ISSN 1392-1207. MECHANIKA. Vol. 31, No. 5, 2025: 486–492

Design and Parametric Study of Lightweight Aluminium Alloy Bumper Beams for Enhanced Crashworthiness Using the Finite Element Method

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https://doi.org/10.5755/j02.mech.40791

1. Introduction

In the automotive industry, ensuring vehicle safety while optimizing performance and efficiency is a key focus in structural component design. Among critical components, the bumper beam plays a vital role in absorbing impact energy and protecting the vehicle's occupants and critical systems during a collision. Traditionally, bumper beams have been constructed using high-strength steel due to its robustness; however, such designs often result in increased component weight, adversely impacting fuel efficiency and limiting energy absorption capabilities during high-speed impacts [1]. Automotive safety research has extensively explored materials and structural layouts for bumpers, focusing on impact resistance and cost-efficiency [2]. The baseline bumper beam in this study, made from Steel 350MC with a thickness of 3 mm, was found to be heavy and less efficient in energy absorption. These limitations necessitated the exploration of alternative materials and designs to meet modern automotive requirements for crashworthiness, weight reduction, and improved fuel economy [3]. The design of bumpers is highly regulated to ensure crashworthiness, and their effectiveness is measured by their ability to absorb and dissipate energy during collisions [4-6]. While traditional bumper designs have focused on enhancing impact resistance through material selection, there is an increasing focus on optimizing geometry and structure to improve performance [7-9]. In terms of geometry, the structure and shape of bumper beams can significantly affect their energy absorption capacity [10, 11]. The study demonstrated that optimizing the geometry of the bumper beam, such as adjusting its thickness, curvature, and cross-sectional profile, could lead to better energy dissipation during impacts. These findings suggest that beyond material properties, geometric configurations play an important role in deter-mining bumper performance in low-speed crashes [12, 13]. Optimization of bumper beam shapes and cross-sections has been extensively studied to optimize the cross-sectional shape of bumper beams, resulting in improved crashworthiness and resistance to low-velocity impacts [14, 15]. Experimental tests and numerical simulations using LS-DYNA have validated these findings [16, 17]. FEA is a powerful tool in the structural optimization of bumper beams and structural analysis in automotive applications. The exploration of sustainable materials and optimized designs in automotive applications has gained significant attention due to the increasing demand for lightweight, high-performance, and environmentally friendly alternatives to traditional materials [18].

In summary, the literature underscores the importance of material properties, geometric optimization, and simulation tools such as FEA in designing effective bumper beams. The current study adds to this body of knowledge by exploring new bumper beam geometries for passenger cars and evaluating these designs through numerical methods. This approach provides a comprehensive understanding of bumper performance and highlights the potential for improved safety features in low-speed impacts. To address these challenges, this research lever-ages advanced numerical simulations methodologies to design and evaluates novel bumper beams using light-weight aluminium alloys. A three-point bending test was chosen as the primary evaluation method to assess stiffness and energy absorption properties [19]. Using the Design of Experiments (DOE) approach [20], several iterations were conducted to identify the optimal design. The study also evaluates the optimized aluminium alloy bumper beam against RCAR (Research Council for Automobile Repairs) slow-speed impact requirements, ensuring its suitability for real-world applications. The final design achieves a significant reduction in mass and an improvement in energy absorption without compromising stiffness. This work con-tributes to sustainable automotive design by providing a comprehensive framework for developing lightweight, crashworthy components that align with industry trends toward fuel-efficient and environmentally conscious vehicles.

2. Numerical Methodology for Testing

The structural performance of automotive bumper beams is crucial for crashworthiness. Three-point bending tests, known for their simplicity and effectiveness, assess stiff-ness and energy absorption, ensuring minimal deformation and occupant protection. Numerical simulations aid material and design exploration, evaluate the predictions. This combined approach enhances crash safety, supports lightweight designs, and aligns with industry goals for performance and sustainability.

2.1. Loading and boundary conditions

The three-point bending test evaluates the structural performance, energy absorption, and deformation of vehicle components like bumper beams under bending loads. It effectively simulates real-world conditions such as frontal collisions. The beam, spanning 440 mm, is supported at both ends, with a central loading arm applying a downward force, replicating a simply supported beam under center-point loading shown in Fig. 1. A constant displacement load is applied using a cylindrical or hemispherical indenter to ensure consistency in testing. Numerical simulations in LS-DYNA use a quasi-static approach, applying a displacement rate of 1 mm/ms over 100 ms, with a total displacement of 100 mm.

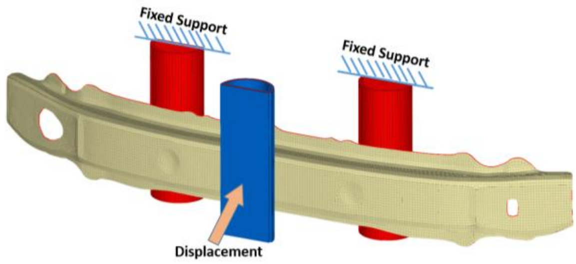


Fig. 1 Three- point bending test for the bumper beam

2.2. Mesh sensitivity study

A mesh sensitivity study is essential in FEA to ensure numerical accuracy while maintaining computational efficiency. For the LS-DYNA bumper beam model, the study refined the mesh from 8 mm to 2 mm. Results from the three-point bending test Table 1 show that mesh sizes be-low 5 mm yield similar maximum stress values. Fig. 2 presents the relationships between the number of elements and maximum stress. This study ensures reliable and efficient simulations, forming the basis for robust design evaluation.

Table 1

Summary of mesh convergence study

Element type	Element size, mm	No of elements	Maximum stress σ_{max}, MPa
2D Shell	8	4036	500.3
	7	5591	528.5
	6	7776	548.6
	5	10750	558.2
	4	17293	558.3
	3	30132	558.7

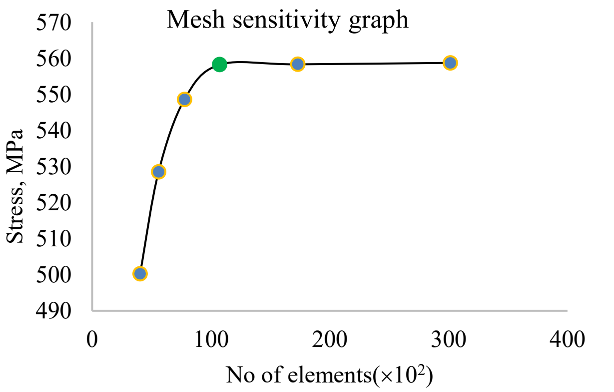


Fig. 2 Relationship with No of elements to maximum stress

2.3. FE model definitions

Developing a LS-DYNA FE model for nonlinear simulations requires precise problem setup for accuracy. Based on the numerical sensitivity study, the bumper beam is modeled using 2D shell elements, combining 3-node triangles and 4-node quads. It is assigned PART_SHELL properties with Element Formulation 16 and 5 integration points. A detailed view of the 2D middle shell modeling with quad and triangle elements is shown in Fig. 3

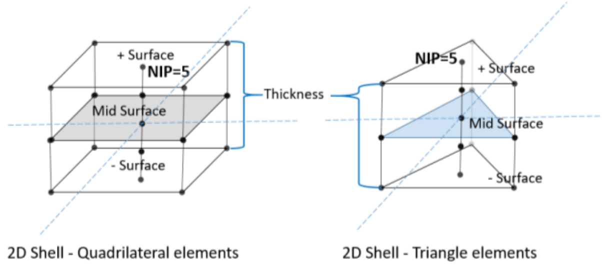


Fig. 3 2D-shell quad and triangle element layers

Bumper beams FE Modeling has achieved with middle surface modeling with 5mm of element average size and of various design of Bumper beam FE model has shown in the Fig. 4.

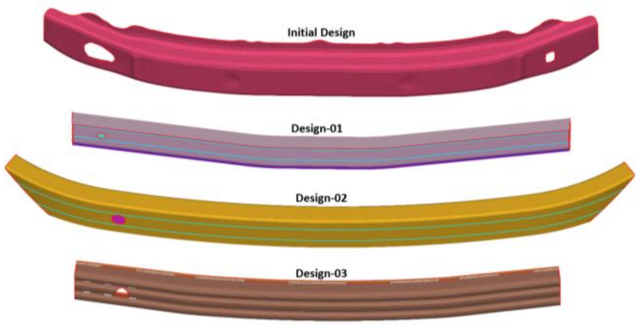


Fig. 4 FE mesh modeling of different bumper beam

Shell thinning effect has activated to capture thickness reduction during plastic deformation. Contact algorithm used as *CONTACT_AUTOMATIC_SINGLE_SURFACE was employed with SOFT=1 penalty formulation, which is widely used in full vehicle crash simulations. This ensures stable and realistic contact behavior between interacting bumper and vehicle structure.

2.4. LS-DYNA material model

The Fig. 5 shows the material model of Aluminum Alloy in MAT24 Card, where the plastic properties are defined through a true stress–plastic strain table. The input table specifies the yield point followed by successive true stress values at increasing plastic strains, enabling the solver to accurately capture the nonlinear plastic hardening behavior of the alloy.

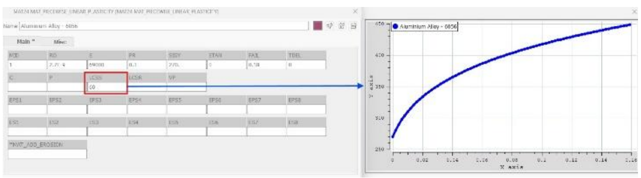


Fig. 5 MAT24 Material modeling of AA6056

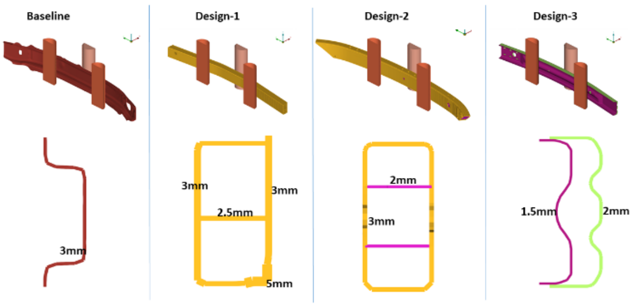
3. Design and Numerical Validation of Bumper Beams

The baseline bumper beam, made of S350MC micro-alloyed steel (3 mm C-section, 6.20 kg), has high mass and low energy absorption (2487 J, 47 kN at 100 mm displacement). To enhance performance, three aluminum bumper beam geometries (Design-01, Design-02, Design-03) were compared with the baseline using DOE. Variables included cross-section thickness, curvature, and alloy type.

Objectives were:

- Maximize energy absorption.
- Minimize mass.
- Maintain stiffness within baseline limits.

Fig. 6 compares the baseline and modified designs, highlighting thickness variations to optimize stiffness and energy absorption.



a b c d

Fig. 6 Vehicle front bumper beam designs: a – Baseline, b – Design-01, c – Design-02, d – Design-03

3.1. Material characterization

Four materials were considered: S350MC steel (baseline), AA6111, AA6082, and AA6056. Their true stress–strain curves were shown in Fig. 7. AA-6111 exhibits limited strength and work-hardening capability, while AA-6082, though stronger than 6111, suffers from reduced ductility. The behavior of AA-6056 positions it closer to the performance of steel S355 in terms of energy absorption potential, but with the added advantage of a much lower density. These characteristics make AA-6056 a particularly suitable for lightweight crashworthy structural components, where both energy absorption and mass optimization are critical design requirements.

3.2. Manufacturability cost–benefit

Baseline steel design: easily produced by cold stamping. Aluminum designs: Feasible via extrusion with bending. While aluminum incurs ~20–30% higher raw

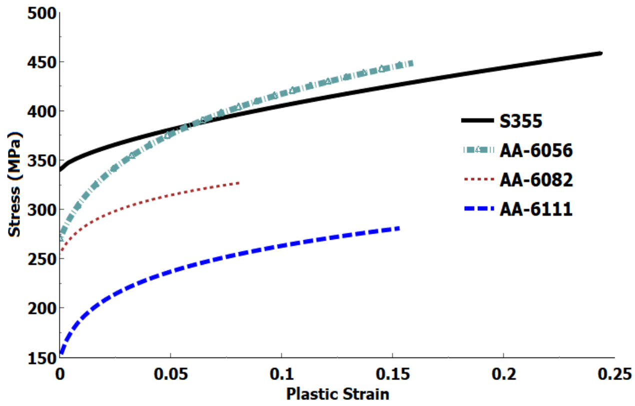


Fig. 7 Stress – strain curves for materials used

material and processing cost, the significant 61% weight reduction offers improved fuel economy and reduced emissions, justifying its adoption in high-volume vehicles.

3.3. Novel design evaluation

The Design of Experiments (DOE) method effectively evaluates bumper beam designs with varying geometries and materials, optimizing strength, energy absorption, and weight. Using LS-DYNA nonlinear three-point bending tests, DOE iterations were conducted, with results summarized in Table 2. This structured approach enhances design efficiency, ensuring safety, performance, and cost-effectiveness. Stress distribution analysis during bending tests provides insights into mechanical behavior, strength, and deformation modes, as shown in Fig. 8.

3.4. Material versus geometry effects

To isolate contributions of Design and Material modifications, Baseline geometry with aluminum and Optimized geometry with steel was simulated, results has shown in the Table. Results showed both geometry and material significantly influence performance, with aluminum alloys—particularly AA6056—showing best energy-to-mass efficiency. ITR10 (AA6056–Base): Too light / underperforming - largest mass saving (~71%) but energy absorption and peak force drop ~50% → not acceptable for crash-worthiness. ITR11 (Steel–D1): Highest protection - large increases in absorbed energy (+54%) and peak force (+58%), but with a weight penalty (+11%). ITR3 (AA6056–D1): Best compromise huge mass reduction (~61%) while

Table 2

Bumper Beam Bending test DOE results summary

ITR. NO	Material				Design of Bumper				Results Measures		
	Steel S350MC	AA 6111	AA 6082	AA 6056	Base	D1	D2	D3	Mass, kg	Energy, J	Force, kN
0	X				X				6.20	2487	47
1		X				X			2.40	1446.0	26.2
2			X			X			2.40	2032.0	35.7
3				X		X			2.40	2707.0	47.6
4		X					X		3.40	1491.0	36.6
5			X				X		3.40	2100.0	49.5
6				X			X		3.40	2771.0	60.4
7		X						X	1.60	442.0	9.3
8			X					X	1.60	363.0	12.6
9				X				X	1.60	838.0	15.5

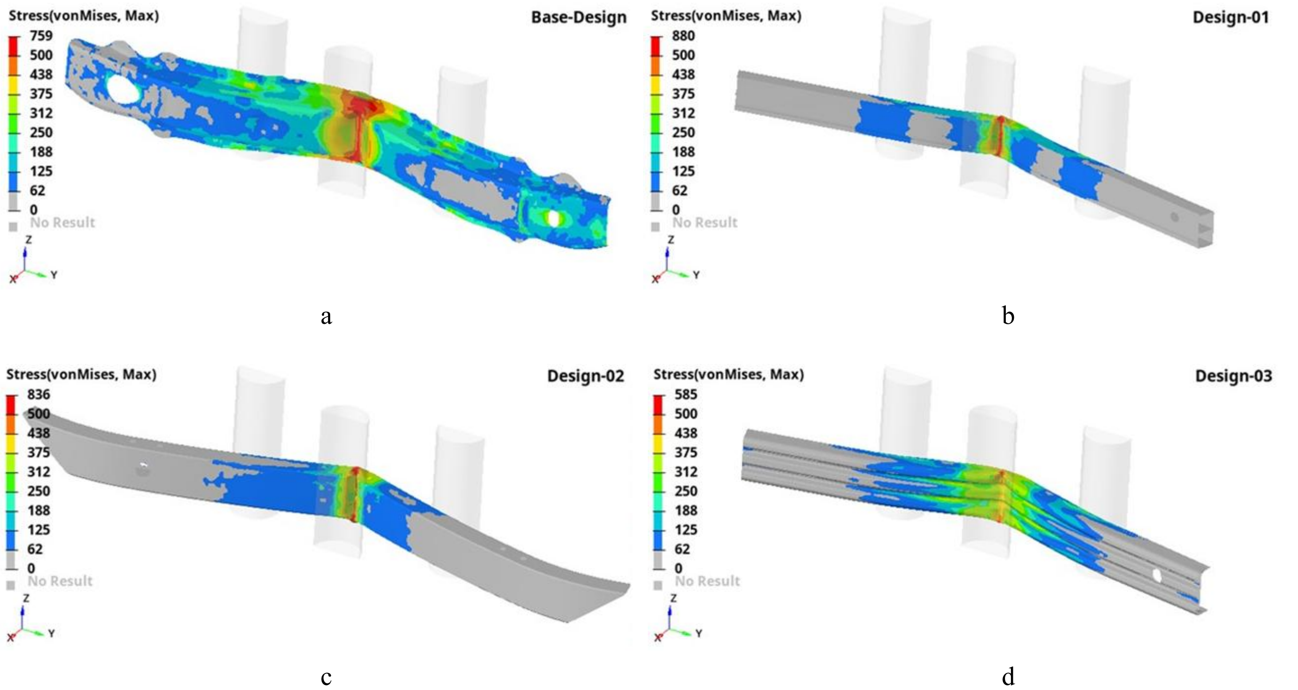


Fig. 8 Deformation with stress contours (MPa) of bumper beam designs: a – Baseline, b – Design-01, c – Design-02, d – Design-03

Table 3

Bumper beam bending test to isolate the contributions of design and material results baseline (ITR0): mass = 6.20 kg, energy = 2487.0 J, force = 47.0 kN

ITR	Material / Design	Mass, kg	ΔMass vs ITR0	Energy, J	ΔEnergy vs ITR0	Force, kN	ΔForce vs ITR0
ITR03	AA6056 / D1	2.40	**−61.3%**	2707.0	**+8.85%**	47.6	**+1.28%**
ITR10	AA6056 / Base	1.82	**−70.6%**	1258.5	**−49.4%**	23.6	**−49.8%**
ITR11	S350MC / D1	6.90	**+11.3%**	3830.2	**+54.0%**	74.3	**+58.1%**

improving energy absorption (+8.9%) and keeping peak force essentially unchanged (+1.3%). Recommended when weight saving and crash performance both matter.

3.5. Results comparison

The DOE methodology used to find the bumper beam design based on mass, energy absorption, and reaction force. Iteration 3 outperformed all others, achieving the highest energy absorption while significantly reducing mass. Compared to the baseline (Iteration 0), it maintains structural integrity with improved crash performance. Designated as Design 01 using AA 6056 aluminum alloy, it reduces mass by 61.3% and increases energy absorption by 8.8%, enhancing fuel efficiency and safety. While reaction force slightly increased, the trade-off is minimal given the substantial benefits. Fig. 9 and Table 4 present detailed comparisons.

Table 4

Bumper beam optimized design results

Iteration	Material	Design	Mass, kg	Energy, J	Force, kN
Baseline	S350MC	Base Design	6.20	2487	47
ITR03	AA-6056	Design-01	2.40	2707.0	47.6
		% of change	**-61.29%**	**+ 8.8%**	

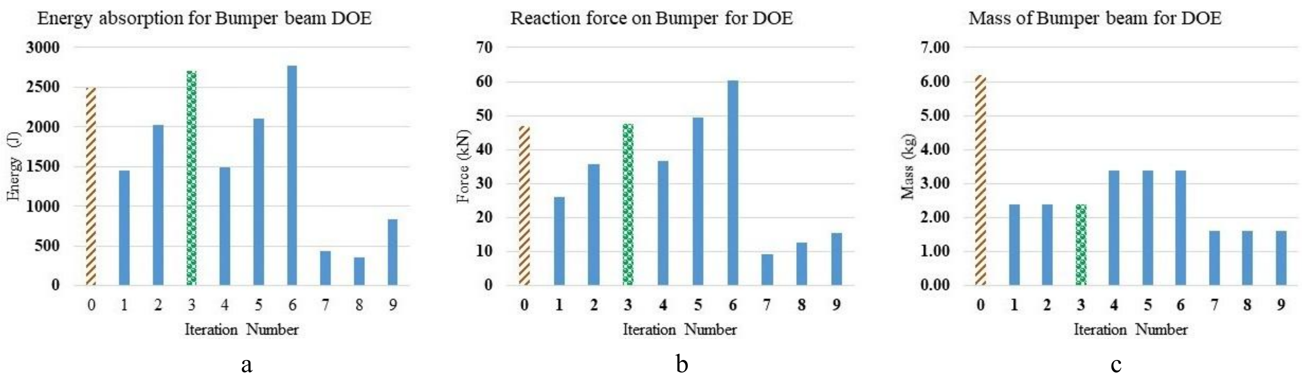


Fig. 9 DOE results comparison for iterations: a – energy absorption chart, b – reaction force chart, c – mass chart

4. RCAR Test

The bumper beam parametric study, evaluated through three-point bending tests, requires further assessment via the RCAR (Research Council for Automobile Repairs) slow-speed test. This standardized crash evaluation measures a vehicle's reparability after low-speed impacts, considering repair complexity, cost, and part availability. Fig. 10 illustrates the RCAR test setup for full vehicle assessment.

In the test, the barrier is mounted on a wall and aligned with the bumper beam for accurate impact. The vehicle, with the bumper system installed, is propelled at 10 km/h into the barrier. Upon impact, the bumper deforms but remains easily replaceable without cutting or welding, ensuring quick and cost-effective repairs.

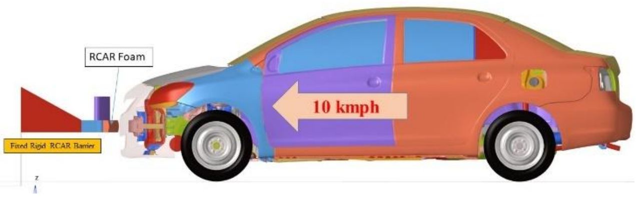


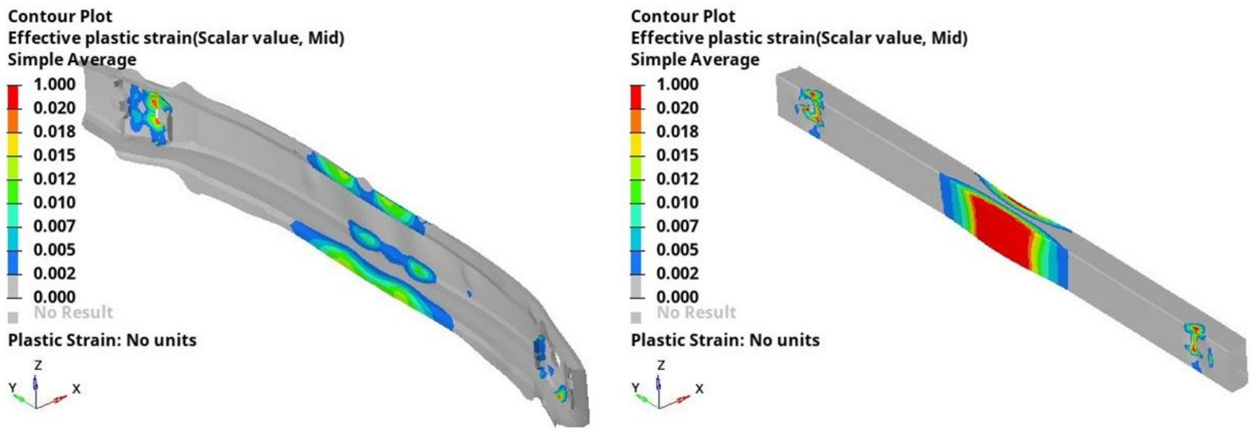
Fig. 10 RCAR vehicle test setup

4.1. RCAR FE model

A full vehicle LS Dyna FE model was considered with a total mass of 1250 kg, comprising approximately 1.57 million elements and 1.53 million nodes. All major front-end components, including the bumper beam, crash boxes, front side members, sub frame, and BIW attachments, were explicitly modeled. The bumper beam was attached to the BIW using bolted connections, enabling post-impact replacement without structural damage.

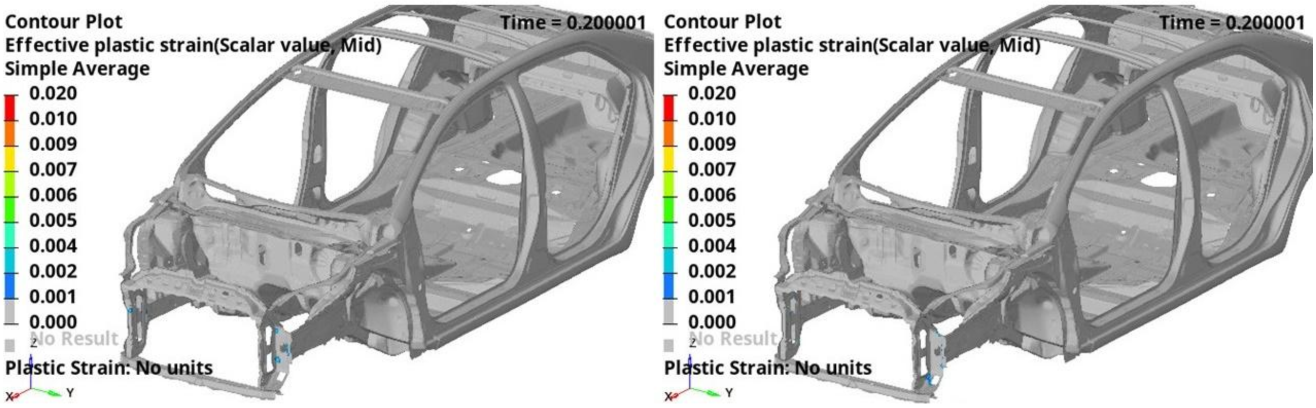
4.2. RCAR test results

The RCAR test results compare plastic stain at Mid-Surface deformation in the Baseline and Optimized bumper beam models shown in Fig. 11. In the baseline model, plastic strain is localized and relatively low, indicating limited deformation and energy absorption. In contrast, the optimized aluminum bumper beam, exhibits higher and more uniformly distributed plastic strain across the mid-section. This behavior reflects enhanced crash energy absorption capacity due to the improved material utilization and lightweight design of aluminum. The deformation response of the Body-in-White (BIW) is shown in Fig. 12. Both the baseline and optimized models reveal plastic strain values below 2%, concentrated around the bumper beam connection regions. Importantly, no visible structural damage or weld failures are observed in either beam, bolted to the BIW, ensures that the main structure remains unaffected by the crash event, thereby facilitating easy removal and replacement of the bumper beam post-impact case. The



a b

Fig. 11 Bumper beam plastic deformation: a – baseline, b – optimized



a b

Fig. 12 Deformation on body in white: a – baseline, b – optimized

optimized beam, bolted to the BIW, ensures that the main structure remains unaffected by the crash event, thereby facilitating easy removal and replacement of the bumper beam post-impact. For the baseline design, the maximum sectional forces recorded were 30.29 kN and 34.73 kN for the LH_FSM and RH_FSM, respectively. In comparison, the optimized model achieved significantly reduced peak forces of 28.10 kN (LH_FSM) and 28.60 kN (RH_FSM), representing reductions of approximately 7% and 18%. These reductions clearly demonstrate that the optimized bumper beam design effectively dissipates crash energy, thereby minimizing load transfer to critical vehicle components.

5. Conclusions

This study successfully demonstrates the potential for improving the performance and efficiency of vehicle bumper beams by using lightweight materials and innovative design modifications. The baseline bumper beam, made from Steel 350MC, was identified to have limitations in terms of high mass, low energy absorption, and its negative impact on fuel efficiency. By transitioning to aluminum alloy materials, particularly AA 6056, and optimizing the design through iterative simulations, significant improvements were achieved. The optimized bumper beam (Design 01) achieved a remarkable 61.3% reduction in mass while improving energy absorption by 8.8%. These enhancements were critical for improving the vehicle's crashworthiness, contributing to better passenger safety and energy efficiency. The use of AA 6056 aluminum alloy ensured that the structural integrity was maintained while reducing the overall weight, resulting in a more efficient and dynamic vehicle.

Furthermore, the bumper beam design met essential crashworthiness criteria, as evidenced by the RCAR test results. No damage on the BIW parts and the plastic strain remained within acceptable limits. Additionally, the optimized bumper design demonstrated reduced section forces in the front side members, further improving energy absorption and protecting critical vehicle components.

Overall, this research provides valuable insights into the design of lightweight, high-performance bumper beams. The findings suggest that aluminum alloys, specifically aluminum alloy 6056, offer a promising solution for reducing vehicle mass, enhancing fuel efficiency, and improving safety. The optimized bumper beam design aligns with current industry needs for lightweight yet strong materials, contributing to the advancement of sustainable automotive innovation and offering significant benefits for real-world vehicle applications.

Acknowledgements

The authors would like to thank the Anna University, Chennai for enabling us to conduct research and Government College of Engineering, Salem, India, for providing the simulation facilities for numerical analysis.

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DESIGN AND PARAMETRIC STUDY OF LIGHTWEIGHT ALUMINUM ALLOY BUMPER BEAMS FOR ENHANCED CRASHWORTHINESS USING THE FINITE ELEMENT METHOD

S u m m a r y

The study focuses on improving the performance and efficiency of a vehicle bumper beam by addressing limitations in the baseline design, which uses Steel 350MC material with a thickness of 3 mm. The baseline design, though robust, is bulky, absorbs limited crushing energy during high-speed impacts, and contributes to reduced fuel efficiency due to its heavy weight. To address these challenges, a three-point bending test was employed to evaluate stiffness and energy absorption characteristics at the component level. Based on numerical simulations, three novel bumper beam designs were developed using aluminum alloy materials to achieve weight reduction while maintaining performance. Design of Experiments (DOE) was utilized to evaluate these designs through iterative three-point bending tests, identifying the optimal configuration using AA6056 material. The optimized bumper beam demonstrated a 61.29% reduction in mass, an 8.8% improvement in energy absorption, and no compromise in stiffness compared to the baseline. Furthermore, the optimized design was evaluated in a slow-speed RCAR (Research Council for Automobile Repairs) numerical simulation to ensure compliance with crashworthiness standards. Results confirmed the optimized bumper beam meets RCAR requirements, highlighting its suitability for real-world application. This research provides automakers with a lightweight, high-performance bumper beam design that enhances crashworthiness, reduces vehicle mass, and improves fuel efficiency, contributing to sustainable automotive innovation.

Keywords: bumper beam, lightweight design, finite element analysis (FEA), three-point bending test, parametric study, mass reduction, RCAR, design of experiments (DOE), LS-DYNA.

Received March 11, 2025
Accepted October 22, 2025