
Crash Cushion with Kinetic Energy Dissipation by Friction

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Abstract: - This paper presents the design and numerical evaluation of a crash cushion that dissipates kinetic energy primarily through controlled friction. A multibody dynamic model was developed in SolidWorks Motion to simulate impact scenarios, friction interfaces, and structural response. Results demonstrate effective energy absorption, reduced peak deceleration, and stable stopping behavior. The study validates the concept and highlights the usefulness of motion-based simulation for preliminary safety system optimization and design comparison.

Keywords: - Crash Cushion, Multi-Stage Impact Attenuator, Energy Dissipation, Road Safety.

1. INTRODUCTION

Crash cushions are critical roadside and industrial safety devices intended to mitigate the consequences of vehicle collisions by absorbing kinetic energy and reducing occupant deceleration during impact. They are commonly installed at hazardous locations such as barrier terminals, bridge piers, and work zones, where fixed obstacles pose a high risk of severe injury or fatality [1,2]. To mitigate the consequences of such accidents, crash cushions are implemented as passive safety devices whose configuration depends on the specific roadway geometry and traffic layout. Accordingly, crash cushions are commonly designed in parallel, Y-shaped, or trapezoidal forms to accommodate different road sections and impact directions [3].

Conventional crash cushions employ mechanisms such as material crushing, plastic deformation of metallic elements, hydraulic damping, or foam energy absorption. The report [4] deals with crash cushions using clusters of hollow circular rubber cylinders as reusable energy absorbers. The report discusses rubber compounds, cylinder geometry, energy absorption, durability, full-scale prototype testing, and life-cycle cost benefits.

A numerical study on an impact attenuation system using nested cylindrical steel tubes, including

energy dissipation and tube crushing, is presented in [5].

Paper [6] develops a crash cushion using LLDPE containers supported by embedded plastic energy-absorbing tubes as dampers. It is analyzed with LS-DYNA simulation, and full-scale crash tests according to EN 1317 were performed.

Cylindrical tubes with discontinuous protrusions to reduce initial peak load and improve stable crushing are studied in [7].

Hydraulic cylinders to absorb energy are presented in [8], the patent for a telescopic crash cushion, and [9], progressive hydraulic cylinder cushioning.

While effective, these systems may suffer from high replacement costs, complex maintenance, or irreversible structural damage after impact.

Friction-based energy dissipation offers an alternative approach that combines mechanical simplicity, robustness, and repeatability. The conversion of kinetic energy into heat through controlled friction forces has been widely applied in braking systems, dampers, and impact mitigation devices due to its predictable behavior and tunable performance [10,11]. By adjusting contact pressure, friction coefficients, and sliding distances, friction-based crash cushions can be designed to provide nearly constant deceleration, which is desirable for minimizing injury risk [12,13].

Advances in computer-aided engineering have significantly improved the development process of crashworthy systems. Multibody dynamic simulations enable detailed analysis of motion, contact interactions, forces, and energy transfer during impact events without the need for costly early-stage physical testing [14]. SolidWorks Motion, in particular, provides an accessible platform for rigid-body dynamics with frictional contacts, making it suitable for preliminary crash cushion studies [15]. Previous research has demonstrated that simulation-based evaluations can reliably predict impact behavior when appropriate contact and friction models are applied [16].

We propose a multi-stage crash cushion that has a modular design and consists of several diaphragms that work independently and progressively. Their role is to dissipate kinetic energy by friction. It is possible to control kinetic energy absorption by setting the parameters of each diaphragm separately.

In this study, the behavior of a diaphragm is investigated through numerical simulation in SolidWorks Motion. The objective is to assess the system's energy absorption capability, impact response, and deceleration characteristics. The results contribute to the understanding of friction-based crash cushions and support their potential use as efficient and reusable safety solutions. The findings can be extrapolated for diaphragms with other parameters (shaft diameter, friction coefficient, relative pressure between shaft and diaphragm).

2. PROBLEM FORMULATION

Parallel crash cushions are commonly used at exit ramp gores, barrier/bridge rail ends, and median/roadside barrier terminals, where the hazard must be shielded, but space is constrained. Thus, the role of the crash cushion is to:

- Prevent a misbehaving vehicle from hitting the rigid object (barrier end, pier, column, etc.) directly.
- Gradually decelerate the vehicle to a safer stop in head-on impacts, which means energy absorption or at least attenuation.
- Reduce crash severity (passenger injury and vehicle damage).

Being a passive safety measure for when a run-off-road event occurs, the crash cushion does not prevent accidents but reduces their severity.

To fulfill its job, the parallel crash cushion has a rectangular geometry aligned with the roadway; see Figure 1. The main elements of the parallel crash cushion proposed by VALTIR [17] are:

1. The base track
2. The impact head
3. The energy absorbing panels
4. The backup
5. The diaphragms

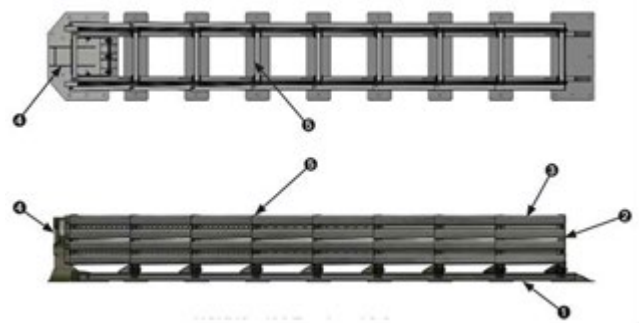


Figure 1. Parallel crash cushion – upper and lateral view.

The solution is stable, has a backup for strong impacts, and contains deformable side panels. The main disadvantage of the system is the potential to harm passengers or pedestrians due to the panels during the crash.

3. PROBLEM SOLUTION

The solution we propose, see Figure 2, consists of a modular system with diaphragms that are fixed on a base track with screws. The diaphragms have cylindrical holes in which a shrink-fit cylinder is mounted. This assembly, in which the hole diameter is slightly smaller than the cylinder/shaft diameter, prevents relative motion by the contact pressure and residual stresses that are developed between the hole and the shaft. Contact area A is:

$$A = \pi dL \quad (1)$$

where d is the shaft diameter and L is the length of the contact surface.

Normal force N is:

$$N = pA = p\pi dL \quad (2)$$

where p is the uniform pressure along the contact length.

Hence, the maximum axial force before slip becomes:

$$F_{ax,max} = \mu_s p\pi dL \quad (3)$$

In Eq. (3), we denoted the static friction coefficient with μ_s .

It is possible to control the dissipated energy by several parameters (μ_s , d , L , p), which is a clear advantage of the proposed crash cushion. This means that each diaphragm can support shrink-fit cylinders to which different pressures are applied; thus, different energies are dissipated after each

shaft removal. In fact, we desire to obtain lower dissipation for the first diaphragm, and the biggest dissipation for the last diaphragm. This evolution is

desired to avoid big decelerations for the initial phase of the crash.

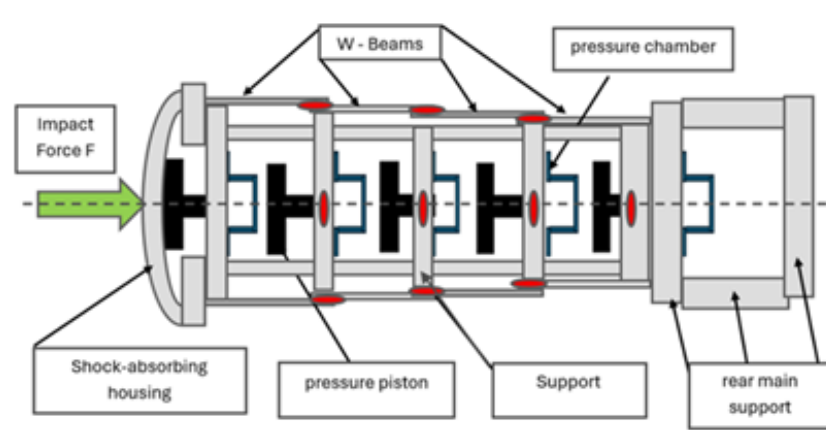


Figure 2. Parallel crash cushion with dissipating energy diaphragms

A detail of the diaphragm assembly is given in Figure 3. We can observe here:

1. The direction of the impact force.
2. Shaft.
3. Diaphragm.
4. Fit hole in the diaphragm.
5. Base track.
6. Screws to fix the diaphragm assembly to the base track.
7. Screws to fix the W-panels to the diaphragm.
8. W-panels.

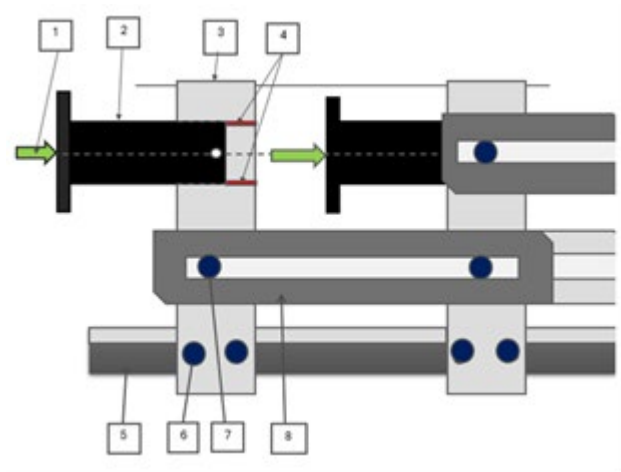


Figure 3. Diaphragm assembly

It is also possible to dissipate energy by friction between the W-panels or by the collapse of the screws that fix the diaphragms to the base track.

A major advantage of the proposed solution is the way the W-panels superpose when a diaphragm assembly is pushed to the back. These panels do not deform severely, and there is no risk of injury for the passengers or pedestrians.

4. NUMERICAL SIMULATION

The Simulation to test the behavior of one diaphragm assembly is performed in SolidWorks Motion. The car that pushes the crash cushion is represented by element 1, the shaft by element 2, and the diaphragm assembly by element 3. There are the same elements as in Figure 3.

Element 3 is fixed, while element 1 can move along the base plane without friction. It pushes the exterior part of the shaft head with a force F that exceeds $F_{ax,max}$ until the inner side of the shaft head impacts the diaphragm. Obviously, for $F < F_{ax,max}$, the assembly in Figure 4 does not move.

This study does not consider the friction force between the W-panels and the shear force acting on the screws that fix the diaphragm to the base track. The latter can be a case study for static analysis.

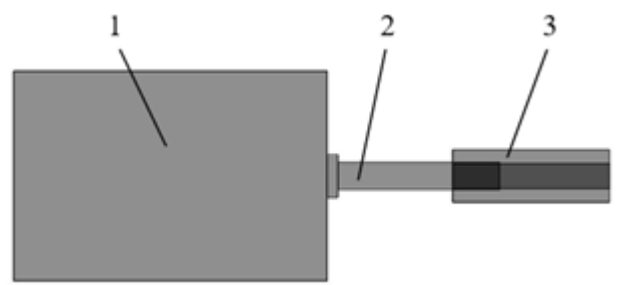


Figure 4. Schematic of the car-shaft-diaphragm assembly

The mass of the car is $m = 912$ kg, and the initial car speed is considered $v = 50$ km/h. The desired stop distance is $s = 8$ m. The kinetic energy E_k of the car at the impact moment is

$$E_k = \frac{1}{2}mv^2 \quad (4)$$

and the average force F_{avg} acting on the shaft is

$$F_{avg} = \frac{E_k}{s} \quad (5)$$

Hence, the average force is found from the mathematical relation

$$F_{avg} = \frac{mv^2}{2s} \quad (6)$$

For the data we consider, the average force F_{avg} is 10995. For simplicity, instead of the car inertia, we consider a permanent force pushing the shaft with $F = 11000$ N. This does not affect the behavior of one diaphragm, i.e., the friction force, energy dissipation, and impact force between the shaft head and the diaphragm.

The mass of the shaft is $m_s = 1.915$ kg. It is considered in the simulation, even if it is not relevant in the real-life application.

The friction coefficient between the shaft and the diaphragm hole is $\mu_s = 0.3$, and the dynamic friction coefficient is $\mu_D = 0.25$. The same friction exists between the shaft head and the diaphragm. The simulation starts when the car is in contact with the shaft head. For the impact between the shaft and the diaphragm, penetration between the three components is not allowed.

The simulation time is set to $T = 0.2$ seconds, which is sufficiently long to capture the whole process. The time resolution is $r = 500$ frames per second and is set to permit fine observation of the system's response parameters.

In Figure 5, we plot the friction force, which shows energy loss and can be controlled by increasing the pressure p between the shaft and hole by setting the diameters of the two components. In the simulation, this is achieved by increasing the friction coefficient. In our study, the average friction force is $f_F = 470$ N.

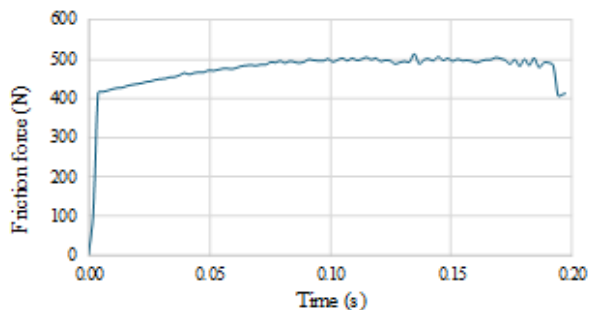


Figure 5. Friction force evolution between the moving shaft and the diaphragm (X-direction)

A parameter that is targeted by using crash cushions is the car acceleration after the crash. Figure 6 reflects this evolution. The deceleration is

around 500 mm/s^2 , which corresponds to 0.005 g . This value is clearly under the limit of actual road safety norms [18], meaning that we can decrease the stopping distance. One can also observe that there is still an acceleration after the internal shaft head reaches the diaphragm; that means supplementary energy must be dissipated. This can happen by sharing of the fixing screws and afterward, by the action of the shaft of the second module (diaphragm assembly).

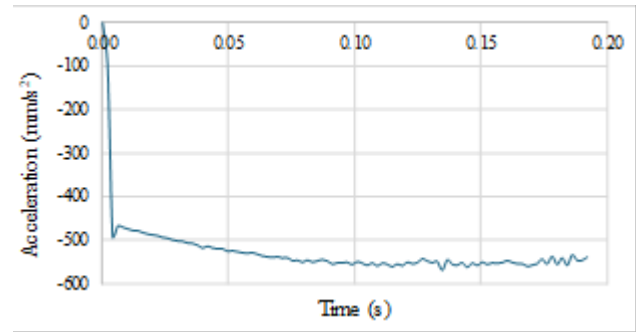


Figure 6. The car acceleration after the crash

The kinetic energy evolution is presented in Figure 7. The shaft can perform a displacement of 260 mm until the shaft head impacts the diaphragm. The kinetic energy diagram also shows that the moving system (car plus shaft) still has energy, and the crash between the car, in fact, by the interposed shaft, and the diaphragm is imminent. The contact is performed involving a residual force. The extent of the impact force is shown in Figure 8.

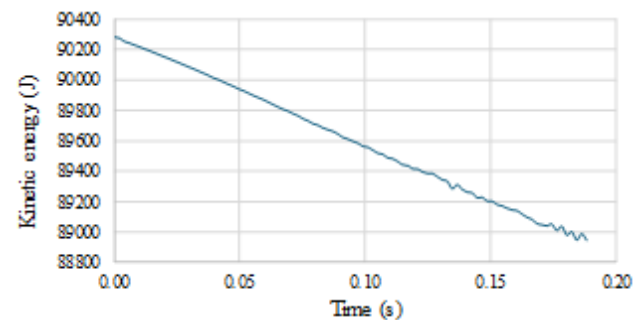


Figure 7. Kinetic energy evolution after the crash

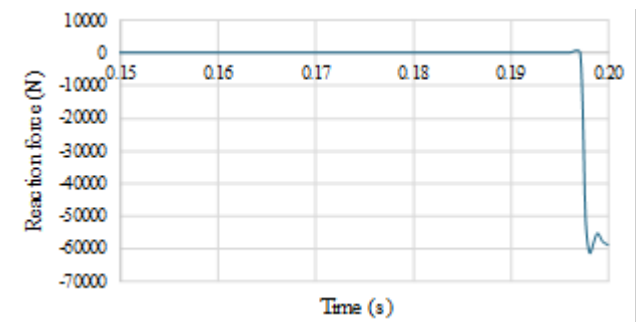


Figure 8. Impact force between the moving assembly (car and shaft) and the diaphragm

To control the car acceleration after the crash, several diaphragm assemblies must be mounted in the crash cushion. For each of them, the friction coefficient μ_s , the diameter d of the shaft, or the contact force p should be increased to ensure a progressive increase of the dissipated energy.

In this study, 3D CAD models were used. The friction coefficient used here was intentionally taken low to capture the effect of the impact of the shaft head and the diaphragm. However, in real cases, this coefficient can be adjusted to fit the needs of different road types (car dimensions, initial speed, etc.). If it is necessary, the friction coefficient can be increased because of the shrink-fit assembly. By controlling the pressure between the components, it is possible to set a higher friction coefficient, which results in a greater reduction in kinetic energy.

Screws with predefined shear force to collapse, together with friction between the W-beam and the diaphragm, respectively between the W-beams, can ensure supplementary energy dissipation.

5. CONCLUSIONS

This work proposed a modular parallel crash cushion that dissipates impact kinetic energy mainly through controlled friction in shrink-fit shaft–diaphragm interfaces. A multibody model in SolidWorks Motion captured contact, frictional sliding, and the subsequent impact between the shaft head and diaphragm. The simulations indicate that friction forces can be tuned via interference pressure, contact length, and friction coefficients to shape a progressive energy-absorption profile, yielding reduced peak deceleration and stable stopping without severe panel deformation. Kinetic-energy and force histories further show that residual energy after the first module can be managed by staged diaphragms and, in future, by including screw shear and panel-to-panel friction. Overall, the results validate friction-based dissipation as a simple, potentially reusable alternative to crash-type systems and demonstrate that motion-based simulation is an efficient tool for early design comparison and parameter optimization prior to full-scale testing. Experimental validation and sensitivity studies will refine parameters and support guidelines.

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