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# IMPACT TEST OF A CRASH-ENERGY MANAGEMENT PASSENGER RAIL CAR

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## ABSTRACT

On December 3, 2003, a single-car impact test was conducted to assess the crashworthiness performance of a modified passenger rail car. A coach car retrofitted with a Crash Energy Management (CEM) end structure impacted a fixed barrier at approximately 35 mph. This speed is just beyond the capabilities of current equipment to protect the occupants. The test vehicle was instrumented with accelerometers, string potentiometers, and strain gages to measure the gross motions of the car body in three dimensions, the deformation of specific structural components, and the force/crush characteristic of the impacted end of the vehicle.

The CEM crush zone is characterized by three structural components: a pushback coupler, a sliding sill (triggering the primary energy absorbers), and roof absorbers. These structural mechanisms guide the impact load and consequent crush through the end structure in a prescribed sequence.

Pre-test activities included quasi-static and dynamic component testing, development of finite element and collision dynamics models and quasi-static strength tests of the end frame. These tests helped verify the predicted structural deformation of each component, estimate a force-crush curve for the crush zone, predict the gross motions of the car body, and determine instrumentation and test conditions for the impact test.

During the test, the passenger car sustained approximately three feet of crush. In contrast to the test of the conventional passenger equipment, the crush imparted on the CEM vehicle did not intrude into the passenger compartment. However, as anticipated the car experienced higher accelerations than the conventional passenger car.

Overall, the test results for the gross motions of the car are in close agreement. The measurements made from both tests show that the CEM design has improved crashworthiness performance over the conventional design. A two-car test will be performed to study the coupled interaction of CEM vehicles as well as the occupant environment. The train-to-train test results are expected to show that the crush is passed sequentially down the interfaces of the cars, consequently preserving occupant volume.

## INTRODUCTION

The Crash Energy Management (CEM) single car impact test is one in a series of full-scale impact tests conducted under the Federal Railroad Administration's Equipment Safety Research Program. Table 1 shows the series of tests, which will be used to compare the crashworthiness performance of existing passenger equipment to modified equipment [1,2,3,4]. This is the first of three impact tests planned to measure the performance of the CEM design integrated with existing passenger cars.

**Table 1. Full-Scale Impact Tests**

| *Test Conditions* | *Conventional Design Equipment* | *Improved Crashworthiness Design Equipment* |
|---|---|---|
| Single-car impact with fixed barrier | November 16, 1999 | December 3, 2003 |
| Two-coupled-car impact with fixed barrier | April 4, 2000 | February 26, 2004 |
| Cab car-led train impact with locomotive-led train | January 31, 2002 | 2005 |
| Single cab car impact with steel coil | June 4, 2002 | June 7, 2002 |

The purpose of the Equipment Safety Research Program is to propose strategies for improving occupant protection. The research approach involves determining appropriate test scenarios to study train-to-train collisions, developing computer models to simulate the structural and dynamic results of the collision, performing the full-scale test, processing the test data and verifying the test with the computer models. These models are then used as a baseline comparison for evaluating changes in design or operation.

Performing this sequence of tests allows a train-to-train collision to be studied in increasing degrees of complexity. The salient features of a collision can be isolated and characterized quantitatively. In the single car test the primary purpose is to observe the modes of deformation and record the force-crush characteristic. In the two-car test, the effect of the impact force being passed through the first car can be studied. Interaction through the coupler between the cars is an important feature. If there is buckling, the interfaces of the two cars may collide. The key observations in the train-to-train test include documenting how contact occurs between the cab car and locomotive, measuring the distribution of crush throughout the consist and observing whether sawtooth buckling occurs between the coupled cars. The possibility that one of the colliding cars may override is an added consideration.

Table 2 lists the critical measurements in each of the tests. These results are needed to ensure appropriate analysis of the equipment and test dummies and confidence in the models.

**Table 2. Test Descriptions and Critical Measurements**

| *Test Description* | *Critical Measurement* |
|---|---|
| Single-Car Test | - Dynamic crush force<br>- Occupant volume deceleration |
| Two-Car Test | - "Sawtooth" lateral buckling of coupled cars<br>- Influence of trailing car on maximum occupant volume deceleration<br>- Effectiveness of occupant protection strategies such as compartmentalization, and rear-facing seats |
| Train-to-Train Test | - Override of colliding cars<br>- Lateral buckling of coupled cars<br>- Effectiveness of compartmentalization, and seats with lap and shoulder belts<br>- Measurement of operator secondary-collision environment and test dummy response |

To improve crashworthiness performance over existing passenger car designs, CEM consists of crush zones specifically engineered to absorb collision energy. Located in the unoccupied ends of the passenger cars, these crush zones consist of a series of components with known structural characteristics. Building passenger cars with crumple zones allows the crush to be distributed throughout the length of a train during a collision [5]. This concept can limit the damaged zone to unoccupied areas in multiple cars as opposed to crushing large volumes of the first car, as is characteristic of existing equipment. The trade-off is that the accelerations experienced by the occupants are higher than in a conventional test, but within survivable limits over such a short period of time.

The test described in this paper was conducted on December 3, 2003. During this test, a cab car retrofitted with a CEM end structure impacted a fixed barrier at 34.1 mph. The specific objectives for this impact test are as follows:

1) Measure the force-crush behavior of the end structure
2) Observe the primary modes of deformation
3) Measure the gross motions of the passenger car
4) Verify that the triggers and crushable elements perform/deform as designed

This paper presents preliminary versions of the targeted test results. The primary concern is to contrast the modes of deformation and gross motions of the CEM car with the results for the conventional vehicle. A more detailed analysis is currently underway.

## CEM DESIGN

The full-scale testing on conventional equipment established a baseline representation of the crashworthiness performance of passenger equipment currently in use. The primary results of the conventional equipment tests demonstrate that the permanent longitudinal deformation attained in a collision is concentrated at the point of impact.

The force-crush curve measured from the tests represents the strength of the design as a function of the amount of structure crushed. Permanent deformation of conventional equipment is characterized by a high initial peak force followed by a relatively constant low force, as shown schematically by the dashed trace in Figure 1. Longitudinal damage exceeding three feet begins to intrude into the passenger compartment.

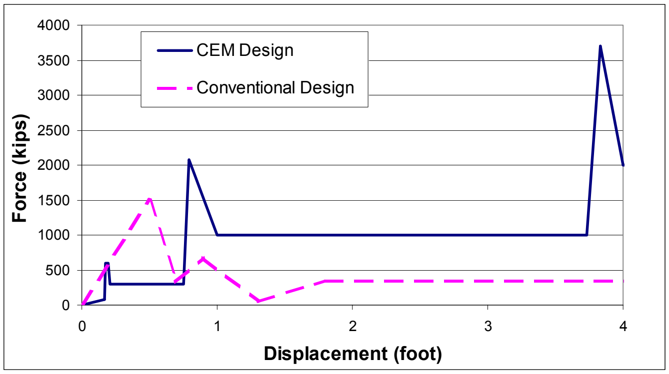


**Figure 1. Comparison of Force-Crush Characteristics**

In the November 16, 1999 test, a single Budd Pioneer passenger car impacted a fixed barrier at 35 mph. At this speed, the conventional passenger car crushed by about 5.4 feet. The kinetic energy involved in this collision was approximately 3 million ft-lbs (4.07 MJ).

The CEM design is intended to limit the structural damage from intruding into the passenger compartment. Crush zones, built onto vehicle ends, are expected to absorb at least 2.5 million ft-lbs (3.39 MJ) in 3 feet of crush.

The specific CEM design selected for the test is a series of trigger mechanisms and crushable components that, when activated, cause the end of the car to crush in a controlled manner. There are three primary crushable elements: the pushback coupler module, the primary energy absorbers, and the roof absorbers. While other designs were reviewed and evaluated [6], a benefit and significant feature of the design shown in Figure 2 is that it divides the impact into separate load paths for service loads and collision loads. The coupler and sliding sill components are a modified version of a conventional draft gear/coupler assembly. Service loads are absorbed into the base between the coupler, draft gear and the aluminum honeycomb. When this system fails in a collision, the load path changes to engage the primary energy absorbers.

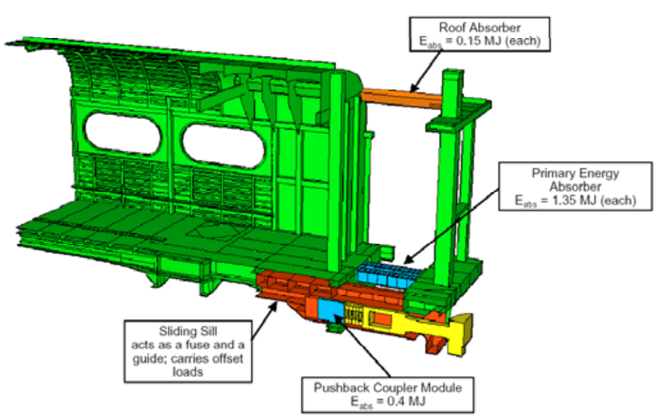


**Figure 2. Cross Section of Crash Energy Management (CEM) Design**

The CEM design has a distinctive step-like force-crush behavior. Figure 3, which is based on a finite element simulation, shows the composite response of this system. The arrows indicate where the trigger mechanism for each component is activated when a high peak force is exceeded. After each trigger, a crushable element is engaged at a relatively constant force.

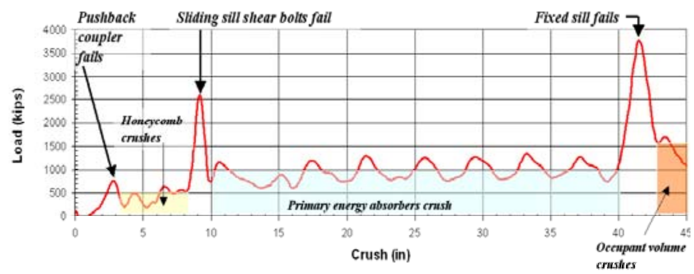


**Figure 3. CEM Load Path (From Finite Element Model)**

Portions of the curve, as indicated in Figure 3, represent the individual characteristics of each element. The pushback coupler has a conventional draft gear pad providing an initially elastic response. At an impact load exceeding about 600 kips, shear bolts fail, allowing the coupler to slide back into the sill and load an aluminum honeycomb element. When this element has been fully crushed, the coupler is encased in the underframe and the load is then transferred to the end frame. When the applied load exceeds about 2500 kips, the sliding sill and roof absorbers begin to be loaded. A second set of shear bolts then fail, allowing the sill to slide and the end frame to load the primary energy absorbers. The primary energy absorbers are rectangular beams made up of eight individual slotted cells designed to collapse in sequence when loaded from one end. The collapse of each cell is indicated by peaks in the trace shown above occurring between 10 and 40 inches. When the primary energy absorbers and roof absorbers are exhausted, (at about 40 inches of crush), the occupant volume begins to be intruded.

## TEST DESCRIPTION

The CEM single-car test took place on December 3, 2003 at the Transportation Technology Center (TTC) in Pueblo, Colorado. The test conditions are intended to be similar to those in the corresponding conventional test. The passenger car impacted the fixed barrier at a speed of 34.1 mph. The kinetic energy in the test was approximately 2.8 million ft-lbs.

The test vehicle, shown in Figure 4, was a Budd Pioneer cab car [7] retrofitted with a CEM design end structure. All work performed on this car was completed at TTC by Transportation Technology Center Inc. The underframe was cut just outboard of the body bolster. Both existing vehicle ends were removed and the CEM design and surrounding car body were installed. Great care was required to ensure that the new ends were properly integrated with the existing structure.

An operational rail passenger vehicle typically weighs approximately 100,000 lbs. The completed test vehicle weighed 71,650 lbs because it was stripped of the majority of its non-structural equipment, as well as seats and other interior fixtures. For similar reasons, the conventional test vehicle weighed approximately 75,000 lbs.

Figure 4. Photograph of Test Cab Car with CEM Design

Instrumentation requirements were defined similarly to the conventional single-car test [8]. A total of 64 data channels were required to instrument the car with accelerometers, strain gauges, and string potentiometers. The car was instrumented to measure:

- the gross motions of the car body and crush zone components in three dimensions,
- the material strain at locations throughout the car body and crush zone,
- vertical car body pitch
- and the local displacements of the crush zone and truck suspension.

Nine high-speed cameras and two video cameras were used to record numerous views of the impact test. The cameras were located to capture the overall car body motions and the modes of deformation of the crush zone from multiple angles. Target markers located throughout the car body enable photometric analysis to be performed on the high-speed film. This provides a secondary set of data to be compared against the data from the accelerometers and displacement transducers.

## MODELING APPROACH

The flow diagram illustrated in Figure 5 shows the modeling process for developing computer models and the measurements that are used to plan the full-scale impact tests. Finite element models provide a measure of the structural force/crush behavior. A collision dynamics model then uses the force/crush characteristic to produce estimates of the gross motions of the colliding bodies. With appropriate three-dimensional crash pulses, the interior occupant models allow the secondary impact motions to be simulated. These models are developed prior to the full-scale test to aid in determining the test conditions. Test results are then compared with the analysis estimates to refine the model. No occupant experiments were conducted in the single car CEM test, but will be included in the upcoming two-car and train-to-train tests to measure likely occupant environments. The single car occupant environment is significantly more severe than the train-to-train collision because the impact must be absorbed by only one crush zone.

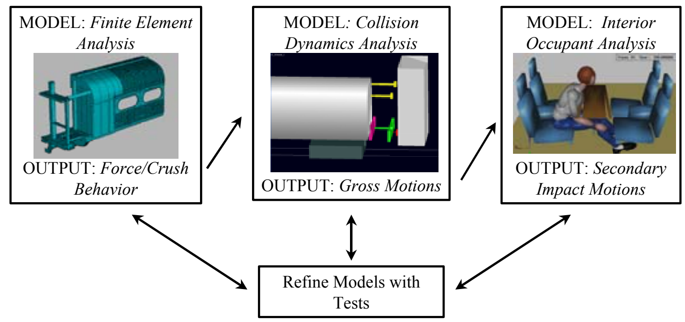


Figure 5. Modeling Process Flowchart

A detailed finite element model was developed by TIAX LLC prior to the full-scale single-car test to estimate the force-crush behavior of the crush zone during an impact [6]. The model represented the Budd Pioneer cab car with the modified end frame and crush zone, according to the CEM design drawings. This model was integral in validating that the key components of the CEM design performed as predicted, i.e. the trigger mechanisms sheared at calculated loads and the crushable elements deformed in certain shapes. The finite element model simulated the force-crush behavior shown in Figure 3. A simplified version of this behavior, shown as the solid trace in Figure 1, was used as an input for the collision dynamics model.

A collision dynamics model was developed to estimate the vehicle and component trajectories as well as the car crush during the collision. ADAMS software [9] was used to build a three-dimensional lumped-mass model. It is an extension of a one-dimensional lumped-mass model that used a single longitudinal spring to represent the CEM design [1]. The structural behavior of the crush zone is modeled as an assembly of components, with each crushable element represented as its own mass and unique nonlinear force-crush characteristic. Figure 6 shows a schematic of this model. Impact forces between the colliding elements represent the interactions that take place within the crush zone and identified by the arrows in Figure 3. The composite behavior of this assembly agrees qualitatively and quantitatively with the graph in Figure 3.

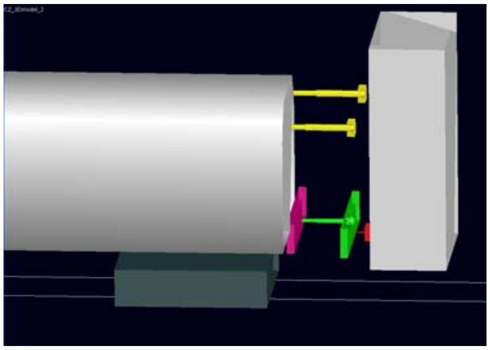

**Figure 6. Schematic of Lumped-Mass Model**

The collision dynamics model is used to predict the gross motions of the car body and the permanent longitudinal deformation during the collision. In addition, by characterizing each component of the crush zone, the individual force contribution and dynamic behavior of each can be estimated. In accord with the design, the crush zone components are constrained to translate only longitudinally and remain in-line during a collision. The car body mass is allowed three translational and three rotational degrees of freedom to simulate the full range of motions during an impact. The trucks are also allowed a full range of motion and use a collection of springs and contacts to simulate the typical suspension elements and the wheel-to-rail interaction, respectively.

The curve in Figure 7 shows the longitudinal crush for various impact speeds according to the pre-test model. The crush is a measure of the displacement of the end frame beginning at the coupler, which extends about 9 inches past the end frame. Beyond 3 feet of crush past the end frame the passenger compartment begins to be compromised. The target test speed was 35 mph, just as in the corresponding conventional test. The triangle indicates the pre-test estimate of crush. The test vehicle is pushed up to speed by a locomotive and released about 1000 feet before the wall; the closing speed can be controlled within 1 mph. The dashed line indicates the actual test speed with a cross marking the measured crush in the test.

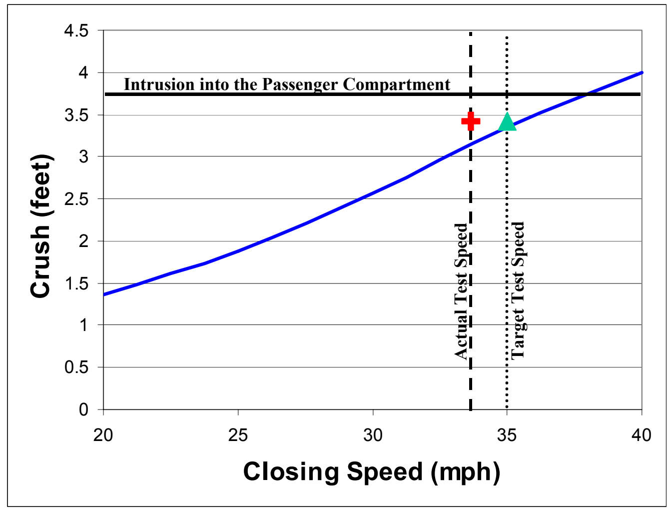


**Figure 7. Crush Estimation vs. Impact Speed**

## TEST RESULTS

The test results indicate that the CEM design has superior crashworthiness performance over conventional equipment. The conventional car experienced more than 5 feet of crush, whereas the CEM design was about 3 feet, limiting the vehicle damage to the unoccupied volume. In addition, there was no visible bending in the roof structure or car body skin.

The photographs in Figure 8 show three stills taken from the high-speed cameras of the CEM and conventional tests. These shots depict the time at which 1) the end frame contacts the wall, 2) midway through the collision and 3) full penetration of the test vehicles.

As seen in the bottom half of Figure 8, the conventional car climbed the wall, causing the front truck to lift off the tracks. These significant lateral and vertical motions are a result of the multiple modes of deformation seen by the draft sill. By employing longitudinally crushable elements in the CEM design, the crush is engineered to remain in-line, which in turn reduces the vertical motion.

**Figure 8. Still Photographs of CEM (top) and Conventional (bottom) Full-Scale Tests**

Initial results of the gross motions confirm the behavior anticipated for the CEM vehicle [1]. Figure 9 compares the velocity-time histories of the collision dynamics model (dark trace) and the test results (light trace). The plot shows excellent agreement between the model and test. The steep slope of the velocity plot shows the intensity and the timing of the collision. The CEM design completes crushing 3 feet in less than 120 milliseconds. This plot is an indication of the higher levels of acceleration in the CEM design in this test compared with the longer deceleration time in the conventional test [1].

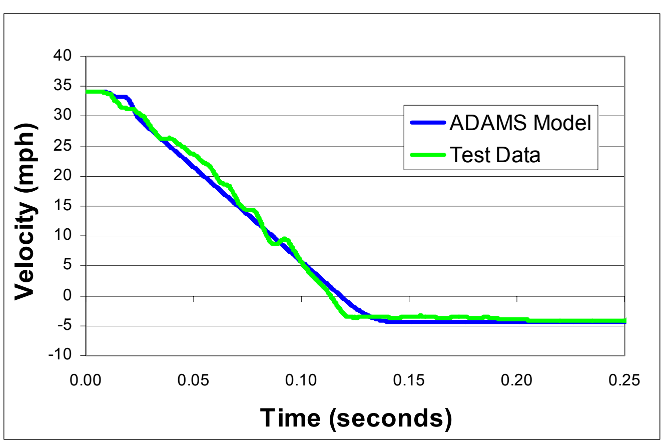


**Figure 9. Velocity-Time Histories**

Figure 10 compares the post-impact photographs of the conventional and CEM test vehicles. Beyond the 5 feet of permanent deformation, local deformations are clearly visible in the roof and car body skin. Contrastingly, the orchestrated collapse of designated crumple zones in the CEM design results in a quick and tidy in-line collision. No damage was visible beyond the intended crushed elements. Because damage is limited to the first three feet of the car, it can be reused after the crush zone is removed from the body and a new crush zone is installed.

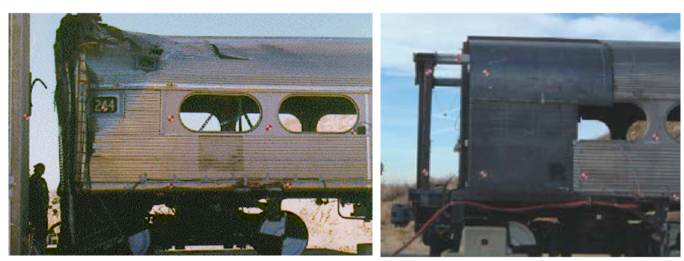

**Figure 10. Post-Impact Photographs of Conventional (left) and CEM (right) Test Vehicles**

The load path moved through the crush zone as predicted and triggered the crush of each of the energy absorbing mechanisms. Upon impact the load path initially triggered the shear bolts of the pushback coupler, causing the coupler to slide into the underframe of the car end. The impact load then transferred to the buffer beam and anti-telescoping plate of the end frame, which initiated the primary energy absorbers and the roof absorbers.

Figure 11 shows the controlled collapse of the CEM design with the key components identified. The pushback coupler and sliding sill become neatly encased under the passenger compartment, allowing the primary energy absorbers to crush. For comparison, Figure 12 shows the conventional underframe counterpart [10]. Its draft sill has multiple modes of deformation and crushes into a contorted shape. The post-test results indicate that the CEM design did perform as intended to allocate crush to specific zones.

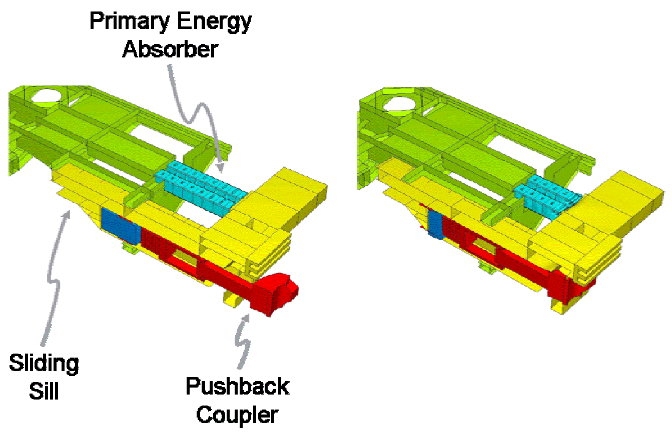


**Figure 11. Schematic of CEM Underframe Pre- and Post-Impact**

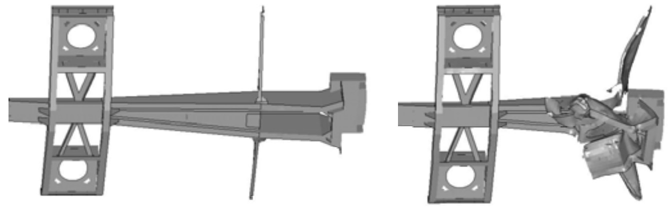

**Figure 12. Schematic of Conventional Draft Sill Pre- and Post-Impact**

Figure 13 shows a partial bottom view of the primary energy absorbers (painted yellow and white), located on both sides of the draft sill. The following pictures show the progressive crush as each cell collapses in sequence. The red arrows in the first picture point at the first cell that will collapse during the impact. The second and third pictures show the energy absorbers half crushed and fully exhausted, respectively. Initially three feet in length, the full collapse of the energy absorbers accounts for about 80% of the total energy dissipated in the crush zone.

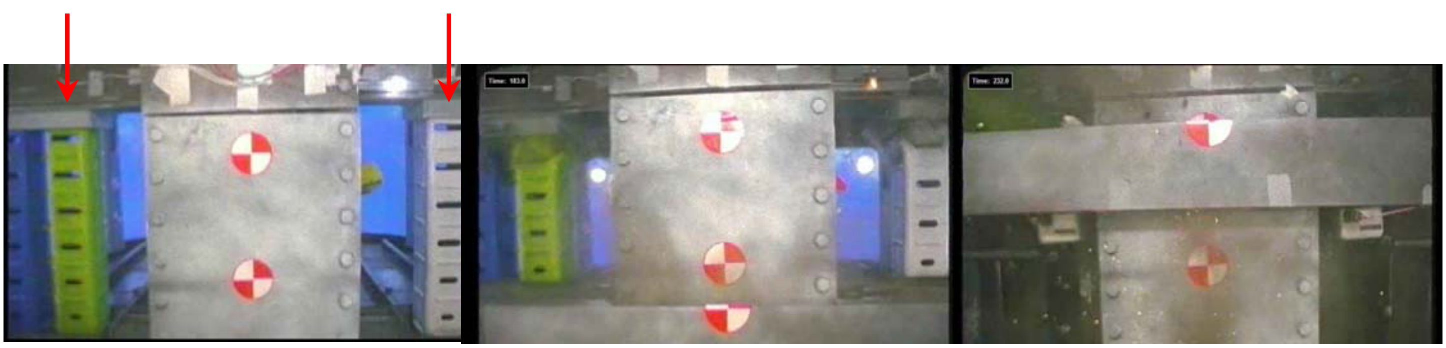

**Figure 13. Still Photographs of Primary Energy Absorbers in Full-Scale Test**

## SUMMARY AND CONCLUSION

The test results show that the CEM crush zone performed as engineered. The following results are evidence of a successful test:

- Crush elements remained in-line.
- Crush elements triggered at approximate loads intended.
- No damage was done to the occupant compartment.

By limiting the crush to a designated unoccupied area, the test demonstrated that the ends of the test vehicle could be readily removed and replaced with a new crush zone. This test indicates that, in the case of operational use, a car that survives a similar collision could potentially be returned to service after replacement of the crush zones.

In comparison with pre-test design estimates, the overall test performance was in close agreement. Single car test data is currently being further processed and analyzed. Additionally, test results are being used to refine the test model. With modified force-crush behavior, the gross motions of the model will more accurately simulate the crushing modes and force levels.

The two-car test will show the transfer of crush to a subsequent series of crush zones as well as the coupled interaction and resultant car body alignment. In addition, multiple interior occupant tests will be performed. The interior environment in the two-car test is a more realistic simulation of the conditions in a train collision than the single car test. Accelerations in each car are influenced by the effects of the interaction between the vehicles.

In the CEM train-to-train test, it is expected that crush will be distributed along the consist. It is anticipated that the crumple zone will contribute to keeping the cars in-line. A variety of occupant tests will also be performed to measure the occupant environment throughout the train.

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