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Design Optimization on Front Side Rail to Improve the Crashworthiness

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Abstract:
The crashworthiness of a car must be evaluated with the load carrying capacity and the crash mode at the initial stage of auto-body design. Auto-body members such as a front side member should be designed to efficiently absorb the kinetic energy during the car crash in order to secure occupants from the impact and penetration. In a vehicle frontal crash, a higher level of energy absorption in the frontal structures occur and its leads to reduce / less injury to the passengers. Front side rails structure used to absorber / transfer the impact force in the body of a vehicle. In order to improve the safety of passengers, the front rail design should be optimized to absorb higher levels of energy in a frontal crash. In this Thesis, an investigation of design optimization of the front side rail, to improve the crash performance of the vehicle. It has to be conducted 10 design optimization concepts (adding Structural tube and bulkheads) in order to reduce the peak impact force while increasing the total energy absorbed at crash. The impacting deformation value compared with existing side rail deformation condition and its reduced 50% from the existing deformation value.
***Key Word**: Crash worthiness; Automobile; Front Side Rail, Deformation.*

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I. Introduction

In a Vehicle Frontal crash, a higher level of energy absorption in the frontal structures occur which leads to reduce or less injury to the passengers. Front side rails structure used to absorb or transfer the impact force in the body of a vehicle. In order to improve the safety of passengers, the rail design should be optimized to absorb higher levels of energy in a frontal crash.

1.1 Crumple Zone:

The crumple zone (also called crush space) is a structural feature mainly used in automobiles and recently incorporated into railcars. Crumple zones are designed to absorb the energy from the impact during a traffic collision by controlled deformation. Typically, crumple zones are located in the front part of the vehicle, in order to absorb the impact of a head-on collision, though they may be found on other parts of the vehicle as well. According to a British Motor Insurance Repair Research Centre study of where on the vehicle impact damage occurs: 65 percent were front impacts, 25 percent rear impacts, 5 percent left side, and 5 percent right side. The car body is divided into three sections: the rigid non-deforming passenger section and the crumple zones in the front and the rearas shown in Figure 1.1. They are designed to absorb the energy of an impact by deformation during collision.

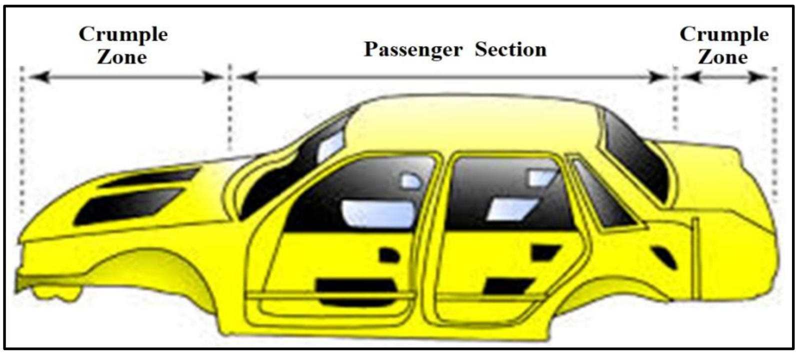


Fig 1.1 Car Body's Crumple Zone

Crumple zones work by managing crash energy, absorbing it within the outer parts of the vehicle, rather than being directly transferred to the occupants, while also preventing intrusion into or deformation of the passenger cabin. This better protects car occupants against injury. This is achieved by controlled weakening of sacrificial outer parts of the car, while strengthening and increasing the rigidity of the inner part of the body of the car, making the passenger cabin into a safety cell by using more reinforcing beams and higher strength steels. Impact energy that does reach the safety section is spread over as wide an area as possible to reduce its deformation.When a vehicle and all its contents, including passengers and luggage are travelling at speed, they have inertia or momentum, which means that they will continue forward with that direction and speed (Newton's first law of motion). In the event of a sudden deceleration of a rigid framed vehicle due to impact, unrestrained vehicle contents will continue forwards at their previous speed due to inertia, and impact the vehicle interior, with a force equivalent to many times their normal weight due to gravity.

The purpose of crumple zones is to slow down the collision and to absorb energy to reduce the difference in speeds between the vehicle and its occupants. Seatbelts restrain the passengers so they do not fly through the windshield, and are in the correct position for the airbag and spread the loading of impact on the body. Seat belts also absorb passenger inertial energy by being designed to stretch during an impact, again to reduce the speed differential between the passenger's body and their vehicle interior. In short, a passenger whose body is decelerated more slowly due to the crumple zone (and other devices) over a longer time survives much more often than a passenger whose body indirectly impacts a hard, undamaged metal car body which has come to a halt nearly instantaneously.High strength sheet steel is used in the reinforcements located under the floor and on the rocker panels, and a new structure that can effectively provide the axial-compression load to the frame is used. This is to absorb the collision energy efficiently and to disperse the load. As a result, cabin deformation will be minimized. Large front bumper reinforcement is used to efficiently dissipate the impact energy into the frame side rails.Crash boxes are provided at the front ends of the frame side rails. These crash boxes reduce the impact that acts on the side rails and minimize body deformation during a minor collision. In order to disperse the impact load, which is caused by a frontal offset collision, the frame structure has been designed to minimize the frame buckling and transfer collision energy more linearly. In addition, high strength sheet steel is used in the reinforcements under the floor. As a result, a more efficient dispersal of the collision impact load has been made possible by controlling frame distortion mode through a combination of the body and frame during a major collision.

It is obvious that to survive high-speed collisions, it is essential to use the frontend crush and available distance between the occupant and the interior. This is accomplished when a restraint is used. The air bag, energy absorbing steering column and safety belts are all restraint systems that slow the occupant shortly after the vehicle starts to decelerate. The front-end crush and interior distance are both useful to some extent. Part of the distance is lost in a harness by slack and belt stretch. The distance between the driver and the steering wheel is lost in the case of the energy-absorbing column restraint, and the distance of the front-end crush and occupant space traversed during the sensing and deployment time for the air bag are lost. Basic concept of car test crash setup is shown in Figure 1.2. Table 1.1 shows the kinetic energy and work done equation used for calculation. Work is calculated from average force on vehicle by wall and sum of crush and rebound of vehicle. Static crush space is equal to the sum of free crush and crushed components. Dynamic crush is equal to the sum of static crush space and dynamic dash intrusion. Detail diagram of car body's front crash zone is shown below in Figure 1.3.

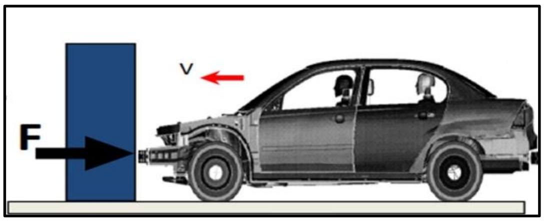


Fig 1.2 Car Body Crash Impact Test Setup

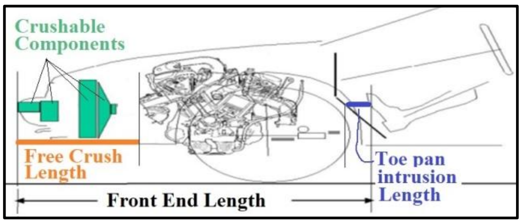


Fig 1.3 Detail of Front Crash Zone

Tab 1.1 Physics of crash calculation

$\boldsymbol{Kinetic\ Energy = \frac{1}{2}mv^2}$ $\boldsymbol{Work\ Done\ =\ F \times D}$ • Where, F = Average force on wall; D = Crush + Rebound of vehicle.	• Dissipate Kinetic Energy into vehicle deformation (or work done) but away from occupant. • Energy dissipation rate is proportional to injury. • Constant force as 'ideal'. • Axial crush as preferred mode. • Maximize crush space & minimize intrusion.

1.2 Frontal Crash Requirement

In recent decades, automotive safety has become a primary design feature. Strict rules and regulations set by governments are persuading car manufactures to design crashworthy vehicles. These restrictions coupled with a highly competitive market have led to innovative industrial advances. Crashworthiness optimization of vehicles has been widely studied, any many methods have been proposed. S-rails, as one of the main structural elements and energy absorbers of the automobile body, have been specifically examined. The more absorbed energy in the front structures of vehicles, the safer passengers will be in a car crash. Different studies have been conducted to increase the level of energy absorption in S rails and to consequently decrease energy transfer through the rails to the cabin. These include but are not limited to alterations in the cross-sectional shapes, dimensions, and thickness of the materials. Numerical analyses have also been investigated in many studies. The scope of this research work is as follows: to improve the side rail stiffness; to increase the occupant safety; to optimize the design; and to meet the crash standard.

The Indian standard named AIS 098 defines the regulation requirement of passenger cars and the AIS 098 test setup is shown in Figure 1.4.Global New Car Assessment Programmer (GNCAP) standard is the vehicle test regulation followed by European countries. GNCAP test setup is shown in Figure 1.5.

Test Barrier Requirements are as follows:

- The vehicle shall overlap the barrier face by 40% ± 20 mm.
- Barrier Mass – 7 x 10^4 kg
- Barrier front to vehicle face ±1˚
- Ground to barrier perpendicular ±1˚

Test Vehicle Requirements are as follows:

- Regular production vehicle handover to test agency.
- Fuel tank shall be filled with water to mass equal to 90% of the mass of a full fuel tank.
- The mass of the measuring apparatus shall not change each axle reference load by more than 5%.

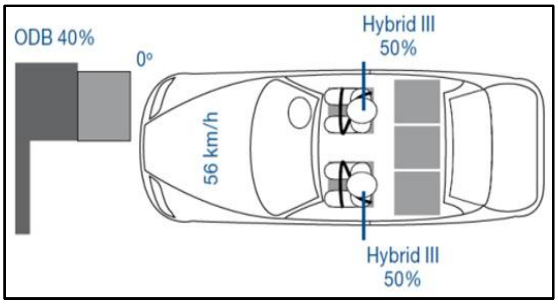


Fig 1.4 AIS 098 Test setup

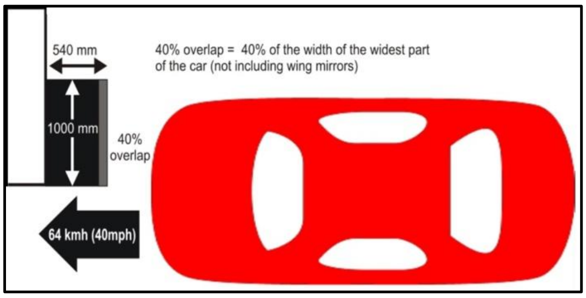


Fig 1.5 GNCAP Test setup

1.3 Literature Survey and Research Gap:

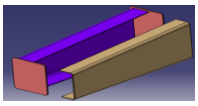
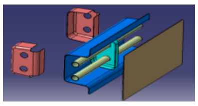
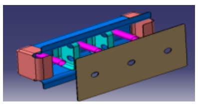
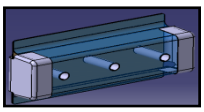
DuBois (2003) of American Iron and Steel Institute, investigated vehicle structureshould be sufficiently stiff in bending and torsion for proper ride and handling. It should minimize high frequency fore-aft vibrations that give rise to harshness. In addition, the structure should yield a deceleration pulse that satisfies the following requirements for a range of occupant sizes, ages, and crash speeds for both genders: Deformable, yet stiff, front structure with crumple zones to absorb the crash kinetic energy resulting from frontal collisions by plastic deformation and prevents intrusion into the occupant compartment, especially in case of offset crashes and collisions with narrow objects such as trees. Short vehicle front ends, driven by styling considerations, present a challenging task to the crash worthiness engineer. Griskevicius(2003) studied about out of the load path during frontal crash. During the frontal crash the side rail absorb most energy of all vehicles construction elements. In order to analyze the energy capabilities of side rail under axial compression loading and to evaluate the influence of longeron's algometrical characteristics and materials degradation on the vehicles safety experimental investigations and numerical calculations were performed. To assess the crashworthiness of longerons the main objective was to study the behavior of thin-walled structural elements under axial loading conditions using the Finite Element (FE) model. The numerical FE models were created using the computer code LS-DYNA.Hamza(2003)presenteda 3D extension to their previous work on vehicle crashworthiness design that utilizes equivalent mechanism models of vehicle structures as a tool for the early design exploration. An equivalent mechanism (EM) is a network of rigid links with lumped masses connected by prismatic and revolute joints with nonlinear springs, which approximate aggregated behaviors ofstructural members during crush. A number of finite element (FE) models of thin walled beams with typical cross sections and wall thicknesses are analyzed to build a surrogate model that maps the beam dimensions to nonlinear spring properties. Using the surrogate model, an EM model is optimized for given design objectives by selecting the nonlinear springs among the ones realizable by thin-walled beams. The optimum EM model serves to identify a good crash mode (CM), the time history of collapse of the structural members, and to suggest the dimensions of the structural members to attain it. After the optimization, the FE model of an entire structure is assembled from the suggested dimensions, which is further modified to attain the good CM identified by the optimum EM model. A case study of a 3D vehicle front half body demonstrates that the proposed approach can help obtain good designs with far less computational.Tischer (2014) presented asimplified model for the EURO NCAP offset deformable barrier suitable for use in the optimization of space frame automotive structures. The model improves the prediction accuracy of discrete structures and components without a force distributing vehicle body shell, by restricting unrealistic local deformation of the barrier. It also drastically reduces the computational effort compared to the shell and solid barrier models typically used.Ibrahim(2009) presented a systematic and practical methodology to conduct vehicle crashworthiness design optimization efficiently at early stages of design. The complicated nature of the physical crash processes of complex vehicle structures makes design optimization for crashworthiness a very challenging task. Moreover, large scale and highly nonlinear nature of crashworthiness simulations of vehicle structure make it impractical to conduct direct optimization on the full nonlinear model of the structure. The thesis includes four main parts. In the first part, an efficient and practical methodology for design optimization of vehicle structures under frontal impact for crashworthiness improvement is presented. In the second part, a methodology for deriving the important relation between minimum structural weight and maximum impact energy is presented. In the third part, the crashworthiness behavior of simple thin walled structures and vehicle structural components made of magnesium due to its light weight is examined and a new methodology for material design optimization is presented. Finally in the fourth part, the effect of imperfection on crush elements performance is studied.Sharpe (2007)studied the requirements of frontal impact legislation and the comparative evaluations of consumer organizations have improved occupant crash protection. Passenger vehicle bodies have crumple zones developed through rigid flat barrier testing and improved passenger cell stability has resulted from consideration of offset deformable frontal impacts. Pressures to minimize cost and weight, whilst still maintaining satisfactory crash performance, could potentially lead to vehicle designs in which the crash behavior of the structure has been optimized for barrier testing. Further, they investigatedon how the energy from a variety of different frontal impacts could be reliably managed within the structure of a medium sized passenger vehicle. The concept structural design developed within this project is intended to provide an acceptable amount of energy absorption independent of the precise orientation of objects with which vehicle collision may occur.This literature survey gives the studies towards straight rail and S-shaped rail crushing behavior;although, many studies completed towards straight rail and S-shaped rail crushing behaviors, no study has investigated the effect of introducing bulkheads and adding structural tube. Hence, this research project will simulate and analyze the additional effects with ten different proposed concepts.

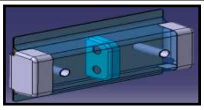
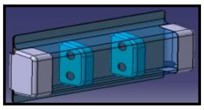
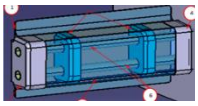
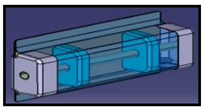
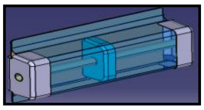
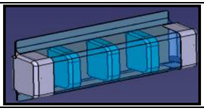
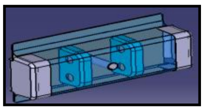
II. Methodology

2.1 CAD Details

The application of internal bulkheads and structural tube may significantly influence the energy absorption. The objective of the project is to investigate the impact of introducing bulkheads and adding structural tube as the main load path and energy absorbers in a frontal vehicle crash. Ten proposed concepts were generated with bulkheads and additional structuraltubes and theCAD details are shown in Table 2.1

Table 2.1 CAD concepts & Details

Concepts & Details	
	Existing Model : No Structural tube & No Bulk heads
	Concept 1 : 2 Structural tube placed in Parallel to impact force & 1 Bulk heads
	Concept 2 : 3 Structural tubes placed in Perpendicular to impact force & 2 Bulk heads
	Concept 3 : 3 Structural tubes placed in Perpendicular to impact force & No Bulk heads

	Concept 4 : 2 Structural tubes placed in Perpendicular to impact force & 1 Bulk heads
	Concept 5 : No Structural tubes & 2 Bulk heads
	Concept 6 : 2 Structural tube placed in Parallel to impact force & 2 Bulk heads
	Concept 7 : 1 Structural tube placed in Parallel to impact force & 2 Bulk heads
	Concept 8 : 1 Structural tube placed in Parallel to impact force & 1 Bulk heads
	Concept 9 : No Structural tubes & 3 Bulk heads
	Concept 10 : 1 Structural tubes placed in Perpendicular to impact force & 2 Bulk heads

2.2 Material Details

The material strength detail for the Existing and Proposed Model are given in Table 2.2.

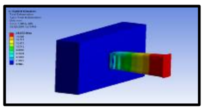
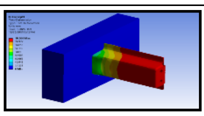
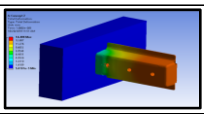
Tab. 2.2: Material Strength of Existing and Proposed Model

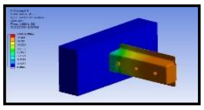
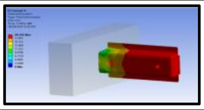
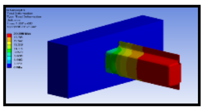
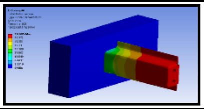
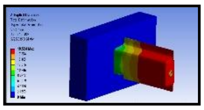
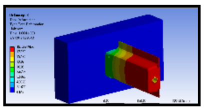
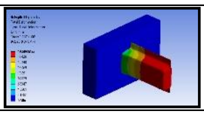
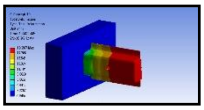
Components	Existing Model		Proposed Model	
	Yield Strength (N/mm^2)	Ultimate Tensile Strength (N/mm^2)	Yield Strength (N/mm^2)	Ultimate Tensile Strength (N/mm^2)
Inner Panel	350	360	380	600
Outer Panel	350	360	350	1115
End Cap	140	260	1180	360
Structural Tube	-	-	140	260
Bulk Head	-	-	140	260

III. CAE Results

Theexisting model and 10 proposed concept models were pre-processedand post-processed completelyusing ANSYS Workbench software. The deformation value of the side rail memberof the existing model and 10 proposed concept models from the CAE analysis areshown in Table 3.1

Table 3.1 CAEResults

Concepts & Details		CAE Deformation Value (mm)
	Existing Model : No Structural tube & No Bulk heads	28
	Concept 1 : 2 Structural tube placed in Parallel to impact force & 1 Bulk heads	19.099
	Concept 2 : 3 Structural tubes placed in Perpendicular to impact force & 2 Bulk heads	14.498

	Concept 3 : 3 Structural tubes placed in Perpendicular to impact force & No Bulk heads	21.832
	Concept 4 : 2 Structural tubes placed in Perpendicular to impact force & 1 Bulk heads	20.202
	Concept 5 : No Structural tubes & 2 Bulk heads	20.008
	Concept 6 : 2 Structural tube placed in Parallel to impact force & 2 Bulk heads	19.995
	Concept 7 : 1 Structural tube placed in Parallel to impact force & 2 Bulk heads	19.524
	Concept 8 : 1 Structural tube placed in Parallel to impact force & 1 Bulk heads	19.529
	Concept 9 : No Structural tubes & 3 Bulk heads	19.804
	Concept 10 : 1 Structural tubes placed in Perpendicular to impact force & 2 Bulk heads	19.987

IV. Results& Discussion

In this research work, the effect of the given below four factors that influence the crashworthiness of the steel front rail were investigated by taking the peak force and the absorbed energy with the variations in the design concepts.

- Number of structural tube used.
- Circular tube with bulkheads – Parallel to impact force.
- Circular tube with bulkheads – Perpendicular to impact force.
- Number of bulkheads.

Based on the analysis of the ten concepts, CAD models were designed (Table 2.1), and deformation analysis was simulated.The results are shown inTable 3.1, deformation valuesof the proposed 10 concepts were compared with the existing model. Concept No. 2 has the lowest stress and deformation value compared with existing & all other proposed models.

V. Conclusions

Along with existing model, ten concepts were proposed, designed and CAE analysis was simulated using the ANSYSWorkbench. The Concept No 2 was selected as it has less deformation and better stiffness and it has improved 51% deformation from the existing model. Hence Concept No 2 shall improve the Crashworthiness and reduce the passenger injury. Further, Concept No. 2 shall be used for physical testing to validate the simulation results.

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