

Topology-Based Design Optimization and Static Analysis of an Automotive Front Bumper Beam for Monocoque Passenger Cars

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Abstract—This research presents a static structural analysis and design optimization of a front bumper beam for a monocoque chassis modeled on the Maruti Suzuki Ertiga. The initial bumper beam model was created and analyzed using Aluminum Alloy 6061 in SolidWorks to evaluate parameters such as Equivalent (Von-Mises) stress, total displacement and factor of safety under static loading conditions. To examine material-based improvement, the analysis was repeated using Aluminum 6061-T6. However, the results showed only negligible differences in stress and deformation. Therefore, the study focused on geometric and topological redesign of the bumper beam. A new optimized design was developed and analyzed using the original material properties. The simulation results show that the proposed design significantly improves structural performance by reducing stress and displacement while increasing the factor of safety of bumper. The study concludes that geometric optimization is more effective than material tempering in enhancing the structural performance and crashworthiness of passenger vehicle bumper systems in car.

Index Terms—Static Analysis, Monocoque Chassis, Maruti Suzuki Ertiga, Bumper Beam, SolidWorks, Aluminum 6061-T6, Design Optimization.I.

1 INTRODUCTION

The rapid growth of the automotive industry in India has led to an increased focus on passenger safety and vehicle structural integrity. In a modern passenger vehicle, the front bumper beam serves as the primary structural component responsible for absorbing kinetic energy during a frontal collision. For vehicles featuring a monocoque chassis such as the Maruti Suzuki Ertiga, the integration of the bumper system

with the body-in-white (BIW) is critical for protecting both the occupants and the internal mechanical components of the engine bay.

1.1 Structural Significance of Bumper Beams

A bumper beam is designed to withstand a specific amount of impact force before deforming. While its dynamic performance is crucial during a crash, static structural analysis serves as a fundamental diagnostic tool to understand the load-bearing capacity, stress distribution, and stiffness of the design. Engineering a beam that balances lightweight characteristics with high structural strength is a persistent challenge in automotive design.

1.2 Material Selection and Optimization

Aluminum alloys have gained prominence in the Indian automotive sector due to their high strength-to-weight ratio. Aluminum 6061 is frequently utilized for its good corrosion resistance and mechanical properties. However, selecting the correct heat treatment such as the T6 tempering grade is essential to maximize performance. This research investigates whether material grade enhancements alone are sufficient to improve safety margins or if geometric redesign is a more effective strategy for the Ertiga's specific chassis configuration.

1.3 Research Objectives

The primary objective of this study is to evaluate the existing front bumper beam of the Maruti Suzuki Ertiga and propose an optimized design. Using SolidWorks Simulation, the study follows a three-stage methodology:

1. Baseline Analysis: Modelling the existing design using Aluminum 6061 to establish current performance metrics.
2. Material Sensitivity Study: Testing the impact of 6061-T6 grade aluminum on the existing geometry.
3. Design Optimization: Introducing a modified geometric design to achieve superior stress distribution and reduced displacement compared to the original factory specifications.

This research aims to provide a localized solution for improving the crashworthiness of popular Indian MUVs through advanced Computer-Aided Engineering (CAE) techniques.

II. PROBLEM STATEMENT

The Maruti Suzuki Ertiga is one of India’s most popular Multi-Utility Vehicles (MUVs) yet the increasing standards for crash safety demand continuous improvement in its structural components. The front bumper beam is the first line of defense in a frontal impact. Now conventional designs often rely on standardized geometries that may not fully leverage the mechanical properties of advanced alloys.

In this specific study, it was observed that simply upgrading the material from Aluminum 6061 to its T6 tempered grade did not yield significant improvements in static structural performance for the existing geometry. This indicates a "performance plateau" where the physical shape of the beam rather than the material strength alone limits the energy absorption and stress distribution. Therefore there is a critical need to redesign the bumper beam geometry to achieve superior structural integrity and safety margins without increasing the overall weight of the vehicle.

III. METHODOLOGY

3.1 Force Calculation

Mass: 1100 kg.
 Initial Velocity: 60m/s.
 Distance: 10m.
 Initial Kinetic Energy:

$$K = \frac{1}{2} \cdot m \cdot v^2$$

$$K = \frac{1}{2} \cdot 1100 \text{ kg} \cdot (60\text{m/s})^2$$

$$K = 1,980,000 \text{ Joules(J)}$$

Maximum Force (F):

$$F = \frac{K}{d}$$

$$F = \frac{1,980,000 \text{ J}}{10 \text{ m}}$$

$$F = 198,000 \text{ Newtons (N)}$$

Peak Max Force:

$$\text{Energy} = \frac{1}{2} \cdot \text{distance} \cdot \text{max force}$$

$$1,980,000 = \frac{1}{2} \cdot 10 \cdot F_{max}$$

$$1,980,000 = 5 \cdot F_{max}$$

$$F_{max} = 396,000 \text{ N}$$

So we assume 400,000 N or 400 kN.

The research follows a systematic Computer-Aided Engineering (CAE) workflow, divided into three distinct phases of modelling and simulation using SolidWorks.

3.2 Phase I: Baseline Modelling and Analysis

3.2.1 Existing Bumper Beam

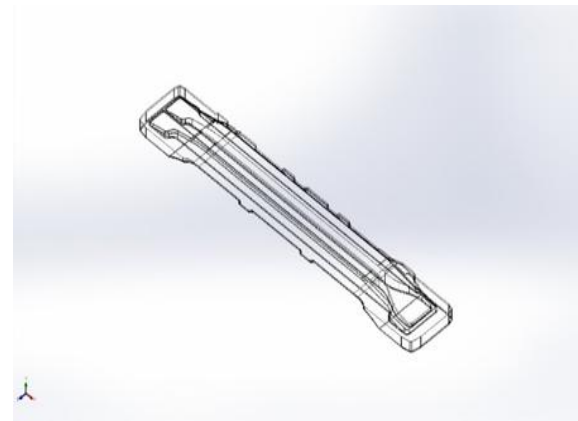


Fig Maruti Suzuki Ertiga Existing Bumper Beam.
 Volumetric Properties:

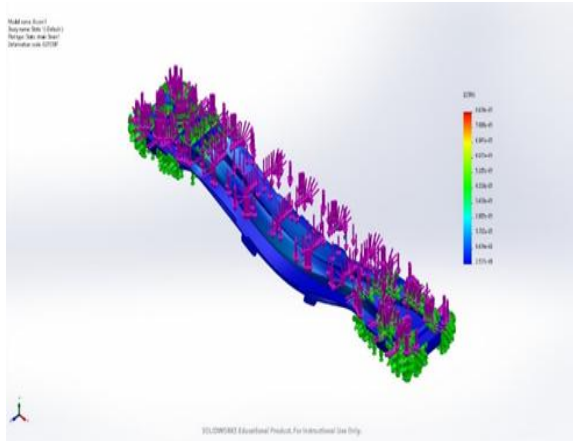


Fig. Strain of Existing Bumper Beam.

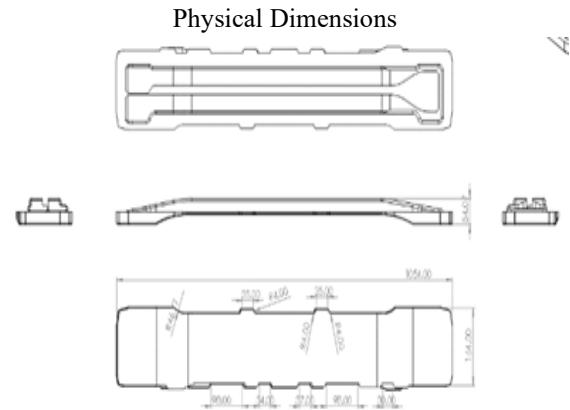


Fig. 2D Drawing and Dimensions of Maruti Suzuki Ertiga Existing Bumper Beam.

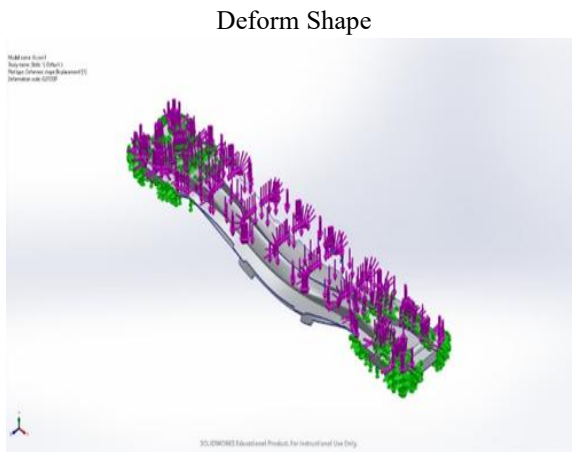


Fig. Deform Shape of Existing Bumper Beam.

Load Factors

Type:	Apply normal force
Value:	400 kN to each point

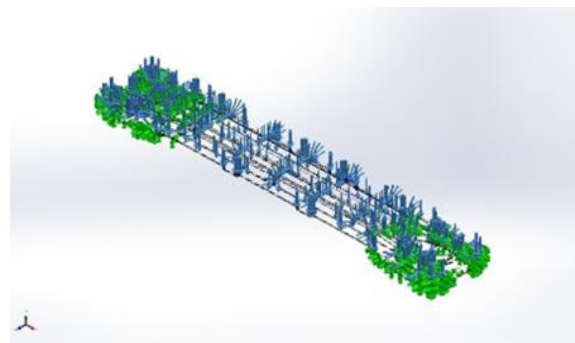


Fig. Applied load on Existing Bumper Beam.

3.2.2 Existing Bumper Beam with New Material

Volumetric Properties

Mass:	2.437633 kg
Volume:	0.000902826 m ³
Density:	2,700 kg/m ³
Weight:	23.88883 N

Material Properties

Name:	6061-T6 (SS)
Model type:	Linear Elastic Isotropic
Default failure criterion:	Max von Mises Stress
Yield strength:	2.75e+08 N/m ²
Tensile strength:	3.1e+08 N/m ²
Elastic modulus:	6.9e+10 N/m ²
Poisson's ratio:	0.33
Mass density:	2,700 kg/m ³
Shear modulus:	2.6e+10 N/m ²
Thermal expansion coefficient:	2.4e-05 /Kelvin

Study Result

Stress

Name	Type	Min	Max
Stress	VON: von Mises Stress	1.622e+03N/m ²	9.993e+10N/m ²

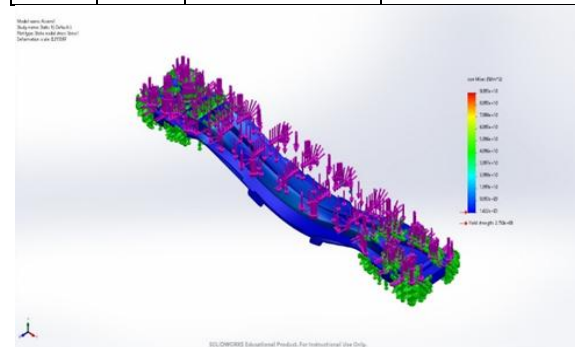


Fig. Stress of Existing Bumper Beam with New Material.

Displacement

Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0.000e+00 mm	5.356e+02 mm

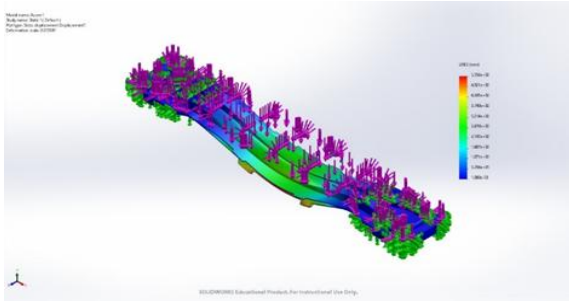


Fig. Displacement of Existing Bumper Beam with New Material.

Strain

Name	Type	Min	Max
Strain	ESTRN: Equivalent Strain	3.615e-08	8.676e-01

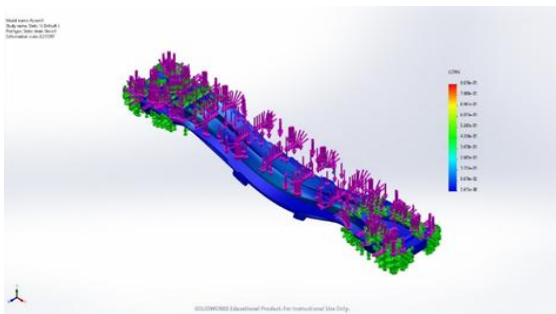


Fig. Strain of Existing Bumper Beam with New Material.

Deform Shape

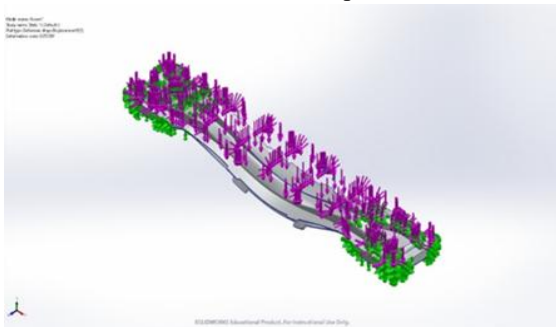


Fig. Strain of Existing Bumper Beam with New Material

3.2.3 New Bumper Beam

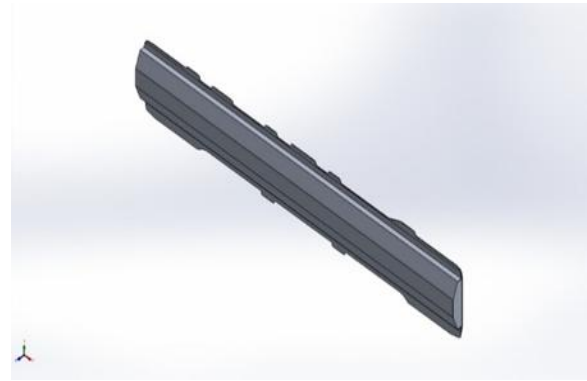


Fig. New Bumper Beam.

Volumetric Properties

Mass	1.874762 kg
Volume	0.000694356 m ³
Density	2,700 kg/m ³
Weight	18.37266 N

Material Properties

Name:	6061 Alloy
Model type:	Linear Elastic Isotropic
Default failure criterion:	Max von Mises Stress
Yield strength:	5.51485e+07 N/m ²
Tensile strength:	1.24084e+08 N/m ²
Elastic modulus:	6.9e+10 N/m ²
Poisson's ratio:	0.33
Mass density:	2,700 kg/m ³
Shear modulus:	2.6e+10 N/m ²
Thermal expansion coefficient:	2.4e-05 /Kelvin

Physical Dimensions

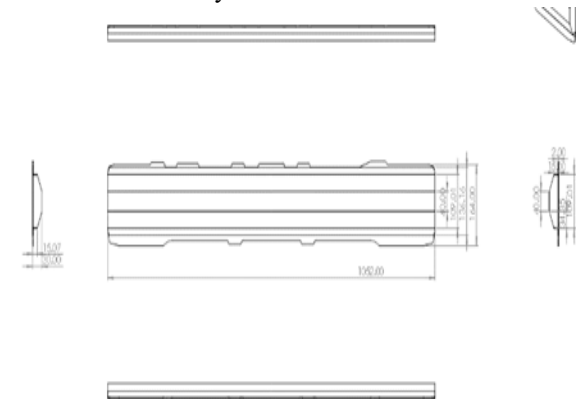


Fig. 2D Drawing and Dimensions of New Bumper Beam.

Load Factors

Type:	Apply normal force
Value:	400 kN

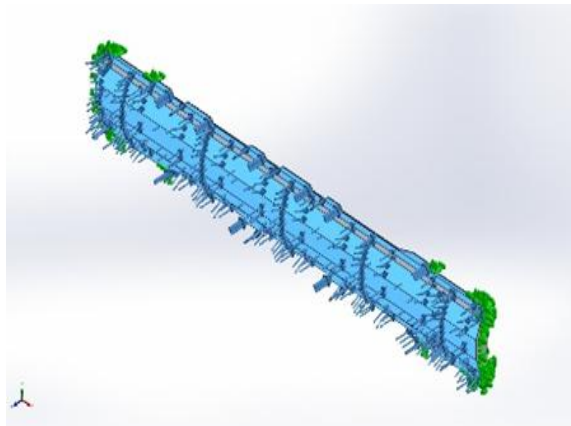
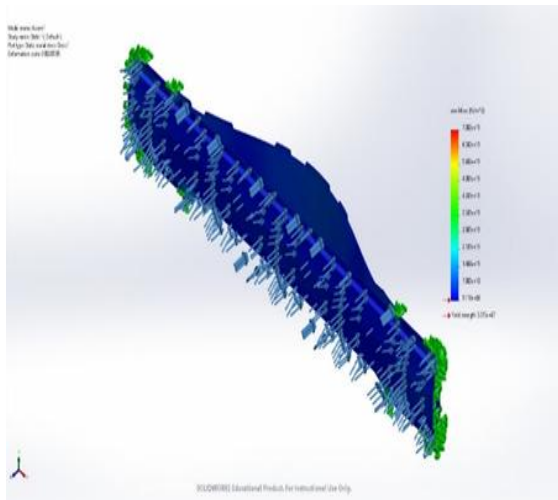


Fig. Applied Load on New Bumper Beam.

Study Result

Stress

Name	Type	Min	Max
Stress	VON: von Mises Stress	9.118e+06 N/m ²	7.002e+1 1N/m ²



Displacement

Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0.000e+00 mm	3.712e+04 mm

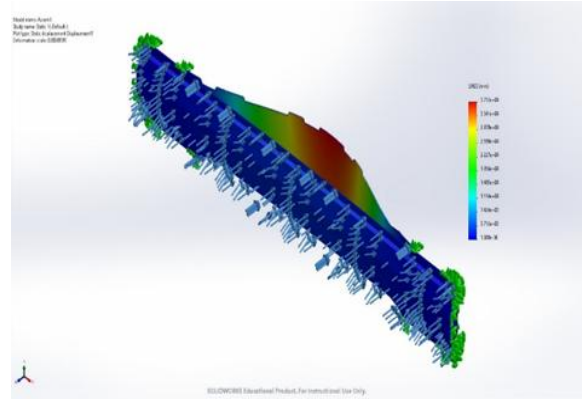


Fig. Displacement on New Bumper Beam.

Strain

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	4.673e-05	3.825e+00

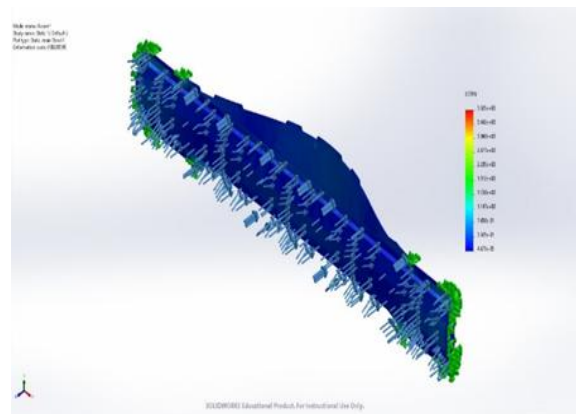


Fig. Strain on New Bumper Beam.

Deform Shape

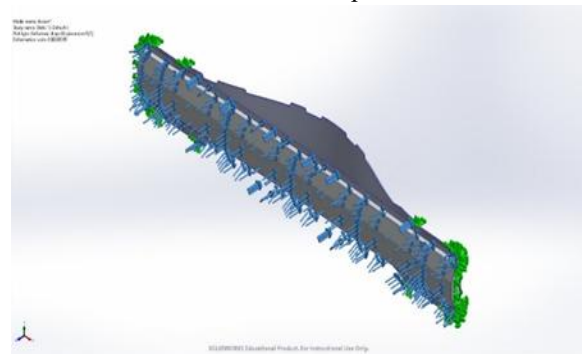


Fig. Deform Shape of New Bumper Beam.

3.3 Result and Discussion of Static Analysis

	Existing Bumper Beam	Existing Bumper Beam with New Material	New Bumper Beam
Mass	2.437633 kg	2.437633 kg	1.874762 kg
			0.562871 kg
Material	6061 Alloy	6061-T6 (SS)	6061 Alloy
Load	400 kN		
Stress	von Mises Stress		
Min.	3.207e+03 N/m ²	1.622e+03 N/m ²	9.118e+06 N/m ²
		1.585e+03 N/m ²	9.114793e+06 N/m ²
Max.	9.993e+10 N/m ²	9.993e+10 N/m ²	7.002e+11 N/m ²
			6.0027e+11 N/m ² six times higher.

Displacement			
Min.	0.000e+00mm	0.000e+00mm	0.000e+00mm
Max.	5.356e+02mm	5.356e+02mm	3.712e+04mm
			3.658e+04mm
Strain			
Equivalent Strain			
Min.	2.537e-08	3.615e-08	4.673e-05
		1.078e-08	4.6705e-05
Max.	8.676e-01	8.676e-01	3.825e+00
			2.9574 times more

- CAD Modelling: The existing dimensions of the Maruti Suzuki Ertiga front bumper beam were captured to create a 3D part file.
- Material Assignment: Aluminum Alloy 6061 was applied to the model.
- Boundary Conditions: A fixed support was applied to the mounting points (where the beam connects to the chassis rails) and a static load (representing a low-speed impact) was applied to the frontal face.
- Simulation: A static structural analysis was performed to record the baseline Von-Mises stress and total displacement.

Phase II: Material Sensitivity Test

- The material properties were updated to Aluminum 6061-T6 to evaluate the impact of tempering on the existing design.

- The simulation was re-run under identical loading and boundary conditions to ensure a "fair test" comparison.

Phase III: Geometric Redesign and Optimization

- Design Modification: Based on the stress concentration zones identified in Phase-I a new bumper beam design was drafted (e.g. changing the cross-section or adding strengthening ribs).
- Final Simulation: The original Aluminum 6061 material was applied to this new geometry.
- Validation: Results were compared against the baseline to confirm improvements in all mechanical parameters.

IV. CONCLUSION

The static structural optimization of the front bumper beam for the Maruti Suzuki Ertiga was successfully

performed using SolidWorks. The research work highlights the importance of design optimization in improving structural performance of passenger car Maruti Suzuki Ertiga. The following conclusions were found:

1. **Material Limitation:** Upgrading the material from Aluminum 6061 to 6061-T6 on the existing bumper geometry provided negligible improvements in static performance proving that material substitution alone is not always a viable solution for structural enhancement. This indicates that material substitution alone may not significantly enhance structural efficiency.
2. **Geometric Superiority:** The proposed new design demonstrated superior structural integrity and better structural performance. Significantly reducing maximum Von Mises Stress and overall deformation compared with the existing model.
3. The proposed bumper beam design showed better structural performance by significantly reducing maximum Von Mises Stress and overall deformation compared with the existing model.
4. **Safety & Efficiency:** The optimized design ensures a higher Factor of Safety (FOS), which is crucial for the Maruti Suzuki Ertiga given its role as a high-occupancy passenger vehicle in Indian road conditions.

Overall of this static structural optimization work suggests that geometric optimization and topology improvements are more effective than costly material combination for enhancing automotive bumper performance. The research provides a practical framework for automotive engineers in India to develop safer and more efficient vehicle structures while maintaining cost effectiveness. Also this work provides a framework for Indian automotive engineers to focus on geometric topology rather than expensive material upgrades to meet evolving safety standards.

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