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Finite Element Analysis of Automobile Bumper Impact Resistant Under Repeated and Oblique Collisions

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Abstract—
This study presents a numerical investigation of the crashworthiness performance of an automotive bumper beam integrated with crash boxes under multiple collision scenarios using ANSYS Explicit Dynamics. The analysis evaluates deformation, stress distribution, and energy absorption under realistic impact conditions. The bumper system consists of a curved hollow rectangular beam with symmetrically positioned square crash boxes based on practical automotive geometry. Two materials, Aluminium 6061-T6 and Automotive HSS 590 Steel, are examined to assess the influence of material properties on crash performance. Nonlinear behavior is modeled using multilinear isotropic hardening to capture plastic deformation during impact. Three collision cases are considered: (i) Repeated low-speed frontal impacts at 5 km/h and 10 km/h to simulate successive minor collisions. (ii) Frontal impact to represent direct crash conditions. (iii) Oblique impacts at 10° and 30°. A high-stiffness wall is used to approximate rigid body interaction. Results show that deformation, stress, and energy absorption vary significantly with material and loading conditions. Repeated impacts lead to progressive structural degradation, emphasizing the importance of residual crashworthiness. The comparative analysis highlights the trade-off between lightweight efficiency and structural strength in material selection. The study extends conventional single-impact approaches by incorporating repeated and oblique collisions, providing a more realistic evaluation framework for bumper systems. The findings support the design and optimization of automotive front- end structures with improved crash performance.

Keywords— Automobile; Bumper ; Impact Resistant; Oblique Collisions .

I. INTRODUCTION

The An automobile, commonly known as a car, is a vital invention that has revolutionized transportation. It enables the movement of people and goods efficiently, contributing to economic growth and improved communication. Modern automobiles combine mechanical, electrical, and electronic systems to provide safety, comfort, and performance. While traditional vehicles operate using petrol or diesel engines, there is a growing shift toward electric and hybrid vehicles due to environmental concerns.

Automobiles are classified into various types, including passenger vehicles, commercial vehicles, two-wheelers, electric vehicles, hybrid vehicles, and special-purpose vehicles. Each type serves a specific function, ranging from personal transport to industrial and emergency applications.

A key safety component of any automobile is the bumper, which is installed at the front and rear ends of the vehicle. The primary function of a bumper is to absorb and dissipate impact energy during collisions, thereby reducing damage to critical components such as the engine, radiator, and headlights. It also plays an important role in protecting passengers and pedestrians.

Figure 1: Nissan Kicks front Bumper

Modern bumpers are designed as multi-layered systems consisting of a fascia, energy absorber, bumper beam, crash box, and mounting brackets. These components work together to improve crashworthiness by absorbing and distributing impact forces. Different types of bumpers include front, rear, energy-absorbing, heavy-duty, and pedestrian safety bumpers.

Figure 2: Types of Automobile Bumper

Bumpers are essential for enhancing vehicle safety, minimizing repair costs, and improving overall performance. They also support advanced technologies by housing sensors and cameras used in modern safety systems.

II. LITERATURE REVIEW

Recent studies on automobile bumper systems have primarily focused on improving crashworthiness, energy absorption, and material optimization using computational and experimental methods. Finite Element Analysis (FEA) has emerged as a dominant tool in analyzing the structural performance of bumper beams under various impact conditions.

Marzbanrad et al. (2009) investigated the role of material properties and geometric configurations in low-speed frontal crashes. Their findings highlighted that while high-stiffness materials reduce deformation, they tend to transfer larger forces to the vehicle structure. Aluminum was identified as an optimal material due to its balance between weight and rigidity. Similarly, Tanlak et al. (2015) emphasized the importance of shape optimization, demonstrating that optimized bumper cross-sections significantly enhance energy absorption and reduce deformation under high-speed impacts.

Material selection has been a key research area. Abrar et al. (2024) conducted a comparative analysis of various materials, including carbon fiber, aluminum alloys, and composites. Their results showed that composite materials such as

GMT and SMC exhibit superior energy dissipation properties, especially in low-speed impacts. Supporting this, Mohammadi et al. (2023) reviewed glass fiber reinforced polymer (GFRP) composites, concluding that they offer substantial weight reduction (up to 60%) while maintaining mechanical strength and improving crash performance. Structural modifications have also been explored extensively. Keni et al. (2021) introduced a honeycomb-based bumper design, which significantly improved energy absorption due to its lightweight and high compressive strength. Similarly, Śliwa et al. (2024) analyzed reinforcement strategies, finding that cross-shaped reinforcements provide better stress distribution and reduced deformation compared to unreinforced designs. In addition to vehicle safety, pedestrian protection has gained attention. Wang and Lu (2002) demonstrated that traditional steel bumpers, although strong, can cause severe injuries due to poor energy absorption. This has led to the development of softer, energy-absorbing materials and hybrid structures. Advanced solutions, such as multi-material lattice designs proposed by Chawla et al. (2025), have shown remarkable improvements in impact resistance and recoverability. Furthermore, innovative technologies like magneto-rheological dampers have been introduced to create semi-active bumper systems capable of dynamically adjusting energy dissipation (Ahamed et al., 2014). These advancements indicate a shift toward intelligent and adaptive safety systems. Pai et al. (2024) investigated filled and unfilled AA6061-T6 bumper beams, showing improved impact resistance with fillers. A related study (Materials Today: Proceedings, 2023) found S-Glass/Epoxy composites outperform aluminum and carbon fiber PEI under high-speed impacts due to superior energy absorption. Tiwari et al. (2025) emphasized lightweight designs using CFRP and optimized honeycomb geometries for enhanced crash performance. Supriya and Prasat (2021) identified polypropylene as an effective material due to lower stress and higher energy absorption. John and N.M. (2014) further reinforced the importance of material optimization using finite element analysis.

Overall, the literature reveals a clear trend toward lightweight composite materials, optimized geometries, and smart energy-absorbing mechanisms. The integration of advanced simulation tools and novel materials continues to play a crucial role in enhancing automotive safety and performance

III. METHODOLOGY

Explicit Dynamics Analysis

The explicit dynamics method was employed because and The explicit dynamics method was employed and is a commonly used method in crashworthiness simulations because it is capable of accurately capturing large deformation, nonlinear material behaviour and complex contact interactions during high-speed impact events [1], [15].

This approach is suitable for analysing the dynamic behaviour during impact events. It is

capable of modelling high-velocity impact problems in which large deformation, nonlinear material properties, and contact interactions occur. This approach is suitable for analysing the dynamic behaviour during impact events. In this study, the bumper reinforcement beam was impacted with a rigid wall. The analysis was done for varying impact velocities to simulate a road crash and low-speed multiple impact cases.The simulation was performed for a given time, and the time step was automatically calculated for stability and accuracy. The simulation involved assessing the equivalent (von Mises) stress, total deformation and energy absorption to investigate the impact behaviour of the bumper beam.

3.1 Cad Modeling

The reinforcement beam and crash box were modelled as a combined entity to simulate their combined impact response. To reduce complexity and ease of calculations, small components like bolts and nuts were ignored.

Table I: Design Parameters

COMPONENTS	PARAMETER	DIMENSIONS
Reinforcement Beam	Length	1155 mm
	Inner Crash Box-to-Crash Box Distance	924 mm
	Width	85 mm
	Height	52 mm
	Shell Thickness	4 mm
	Flex (radius)	1490 mm
Crash Box	Length	150 mm
	Width	75 mm
	Height	75 mm

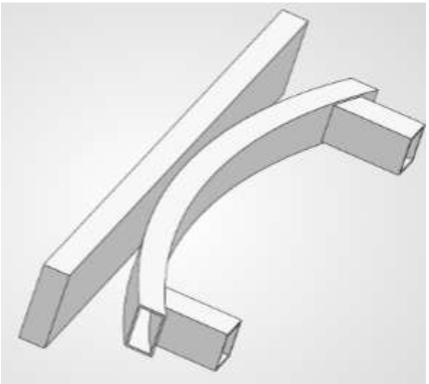


Figure 3: Model Setup of Bumper Beam–Crash Box and Wall Assembly

3.2 Material Selection

The critical choice of materials is a key factor in the determination of crash performance since the stiffness and yield strength are directly related to deformation behavior and energy-absorption ability during impact. The following Bumper materials selected for the study, 1. High Strength Steel Grade 590, 2. Aluminum 6061-T6.

3.3 Meshing

The finite element mesh was created using ANSYS with an explicit dynamics solution. A refined mesh was used to simulate the dynamic behaviour of the bumper. The overall element size was 3 mm and local mesh controls were adopted for accuracy in the key areas. The reinforcement beam and crash box had a finer mesh with element size of 5.2 mm for the body, 4.2 mm at the contact face and the wall had a coarser mesh with element size 13.5 mm for the body and 6.5 mm at the contact face to save time. The mesh contained about 59,616 nodes and 126,351 elements (tetrahedral (Tet4) and hexahedral (Hex8) elements).

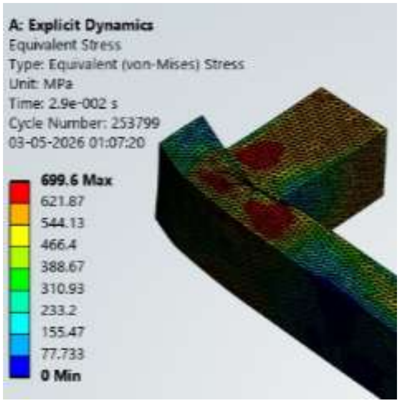
Figure 4: Mesh of Bumper assembly

3.3 Boundary Conditions

A velocity was applied to the wall that moves towards the bumper reinforcement beam to simulate the impact scenario. Various velocities were taken into account to simulate different conditions. To study the road collision, a velocity of 8.33 m/s was assigned, whereas in order to study multiple impacts during parking and traffic, a velocity of 5 m/s and 10 m/s was considered.

IV. RESULTS AND DISCUSSION

4.1 Stress Distribution at Different Impact Angles



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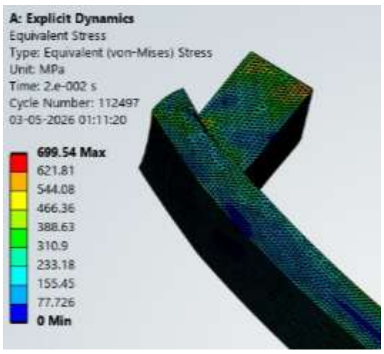

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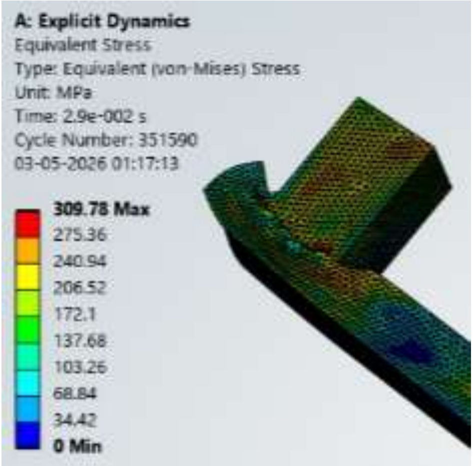
Figure 4:Stress Distribution of HSS 590 under Oblique Impact Angles: a) 10°, b) 30°



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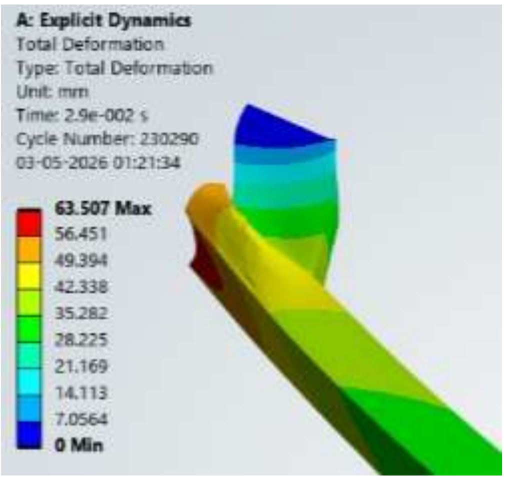


(b)

Figure 5: Stress Distribution of Aluminum under Oblique Impact Angles: a) 10°, b) 30°

Figure 6: Stress Distribution of HSS 590 Aluminum 6061 with Oblique Angles

Oblique impact testing at 10° and 30° on HSS 590 and Aluminium 6061 bumper beams produces combined bending, torsion, and shear stresses. Peak von-Mises stress remains nearly unchanged, with HSS 590 around 699.6 MPa and Aluminium 6061 about 310 MPa, both exceeding yield strengths and causing localized plastic deformation. However, impact angle affects stress distribution: 10° creates central compression, while 30° induces asymmetrical stresses. HSS 590 shows localized peaks, whereas Aluminium 6061 distributes stress more widely due to its flexibility.

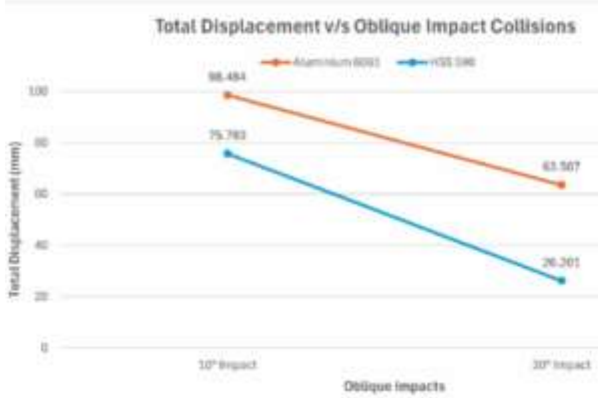


Figure 7: Displacment of HSS 590 Aluminum 6061 with Oblique Angles

The overall deformation behaviour of the bumper beam under oblique impacts at 20 km/h was analysed on HSS 590 and Aluminium 6061 in oblique impacts at 20 km/h. Oblique collisions cause the normal and tangential components of forces that produce bending, twisting, and sliding sideways deformations. The derived displacement contours and comparison graph clearly indicate the effect that material stiffness and impact angle have on the structural deformation.

Figure 8: Stress Variation of HSS 590 and Aluminium 6061 under Repeated load at 10 km/h

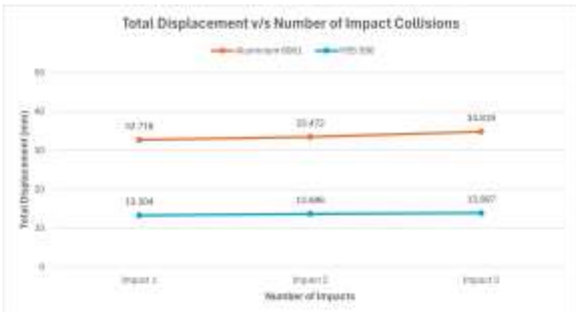


Figure 9: Displacment of HSS 590 and Aluminium 6061 under Repeated load at 5 km/h

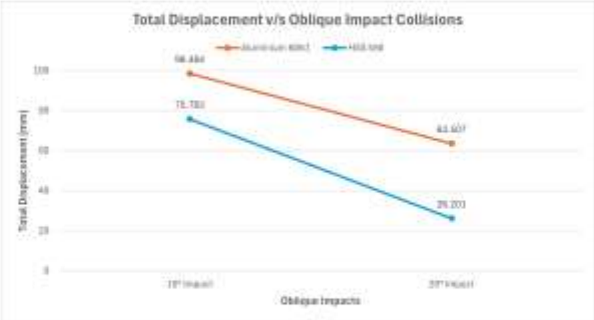


Figure 9: Displacment of HSS 590 and Aluminium 6061 under Repeated load at 10 km/h

The comparative graph indicates that the initial rigidity was lower, and the comparative graph reveals that the displacement of Aluminium 6061 was much larger than HSS 590 in the first impact (86.685 mm vs 49.101 mm), which proved the latter to be less rigid. But on the third impact, both materials recorded close value of displacements (29.008 mm in Aluminium and 27.915 mm in HSS 590), a fact that triggers the conclusion that repeated collisions resulted in significant changes in the structure of both beams.

When comparing the values of displacement at 10 km/h to the 5 km/h case, it was discovered that the value of displacement at 10 km/h was considerably higher in both materials, as would be expected. This is not surprising since the kinetic energy increases with the square of the velocity.

Table II: Comparison of oblique with other conditions

Oblique Impact, 20 Kmph	10°	Von-Mises Stress (Mpa)	309.78	699.6
		Total Displacement (mm)	98.484	75.783
	30°	Von-Mises Stress (Mpa)	310	699.54
		Total Displacement (mm)	63.507	26.201
Single Impact, 20 kmph	**0°**	Von-Mises Stress (Mpa)	310	699.8
	0°	Total Displacement (mm)	205.9	143.34

Comparison study was carried out thoroughly to determine the effect of impact speed, loading conditions, and materials used on the performance of the bumper assembly during crash testing. Comparisons have been done on the basis of the behavior and development of deformation and stresses within the assembly.

Effect of Material on Deformation Behavior

For all loading cases, Aluminium 6061-T6 material shows more deformation compared to HSS 590 steel. At a velocity of 30 km/h (8.33 m/s), deformation of Aluminium material is 205.96 mm, while that of HSS 590 is 140.34 mm, indicating 47% more deformation in Aluminium material. With respect to 10° oblique collision, the deformation for Aluminium material is 98.484 mm as opposed to 75.783 mm for HSS 590 steel.

Effect of Repeated Impacts

For a low speed of 5 km/h, there is a gradual increase in deformation based on the number of collisions for the two materials. For aluminium, the deformation increases from 32.718 mm to 34.819 mm, while for HSS 590, the deformation increases from 13.304 mm to 13.897 mm, indicating progressive damage and deformation.

However, for a high speed of 10 km/h, the scenario changes significantly. Aluminium shows a considerable decrease in deformation, where its deformation drops from 86.685 mm in the first collision to 29.008 mm in the third collision. Similarly, for HSS 590, there is a notable reduction in deformation from 49.101 mm to 27.915 mm.

This indicates that, at high speeds, most of the damage to the structure occurs during the first collision, leading to geometric stiffness and less deformation in successive collisions.

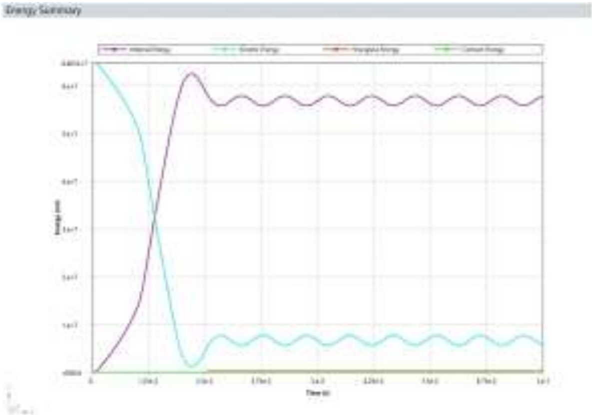
Effect of Impact Angle (Oblique Collisions)

Angle of impact is an important factor that affects deformation behavior significantly. Increasing the impact angle from 10° to 30° results in a decrease in deformation value for both materials. It was found out that deformation in the case of aluminum decreased from 98.484 mm to 63.507 mm (35%) and 75.783 mm to 26.201 mm (65%) in the case of HSS 590. It can be explained by the change in the distribution of impact force. **Stress Response Comparison**

Aluminium 6061-T6 maintains similar stress readings, ranging between 306 MPa and 310 MPa, suggesting yielding followed by a steady plastic deformation stage. However, HSS 590 shows increased stress readings of between 661 MPa and around 700MPa, with an increasing trend noted after each impact.

Velocity-Dependent Behavior

There is clear dependency on impact velocity. Increasing the speed from 10 km/h to 20 km/h results in great increase in deformation. In particular, aluminium deformation changes from 86.685 mm to 205.96 mm, whereas HSS 590 deformation ranges between 49.101 mm and 140.34 mm.



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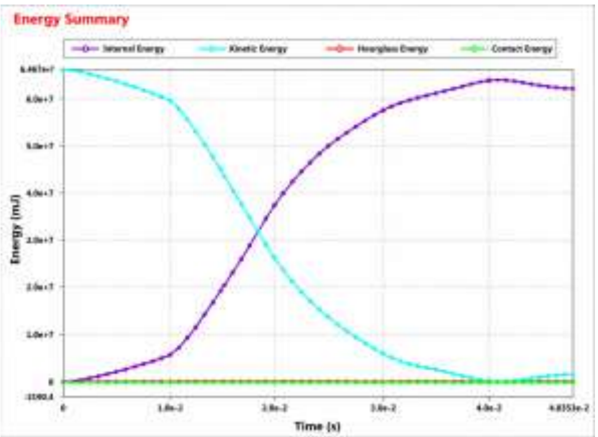

(b)

Figure 10: Energy Absorption Characteristics of Bumper Beam under Frontal Impact (0°) at 30 km/h: a) HSS 590, b) Aluminium 6061

Engineering Implication

Based on the above findings, it can therefore be concluded that there is no perfect bumper construction made from a single material. Instead, a better method of using aluminum to absorb energy while HSS 590 is used to reinforce the structure will provide an ideal result. The fact that the study involves both oblique and repetitive impacts shows that a real-life car accident cannot be effectively modeled using single front impact only.

V. CONCLUSION

It is observed from the findings that material plays an important role in the performance of a bumper system. Aluminum 6061-T6 material suffers much more deformation than Automotive HSS 590 material; specifically, the largest deformation is recorded for aluminum at a value of 205.96 mm when tested at 20 km/h. This means that aluminum material absorbs more energy than steel because of its property of plastic deformation. In addition, Automotive HSS 590 steel suffers less deformation (140.34 mm at 30 km/h) but has higher stress values (up to 700 MPa). Hence, automotive steel has high resistance and ability to withstand loads compared to aluminum.

The results of oblique impact show that the level of deformation is significantly reduced with an increase in the angle of impact. Such behavior is caused by the redistribution of forces acting on the object, in which the normal force decreases, and the tangential forces increase, reducing compression. Nevertheless, the level of stress does not change significantly, implying that the degree of yielding depends less on the impact direction and more on its intensity.

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