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Study on Optimization and Crash Worthiness of A Composite Side Car Door

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Abstract: *The increasing demand for lightweight, fuel-efficient vehicles has led to the widespread adoption of composite materials in automotive structural components. This study focuses on the optimization and crashworthiness analysis of a composite side car door, aiming to enhance impact resistance while minimizing weight. A finite element model of the side door was developed using advanced composite layups, including carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP). Material selection, ply orientation, and stacking sequence were optimized using a multi-objective optimization framework to achieve a balance between mechanical performance and manufacturability. Crashworthiness was evaluated through virtual simulations under side-impact scenarios in accordance with NCAP regulations. Key performance metrics such as intrusion distance, energy absorption, and peak impact force were analyzed. The optimized composite design demonstrated a significant improvement in energy absorption (up to 30%) and a reduction in door weight by 40% compared to traditional steel structures, without compromising safety. This research highlights the potential of tailored composite structures in enhancing automotive safety and performance. The integration of optimization techniques and crash simulations offers a practical approach for next-generation lightweight vehicle design.*

Keywords: carbon fiber-reinforced polymer

I. INTRODUCTION

Response of crash testing and model simulation is the characteristics of a vehicle structural is the “crash signature”, commonly referred to as the crash pulse. During impact this is the deceleration time history at a point in the vehicle. The significant structural behavior and the gross motion of the vehicle in a frontal impact can be identify by crash pulse at point on the rocker panel at the B-pillar which is presumed to identify. Dynamic analysis on other locations, such as radiator and the engine, are frequently chosen to record the crash pulse for components. The structural stiffness, damping at that location, and on external interactions from neighboring components all depends on the nature of crash response [1].

To prevent the occupant injuries at the time of accidents must sustain impact loading on the vehicle which is the ability of crashworthiness. Frontal impact on vehicle is more dangerous, but Side impact crash is second dangerous. One of the most hazardous crashes causing death and injuries annually around the world because there is no room for large deformation of the vehicle structures. Therefore, it can be concluded that by improving the qualities like strength, toughness etc. in the vehicle body-door in side impacts because side door may have less impact zone and lower rigidity compared with the bumper [2]. The National Highway Traffic Safety Administration (NHTSA) who released Global rating for accident that Side impact collision are the second most frequent causes for serious accidents after frontal impact. To reduce the crash pulse transferred to human in side impacts by so many researches focusing on the ability of vehicle structure to absorb the impact energy.

The safety of passenger is very important also need to improve fuel efficiency and gas emission regulation. The price of the fuel and the requirement of the fuel is becoming day by day most wanted and increasing, also emission of chemicals from the vehicle exhaust pollute the atmosphere and also increased risk in global temperature.

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The biggest issues in automotive industry is how to improve safety and gas emission regulation. These all issues are directly involved in final vehicle design. Crashworthiness standard and fuel efficiency are particulars which are required by manufacturers. These manufacturers approximately make design changes in their vehicle structure and also introducing good structural components that satisfy the overall design objectives [3].

Fig.1.1 Intrusion beam inserted in actual side car door model.

Glass fiber-reinforced composite material with high specific stiffness (stiffness/ density) and high specific strength (strength/density) have been used in aircraft and space vehicles. Even other properties are high damping and impact characteristics [4]. As day by day requirement or demand of composites is increasing due to fall in price rate these materials are used widely in for sport goods, leisure supplies, machine tools and in the structure of automobiles. Study was made and report was submitted to United States of America and Canada. They made prediction that plastics and composites may be widely utilised for body panels, flexible components, bumper systems, trims, driveshaft and transparent parts of cars. The continuously reducing the weight of cars has increased fuel efficiency [5]. It should be done by keeping safety of cars and increasing the fuel efficiency of cars. Increase of the fuel efficiency is by employing the glass fiber reinforced composite materials in the body of cars. These fiber-reinforced composite material have ability to absorb energy to prevent occupant injuries [6].

1.1 Crashworthiness

The design must be improved in vehicle so that higher speeds its passenger should not experience a net deceleration. Crashworthiness is defined as “the ability of the vehicle to absorb energy to prevent occupant injuries in the event of an accident”.

Crashworthiness can be classified into three:

- Fire, Biomechanics.
- Combustion
- Material Engineering Design.

Crashworthiness features also consider air bags, crumple zone, side impact protection, seat belts etc.

Vehicle safety is not same as crashworthiness. The features like ABS (Anti Braking System) helps in avoiding accident, safety of vehicle also depends on crashworthiness. There may be some significant defects in crashworthiness, even though vehicle might be safer than another vehicle. Considering absorption of kinetic energy involved in structural crashworthiness and are considering materials and design suitable for controlling and predicating energy absorption. In this process internal work of the two bodies involved in the crash is converted by the kinetic energy of the colliding bodies. There may be involvement of material failure, structural instabilities and global and failure of joints. In addition, effects like strain rate and inertia play important role in the response of structures involved.

Crashworthiness of a material is expressed in terms of specific energy absorption, Es=F/D, where F is the mean crush stress. Based on stiffness and strength of the structure is far away from the better in case of protecting the passengers.

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Keep the forces in well below dangerous accelerations, rather structure should collapse. In the well-defined deformation. However, under load deflection curve, the amount of absorbed energy equals the area and these two criteria's are somewhat contradictory. Thus this case shows us that it is not only important to know how much energy is absorbed but also how it is absorbed. We need to add more things rather than just designing the structures, but it should withstand static and fatigue loads, during impact the structure must be allowed to absorb maximum energy.

1.2. Crash Analysis Test and Types

A crashworthiness and crash compatibility for automobiles or related components must undergo a crash-test which is form of destructive testing usually performed in order to ensure safe design standards. To test the cars safety performance different types crash condition. vehicle manufactures must crash test their respective cars under different angles, different sides and with different object including other vehicles [7].

For any testing of crash of vehicle there required lots of vehicles must be destroyed for the test and also with it require time and uneconomical. Now a days computerized simulation crash-testing is one new recent trend which is gaining vast popularity. In this simulation finite element model is generated instead of real vehicle for testing various department which is carried out before using actual vehicle.

The most common types of crash tests are listed below.

- Front impact test
- Front offset crash test
- Rear impact test
- Roll over test
- Side impact test

1.3 Side impact Analysis

Side impact are second dangerous crashes occur after the frontal impact so annually causing death and injuries around the world is large. These side impact accidents happen to be with trees, posts or poll, highlighting their severity to showing the significance of it comparing to frontal crash events.

Designers of various sectors related to automobile world are trying to minimize the impact energy absorbed by vehicle during such accidents and reduce the crash pulse transferred to human in side impacts [8]. Nowadays the presence of smart material like composites and the better advancement of crashworthiness knowledge have led to improvements in passenger safety, occupant protection and structural weight and design have been innovations are particularly developed in high speed crash mode [9].

During accident frontal impact generally involves straight involves the vehicle's bumper is impacted either in low or high-speed mode which is investigated by man researcher. Hence, it is concluded that strengthening the vehicle's body-door in side impacts demands to requires more focused attention due to having lower rigidity compared to bumper and less impact zone area. Even we can see that from other side could lead to the loss over profit when crash because we have to high maintenance cost like repairing dent and repainting of the body. Side to side car and pole impact are the two diverse styles side impact is divided.

1.4 Glass Fiber Composite Materials

To overcome some solution different material is used such as Fiberglass instead of steel structures. Fiberglass is also called as glass-reinforced plastic, GRP, glass-fiber reinforced plastic, or GFRP is a fiber reinforced polymer matrix reinforced by fine fibers of glass. Fiberglass is an extremely strong, lightweight and robust material. Although strength of the carbon fiber is more than glass fiber. Glass fiber has less stiffness, the material is less brittle, and the raw materials are more cheap. By using molding processes, it can easily have formed using molding processes, but when compared to metals it is more favorable because of bulk strength and weight properties.

Glass Fiber is also used as reinforcing agent in many polymer products, as it is much cheaper and significantly less brittle, these are commonly used as insulating material.

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1.5 Objective of Study

1. The main objective of project work is to provide good design structure for side doors.
2. To replace steel intrusion beam of side car door with glass epoxy fiber.
3. To reduce the weight of the car un order to increase in efficiency of fuel.
4. To understand the crashworthiness energy absorption capability, which should be high ensuring and minimum impact on the side car door.
5. To know the difference between two materials steel and glass fiber composite material and understand the properties of both and evaluation.
6. To carry out experiment on both materials through static and dynamic analysis using suitable software.

1.6 Methodology

The project begins with the development of the better designed side impact / intrusion beam, then comparing with a current steel beam for total energy absorption. The FMVSS 214 and ECE R95 are kept some standards for glass epoxy fiber composite material which should fulfill the cross section and thickness of beam is designed out by finding out by the total energy absorption and peak load carrying capacity. The material property of the steel beam is changed from steel to thermoplastic glass epoxy fiber composite.

Glass fiber composite material beam is found out by finding the intrusion and acceleration at the center of the beam by implementing them into the finite element model of Ford Taurus Car Door model and tested according to the FMVSS 214 and ECE R95 [8].

II. LITERATURE SURVEY

In some of studies done by expert in ensuring safety of vehicle there is to ensure that parts of cars should be replaced by composite material so experts researched more on composite material for vehicles parts to increase safety and efficiency of vehicles and also reduces weight.

Composite materials offer high specific stiffness (stiffness/density) and high specific strength (strength/density), and this design can absorb greater deformation. In comparison to the other materials, they have exceptionally strong impact load absorption and damping qualities.

Tae Seong Lim [11]. Now a day's passengers require two important things in car those are fuel efficiency and emission gas regulation. To increase fuel efficiency without compromising with the safety issues so they employed fiber reinforced composite materials in the body of cars because composite materials have higher specific stiffness and higher strength than compared to conventional steels or aluminum.

In this study done by Tae Seong Lim is on car side doors he replaced the steel intrusion beam with reinforced composite material which made of glass fiber. In this study weight of door dramatically decreased but deformation could be absorbed by vehicle during an accident. The composite beam and brackets on the car had to undergo static bending tests, which were performed for optimum fiber sequence and then testing of static tensile of joints. The designed mechanical joint was made to fail with fiber shear-out mode, to enhance the energy absorption characteristics of the composites impact beam during side-door collision of passenger cars which impact energy might be dissipated. During the static bending test, the manufactured composite beam was fixed in compact side-doors of passenger's car. From the test, it was found that the composite impact beam 70% high strength steel beam has comparable static bending strength. The static strength of the composite impact beam manufactured using this method has given 20% increase and also the weight of the fiber-reinforced composite beam was also lower than that of the steel impact beam.

Ali Ghadianlou [12]. In collisions or accidents, first mind comes is safety of passenger and then insurance cost plays very important role. In which reduction of structural damage and repair fixing costs plays an important role. In this study, a pole impact test is carried out on frontal door to assess permanent damage done on doors. To reduce damage on side doors, two significant parameters were including considered: material and geometry. To study the effect of side door collisions with poles, so various materials where examined taken in first phase, six different material sheets were used to investigate the rigidity and strength of the structure. In the second phase, the geometry was considered for side door design and modification which was performed by via creating new CAD-reinforcing ribs. Consequently, to

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achieve lower losses like permanent damage so strength in elasto-plastic mode, maximum deflection and plastic strain of the equipped system were evaluated representing.

In order to design the side door beam, there is two major factors were considered. First of all, the side door should be high to absorb internal energy. Second place, low-speed impact scenarios model we must avoid any plastic displacement of the door plate should be minimized as much as possible.

Elaheh Ghassemieh [13]. In the field of automation there is need of comprehensive account of the materials for manufacturing. Whenever we think manufacturing, we always required materials which possess properties and characteristics for manufacturing the automotive parts. In later sections which deals with history of development of material in automotive from traditional to the most recent ones. In the class of metallic material like steels, aluminum and magnesium and most recent alloys are explained neatly to understand automotives. Some of description of properties, manufacturing process and joining process are described. The problem and advantages of material are also reported. The other type material to be considered are composites and plastics with synthetic or natural fiber as reinforcement.

While composite type of fiber material is used and natural fiber hold a relatively new place with substantial potential for growth due to the growing environmental concerns. The cost analysis is presented because the main thing in composite material is cost barriers. Also second barrier for automotive parts is manufacturing process for production is complex. A review of manufacturing process for synthetic and natural fibers is also offered to the composites.

Chang Hun Lee [14]. This paper designates a study on the Taguchi method, which is used to determine the sensitivity of various design factors in reducing occupant's injury from side-impact accident. For analysis a full mid-sized vehicle finite element model is used under two different side impacts standard – SINCAP AND ECE-R 95. When may have major effect on side impacts setup required for analyzing the design factors so there is need of using LS orthogonal array. After the test they concluded that occupant compartment must be strengthen so that protection increases this lowers the injury values in SINCAP. In ECE-R 95 has criteria for critical occupant injury that it should be considered that no single factor has major effects on rib deflection so it is considered. Taguchi method usage may be limited in crash analysis but it was found to useful tool, for predicting the effect of various design factors on structure effect.

From SINCAP analysis results, every factor has some degree of sensitivity to the occupant injury. Specially, adding door trim padding or pusher foam which reduce both TTI and pelvis acceleration.

Heinrich Weber [15]. Now a day's automotive world requires increased crash safety and lower weight at reduced cost are important requirement of occupants. Side impact protection beams have to meet these requirements. It was the uses of high ultra-high strength steel demonstrates to be an efficient approach to reach this target. The presentation indicates displays comparison between a press manufacturing and a combined roll forming/laser welding process. This comparison indicates considerable cost savings for the roll forming alternative. Recent developments of laser welding technology and roll forming will provide further weight and cost reduction. Up to now roll formed sections had a uniform wall thickness. Now variable wall thickness can provide section by roll forming. This allows for load-commensurate section design. This dramatically developed potential is not only influence for side impact doors but also for body-in-white. A couple European custom roll forming companies are already installed with this technology. The market models as well as for high-volume vehicles.

Matthew Hung [16]. Basic characteristics of vehicle structural response in crash testing and model simulation is the "crash signature," commonly referred to as the crash pulse. During impact of vehicle in accident the above crash signature is deceleration time history. The gross motion of the vehicle in the frontal impact is the significant structural behavior and the crash pulse at a point on the rocker panel at the B-pillar is presumed to identify. Other locations, such as the radiator and engine, are frequently chosen to record the crash pulse for component dynamic analysis. The nature of accident also depends on structural stiffness, damping, mass at the location and on external interaction from foreign neighboring parts or components. In this study also involves air bag crash sensing, deployment and crash recorder data analysis are also prepared and presented.

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III. RESULTS & DISCUSSION

We need to check the trend observed in global energy plots, percentage of added mass and crush resistance vs. displacement to see if they are within required acceptance criteria.

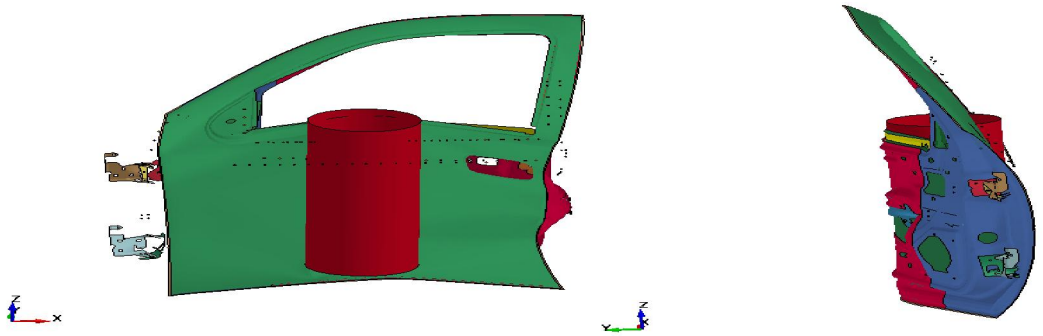

Fig. Simulated car door model.

Global Energy Plots

Global energy plots can be plotted using the ASCII file "glstat" generated during the analysis. In global energy plot we mostly see total energy, internal energy, kinetic energy and hourglass energy.

As vehicle is not moving kinetic energy (KE) would be zero. When rigid cylinder impacts the door, internal energy continuously increases. As the total energy is the sum of all the energies, it is also increasing along with internal energy. Generally this trend of energies is observed in quasi static analysis.

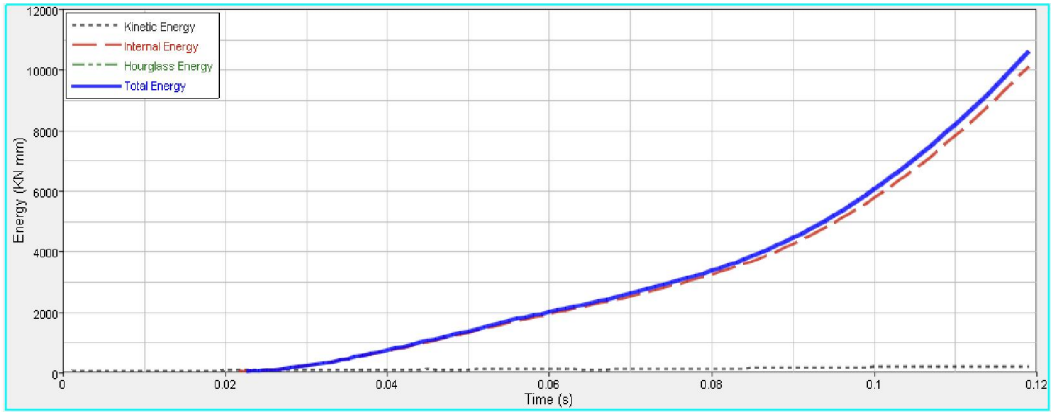

Fig. Energy vs Time Graph of S shaped steel

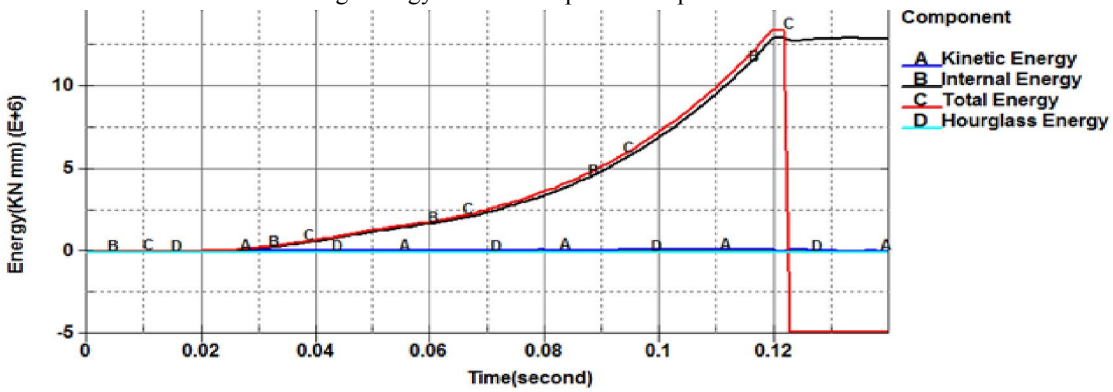

Fig. Energy vs Time Graph of Glass-Epoxy Composite Intrusion Beam.

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Added mass (%)

Along with global energy plots we have to see the percentage mass added during analysis before going for post processing. This added mass percentage (%) always should be less than 5 %. In our case mass added is 0.56 % in S shaped steel intrusion beam were as 0.17% in fiber composite materials. So we are far below than 5 %, i.e. mass added is within the required acceptance range.

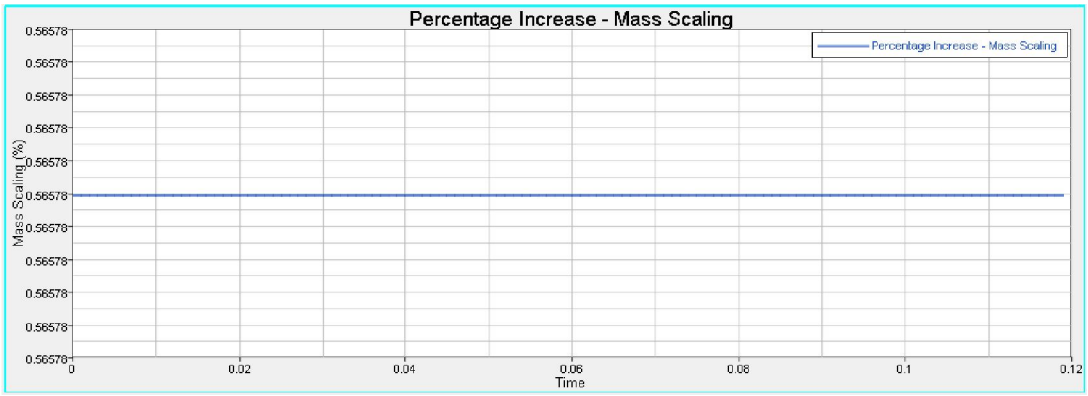

Fig. Mass scaling % graph of S shaped steel intrusion beam.

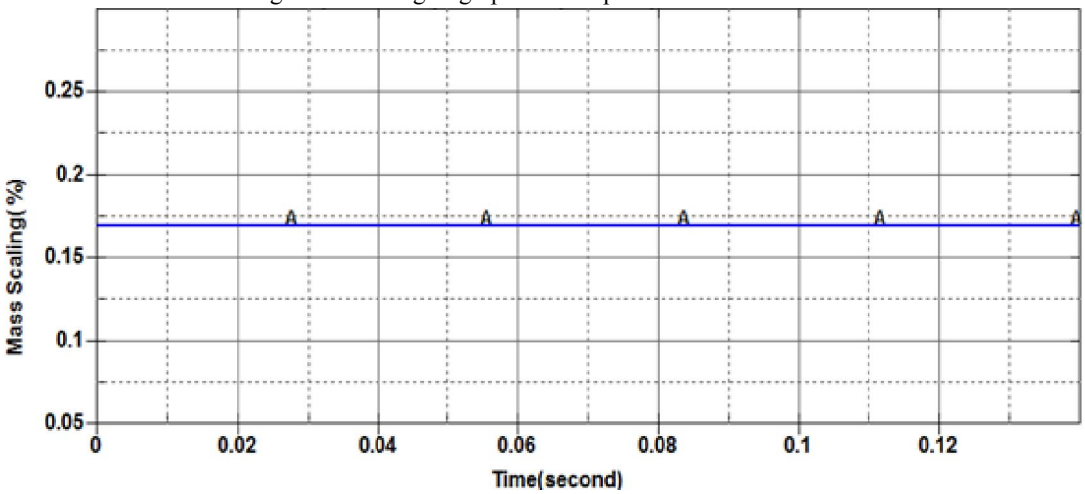

Fig. Mass scaling % graph of Glass-Epoxy composite intrusion beam.

Crush resistance Vs. Displacement

We need to measure crush resistance vs. displacement. Initially we have given 450 mm displacement to rigid cylinder i.e. displacement vs. time. And after analysis is complete, we got force vs. time from ASCII file "rcforc". Hence in order to get the force vs. displacement, we have to cross plot these two curves.

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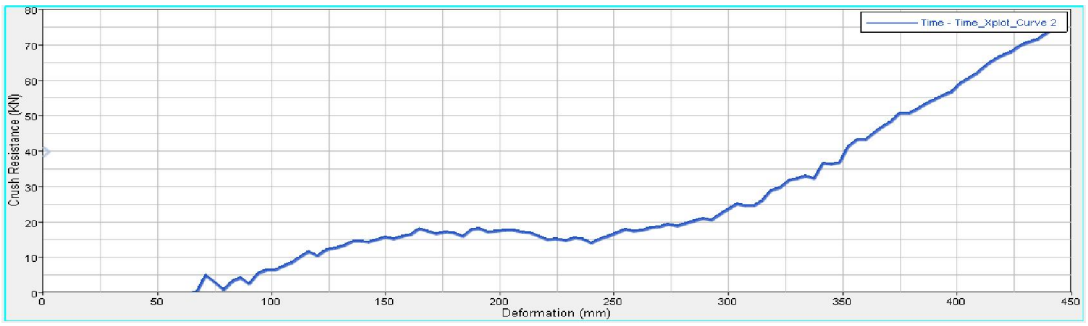

Fig. Crush resistance vs Deformation graph of S shaped steel intrusion beam.

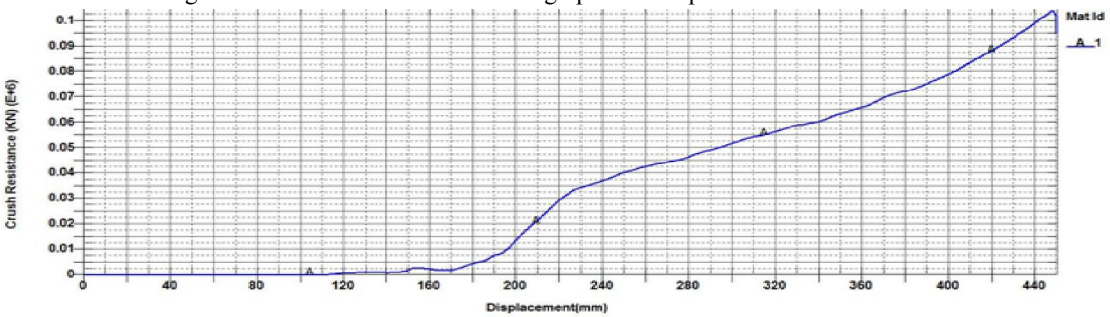

Fig. Crush resistance vs Deformation graph of glass-epoxy composite intrusion beam.

As per the static requirements of the FMVSS 214, force vs. displacement has been divided in 3 zones.

- Initial crush resistance (0-150 mm)
- Intermediate crush resistance (150-300 mm)
- Peal crush resistance (300-450 mm)

Table Requirements of Crush Resistance as per FMVSS 214 and ECE R95

	Rigid cylinder travel along Y-direction (mm)	Acceptance without seats (KN)	Acceptance with seats (KN)	Observed crush resistance force (KN) (Steel)	Observed crush resistance force (KN) (Composite)
Initial mean crush resistance (KN)	0-150	>10	>10	15.7	5.0
Intermediate mean crush resistance (KN)	150-300	>15.6	>19.5	23.80	52.50
Peak crush resistance (KN)	300-450	>31.2	>53.4	77.14	125.00

In the above table, we see the observed crush resistance along with the target requirements for acceptable criteria with and without seats installed. In our project, we are dealing with door model without seats. As per the standards, initial mean crush resistance up to first 150 mm should be greater than 10 KN, and observed crush resistance in S shaped steel beam is 15.7 KN were as in fiber composite is 5 KN as it is below the criteria due to improper location of the beam as for the Intermediate mean crush resistance for up to 150 mm – 300 mm displacement, should be greater than 15.6 KN and for peak crush resistance up to 300mm – 450 mm displacement, should be greater than 31.2 KN. For both intrusion beams conditions observed crush resistance is well above the required criteria. So in all the cases it is meeting with the acceptance criteria described by FMVSS 214& ECE R95 for side impact of a passenger car door with moving rigid pole.

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IV. CONCLUSION

In this paper, glass fiber composite side-door intrusion beams were designed, fabricated, and analyzed through three-point static bending tests and numerical simulations. The results revealed that beams with circular cross-sections were more susceptible to local collapse and fracture under relatively low concentrated loads due to buckling. In contrast, beams with square cross-sections demonstrated the ability to withstand external loads comparable to high-strength steel intrusion beams. Notably, the use of glass fiber composites achieved a significant weight reduction of approximately 44% compared to steel counterparts, without compromising structural performance.

The left-hand side door of a passenger car was further modeled and analyzed using LS-DYNA software in accordance with FMVSS 214 and ECE R95 side-impact standards, ensuring industrial relevance and correlation with practical crash test requirements. The computational results indicated that the "S" shaped glass fiber composite intrusion beam not only reduced overall beam weight but also exhibited superior energy absorption characteristics compared to steel. Consequently, the glass composite beam proved effective in minimizing door intrusion and thereby reducing the risk of occupant injuries.

From the comparative analysis, the following key conclusions are drawn:

- Glass fiber composite beams provide a substantial reduction in weight while maintaining structural integrity.
- They absorb higher deformation energy than steel, offering enhanced crashworthiness despite the reduced mass.
- Their performance satisfies both FMVSS 214 and ECE R95 side-impact protection standards.
- Mechanical properties of composites can be optimized through modifications in fiber–matrix composition and volume fraction.
- Due to their high stiffness-to-weight ratio and strength, glass fiber composites are promising candidates for replacing conventional metallic materials in vehicle structures.
- Although composite beams are prone to buckling under impact loading, this limitation can be mitigated through careful design modifications, improved fiber orientation, and optimized matrix reinforcement. With further advancements, glass fiber composites hold strong potential for widespread use in the automotive sector.

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