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IMPACT TESTS OF CRASH ENERGY MANAGEMENT PASSENGER RAIL CARS: ANALYSIS AND STRUCTURAL MEASUREMENTS

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ABSTRACT

Two full-scale impact tests were conducted to measure the crashworthiness performance of Crash Energy Management (CEM) passenger rail cars. On December 3, 2003 a single car impacted a fixed barrier at approximately 35 mph and on February 26, 2004, two-coupled passenger cars impacted a fixed barrier at approximately 29 mph. Coach cars retrofitted with CEM end structures, which are designed to crush in a controlled manner were used in the test. These test vehicles were instrumented with accelerometers, string potentiometers, and strain gages to measure the gross motions of each car body in three dimensions, the deformation of specific structural components, and the force-crush characteristic of the CEM end structure.

Collision dynamics models were developed to predict the gross motions of the test vehicle. Crush estimates as a function of test speed were used to guide test conditions. This paper describes the results of the CEM single-car and two-car tests and provides results of the structural test.

The single-car test demonstrated that the CEM design successfully prevented intrusion into the occupied volume, under similar conditions as the conventional test. During both CEM tests, the leading passenger car crushed approximately three feet, preserving the occupant compartment. In the two-car test, energy dissipation was transferred to the coupled interface, with crush totaling two feet between the two CEM end structures. The pushback of the couplers kept the cars in-line, limiting the vertical and lateral accelerations. In both the conventional tests there was intrusion into the occupant compartment. In the conventional two-car test sawtooth lateral buckling occurred at the coupled connection.

Overall, the test results and model show close agreement of the gross motions. The measurements made from both tests demonstrate that the CEM design has improved crashworthiness performance over the conventional design.

INTRODUCTION

As part of the Federal Railroad Administration's Equipment Safety Research Program, a series of full-scale impact tests are currently being conducted. The purpose of this program is to propose strategies for improving occupant protection under common impact conditions. This is accomplished by comparing conventional passenger equipment to a modified design under similar collision conditions. The sequence of tests shown in Table 1 allows the study of in-line collisions in increasing degrees of complexity. The modified equipment was expected to show incremental crashworthiness improvement over the current equipment.

Table 1. Full-Scale Impact Tests

	Test Conditions	*Conventional Design Equipment*	*Modified Design Equipment*
In-line impact tests	Single coach car with fixed barrier [1], [5]	11/16/1999 35.1 mph	12/3/2003 34.1 mph
	Two coach cars with fixed barrier [2]	4/4/2000 26.3 mph	2/26/2004 29.3 mph
	Cab car-led train with locomotive-led train [3]	1/31/2002 30.0 mph	2005
Oblique impact tests	Single cab car with steel coil [4]	6/4/2002 14.4 mph	6/7/2002 14.0 mph

The completed conventional tests were intended to establish performance of the existing fleet. The first two in-line tests of the modified design have been completed and the train-to-train test is tentatively planned for late 2005. This paper will discuss the initial comparisons of the crashworthiness performance of the conventional passenger equipment with modified equipment as well as the structural performance of the design through the test data.

The secondary objectives of the tests are related to the modeling development process. Computer models were used to predict the collision outcome and to determine the pre-test conditions. The models are modified based on the test results for future use in predicting outcomes for similar collision scenarios.

In the single-car test, the critical measurements are made to obtain a force-crush characteristic and to measure the gross motions of the test equipment. The two-car test adds consideration of the interactions of the coupled connection, i.e. measuring the vertical and lateral motions of the car respective to each other and observing the potential for sawtooth lateral buckling to occur. The train-to-train test focuses on the interactions of the colliding equipment, i.e. how the equipment engages and the potential for override of the colliding vehicles. Additionally, the effects of the collision throughout the train are measured.

Table 2 lists the key measurements made during each test. The modified design for the in-line collisions consists of a crush zone intended to provide controlled progressive collapse of an unoccupied region. The italicized text of Table 2 identifies the benefits of the crush zone. The modified design enhances the crashworthiness performance of the passenger car by limiting the vertical and lateral motions of the vehicle and allocating crush to the designated crush zones at each end of the passenger cars.

Table 2. Test Descriptions and Critical Measurements

Test Description	*Key Observations*
Single-Car Test	- Modes of deformation - Dynamic crush force - Gross motions of vehicles - *Minimized vertical and lateral motions*
Two-Car Test	- Interactions of coupled cars - *Cars remain in-line* - *Distribution of crush to the trailing car*
Train-to-Train Test	- Interactions of colliding equipment - Override of colliding cars - Lateral buckling of coupled cars - *Distribution of crush along consist* - *No override and no lateral buckling*

This paper primarily describes the test conducted on February 26, 2004. During this test, two coach cars retrofitted with Crash Energy Management (CEM) end structures impacted a fixed barrier at 29.3 mph. An analysis of the structural test results, model predictions, and a comparison with the corresponding conventional equipment tests are described below.

BACKGROUND

A goal of the full-scale testing program is to show how a modified design can improve crashworthiness performance by increasing occupant volume preservation. Testing of conventional equipment has established a baseline against which the second set of tests can be evaluated.

There are two important performance differences between conventional and CEM designs. CEM cars can more efficiently absorb collision energy and crush is transferred to the following cars in a train rather than being concentrated exclusively on the lead car. The CEM design developed for these tests is intended to absorb at least 2.5 million ft-lbs in the first three feet of the end structure [6]. This dissipation is accomplished by the controlled crush of three primary components: the pushback coupler/draft gear assembly, primary energy absorbers, and the roof absorbers.

The distinctions between the conventional and CEM equipment can be illustrated in idealized force-crush characteristics. Collision performance of conventional equipment typically concentrates crush at the front end of the lead passenger car of the colliding vehicles. Figure 1 shows that there is little resistance to deformation once the peak load is exceeded. The tiered force-crush behavior that characterizes a CEM design is illustrated in Figure 2. The dashed line shows the concept used to prescribe the design and the solid line is a schematic representation of the test results. The initiation of failure at each stage involves a peak load followed by a slightly lower uniform load that sustains the progressive collapse of each element. The third peak represents the loading of the draft sill. The occupant compartment begins to be challenged when the third peak of the CEM load characteristic is exceeded. Beyond this point, the passenger car crushes with a load characteristic similar to a conventional car. The series of elements that make up the CEM design create the double-tiered characteristic, which causes the load to be passed to successive crush zones before the leading one is exhausted. Note that both figures have the same load scale. The scale of crush distance shows the unoccupied region of the car. Once the initial peak of the conventional characteristic is reached the passenger car crushes at a relatively constant load. The CEM design must exceed the increasing double-tiered load characteristic before intrusion into the occupant compartment occurs. Comparison of the areas under the curves in Figure 1 and Figure 2 shows that the CEM design can absorb a larger amount of energy than the conventional design before compromising the passenger compartment.

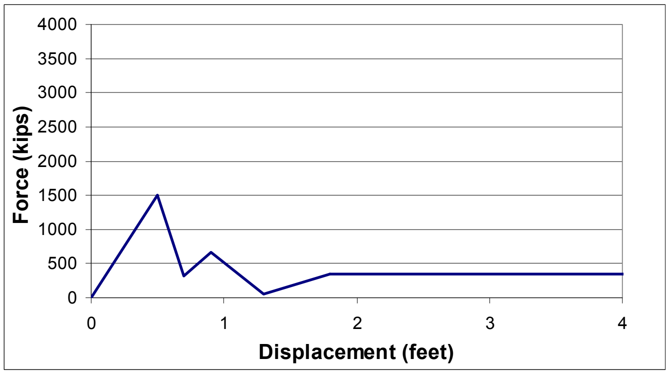

Figure 1. Idealized Force-Crush Curve for Conventional Design

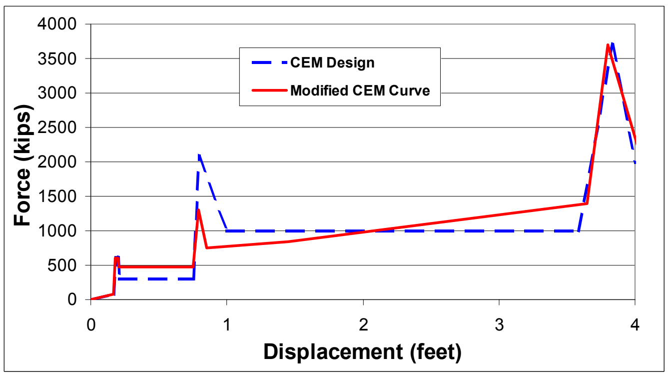

Figure 2. Idealized Force-Crush Curve for CEM Design

The Crash Energy Management design developed for these tests is characterized by a collection of trigger mechanisms supported by crushable elements. Figure 3 [6] is a cross section taken from a finite element model developed for analysis of the CEM system during design. This schematic identifies the primary components and the layout of the system. The first set of bolts shear at a prescribed load, allowing the coupler/draft gear assembly to slide back and crush an aluminum honeycomb module. When the coupler has reached its full stroke, resting in a position in-line with the end frame, the load is then transferred to the anti-telescoping plate and the end beam via the anticlimber. A second series of shear bolts act as a fuse for the sill, which slides back into the underframe causing the end frame to crush the primary energy absorbers. Simultaneously, rivets fail in shear, triggering the collapse of the roof absorbers and the resultant crush of additional aluminum honeycomb modules.

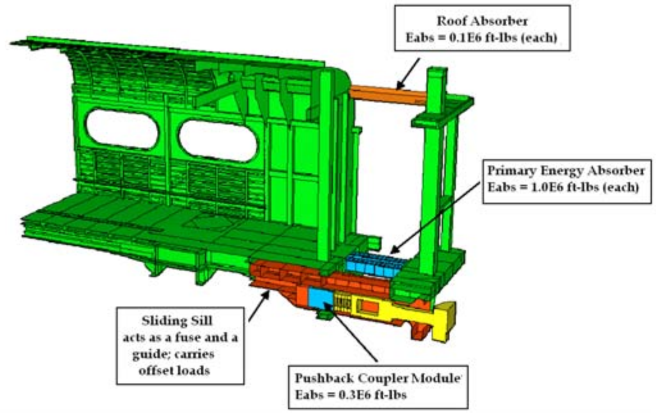

Figure 3. Cross Section of Crash Energy Management (CEM) Design

The end structure has a multi-tiered load path, allowing for service loads and collision loads to be accommodated separately. Low-level service loads are absorbed by the elastic deformation of the conventional draft gear and the coupler/draft gear assembly can absorb higher service loads. The primary energy absorbers are activated only when this system is exhausted, as in a collision condition. This feature ensures the integrity of the crush zone by preventing the primary energy absorbers from being inadvertently triggered during daily operation.

TEST DESCRIPTION

The single-car test of a passenger car retrofitted with a CEM end structure was conducted on December 3, 2003 at the Transportation Technology Center (TTC) in Pueblo, Colorado. At a closing speed of 35.1 mph, approximately 3 feet of crush occurred, measured from the end frame. The crush zone collapsed as intended in a progressive controlled manner, and was nearly exhausted. Details of the test set-up, test conditions, and instrumentation are described in a previous paper [5].

On February 26, 2004 the CEM design was tested in a two-car impact with a fixed barrier. The test vehicles were Budd Pioneer cab cars retrofitted with the CEM end structure. The cars were pushed by a locomotive and released approximately 1000 feet away from the wall, colliding at a closing speed of 29.3 mph. A target test speed of 28 mph was chosen from pre-test models to load the crush zone just below its capability.

A typical passenger car in service weighs approximately 100,000 lbs. The Budd cars used in the CEM test were stripped of all interior seating and fixtures, as well as some exterior operational equipment. The final weights of the two test vehicles were 74,875 lbs (lead car) and 75,250 lbs (trailing car). Each CEM end structure (two per car) accounts for about 5000 lbs and each truck weighs about 7700 lbs.

The building of the test vehicles was a careful integration process performed at TTC by Transportation Technology Center Inc. (TTCI). Initial preparation of the Budd Pioneer passenger cars involved precise cuts of the car body skin and underframe just outboard of the bolster and removal of the existing end structure. The CEM end structure was then carefully integrated onto the current structure, with measures taken to meet all fabrication and construction practices. It should be noted that, because the CEM system was designed to be retrofitted onto an existing passenger car it adds no extra length or weight to the replaced structure of the Budd Pioneer coach cars. Figure 4 shows a photograph of the test vehicles located near the fixed barrier just prior to the test.

Figure 4. Photograph of Test Vehicles Prior to Two-Car Test

Instrumentation was located in order to provide the post-test data necessary to make the critical measurements described in Table 2. Each test car was instrumented with displacement transducers, accelerometers and strain gauges to take on-board data of critical measurements for analysis and modeling comparisons. String potentiometers measure relative displacements in the critical areas of the crush zone, which are useful for evaluating the timing and sequence of events. Accelerometers were placed along the carbody and on the primary components of the crush zone to measure the gross motions in three dimensions. Strain gages are used to gather strain rates to measure the timing and follow the path of structural deformation through the crush zone as well as the pulse of the collision force through the car body. 123 data channels were used for the 46 accelerometers, 39 strain gages and 38 string potentiometers. The cars were also equipped with test dummies in various seating configurations and instrumented with an additional system of data channels [7].

13 high speed cameras and 4 video cameras recorded numerous views of the test and are used to perform post-test photometric analysis that provides a secondary set of relative gross motions and displacement measures.

MODELING APPROACH

Developing computer models prior to the test provides the benefit of conducting a test that is properly documented and understood. With the models the instrumentation can be located and ranged to most effectively specify critical measurements. Details of the test conditions, such as closing speed are determined from pre-test simulations so that the equipment can be tested to a critical failure point. These models can then be used to extrapolate results to other test conditions.

Figure 5 shows a flow diagram that maps out the strategy used when conducting a full-scale test. The diagram shows how the test has been broken down into various levels of necessary analysis. The finite element model evaluates the various modes of deformation that occur and the load path. The force-crush behavior of the system is then used as model input that defines a non-linear spring of a lumped-parameter collision dynamics model. The model produces the gross motions of the car bodies and timing of events. The collision dynamics model supplies a three-dimensional crash pulse for the interior occupant models. These models generate the secondary motions experienced by the occupants in various seating arrangements. These three models are developed prior to the test and aide in determining the test conditions and required instrumentation. Once the test is completed the collision data is then compared to the models and refinements can be made to further the understanding of the collision scenario. These models can then be used to predict results for similar collision conditions.

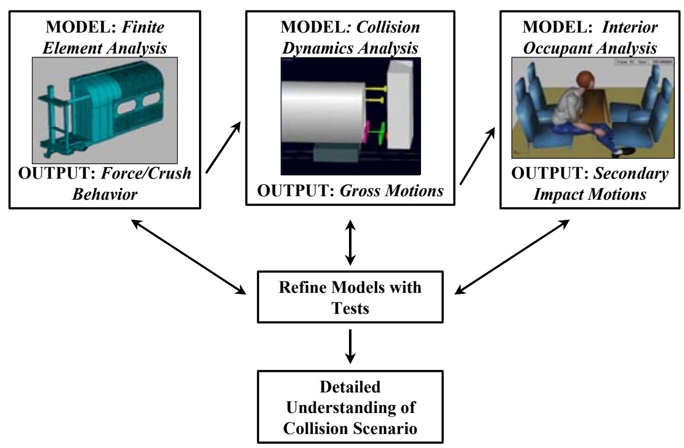

Figure 5. Modeling Process Flow Diagram

The finite element model was developed during the CEM design process [6]. Component testing required detailed simulations to verify that each component crushed as expected. The full-car model was built in accordance to the assembly drawings used for the integration of the CEM design onto the Budd coach car. The finite element model produced the initial representation of the composite force-crush characteristic of the CEM system, as shown in Figure 6.

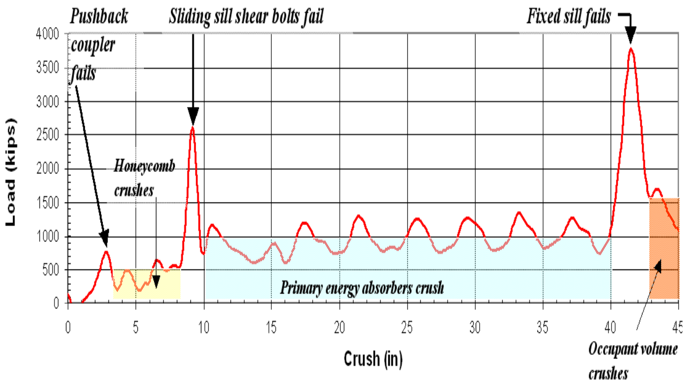

Figure 6. CEM Force-Crush Curve from Finite Element Model

Prior to the single-car test of the CEM design, the finite element model provided the estimate for the input parameters used in the collision dynamics model. The idealized form of this curve is the dotted trace shown in Figure 2. The solid line shows revisions made to this characteristic after the test data was processed and analyzed.

The collision dynamics model is a lumped-parameter representation of the colliding bodies. The schematic shown in Figure 7 shows the CEM two-car mass-spring representation. The vehicles are broken into smaller sub-systems (i.e. main car body, individual components of the crush zone, trucks) connected by springs to represent their structural stiffness or suspension characteristics. Various connecting joints allow for the appropriate multi-dimensional movement between each rigid body. Constraints are applied to simulate structural limitations. Point-to-point impact forces are tuned to classify the interaction of colliding surfaces. From this three-dimensional model, the gross motions of each rigid body can be produced for any set of initial conditions. Additionally, the crush distribution and sequence of events, both within each crush zone and at each crush zone can be simulated.

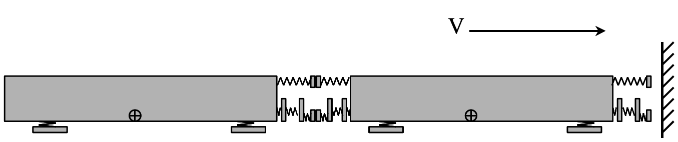

Figure 7. Schematic of Collision Dynamics Model

The amount of crush was simulated at varying test speeds to determine the impact speed at which the test should be conducted. Figure 8 shows the plot used to choose the speed for the two-car test. The pre-test force-crush characteristic was used to make these predictions. The dashed blue and solid green lines show the amount of crush at the lead car and coupled interface, respectively. The solid horizontal line shows the distance at which the crushed structure begins to intrude into the occupant compartment. The test speed, indicated by the dashed vertical line was chosen to challenge the lead crush zone just under its capability for preserving occupant volume. At the test speed, the lead car was expected to nearly exhaust the CEM system, crushing almost 40 inches. At the coupled interface, the couplers would pushback, crushing 8 inches each and the primary energy absorbers would just begin to crush. The solid green line indicates the cumulative crush of the two crush zones at the coupled interface. The CEM design is intended to both limit damage to the unoccupied area at higher speeds than the conventional test and also transfer the crush to the successive crush zones.

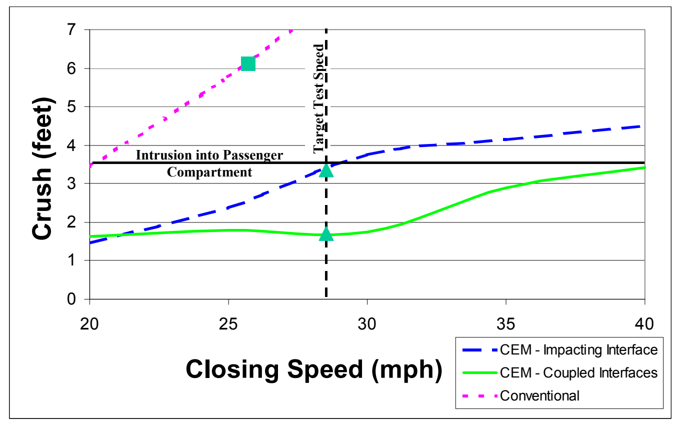

Figure 8. Crush Estimation Versus Impact Speed

The corresponding results of the conventional test are plotted on the graph by the dotted pink line. The conventional test was conducted at a speed of 26 mph. At this speed, about 6 feet of crush occurred. The incremental increase in crashworthiness protection can be seen by comparing these results. The line marking intrusion into the passenger compartment is a critical condition in determining the "safe speed" for the operation of each of these designs. This plot anticipates the CEM design to have an effective safe speed increase over the conventional design of almost 50%.

ANALYSIS OF TEST RESULTS

During the CEM two-car test the lead car crush zone was nearly exhausted, crushing 3 feet in less than 120 milliseconds. At the coupled interface, both pushback couplers failed, allowing the anticlimbers to engage and both crush zones to activate; the coupled interface crushed a total of 2 feet. Intrusion into the occupant volume was prevented and the vertical and lateral motions were limited. Approximately 3.5 million ft-lbs were absorbed by the three crush zones.

Crush

The photographs shown in Figure 9 compare the damage of the lead car in both the conventional and CEM tests. Using the trucks as a reference point in each photograph, the difference in the amount of structure crushed is easily noticeable. The conventional car impacted with the wall and climbed the wall as the car body crushed a total of 6 feet. The sill is the most significant structural member of the underframe and tends to deform gracelessly into a contorted mass of metal, causing uncontrolled crushing of the end. The conventional tests established that the draft sill can have varying modes of deformation under similar impact conditions [8]. Consequently, the uncontrolled crush of the draft sill at the base of the structure causes the car to climb the wall as it crushes.

Figure 9. Post-Test Photographs of Conventional (left) and CEM (right) Vehicles

On the other hand, the lead car of the CEM test crushed a total of 3 feet, as intended. This measurement from the end of the car corresponds to the lower triangular marker in Figure 8, which includes the crush of the coupler in the total crush measurement. Each element of the crush zone is designed to crush in a controlled manner, which effectively limits the vertical and lateral motions of the carbody during the impact. The CEM end structure collapsed in the prescribed series of events shown in Figure 6. The coupler initially impacted the wall, causing the bolts to shear at a load of approximately 600 kips and the honeycomb module to crush as the coupler slid back. The end frame was then loaded to approximately 1,300 kips, activating the trigger mechanisms in the sill and the roof absorbers. The primary energy absorbers and the roof absorbers subsequently crushed as the gap between the end frame and the vestibule wall/bolster diminished.

Crush was successfully passed to the coupled interface as the first crush zone collapsed. At approximately 60 milliseconds, both couplers triggered and began to recede into the underframe. The anticlimbers engaged as the end frames came together and load then passed into the crush zones of both ends. The load pulse through the two cars triggered the rear crush zone of the lead car slightly before the second car crush zone. The bolts of the sliding sills failed causing the primary energy absorbers to begin to crush as predicted. The primary energy absorbers of the trailing end of the lead car crushed a total of 10 inches. The second car's energy absorbers just began to crush, deforming approximately 1 inch.

Gross Motions

Figure 10 shows the final positions of the two cars during the conventional and CEM tests. During the conventional two-car test, sawtooth lateral buckling occurred at the coupled connection and the left track buckled under the lateral load. During the CEM two-car test the cars remained in-line relative to their mechanically allowable vertical and lateral variations of 3-5 inches. The front end of the lead vehicle in the conventional test lifted approximately 6 inches off the track. In comparison, the front end of the lead CEM vehicle rose up by no more than 2 inches.

Figure 10. Post-Test Photographs of Conventional (top) and CEM (bottom) Coupled Connections

Figure 11 shows an overhead view of the stills from the high speed camera for the conventional and CEM tests. The first photograph shows the cars at the time of impact (indicated by the flash of light). Relative lateral offset of the cars is marked with white lines in the photographs. In both tests, at the time of impact the cars were offset laterally by approximately 1.5 inches. The second still shows the offset at the time of maximum crush for each test. Sawtooth lateral buckling occurred in the conventional test causing the rail to roll. As can be seen in the top photograph of Figure 10, the cars rested approximately 13 inches out-of-line at the end of the collision. Contrastingly, in the CEM test the cars remained in-line as the coupler pushed back and the anticlimbers engaged (indicated by the dotted oval). The test shows that the controlled collapse of the crush zones effectively helps keep the cars in-line.

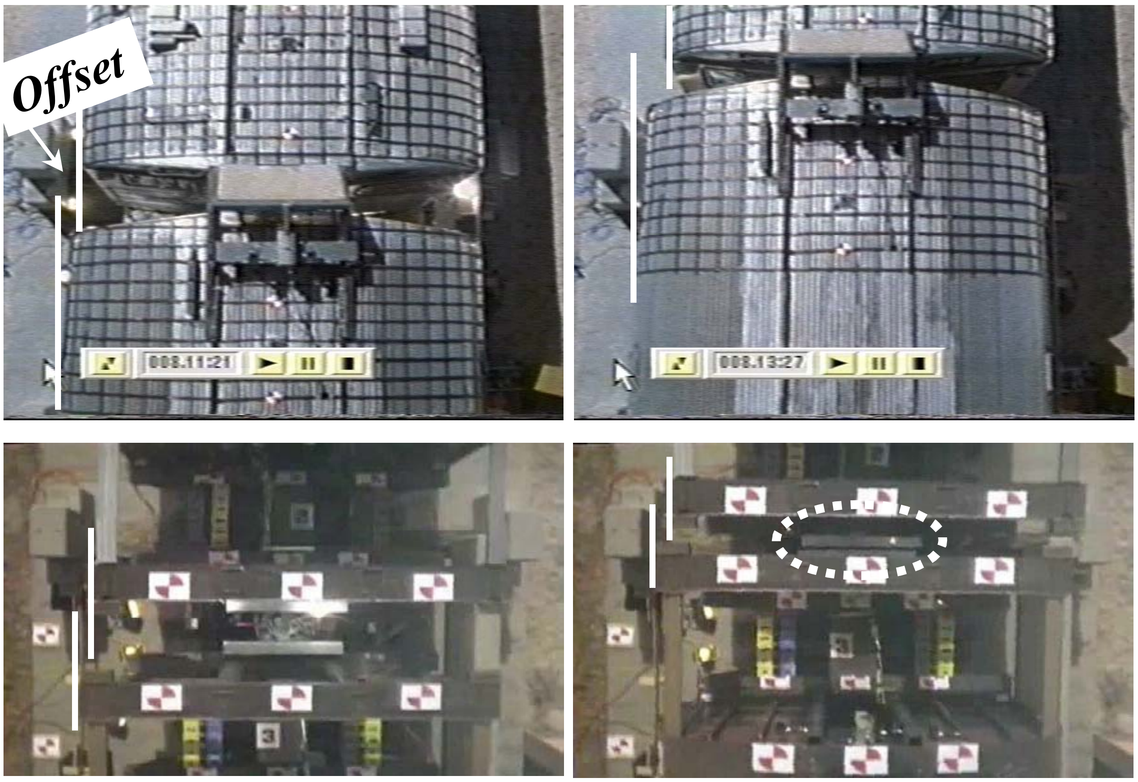

Figure 11. Still Photographs of Coupled Interface for Conventional (top) and CEM (bottom) at Time of Impact (left) and Maximum Crush (right)

The model and the test results show close agreement in the gross motions of the colliding vehicles. The velocity-time history of the single car test results are shown in Figure 12. The velocity and displacement measurements show very good agreement in the initiation of deceleration and the amount of crush.

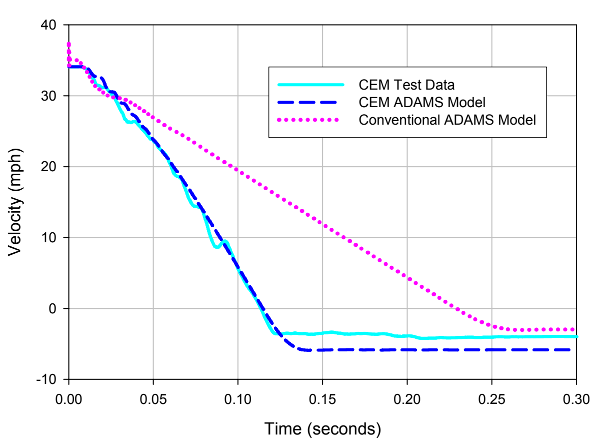

Figure 12. Single-Car Velocity Plot

The CEM design exhibits a faster average deceleration rate than the conventional design. The crushing sequence in the CEM design completes in about 120 milliseconds, while the conventional design takes almost twice as long to rebound off the wall.

Post-test analysis of the force-crush measurements allows for the characteristics of each component to be refined from the initial estimate of the overall force-crush behavior. The results of the single car test indicated that the first two plateaus of the composite force-crush curve required some fine-tuning. Modifications were made to the behavior as shown by the solid line in Figure 2. The crush plateau of the aluminum honeycomb module was increased. The initial peak of the primary energy absorbers was lowered. The plateau of the energy absorbers was replaced by a line with an upward slope. The characteristic for the energy absorbers accounts for the same total energy over the 30 inches of crush length as the previous plateau characteristic. After refining the input force-crush behavior to the collision dynamics model, the velocity-time histories matched the deceleration rates more closely throughout the collision.

The two-car test verified the force-crush behavior observed in the single-car test, particularly that the primary energy absorbers require an increasing force to sustain crush. Understanding this behavior improved the overall agreement of the gross motions. With these changes all the important dynamic features were captured in both the single-car and two car tests.

Figure 13 shows the agreement of the model and test data in relation to the sequence of events. The lead car initially decelerates as the pushback coupler crushes. The change in slope indicates the initiation of crush in the primary energy absorbers of the lead crush zone. Crush at the coupled connection begins at approximately 60 milliseconds. The lead car then rebounds off the wall at around 150 milliseconds, but the trailing car continues moving forward and pins the lead car to the wall until it comes to a stop. The trailing car rebounds off the wall traveling at a higher speed than the lead car. This behavior differs from the corresponding velocity history of the conventional two-car test. In that case, the lead car begins to crush and the two cars decelerate together as a single mass [2].

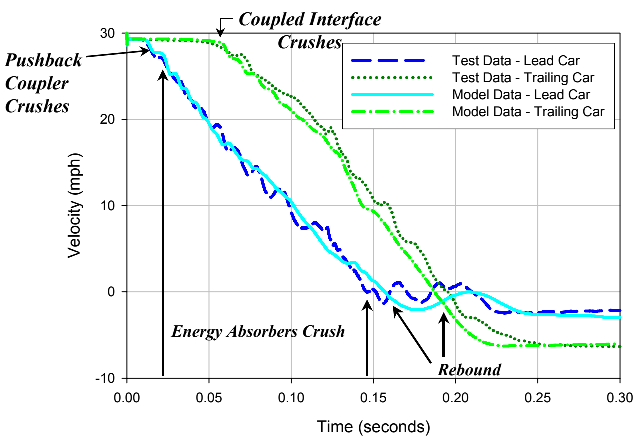

Figure 13. Two-Car Velocity Plots

The velocity plot shows that the model captures proper timing of the initial crush of the pushback coupler, indicated by the matching initial slopes of the lead car. The change in the deceleration of the lead car indicates the crush of the energy absorbers. The results of the single and two-car test have established confidence in how the CEM design functions under varying test conditions.

The slopes of the curves in Figure 12 and Figure 13 represent average accelerations. Figure 12 shows that the CEM single-car test has a more severe occupant environment than its conventional counterpart. Each of the cars in the two-car test has an average acceleration lower than that in the single-car test. It is anticipated that in the train-to-train test, the additional cars will further reduce the severity of the occupant-environment. The analysis of the interior occupant experiments performed in the two-car test are discussed in a companion paper [7].

SUMMARY AND CONCLUSION

The purpose of this program is to assess and improve occupant protection in passenger trains by evaluating incremental crashworthiness improvements over the current levels. The tests to date in the Equipment Safety Research Program demonstrate that the CEM design has superior crashworthiness performance over the conventional design. The CEM design incorporates a series of crushable elements to absorb the collision energy in a more efficient manner than the conventional design, which was built to meet maximum strength requirements. The two-car test also demonstrates that the crush can effectively be passed back to the subsequent crush zones, thereby distributing the crush to the non-occupied crush zones. In addition, the test results show that the coupled car interactions can be controlled, and that sawtooth buckling, and consequent derailment, can be successfully minimized.

The collision dynamics models were used to study the kinematic and dynamic response of the individual crush zone components and the resultant car body motions. Modifications were made to the pre-test force-crush behavior by comparing the test results and model simulations. These results suggest a gradually increasing load characteristic for the primary energy absorber which produces a steadily decreasing velocity for the first car. This sloped load characteristic also aids in distributing crush to successive crush zones. In both CEM tests, the post-test results show very good agreement between the model and the results.

The observed and simulated behavior in the one and two-car tests will be used to design and construct the equipment in the CEM train-to-train test. In the train-to-train test of conventional equipment, crush was focused on the impacting cab car and considerable occupant volume was lost. In addition, the cab car overrode the locomotive. In the train-to-train test of CEM equipment, it is expected that the occupant volumes will all be preserved, including the space for the operator [9]. Crush will be distributed to the successive crush zones as demonstrated in the two-car test.

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