Reusable roadside impact attenuation devices
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Abstract

Advanced computer and materials technologies are employed to develop reusable, maintenance-free roadside safety hardware. These devices dissipate large amounts of kinetic energy, undergo significant deformations and strains without fracturing, and regain their original shapes and energy dissipation potentials upon removal of the impact load. It is demonstrated that computer simulation is a cost effective design optimization tool whose use can reduce the number of expensive full scale crash tests required to develop new safety hardware.

Introduction

Accidents involving motor vehicles are a major worldwide health problem which constitutes a great economic and social loss to society. In the United States, for instance, the potential years of productive life that are lost before age 65 as a result of motor vehicle related injuries and deaths are greater than those lost to cancer or heart disease. One cost-effective way to reduce the serious injuries and fatalities associated with vehicular impacts with roadway and roadside hazards is through the use of impact attenuation devices. The development of effective roadside safety features over the last three decades has been characterized primarily by expensive full-scale crash testing in a trial-and-error mode. This expensive approach to generating guardrail, crash cushion, and break-away pole products was necessary because of the complicated nature of the impact events involved and the
limitations of computer hardware and software. A high-speed impact of a vehicle into a roadside safety feature is an extremely complicated occurrence. However, because of recent technological advances in the sophistication of finite element software and the power of computer hardware it is now feasible to accurately model these vehicle/roadside safety feature crashes. The result has been a series of new safety devices that have been developed with a minimum of expensive full-scale crash tests because finite element computer models were first employed to design the systems. This approach maximizes the probability that the full-scale crash tests will be successful. Furthermore, computer simulations made it possible to model impact scenarios that are difficult or impossible to crash test. For example, full-scale crash tests are conducted on level terrain with tracking vehicles that are out of gear and are travelling rectilinearly. Most real world accidents involving roadside hardware involve non-tracking, braking, in-gear vehicles that are undergoing curvilinear motion.

Another application of advanced technology is the use of ‘smart materials’ in roadside safety devices. Most impact attenuation devices currently in use throughout the world require the expensive replacement of damaged structural components and spent energy dissipating elements following an impact event. Until these repairs and refurbishments are carried out, these safety devices are largely ineffective in that they are not able to dissipate kinetic energy in a subsequent impact in an acceptable manner such that relevant occupant risk parameters are within prescribed limits. In some cases, a significant time elapses before damaged impact attenuation devices are repaired and restored to effective operating status. This system ‘down-time’ is a source of danger to the motoring public and a potentially serious tort liability exposure for the transportation agency involved.

This paper describes how the employment of smart materials and advanced computer technologies can be employed to frugally develop reusable, maintenance-free roadside safety hardware. Such devices can dissipate large amounts of kinetic energy, undergo significant deformations and strains without fracturing, and then essentially regain their original shapes and energy dissipation potentials upon removal of the loads.

The smart material – high-molecular-weight/high-density polyethylene

High-molecular-weight/high-density polyethylene (HMW/HDPE) is an energy dissipating thermoplastic that possesses the properties of self-restoration and reusability. This polymer is characterized by its opacity,
Structures Under Shock and Impact

chemical inertness, toughness at both low and high temperatures, and chemical and moisture resistance. High density can be achieved because of the linear polymer shape, which permits the tight packing of polymer chains. A HMW/HDPE tube, for example, when crushed laterally between two plates to complete collapse, will restore itself to approximately 90% of its original shape upon removal of the load. It can be reloaded and unloaded repeatedly, exhibiting almost identical load-deformation (energy dissipation) characteristics. It remains ductile at temperatures below -40°F (-4°C) and its energy dissipation potential is still significant at temperatures above 100°F (38°C). High-molecular-weight / high-density polyethylene exhibits the following favorable material characteristics:

- high stiffness
- high abrasion resistance
- high chemical corrosion resistance
- high moisture resistance
- high ductility
- high toughness
- high tensile strength
- high impact resistance over a wide temperature range

An extensive series of quasi-static and impact experiments were carried out to establish the energy dissipation, self-restoration, and hysteresis characteristics of HMW/HDPE cylinders as functions of temperature and loading rate. The details of this testing program are available in Carney.¹²

Smart impact attenuation devices

Narrow hazard crash cushion designs

Narrow hazard HMW/HDPE crash cushions have been designed for three different impact speed applications: 100, 88.5, and 70 km/h. The 70 and 100 km/h devices are shown in Figure 1. They are composed of HMW/HDPE cylinders with wall thicknesses varying from 20.23 mm to 43.54 mm. All cylinder diameters are 0.92 m, and all cylinder heights are 1.22 m. All three of these narrow hazard devices have been accepted by the Federal Highway Administration for use on the National Highway System under the NCHRP Report 350 Ross³ guidelines.
A high impact speed truck mounted attenuator

Truck mounted attenuators (TMA) are portable crash cushions employed in movable roadway maintenance, repair, and construction applications. A reusable HMW/HDPE 100 km/h TMA has been developed and is shown in Figure 2. It is composed of four polyethylene cylinders. The largest cylinder is 3.048 m long and has a wall thickness of 48 mm. This cylinder is manufactured by wrapping multiple layers of the material around a mandrel. Two 0.91 m diameter extruded polyethylene cylinders are attached inside the largest cylinder, adjacent to the rear of the support truck. The wall thicknesses on these cylinders are 37 mm and they are attached to the larger cylinder and to each other with two 22 mm diameter bolts at the contact points. The fourth cylinder measured 0.91 m OD and has a wall thickness of 46 mm. Like the REACT family of narrow hazard crash cushions, this reusable TMA has been accepted by the Federal Highway Administration for use on the National Highway System under the NCHRP Report 350 guidelines. The details of the crash testing program are reported in Carney.
Wide hazard crash cushion

An effective reusable wide hazard crash cushion made of clusters of HMW/HDPE has also been designed and shown in Figure 3. The width of this crash cushion is variable, depending on the width of the hazard to be shielded. In Figure 3, all of the cylinders have diameters of 0.91 m, the system width is 2.74 m, and the length of the system is 6.25 m.
Figure 4. Finite Element and Crash Test Responses for 2000 kg Impact Case
Finite element modeling example

The design of the truck mounted attenuator was optimized using finite element modeling with DYNA3D software. All simulations were run on a Sparc<sup>4</sup> workstation running Solaris 2.4. The model contains 8547 nodes, 280 solid elements, and 7260 four-node shell elements. Five integration points were employed through the shell thickness. It is emphasized that the finite element simulations were conducted prior to the full-scale crash tests being conducted. A comparison of the DYNA3D predictions and the experimental crash test results at various instants in time are shown in Figure 4. This figure deals with the impact response of the TMA when subjected to a 100 km/h impact with a 2000 kg truck. Note that the TMA employs a nested cluster of HMW/HDPE cylinders. The inside cylinders are only partially deformed during a high speed impact with a light vehicle. They are fully utilized, however, in the high speed impact with the 2000 kg pickup truck.

The TMA deforms in an asymmetric mode even though the impact is at the line of symmetry of the device. This occurs in the finite element modeling due to numerical rounding and in real life because of inevitable material and geometric imperfections. It can be shown that the energy dissipated during the asymmetric deformation mode is slightly less than that absorbed in the symmetric one. The two configurations at corresponding time snapshots are certainly qualitatively similar. Quantitative measures of the simulation and crash test results are shown in Figure 5 and Tables 1 and 2. Figure 5 presents two versions of the acceleration-time history of the center of gravity of the 2000 kg pickup truck during the impact event. The solid curve is the experimental crash test response and the dashed curve is the finite element prediction. The accepted procedures for acquiring occupant risk data involve the numerical integration of acceleration-time data. Of primary concern are the magnitudes of the hypothetical occupant impact velocity with the interior of the vehicle and the maximum 10 ms. average deceleration of the occupant following this impact. The recommended threshold values for occupant impact velocity and ridedown deceleration are 12 m/s and 20g respectively. A comparison of the predicted versus actual occupant risk parameters are shown in Table 1 for 820 and 2000 kg impacts and show excellent agreement.

There are several quantifiable validation criteria which can be employed to permit analysts to make objective decisions about the quality of finite element models and their ability to accurately model impact events. These mathematical techniques are described in Ray<sup>5</sup> and include the following suggested validation measures:
114 Structures Under Shock and Impact

1. The average residual between the two accelerations versus time responses, $\bar{e}$, should be less than 5% of the peak acceleration.
2. The standard deviation of the residuals, $\sigma_e$, should be less than 20% of the peak acceleration. The $t$-statistic, defined as:

$$T = \frac{\bar{e}}{\sigma_e / \sqrt{n}}$$

Where $n$ is the number of paired samples, should have an absolute value of less than 3.0.

Results are shown in Table 2 for both the 820 and 2000 kg impact cases. The average residuals are well below the suggested limit of 5% of the peak acceleration. The standard deviations of the residuals hover just below or just above the suggested limiting value of 20% of the peak acceleration. Finally, the absolute value of the $t$-statistics are below the maximum value of 3.0.

Figure 5. Crash Test and Simulation for 100 km/h Impact into TMA with 2000 kg truck.
<table>
<thead>
<tr>
<th>NCHRP Report 350</th>
<th>3-50</th>
<th>3-51</th>
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<tbody>
<tr>
<td>Vehicle Mass (kg.)</td>
<td>820</td>
<td>2000</td>
</tr>
<tr>
<td>Occupant Impact Velocity (m/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Simulation</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>• Crash Test</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Occupant Ridedown Deceleration (g's)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Simulation</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>• Crash Test</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 1. Predicted Versus Actual Occupant Risk Parameters

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Recommended Limiting Values</th>
<th>2000 kg 60 Hz/10 msec.</th>
<th>820 kg 60 Hz/10 msec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Residual $T = \frac{\bar{a}}{\sigma_e / \sqrt{n}}$</td>
<td>0.050</td>
<td>0.028</td>
<td>0.022</td>
</tr>
<tr>
<td>Standard Deviation $\frac{\sigma_e / a_{peak}}{}$</td>
<td>0.200</td>
<td>0.213</td>
<td>0.161</td>
</tr>
<tr>
<td>$T = \frac{\bar{a}}{\sigma_e / \sqrt{n}}$</td>
<td>3.000</td>
<td>2.504</td>
<td>2.434</td>
</tr>
</tbody>
</table>

Table 2. Analysis of Variance for 820 and 2000 kg Tests and Simulations ($n = 370$).

In summary, the simulation and crash test results for both the 820 kg automobile test and the 2000 kg pickup truck tests are qualitatively and quantitatively similar. This result validates the argument that it is not always necessary to employ 50,000-100,000 element models to achieve accurate results in impact problems.

**Concluding Remarks**

This paper has demonstrated that computer simulation is a cost effective design optimization tool whose use can reduce the number of expensive full scale crash tests which are required to develop new safety hardware. A validated finite element model can be employed in place of some full-scale
crash tests to determine the impact response of the crash cushion and assess the occupant risk. Full-scale crash testing will continue to be required as one important tool to be employed in developing safety hardware. However, the expense of full-scale crash testing, coupled with the practical limitations of crash testing technology, will continue to limit the number and variety of impact scenarios that can be tested. This paper shows that recent technological advances in materials science and computing power have resulted in more effective, reusable safety devices. Lives will be saved as the resulting better understanding of the ways in which safety devices behave under real-world impact conditions inevitably leads to more effective designs. It is also demonstrated herein that it is feasible to develop an energy dissipating medium that can dissipate large amounts of kinetic energy, undergo large deformations and strains without fracturing, and, most importantly, restore itself to its original size, shape, and energy dissipation potential when the forcing function is removed. The potential financial, legal, and safety payoffs for highway operations associated with developing highway safety devices that are essentially maintenance-free are enormous. Maintenance costs associated with the repair of impact safety devices would be greatly reduced or eliminated. Tort liability exposure related to damaged or collapsed hardware would be significantly decreased. Finally, the safety of the motoring public and the maintenance personnel involved in maintaining and repairing damaged hardware would be greatly enhanced.

Acknowledgment

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References


