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Energy Characteristics of Multi Structure Truck RUPD under Collision

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Abstract

The development of crashworthy and safe vehicles depends on energy characteristics of components participating in collision. This study is carried out for analysing the energy absorption characteristics of a car bumper and stationary Rear under run protection device (RUPD) on heavy vehicle in frontal crash scenario. The structural variation in the RUPD in terms of shape and thickness of are investigated for velocity, deceleration, internal energy and displacement. The comparison on these parameters is investigated for conventional straight bar, Curved bar with spacer and Curved bar with attenuator. The methodology used is finite element analysis through numerical simulation on LS-Dyna explicit solver. This method is widely used in automotive industries for dynamic non-linear simulations as an economic tool than a real life testing. The results show that the new suggested structures have remarkable change in impact properties and deceleration in velocity after the collision.

Keyword: Finite element analysis; LS-Dyna; Crashworthiness; RUPD; explicit; numerical simulation.

INTRODUCTION

Ability of a material or structure to absorb energy under a force or mechanical loading is called its Energy absorption capacity. It is important to evaluate the energy absorbing characteristics (EAC) of various materials and structures because of its use in many engineering applications. Its use is widely identified in automobiles where severe impacts cause serious damage to the vehicle and occupants [1]. The technique to find out the EAC involves evaluation of specific energy absorption, crash force efficiency, peak and mean force. While when the vehicle crash is to be evaluated, the characteristics like elemental increase in internal energy, strain, deceleration pattern of vehicle and displacement are considered. Furthermore, the vehicles are now being designed for shorter life and for better mileage. This reduces the material content of the vehicle and in turn lesser overall weight. This increases the chances of injuries and fatalities during the crash. Energy absorption techniques are predominantly used in automobiles, aerospace and blast industries [2].

This research focuses on energy analysis of a car bumper and a rear under run protection device (RUPD) mounted on rear of a heavy vehicle in a crash situation. The under ride crashes are the accidents in which the lighter and smaller vehicles under-rides the heavy vehicles (GVM < 3.5t) from front, side or rear. An under ride crash between heavy trucks and light vehicles can prove to be fatal for passengers of light vehicles owing to the differences in height between the truck front, side or rear, and front of the passenger car front. In addition, the resistance offered by the truck is very high and energy dissipation by deformation is low due to its inherent properties; however, it may be possible to minimize the consequences of these collisions by using correct passive safety devices, such as energy absorbing under ride guards. The aim of this work is to optimize the design of Rear under run protection device for heavy vehicles like trucks, trolleys, buses in totality with structure and material aspects of protective devices, so that when a lighter vehicle i.e. car, crashes with it, minimum energy is transferred to the occupant of lighter vehicle.

The occupant safety of a vehicle has become utmost features for a manufacturer. Many regulations are imposed to this effect and being followed by the manufacturers of vehicles. Simulation software and higher speed computing facilities, in the present days, have provided a cost effective tool for product design and testing even before manufacturing. The flexibility for designing in terms of material selection and geometry variations has increased for faster and optimized outputs. Computer aided design (CAD) and computer aided engineering (CAE) are increasingly used in automobile designs.

This paper studies the energy analysis of a car bumper and a rear under run protection device (RUPD) of a heavy vehicle in a crash situation. The under ride crashes are the accidents in which the lighter and smaller vehicles under-rides the heavy vehicles with gross vehicle mass less than 3.5 tons, from front, side or rear. A crash between heavy trucks and light vehicles can prove to be fatal for passengers of light vehicles because of the difference in height between the truck at all four sides and the car. Moreover, the resistance offered by the truck is very high and energy dissipation by deformation is low due to its inherent properties; however, it may be possible to minimize the consequences of these collisions by using correct passive safety devices, such as energy absorbing under ride protection system. The aim of this work is to optimize the structural design of rear under run protection device for heavy vehicles like trucks, trolleys, buses in totality, so that when a lighter vehicle i.e. car, crashes with it, minimum energy is transferred to the passengers of lighter vehicle.

The analysis on RUPD structure is attempted by many authors. Various types of shapes like circular tubes, square tubes, frustum, struts, honeycombs, and sandwich plates generally used for different industrial, structural or automobile applications are analysed for reaction force and energy absorption [3-6]. Researchers have also attempted to modify the structures by adding imperfections like notches, grooves and slots on pipe structures to help improve energy absorption during axial impact loading [7-9]. The computer simulation using finite element analysis (FEM) and LS-Dyna code has made all these complicated studies feasible and their results indicates a good agreement between numerical analysis and experimental studies.[6,9,10,11] The analysis on direct RUPD structure is also attempted by many authors. Kaustubh Joshi et al. (2012) [12] has analysed the straight bar with circular cross section through explicit FE code LS-Dyna and verified the results in compliance to IS 14812:2005 [13]. Sumit Sharma et al. (2015) also analysed straight bar RUPD using Hypermesh and Radioss using strain mapping method to optimize the design [14].

METHODOLOGY

The method of simulation is adopted for conducting different analysis for design of RUPD. This has substantially reduced the processing time and cost involved in the product development. The validity of simulation methods is established by Yoshito Itoh et al. [15] in their paper, describing dynamic simulation of heavy trucks and a rigid concrete barrier. The entire work was modeled by Finite element methods and simulation was carried out on LS-Dyna for the collision. The on-site full scale experiment of the same conditions of collision was also conducted. The comparison of results indicated a close match with simulation, thus approving computer simulation as an economic tool for the safe designs of vehicles. Tan et al. [16] uses finite element analysis (FEM) as powerful analytical tool for development of high fidelity FE model of motorcycle telescopic front fork. The components were designed and analyzed in LS-Dyna environment. The simulation agreed closely to the physical testing with closely matching the reaction forces and deviation of 1.4% based on work done to deform the fork. Mantaras D. A. et al. [17] uses LS-Dyna explicit Lagrangian numerical model to simulate crash performance of road side motorcyclist protective devices. The virtual test validates and adjusted to the results of experimental program that ensures validity and accuracy of virtual simulation. Yehia A. Abdel-Nasser [18] simulates the crashing of heavy vehicle with lighting column and suggested new material for column for higher energy absorption of impact. These research works of simulation have motivated to take up car crash problems for enhancing crashworthiness.

Figure 1 shows three structure designs of RUPD in consideration, i.e. (i) Straight bar (ii) Curved bar and spacer (iii) Curved bar with attenuator assembly.

The assembly consists of 100 sq. mm. x 3 mm thickness square section bar and box section of vertical member with 8 mm thickness. The bar thicknesses were also changed to 3.5 mm and 4.5 mm. so that the effect of thickness can also be evaluated. The two components are connected by welding to each other and the vertical member is welded to the Chassis. Figure 1 indicates RUPD design with Curved bar connected to vertical member through a spacer box and through an attenuator. All the three components are assembled through welding. This assembly is also welded to the truck chassis. Table 1 defines the research problem goal for input variables and proposed outcome.

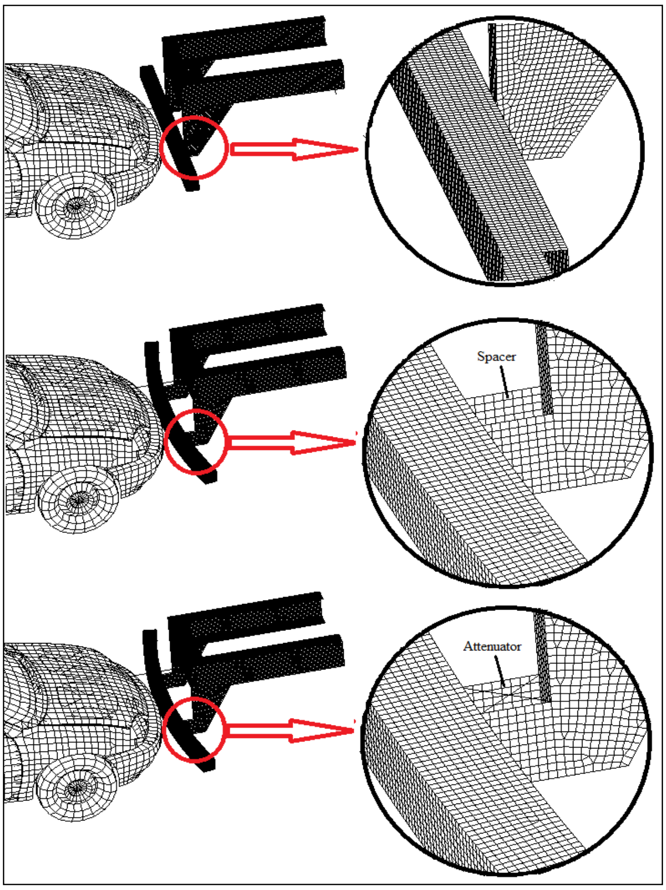

Figure 1: Assembly Setup for (i) Straight Bar, (ii) Curved bar with Spacer and (iii) Curved Bar with Attenuator RUPD

Table 1: Problem goal

Input Variables		*Proposed outcome*
One Vehicle / Striking speed		Vehicle Global Energy
One Crashing position	→	Vehicle acceleration
Two RUPD Design		Internal Energy absorption in design components
Three RUPD thickness		RUPD displacement

Explicit Time Stepping Method (ETSM)

Explicit method is used to analyze and obtain numerical approximations of time-dependent ordinary and partial differential equations. Explicit methods take less computing time and space on the disk. Explicit methods are used to calculate the state of a system at a later time from the state of the system at the current time. If $Y(t)$ is the current system state and $Y(t+\Delta t)$ is the state at the later time (Δt is a small time step), then, for an explicit method:

$$Y(t + \Delta(t)) = F[Y(\Delta t)]$$

Finite Element Modeling of Car and RUPD

The Car model used in this work is taken from Grab-CAD website [19]. The material of different parts and contacts are well defined in model. Although the car models have many parts, the car model used here is reduced to 206 parts. These parts are defined 186 shells, 8 discrete and 3 beam components. The RUPD components are designed on CAD and they are defined as shell components.

The Straight bar RUPD carries two components: Straight bar and Vertical member, while the Curved bar RUPD structure assembly has three components viz. Curved bar, Vertical member and spacer. The assembly components are not having any intricate features; the meshing is done with automatic mesh generation option on Altair Hyperworks. It has provided a reasonable coverage of surface area representing entire component geometry. All of these components are having very less thicknesses as compared to their surface area; hence their section in LS-Dyna is modeled as SECTION_SHELL [20]. The thickness of RUPD bar and spacer is 3.0 mm. which is taken out from the survey conducted on various RUPD being used on heavy vehicles. However, analysis is also done with 3.5 and 4.5 mm thickness of bar and spacer. The Vertical member is a heavy section with 8 mm. thickness.

The material card for the RUPD components is defined under MAT_PIECEWISE_LINEAR_ PLASTICITY card. The table 2 describes the material of all the three parts. The true strain-stress curve all the materials used is entered and assigned to respective materials.

The car crashes with a RUPD connected to a stationary heavy vehicle in the centre. The end of the cut section of Chassis is considered as Single point constraint (SPC). The SPC created using the nodes at the end of the chassis section. All the loads and boundary conditions that occur in the actual crash event are modelled to simulate a full vehicle car crash. The gravitational loads and friction between the tires & road surface are also accounted for in the simulation.

The deceleration is considered as 0.5g for dry tar road. The car is modeled and placed before the RUPD structures. The initial speed of the car is taken 80 kmph (highway limit) [21] which reduce to 36.26 kmph at the time of strike with a striking distance of 40 meters. The car strikes at the centre of RUPD simulates for the Point P_3 as shown in figure 3. The speed is defined at INITIAL_VELOCITY card of LS-Dyna. CONTACT_AUTOMATIC_SINGLE_SURFACE card on LS-Dyna is selected for contact definition and to establish the interface between various parts of car and RUPD participating in simulation. The termination time is considered as 0.2 sec. The LS-Dyna keywords were referred from LS-DYNA Keyword User Manual [20]. After pre-processing, LS-Dyna solver is run to simulate the crashing of car against the set parameters of RUPD.

As shown in Table 3, nine simulations are carried out each having 4 outputs in the form of Global energies, Car acceleration, RUPD Internal energy and Displacement of RUPD. The simulations are carried out with three types of structures of RUPD and RUPD bar varying in three thickness values. The striking speed will be kept constant with 36.26 m/s and constant termination time of 200 ms for all the nine sets of simulations.

SIMULATION RESULTS AND DISCUSSIONS

The simulation results were found out for three parameters which are useful in further discussion and conclusion for selection of the suitable design. The correctness of numerical analysis is evaluated by balancing the energies before and after the crash. The kinetic energy of moving car gets transformed into friction and internal energies of various components of RUPD and car participating in crash. Figure 2, 3 and 4 shows the simulation of three RUPD structures in consideration.

Table 2: Properties of component Material

Sr. No.	Structure	RUPD Thickness (mm)	Mass density	Poison's ratio	Young's modulus
1 2 3	Straight, Curved with spacer and Curved with attenuator RUPD (100x100 Sq. mm.)	3 3.5 4.5	7.89E-009	0.3	2.1E+005

Table 3: Design of Simulation experiment

Sr. No.	Structure	RUPD Thickness (mm)	Speed	Crashing position
1	Straight RUPD bar (100x100 Sq. mm.)	3	Initial speed = 80 kmph Striking speed = 36.26 m/s	Point P_3 (Refer Figure 4)
2		3.5		
3		4.5		
4	Curved RUPD bar (100x100 Sq. mm.)	3		
5		3.5		
6		4.5		
7	Curved RUPD bar with attenuator (100x100 Sq. mm.)	3		
8		3.5		
9		4.5		

Design of Simulation Experiment

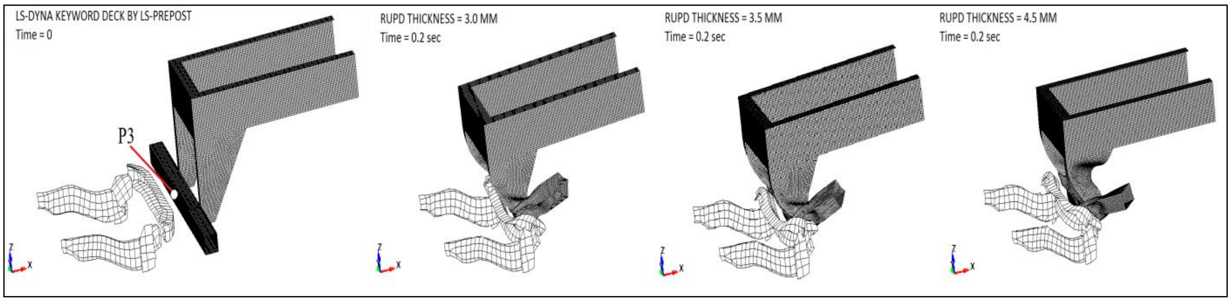

Figure 2: Crash simulation for Straight bar RUPD with thickness 3.0 mm, 3.5 mm and 4.5 mm

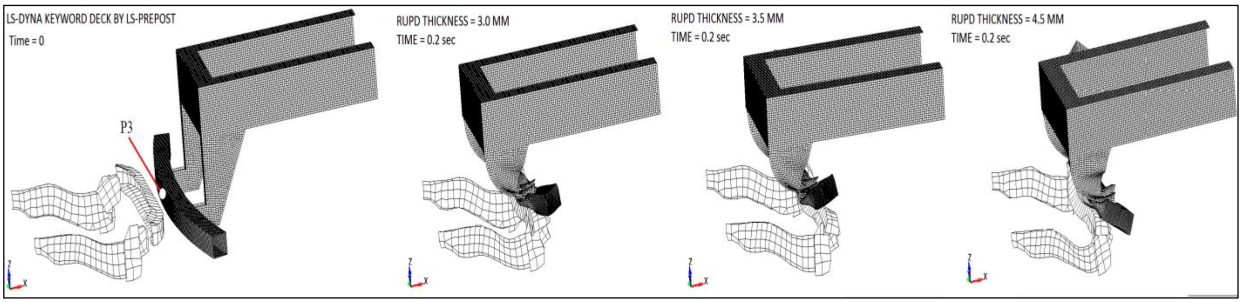

Figure 3: Crash simulation for Curved bar with spacer RUPD with thickness 3.0 mm, 3.5 mm and 4.5 mm

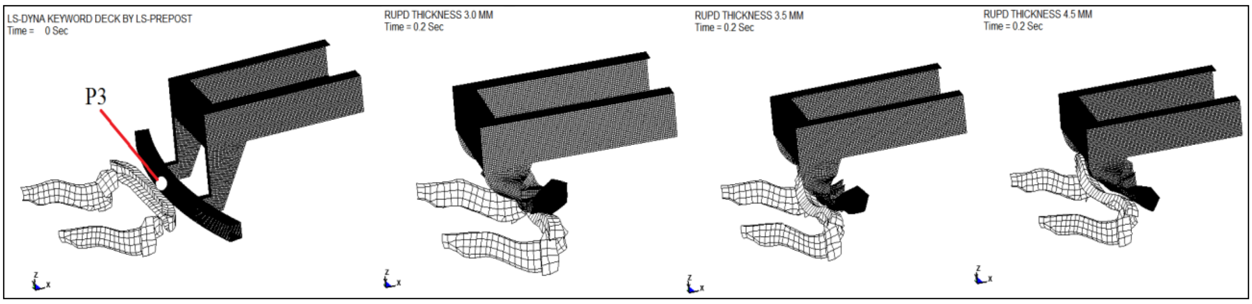

Figure 4: Crash simulation for Curved bar with attenuator RUPD with thickness 3.0 mm, 3.5 mm and 4.5 mm

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Vehicle velocity and acceleration after crash

The acceleration of the car is an important consideration to be analyzed because it has direct effect on the occupants of the car. After crash, the stopping distance is very small, and hence a large force is generated at barrier. This force is `g-force' (g for gravitation) used to measure the type of acceleration which causes weight. According to FMVSS 223 [22], in the barrier test of rear under run device, the vehicle acceleration should not increase more than 30g.

The velocity and acceleration curves in Figure 5(i), 5(ii) and 5(iii) compare the three cases for all the RUPD structure bars with 3.0 mm, 3.5 mm and 4.5 mm thickness. The car striking straight bar RUPD bear more impact causing it to stop at 0.1 seconds after crash. The car takes longer time (0.15 sec) to stop in case of Curved bar with both spacer and attenuator because of sequential deformation of curved bar, spacer / attenuator and vertical member.

The deceleration is very rapid in case of Straight bar RUPD, wherein it reaches to maximum value in a very short time of 0.05 sec. It gradually reduces till the vehicle comes to rest. This indicates the severity of impact and its effect on occupants. The deceleration pattern, in case of Curved bar with spacer and Curved bar with attenuator, is gradual and it differs for different bar thicknesses. The deceleration is in two stages for 3.0 and 3.5 mm Curved bar with spacer. Initially, for 0.05 seconds, the car retards to approximately 6g, slows down for a while and then reaches to its maximum value at 0.1 second. For 4.5 mm thickness, deceleration is continuous till it gains maximum value. This indicates that the 4.5 mm thick bar offers more resistance and behaves linearly deceleration without break. In case of Curved bar with attenuator, the staged deceleration is for 3.0 mm thick bar only. For other two thicknesses, it is linear and single stage to reach to maximum value.

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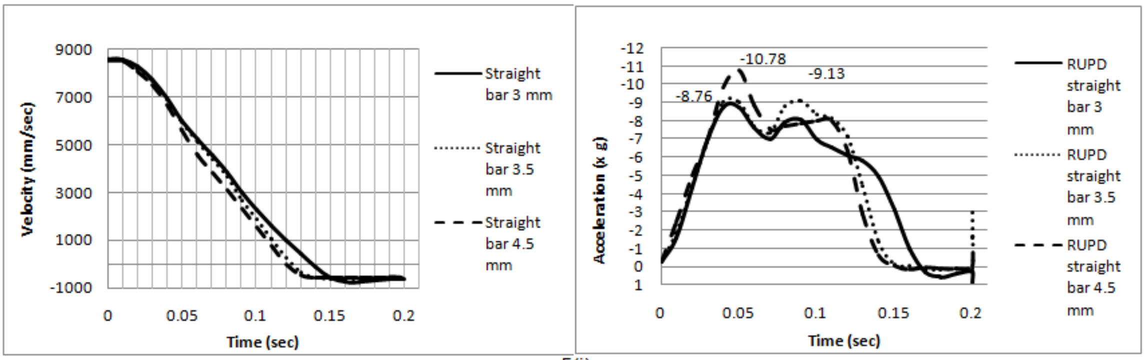
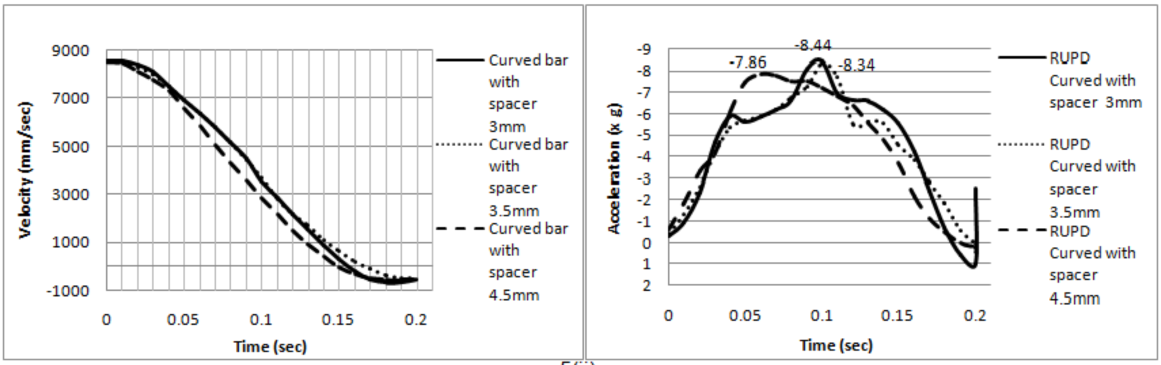


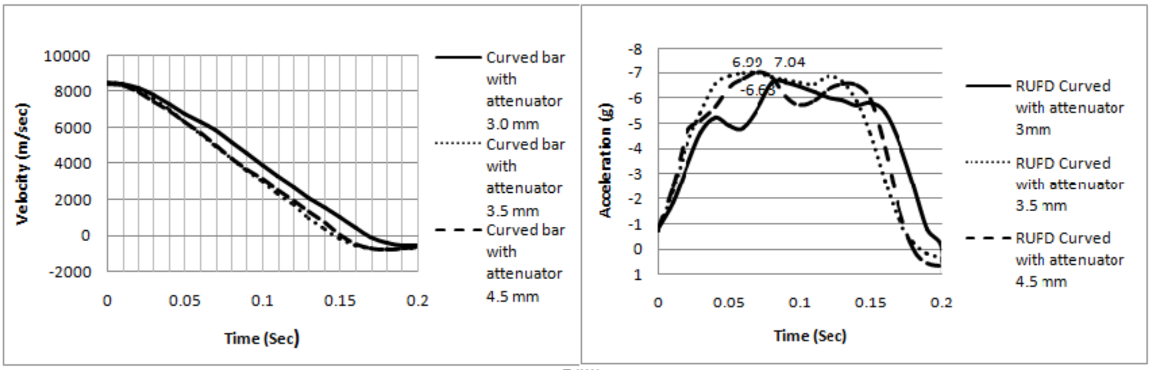
5(i)

Figure 5(i): Velocity and Acceleration Plots for Straight Bar for Different Thicknesses



5(ii)

Figure 5(ii): Velocity and Acceleration Plots Curved Bar with Spacer for Different Thicknesses



5(iii)

Figure 5(iii): Velocity and Acceleration Plots for Curved Bar with Attenuator for Different Thicknesses

Internal Energy of bumper and RUPD after crash

It is important to evaluate the energy absorption by car bumper and the RUPD. After the crash, the kinetic energy of car gets converted raising the internal energies of major components in role. The car has a provision of bumper specially designed for absorbing the impact energy. The RUPD also absorbs some energy due to crash impact. It is important to analyze the distribution of absorption energy among bumper and RUPD. If more energy is absorbed by RUPD, less amount of energy is diverted towards the occupants. The relative distribution of energy absorption by different RUPD structures is shown in figure 6(i – iii).

Figure 6(i) shows the energy absorption in case of Straight bar RUPD for 3.0, 3.5 and 4.5 mm thicknesses. It is observed that the difference in Internal energy absorption by bumper and RUPD is increasing with increase in bar thickness. Also the difference is very small amount.

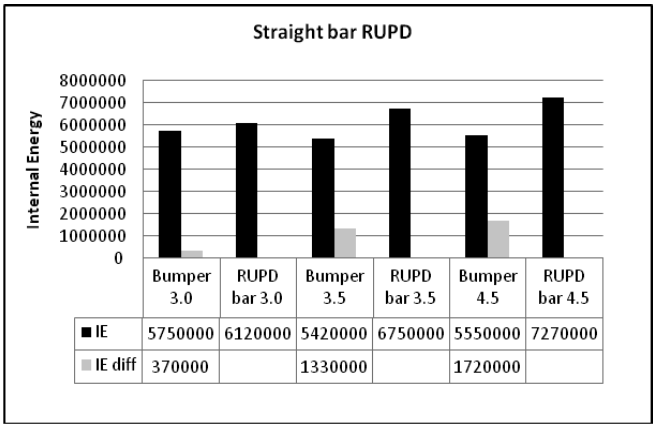


Figure 6 (i): Internal Energy Plots for Straight Bar for Different Thicknesses

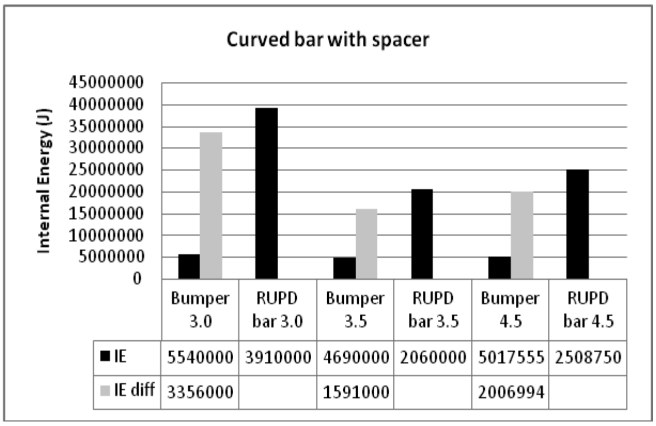


Figure 6 (ii): Internal Energy Plots for Curved Bar with spacer for Different Thicknesses

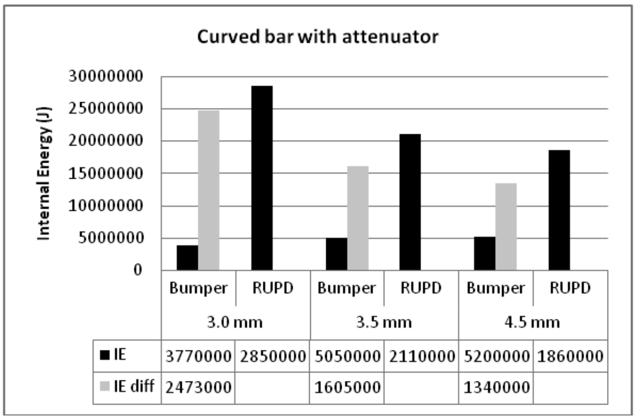


Figure 6 (iii): Internal Energy plots for Curved bar with attenuator for different thicknesses

However, the energy absorption by both bumper and RUPD are substantial. Therefore, the occupants are not safe with straight bar RUPD.

Figure 6(ii) indicates large improvement in energy absorption pattern for both car bumper and Curved bar and spacer RUPD. Here the internal energy difference is substantial for all the three thickness cases with maximum for 3.0 mm thick bar and minimum in 3.5 mm thick bar. The energy absorbed by Curved bar and spacer is more for all the three thicknesses than that of car bumper. And less amount of energy is diverted towards the car. Therefore, the effect of crash impact will be very less on the car occupants.

Figure 6(iii) depicts the energy absorption for RUPD with Curved bar and attenuator. In this case, also the improvement in absorption pattern is observed as compared to Straight bar RUPD. However, the difference in internal energy absorbed by car bumper and RUPD is lesser than RUPD with Curved bar and spacer. This is true for all the thickness combinations of RUPD bar.

It can be deduced from above simulation plots that in case of Straight bar RUPD, the increase in internal energy gradually increases with bar thickness. The increase in bar thickness increases the structure rigidity to absorb more. But after total crushing of bar, the Vertical member attached to it starts deforming and thereby absorbing the rest of the energy. So the cumulative effect indicates increase in internal energy with thickness. This is the case of greater deformation both in case of car bumper and RUPD.

In the cases of Curved bar with spacer and Curved bar with attenuator, the energy absorption is more in RUPD than the car bumper for all the three thickness of bar. Here the energy absorption is taking place in four stages. First, the energy absorbed in straightening of curved bar; second, energy taken for deforming the bar; third, energy absorbed for crushing the spacer and lastly, energy absorbed by vertical member. The energy absorbed by vertical member is very small, as most of the energy is absorbed in first three stages. This also prevents the vertical member to damage. A very less energy is diverted towards occupant, making a safer situation for occupants.

Displacement of RUPD after crash

The displacement of RUPD indicates the distance of under run of the car. The IS 14812:2005 code limits this to 400 mm as safe distance. Figure 7 and 6 show the relative displacement of Straight bar, Curved bar with spacer and Curved bar with attenuator RUPD for the three thicknesses 3.0, 3.5 and 4.5 mm. It is evident that for 3.0 mm thickness, the deformation curve reaches to maximum of 323 mm at 0.1 sec. The distance for 3.5 and 4.5 mm bar thickness is 309 and 286 mm respectively, which indicates more resistance offered by bar due to increase in thickness.

In the case of Curved bar with spacer structure, the deformation for 3.0 and 3.5 mm configuration is nearly same i.e. 396 and 399 mm. For 4.5 mm bar, it reaches to 366 mm. The increase in deformation as compared to straight bar RUPD, is due to curvature of bar and spacer of 100 mm. The deformation in vertical member is very less.

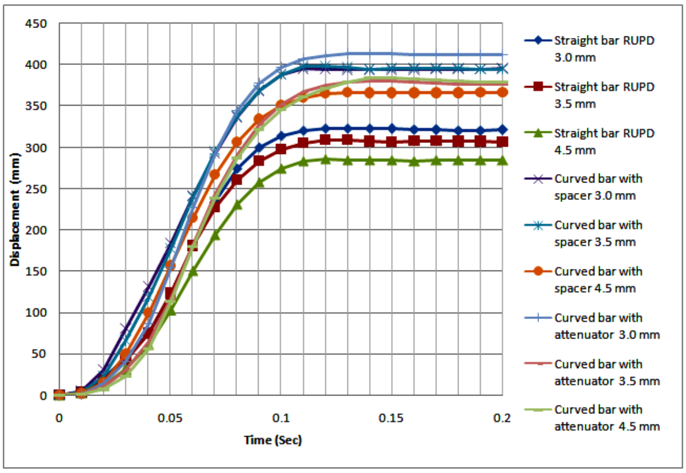


Figure 7: Displacement Curves for (i) Straight Bar, (ii) Curved Bar with Spacer and (iii) Curved Bar with Attenuator for Different Thicknesses

Similarly, the deformation in case of Curved bar with attenuator is observed as 413, 380 and 384 mm for 3.0, 3.5 and 4.5 mm thickness of RUPD bar respectively. The deformation is exceeding the IS code limit of 400 mm for 3.0 mm thickness case, while the deformation is nearly same for 3.5 and 4.5 mm

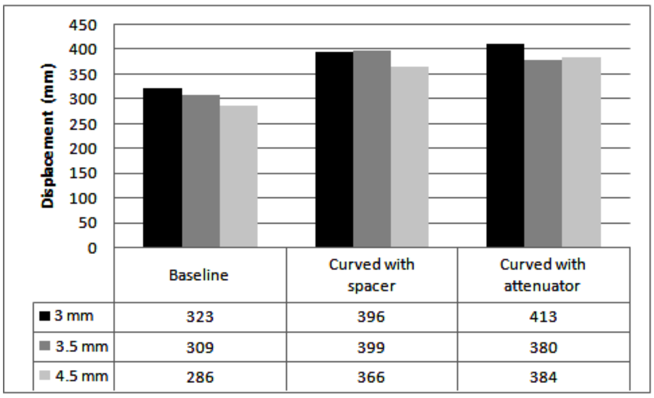


Figure 8: Comparative Displacement for (i) Straight Bar, (ii) Curved Bar with Spacer and (iii) Curved Bar with Attenuator for Different Thicknesses

CONCLUSION

The following conclusions are drawn from above crash simulation that the Curved rear under run protection device (RUPD) with 3.0 mm thickness offers better design because of:

1. The deceleration is two staged and maximum value reaches to 8.44g after the crash is which well within the acceptable limits. Hence the occupants will be in safe limits of force which will be exerted during sudden deceleration after crash.
2. Although the staged deceleration is also observed for 3.5 mm Curved bar and spacer and 3.0 mm Curved bar with attenuator, the maximum displacement of RUPD bar

observed is least in case of 3.0 mm Curved RUPD with spacer (396 mm) which is within the deformation limit requirements of IS 14812:2005.

3. The kinetic energy of the car after its crash impact is majorly absorbed by 3.0 mm Curved bar and spacer RUPD structure (increasing Internal energy) and very little amount of energy are diverted towards car for its bumper to absorb. Therefore, this RUPD structure will offer better safety during a crash scenario.

The virtual simulation can be used to eliminate physical testing of mechanical systems thereby reducing the time and cost of development.

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