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Advancing Side-Impact Safety in Cars: Innovations in Structural Design, Energy Absorption, and Intelligent Protection Systems

Guide: Vishal A. Meshram
Participants: Maitrey Athavale, Ayuj Aundhekar , Atharva Raut , Aryan Sutar,
Department of Engineering, Science and Humanities (DESH)
Vishwakarma Institute of Technology, Pune, Maharashtra, India

Abstract The increasing number of accidents has significantly contributed to more than 24.3% of global deaths, with a notable portion attributed to insufficient side impact reinforcement in vehicles. The lack of adequate protection during side collisions has highlighted critical safety gaps. This paper addresses the shortcomings of current side-impact safety systems and proposes a multi-faceted approach that includes innovative structural reinforcements, use of advanced materials, and intelligent systems to enhance passenger protection. Computer-Aided Engineering (CAE) techniques are applied to optimize material placement for load management while maintaining cost-effectiveness and compliance with safety standards.

I. Keywords

carbon fiber impact beam, Computer-Aided Engineering (CAE), crumple zone, shatter-proof Carbon windows, side-impact protection, crash safety, vehicle safety standards, occupant protection, crashworthiness, impact mitigation, automotive safety innovations, structural reinforcement, passive and active safety systems, airbag deployment strategies, sensor technology, advanced crash testing, regulatory compliance, biomechanics in collisions, energy absorption mechanisms

II. INTRODUCTION

Side-door impact beams are mounted on the door panel of a passenger car to ensure passenger safety during side impacts. Material stiffness is an important factor in side impact performance. Impact-absorbing beams are an effective way to absorb high impact energy, with diagonal beams usually made from metals due to their high strength.[1] Composites like carbon fiber offer a higher strength to weight ratio. Making them a better material choice compared to metals. A circular pipe made of prepreg carbon fibers can be used to reinforce the side panels of the vehicle. By diagonally attaching the carbon fiber pipe, the intrusion of external material inside the passenger region is prevented.[2] This solution is advantageous as it adds minimal weight to the panel, making it an ideal material for this purpose. Additionally, the plastic part of the inner wall of the doors can be replaced with a more reliable material, making it more resistant to penetration during impact.[3] The concept of a crumple zone can be introduced, incorporating a crushable material that absorbs most of the energy generated during an impact. This material would distribute the remaining load to the reinforced material placed behind it, ensuring even distribution of the remaining energy.[6] Another option is the concept of triangulation, where hard, non-brittle metals are used to integrate a triangular structure. This structure would be effective in distributing the impact in a node-to-node format, reducing the direct impact on the internal panel of the passenger side. Previous research has shown that the main obstacles to advancing side impact panels are cost, weight, and the level of difficulty in implementing solutions at the industry level. This method addresses these factors while also enhancing the side impact's strength and reliability.[4] Various materials will be tested to determine their flexural rigidity, hardness, toughness, and other factors essential in designing stronger side panels, with minimal impact on cost. Additionally, materials with a high strength-to-weight ratio will be considered.[5] Despite the presence of side airbags, many deaths occur due to the high deployment speed of the airbag and the force with which passengers hit the side of the vehicle, resulting in higher impacts on the neck region. This often leads to neck fractures, causing chronic health issues. One solution to minimize this is the design of a curved headrest that will hold the passenger's head in place during impact while also enhancing the vehicle's ergonomics. The curved headrest would also be beneficial during frontal impacts, making it an optimal design for headrests. Since airbags are currently deployed from the inside of the vehicle, passengers may be more prone to injuries. To address this, airbag technology could be adapted to deploy on the outer side of the doors. Using sensors like LIDAR, the system could calibrate the possibility of an impact and deploy the airbags on the outer side accordingly through small, accessible spaces that are free for installation.[1] Additionally, sensors could trigger an automatic signal in the steering system, which would move the vehicle away from the side of the impact, reducing the chances of a side collision. A 360-degree camera system could be used to cover blind spots for the driver, improving safety when driving in close areas or changing lanes on a freeway.[4] Lastly, increasing reinforcements in the floor-to-roof connection would help reduce plastic deformation during impacts or rollovers.[3]

III. LITERATURE REVIEW

Side-impact collisions pose significant risks to vehicle occupants due to the limited crumple zones available for energy dissipation. To address this challenge, researchers have emphasized the role of advanced materials such as carbon fibre–reinforced polymers (CFRP) and aluminium honeycomb structures, both of which enhance energy absorption and minimize vehicle intrusion. CFRP beams provide a high strength-to-weight ratio, while aluminium crumple zones effectively dissipate crash energy. Structural innovations, including triangulated reinforcements and reinforced floor to roof connections, have also been investigated for their ability to improve overall crash resistance. In parallel, ergonomic enhancements such as curved headrests are designed to reduce neck injuries caused by high-speed airbag deployment. Furthermore, emerging technologies such as sensor-based external airbag systems using LiDAR, along with ADAS-enabled automatic steering adjustments, provide pre-crash protection and impact avoidance. Real world crash data from organizations like NHTSA, IIHS, and Euro NCAP have been instrumental in refining injury models and guiding safety design improvements. Collectively, literature supports a multi-faceted approach that integrates material advancements, structural reinforcements, energy absorption strategies, and intelligent safety systems to significantly improve side-impact protection while ensuring cost efficiency.

IV. METHODOLOGY/EXPERIMENTAL

Material properties In a study conducted it was found that aluminum is a great material and very compatible for making the side impact panels but it was never practically implemented so here we will be studying the properties of aluminum along with other elements and showing why we have selected aluminum as the ideal element for the zone of crushing Here are the mechanical properties of a few metals that we have compares alongside with aluminum that show why aluminum is an optimal choice for using in crumbling.

TABLE 1 – MECHANICAL PROPERTIES OF ALUMINIUM ALONG WITH A FEW OTHER METALS

Metal	Young's Modulus	Yield Strength	Ultimate Strength
Aluminium (6061 – T6)	69	275	310
Steel (AISI 1045)	200	530	625
Titanium (Grade 5-Ti-6AI4V)	110	880	950
Copper	110	70	220
Brass (C36000)	100	125	345
Nickel (commercially pure)	200	140	450
Tungsten	400	750	980

2)Crash energy Management Summary of Crash Energy Management in Side Impact Crash energy management in side-impact collisions focuses on absorbing and distributing impact forces to minimize injury risks. Crumple zones, often made from aluminum honeycomb structures, deform in a controlled manner to absorb energy efficiently. Side-impact beams, constructed from durable steel or carbon fiber reinforced polymers (CFRP), help prevent cabin intrusion. Triangulated reinforcements and floor-to-roof connections further enhance structural integrity by spreading impact forces across multiple points. Innovative solutions such as external airbags activated by sensors add an extra layer of protection before a crash occurs. Real-world crash data from organizations like NHTSA, IIHS, and EURO NCAP help refine these safety systems. Multi-material designs, integrating CFRP beams with aluminum crumple zones, offer optimal crash performance without adding excess weight. Future advancements, including active safety mechanisms and energy-absorbing nanomaterials, aim to further improve side impact protection in vehicles.

TABLE 2-EFFECTIVENESS OF HONEYCOMB STRUCTURE IN DIFFERENT DIRECTIONS AND PLANE

Load Direction	Mechanism	Effectiveness	Applications
Axial	Vertical walls carry load like columns	High	Crash absorbers, aerospace panels
Lateral	Walls bend and share load	Moderate	Packaging, impact panels
Out-of-plane	Cells act as sandwich core	Very High	Aircraft wings, composites
Shear	Hexagonal walls resist sliding	Moderate–High	Sandwich panels, bridges

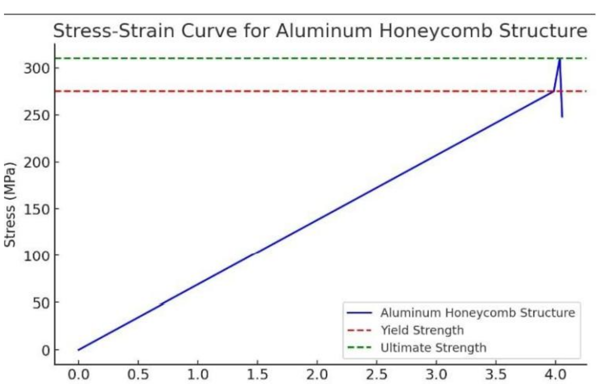
Accident data analysis Using crash database like NHTSA, IIHS, EURO NCAP and NHAI to assess the real-world side impact crash tests and trends and for developing an injury probability model while assessing with the ergonomics viability of our new safety technologies

V. Results

The chief motive of this research is to enhance side-impact safety of passenger vehicles by utilizing innovative materials and techniques that improve energy dissipation, structural reinforcement, and ergonomic design, while maintaining compatibility with industry standards. By employing advanced materials like carbon fiber, the integration of crumple zones, and innovative airbag deployment strategies, this research aims to address critical vulnerabilities in current vehicle safety systems. Material Selection and Performance One of the key findings from our study is the significant advantage of using carbon fiber over traditional metals for reinforcing side-impact beams. Carbon fiber offers a high-quality strength to weight ratio, making it appropriate material for maintaining vehicle performance without adding excess weight. When applied in the form of prepreg carbon fiber pipes, these beams can be strategically placed inside the vehicle's side panels to prevent intrusion during a side impact. This approach not only strengthens the vehicle's ability to absorb and distribute the force of a side collision but also improves fuel efficiency by maintaining the vehicle's lightweight structure. Additionally, the use of aluminum for the crumple zone shows promise. Aluminum's properties, such as high energy absorption capacity and low weight, make it a suitable candidate for dissipating crash energy. By implementing aluminum in the form of honeycomb cores or triangulated structures, the crumple zone can capably absorb and redirect energy away from the passenger cabin. This method also ensures that the crumple zone can deform in a controlled manner, reducing the risk of injury to passengers. Comparative testing of different materials in terms of flexural rigidity, toughness, and cost-efficiency will be conducted to ensure that the selected materials offer optimal performance at a competitive cost. Crash Energy Management The integration of advanced crash energy

management systems are another critical element in improving side-impact safety. The use of aluminum-based honeycomb structures within the crumple zone has been shown to effectively dissipate energy in multiple directions. The honeycomb structure's ability to deform and collapse in a controlled manner significantly reduces the impact force transferred to the vehicle's occupants. This technique, coupled with the triangulation structure made from nonbrittle metals, provides an efficient way to distribute the impact energy in a node-to-node manner, further mitigating the risk of injury during a side collision. In addition to material advancements, real-time crash data analysis using crash databases like NHTSA, IIHS, and EURO NCAP will inform the development of a more refined injury probability model. By analyzing side-impact crash data from these sources, it will be possible to assess the effectiveness of the new technologies and materials in reducing injury severity. This data-driven approach ensures that the designs will be optimized based on real-world crash scenarios and injury patterns. Ergonomic and Safety Enhancements The ergonomic improvements in the design, such as the development of a curved headrest, address the issue of neck injuries caused by rapid side airbag deployment. By incorporating a headrest with a curvature designed to stabilize the passenger's head during a side impact, the risk of severe neck injuries, such as fractures, can be significantly reduced. This design improvement also benefits frontal collisions, providing an optimal solution for head and neck support. Moreover, the introduction of external airbags, deployed using sensors like LIDAR, represents a groundbreaking innovation in side-impact safety. By positioning airbags on the exterior of the vehicle, passengers are better protected from the high-force impacts often experienced when airbags deploy from the interior. This method of airbag deployment minimizes the risk of injury from the airbags themselves, which can cause harm when deployed at high speeds. Finally, the implementation of intelligent systems, such as automatic steering adjustments triggered by sensors, is another crucial step toward enhancing side impact safety. These systems can preemptively maneuver the vehicle away from the impending impact, significantly reducing the likelihood of a side collision. Conclusion In summary, this research demonstrates that a combination of advanced materials, innovative structural designs, and intelligent safety technologies can significantly improve vehicle side-impact safety. By utilizing materials like carbon fiber and aluminum, optimizing crumple zone design, and incorporating real-time data analysis, the new safety systems can provide superior protection while maintaining cost efficiency. Additionally, ergonomic designs and the use of external airbags further enhance passenger safety during side collisions, offering a holistic approach to improving side-impact safety in vehicles. The proposed solutions represent a step forward in addressing the critical gaps in current automotive safety systems, ultimately contributing to a reduction in fatalities and serious injuries in side-impact.

Fig 2 – STRESS STRAIN GRAPH OF ALUMINIUM HONEYOMB STRUCTURE



CONCLUSION

This research demonstrates that integrating advanced materials like carbon fiber and aluminum, along with innovative safety technologies, can significantly enhance vehicle side impact protection. By optimizing crumple zones, improving energy distribution, and incorporating external airbags, we can better safeguard passengers during side collisions. Additionally, ergonomic improvements, such as curved headrests, and intelligent systems like automatic steering adjustments, further reduce injury risks. These advancements not only improve safety but also maintain cost-effectiveness, offering a comprehensive solution to address critical vulnerabilities in current vehicle safety designs.

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REFERENCES

[1] Kalyan S. Cheruvu, Anindya Deb, Mark O. Neal, and Jenne-Tai Wang "Setting vehicle side impact safety design

target using a regression-based approach" in the International Journal of Vehicle Safety in 2007
[2] S. S. Jermakian and A. T. McCartt "Do NHTSA Vehicle Safety Ratings Affect Side Impact Crash Outcomes?" in the Traffic Injury Prevention journal in 2020
[3] R. P. Bligh and W. L. Menges "Side-Impact Crash Test and Evaluation Criteria for Roadside Safety Hardware" published in Transportation Research Record in 1998
[4] Yuan Chen, Xinying Cheng, and Kunkun Fu" Multi-material design of a vehicle body considering crashworthiness safety and social effects" published in International Journal of Crashworthiness in 2019
[5] Zihong Wu, Yan Zhao, Kang Yang, Juan Guan, Shaokai Wang, Yizhuo Gu, Min Li, Yiyu Feng, Wei Feng, and Robert O. Ritchie "Enhancing the Mechanical Performance of Fiber- Reinforced Polymer Composites Using Carbon Nanotubes as an Effective Nano-Phase Reinforcement" published in Polymers journal in 2021
[6] Derviş Özkan "Carbon Fiber Reinforced Polymer (CFRP) Composite Materials: Their Characteristic Properties, Industrial Application Areas, and Their Machinability" published in 2020
[7] Mei-Ni Su and Ben Young "Mechanical Properties of High Strength Aluminium Alloy at Elevated Temperatures" publishes by ce papers in 2017