Optimizing Reinforcement Beam for Low-Speed Collision Performance Using Multicriteria Decision Making

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Abstract. Ensuring vehicle safety during low-speed collisions is a fundamental aspect of modern automotive engineering. This study optimizes bumper reinforcement beam designs for sedan vehicles through systematically evaluating section profiles, materials, and thicknesses. Three section types (C Hat, B Hat, and D Hat), three materials (AL2024T86, CFRP T700S, and Steel Bare /E.G.-H.F.80Y 100T), and three thickness variants (4 mm, 5 mm, and 6 mm) were analyzed using finite element simulations under longitudinal and lateral impact conditions following UN ECE R42 standards. Key performance parameters included energy absorption, deformation resistance, and stress distribution. The Simple Additive Weighting (SAW) method was employed to determine the optimal configuration objectively. Results indicate that the C Hat section with AL2024T86 achieved the highest score (1.218) in the initial evaluation. Subsequent analysis across materials reaffirmed AL2024T86 as the superior material (1.7731). Final testing based on thickness variations revealed that a 6 mm C Hat section using AL2024T86 yielded the most effective combination (1.001). The findings offer a quantitative framework for reinforcement beam selection, contributing to improved crashworthiness and structural efficiency in automotive design.

Keywords: Reinforcement Beam, Finite Element Method, Simple Additive Weighting.

1 Introduction

Vehicle production has shown a consistent upward trend, with sales in Asia increasing by 9.17% from 2019 to 2024 [1]. This growth reflects rapid industrial and economic expansion; however, it also correlates with a rising risk of traffic accidents. According to a 2021 WHO report, Southeast Asia recorded 212,135 deaths caused by road accidents [2], highlighting the urgent need for improved vehicle safety systems.

Passenger car accidents often involve front and rear collisions. Previous research [3] revealed that low-speed accidents, particularly in urban areas, frequently impact both parts of the vehicle, with the direction of impact at intersections being unpredictable.

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Vehicle safety design is divided into active safety and passive safety protection. Bumpers, both front and rear, absorb the energy of low-speed collisions to protect the vehicle's main structure, such the frame chassis [4][5].

In conventional vehicles, bumpers protect engine components. However, in electric vehicles, bumper optimization remains essential. A previous study [6] demonstrated that optimizing bumper structures can effectively reduce collision acceleration from 80 g to 67.1 g and accelerated collision energy absorption from 65 m/s to 40 m/s, significantly improve safety.

Crash simulation using the finite element method (FEM) offers a solution for replicating accident scenarios design and simulation, ensuring vehicles meet applicable safety standards [7].

Previous researchers [8] often tested new bumper designs in impact tests, that studied crash boxes on bumpers to assist reinforcement beams in absorbing collision energy, with the best results achieved in the combination of conic and notched shapes (SCN), showing the lowest force (88.3 kN), high crumpling efficiency (46.7%), and better fold consistency [8]. Meanwhile, another research [9] compared variations in bumper materials and found that Aluminum 2024 T-86 could replace Carbon Fiber for collisions up to 30 km/h, reducing stress by 21%, increasing deformation by 6%.

Despite extensive research on bumper design and material selection, no studies have comprehensively compared various variable within the same simulation on actual vehicle crash test scenarios. This study fills that gap by investigating multiple section, materials, and thickness to determine the optimal reinforcement beam combination for impact energy absorption. Simulations were conducted using ANSYS 2024 R1, guided by the UN ECE R42 regulations for vehicle protective devices [10][11]. Using ANSYS Explicit Dynamics ensures high accuracy in replicating real crash conditions, providing reliable results for evaluating vehicle safety.

The research adopts a systematic, multi-stage approach combined with an elimination process at each testing stage. In each phase, alternative designs are evaluated based on several safety parameters, such as maximum deformation, peak stress, and energy absorption capacity [12]. The Simple Additive Weighting (SAW) method combines these parameters, providing a quantitative and objective assessment of each design alternative. By assigning weights to the performance criteria, the SAW method enables the identification of the most optimal solution while systematically eliminating suboptimal alternatives at each stage [13][14].

Through applying SAW in a multi-criteria decision-making framework, this research aims to deliver an optimal bumper design that meets global safety standards while advancing automotive safety technology. SAW was chosen due to its simplicity, transparency, and ability to handle multiple conflicting criteria, making it an ideal method for selecting the best combination of section shape, material, and thickness. By assigning appropriate weights to each criterion based on its importance and aggregating the results, SAW allows for a comprehensive and objective evaluation of design alternatives. This study provides critical insights that can be directly applied to the automotive industry, enhancing vehicle safety and overall performance. The results are expected to have significant implications for future bumper design strategies, contributing to safer vehicles and improved crashworthiness [15].

2 Methodology

2.1 Product Design Specification (PDS)

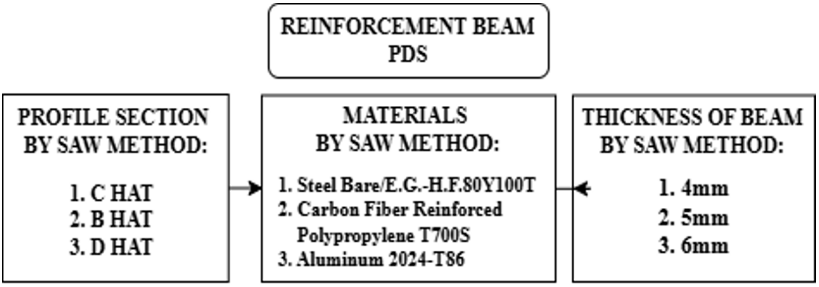

Fig. 1. Product Design Specification

The PDS depicted in Fig. 1, delineates the mapping of the variables to be studied and serves as a framework for this research. To select the optimal bumper design with the best impact energy absorption, this study evaluates several alternatives using an elimination method, with the results evaluated using that method [13][16]. The most effective bumper design is determined by a multifaceted evaluation process that incorporates key performance criteria, including maximum deformation, stress, and energy absorption [4].

Profile Section.

This study builds upon the previous research [17], which identified the types of reinforcement beams that are commonly used. Our study extends the research by adding one profile section, which is the D Hat section, and applying an elimination method with various parameters. Fig. 2 shows the design of each part:

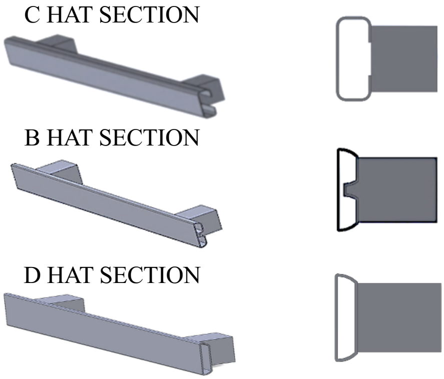

Fig. 2. Various Profile Section

1. C Hat Section, with an open cross section with a simple geometry, typically used in applications subjected to moderate or low mechanical loads. Its open design allows for easier manufacturing and assembly, although it provides limited torsional rigidity compared to closed profiles.
2. B Hat Section, featuring two symmetrical chambers that enhance stiffness and load bearing capability. It combines the strength characteristics of closed profiles with the design flexibility of open sections, making it suitable for components that require both structural efficiency and lightweight performance.
3. D Hat Section, with a characterized by its hat shaped closed profile, this section offers superior structural integrity and high stiffness. It is widely applied in vehicle structures that demand an optimal balance between strength, crashworthiness, and weight efficiency, making it ideal for energy absorption components such as bumper beams.

Materials

A previous study [9] investigated the characteristic values of material variations used in bumpers through impact testing. Our study extends the research by adding one material, which is the Advanced High Strength Steel DP780 for impactor material. Then, this study adding the elimination method, for multi-decision making [12]. Table 1 shows the material properties used in this test.

Table 1. Material Properties

MATERIAL	**Density (kg/m^3)**	**Poisson's Ratio (v)**	**Young Modulus (MPa)**
Advanced High Strength Steel DP780 (Impactor)	8.000	0,27 - 0,30	210.000 – 300.000
Steel Bare/E.G.-H.F.80Y 100T	7.860	0,30	207.000
Carbon Fiber Reinforced Polypropylene T700S	1.800	0,20	230.000
Aluminum 2024-T86	2.780	0,33	72.400

Thickness of Beam

The thickness of the beam is a critical factor in determining the bumper's ability to absorb energy and maintain structural integrity during a collision. Research about beam structure [16] say a thicker beam generally provides better energy absorption and resistance to deformation, enhancing vehicle safety. However, it also increases the weight of the bumper, which can affect vehicle performance and fuel efficiency. This study tests various beam thicknesses to find the optimal balance between energy absorption and weight, in line with the Product Design Specification (PDS) [18].

2.2 Multi Decision Evaluation Use Simple Additive Weighting Method (SAW)

Evaluation Criteria and Weighting

The tests were conducted using a pre-configured impactor model, as shown in Fig. 3 and Fig. 4. Each Test considered three primary parameters to evaluate the bumper design performance:

1. Deformation (mm): This measures the extent of the reinforcement beam deformation due to impact. Lower values indicate better performance in absorbing collision energy.
2. Von Mises Stress (MPa): Measures the maximum stress distribution experienced during impact. Lower stress indicates better design stability and strength.
3. Energy Absorption (J): the capacity of the reinforcement beam to absorb impact energy. A higher value indicates a more effective design in reducing impact.

The simulation uses 0.001 seconds per time step, for a total of 100-time steps, to capture the impact movement with a high level of resolution. This enables more detailed and accurate analysis at each stage of the collision.

Weights are assigned to each criterion based on a predetermined scale. These weights were assigned through a survey involving automotive experts, engineering lecturers, and design practitioners with extensive experience in automotive structure, materials, and design. The experts were asked to evaluate the relative importance of various design criteria such as energy absorption, material strength, and deformation resistance by completing a structured questionnaire. The responses were then analyzed and aggregated to determine the weight for each criterion. In this process, energy absorption received the highest priority, as it is directly correlated with user safety and the overall effectiveness of the bumper in mitigating collision forces, as outlined in UN ECE R.42 regulations [11]. This method ensured that the weightings were not arbitrary but grounded in expert consensus, providing a well-rounded and scientifically supported basis for the optimization model [14].

The following weights have been assigned based on the methodology proposed in a previous study [4]:

1. Deformation (WD) : 0.31
2. Stress (WS) : 0.29
3. Energy Absorption (WE): 0.4

Data Normalization

Normalization is performed to align each parameter to the same evaluation scale with the following conditions:

1. For deformation and stress : $(Nij = \frac{\max(Xj)}{Xij})$ (1)

2. For energy absorption : $(Nij = \frac{Xij}{\max(Xj)})$ (2)

Notes:

Nij	: Normalization value of parameter j in alternative i
Max (Xj)	: Maximum value of parameter j across all alternatives
Xij	: Original parameter value

Total Score Calculation.

After normalization and weighting, the total score for each alternative is calculated using the SAW formula. Because the study has two types of crash tests, longitudinal test and side test, each type of test is given a final test weight of 50% for calculation final score (Si).

$$Si = WD \times NDi + WS \times NSi + \ WE \times NEi$$

Notes:

Si	: Total score per alternative
WD	: Deformation weight value
NDi	: Deformation calculation results per alternative
WS	: Stress weight value
NSi	: Calculated Stress values per alternative
WE	: Energy absorption weight value
NEi	: Energy absorption calculation results alternative

Determination of Best Design

The total score (Si) derived from the SAW method provides an objective measure for comparing and ranking all design alternatives, with the highest scoring combination selected as the final recommended design. This approach is also supported by the methodology discussed in reference [14], as it effectively identifies the most optimal configuration that efficiently absorbs impact energy, minimizes deformation, and ensures a safe distribution of stress across the structure.

2.3 Regulation and Simulation

The collision simulation was conducted using ANSYS Explicit Dynamics 2024 R1, with the Finite Element Analysis (FEA) method, to obtain results and form the basis for analyzing the structural response of the reinforcement beam on the bumper in various collision scenarios [7] [8]. The geometric model was created using SolidWorks 2021 and then imported into ANSYS for impact testing simulation.

Before to the simulation runs, a mesh convergence was performed to validate the accuracy of the numerical model. The mesh was refined iteratively, testing different element sizes to observe their effect on key response variables such as maximum stress, deformation, and energy absorption. Mesh quality was carefully evaluated, with element quality values approaching 1, indicating excellent mesh integrity and ensuring accurate and stable simulation results.

Two crash test scenarios based on UN ECE R42 [11] regulations were used, as shown in Fig. 3 for the impactor and Fig. 4 for the impact direction types:

1. Longitudinal Test with an impactor speed of 4 km/h (1.11 m/s);
2. 60° Side Test with an impactor speed of 2.5 km/h (0.69 m/s).

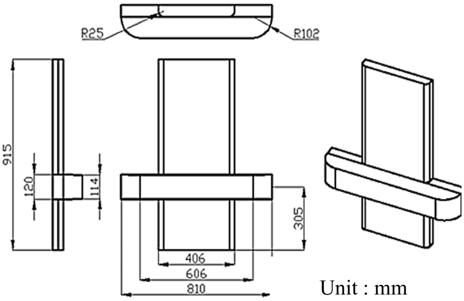

Fig. 3. Impactor From UN ECE R42 [11].

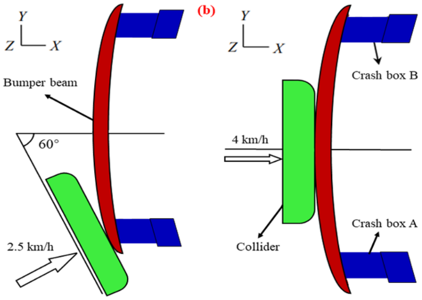

Fig. 4. Longitudinal Test and Side Test [4].

The impactor was utilized in longitudinal and side-impact tests to simulate the forces acting on the vehicle's bumper during a collision. The speed and direction of the impactor were controlled to replicate real collision conditions accurately. The orientation of the applied forces in both tests was designed to mimic accident scenarios, ensuring that the simulation results are representative of collision and can be used to assess the performance of the bumper design under conditions.

3 Results and Discussion

3.1 Profile Parameters

As shown in the graphs in Fig. 5, Fig. 6, Fig. 7 and Table 2, the calculated values for low-speed crash conditions were obtained from both the longitudinal and side-impact tests. After evaluating the three designs and applying the Simple Additive Weighting (SAW) method for elimination, the C Hat Section achieved the highest SAW value of 1.218 points, indicating its optimal performance among all alternatives.

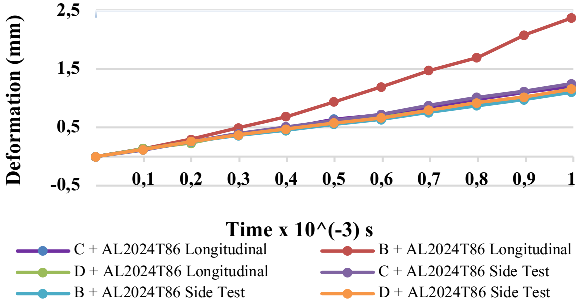

Fig. 5. Maximum Deformation Profile Parameters

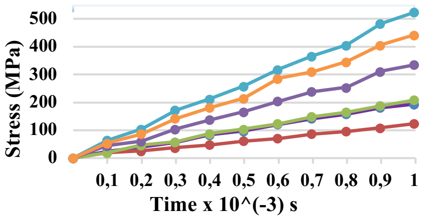

Fig. 6. Von Mises Stress Profile Parameters

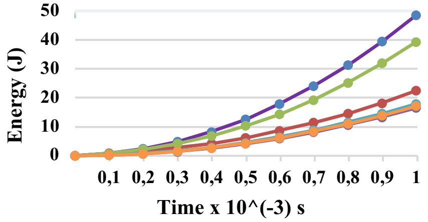

Fig. 7. Energy Absorption Profile Parameters

Table 2. Result for First Step PDS with SAW Method

STEP 1	TEST	DATA NORMALIZATION			FINAL SCORE
		DEFORMATION	STRESS	ENERGY	
C Hat Section with AL2024T86	L	1,976	1	1	1,218
	S	1	1,565	0,922	
B Hat Section with AL2024T86	L	1	1,565	0,462	0,996
	S	1,134	1	1	
D Hat Section with AL2024T86	L	2,044	0,931	0,811	1,142
	S	1,082	1,181	0,957	

For the longitudinal test, the C Hat Section exhibited the highest performance, with a total deformation of 1.2057 mm, von Mises stress of 194.40 MPa, and energy absorption of 48.773 J. The D Hat Section recorded a deformation of 1.1657 mm, stress of 208.64 MPa, and energy absorption of 39.535 J. In comparison, the B Hat Section had the largest deformation of 2.3827 mm, with stress of 124.16 MPa and energy absorption of 22.575 J.

For the side test, the C Hat Section maintained its superior performance with a deformation of 1.2538 mm, a stress of 334.64 MPa, and an energy absorption of 16.605 J. The B Hat Section showed the lowest deformation at 1.1056 mm but recorded the highest stress of 523.60 MPa, with an energy absorption of 18.001 J. The D Hat Section had a deformation of 1.1582 mm, a stress of 443.17 MPa, and an energy absorption of 17.244 J.

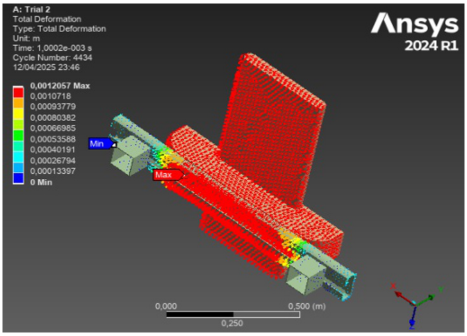

Fig. 8. Deformation of C Hat Section with AL2024T86

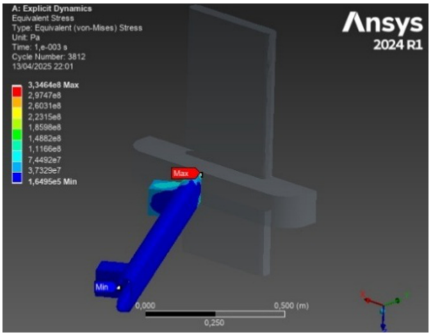

Fig. 9. Von Mises Stress of C Hat Section with AL2024T8

This is further confirmed by the results shown in Fig. 8 and Fig. 9, where C Hat Section is highlighted as the top performing design in terms of energy absorption across both tests. At the same time, D Hat Section excelled in minimizing deformation in the longitudinal test, and B Hat Section recorded the highest stress in the side test.

The results from this study align with the issues highlighted in the introduction, where the increasing risk of low-speed collisions in city cars necessitates improved bumper designs. The C Hat Section demonstrated the best energy absorption performance across the longitudinal and side-impact tests, directly addressing the need for optimal impact energy dissipation. Unlike previous studies [8] and [9], which focused on separate crash box designs or material variations, this study innovatively integrates section shape, material, and thickness in a unified simulation framework. By utilizing the SAW method, the research fills the gap of prior work by offering a comprehensive, objective evaluation of multiple design parameters. These findings confirm the C Hat Section's effectiveness in meeting safety standards and contribute new insights that could guide future bumper design strategies, improving crashworthiness and overall vehicle safety in low-speed collisions.

3.2 Material Parameters

As shown in the graphs in Fig. 10, Fig. 11, Fig. 12 and Table 3, the calculated values for low-speed crash conditions were obtained from both the longitudinal and side-impact tests. After evaluating the three designs and applying the SAW method for elimination, C Hat Section with AL2024T86 achieved the highest SAW value of 1.7731 points, indicating its optimal performance among all alternatives.

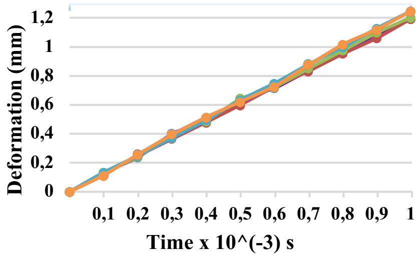

Fig. 10. Max deformation Material Parameters

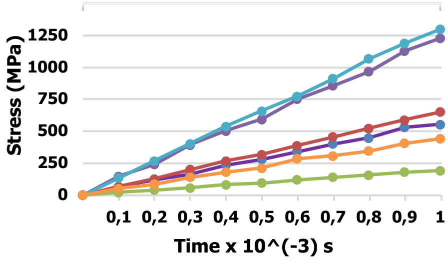

Fig. 11. Von Mises Stress Material Parameter

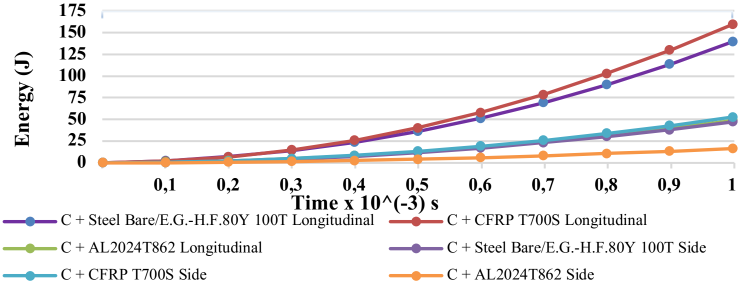

Fig. 12. Energy Absorption Material Parameters

Table 3. Result for Second Step PDS with SAW Method

STEP 2	TEST	DATA NORMALIZATION			FINAL SCORE
		DEFORMATION	STRESS	ENERGY	
C HatSection with Steel Bare/E.G.-H.F.80Y 100T	L	1,997	1,171	0,875	1,219
	S	1,001	1,717	0,811	
C HatSection with CFRP T700S	L	1,995	1	1	1,215
	S	1,004	1,548	0,909	
C Hat Section with AL2024T86	L	1,981	3,352	0,304	1,773
	S	1	4,887	0,284	

For the longitudinal test, C Hat Section with AL2024T86 exhibited a total deformation of 1.2057 mm, von Mises stress of 194.40 MPa, and energy absorption of 48.773 J. C Hat Section with CFRP T700S recorded a deformation of 1.1970 mm, stress of 651.70 MPa, and energy absorption of 160.31 J. In comparison, C Hat Section with Steel Bare/E.G.-H.F.80Y 100T had the lowest performance in this test, with a deformation of 1.1962 mm, stress of 556.10 MPa, and energy absorption of 140.4 J.

For the side test, D Hat Section with CFRP T700S maintained a superior performance with a deformation of 1.2481 mm, stress of 1,056.40 MPa, and energy absorption of 53.045 J. D Hat Section with Steel Bare/E.G.-H.F.80Y 100T had a deformation of 1.2519 mm, stress of 952.27 MPa, and energy absorption of 47.359 J.

In contrast, D Hat Section with AL2024T86 exhibited a deformation of 1.2538 mm, stress of 334.64 MPa, and energy absorption of 16.605 J.

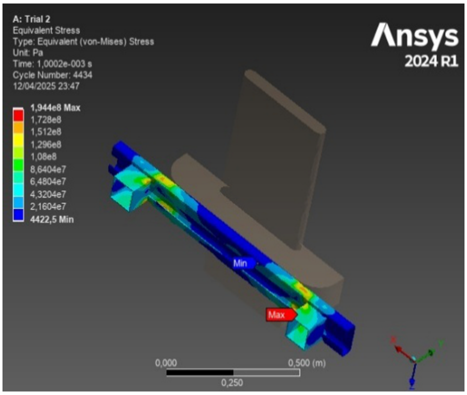

Fig. 13. Von Mises Stress of C Hat Section with AL2024T86

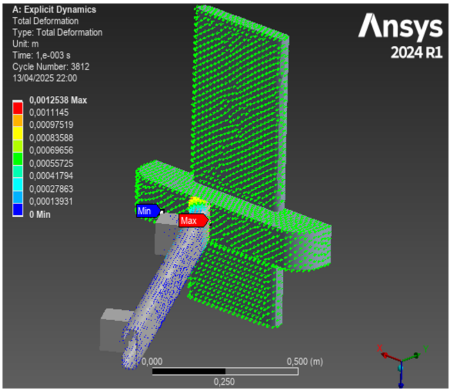

Fig. 14. Max Deformation of C Hat Section with AL2024T86

These results are further confirmed by the data shown in Fig. 13 and Fig. 14, where C Hat Section with AL2024T86 is highlighted as the top design in terms of energy absorption performance across both tests. At the same time, D Hat Section with CFRP T700S excelled in energy absorption in the side test, and C Hat Section with CFRP T700S showed the best stress performance in the longitudinal test.

3.3 Thickness Parameters

Step 3 in the elimination process represents the final stage. As shown in the graphs in Fig. 15, Fig. 16, Fig. 17 and Table 4, where the optimal combination of design and material thickness is determined. Based on the previous steps, the best design was the C Hat Section with AL2024T86. This step specifically focuses on evaluating the effect of material thickness, which is crucial in determining the bumper's final performance. The thicknesses of 4 mm, 5 mm, and 6 mm were analyzed, with each thickness influencing the design's deformation, stress, and energy absorption capacity.

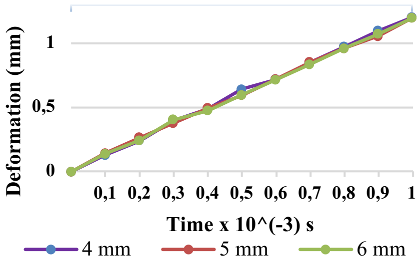

Fig. 15. Max Deformation Thickness

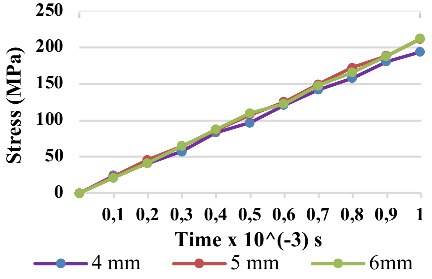

Fig. 16. Von Mises Stress Thickness

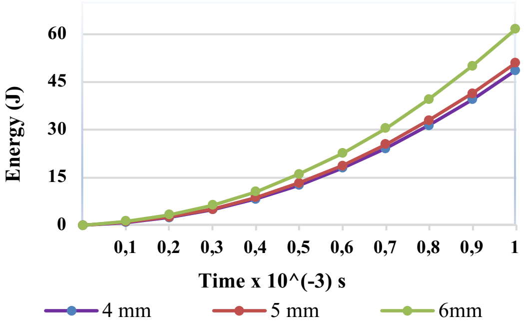

Fig. 17. Energy Absorption Thickness Parameters

Table 4. Result Thickness Parameters Test

Thickness	Mass (kg)	Volume (m^3)	Max Deformation (mm)	Von Mises Stress (MPa)	Energy Absorption (J)
4 mm	4,5289	1,6291	1,2057	194,40	48,773
5 mm	5,0967	1,8334	1,2023	212,22	51,103
6 mm	6,2406	2,2448	1,2003	212,85	61,807

The simulation results for the different thicknesses were as follows: for 4 mm thickness, the deformation was 1.2057 mm, the maximum equivalent stress was 194.40 MPa, and the energy absorption was 48.773 J. For 5 mm thickness, the deformation was slightly better at 1.2023 mm, with increased stress to 212.22 MPa and an energy absorption of 51.103 J. The 6 mm thickness showed the lowest deformation (1.2003 mm) but the highest stress (212.85 MPa) and the best energy absorption (61.807 J), indicating a better overall performance in terms of energy dissipation.

Table 5. Result for Third Step PDS with SAW Method

STEP 3	DATA NORMALIZATION			FINAL SCORE
	DEFORMATION	STRESS	ENERGY	
4 mm	1	1,095	0,789	0,944
5 mm	1,003	1,003	0,827	0,933
6 mm	1,004	1	1	1,001

As shown in Table 5 normalizing the data for deformation, stress, and energy absorption, the Simple Additive Weighting (SAW) method was applied to calculate the final scores. The normalized scores for 4 mm thickness were 1 for deformation, 1.095 for stress, and 0.789 for energy, resulting in a final score of 0.944. For 5 mm thickness, the scores were 1.003 for deformation, 1.003 for stress, and 0.827 for energy, leading to a final score of 0.933. 6 mm thickness achieved the highest normalized scores across all parameters, with a deformation score of 1.004, stress score of 1, and energy score of 1, resulting in a final score of 1.001. Thus, 6 mm thickness emerged as the optimal choice based on the SAW evaluation.

4 Conclusions

This study focus to optimize city cars low-speed collision performance by exploring various reinforcement beams, materials, and thickness designs, using the Simple Additive Weighting (SAW) method as a multicriteria decision making approach. Through comprehensive analysis involving longitudinal tests, side impact tests, and a subsequent elimination process, this identifies the most effective bumper design combination that ensures optimal energy absorption, minimal deformation, and safe stress distribution.

The final step of the analysis using the SAW method, a score of 1.001 was obtained for a thickness of 6 mm, indicating that the combination of the C Hat Section with AL2024T86 at this thickness is the optimal choice. This design demonstrates excellent energy absorption capabilities, with the lowest deformation and stress levels observed during both crash tests, highlighting its strong potential for enhancing vehicle safety. Furthermore, the material thickness analysis shows that a 6 mm thickness provides the best balance between energy absorption and structural strength, achieving the highest final SAW score.

The research examines different design parameters and bumper performance and provides insights into selecting the optimal combination of materials and thickness for better safety standards. By combining ANSYS 2024 R1 simulations and UN ECE R42 regulations, this study aims to be beneficial in the future, contributing to safer and more efficient vehicles in low-speed collisions.

For future research, it would be valuable to expand this study by investigating additional material combinations and exploring alternative reinforcement beam shapes that may offer improved performance in different collision scenarios, such as higher speed impacts or off center collisions. Moreover, incorporating real world crash data and validating simulation results with physical testing would enhance the reliability and applicability of the findings. Future studies could also examine materials long-term durability and behavior under repeated low-speed impacts, providing a more comprehensive understanding of the optimal materials and designs for long term vehicle safety.

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