Development of a Hybrid Energy Absorbing Reusable Terminal (HEART) Using Finite Element Modeling in LS-DYNA for Roadside Safety Applications

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Abstract

The Hybrid Energy Absorbing Reusable Terminal (HEART) is a newly developed crash cushion or an end terminal to be used in highway safety applications that will mitigate injuries to occupants of errant vehicles.

The HEART is composed of corrugated plates of High Molecular Weight/High-Density Polyethylene (HMW/HDPE), supported on steel diaphragms, which slide on a fixed rail. Kinetic energy from errant vehicles is converted to other energy forms through the folding and deformation of HDPE material. Many previous designs utilize the plastic or permanent deformation of plastics or steels to accomplish this goal. However, HEART is a reusable and self-restoring crash cushion, and therefore has a major cost advantage over the conventional crash cushion designs.

HEART has been designed and optimized through an extensive use of finite element modeling. The objective of this paper is to present the finite element modeling and simulation approach adopted to arrive at the final design of the HEART cushion.

In order to meet the National Cooperative Highway Research Program (NCHRP) Report 350 guidelines, all roadside safety devices need to pass the report's requirements from an 820 Kg and a 2000 Kg vehicle impacting at 100 Km/h. For HEART to meet the NCHRP Report 350 evaluation criteria, a large number of design parameters were investigated. Among these were the thickness of the HDPE plates, the height of the plates, the length of the plates between two consecutive steel diaphragms, etc. Initially, simple finite element models were developed using beam elements as HDPE plates in LS-DYNA. A large number of configurations were tested with these simple models to gain an insight to the problem and to narrow down the number of parameters. Later on, detailed finite element models with shell elements as HDPE plates were developed to come up with the final configuration of the device. HEART crash cushion has passed the full-scale test requirements in accordance with guidelines presented in NCHRP Report 350.

Development of the HEART cushion is a good example of the use of finite element analysis as a tool for analysis, design and optimization of roadside safety devices.

Introduction

Longitudinal safety barriers, such as guardrails and median barriers, are frequently installed on highways to contain and/or redirect the errant vehicles away from a safety hazard. When these longitudinal barriers are installed within the clear zone or in a manner such that they might be hit head-on by an errant vehicle, it is essential that these safety barriers be terminated with an end treatment that will not spear, vault, or roll the vehicle.

Roadway crash cushions are widely used to absorb energy and decelerate impacting vehicles in a controlled manner. Typically, crash cushions are positioned to shield motorists from fixed objects located within the roadway environment. Crash cushions are often positioned in front of obstacles such as concrete columns and abutments. Also, crash cushions are often located at the end of a guardrail installation to prevent the upraised end of the guardrail from spearing an impacting vehicle.

There are numerous crash cushion designs that rely upon frangible members, or members that are intended to shatter or be destroyed upon impact, to absorb the energy associated with a vehicular impact. A number of previous crash cushion designs also rely upon the permanent deformation of plastics or steels to absorb the kinetic energy of errant impacting vehicles. The drawback of these designs is that the crash cushion must either be completely replaced after each collision, or must undergo major repairs. Consequently a significant time and expense is incurred in replacing/repairing such crash cushions.

Some recent designs of crash cushions have focused on reusability and self-restoration as a way to decrease life-cycle costs. A new crash cushion, the Hybrid Energy Absorbing Reusable Terminal (HEART), is a combination of plastic and steel, which forms a largely self-restoring and largely reusable crash cushion.

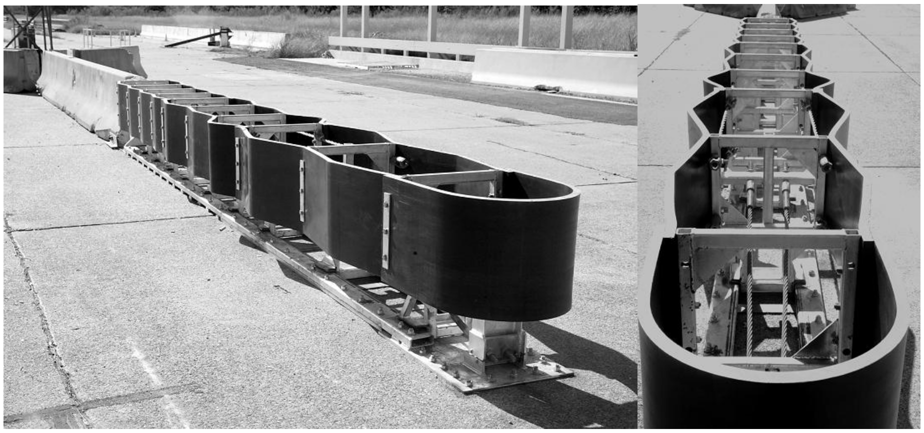

Figure 1. Hybrid Energy Absorbing Reusable Terminal (HEART) crash cushion.

The HEART is composed of corrugated thermoplastic plates of High Molecular Weight/High-Density Polyethylene (HMW/HDPE), supported on steel diaphragms, which slide on a fixed rail as shown in Figure 1. Hinging of the plastic plates allows for energy dissipation. Varying diaphragm spacing controls stiffness of the crash cushion. In operation, a vehicle colliding in an end-on manner with the upstream end of the energy absorbing crash cushion will cause the corrugated panels to bend angularly at their points of flexure and thus cause the cells to collapse axially, dissipating the kinetic energy of the vehicle. The use of thermoplastic, such as polyethylene, results in a reversible, self-restoring collapse of the crash cushion; meaning the crash cushion is reusable after most collisions.

Finite element analysis with LS-DYNA was used extensively to develop the final configuration of the HEART crash cushion. The modeling and simulation approach is presented below.

Approach

The design process started from a conceptual stage with the objective to disseminate the kinetic energy of a vehicle (820 Kg passenger car and a 2000 Kg pickup truck) traveling at 100 Km/h to mainly plastic deformation of sequentially folding HMW/HDPE plates. The plates were to be attached to steel diaphragms that were to slide on a fixed rail as the vehicle compressed the crash cushion. The National Cooperative Highway Research Program (NCHRP) Report 350 evaluation criteria, which is used for approving any new roadside safety device, comprises of three main components; a) the structural adequacy of the vehicle after the impact, b) the post-impact vehicle trajectory, and c) the occupant risk (Ross 1993). For this design concept, meeting the occupant risk criteria was the toughest design challenge. According to NCHRP Report 350, the occupant risk numbers a calculated based on Flail Space Model, where the impact velocity and Ridedown acceleration of an unrestrained point mass occupant are calculated based on the acceleration data from the test vehicle (Ross 1993). The Occupant Impact Velocity (OIV) and the Ridedown acceleration values should not be more than 12 m/s and – 20 g’s respectively for a roadside safety device to pass the evaluation criteria.

During the course of this design process, a large number of finite element simulations were conducted and occupant risk numbers for each of these cases were calculated. These numbers were used as a guide to lead to the final configuration of the HEART crash cushion.

Design Parameters

The design parameters investigated were the following.

- Thickness of the HMW/HDPE plates
- Height of the HMW/HDPE plates
- Length of the HMW/HDPE plates between adjacent steel diaphragms
- Sequence of various HMW/HDPE plate thicknesses to achieve variable cushion stiffness
- Sequence of various HMW/HDPE plate heights to achieve variable cushion stiffness
- Sequence of various HMW/HDPE plate lengths to achieve variable cushion stiffness
- Eccentricity in the HMW/HDPE plates between two steel diaphragms

In order to develop a device that would successfully stop an 820 Kg passenger car and a 2000 Kg pick-up truck, a varying stiffness along the length of the crash cushion is required.

The thickness and the height of the plates directly control the stiffness of the HMW/HDPE plate. The design matrix included three different thicknesses (25 mm, 32 mm and 38 mm) and four different plate heights (305 mm, 457 mm, 508 mm, 607 mm). The length of the plate between two consecutive diaphragms is also a factor in controlling the stiffness of that particular segment of the crash cushion. A longer HMW/HDPE plate would fold/buckle at lower loads as compared to a shorter plate segment. Three different lengths (1219 mm, 813 mm and 610 mm) were evaluated in the design matrix. Other than variation in the thickness, height and length of the plates, the sequence/pattern of each of these parameters was also evaluated.

As can be seen from Figure 1, a small amount of eccentricity was developed at the center of each of the plate segments. This was done to insure that during a vehicular impact, the plates fold/buckle outward, away from the center line of the crash cushion. Several eccentricity values were also evaluated in the design matrix.

During the entire course of the design process, from simplified to detailed models, a total of approximately 220 finite element simulations were conducted. Majority of these simulations were used to evaluate different design variations, and to close in on a final configuration that was most liable to pass the NCHRP Report 350 test criteria.

Material Model

The commercial designation for the HMW/HDPE sheeting used is PE3408 and was produced by Compression Polymers Group of Scranton, PA. LS-DYNA material model MAT_PLASTIC_KINEMATIC (MAT_003) was used to model the HMW/HDPE plates.

Simplified Finite Element Beam Models

Given the list of design parameters as mentioned above, a large number of simplified finite element simulations were conducted. The simplified models consisted of HMW/HDPE plates modeled by Hughes-Liu beam elements. The cross-section of beam elements was defined such that it had the thickness and width of the HMW/HDPE plates. The vehicle impact was modeled using a rigid block of 3D solid elements as shown in Figure 2. The rigid block had the mass of the impacting vehicle (i.e. 820 Kg for a small passenger car, or 2000 Kg for a pickup truck) and the required initial velocity (100 Km/h).

In this simplified beam model, steel diaphragms were included using lumped masses between two adjacent segments as shown in Figure 3. Figure 2 and Figure 3 also show that in the absence of a rail system, the model was constrained such that it could only translate along the direction of impact. One end of the crash cushion model was merged to move with the rigid block while the other end was fully constrained. The deformed shape from a typical simulation result is shown in Figure 4.

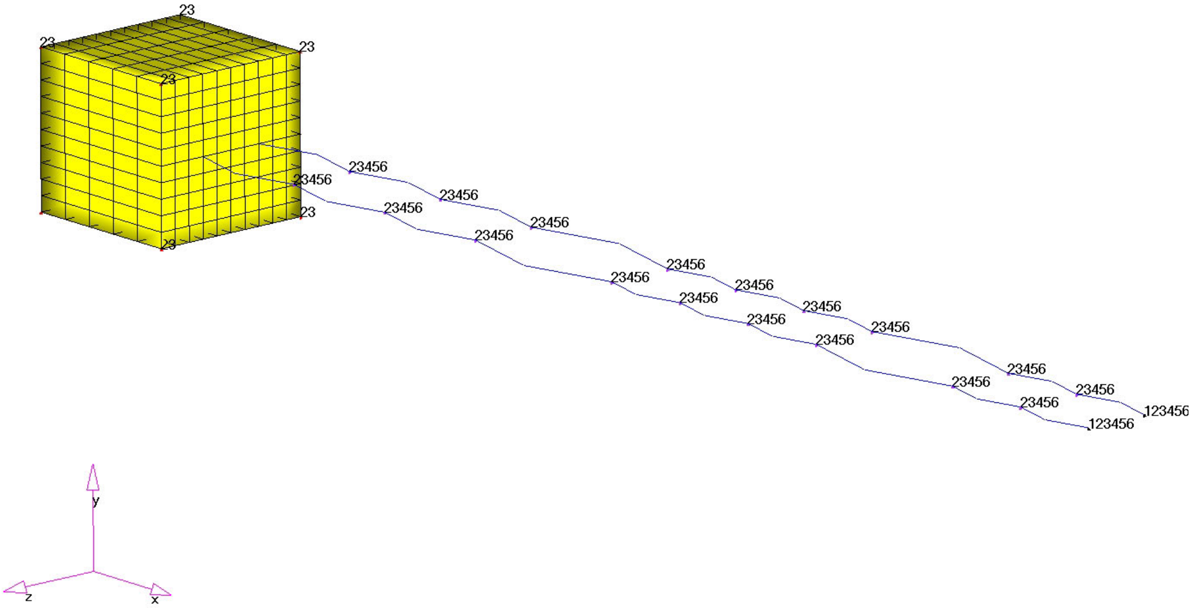

Figure 2. Simplified beam model for HEART crash cushion.

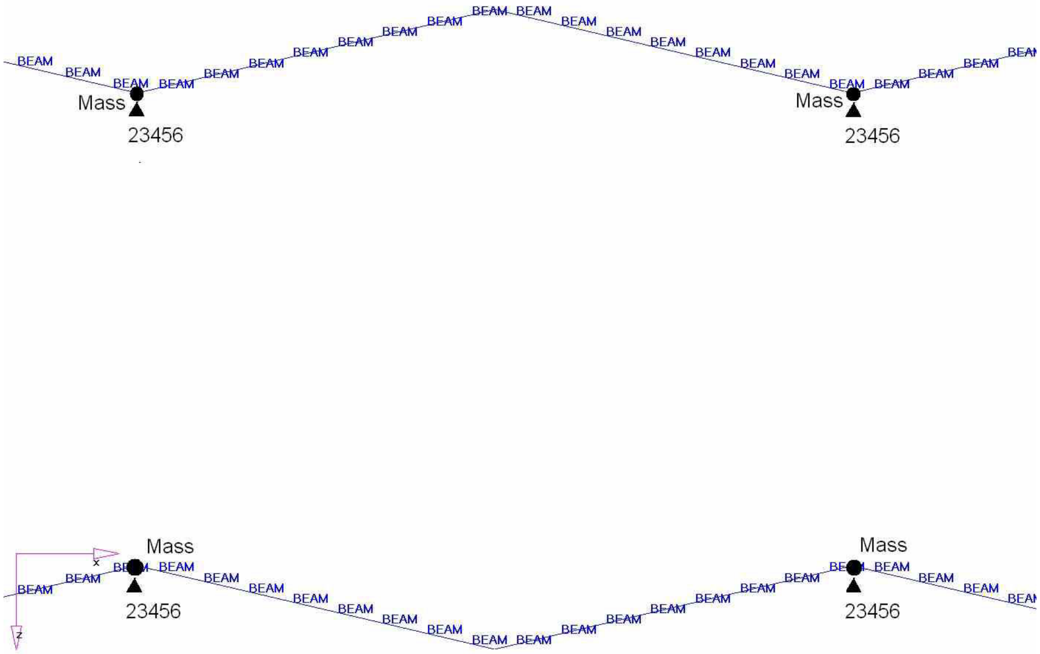

Figure 3. Finite element model detail for the simplified beam model.

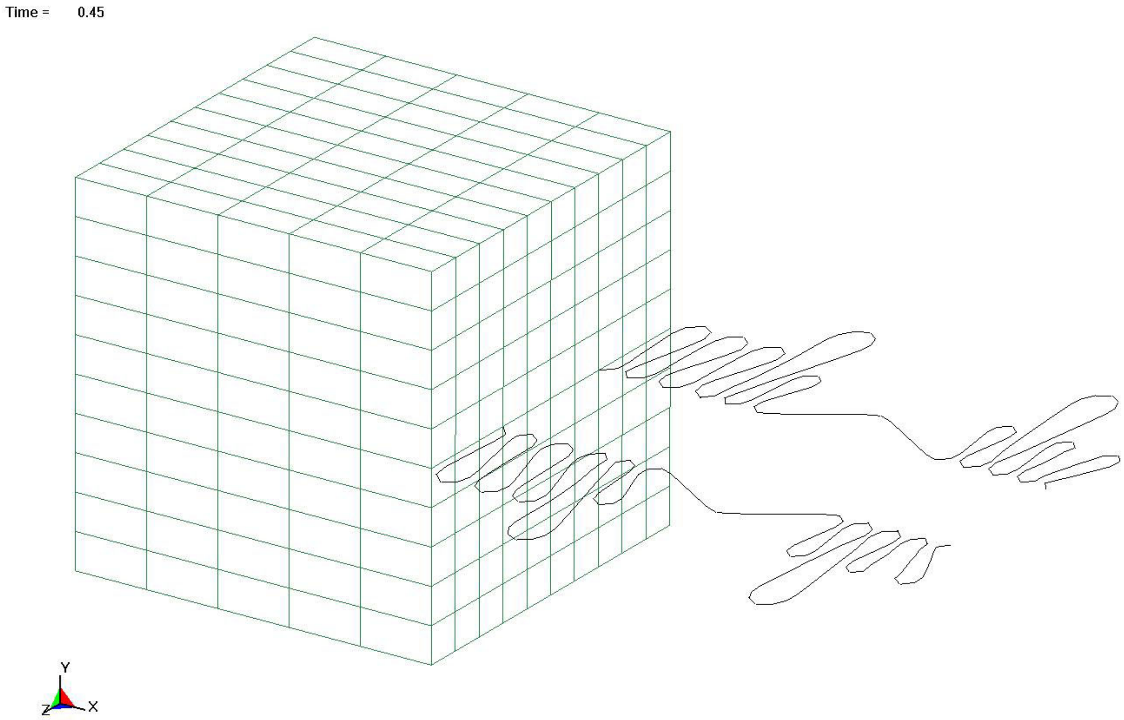

Figure 4. Deformed state of the simplified beam model for HEART crash cushion.

Based on results from these simplified models, it was concluded that the appropriate plate thickness and height would be 32 mm and 508 mm respectively. It was found that the length of the plates between adjacent diaphragms could adequately control the stiffness of the crash cushion. Therefore, the thickness and the height of the plates were not varied in subsequent simulation study.

Lengths of the HMW/HDPE plates between adjacent steel diaphragms of crash cushion were defined as ‘long’, ‘medium’ and ‘short’ (long = 1219 mm, medium = 813 mm and short = 610 mm). In order to achieve variable stiffness along the crash cushion, following five unit configurations were suggested.

- long+long
- long+short+short
- short+short+long
- medium+medium+medium
- short+short+short+short

So basically a ‘long+short+short’ unit implied three adjacent segments of plate lengths 1219 mm, 610 mm and 610 mm. From the simplified beam model study, it was perceived that some combination of any three of the above five units would yield a final configuration meeting the NCHRP Report 350 evaluation criteria.

Pendulum Testing and Finite Element Model Validation

Detailed finite element models were developed as the next step. Before developing models for the full-scale crash cushion configurations, smaller unit models were developed.

The smaller unit configurations were crash-tested using an 871 Kg pendulum impactor with a rigid bumper nose. The pendulum was dropped from a height such that the impact velocity was 35 Km/h. The acceleration data was collected from the pendulum impactor. These pendulum drop tests were also simulated with the detailed models similar to the one shown in Figure 5 thru Figure 7. The acceleration data collected from one such case is presented in Figure 8 and shows good correlation with the crash test data.

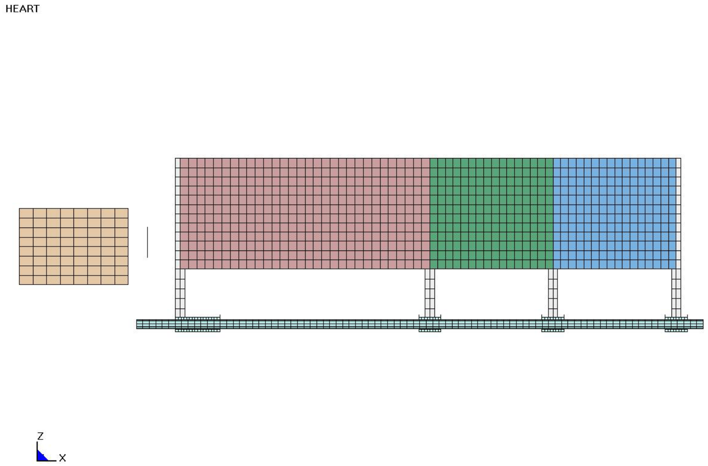

Figure 5. Detail finite element models for a 'long+short+short' unit (side view)

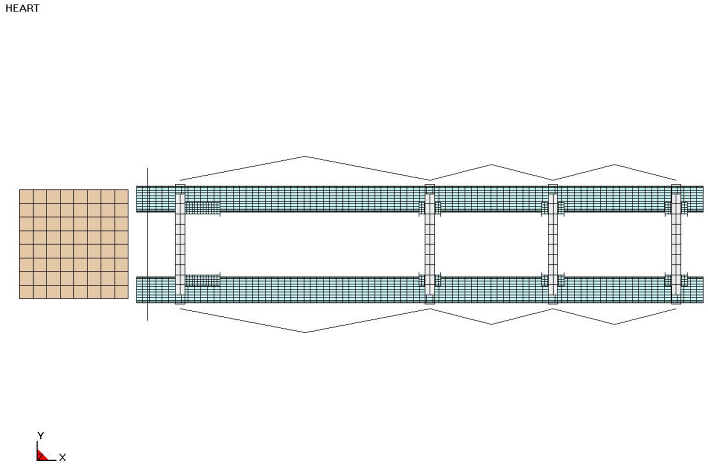

Figure 6. Detail finite element models for a 'long+short+short' unit (top view)

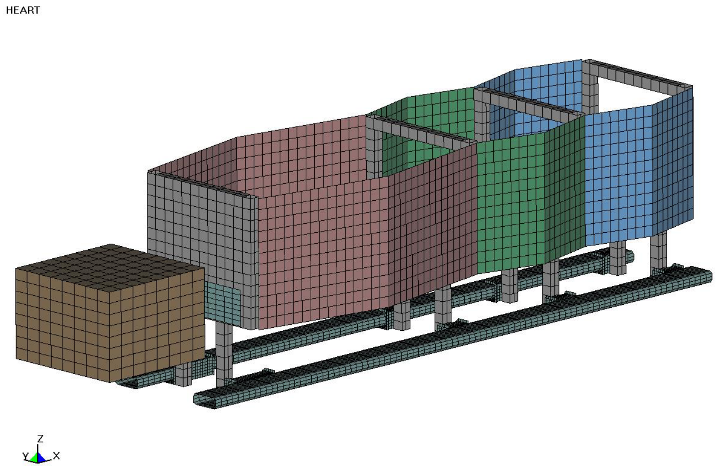

Figure 7. Detail finite element models for a 'long+short+short' unit (isometric view)

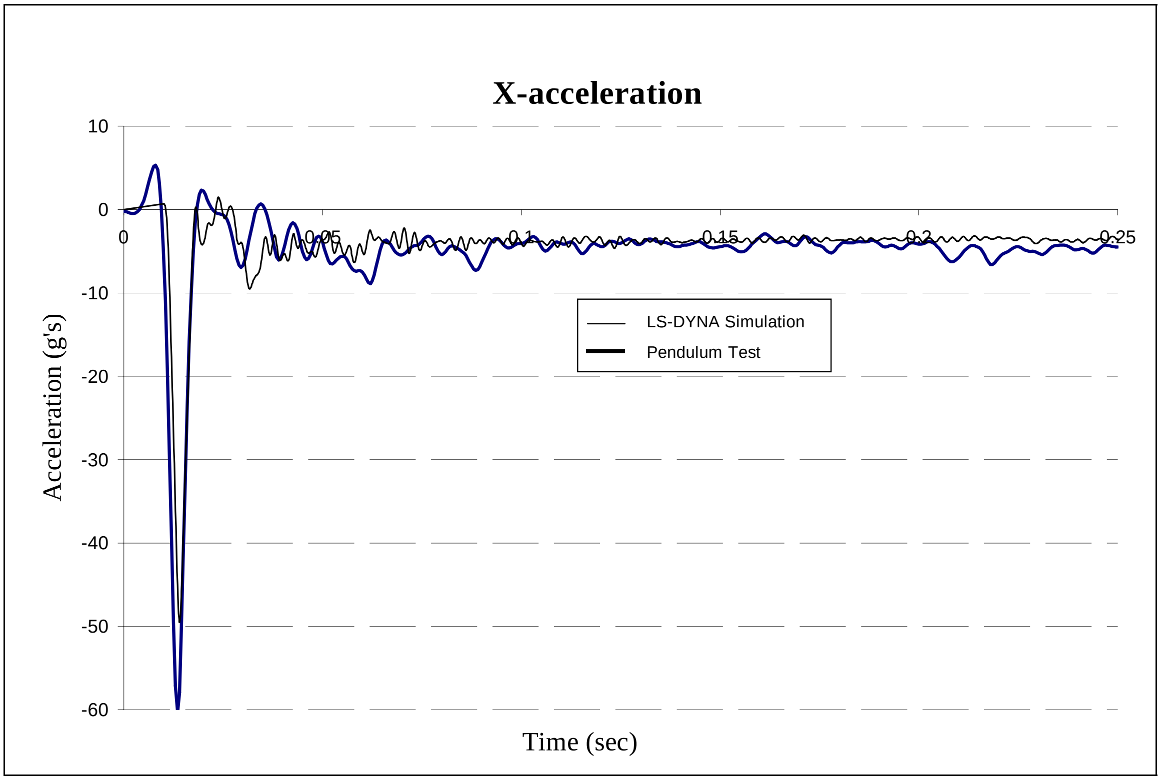

Figure 8. Acceleration plots for a 'long+short+short' unit.

The HMW/HDPE plates were modeled using fully integrated shell elements. The steel diaphragms and rail were modeled as rigid materials since no significant deformation takes place in these parts. The pendulum head and the bumper plate were also modeled rigid with proper mass and velocity assigned to them.

Full Scale Finite Element Shell Models

Once the finite element models were validated through pendulum testing, several configurations were tested using full-scale finite element models. One such configuration is shown in Figure 9. This crash cushion model is an extension of the smaller unit configurations developed for validation against the pendulum tests. A simplified finite element vehicle model was used in these simulations. The rear end of this 820 Kg vehicle model is mostly a rigid structure with lumped masses. Front part of the vehicle is deformable, but is nevertheless simplified compared to other more detailed models available. The advantage of using this vehicle model was the savings in CPU time for completing full-scale simulations. Since a large number of simulations were to be made, this vehicle model provided a fast and reasonably accurate measure of including the vehicle frontal crush in the model.

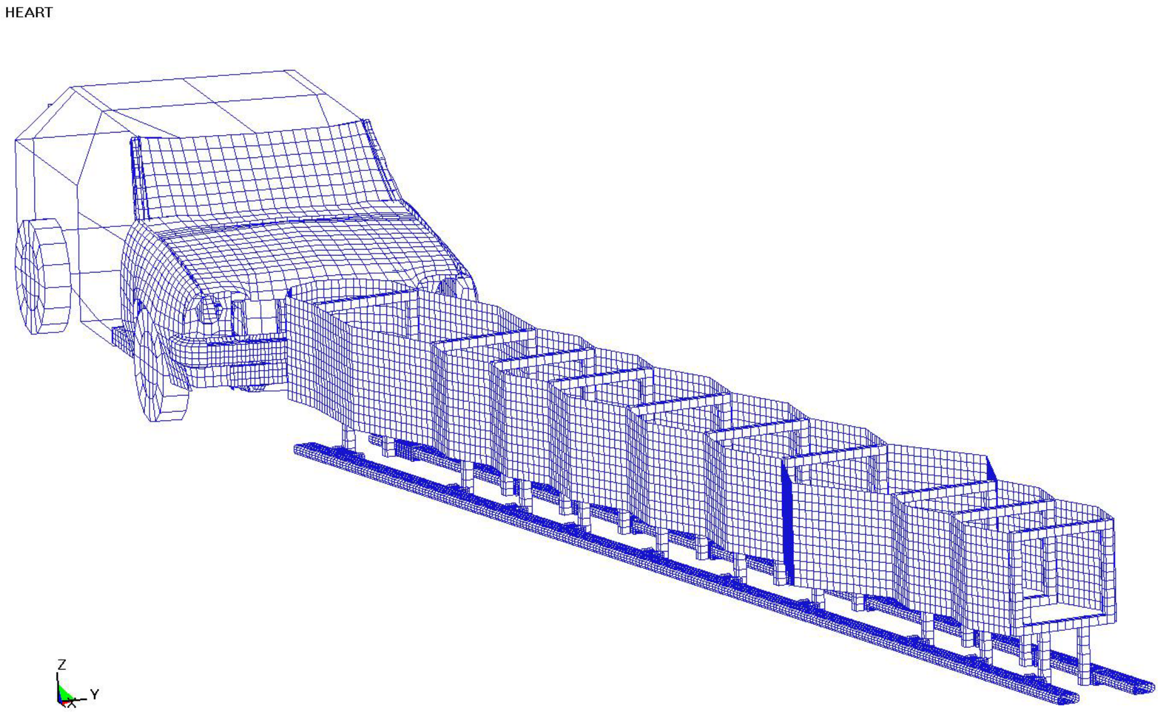

Figure 9. Detail finite element models for the HEART crash cushion.

After several design iterations, a configuration that passed the OIV and Ridedown accelerations criteria was selected based on the acceleration data from simulation results. This configuration is the one shown in Figure 9. It consisted of one ‘long’, two ‘short’, three ‘medium’, one ‘long’ and two ‘short’ segments in that order. A HMW/HDPE nose was also added to the impact side of the cushion. The prototype with this configuration was built and tested according to the NCHRP Report 350 test designation 3-32. An 820 Kg passenger car impacted the crash cushion end-on at a nominal impact speed and angle of 100 Km/h and 15 degrees with the centerline of the vehicle aligned with the centerline of the nose of the crash cushion.

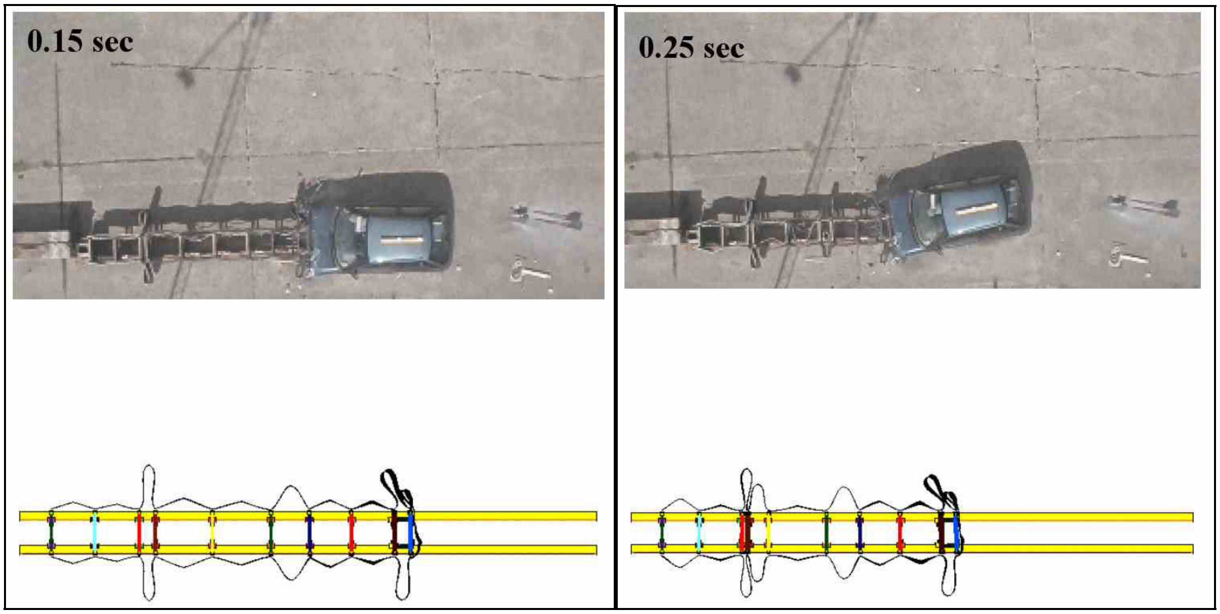

Figure 10. Deformation comparison between simulation and test (car model hidden in simulation).

The comparison between crash cushion deformation in the simulation and the actual test are shown in Figure 10. It can be seen that the deformation results from the simulation correlate very nicely to the test. However, the simulation predictions of the occupant risk numbers did not match the test numbers. The occupant risk values in the test (OIV = 13.4 m/s and Ridedown acceleration = –27.4 g) were higher than what was predicted (OIV = 11.4 m/s and Ridedown acceleration = –16.8 g). Consequently the test did not meet the NCHRP Report 350 requirements, even though the simulation results for deformation showed a nice correlation. The acceleration data obtained from the vehicle model was not accurate enough due to the simplified nature of the model. In order to acquire more reliable acceleration data, a very detailed vehicle model would have to be used. However, making design iterations with such a detailed vehicle model gets very expensive from CPU time requirement’s standpoint. To eliminate this problem, following simulation approach was adopted, which lead to the final successful HEART crash cushion configuration.

Using Finite Element Analysis as a Guide to Final Design

A relatively simple finite element model was developed without the rail and steel diaphragms. A surrogate impactor model as shown in Figure 11 replaced the vehicle model. This impactor consisted of a rigid block with the mass of the vehicle, a spring element with the stiffness value approximately comparable to vehicle frontal crushing and a rigid plate that impacted the crash cushion. The impactor model was constrained to translate along a single direction.

Using this simplified modeling approach, the previously tested design configuration was modeled. Occupant risk numbers obtained from this model were compared to the numbers obtained from the actual test. The difference between the two sets of data was factored into any further simulations.

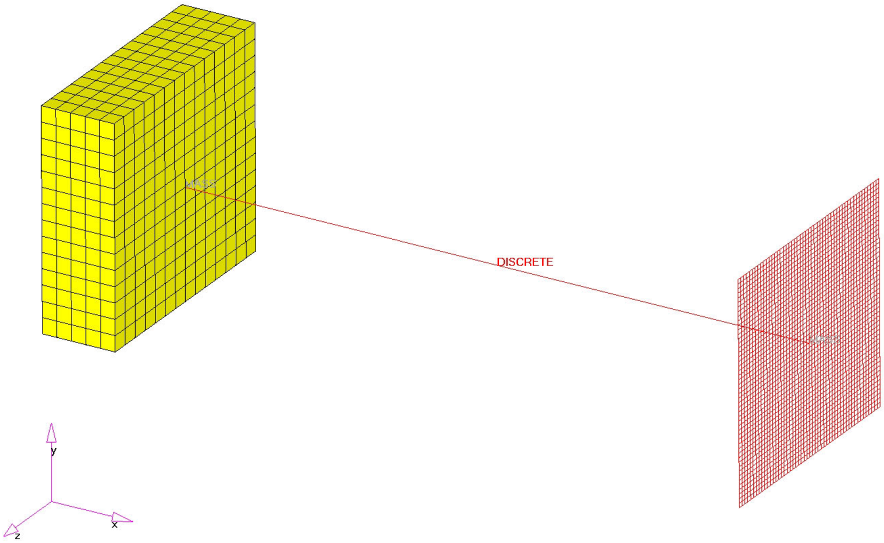

Figure 11. Surrogate impactor with spring for vehicle frontal crush

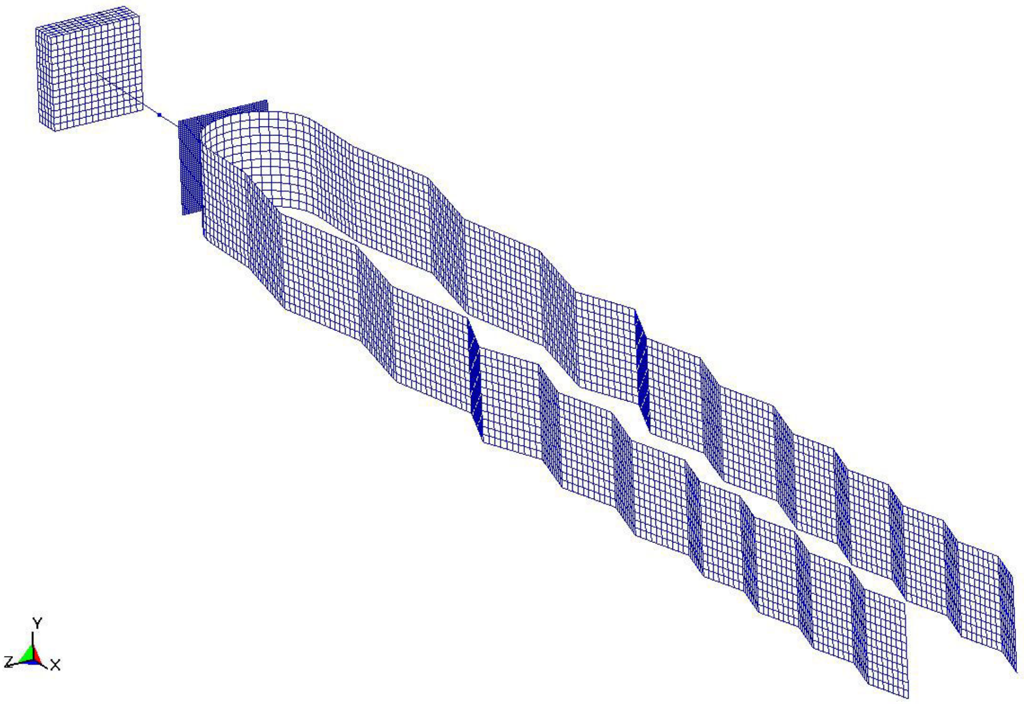

Figure 12. Simplified HEART model with surrogate impactor.

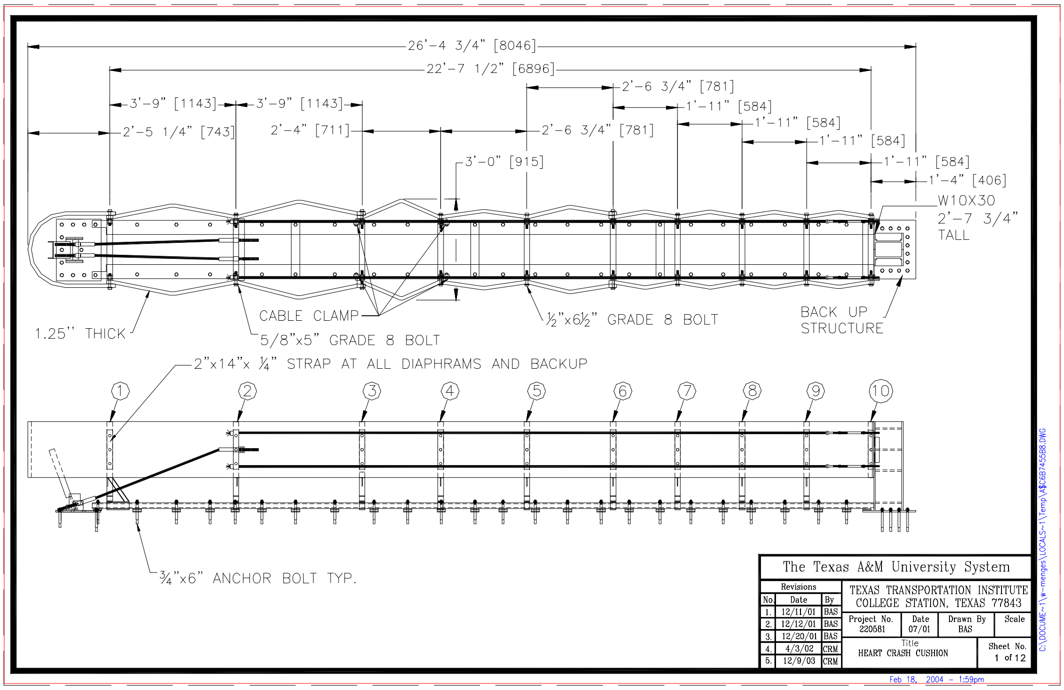

Figure 13. Final HEART crash cushion design.

Using this approach, several more iterations were made to arrive at the final configuration of the design as shown in Figure 12. A prototype with this configuration was built according to the drawing shown in Figure 13 and was tested as required by NCHRP Report 350 evaluation criteria. The HEART crash cushion met all requirements of the NCHRP Report 350.

Conclusion

The Hybrid Energy Absorbing Reusable Terminal (HEART) is a newly developed crash cushion for highway safety applications. It is composed of corrugated plates of HMW/HDPE that fold and buckle under the vehicle impact, thus disseminating the kinetic energy of the vehicle. As opposed to the conventional crash cushion designs, HEART is a reusable and self-restoring crash cushion, and therefore has a major cost advantage.

HEART has been designed and optimized through an extensive use of finite element modeling. Starting from simplified beam models, a large number of parameters were evaluated. Detailed models were then developed and validated through pendulum testing. Further details were added to develop the full-scale models. The finite element modeling and simulation approach adopted to arrive at the final design of the HEART cushion was presented in this paper.

References

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