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Research paper

A Review on Optimization of Vehicle Frontal Crashworthiness for Passenger Safety

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Abstract

In engineering and technology safety of human life has always been a top priority. With the increasing usage of vehicles in everyday life, probability of deaths and injuries has also increased. This paper provides a critical review on the optimization of vehicle frontal crashworthiness studied by researchers using various methods. They investigated the effects of crash at a defined speed using the method of FRB and ODB impact. It further discusses other methods that can be used to save passengers' life. Also, the designing and manufacturing limitations faced by engineers in actual development processes. Finally, it is concluded that improved structure design and material composition can significantly increase the overall crashworthiness of the vehicle.

Keywords: *Crashworthiness; Frontal Impact; FRB; Overlap Collision; Optimization; Vehicle*

1. Introduction

The first death in vehicle occurred in 1889 in New York. This event led to the birth of automotive safety as a field of study. Since then, occupant safety became the necessary requirement in vehicle design objectives [1]. Actual accident statistics prove that the large proportion of drivers are severely injured in frontal collisions [2]. Vehicle structure should be stiff enough to save the passengers and vehicle itself. Also, it should not be so soft that a small pedestrian collision results in the intrusion of vehicle parts into human being [3]. These two requirements are exactly opposite to each other. Optimum design of a vehicle in terms of safety, requires it to have exactly the right amount of stiffness so it can absorb right amount energy at the time of crash as well as not intrude into the passenger compartment.

2. Methods of Optimization

There are many methods to optimize vehicle frontal crashworthiness. Each has its own pros and cons and limitations. Some of them are discussed in the following headings.

2.1 Front Rigid Barrier (FRB) Impact

There are three categories of tests: component tests, sled tests, and full-scale barrier impacts; with increasing complexity from component to full-scale tests. The typical full-scale barrier test involves collision of a vehicle into a barrier on specified initial conditions and it typically uses a full car [4]. One of them is Front Rigid Barrier (FRB) impact test. Usually FRB impact test looks like this (as shown in fig. 1). Whole front of the car makes contact with the rigid body and damages are analyzed. In FRB impact test small-scale deformations occurred. In other words, chances of chest and head injury increased due to the force of inertia. So, the vehicle is saved from heavy loss, but lives of passengers are in danger [5].

2.2 Offset Deformable Barrier (ODB) Impact

Figure 1. Front Rigid Barrier (FRB) Impact Test

These collisions can be with a fixed object like pole or with another vehicle; either moving or stationary. In one study the crash test took at a speed of 64.4 km/h and 25% of the car's front was crashed with a rigid body. It was found out that upper rails serve as life saver while front rails are not of that much help in this type of collision [2]. In this impact only one side of the vehicle is targeted, and deformation is larger than the FRB impact. Thus, the intrusion of external compartment occurs. This, it is the main factor of injury in ODB crash. It has been assumed that crash will happen at the same angle with same velocity. Also, the material type on which it collides is not taken into consideration. This can lead us to drastically different results in real life situation. Moreover, in 1998, the “40% Offset Deformable Barrier” crash test at the speed of 56 km/h was adopted in the ECE R94/01. In 2006, China issued the new regulation (C-NCAP) which was suitable for the assessment of new car in domestic auto market, including the evaluation of the FRB (100% Front Rigid Barrier) impact and the ODB (40% Offset Deformable Barrier) impact. These tests are for A0 Class of the vehicle [5].

2.3 Optimization of Longitudinal Beams

Longitudinal beams are the most important parts for maintaining frontal impact crashworthiness. In this study, the optimization of beams is based on 100% RB (Rigid Barrier) Impact and 40% ODB (Offset Deformable Barrier) Impact. Simulation is based on Finite Element model and validated by actual crash tests as shows in the figure below [6].

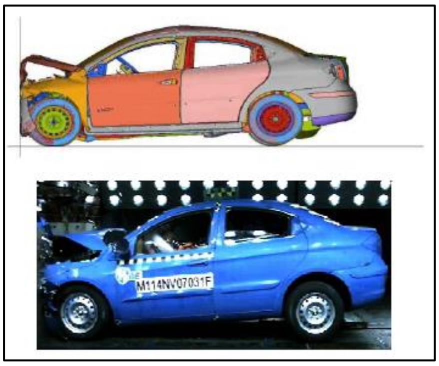

Figure 2. Crash Test

Surrogate model is built by Kriging and optimization method NSGA-II (Non-Dominated Sorting in Genetic Algorithms-II). Finally, the result shows that 100% RB and 40% ODB impact must be considered together for designing longitudinal beams.

2.4 Weight Reduction in Vehicles

Vehicle stiffness and pedestrian safety is generally dealt separately, but in one study it is merged as a single problem of weight reduction by keeping into consideration the requirements set by USNCAP (United States New Car Assessment Program) and IIHS (Insurance Institute for Highway Safety). In this study researchers have focused on reducing the overall weight of the car’s front by considering individual components [3]. It should be noted that study is based on the low height sedan and results cannot be used for high vehicles such as SUVs. Focus is on the impact of collision with pedestrian’s tibia. Light objects will have a lighter impact compared to heavier and rigid objects. Crash test simulation was done at 40 km/h with a height of bumper equal to 25 mm from the ground. Designing light weight structures is a difficult task because of the complexity in simulations. Therefore, most of simulations are based on surrogates (metamodels). Metamodel is the model of a model which runs in place of actual simulation. It was concluded that mass reduction up to 40% is possible [3].

Moreover, on average, around 80,000 cars are registered every year. With today’s advanced computational tools, it is possible to cut down 8 kg of total weight of the car which can save up to 95 tons of steel and 842.6 barrels of fuel per annum without significantly affecting the crashworthiness. This will save up to RM0.58 million in total which can boost up the economy for good [7]. As now it is 2018, this saving can be increased more with more sales in vehicles per annum.

2.5 Front Collision with Lighting Columns

As the frontal collisions are most common, there is high number of collisions with street columns especially with the lighting poles. Currently, these lighting poles have a material yield strength of about 355 N/mm^2. [8].

It was evident by the test that the pole has absorbed very little energy and deformation is negligible. All the impact and energy are absorbed by the vehicle.

Then several simulations were carried out by using another material having following material properties. E = 2.5 GPa, p = 2500 kg/mm^3 and r_o = 100 MPa. By changing the pole thickness for every iteration, following quality results were obtained (as shown in fig. 3). It can be concluded that lesser pole thickness will give more desirable results which eventually lead us to better safety of the vehicle and its occupants [8].

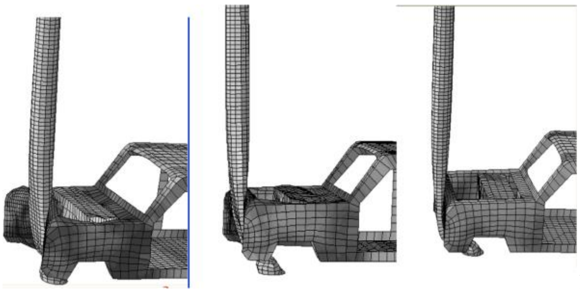

Figure 3. Front Collision Test with Variable Pole Thickness

Some obvious assumptions are taken such as the pole is fixed from bottom and free to move from top, has specific dimensions and vehicle has certain mass and is travelling with a certain velocity. This method has also another limitation which is changing the material of all the poles already installed on roads. Furthermore, it does not play any role in the collision of other pole like objects such as trees.

2.6 Pole Impact at Different Positions

One of the methods of study and optimizing frontal impacts is to study the damage at different spots of the car under same conditions. In this study three cases are considered using an FE model. Car crash with a rigid pole at frontal center, 25% left offset and 35% left offset with respect to the center line of the car. The model of the car, weighing 1370 kg, was validated through 2009 C-NCAP guideline. Whereas as the pole model was a rigid cylinder with 254 mm diameter. Initial impact velocity was set to 56 km/h and the computation time was 180 ms [9]. Results and conclusion were made by comparing the output values of three cases using following parameters. Observed results are summarized and shown in the table below:

Table 1. Car Crash Results from Different Offsets

Parameter	No offset	25% offset	35% offset
Acceleration (g)	50	36	44
Energy Absorption (kJ)	64.6	86.4	26.5
Intrusion at Front Side (mm)	620	727	805
Intrusion at Passenger Side (cm)	16.5	16.0	18.1

*Note that the intrusions in passenger compartment were analyzed in detail using each part, whereas in this table only the average is shown of those intrusions in longitudinal axis. Similarly, only positive peak acceleration value in X direction is shown in the table. [9].

As a conclusion of this study it can be said that 35% offset impact is the worst case in terms of intrusion in passenger compartment, then comes 25% offset impact and finally the center impact. Redesigning of critical components can increase the crashworthiness for this type of accidents. Limitations of this study are, (a) points of contact during crash which are assumed as general and, (b) impact of pole due to different structure and material. Crash at different points on car would result in different deformation and intrusions. Moreover, the actual pole or another rigid body will exhibit different outcome in real situation because of the difference in shape, dimensions and material properties. Simulations of the current study are shown in fig. 4.

Figure 4. Pole Impact Simulation on Car Crash from Different Offset

2.7 Optimization of Crash Box

In 2012, two researchers from China and Sweden proposed an idea based on RCAR (Research Council for Automobile Repairs) impact test. Their study was to optimize the crash box for low speed impacts. Many other researchers have also done some research on low velocity impacts; as mentioned by these authors. These authors developed an FE model based on America's top selling sedan, Ford Taurus. The model was validated by 100% FRB and 40% ODB impact tests. They intercepted longitudinal beam and added crash box before the bumper. It was found out that without crash box all the impact was absorbed by longitudinal beam, but after the addition of crash box it absorbed most of the energy. By doing this, repair cost decreased significantly and life of the beam also increased [10]. Table below shows the energy absorption by components with and without crash box:

Table 2. Energy Absorption by Components with and without Crash Box

Structures	Bumper Energy (J)	Crash Box Energy (J)	Beam Energy (J)
Original	3777	0	3513
Improved	3590	3730	340

It was concluded that proper design of the crash box i.e. its thickness can save the beam substantially. Not to forget the limitations of this study which are speed and range of values for the design. This design has a low range of values and the study does not contribute to the high-speed impacts. Fig. 5 shows the structure before and after addition of the crash box:

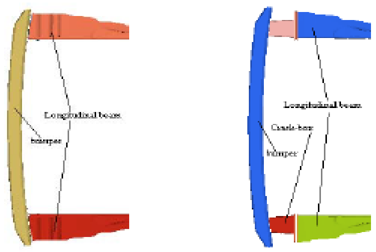

Figure 5. Beam Structure Before and After Addition of Crash Box

3. Manufacturing Issues and Limitations

There are mainly three elements used in automotive manufacturing. Namely, metals, ceramics and polymers. Mixture of any two or more makes a composite material. Composites are made to enhance the material properties which cannot be achieved by using the base material alone. They are better in static as well as impact loading and serve a lightweight component without affecting safety; but depending on the application. The use of composites provides various benefits including weight reduction and increased strength [11]. When the composite material is to be used for a certain part, it is necessary to redesign it. Just swapping the composite with currently used steel or other material is not enough. Proper selection of new material along with the manufacturing technology is to be specified. Performance, cost and production rate of the composite part will depend on the technology used; they are all linked with each other. In this study "Pultrusion" and "Die Forming" processes are opted for making a vehicle bumper which mainly consists of a beam and crash box for energy absorption during crash [12]. Pultrusion is an economical process for making constant cross-section composite structures whereas the Die Forming operation has the capability to build integrated crash box with the beam which is a considerable advantage. Joining process in composite materials is not as easy as in plain metals. This advantage in Die Forming operation removes the need for extra material and time which is required for joining process. Both processes have their pros and cons. At the end it is concluded that transverse beams can be made using composites rather than traditional steel in order to decrease the vehicle weight. It does not compromise on the structural safety of the car. The trend of increasing manufacturing qualities heads towards the development and application of various kinds of steel sheets with higher strength properties [13][14][15]

4. Conclusion and Recommendations

Vehicle crashworthiness has been a topic of discussion since long because it is directly linked with human safety which is the number one priority of any engineering product. In this paper various findings of previous researchers have been critically analyzed and it is found out that there is still a room for betterment. Proper design and material selection is recommended to further increase the vehicle stiffness to the correct degree. Moreover, optimization of crash box and overall weight reduction of the vehicle are also suggested. Whereas, the idea for replacing the material for lighting columns is not appreciated. FE models are capable enough to take part in further research as they gave close results to that of a real experiment.

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