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Investigation on Energy Absorption Characteristics of a Car Bumper and Truck RUPD under Crash Impact

Tapan Jain[#1], Neeraj Kumar[#2]
[#1]Mechanical Engineering Department, Acropolis Institute of Technology & Research, Indore, India
[#2]Mechanical Engineering Department, Suresh Gyan Vihar University, Jaipur, India
[#1]tapanjain@acropolis.in
[#2]neeraj1mech@gmail.com

Abstract—**The understanding of energy absorption characteristics of bumper and rear under run protection device (RUPD) is necessary for the development of safe and crashworthy vehicles. The purpose of this research is to study the energy absorption performance of car bumper and rear under run protection device during a collision. Variations in the shape of structure of protection device and its thickness is considered for investigating how these factors affect the energy absorption characteristics of two contacting bodies. The design of under run protection device can be evaluated using finite element methods at the design stage. Comparison were conducted for three types of structure designs of bar of rear under run protection device. The impact energy of the crashing car was investigated for its conversion and distribution among the direct contacting bodies during the period of collision. The relative change in energy absorption characteristics, change in vehicle velocity & deceleration and under run displacement were investigated numerically through simulation on LS-Dyna explicit solver. The results of the research shows that the change in structural design of bar can help in reducing the impact energy transfer towards the car bumper and lowering the injury level of the occupants of under running vehicles. The results were compared to satisfy the regulations stated in IS14812:2005 for design of protection device.**

Keyword - Rear under run protection device (RUPD), IS14812:2005, explicit, finite element analysis, LS-Dyna

I. INTRODUCTION

A lot of challenges are being faced by designers while designing for dynamic stability of a structure subjected to impact loads. It has become significant for a designer to optimize the material and geometry of the structure especially in automobiles, for reduced weights and enhanced functionality under crash situations. Moreover, many safety regulations are been imposed by governments on automobile manufacturers. Also the occupant of a vehicle looks for utmost safety features before purchase. 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 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 severity of impact will still depend on the barrier or the body to which the collision takes place. Federal Motor Vehicle Safety Standards (FMVSS) 233 [1] for rear impact guards, implemented in early 1930's, provides for structural integrity of under run device by regulating the cross section of vertical height of guard, its strength and energy absorption. The standard also directs for testing of under run device for its deformation under specified impact forces on the predefined locations. Similar regulations were implemented by European standards as EC Directives 2000/40/EC in August 2003 and East African Standards (CD/K/005:2008) [2]. Since this work is conducted in Indian scenario, the regulation used is Indian Standard, IS 14812:2005 [3]. This standard provides for structural and dimensional design of under run device along with the testing procedures and requirements of a suitable device.

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 [4-7]. 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 [8-10]. 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.[7,11,10,12] The analysis on direct RUPD structure is also attempted by many authors. Kaustubh Joshi et al. (2012) has analyzed 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 analyzed straight bar RUPD using Hypermesh and Radioss using strain mapping method to optimize the design [14].

II. METHODOLOGY

The design analysis of RUPD with Straight bar, Curved bar with spacer and Curved bar with attenuator is carried out using numerical simulation. The RUPD assembly (Figure 1) consists of a bar, spacer and vertical member box section. This vertical member is bolted to Chassis of the truck. This box section is welded to the rounded bar with a spacer. The spacer is welded with the box section and the RUPD bar.

A. Finite Element Modelling of RUPD

The parts of RUPD are meshed with automatic mesh generation on Hypermesh. The surfaces are large as compared to the thickness and therefore they are meshed with shell elements and assigned with "SECTION_SHELL". The thickness of 3.0 mm, 3.5 mm and 4.5 mm is assigned to different structures with straight bar, curved bar and spacer, and Curved bar with attenuator. The Vertical box section is built with 8.0 mm thickness. The shell elements are used with the minimum thickness value among the components to represent welded joints. The components are welded together in all the cases. This assembly is the bolted to the chassis member. The figure 1 shows the meshed model of three different RUPD setup.

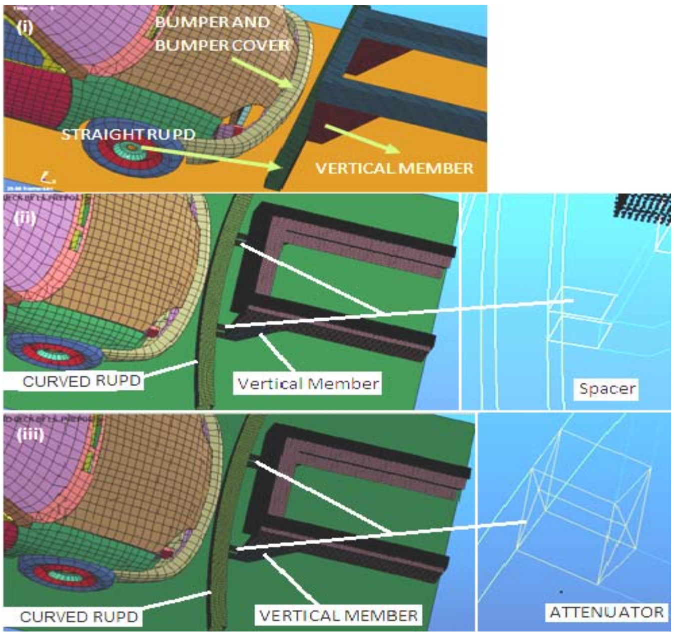


Figure 1: Assembly Setup for (i) Straight Bar, (ii) Curved bar with Spacer and (iii) Curved Bar with Attenuator RUPD for Different Thicknesses

B. Finite Element of Car

The Car model used in this work is taken from GrabCAD. GrabCAD produce variety of Car models freely available for the purpose of analysis. 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 material properties for all the car components are predefined.

The material card for the RUPD components is defined under MAT_PIECEWISE_LINEAR_PLASTICITY card. The material properties defined for the setup are given in table 1. The true strain-stress curve all the materials used is entered and assigned to respective materials. The interface between the RUPD bar and the Car is defined using CONTACT_AUTOMATIC_SINGLE_SURFACE card to establish contact between parts during simulation through LS-Dyna solver. The TERMINATION card defines the termination time of simulation and is kept as 0.2 sec. The LS-Dyna keywords were referred from LS-DYNA Keyword User Manual [15].

TABLE I. Properties of Materials in Setup

Part name	Mass Density	Poison's ratio	Young Modulus
Bar	7.89E-009	0.3	2.1E+005
Spacer / Attenuator			
Vertical box			

C. Loading and Boundary conditions

The loading and boundary conditions are those which are set on the numerical model to simulate the actual physical conditions. These conditions applied in accordance to IS 14812:2005 are described section 2.3.1 and 2.3.2.

1) Boundary conditions: The nodes at end of the chassis cut section are constrained in all the directions to make it fixed. This simulates the heavy truck in stationary condition in lead vehicle stationary (LVS) type of crash. The end of the cut section of Chassis is considered as Single point constraint (SPC). The SPC is created using the nodes at the end of the chassis section (Figure 2). The chassis is also a critical component and may be difficult to change in case of deformation due to crash.

2) Loading condition: Figure 2 depicts a typical loading and boundary conditions during a crash scenario. The car is simulated to strike the stationary truck from rear on rear under run protection device (RUPD) The initial speed of the car is taken 80 kmph (highway limit) [16] which reduce to 36.26 kmph at the time of strike with a striking distance of 40 meters. The car strikes at the center of RUPD simulates for the Point P_3 according to the crashing points mentioned in IS 14812:2005.

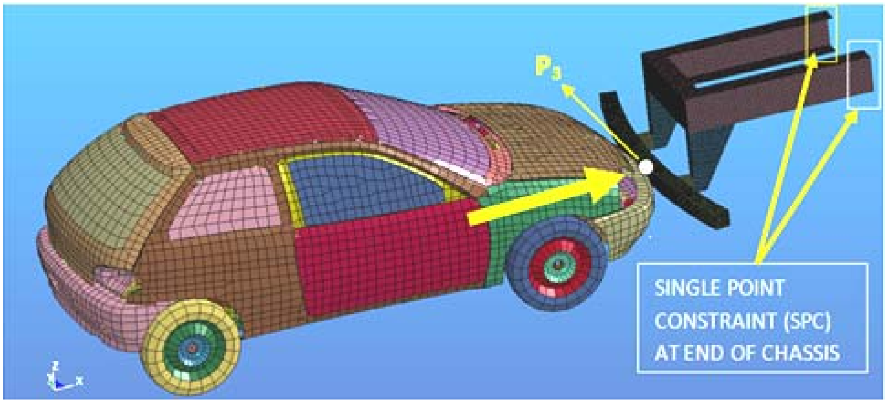


Figure 2: Boundary and Loading Conditions in Crashing Scenario

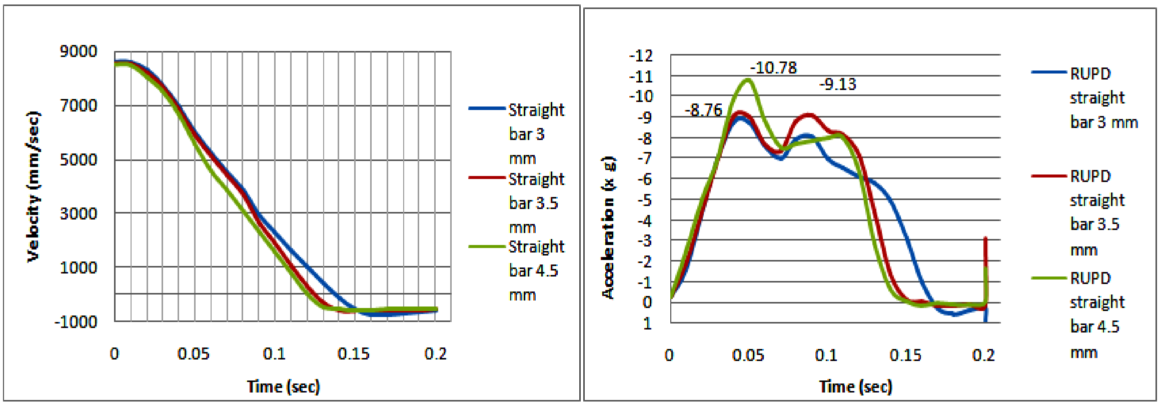
III. SIMULATION RESULTS AND DISCUSSION

The simulation was conducted to find velocity and deceleration of car after crash, Internal energies of car bumper and RUPD and deformation. These three parameters are useful in further discussion and conclusion for suitability of structure 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.

IV. SIMULATION RESULTS AND DISCUSSION

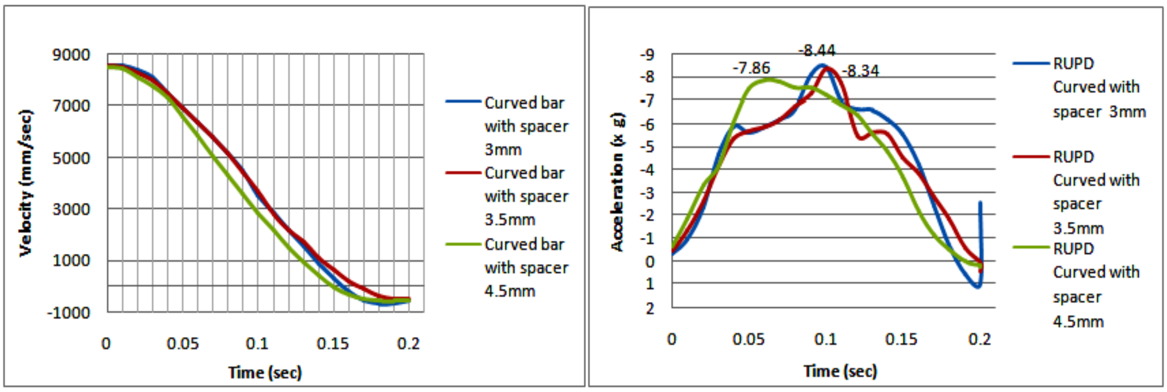
A. Vehicle velocity and acceleration after crash

The acceleration of the car is an important consideration to be analysed 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 [1], in the barrier test of rear under run device, the vehicle acceleration should not increase more than 30g.



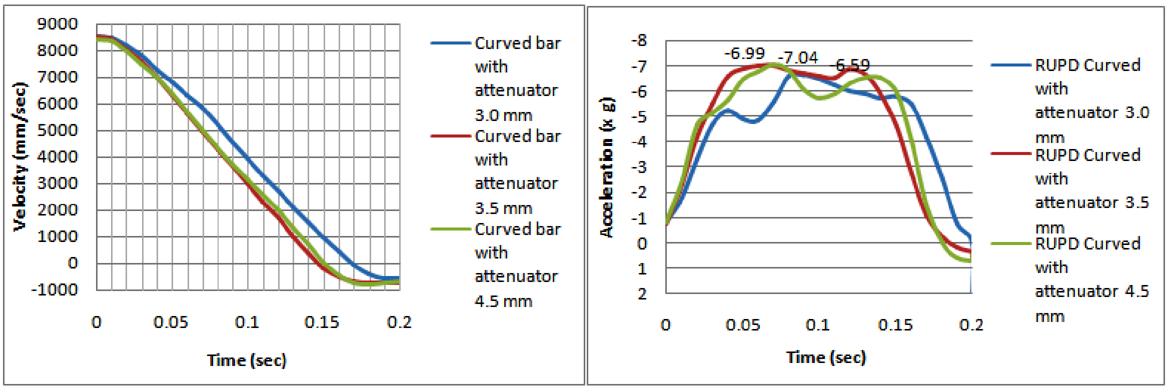
3(i)

Figure 3(i): Velocity and Acceleration Plots for Straight Bar for Different Thicknesses



3(ii)

Figure 3(ii): Velocity and Acceleration Plots Curved Bar with Spacer for Different Thicknesses



3(iii)

Figure 3(iii): Velocity and Acceleration Plots for Curved Bar with Attenuator for Different Thicknesses

The velocity and acceleration curves in Figure 3(i), 3(ii) and 3(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.

B. 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 analyse 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 4(i – iii).

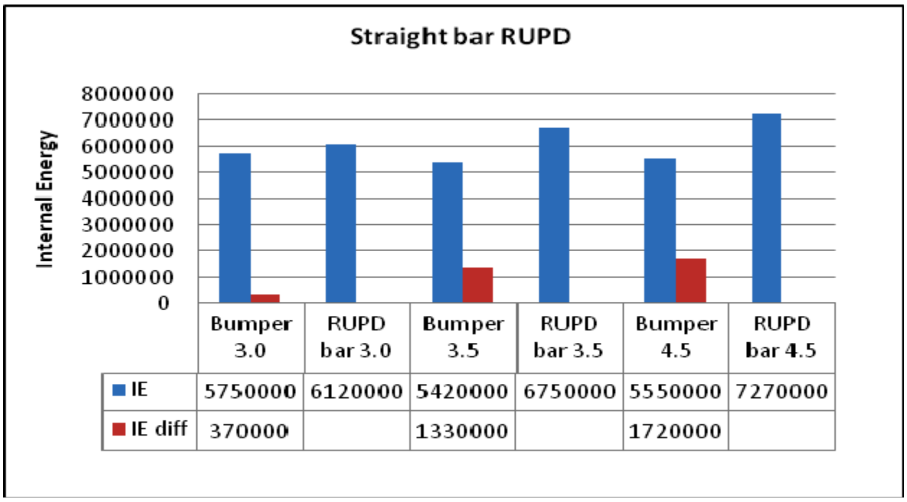


Figure 4 (i): Internal Energy Plots for Straight Bar for Different Thicknesses

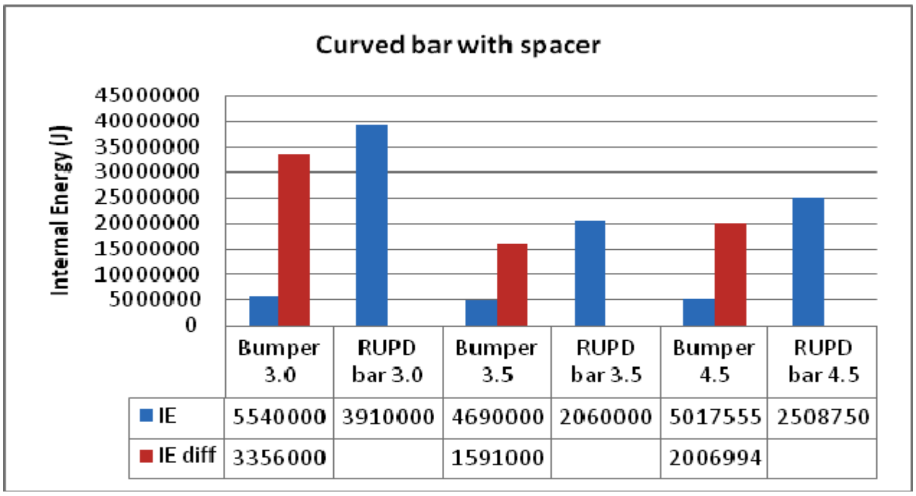


Figure 4 (ii): Internal Energy Plots for Curved Bar with Spacer for Different Thicknesses

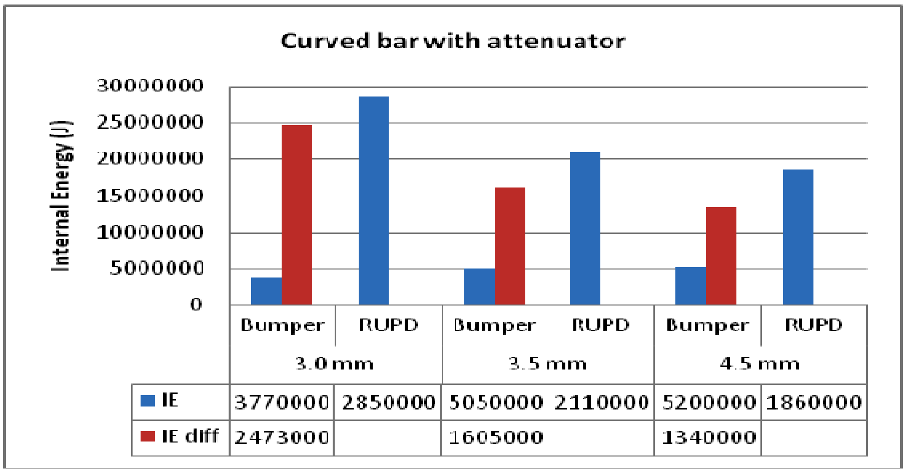


Figure 4 (iii): Internal Energy plots for Curved bar with attenuator for different thicknesses

Figure 4(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. However, the energy absorption by both bumper and RUPD are substantial. Therefore, the occupants are not safe with straight bar RUPD.

Figure 4(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 4 (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.

C. 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 5 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. 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.

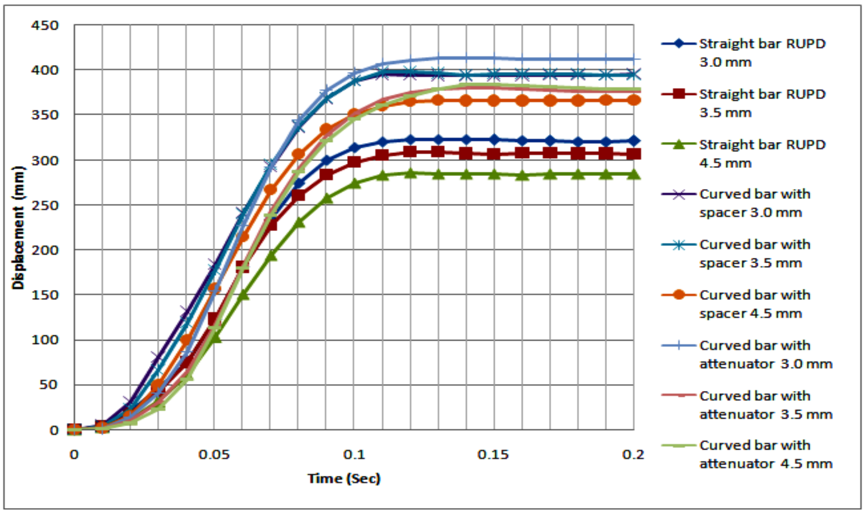


Figure 5: Displacement Curves for (i) Straight Bar, (ii) Curved Bar with Spacer and (iii) Curved Bar with Attenuator for Different Thicknesses

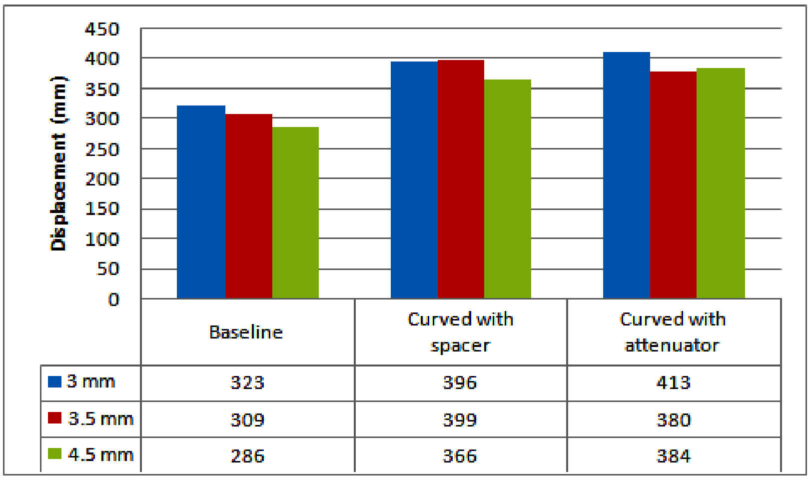


Figure 6: Comparative Displacement for (i) Straight Bar, (ii) Curved Bar with Spacer and (iii) Curved Bar with Attenuator for Different Thicknesses

V. 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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AUTHOR PROFILE

Tapan Jain, is Associate Professor at Acropolis Institute of Technology & Research, Manglia square, Indore-Dewas Bypass, Indore - 453771, MP (India). He did his Masters program from New Jersey Institute of Technology, Newark, NJ, USA in Manufacturing Systems Engineering. He is having 25 years experience in both Industry and Academics. Prof. Tapan Jain has published/ presented 8 papers in National journals/ conferences. He has been faculty adviser for SUPRA and BAJA SAEINDIA events for last 4 years. He has guided many UG projects and Four PG dissertations. He is also involved in training and operational consultancies to industry & training institutes. He has to his credit many installations of Coordinate Measuring Machines in various major engineering industries.
Areas of Work –Static & Dynamic Analysis (ANSYS, LS-Dyna), Automobile Engineering, CAD/CAM/CAE, Manufacturing Automation, and Industrial Engineering.

Neeraj Kumar, is Professor and Head in Mechanical Engineering Department of Suresh Gyan Vihar University, Jaipur, (Rajasthan), India. He specialization is Manufacturing Systems Engineering. He is having 20 research paper to his credit in International, National and Conferences.