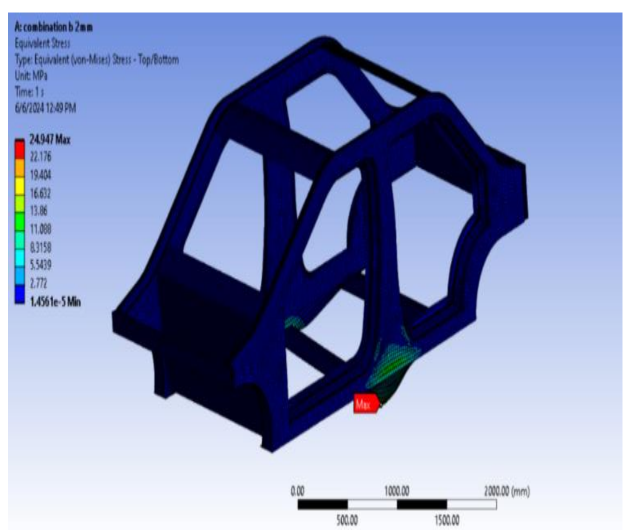

Fig. 4 Max.stress in pitching for combination of metals 2mm thick

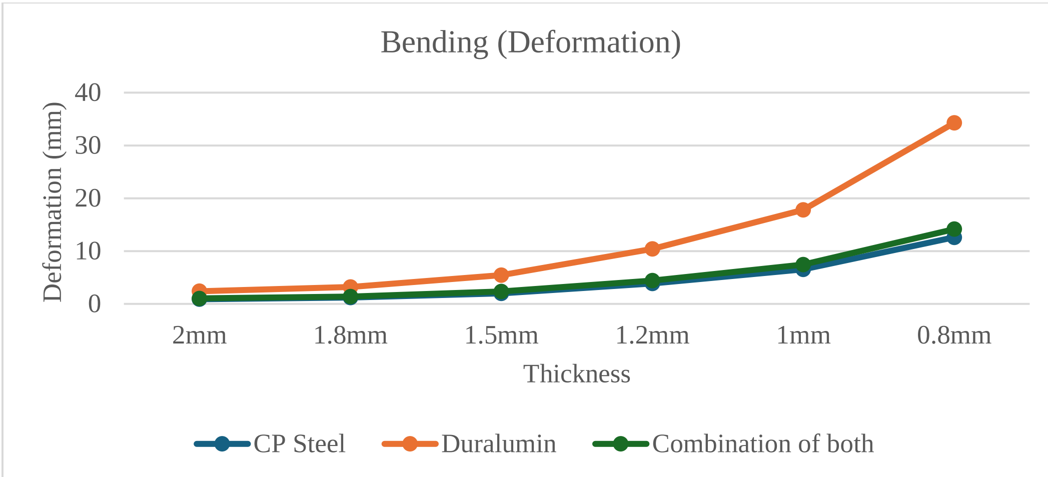

Fig. 5 Maximum deformation for pitching

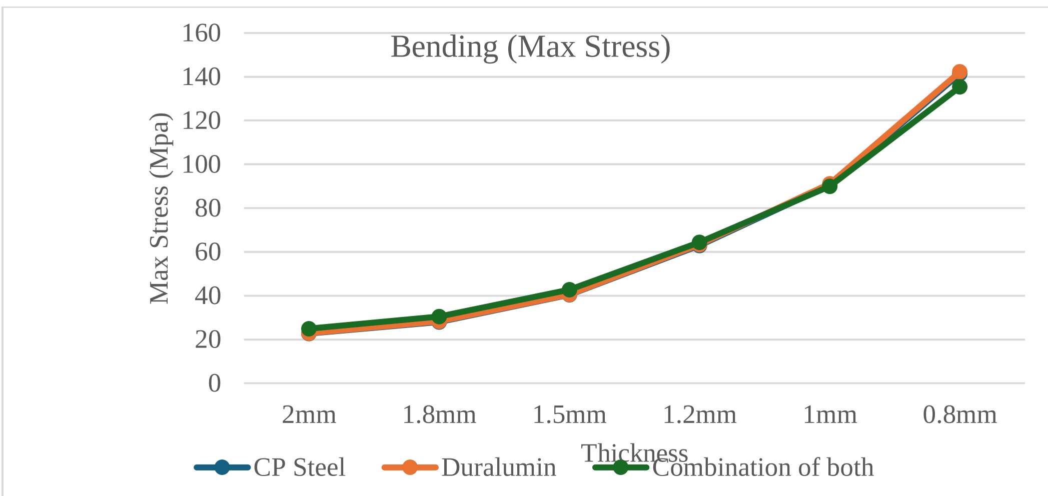

Fig. 6 Maximum stress for pitching

3.2.2. Steering (Rotation about Z)

The static structural analysis has been done for CP Steel, Duralumin, and a combination of both under rotation about the Z axis with the loading conditions mentioned in Table 3. The maximum deformation and maximum stress plots in steering for a combination of metals with 2 mm thickness are shown in figures 7 and 8. The parametric study in Ansys software is conducted, and the results of total deformation and maximum stress are represented in Table 7 and shown in Figures 9 and 10, respectively.

Table 7. Total deformation and maximum stress for steering

Material	CP Steel		Duralumin		Combination of both	
t (mm)	**Deformation** (mm)	**Stress** (MPa)	**Deformation** (mm)	**t** (mm)	**Deformation** (mm)	**Stress** (MPa)
2.0	20.078	130.402	55.397	128.163	52.10	253.496
1.8	21.333	135.997	58.856	133.673	55.648	275.699
1.5	24.498	157.125	67.588	155.786	46.560	228.252
1.2	29.142	194.069	80.403	192.451	55.256	268.101
1.0	33.596	227.707	92.696	225.822	63.591	312.581
0.8	40.092	273.314	110.631	271.025	75.718	370.780

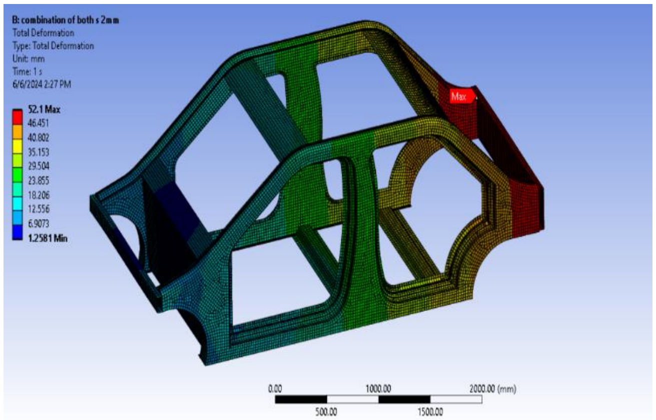

Fig. 7 Total deformation of steering for the combination of metals 2mm

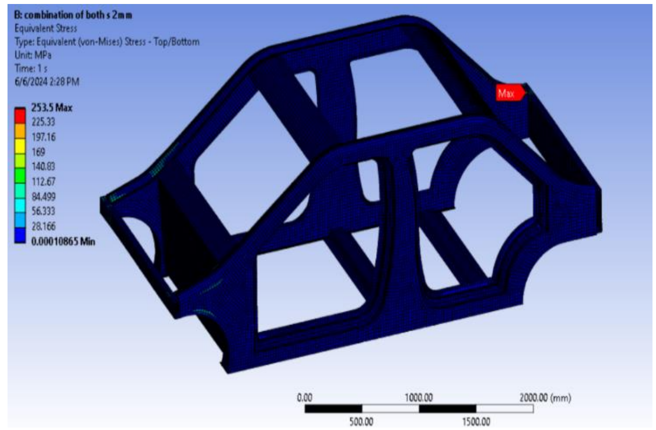

Fig. 8 Maximum stress of steering for the combination of metals 2mm

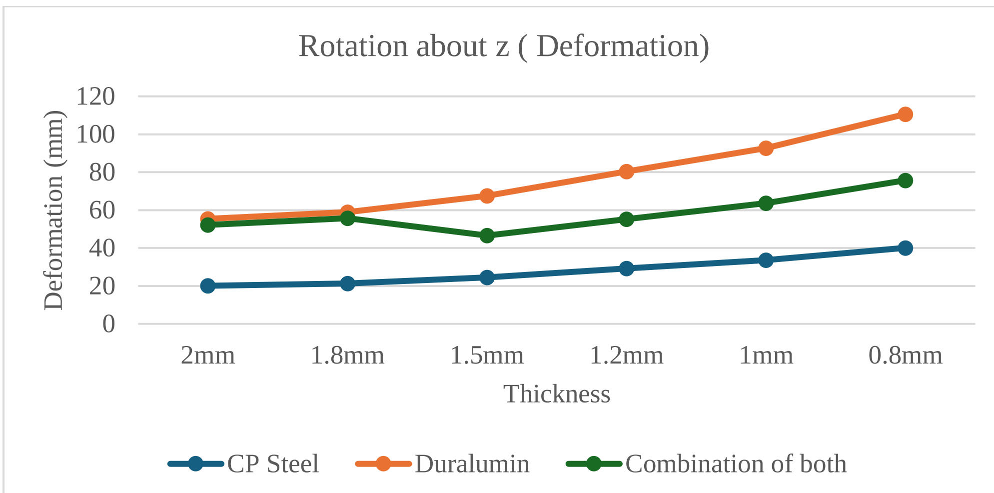

Fig. 9 Maximum deformation for steering

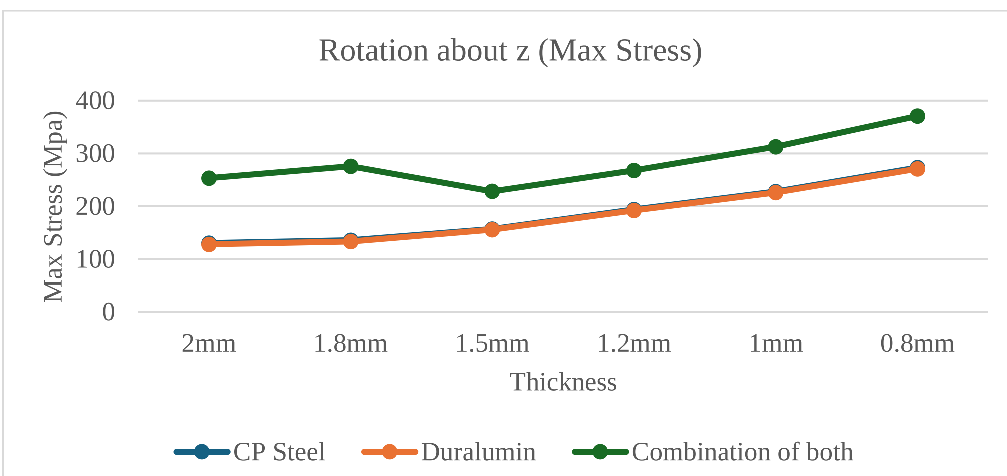

Fig. 10 Maximum stress for steering

3.2.3. Rolling (Rotation about Y)

The static structural analysis has been done for CP Steel, Duralumin, and a combination of both under rotation about the Z axis with the loading conditions mentioned in Table 3. The maximum deformation and maximum stress plots in rolling for the combination of metals with 0.8 mm thickness are shown in Figures 11 and 12. The parametric study in Ansys software is conducted, and the results of total deformation and maximum stress are represented in Table 8 and shown in Figures 13 and 14, respectively.

Table 8. Total deformation and maximum stress for rolling

Material	**CP Steel**		**Duralumin**		**Combination of both**	
t (mm)	**Deformation** (mm)	**Stress** (MPa)	**Deformation** (mm)	**t** (mm)	**Deformation** (mm)	**Stress** (MPa)
2.0	11.774	274.635	29.751	237.513	22.083	286.487
1.8	12.890	297.694	32.311	260.928	23.322	298.172
1.5	15.193	343.280	37.649	308.322	20.286	292.125
1.2	18.428	403.150	46.999	374.084	24.067	362.235
1.0	21.384	453.061	56.347	431.891	28.778	429.066
0.8	25.445	514.877	69.770	506.363	35.688	529.080

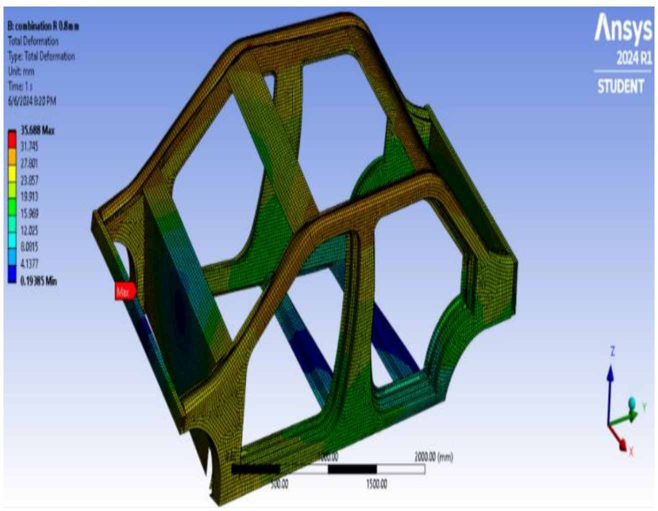

Fig. 11 Total deformation of rolling for the combination of metals 0.8mm

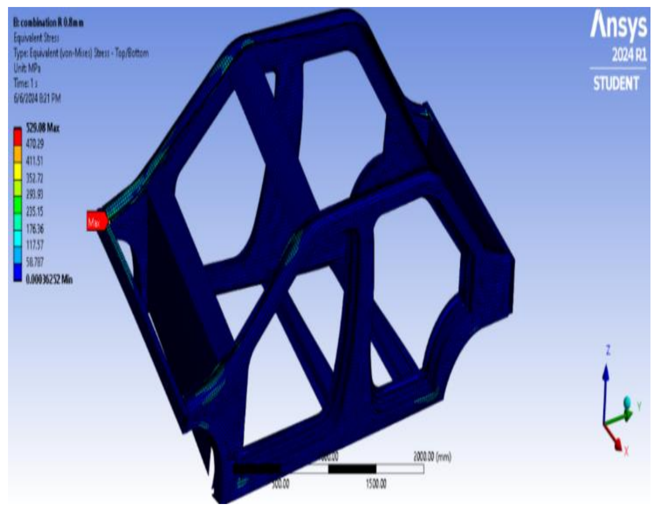

Fig. 12 Maximum stress of rolling for the combination of metals 0.8mm

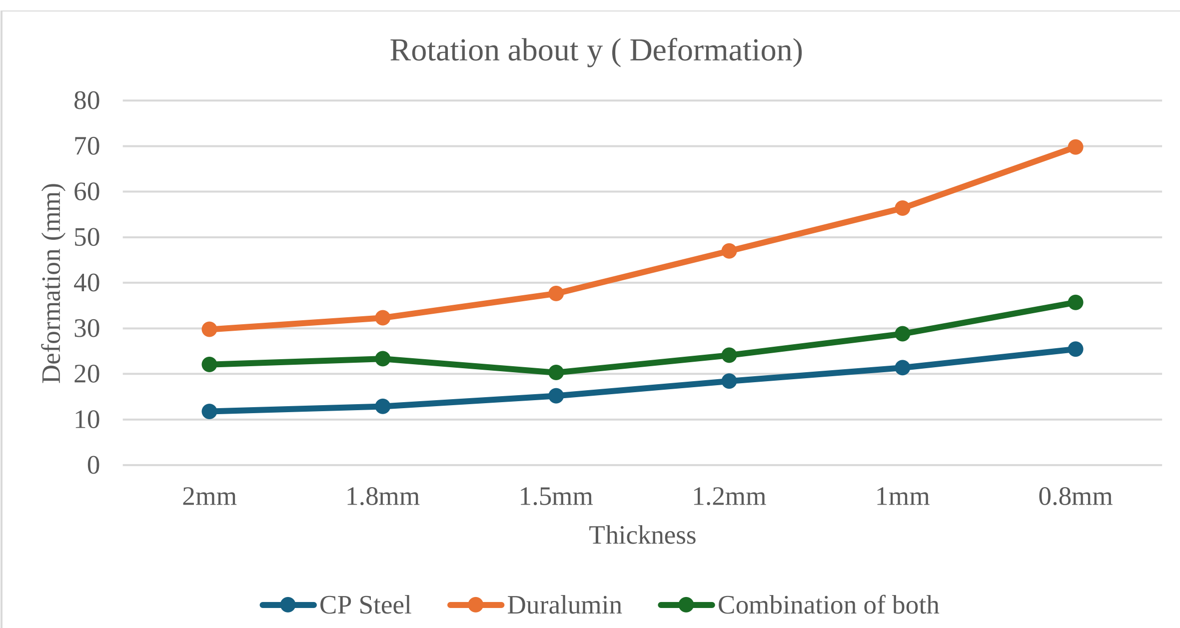

Fig. 13 Maximum deformation for pitching

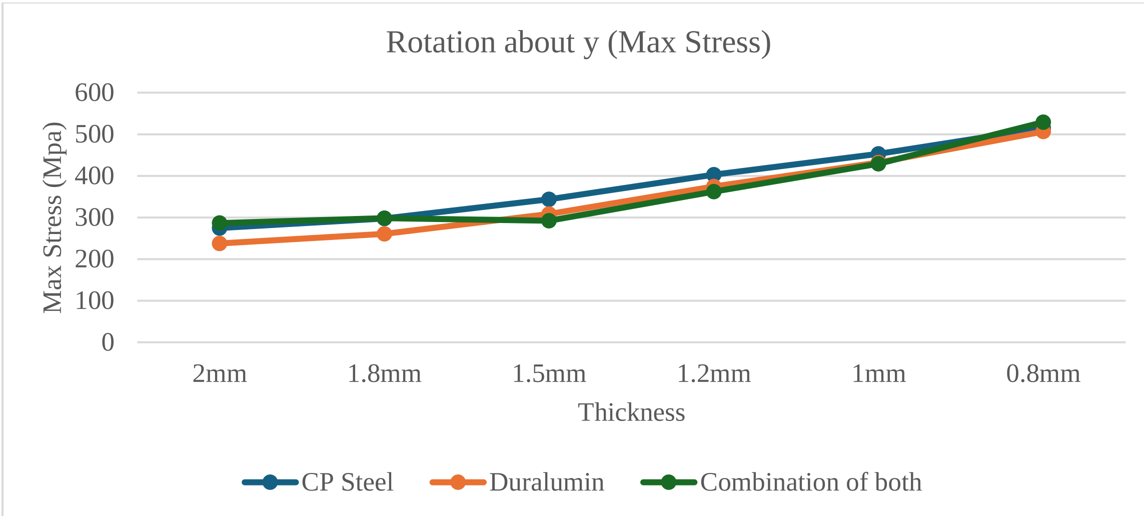

Fig. 14 Maximum stress for rolling

3.4. Explicit Dynamic Analysis

3.4.1. Side Crash Analysis

An explicit dynamic analysis is performed by using different materials at varying thicknesses of 2mm, 1.5mm, 1.2mm, 1.8mm, 1mm, and 0.8mm. Analysis has been done for CP Steel, Duralumin, and a combination of both with the loading conditions mentioned in Table 4. The maximum deformation and maximum stress plots during side crashes for a combination of metals with 2 mm thickness are shown in Figures 15 and 16. The results of these analyses have been compiled into a comprehensive Table 10 and shown in Figures 17 and 18.

Table 10. Total deformation and maximum stress for side crash

Material	**CP Steel**		**Duralumin**		**Combination of both**	
t (mm)	**Deformation** (mm)	**Stress** (MPa)	**Deformation** (mm)	**t** (mm)	**Deformation** (mm)	**Stress** (MPa)
2.0	36.710	846.365	66.608	834.403	28.310	915.653
1.8	38.083	939.248	65.359	877.919	32.186	929.116
1.5	42.695	1390.959	84.021	862.094	35.261	1022.850
1.2	53.206	1562.637	103.944	934.745	46.550	1475.372
1.0	74.711	1652.670	111.321	882.120	67.319	1598.672
0.8	97.496	1852.398	121.674	964.889	93.049	1800.348

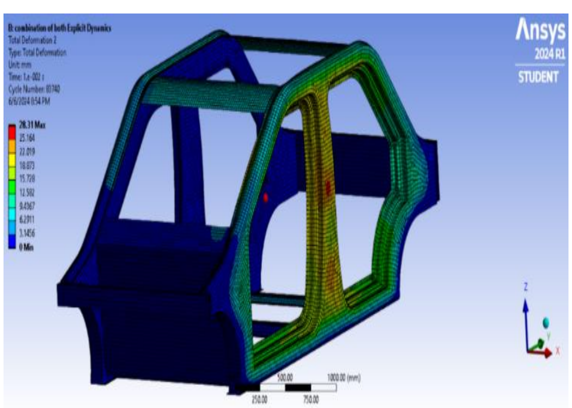

Fig. 15 Total deformation for side crash analysis of combination material for 2 mm thickness

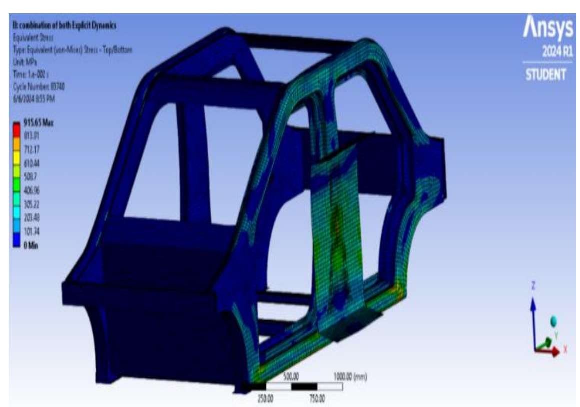

Fig. 16 Maximum stress for side crash analysis combination material for 2 mm thickness

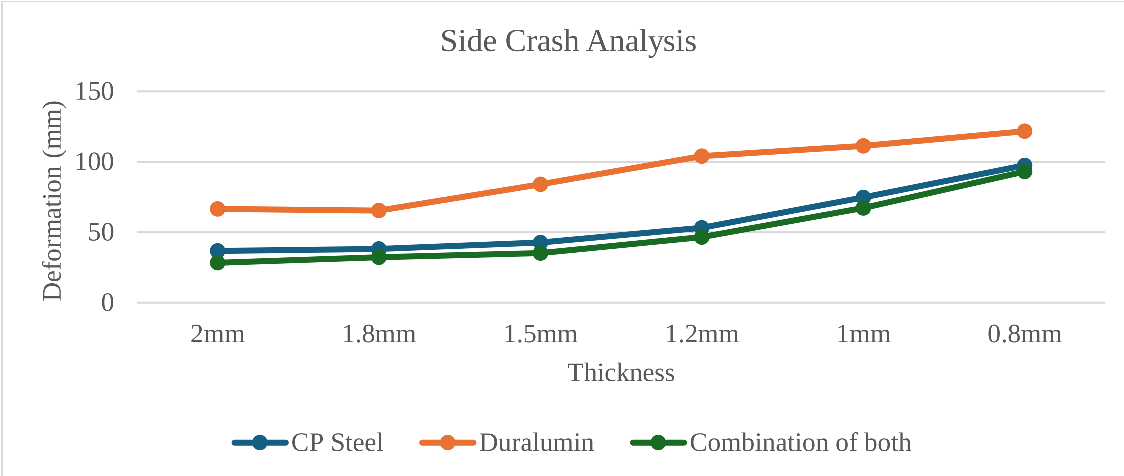

Fig. 17 Maximum deformation for side crash

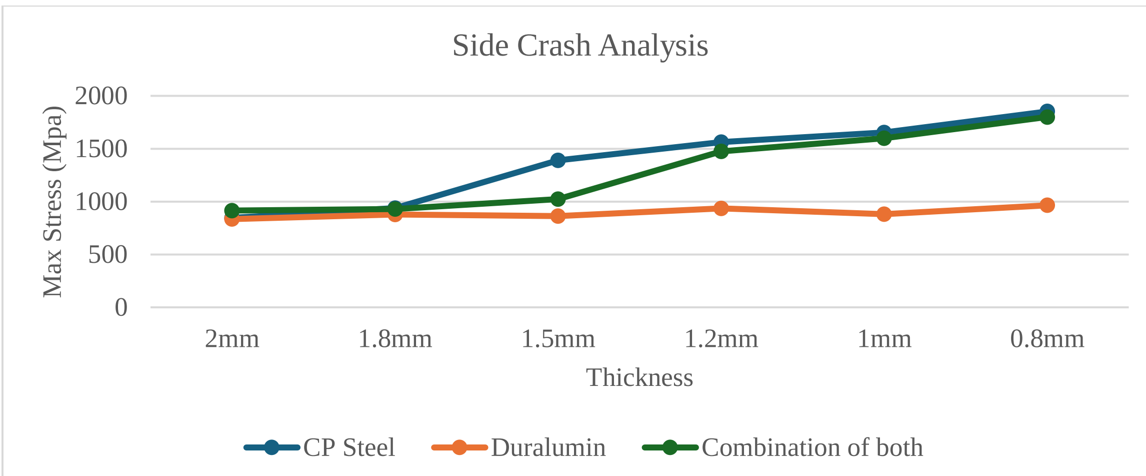

Fig. 18 Maximum stress for side crash

3.4.2. Frontal Crash Analysis

The frontal explicit dynamic analysis using various materials of thicknesses 2.0 mm, 1.2 mm, and 0.8 mm is performed. Analysis has been done for CP Steel, Duralumin, and a combination of both with the loading conditions mentioned in Table 4. The maximum deformation and maximum stress plots during side crashes for a combination of metals with 1.2 mm thickness are shown in Figures 19 and 20. The results of these analyses have been compiled into a comprehensive Table 11 and shown in Figures 21 and 22.

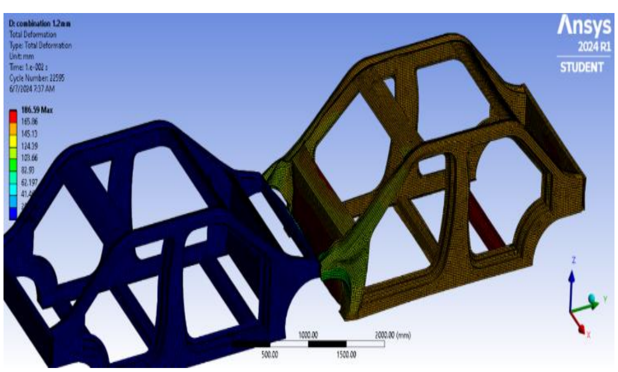

Fig. 19 Total deformation of the combination of materials in frontal impact for 1.2mm thickness

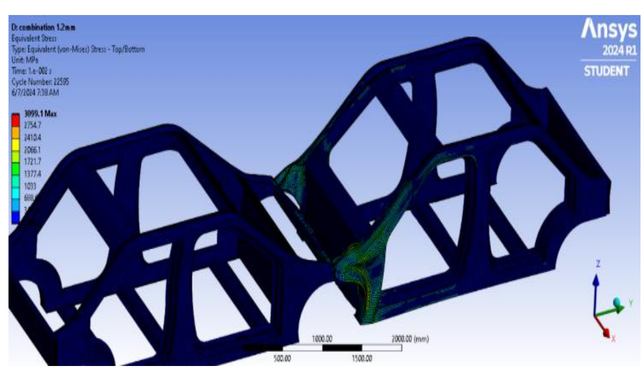

Fig. 20 Maximum stress of combination of materials in frontal impact for 1.2mm thickness

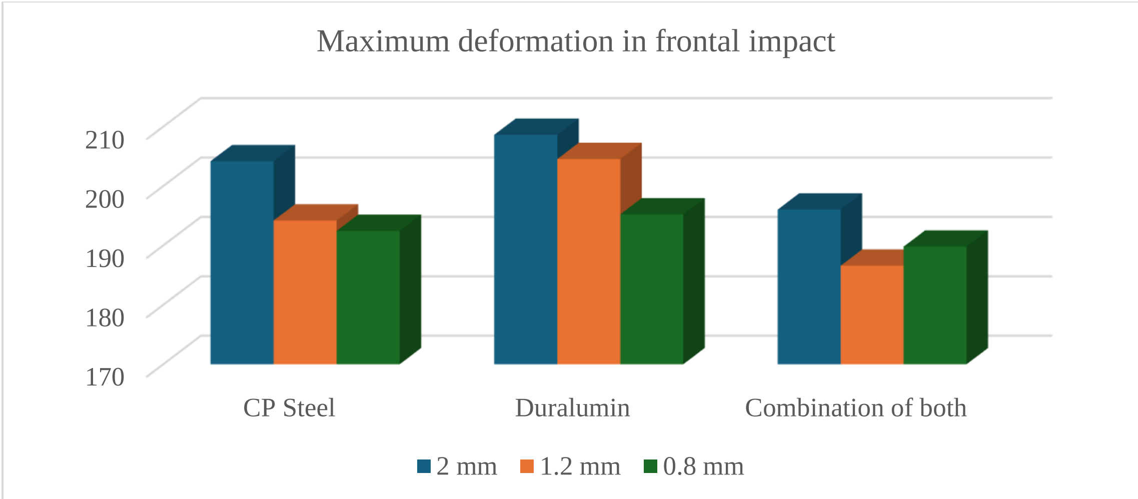

Fig. 21 Deformation in frontal impact

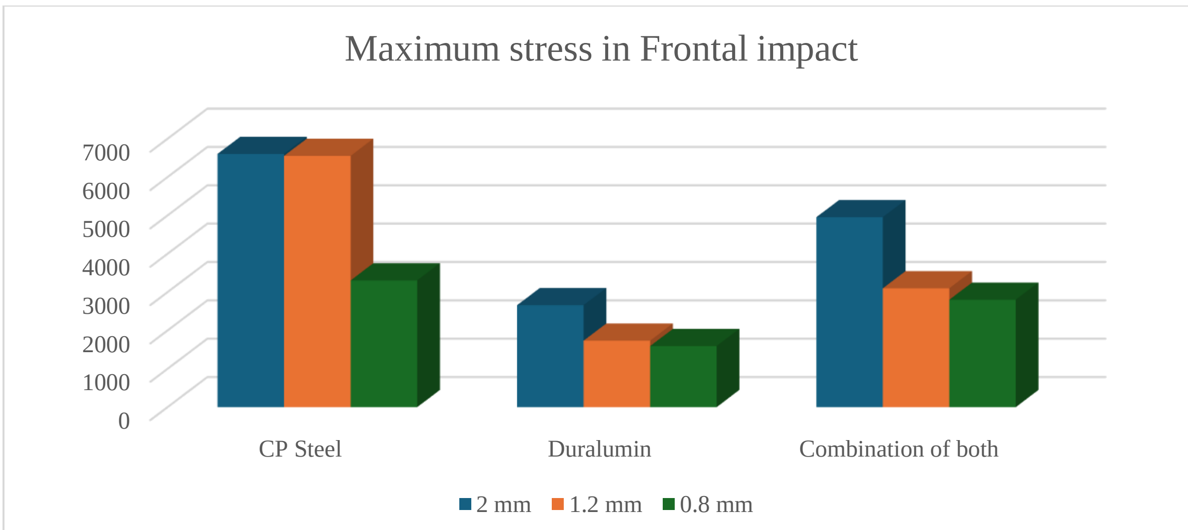

Fig. 22 Maximum stress in frontal impact

Table 11. Total deformation and maximum stress for frontal crash

Material	CP Steel		Duralumin		Combination of both	
t (mm)	Deformation (mm)	Stress (MPa)	Deformation (mm)	Stress(MPa)	Deformation (mm)	Stress (MPa)
2.0	204.18	6603.3	208.63	2658.3	196.04	4953.5
1.2	194.20	6553.3	204.55	1733.5	186.59	3099.1
0.8	192.45	3305.1	195.24	1592.1	189.80	2800.5

4. Conclusion

The Body in White (BIW) structure of the Bolero vehicle was analysed under static structural and crash-worthiness conditions by varying thicknesses from 2.0 mm to 0.8 mm. The static structural analysis in pitching showed that for CP Steel, deformation ranged from 0.897 mm to 12.602 mm, with maximum stress ranging from 22.701 MPa to 141.365 MPa. For Duralumin, deformation ranged from 2.389 mm to 34.255 mm, with maximum stress from 22.859 MPa to 142.256 MPa. The combination of both materials showed deformations from 1.049 mm to 14.151 mm and stresses from 24.947 MPa to 135.364 MPa. Also, deformations and stress ranges are observed during the Rolling and Yawing motions of the vehicle. In an explicit analysis for crashworthiness, CP steel showed deformations from 36.710 mm to 97.496 mm and stresses from 846.365 MPa to 1852.398 MPa for side impacts, while frontal impacts ranged deformations from 204.18 mm to 192.45 mm with stresses from 6603.3MPa to 3305.1MPa.

Duralumin exhibited deformations from 66.608 mm to 121.674 mm and stresses from 834.403 MPa to 964.889 MPa for side impacts, and deformations from 208.63 mm to 195.24 mm and stresses from 2658.3 MPa to 1592.1 MPa for frontal impact. The combination material had deformations from 28.310 mm to 93.049 mm and stresses from 915.653 MPa to 1800.348 MPa for side impacts, and deformations from 196.04 mm to 189.80 mm with stresses from 4953.5 MPa to 2800.5 MPa for frontal impacts. The combination of CP Steel and Duralumin with a thickness of 1.2 mm proved to be most effective in reducing deformation and stress in both side and frontal impacts. This configuration was found to be optimal for weight reduction, lowering the vehicle's weight from 189.51 kg to 154.26 kg, i.e., a reduction of 18.6%. Therefore, it is recommended to use Duralumin for reinforcement and CP Steel for other structural members at 1.2 mm thickness to achieve a lighter and sufficiently strong vehicle structure.

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