Design And Safety Improvement of Side Door Intrusion Beam Using Explicit Analysis and Testing

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Abstract- The side door intrusion beam is an essential structural element in car safety, intended to safeguard people during side-impact incidents. This project emphasizes the optimization of design and enhancement of safety for the side door intrusion beam utilizing a blend of explicit finite element analysis (FEA) and empirical testing. A comprehensive CAD model of the beam is created, and material selection is conducted with regard to strength, energy absorption, and manufacturability. Explicit dynamic analysis is performed to model side-impact scenarios, assessing factors such as maximum intrusion force, energy absorption, and deformation characteristics. Design improvements, including optimization of cross-sectional shape and upgrades in materials, are implemented based on the simulation results to increase performance. Prototype beams are ultimately fabricated and subjected to controlled impact testing to corroborate the modeling results. The research illustrates that the amalgamation of computational analysis and experimental testing facilitates a methodical strategy for augmenting the structural efficacy and occupant safety of side door intrusion beams, providing valuable insights for advancements in automobile design.

I.INTRODUCTION

As the frequency of car accidents continues to rise and crashworthiness standards around the world become stricter, research into automotive safety has emerged as a top priority. With such a small area to crumple between the hit site and the passenger compartment, side-impact incidents continue to rank among the most hazardous kinds of accidents. The side door and its internal reinforcements, in contrast to frontal impacts, have a much smaller deformation region in which to absorb impact energy.

In order to guarantee that occupants, survive lateral hits, the side door intrusion beam is one of the most important structural components. One way to prevent the door from bending inward in the event of a collision is to install a longitudinal reinforcement called an intrusion beam on the side of the door. Its principal role is to limit damage to the passenger compartment, absorb and disperse crash energy, and keep the door from collapsing. Many things affect how well this beam works, including its geometry, cross-sectional shape, material qualities, thickness, and how it interacts with the other structures around the door, like the outer shell, latches, and hinges. In an effort to maximize collision energy absorption while minimizing weight, vehicle manufacturers have explored various beam shapes and materials over the years.

Components that are crash-critical are increasingly being made of high-strength steels, aluminum alloys, and fiber-reinforced composites due to the current industry trend toward lightweight design, safety in electric vehicles (EVs), and sustainability. The use of state-of-the-art simulation tools such as LS-DYNA, Abaqus Explicit, and PAM-CRASH has also enabled engineers to accurately assess crash performance prior to physical testing on a larger scale. Even with these advancements, there are still major obstacles to overcome. Complex deformation modes, strain-rate effects, and material failures are common in real-world crash situations, and they can be challenging for models to adequately represent. The ongoing disparity between experimental and simulation findings emphasizes the necessity for enhanced modeling approaches, validation procedures, and correction methodologies.

Additionally, side intrusion beams need to find the sweet spot between lightweight, crashworthiness, affordability, and manufacturability. Engineers are under growing pressure to find lighter, more efficient vehicles with longer ranges and better fuel economy, so they're looking into novel shapes and materials that may absorb more energy without compromising structural integrity. Although there have been encouraging results with honeycomb structures, composite laminates, tailor-welded blanks, and multi-segment crash elements, further systematic testing and validation is needed to determine their practical application.

In light of this context, the current study concentrates on the enhancement and design of a side door intrusion beam's safety performance through experimental testing and explicit dynamic analysis. The objective of the project is to optimize beam geometry for improved crash performance, achieve an optimal balance of strength, energy absorption, and lightweight design, and bridge the distance between numerical simulations and physical behavior. Additionally, the work will evaluate alternative material configurations. By integrating simulation-driven optimization with real-world testing, the research contributes to the advancement of more efficient and secure side-impact protection systems for contemporary vehicles.

II.LITERATURE REVIEW

1. Pang et al. (2024)
Pang et al. (2024) investigated the mismatch between simulation and experimental results in side-impact sled collision testing. They noted that while numerical simulations are widely used in crash safety analysis, they often fail to capture real-world variations. To address this, the authors proposed a correction method that combines simulation and experimental data to improve prediction accuracy. Side sled collision tests were conducted alongside explicit FE simulations, and comparisons showed deviations in intrusion, acceleration, and deformation patterns. Their correction model adjusted simulation outputs based on experimental observations, significantly improving result alignment. The study demonstrated that such correction methods enhance reliability in crash simulations, especially for components like intrusion beams where accurate predictions are essential.

2. Alkandari & Alhumaidah (2022)
Alkandari and Alhumaidah (2022) applied optimal control techniques to analyze and improve the side-impact safety of vehicle frame structures. Unlike traditional simulations, their approach combined control algorithms with crash dynamics to evaluate and optimize structural responses. Finite element simulations were carried out to study intrusion, acceleration, and energy absorption under side impact. The optimal control method helped adjust parameters such as stiffness and impact conditions to achieve better crash performance. Results showed reduced intrusion and improved load distribution compared to baseline models. The study emphasized the systematic approach to enhancing safety through the integration of control theory with crash simulations, despite the need for real-world testing.

3. Gilabert & Hao (2023)
Gilabert and Hao (2023) Investigated thermoplastic composites for door anti-intrusion beams via a simulation-driven design methodology. They employed a gradual methodology, systematically revising design parameters through finite element simulations subjected to side-impact loading. The findings demonstrated that thermoplastic composites provided comparable or enhanced crash performance relative to steel, while being considerably lighter. The materials exhibited sequential failure modes, facilitating energy absorption during collisions. Their research highlighted the sustainability advantages, as thermoplastics are more readily recyclable than thermosets. The research determined that simulation-assisted composite design is an efficient method for producing lightweight and crash-resistant intrusion beams.

4. Papaiya, Schuster & Shaik (2023)
Papaiya et al. (2023) Engineered composite side door intrusion beams to fulfill the requirement for lightweight yet secure vehicle frameworks. They conducted finite element simulations of side impacts to compare metallic beams with composite versions. Composite beams, particularly those constructed from CFRP, demonstrated enhanced energy absorption and regulated progressive failure. GFRP beams exhibited commendable performance and

demonstrated greater cost-effectiveness, albeit with marginally reduced stiffness. The research additionally examined production methods, including RTM and compression molding, to evaluate their practicality. The research indicated that composite beams can substitute standard metal beams if manufacturing difficulties are effectively addressed.

5. Abdulqadir & Tarlochan (2022)
Abdulqadir and Tarlochan (2022) investigated hat-shaped composite structures for use as B-pillars and intrusion beams, which could serve as lightweight and crash-safe substitutes. In order to assess the energy absorption and deformation behavior, scientists utilized CFRP and GFRP beams to mimic side collisions. GFRP provided a strong and inexpensive alternative to steel beams, while CFRP beams exhibited superior performance in terms of controlled failure and high stiffness. Fiber orientation and ply sequencing were also highlighted as critical factors influencing crash performance in the study. The viability of RTM manufacturing was evaluated, taking into consideration issues like void formation and fiber alignment. Based on the results, further testing is needed to confirm that composite hat structures offer adequate side impact protection.

6. Gouzi et al. (2024)
Gouzi et al. (2024) utilized Chang failure criteria to forecast progressive damage during collisions in a numerical evaluation of CFRP crash boxes. With remarkable realism, their simulations caught intricate failure modes like matrix cracking and fiber breakage. While steel maintained regulated deformation, CFRP absorbed more energy per unit weight. Crash performance is affected by several factors, including stacking sequence, laminate thickness, and fiber orientation, as shown in the study. There are a number of drawbacks to CFRP, despite its many benefits, including its high cost and complicated manufacturing process. There is much promise for lightweight composite designs, and these results are especially pertinent to intrusion beams.

7. More et al. (2020)
More et al. (2020) analyzed different side door intrusion beam designs using FEA to optimize crash performance. They evaluated several cross-sections, including tubular and rectangular shapes, under dynamic side-impact simulations. Tubular beams showed superior energy absorption and lower intrusion compared to rectangular designs. High-strength steel offered better crash resistance but with manufacturing challenges, whereas mild steel was easier to form but less effective in impact conditions. The study highlighted the importance of balancing geometry, material choice, and manufacturability. The authors recommended simulation-led optimization followed by experimental validation.

8. Dhaigude et al. (2021)
Dhaigude et al. (2021) studied side door intrusion beams using explicit FEA to evaluate crash behavior under side impacts. They analyzed different beam geometries and materials, including mild steel, HSS, and aluminum. Tubular beams performed best due to uniform stress distribution and controlled deformation. While HSS provided high stiffness, it posed production challenges, and aluminum beams, although lightweight, showed higher deformation. The study emphasized optimizing thickness and geometry for better energy absorption. They concluded that combining simulation and experimental testing is essential for reliable beam design.

9. Puri et al. (2025)
Puri et al. (2025) designed intrusion beams based on honeycomb to decrease weight and increase crashworthiness. They used precise impact simulations to see how honeycomb beams with various cell shapes fared. Compared to conventional solid beams, these structures exhibited better energy absorption and more manageable deformation. Honeycomb made of aluminum was lightweight and strong, whereas honeycomb made of composite was more complicated to manufacture but improved performance even more. Lessening the likelihood of failure in specific areas, the beam's stress distribution was more consistent. According to the research, honeycomb beams are a lightweight and sturdy substitute for traditional vehicle safety features.

10. Yang et al. (2025)
Yang et al. (2025) optimized side door structures for electric micro-commercial vehicles exposed to side-pole impacts. Using detailed FE simulations, they evaluated intrusion, energy absorption, and stress patterns under various impact conditions. Optimization techniques were applied to refine geometry, material selection, and thickness distribution. Results showed that high-strength steel and lightweight materials reduced intrusion while improving energy absorption. Their study

emphasized integrating intrusion beams with B-pillars and other reinforcements for better crash performance. The authors concluded that simulation-driven optimization improves EV safety but must be validated experimentally.

Novelty of work: The novelty of this work lies in combining explicit dynamic analysis with experimental testing to develop a more accurate and reliable side door intrusion beam design. The study introduces a correction-based approach to reduce simulation–experiment deviation, improving prediction of deformation and intrusion. It also explores optimized beam geometries and lightweight material configurations to enhance energy absorption without increasing weight. An iterative simulation-guided optimization method is used to achieve controlled progressive deformation for better occupant protection. Overall, the work provides a validated, lightweight, and crash-efficient intrusion beam design that improves side-impact safety.

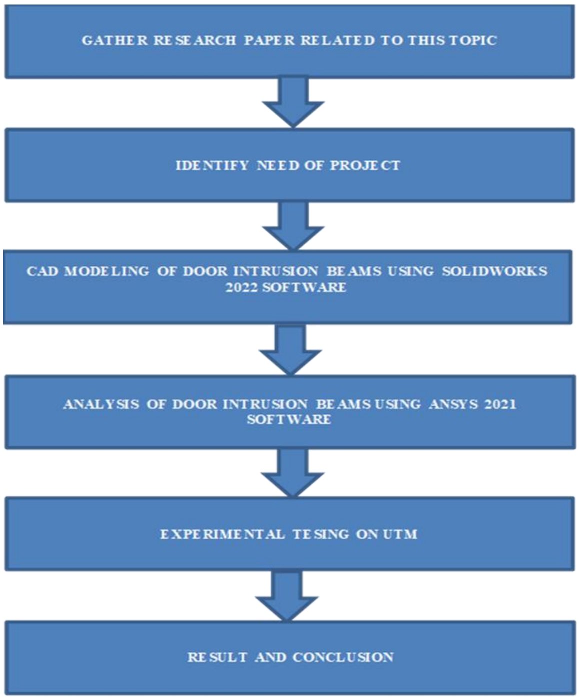
III.PROBLEM STATEMENT

- Currently, there is a need for a comprehensive understanding of how various side door intrusion beam geometries and materials perform under dynamic side impact conditions.
- Without systematic investigation and optimization using advanced analytical tools and validation through testing, sub-optimal designs may lead to inefficient energy absorption, unpredictable deformation modes, and compromised occupant safety during a side collision.
- Therefore, the problem this research addresses is the lack of a detailed, experimentally validated, and computationally optimized understanding of the influence of different side door intrusion beam designs on their energy absorption capacity and structural integrity during side impact scenarios.
- This gap hinders the ability to select and design intrusion beams that maximize passive safety performance while also meeting modern vehicle requirements for reduced weight and manufacturing cost.

IV.OBJECTIVES

- To design and model several different cross-sectional geometries for a side door intrusion beam.
- To perform explicit Finite Element Analysis (FEA) on the proposed designs to simulate their behavior under side- impact conditions.
- To evaluate the performance of each design based on key crashworthiness parameters, including specific energy absorption (SEA), crush force efficiency (CFE), and initial peak force.
- To conduct experimental three-point bending tests on the most promising designs to validate the numerical simulation results.
- To identify an optimal side door intrusion beam design that provides superior energy absorption, reduces passenger compartment intrusion, and is lightweight and cost-effective.

RESEARCH METHODOLOGY



V.FINITE ELEMENT ANALYSIS

Mathematically, Finite Element Analysis (FEA) breaks down complicated circumstances into manageable, discrete problems. The analysis of non-linear FEA problems is intrinsically more challenging than that of linear problems. The "principle of superposition," which asserts that the sum of the effects of many forces acting on a system equals the sum of those effects when applied independently, is now outdated. As an approximation technique, finite element analysis relies on the following factors to determine its accuracy:

- Model quality of the CAD
- Material characteristics utilized (also called as associated assumptions)
- Representation of Load and boundary conditions
- Solution algorithm

In nonlinear finite element analysis, the relationships that are expected to be linear in linear finite element analysis may be disrupted.

a) Significant Deformations: The majority of metallic materials become inoperative when the strain exceeds one or two percent. Rubbers, elastomers, and plastics can be elongated to several hundred percent, necessitating finite (large) strain analysis.

b) A linear relationship between strain and displacement no longer exists. This holds true if the rotations increase while the tensions remain constant. The alterations in the distorted configuration can no longer be overlooked. Buckling, rubber analysis, metal forging, and other physical phenomena require a quadratic or logarithmic strain-displacement relationship (Green-Strain). Engineering stress is no longer permissible due to geometric alterations; thus, real stress or Cauchy stress should be utilized instead.

c) The stress-strain relationship may exhibit nonlinearity. This phenomenon may manifest even when stress is exerted inside the material's effective stress range. This behavior, similar to that of elastomers, is seen in most metals, rubbers, and certain composite materials that display interactions involving material nonlinearity, significant deformations, and intricate boundary conditions influencing the overall structural response. asymmetric tensile and compressive characteristics.

d) The initial equilibrium equations (which relate stress to loads) may require revision. Due to the structural geometric variations in form. The load in nonlinear finite element analysis is no longer proportional to the displacement due to these interactions.

Software Analysis Methodology

Step 1: Material Definition - Define the properties of all materials used in the analysis, such as copper, steel, gray cast iron, composites, or fluid domain materials, in the Engineering Data section. By default, ANSYS provides structural steel as a predefined material.

Step 2: Geometry Import - Import the component geometry created in CAD software (e.g., CATIA, Pro/ENGINEER, SOLIDWORKS, or Inventor) into the Geometry section. Any required modifications can be performed using DesignModeler or SpaceClaim.

Step 3: Material Assignment and Connections - Assign the appropriate material to each component (e.g., ABS, PP) in the Model section. Define contact interactions between components, such as bonded, frictionless, frictional, or no separation, for multi-body assemblies. Perform meshing (discretization) to divide the model into finite elements. For 3D geometries, tetrahedral or hexahedral elements are preferred; for 2D geometries, quadrilateral or triangular elements are commonly used.

Step 4: Boundary Conditions - Apply the necessary boundary conditions for the analysis, including fixed supports, forces, pressures, displacements, or velocities, depending on the study requirements.

Step 5: Non-Linearity Consideration - If required, include non-linear effects in the analysis. ANSYS uses the Newton-Raphson method to iteratively approximate displacements until convergence is achieved.

Step 6: Solution - Once the problem is fully defined, select the Solve option to compute results, such as equivalent stress, strain, deformation, strain energy, and reaction forces.

1. EXPLICIT DYNAMIC ANALYSIS OF DOUBLE HAT-TYPE SIDE DOOR IMPACT BEAM

ENGINEERING DATA – STRUCTURAL STEEL

Structural steel is a specially designed material widely used in construction and infrastructure projects. It is available in many shapes and sizes to meet different structural requirements. In most cases, it is manufactured as long members such as beams, with carefully designed cross-sections that help them carry specific loads efficiently. In developed countries, strict standards are followed to control factors like dimensions, chemical composition, mechanical properties (such as tensile strength), and even storage practices. These regulations help ensure consistent quality, safety, and reliable performance in real-world applications.

Table 1: Details of engineering material

Structural Steel

Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	2e+05 MPa
Poisson's Ratio	0.3
Bulk Modulus	1.6667e+05 MPa
Shear Modulus	76923 MPa
Isotropic Secant Coefficient of Thermal Expansion	1.2e-05 1/°C
Compressive Ultimate Strength	0 MPa
Compressive Yield Strength	250 MPa
Strain-Life Parameters	

Geometry

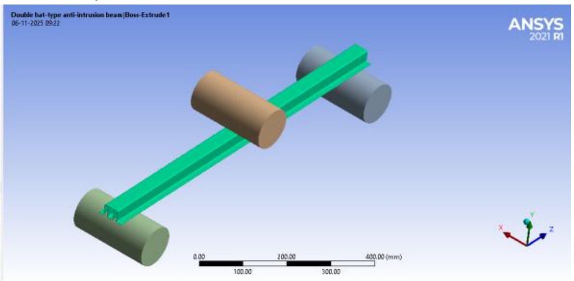
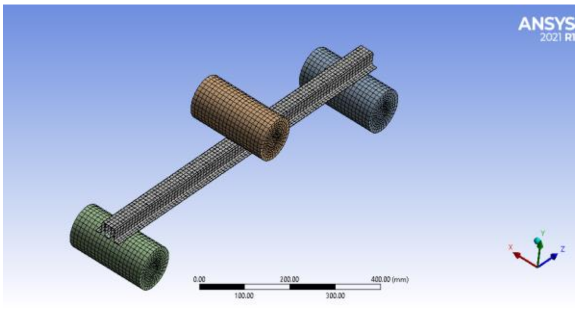


Fig.1. Geometry model of double hat-type side door impact beam with three-point loading

Meshing

Meshing is a key step in any engineering simulation, where complex geometries are broken down into smaller, manageable elements that represent the behavior of the overall structure. The way a mesh is created plays a crucial role in determining how accurate, stable, and fast the simulation will be. In practice, a large portion of the total simulation time is often spent on meshing, so having efficient and automated tools can significantly improve productivity as well as the quality of results.

ANSYS provides a robust and intelligent meshing platform designed to simplify this process while maintaining high accuracy. It offers a wide range of meshing techniques, from quick automatic generation to more refined, user-controlled approaches. These capabilities cover everything from linear to higher-order elements and from fast tetrahedral and polyhedral meshes to high-quality hexahedral and Mosaic meshes, allowing engineers to choose the most suitable method for their specific application.



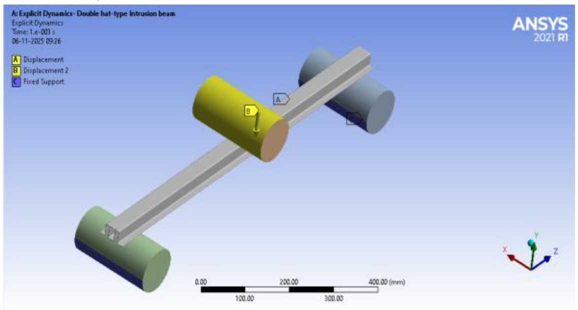
Type	Element Size
Element Size	10.0 mm

Statistics	
Nodes	21399
Elements	17310

Fig.2. Finite mesh model of double hat-type side door impact beam with three-point loading

This finite mesh model contains 21399 nodes and 17310 elements and the size of element is 10 mm.

Boundary conditions:



Coordinate System	Global Coordinate System
X Component	0. mm (ramped)
Y Component	-5. mm (ramped)
Z Component	0. mm (ramped)

Tabular Data

	Steps	Time [s]	X [mm]	Y [mm]	Z [mm]
1	1	0.	0.	0.	0.
2	1	1.e-003	0.	-5.	0.
*					

Fig. 3: boundary condition of double hat-type side door impact beam with three-point loading.

Result

1. Total deformation

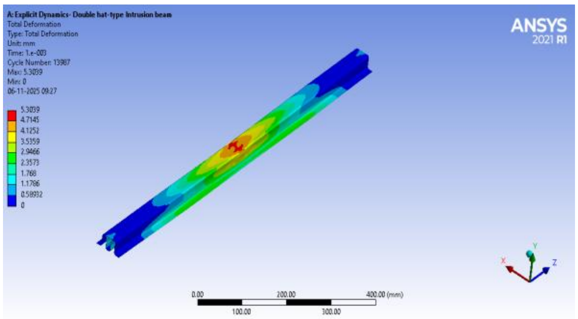


Fig. 4: total deformation of double hat-type side door impact beam with three-point loading

2. Directional Deformation

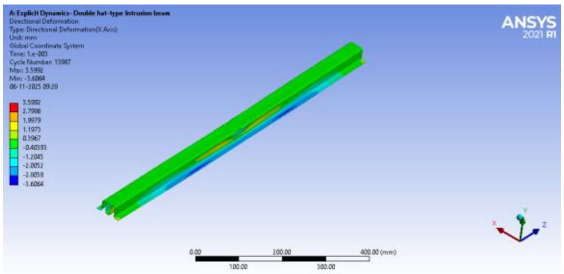


Fig. 5: directional deformation of double hat-type side door impact beam with three-point loading

3. Equivalent stress

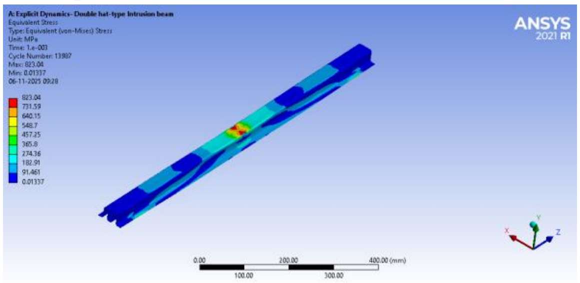
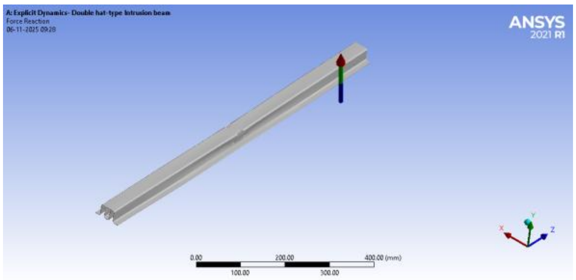


Fig. 6: equivalent stress of double hat-type side door impact beam with three-point loading

Force reaction



Maximum Value Over Time	
X Axis	6.4933 N
Y Axis	125.78 N
Z Axis	128.18 N
Total	167.89 N

Fig. 7: Force reaction of double hat-type side door impact beam

2. EXPLICIT DYNAMIC ANALYSIS OF M-TYPE SIDE DOOR INTRUSION BEAM

Geometry

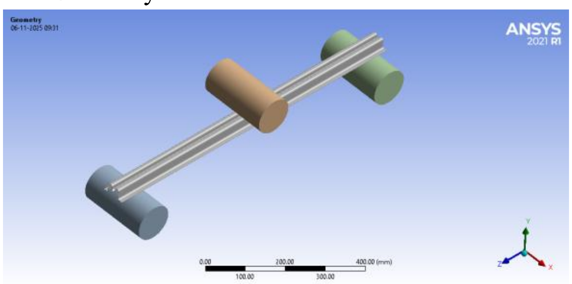
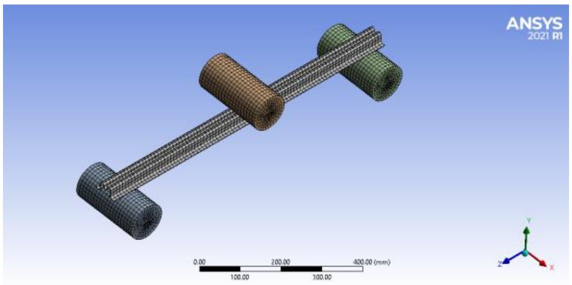


Fig. 8: Geometry model of M-type side door intrusion beam with three-point loading

Meshing



Statistics	
Nodes	19019
Elements	15540

Fig. 9: finite mesh model of M-type side door intrusion beam with three-point loading

This finite mesh model contains 19019 nodes and 15540 elements and the size of element is 10 mm.

Boundary conditions

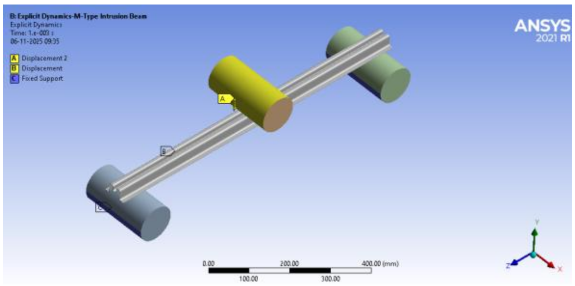


Fig. 10: boundary condition of M-type side door intrusion beam with three-point loading

Results

1. Total deformation

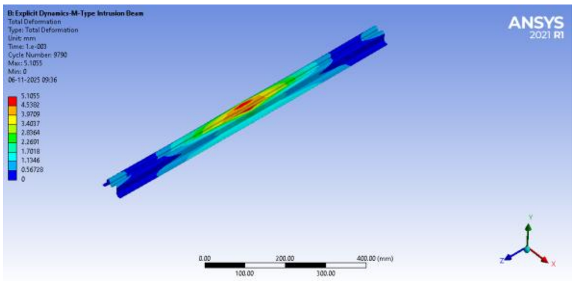


Fig. 11: total deformation of M-type side door intrusion beam with three-point loading

2. Equivalent stress

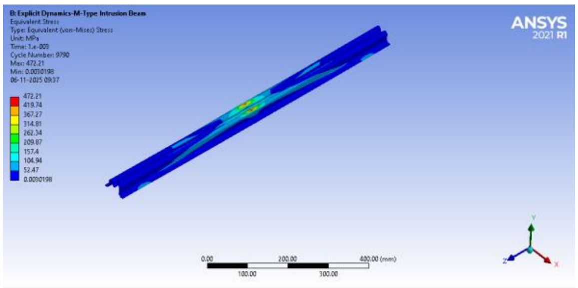


Fig. 12: equivalent stress of M-type side door intrusion beam with three-point loading

3. Directional deformation

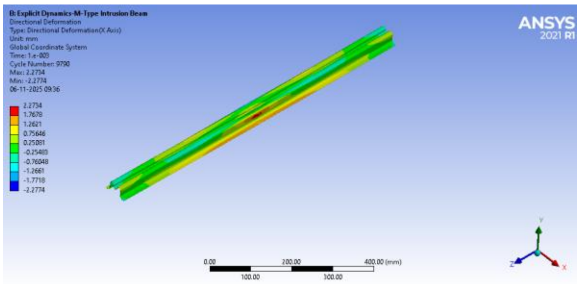
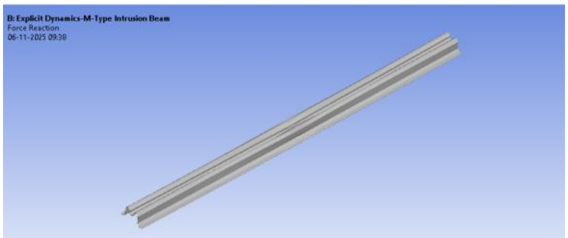


Fig. 13: directional deformation of M-type side door intrusion beam with three-point loading

Force reaction



Maximum Value Over Time	
X Axis	125.22 N
Y Axis	455.07 N
Z Axis	170.96 N
Total	532.23 N

Fig. 14: Force reaction of M-type side door intrusion beam with three-point loading

3. EXPLICIT DYNAMIC ANALYSIS OF HAT - TYPE SIDE DOOR INTRUSION BEAM

Geometry

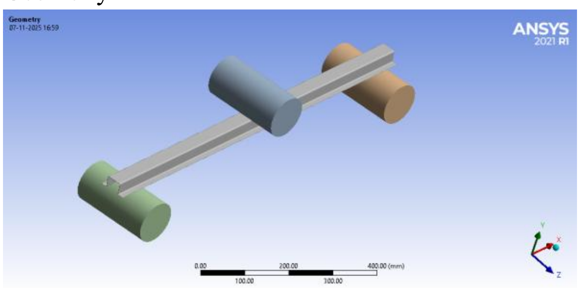
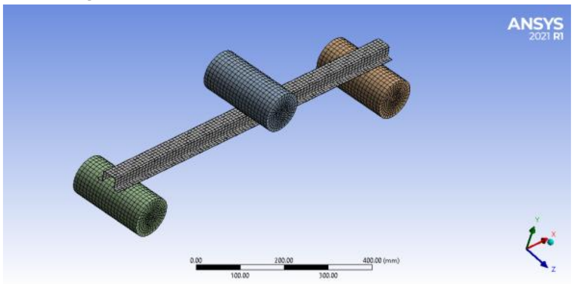


Fig. 15: Geometry model of Hat -type side door intrusion beam with three-point loading

Meshing



Statistics	
Nodes	19579
Elements	16050

Fig. 16: finite mesh model of Hat -type side door intrusion beam

This finite mesh model contains 19579 nodes and 16050 elements and the size of element is 10 mm.

Boundary conditions

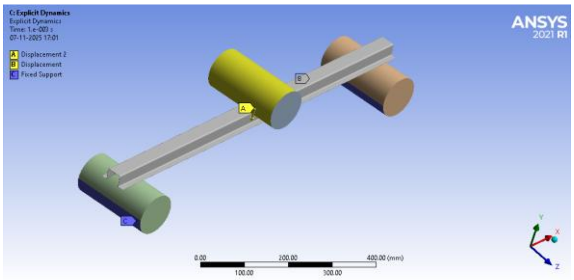


Fig. 17: boundary condition of Hat-type side door intrusion beam

Results

1. Total deformation

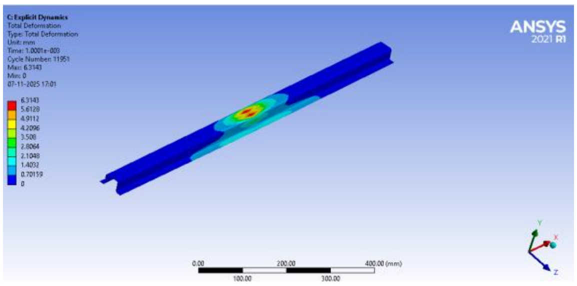


Fig. 18: total deformation of Hat-type side door intrusion beam

Directional deformation

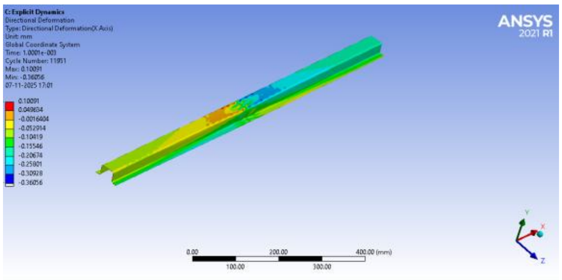


Fig. 19: direction deformation of Hat -type side door intrusion beam with three-point loading

Equivalent stress

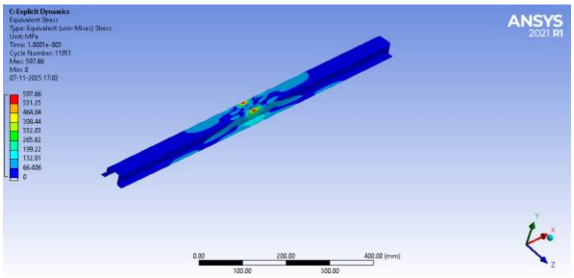
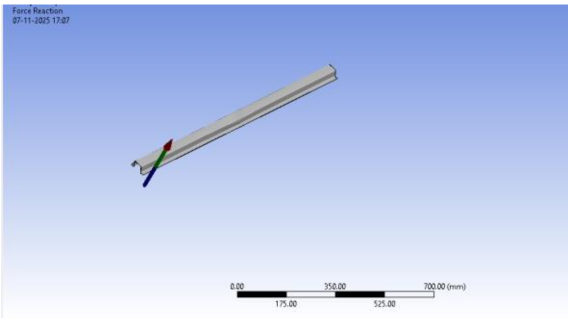
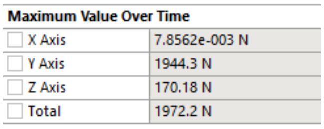


Fig. 20: equivalent stress of Hat -type side door intrusion beam with three-point loading

Force reaction





Maximum Value Over Time	
X Axis	7.8562e-003 N
Y Axis	1944.3 N
Z Axis	170.18 N
Total	1972.2 N

Fig. 21: force reaction of Hat -type side door intrusion beam

FEA RESULTS

Parameter	DOUBLE HAT-TYPE SIDE DOOR IMPACT BEAM	M-TYPE SIDE DOOR INTRUSION BEAM	HAT-TYPE SIDE DOOR INTRUSION BEAM
Directional Deformation	3.5992 mm	2.2734 mm	0.10091 mm
Equivalent (von-Mises) Stress	823.04 MPa	472.21 MPa	597.66 MPa
Force Reaction	167.89 N	532.23 N	1972.2 N

V.MANUFACTURING OF THE COMPONENT

Laser cutting

Laser cutting is a technology that uses a laser to vaporize materials, resulting in a cut edge.

As a high-tech method of production, laser cutting involves the utilization of a laser beam that is extremely concentrated and high-energy in order to cut materials along a predetermined path. Computer numerical control (CNC) technology is used to manage the movement of the beam, while a system of precision optics is responsible for directing the beam. Because of this combination, the laser is able to follow precise directions. Within the context of industrial settings, the movement of the cutting head is controlled by programmable codes, which are often G-code. Because of this, the gadget is able to generate intricate patterns and intricate shapes in a speedy and consistent manner.

Laser cutting process steps

- Pick out a suitable lens and nozzle, and give them a good cleaning before you begin.
- Point the new direction. Adjust the cutting head so it is focused correctly;
- Verify and replace the nozzle's center.
- Installing the sensor for the cutting head;

- Make sure the cutting gas you choose is sprayed properly, and choose the right one.
- Make an effort to cut the cloth. Verify the accuracy and smoothness of the cut after cutting the material. To ensure that the requirements are met and that any errors are caught during proofreading, please adjust the equipment settings accordingly.
- Enter the equipment cutting system after you have set up the work item designs and typeset them.
- Start cutting after you turn the cutting head.
- A person or people should be present at all times to observe the cutting. In the event that an urgent action is required, press the emergency stop button.
- Check the accuracy and precision of the first sample cut.heck the cutting quality and accuracy of the first sample.

Bending Process:

Bending is a fundamental metal forming operation in which a sheet or tubular workpiece is reshaped by inducing permanent deformation without any material removal. The process is typically performed using equipment such as press brakes, rolling machines, or specialized tube bending systems. When an external force is applied, the material initially responds elastically; however, as the applied stress exceeds the yield strength, plastic deformation occurs, resulting in a permanent change in shape.

During bending, a non-uniform stress distribution develops across the cross-section. The inner region of the bend is subjected to compressive stresses, while the outer region experiences tensile stresses. Separating these two zones is the neutral axis, where the strain remains zero. The final bend geometry and quality are governed by factors such as material characteristics, thickness, bend radius, and the magnitude of the applied load. Effective control of these parameters is essential to achieve dimensional accuracy and to prevent defects such as cracking, wrinkling, and spring back..

In order to achieve the necessary strength and guarantee proper fitment within the door frame, side door intrusion beams are manufactured using bending methods to mold the component to the desired curve and profile.

Manufactured and final testing intrusion beam:

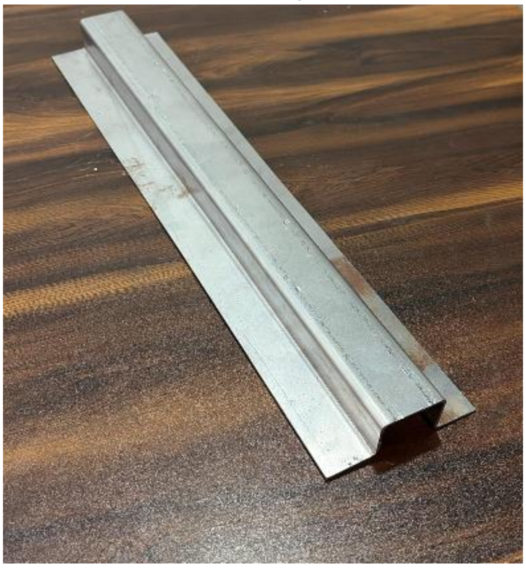


Fig. Final manufactured Hat type side door anti-intrusion beam.

VI.EXPERIMENTAL TESTING

The goal of experimental testing is to check the accuracy of numerical data by looking at how a component actually behaves when loads are put on it. In this study, a compression test is used to find out how strong the axle specimen is and how it deforms under load.

The test checks for stiffness, elasticity, and how things break by putting a stress on them and monitoring how they change shape. The resulting load-deformation curve helps us understand important properties like structural stability, elastic region, and maximum load capacity. This experimental method checks and compares FEA findings with actual performance data to make sure the results are accurate.

A Universal Testing Machine (UTM) can test the mechanical properties of materials and parts by putting them under several types of stress, such as tension, compression, and bending. It applies a controlled force to a sample and then analyzes how much it changes shape to find out things like elasticity, stiffness, and strength. Labs that test materials often use UTMs to check that their designs and computer simulations are correct.

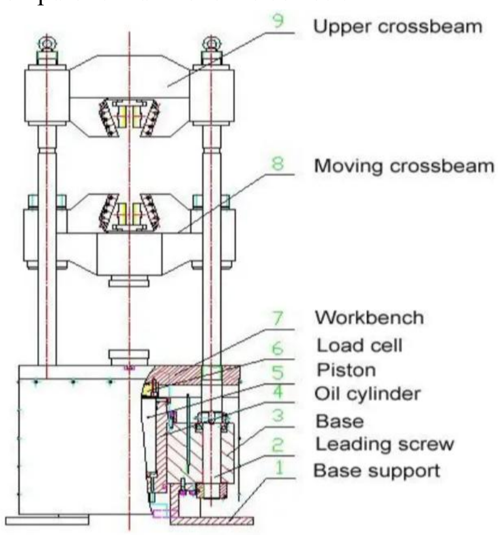


Fig. Schematic Diagram of a UTM.

Testing photograph

Fig. Specimen under flexural test using a UTM.

Testing graph

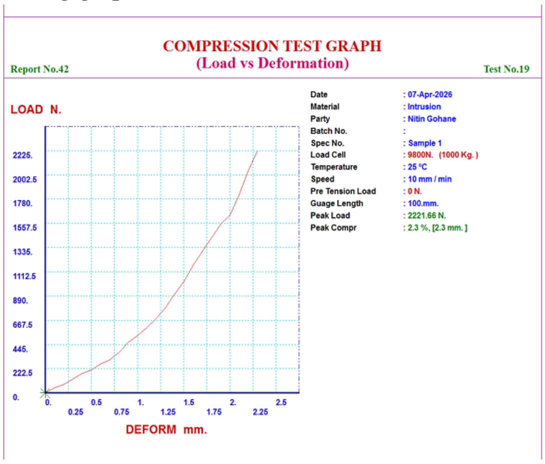


Fig: Graph shows load vs deformation during flexural test

The above fig. shows the graph of displacement v/s load for Hat type side door anti-Intrusion beam. Displacement is taken on X-axis and load in N is taken on Y-axis.

VI. CONCLUSION

- The present study investigates the structural performance of three different side door intrusion beam configurations under impact loading using explicit finite element analysis, followed by experimental validation.
- The comparative assessment was carried out based on key parameters such as directional deformation, equivalent stress distribution, and force reaction.
- The simulation results clearly indicate that the hat-type intrusion beam exhibits superior

crashworthiness performance among the considered designs.

- The hat-type beam demonstrated a significantly lower directional deformation of 0.10091 mm compared to the other configurations (3.5992 mm and 2.2734 mm), indicating its high stiffness and enhanced resistance to intrusion during side-impact conditions.
- Furthermore, the force reaction obtained for the hat-type beam was 1972.2 N, which confirms its ability to effectively transfer and redistribute impact forces across the vehicle structure.
- This behaviour minimizes localized deformation and reduces the risk of cabin intrusion, thereby improving occupant safety.
- To validate the numerical findings, experimental testing was conducted using a three-point bending (flexural) test. The results showed a reasonable agreement with the simulation trends, thereby confirming the reliability of the finite element model and analysis approach. The experimental observations also verified the structural integrity and load-bearing capability of the optimized design.
- In conclusion, the hat-type side door intrusion beam demonstrates superior performance in terms of stiffness, energy transfer capability, and deformation resistance. The combined use of explicit analysis and experimental validation provides a robust and reliable framework for intrusion beam design. The findings suggest that the proposed hat-type configuration is highly effective for improving side-impact crashworthiness and can be considered a suitable design for modern automotive safety applications.

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