Smart frictional impact energy absorber

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Abstract - This paper presents an innovative device for use as an impact energy absorber. The absorber consists of a central solid core surrounded by a cell containing circular solid rods. The entire assembly is enclosed inside a circular cylinder. Radial forces between the core and the rods surrounding it are controlled by means of setscrews and nuts fixed on the cylinder. Energy is dissipated by friction forces generated at the contact surfaces when the central core is displaced axially in either direction. Smartness of this absorber is achieved by making the rate of the absorber variable depending on the input kinetic energy of the vehicle.

Quasi-static experimental investigations were carried out and the results clearly illustrate the effect of the number of rods in contact and the applied radial forces on the absorbed energy, and also demonstrate the controllability of the absorption rate.

NOTATION

d	bolt diameter
e	area under load-displacement curve
E	kinetic energy
F	axial force
F_{av}	average axial force
F_f	frictional force
F_p	plowing force
F_s	static force
n	number of rods in contact
m	mass of the automobile
R	radial force
T	applied torque
v_i	instantaneous speed of the vehicle
μ	dynamic coefficient of friction

INTRODUCTION

With the increase in speed of transportation systems, researchers are looking for ways of minimizing serious injuries and damage to passengers and vehicles respectively. In such cases, shock absorbers are employed based on converting the kinetic energy into pressure energy in compressible fluids, elastic strain energy in solids, recoverable deformation in shape memory structures and permanent plastic deformation in metallic absorbers. These mechanisms of absorption have been investigated in areas of automotive engineering and impact crashworthiness. For example, plastic deformation of metallic structures has been used as impact energy absorbers for decades. The kinetic energy of the impact is dissipated in the absorber in an irreversible process through a sequence of plastic deformation work. There have been so many suggested mechanisms of plastic deformation in the literature. Some of the well-known modes of deformations include, axially compressed metallic tubes [1], tearing energy in splitting of square and round tubes [2], lateral loading of braced cylinder shells [3], axial compression of polyurethane foam-filled tubes [4], axial crushing of sand-filled tubes [5], axial crushing of wood-filled tubes [6] and inversion of metallic frusta [7].

In these mechanisms of plastic deformation, the energy absorbed is made in an irreversible manner, mostly in a single direction, and the structure is deformed plastically thus the absorber can be used only once. Also, all of these absorber systems are made at constant absorption (crushing) rate, thus are considered to be passive systems. Attempts are made here to propose an active absorber by making the average absorption force to be proportional to the vehicle energy.

A car bumper has a primary function of absorbing a collision in a proper manner. A localized damage to the bumper is highly wanted in an attempt to absorb the kinetic energy of the moving automobile. This deformation in the bumper will reduce the deceleration pulse felt by the passenger, thus reducing the injury risk from impact.

Bumpers include air-filled pneumatic systems where air is released through a valve at a predetermined rate during impact. Other bumper designs found in literature are for instance systems that include woven ceramic bumpers made of a cloth layer and an aluminium back sheet [8], double-beam thermoplastic bumper [9,10], composite beam bumper made of glass fibre in epoxy matrix [11], and cubic foam bumper [12]. However, these energy absorbers are made for certain purposes, like to get substantial weight reduction or for geometrical recovery to original bumper shapes after been subjected to small loads.

The rate of the absorber (crushing rate) is a very sensitive issue in the study of vehicle occupant safety, damage of transported goods or the vehicle structure itself. The rigid absorber or bumper will transmit the approaching shock wave to the vehicle structure and hence to the passengers. On the other hand, soft or weak bumpers will not absorb much energy before collapsing, hence the pulse will also be transmitted to the vehicle structure. Therefore a balance must be struck so that bumpers susceptible to low rate are used in low-speed impacts and bumpers susceptible to high rate used in high-speed impacts. Passive bumpers with single rate (low or high) function will not solve this problem because vehicles are expected to collide with either stationary or moving objects at different speeds.

In this paper a variable-rate and reusable energy absorber with no bodywork bumper is presented. This innovative system of smart frictional energy absorber is made of a central solid low carbon steel core surrounded by a number of steel rods. The steel rods are pressed against the central core and are held fixed, while the central solid core is forced to move axially. Performing friction work between the core and the rods dissipates energy. The system is thereby considered best suitable for automotive industry where it can be used as part of an actively controlled automobile bumper. In this case the friction force can control the absorption rate, which should be proportional to the automobile impact energy.

THE ABSORBER

Figure 1 shows the proposed energy absorber system that consists of a solid steel central core surrounded by a number of stationary solid steel rods that exert two point forces at equal distance from the free boundary. These forces represent the normal force (R) between the core and the rods. Steel rods are constrained in axial direction while the central core is forced to slide along the rods by means of axial force (F). The relation between the axial force (F) and the normal radial force (R) depends on some factors including the coefficient of friction between the core and the rods, and the number of rods in contact with the core.

The number of steel rods in contact with the central core is varied for the sake of increasing the energy dissipated by the absorber. In all configurations coplanar radial forces were applied so as to converge on the axis of the central core.

THE SMART ABSORBER

Most of the commercial absorber systems are made to be passive ones. The passiveness is attributed to the constant spring rate of the bumper. Few exceptions for instance those made using pneumatic systems have orifice diameters that control the variability of absorption forces. The system proposed herein is a smart energy absorber illustrated in Figure 2. In this design a sensor is used to measure the speed of the vehicle. By measuring this speed, one can determine the kinetic energy (E) of the vehicle, which is simply given as,

$$E = \frac{1}{2} m v_i^2 \qquad [1]$$

Where m is the mass of the automobile in kg and v_i is the instantaneous speed of the vehicle. The axial crushing force in the absorber can be made proportional to the kinetic energy of the moving vehicle. In the proposed system the controller can achieve this by two means:

1. By increasing the number of rods in contact with the central core, and
2. By increasing the radial force between the core and the rods.

Both of these factors have some upper bounds. The first one is limited by the space surrounding the core and the core radius to rod radius ratio. The second one is limited by the yield strength of the weaker material of the core or rods and by maximum axial force that can be carried by the setscrew before yielding.

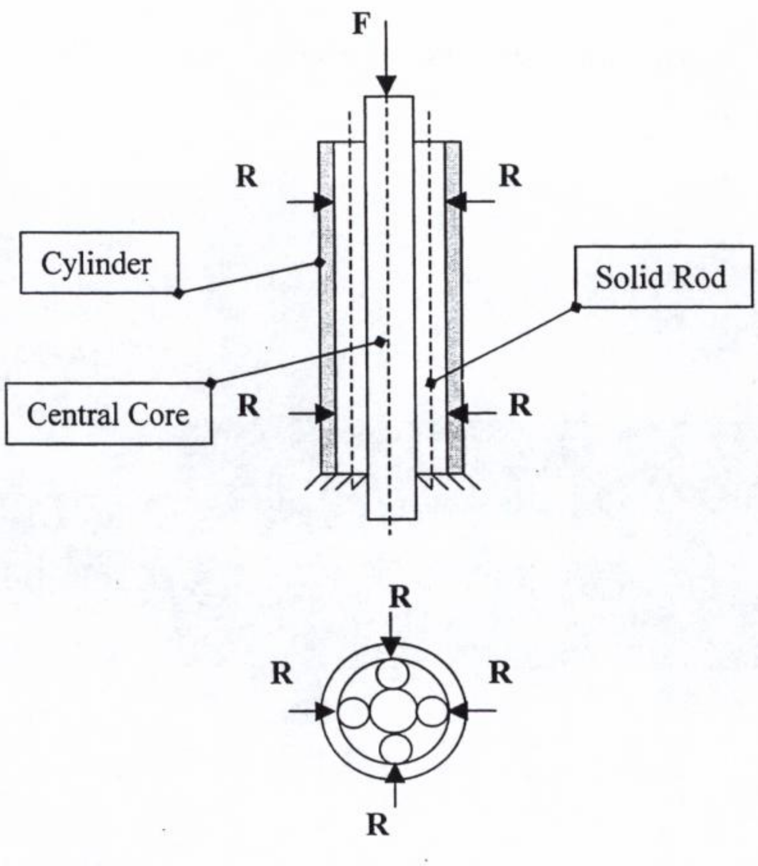

Figure 1. The double acting frictional absorber.

EXPERIMENTAL

The absorber was manufactured from low carbon steel. The solid central core and the surrounding rods were machined from solid cylindrical bars. The entire assembly was enclosed inside a thin circular cylinder that embodies the energy unit. Two 10-mm diameter setscrews were provided per rod to control the radial forces between the core and the corresponding active rod. Nuts were welded to the external surface of the cylinder 50-mm from the outer edge of the cylinder. Energy dissipated by the friction forces was generated at the contact surfaces when the central core was displaced axially in either direction. This feature characterizes the device as double acting impact energy absorber. The absorber can be used after the impact by loosening the setscrews and pulling the central core to its original position. The diameter of the solid core is 40-mm while the rods are of 25-mm diameter. Length of the contact lines between the rods and the central core is 300-mm, i.e. length of the rod as in Figure 1. Figure 3 is a photograph showing the assembly of the absorber.

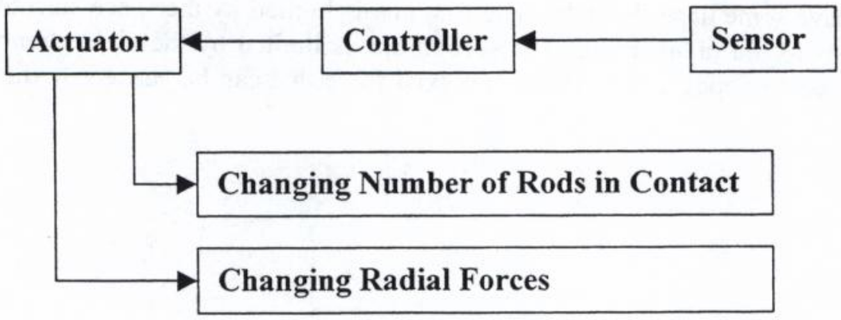

Figure 2: The system of smart absorber.

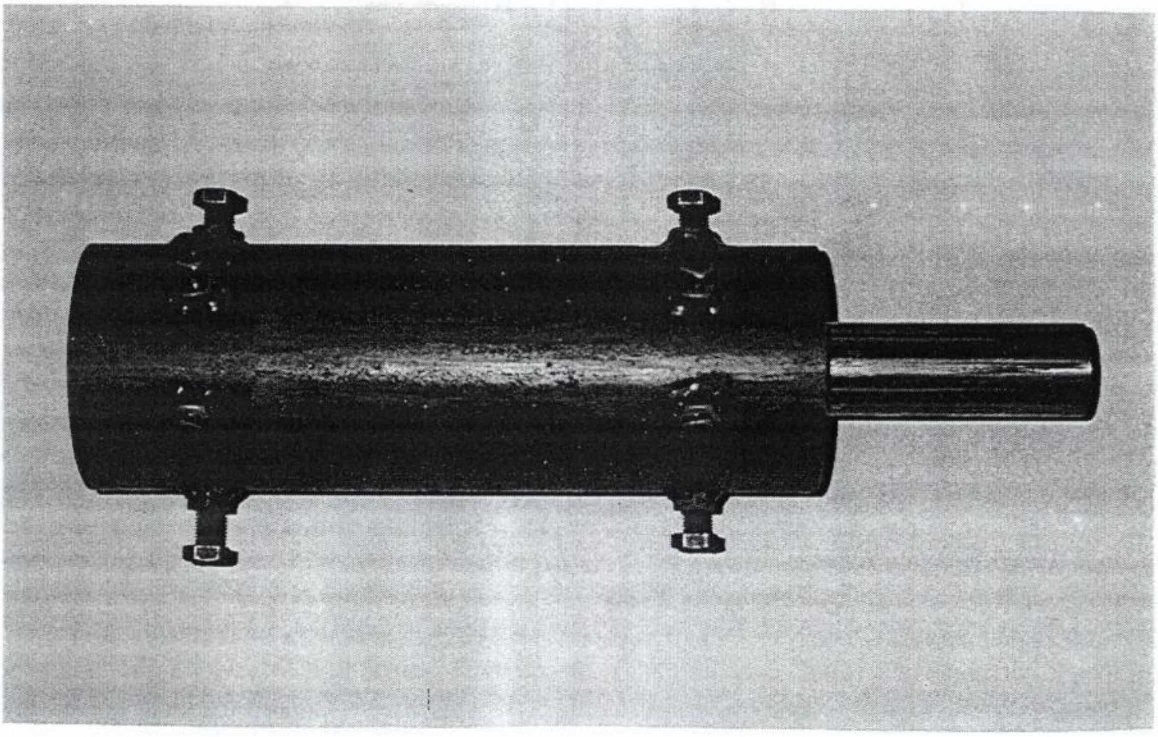

Figure 3. A photograph showing the absorber.

A series of quasi-static tests were carried out using a 10-ton Universal Instron Testing Machine. A loading rate of 10 mm/min was maintained throughout these tests. The numbers of rods in contact were changed from 2 to 6. Measuring the applied torque on each screw using a torque wrench controlled the radial forces. The relationship between the radial force (R) in the bolt and the applied torque (T) is approximated as [13],

$$T = 0.2\, d\, R \qquad [2]$$

Where d is the major bolt diameter. Radial forces are changed from a minimum value of 2500 N to a maximum value of 15000N, and the corresponding applied torque is varied from 5 Nm to 30 Nm. Values above 30 Nm would cause permanent deformations in the setscrews.

A simple test was carried out to determine the static coefficient of friction (μ) between the central core and the surrounding rods. The value of 0.3 was obtained. In the experimental study the central core was pressed axially for 100-mm displacement, which was a typical displacement value for actual car bumper [14]. The area under the load-displacement diagram represents the amount of energy that is absorbed by the bumper. By equating this energy to the energy of a moving vehicle with mass m, one can calculate maximum permissible impacting speed of the vehicle or,

$$v = \sqrt{\frac{2\,e}{m}} \qquad [3]$$

Where e represents the area under the load-displacement curve.

RESULTS AND DISCUSSION

Figures 4 and 5 show the experimental results of the energy absorber under quasi-static loading conditions. In Figure 4 the load-displacement curves are given for two rods (n=2) in contact with the central core at various radial force levels. Radial forces are changed from 5000 N to a maximum value of 15000N.

As expected, the axial sliding force increases as the radial force is increased. The elastic behaviour of the core has insignificant contribution, and most of the energy is absorbed by friction at the interface surfaces. Thus, the elastic effect and elastic energy absorption are negligible in this study. Such assumption is widely accepted in large plastic deformation of car bumper [14]. The load displacement curve starts from the origin and goes linearly to a peak value before it falls down. That peak value represents the static force (F_s), which is a measure of the static coefficient of friction between the core and the rods. The axial force falls to a lower level after a displacement of about 2 mm, and essentially remains at that level until the end of the experiment. The latter level is caused by the dynamic coefficient of friction. The slight variation in the axial force is a result of the change in the contact condition between the mating steel parts as the sliding continues. The figure shows clearly how the absorber dissipates more energy as the clamping force increases.

In Figure 5 the load-displacement curves are given for different number of rods in contact with the central core at the same radial force, R=10000 N. The effect of increasing the rods in contact is clear. Hence, the load-displacement curves for 2, 3 and 4 rods are given as solid, dashed and dotted-dashed lines, respectively. The gradual increase in the axial sliding force for n=4 after 40-mm displacement is believed to be due to the presence of loose particles digging into the surfaces. It was observed that these loose particles were pitted from the contact surface because of the ploughing effect. Rough scratched surfaces were noted on the contact surfaces after that test (n=4, R=10,000 N).

The average axial force (F_{av}) is plotted vs. the number of rods (n) and the radial force (R) in Figure 6, which shows the dependency of the dissipated energy on the radial clamping force and the number of rods in contact.

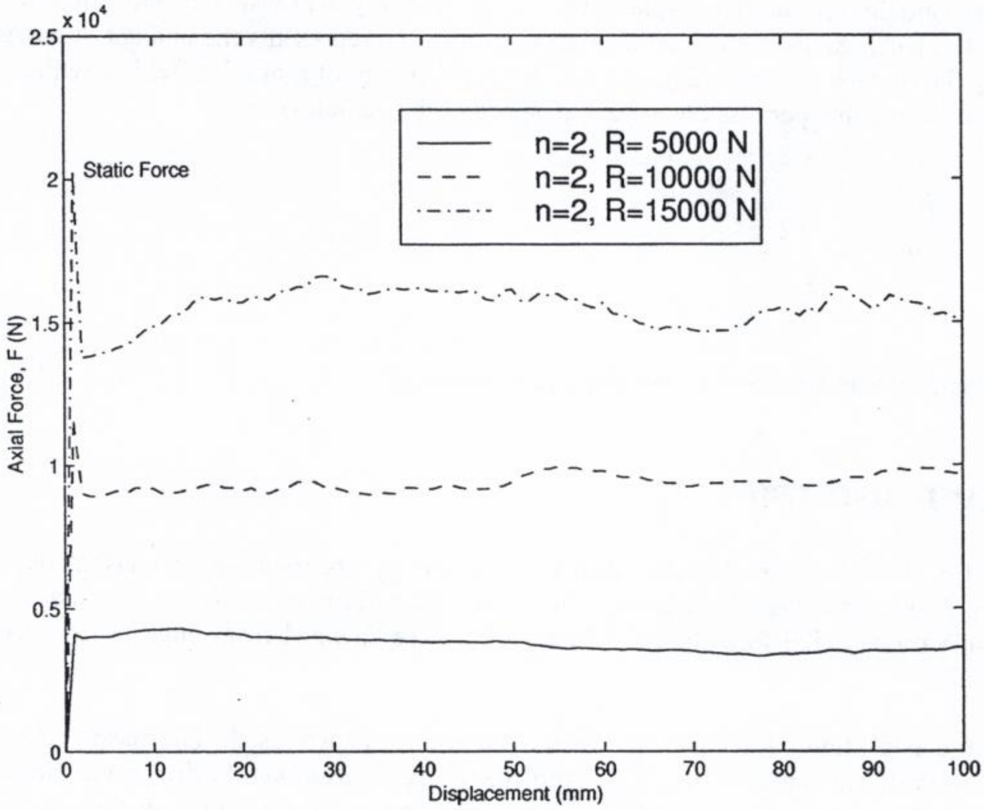

Figure 4. Effect of increasing the radial force (R) on the dissipated energy at two rods (n=2) in contact.

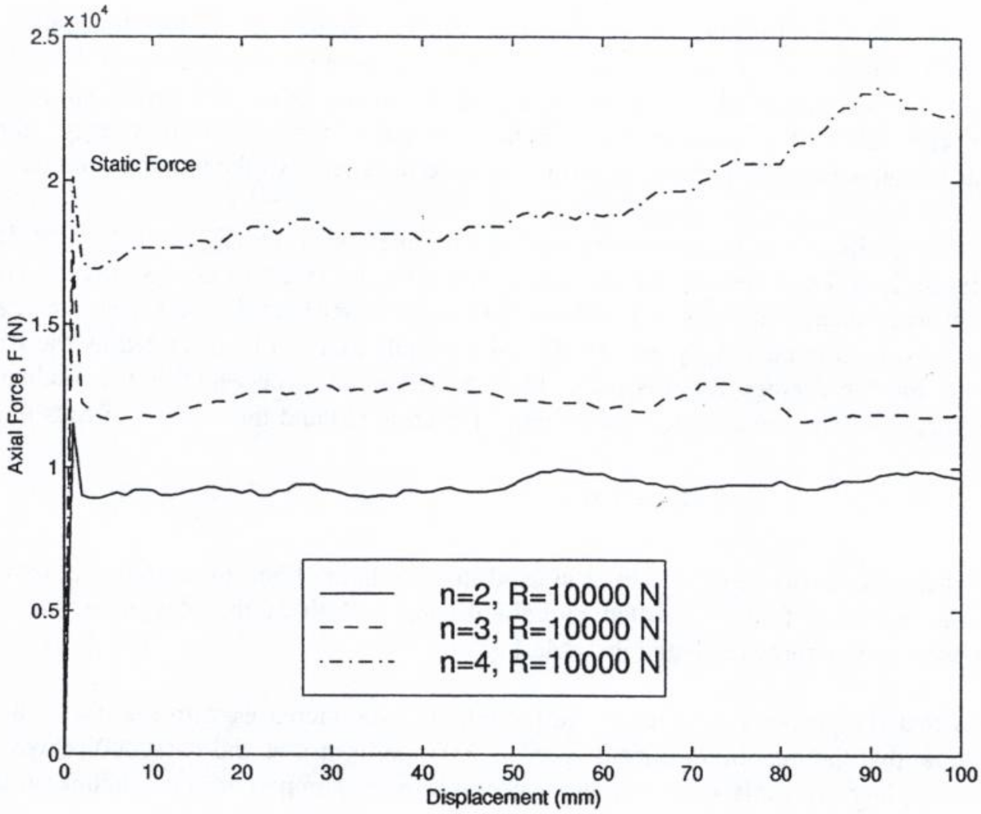

Figure 5. Effect of increasing the rods in contact (n) on the dissipated energy at constant radial force (R=10000 N).

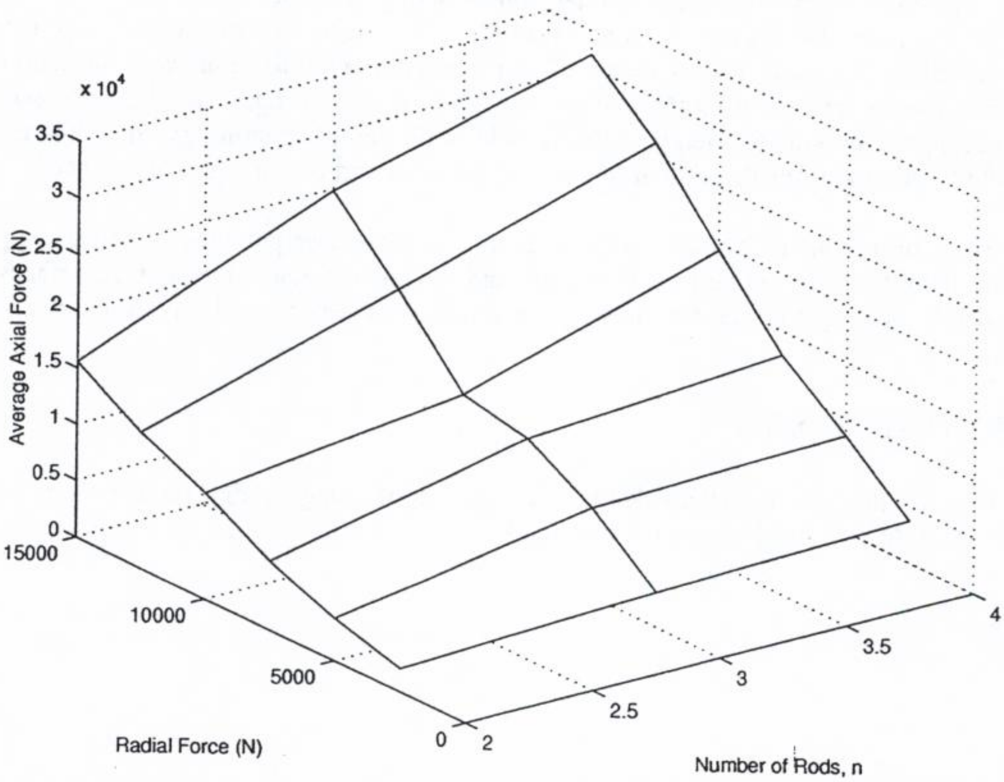

Figure 6. Average axial force (F_{av}) as a function of the number of rods in contact (n) and the radial force (R).

It can be seen from Figures 4-6 that the absorber behaves as a linear system, which depends on the number of rods in contact and the radial clamping force. This demonstrates the controllability of the energy absorber that has the radial force proportional to the square of the automobile speed. In that case the absorption rate of the absorber becomes proportional to the automobile energy. Similarly number of rods in contact can be made to be proportional to the energy of the moving vehicle.

Table 1 lists the details of the experimental work. The average force (F_{av}) is listed for different absorber configurations, i.e. different rods in contact and different levels of normal force. The table includes the absorbed energy in Jules that represents the area under load-displacement curve, and the corresponding maximum impacting speed of a 1000-kg vehicle that can be absorbed by the frictional absorber. Note that the average force is grater than the frictional force which is the product of the normal radial force (R) and the dynamic coefficient of friction (μ) and the number of rods in contact (n) or,

$$F_f = R\, n\, \mu \qquad [4]$$

Due to the fact that some of the energy is dissipated in ploughing effect, the difference between the average and the frictional forces is called ploughing force. Both of the ploughing force and its percentage of the average force are listed in Table 1.

It can be seen that the percentage value of the ploughing force increases with the rise in the radial force. Also, note that the maximum impact speed is 9.07 km/hr at n=4 and R=10000 N which looks like a small value, however, this value is quite acceptable when compare to a maximum value of 9.6 km/hr for actual car bumper design as reported in [14].

CONCLUSIONS

In this paper an innovative smart frictional double-acting reusable energy absorber is introduced. Energy is dissipated by friction between a solid central core and surrounding solid rods. The absorption rate can be controlled by means of increasing the radial force between the central core and the external rods or by increasing the number of active rods in contact. The adaptive absorber can be made to dissipate the kinetic energy of the vehicle at different impacting speed. This represents an acceptable solution to rigid absorber at low impact speed or soft one at high impact speed.

Experimental results validate these predictions and hence bolster potential of this energy absorber. The controllability of the active rods in contact and the radial force at the contact surfaces nominate this absorber as a good one for automotive application when used in an interactive "smart" environment.

ACKNOWLEDGEMENT

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Table 1. Details of experimental work.

No. of Rods (n)	Radial Force (R)	Average Force (F_{av})	Frictional Force (F_f)	Ploughing Force (F_p)	F_p/F_{av} %	Absorbed Energy	Impact Speed
Unit	N	N	N	N		J	km/h
2	2500	2120	1500	620	29.2	212	2.34
2	5000	3840	3000	840	21.9	384	3.16
2	7500	6240	4500	1740	27.9	624	4.02
2	10000	9580	6000	3580	37.4	958	4.98
2	12500	12270	7500	4770	38.9	1227	5.64
2	15000	15870	9000	6870	43.3	1587	6.41
3	2500	3180	2250	930	29.2	318	2.87
3	5000	8000	4500	3500	43.8	800	4.55
3	7500	11440	6750	4690	41.0	1144	5.45
3	10000	12590	9000	3590	28.5	1259	5.71
3	12500	19250	11250	8000	41.6	1925	7.06
3	15000	25320	13500	11820	46.7	2532	8.10
4	2500	3750	3000	750	20.0	375	3.12
4	5000	8630	6000	2630	30.5	863	4.73
4	7500	13090	9000	4090	31.2	1309	5.83
4	10000	19730	12000	7730	39.2	1973	7.15
4	12500	26580	15000	11580	43.6	2658	8.30
4	15000	31740	18000	13740	43.3	3174	9.07
6	2500	6950	4500	2450	35.3	695	4.24
6	5000	13850	9000	4850	35.0	1385	5.99

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