



U.S. Department
of Transportation

Federal Railroad
Administration

Full-Scale Locomotive Dynamic Crash Testing and Correlations: Locomotive Consist Colliding with Steel Coil Truck at Grade Crossing (Test 3)

Office of Railroad
Policy and Development
Washington, DC 20590



NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. Any opinions, findings and conclusions, or recommendations expressed in this material do not necessarily reflect the views or policies of the United States Government, nor does mention of trade names, commercial products, or organizations imply endorsement by the United States Government. The United States Government assumes no liability for the content or use of the material contained in this document.

NOTICE

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report.

REPORT DOCUMENTATION PAGE			<i>Form Approved</i> <i>OMB No. 0704-0188</i>
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.			
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE September 2011	3. REPORT TYPE AND DATES COVERED Technical Report	
4. TITLE AND SUBTITLE Full-Scale Locomotive Dynamic Crash Testing and Correlations: Locomotive Consist Colliding with Steel Coil Truck at Grade Crossing (Test 3)		5. FUNDING NUMBERS	
6. AUTHOR(S) Gopal Samavedam and Kash Kasturi			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Foster-Miller, Inc. 350 Second Avenue Waltham, MA 02451-1196		8. PERFORMING ORGANIZATION REPORT NUMBER DFRA.010328	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Railroad Administration Office of Railroad Policy and Development 1200 New Jersey Avenue, SE Washington, DC 20590		10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT/FRA/ORD-11/16.I	
11. SUPPLEMENTARY NOTES Program Manager: John Punwani			
12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public through the FRA Web site at http://www.fra.dot.gov .		12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) This report presents the test results and finite element correlations of a full-scale dynamic collision between a locomotive and a highway truck loaded with two heavy steel coils. The locomotive consist was moving at 58 miles per hour before it struck a highway truck carrying heavy steel coils. The test showed significant damage to the locomotive front end, the collision posts and the firewall. The locomotive and the cars in its consist were fully instrumented with accelerometers, strain gauges, and anthropomorphic test dummies. High-speed photographic coverage of the events was also employed. The report presents the test data and the dynamic finite element modeling results.			
14. SUBJECT TERMS Full-scale collision tests, locomotive collision post, grade crossing collisions, locomotive crashworthiness, dynamic finite elements, anthropomorphic test dummy		15. NUMBER OF PAGES 37	
		16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

- 1 inch (in) = 2.5 centimeters (cm)
- 1 foot (ft) = 30 centimeters (cm)
- 1 yard (yd) = 0.9 meter (m)
- 1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

- 1 square inch (sq in, in²) = 6.5 square centimeters (cm²)
- 1 square foot (sq ft, ft²) = 0.09 square meter (m²)
- 1 square yard (sq yd, yd²) = 0.8 square meter (m²)
- 1 square mile (sq mi, mi²) = 2.6 square kilometers (km²)
- 1 acre = 0.4 hectare (he) = 4,000 square meters (m²)

MASS - WEIGHT (APPROXIMATE)

- 1 ounce (oz) = 28 grams (gm)
- 1 pound (lb) = 0.45 kilogram (kg)
- 1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

- 1 teaspoon (tsp) = 5 milliliters (ml)
- 1 tablespoon (tbsp) = 15 milliliters (ml)
- 1 fluid ounce (fl oz) = 30 milliliters (ml)
- 1 cup (c) = 0.24 liter (l)
- 1 pint (pt) = 0.47 liter (l)
- 1 quart (qt) = 0.96 liter (l)
- 1 gallon (gal) = 3.8 liters (l)
- 1 cubic foot (cu ft, ft³) = 0.03 cubic meter (m³)
- 1 cubic yard (cu yd, yd³) = 0.76 cubic meter (m³)

TEMPERATURE (EXACT)

$$[(x-32)(5/9)] \text{ } ^\circ\text{F} = y \text{ } ^\circ\text{C}$$

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

- 1 millimeter (mm) = 0.04 inch (in)
- 1 centimeter (cm) = 0.4 inch (in)
- 1 meter (m) = 3.3 feet (ft)
- 1 meter (m) = 1.1 yards (yd)
- 1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

- 1 square centimeter (cm²) = 0.16 square inch (sq in, in²)
- 1 square meter (m²) = 1.2 square yards (sq yd, yd²)
- 1 square kilometer (km²) = 0.4 square mile (sq mi, mi²)
- 10,000 square meters (m²) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

- 1 gram (gm) = 0.036 ounce (oz)
- 1 kilogram (kg) = 2.2 pounds (lb)
- 1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

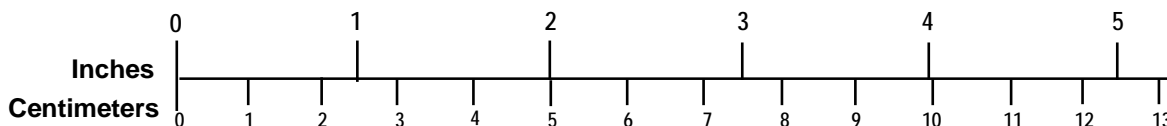
VOLUME (APPROXIMATE)

- 1 milliliter (ml) = 0.03 fluid ounce (fl oz)
- 1 liter (l) = 2.1 pints (pt)
- 1 liter (l) = 1.06 quarts (qt)
- 1 liter (l) = 0.26 gallon (gal)
- 1 cubic meter (m³) = 36 cubic feet (cu ft, ft³)
- 1 cubic meter (m³) = 1.3 cubic yards (cu yd, yd³)

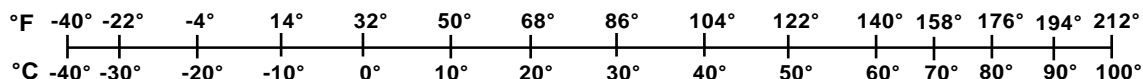
TEMPERATURE (EXACT)

$$[(9/5) y + 32] \text{ } ^\circ\text{C} = x \text{ } ^\circ\text{F}$$

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price \$2.50 SD Catalog No. C13 10286

Updated 6/17/9

Acknowledgments

This report discusses full-scale rail vehicle collision tests and test data correlations with dynamic finite element analysis. Foster-Miller, Inc., performed this work under contract DTFR53-01-D-0029 Task Order 0001 from the Federal Railroad Administration (FRA) for the Locomotive Crashworthiness Research Program.

Mr. John Punwani, FRA Office of Research and Development, is the Contract Officer's Technical Representative. The author thanks Mr. Punwani for his technical direction and involvement in the project.

The support of Ms. Claire Orth, (retired) Chief of Equipment and Operating Practices, FRA Office of Research and Development, is gratefully acknowledged.

The authors would like to express their gratitude to Mr. Gunars Spons for his coordination of the test activities at the Transportation Technology Center. Thanks are also due to Transportation Technology Center, Inc. test personnel, particularly Mr. Russ Walker, Mr. Mark White, and Dr. Barrie Brickle.

The authors want to thank Dr. Bud Zaouk for his help in the final revision of this report.

Contents

Executive Summary	1
1 Introduction	2
1.1 Background	2
1.2 Objectives	2
1.3 Organization of the Report	2
2 Overall Approach	4
2.1 Test Setup	4
2.2 Test Methodology.....	4
2.3 Modeling Methodology.....	9
2.4 Correlation of Simulation and Test Results	11
3 Test Results and Correlation with Simulation.....	14
3.1 Correlations of the Collision Results.....	16
3.2 Damage to ATD	25
3.3 Assessment	25
4 Conclusions	26
5 References	28
Abbreviations and Acronyms	29

Illustrations

Figure 1. Test Setup	4
Figure 2. Location of Strain Gauges on the Collision Post.....	6
Figure 3. Locations of Strain Gauges on the Underframe	7
Figure 4. Location of Strain Gauges on Center Post of the Windshield.....	7
Figure 5. FEM of Trailer with Steel Coils	10
Figure 6. Model Alignment of Striking and Target Vehicles	10
Figure 7. Video Camera Positions	13
Figure 8. Striking Test Consist before Collision	14
Figure 9. Loaded Trailer with Steel Coils before Collision.....	14
Figure 10. Stationary Vehicle at Grade Crossing after Test Collision	14
Figure 11. Damage to Locomotive after Collision	15
Figure 12. Test 3: Kinematic Comparison between Test and Simulation	16
Figure 13. Locomotive Cab Damage Due to Steel Coil	18
Figure 14. Simulated Damage to Locomotive	18
Figure 15. Locomotive Floor Cab Acceleration Filtered at 25 Hz	19
Figure 16. Locomotive Cab Floor Acceleration Filtered at 60 Hz	19
Figure 17. Right Collision Postlongitudinal Strain at Location 3.....	20
Figure 18. Right Collision Postlongitudinal Strain at Location 5.....	21
Figure 19. Right Collision Postvertical Strain at Location 8.....	21
Figure 20. Right Collision Postvertical Strain at Location 10.....	22
Figure 21. Left Collision Postlongitudinal Strain at Location 5.....	22
Figure 22. Left Collision Postvertical Strain at Location 8	23
Figure 23. Left Collision Postvertical Strain at Location 10	23
Figure 24. Underframe Longitudinal Strain at Location 6	24
Figure 25. Windshield Postbottom Left Vertical Strain	24
Figure 26. Test 3: ATD Position before Collision.....	25
Figure 27. Quasi-Static Longitudinal Load vs. Strain of an SD70-MAC Collision Post.....	27

Tables

Table 1. Locomotive and Hopper Car Accelerometers	8
Table 2. ATD Instrumentation.....	9
Table 3. Node Locations Identified for Acceleration	12
Table 4. Strains Identified for Correlation.....	12
Table 5. Correlation of Acceleration Amplitudes in Longitudinal Direction (g)	20

Executive Summary

The Federal Railroad Administration (FRA) initiated the Locomotive Crashworthiness Research Program with the ultimate objective of minimizing crew injuries in the event of collisions involving railroad vehicles or railroad and highway vehicles. This report presents a full-scale dynamic crash test between a locomotive and a highway truck carrying heavy steel coils. The project team performed full-scale dynamic tests representing common scenarios at the Transportation Technology Center (TTC) during this study.

The test scenario and the test requirements definition were developed by Foster-Miller, Inc. Transportation Technology Center, Inc. (TTCI), conducted the test and measured the collision sequence, structural damage, decelerations, and strains at critical locations. They also measured the response of an instrumented anthropomorphic test dummy (ATD). Foster-Miller correlated results with finite element model (FEM) predictions. The test locomotive was supplied by Sharma and Associates.

This collision speed of the locomotive was 58 miles per hour (mph). Locomotive front end damage was extensive. One of the collision posts facing the steel coil sheared off completely at its bottom, above its weldment line on the locomotive frame. There was significant intrusion into the cab. The firewall collapsed completely.

FEM simulations reasonably predicted the overall collision dynamic sequences and damages to the locomotive, and showed massive damage to the collision posts and cab interior. The simulations also successfully predicted intrusion in occupied cab space and injury risks to crewmembers.

The principal lessons from this test were:

- ◆ The worst loading on the collision post by the steel coil impact would be when it is aligned with the collision post.
- ◆ The collision post struck by the massive coil was sheared off just above its weld to the underframe. The elevation of the coil just before locomotive impact was just above the anticlimber and underframe structure.
- ◆ A substantial portion of the hood and cabin was also damaged.

1. Introduction

1.1 Background

Locomotive crashworthiness research is important in the assessment of crew safety in the event of collision accidents. The crushing of the front end of the locomotive could reduce cab volume. The impact could generate high decelerations inside the cab, and a crew can experience secondary impacts. Structural improvements can improve locomotive crashworthiness. These improvements can be validated by finite element methods and testing research.

FRA initiated a research program on improved locomotives crashworthiness for improved crew safety in a collision with other vehicles. The research program has several objectives directed toward developing S-580 standards and validating the standards based on analytical simulation and testing. The analysis includes validating dynamic finite element solutions for collisions with full-scale field testing.

The test reported here involved the following collision scenario:

- The striking, or bullet, consist has an SD70-MAC locomotive leading three fully loaded hopper cars.
- The target is a tractor trailer truck carrying heavy steel coils. The bullet consist speed was 58 mph, striking the target at a right angle.

This test represents a type of highway-rail grade-crossing accident. One such accident occurred on March 15, 1999, in Bourbonnais, IL. The Bourbonnais event was a train-truck collision between an Amtrak passenger train and a semitruck in the city of Bourbonnais, south of Chicago. An Amtrak passenger train struck a semitruck, loaded with steel. The accident resulted in the deaths of 11 of the train's passengers, 122 injuries and more than \$14 million in damages.

1.2 Objectives

The objectives of the Phase I program were to:

1. Obtain information to validate finite element simulations.
2. Define test requirements with details of the collision scenarios, test equipment, measurements, and instrumentation for each test. The measurements should include the dynamic strains in the collision posts and the deceleration levels on the cab floor.
3. Deploy an ATD in the cab to evaluate crew injuries caused by intrusion, high decelerations, and secondary impacts.

1.3 Organization of the Report

Section 2 describes the overall approach of the current task. This section presents test procedures, instrumentation, and measurements. A brief description of the model development and analysis is then provided, followed by an explanation of how the test and simulation results are correlated.

Section 3 gives a description of the test results and correlations of the test and simulation results. The first test was a collision between a moving locomotive consist and a stationary hopper consist. The section provides test setup and damages to locomotive and other vehicular

structures, followed by a brief description of the corresponding simulation model. Section 3 presents correlations of measured and predicted parameters, including the overall collision sequences, accelerations, and strains at predetermined locations.

Section 4 presents the conclusions. Section 5 contains a list of references used in the research.

2. Overall Approach

2.1 Test Setup

This test involved a collision between a locomotive and a trailer truck carrying heavy steel coils. In comparison to the log truck scenario, this represents a much larger mass striking the locomotive front at a higher (relative) speed. The locomotive consist with three trailing loaded hopper cars struck the stationary trailer carrying steel coils at 58 mph. The trailer was an 18-wheeled vehicle. The truck and the trailer together weighed 25,000 pounds (lb). The front and rear steel coils weighed 20,500 and 35,000 lb, respectively. The coil located on the rear of the trailer was aligned with the right collision post of the moving consist. Figure 1 shows the test setup scenario at the grade crossing.

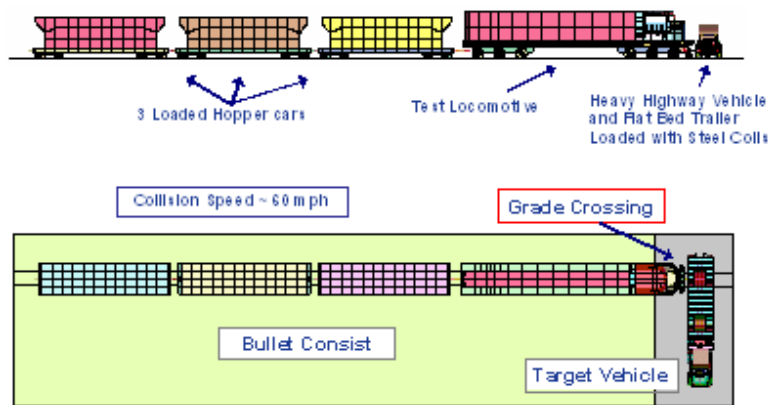


Figure 1. Test Setup

For the test, the project team collected a total of 5 seconds (s) of data, starting one seconds before the initial impact and continuing for 4 seconds after the initial impact. The computer simulations of the crash event covered the first one second after the initial impact, which was sufficient to capture the major damage in the locomotive structure. The number of nodes in the model is approximately 40,000 with each node having 6 degrees of freedom.

All FEMs were developed using HyperMeshTM [1] a high-performance FE preprocessor. Simulations were performed using LS-DYNA [2], a commercial nonlinear explicit finite element analysis code developed by Livermore Software Technology Corporation. LS-DYNA is used to solve the complex governing differential equations of structural, fluid, magnetic, and other engineering analysis problems. It is capable of accurately predicting the behavior of nonlinear large-deformation crash problems.

2.2 Test Methodology

2.2.1 Test Consists and Equipment

Sharma and Associates in the project team built the test locomotive from a used SD-45 without the engine. Its structural members were similar to a SD70-MAC locomotive.

The loaded hopper cars that formed the striking locomotive consist came from existing TTC stock. The project team procured the flatbed trailer and steel coils.

2.2.2 Test Procedures and Instrumentation

The dynamic impact tests employed an active locomotive to push the striking test consist (locomotive and three loaded hopper cars). It was released from the pushing locomotive at a predetermined speed and location, and then ran along the track into the stationary target.

A series of speed calibration runs before each test determined the release distance and the speed of the moving consist at release point. A laser speed trap and a standard radar gun measured the speed of the moving consist at impact.

The contact of tape switches on the front of the locomotive triggered all onboard instrumentation. The data was then saved for 1 s before and 4 s after trigger, for 5 s of data. Gauges collected data at a rate of 12,800 hertz (Hz) and saved them onto modular data bricks located on board the locomotive. The data was downloaded to a computer after the test was complete.

Strain gauges, accelerometers, and string potentiometers characterized the behavior of the vehicles during the collisions. Strain gauges installed on the collision posts, underframe, and windshield posts measured the impact loads on these components. Three-axis strain gauge rosettes at the base of each collision post measured the shear at this location. The project team installed accelerometers at two locations in the locomotive cab and in the hopper car behind the locomotive. An instrumented coupler between the locomotive and the first hopper car measured the force transferred between the vehicles. String potentiometers between the locomotive and first hopper car measured the relative three-dimensional displacements of the two vehicles during the collision.

Five high-speed film cameras and six video cameras recorded the motions during each impact test.

2.2.3 Test Measurements

The project team measured the vehicle geometries, the weights of all the moving and stationary consists, and the positions of all the transducers before the test, plus the weights of steel coils and the trailer. TTCI provided detailed drawings with the dimensions of the steel coils and trailer, and their relative positions and settings.

An onboard data acquisition system recorded strain and acceleration during the test. Data synchronized with a time reference corresponding to the moment of impact were recorded by the tape switches. An SAE J211 [3] filter digitally filtered acceleration data after test data collection at 1,000, 100, 60, and 25 Hz. Foster-Miller used only 25 and 60 Hz data in comparisons with the finite element predictions.

The following subsections describe measured items for the test.

Test Locomotive Speed

A laser speed trap and a wayside handheld Doppler RADAR Speed Gun (± 0.1 mph) measured the speed of the test locomotive just before impact.

Collision Post Strain

Uniaxial strain gauges on collision posts measured strain in the longitudinal direction. The following convention was used for rosette strain gauges installed on collision posts:

- Right collision post: Direction 1 = vertical
Direction 2 = diagonal
Direction 3 = longitudinal
- Left collision post: Direction 1 = longitudinal
Direction 2 = diagonal
Direction 3 = vertical

Figure 2 shows the locations of the strain gauges on the left and right collision posts. Gauges 1 through 5 are uniaxial in the longitudinal direction; gauges 6 through 10 consist of three arm rosette gauges with measurement in the longitudinal, vertical, and a third diagonal arm in the same plane.

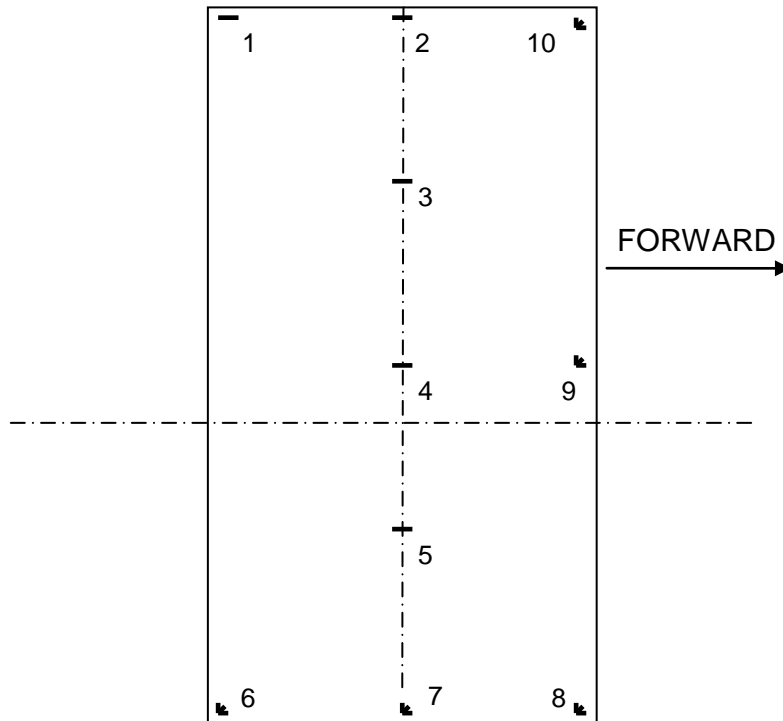


Figure 2. Location of Strain Gauges on the Collision Post

Longitudinal Strain on the Underframe

Figure 3 shows the locations of the strain gauges on the locomotive's underframe. Gauges on the underframe are all uniaxial in the longitudinal direction.

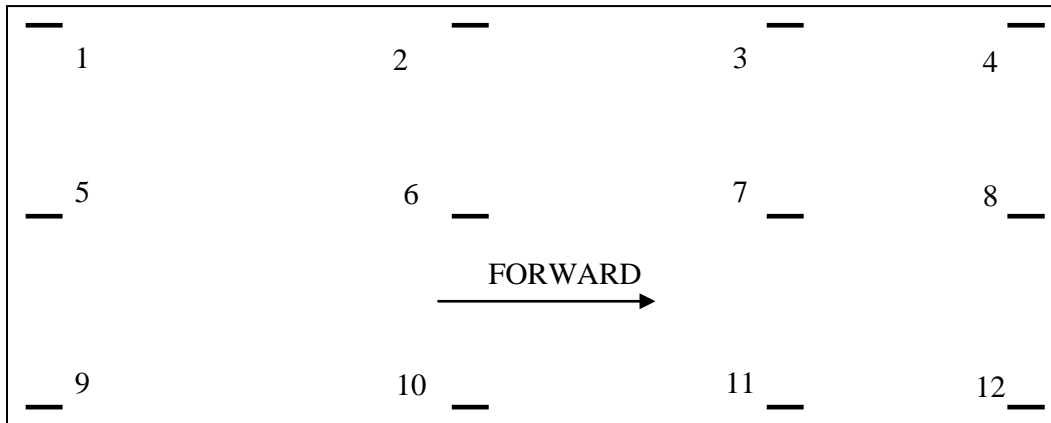


Figure 3. Locations of Strain Gauges on the Underframe

Vertical Strain at the Center Post of the Windshield

Figure 4 shows the location of the strain gauges on the center post of the windshield.

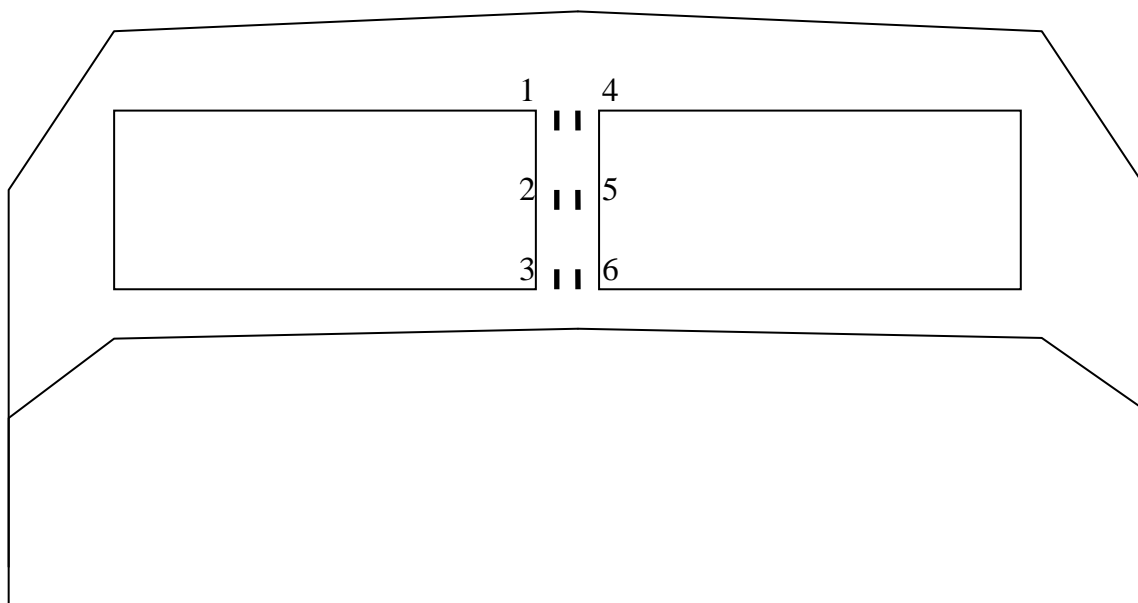


Figure 4. Location of Strain Gauges on Center Post of the Windshield

Additional Strain Measurements

Strain gauges recorded measurements for longitudinal strain of the coupler between the moving locomotive and first hopper car.

Acceleration

The project team used a triaxial accelerometer on the floor of the cab near the engineer's seat to measure the motions of the cab floor. The project team also used triaxial accelerometers at center-sill, at the centerline (axially and laterally) of the first two hopper cars in the moving

consist to measure the motions of the hopper cars. The project team installed additional triaxial accelerometers at other locations for the test which recorded the accelerations on the locomotive floor and on the first two hopper cars.

Table 1 shows accelerometer locations, accelerometer types, and measured acceleration components for the three test scenarios.

Table 1. Locomotive and Hopper Car Accelerometers

Location	Accelerometer	Measurement	
Locomotive floor	Three axis	Longitudinal	X
		Lateral	Y
		Vertical	Z
Locomotive floor (redundant)	Three axis	Longitudinal	X
		Lateral	Y
		Vertical	Z
Locomotive, above event recorder**	Three axis	Longitudinal	X
		Lateral	Y
		Vertical	Z

** Applies to Test 2 and Test 3 Scenarios only.

The test recorded accelerations at a sample rate of 12,800 Hz. An SAE J211 filter then digitally filtered data at 1,000, 100, and 25 Hz. The project team used the following sign conventions for the accelerometers:

- X-axis is longitudinal, with positive toward the impact end of the locomotive (forward)
- Y-axis is lateral, with positive toward the right side when facing in the + x-direction (rightward)
- Z-axis is vertical, with positive down toward the ground (downward)

ATD Accelerations and Forces

An instrumented ATDs measured head and chest accelerations and the forces in the neck and femur during the collision.

Table 2 shows the ATD instrumentation locations, type of instrumentation, and measurement orientation. For this test, the ATD was placed in a seated position at the base of the cab stairwell.

Table 2. ATD Instrumentation

Location	Transducer	Measurement	
Head	Three-axis accelerometer	Longitudinal	X
		Lateral	Y
		Vertical	Z
Chest	Three-axis accelerometer	Longitudinal	X
		Lateral	Y
		Vertical	Z
Upper neck	Six-axis load cell	Longitudinal	X
		Lateral	Y
		Vertical	Z
		Roll	
		Pitch	
		Yaw	
Femur	Two single-axis load cells	Longitudinal (left)	X
		Longitudinal (right)	X

Photography and Video

Five high-speed film cameras and six video cameras recorded each collision. The selected camera coverage provided views of the left and right sides of the vehicles, overhead views, and an overall impact view. The locomotive cab also contained a video camera.

2.3 Modeling Methodology

2.3.1 Rail Vehicles

All entities included in the testing required FEMs to simulate field test conditions. The following structural models simulated the three test scenarios and reproduced the behavior of the locomotive and tractor trailer throughout the test collision process:

- Locomotive
- Loaded hopper cars
- Track system
- Flatbed trailer and steel coils

The models have the following characteristics:

- Appropriate basic structural and mechanical components (including the locomotive, trailing cars, separate bogies and suspension, and draft gear) using shell, plate, beam, and solid finite elements.
- Masses.
- Detailed models of the locomotive and the three hopper cars of the striking consist.
- A nonlinear spring between the vehicles to represent the effects of the draft gear, its travel stops, and clearance.

- Nonlinear material properties of all deformable structures, with elastic, elasto-plastic, and fully ductile (where applicable) behavior up to fracture (ultimate strength).
- Ground interaction by an orthogonal friction matrix, which considers high friction values transverse to wheel rotation and low values in the line of rolling motion.

2.3.2 Tractor Trailer and Steel Coil

Figure 5 shows the detailed model of the trailer and the steel coils. Figure 6 shows the striking and target vehicle models before simulated collision.



Figure 5. FEM of Trailer with Steel Coils



Figure 6. Model Alignment of Striking and Target Vehicles

2.3.3 Structures and Dimensions

The locomotive in this test was an SD70-MAC type, fabricated by modifying an SD-45 to satisfy AAR 1990 S-580 crashworthiness standards. To represent the actual locomotive in the real test, the model incorporated appropriate metal sheet thickness, masses, and inertia. Three loaded hopper cars models were attached to the rear of this locomotive model.

For this test scenario, the trailer had two side beams, two T-beams in the center parallel to the side beams, and 120 cross beams (small T-beams perpendicular to the side beams). The model also included two steel coils along with their attachments to the trailer. One of the coils in the model was placed in line with the right collision post to represent the worst case scenario.

The total weight of the truck and the trailer was 25,500 lb. The steel coil in line with the collision post weighed 35,000 lb. The coil was 56 inches (in) in diameter and 33.25 in wide. The project team also placed the smaller coil (66 in. in diameter and 41 in wide) weighing 20,500 lb on the trailer.

2.3.4 Boundary Condition and Constraints

Friction forces simulated the interaction between the structures (locomotive, hopper cars, trucks, and truck trailers) and ground. Output from analytical studies assigned the friction coefficient in the transverse direction of the wheels to be 0.6. In the rolling direction, it was taken as 0.3. The tailored spring rate of the couplers provided the correct impact momentum to the locomotive.

2.3.5 Loading Condition

Initial inputs to the model were the initial moving consist velocities and the gravity forces. Initial simulation velocity value was the velocity of the test locomotive recorded immediately before impact.

2.4 Correlation of Simulation and Test Results

The simulation results were compared with the test data in terms of dynamic event sequences, accelerations, and strain. Simulations predict the first 1 s of the crash event, starting immediately after impact. An SAE filter digitally filtered the accelerations calculated from simulations at 25 and 60 Hz using a postprocessing program of LS-DYNA. Posttest correlation compared the results after the filtration with the corresponding test data filtered at the same frequencies.

2.4.1 Dynamic Event Sequence

Posttest processing compared the dynamic event sequence obtained from the collision simulation with recorded photographic and video information from the test. The following dynamic events comprised the test and simulation correlations.

- Deformation of major structural components
- Relative positions of the locomotive and impacted target vehicles
- Component failures

2.4.2 Acceleration

The project team collected acceleration data at certain locations for comparison with simulation data. For comparison with test data, the model depicted the corresponding nodes and derived the accelerations of these nodes from the simulation output. A selected filter first filtered the simulated accelerations. Sign conventions for the accelerations are as follows:

- Longitudinal: Positive is forward acceleration
- Lateral: Positive is rightward acceleration
- Vertical: Positive is downward acceleration

Table 3 describes the locations of the structure identified in the simulations. The simulation values for these nodes were compared with measured test data.

Table 3. Node Locations Identified for Acceleration

Location	Node Flagged	Comparison
Locomotive floor	Near engineer's seat	Longitudinal X
First moving hopper car	Center of centerline at center sill	Longitudinal X
Second moving hopper car	Center of centerline at center sill	Longitudinal X

2.4.3 Strain

Table 4 lists the identified locations for strain correlation. The model identified elements at the strain gauge locations in the tests. Positive values show tension and negative values show compression.

Table 4. Strains Identified for Correlation

	Identified Location	Vectors	Strain Gauges in Test
Collision post (left & right)	3	Longitudinal	Standard
	5	Longitudinal	Standard
	8	Vertical	Rosette
	10	Vertical	Rosette
Underframe	6	Longitudinal	Standard
	8	Longitudinal	Standard
Center post of windshield	1	Vertical	Standard
	6	Vertical	Standard

2.4.4 Video

The impact test was recorded with three high-speed film cameras and three video cameras. Camera coverage provided views of both the left and right sides of the vehicles, and an overall impact view. There was a video camera in the cab of the locomotive. Figure 7 shows the film and video camera locations for the test.

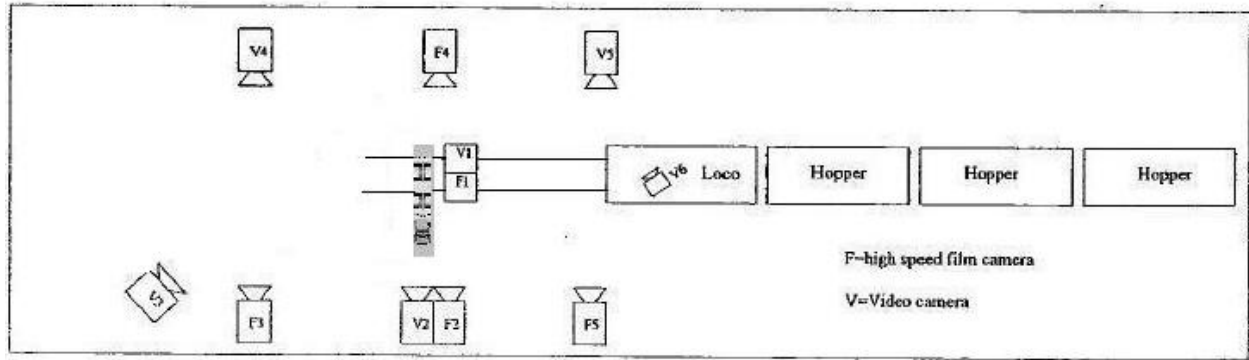


Figure 7. Video Camera Positions

3. Test Results and Correlation with Simulation

Figure 8 and Figure 9 show the locomotive consist and the tractor trailer carrying the steel coils used in the test.



Figure 8. Striking Test Consist before Collision



Figure 9. Loaded Trailer with Steel Coils before Collision

The rear steel coil was embedded in the locomotive after the impact, whereas the truck, trailer, and forward steel coil were pushed to the side of the tracks. Figure 10 shows postcollision damage to the truck and trailer.



Figure 10. Stationary Vehicle at Grade Crossing after Test Collision

After the collision, the locomotive proceeded beyond the grade crossing and was stopped by a ballast obstruction a few hundred yards down the track. Before the locomotive consist stopped, the steel coil got dislodged from the locomotive and fell onto the ground. Figure 11 shows postcollision damage to the front of the locomotive.



Figure 11. Damage to Locomotive after Collision

3.1 Correlations of the Collision Results

Figure 12 shows a comparison of the kinematics of the simulation and the test.

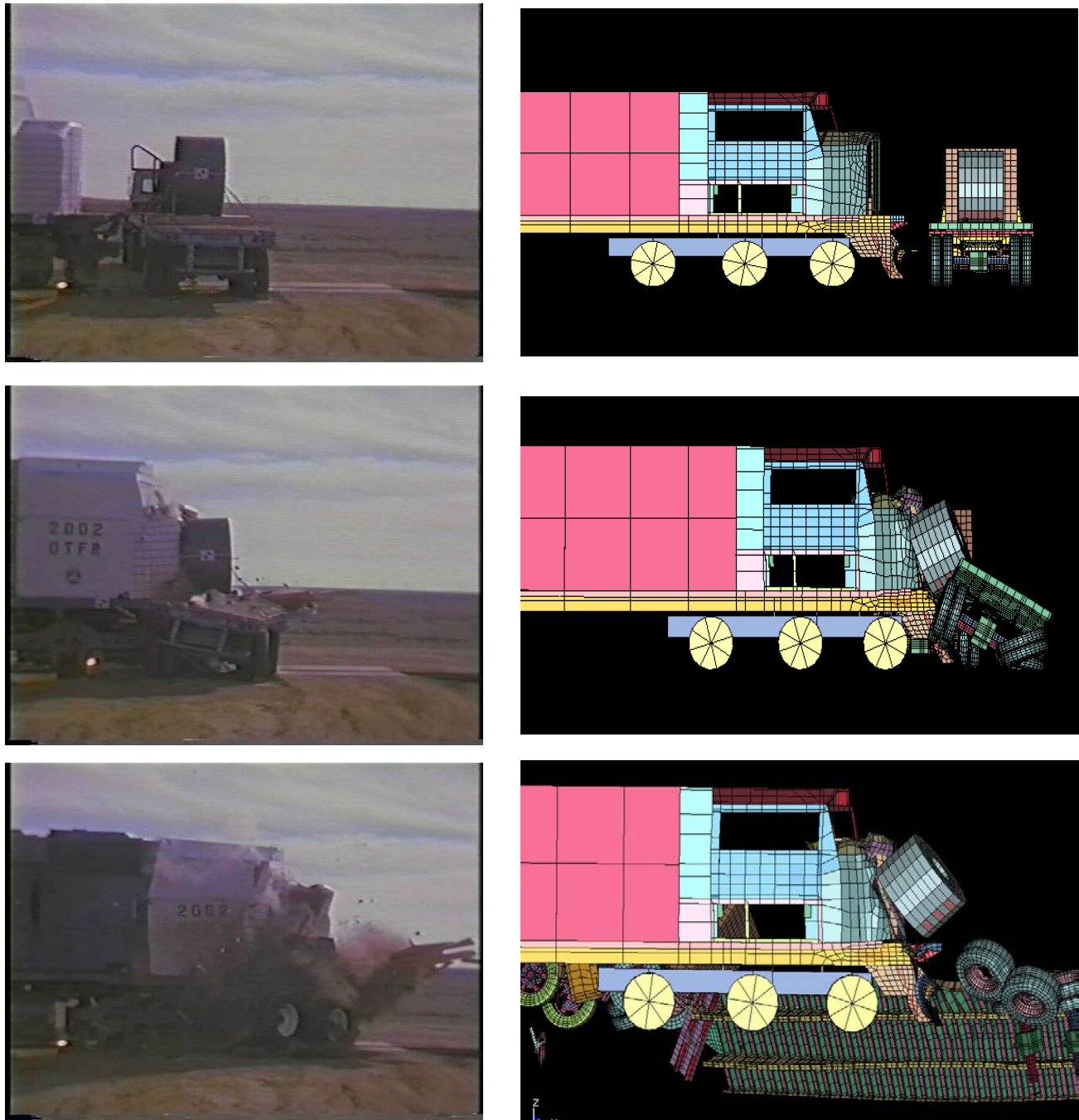


Figure 12. Test 3: Kinematic Comparison between Test and Simulation

The high-speed video revealed the following dynamic sequences:

- Initial contact between the striking locomotive and the trailer with coils occurred at the anticlimber and the trailer's outside edge. Components below the anticlimber, such as

the draft gear, coupling system, and plow, were trapped under the trailer. The anticlimber pushed the trailer, causing deformation and damage.

- As the trailer was crushed and pushed forward, the anticlimber and nose of the cab approached the coil. The right side of the anticlimber structure buckled with plastic deformation.
- The locomotive continued forward, and the steel coil impacted the right collision post. The coil sheared off the collision post and intruded into the cab operator space of the locomotive.

Significant damage also occurred to the ATD, which was placed in the stairwell for evaluating the stairwell's potential for crew refuge.

3.1.1 Dynamic Sequences

The LS-DYNA simulation of the test showed the same trend as the test, specifically:

- Initial contact occurred between the central vertical stiffeners bracing the underside of the anticlimber and the outside longitudinal beam of the trailer.
- The anticlimber skimmed the trailer top, cut the trailer, and eventually crushed the trailer.
- The draft gear pocket crushed several lateral trailer cross beams in its path.
- The anticlimber impaled the rear steel coil and was crushed in the contact zone. Six stiffeners were under the anticlimber. Two stiffeners of the anticlimber buckled out.
- The outer frame on the right of the anticlimber also buckled. Permanent deformation of the locomotive's vertical front plate occurred. The coil's bottom bent the vertical front plate.
- The contact between the coil and the nose cab destroyed the nose cab's front and hood. The coil crashed into the right collision post. The contact deformed the right collision post into the forward cab area. Simulation results show the collision post yielding but not failing. The impact compromised the forward portion of the cab, yet the operator's seat area is intact. Figure 13 and Figure 14 show the damage to the front end of the locomotive. The truck and trailer are not shown for clarity.

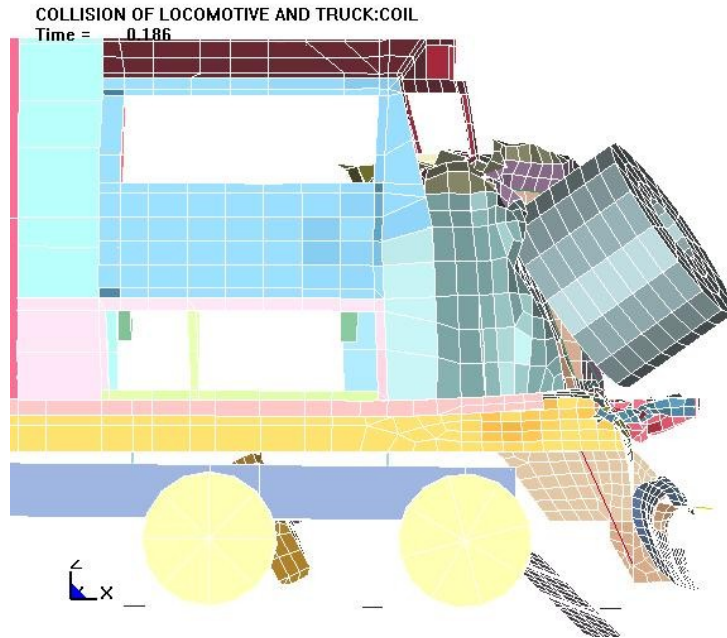


Figure 13. Locomotive Cab Damage Due to Steel Coil

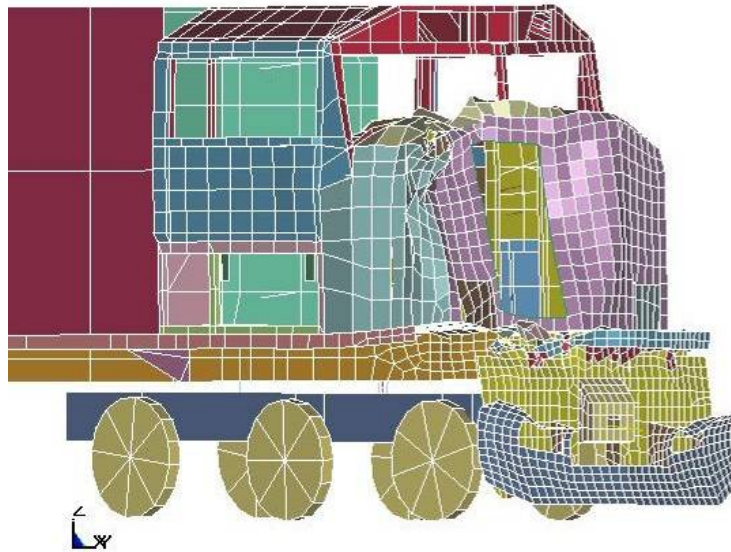


Figure 14. Simulated Damage to Locomotive

3.1.2 Acceleration Correlations

Posttest processing compared node accelerations in the model with measured test accelerations for the locomotive and the first two moving hopper cars. Figure 15 and Figure 16 show the acceleration correlations between test vehicles and results from the computer simulation filtered at 25 and 60 Hz, respectively.

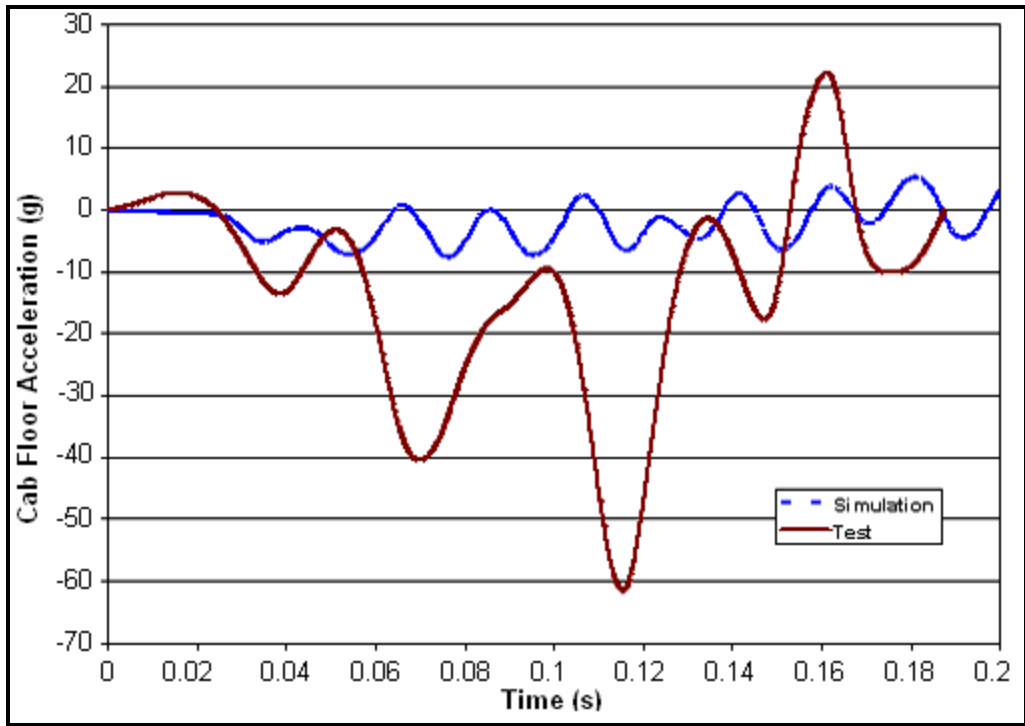


Figure 15. Locomotive Floor Cab Acceleration Filtered at 25 Hz

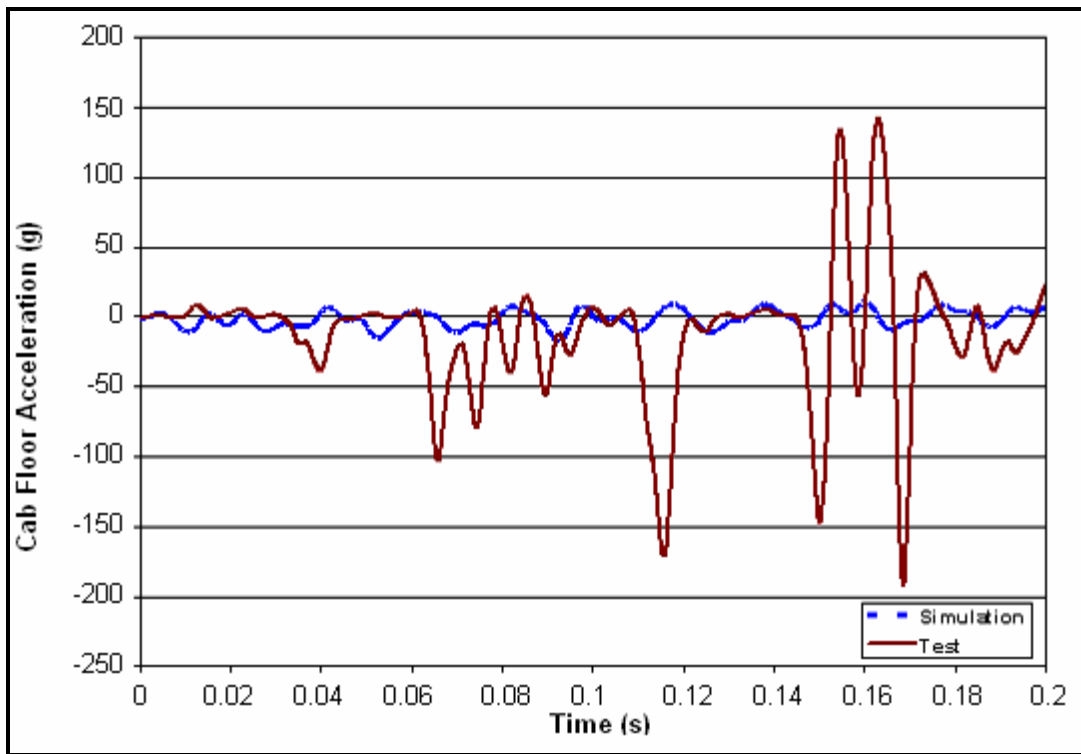


Figure 16. Locomotive Cab Floor Acceleration Filtered at 60 Hz

Simulation accelerations in the locomotive longitudinal direction do not correlate well with the test accelerations. Close examination of the high-speed film data revealed that the coil penetrated the cabin and impacted with the accelerometers. Consequently, the test values are not considered reliable.

Table 5 shows test and simulation acceleration data for the hopper cars; the correlation is not good.

Table 5. Correlation of Acceleration Amplitudes in Longitudinal Direction (g)

Filter Frequency	Locomotive Cab Floor (g)		Hopper 1 (locomotive consist) (g)		Hopper 2 (locomotive consist) (g)	
	Test	Simulation	Test	Simulation	Test	Simulation
25 Hz	61.5	7.7	5.5	12	3	11
60 Hz	192.2	17.5	6.7	9.11	1.4	1.0

3.1.3 Strain Correlations

Figure 17 through Figure 25 show strain data compared at the collision posts, underframe, and center windshield post of the locomotive.

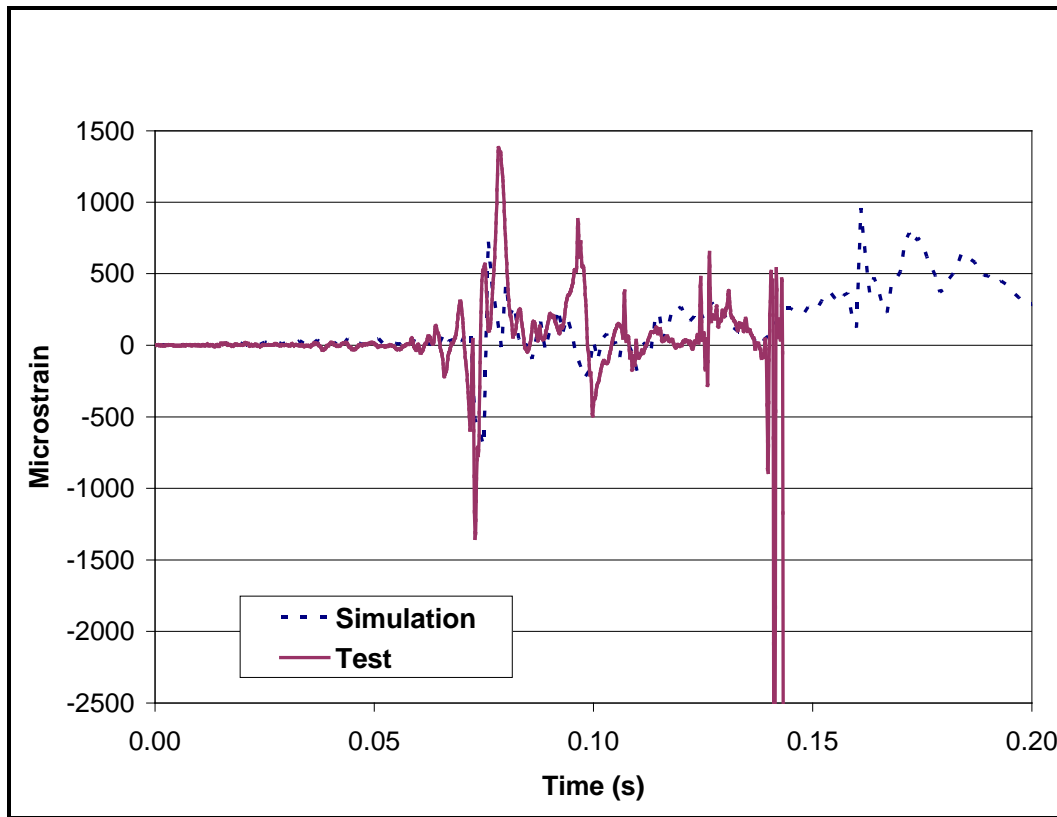


Figure 17. Right Collision Postlongitudinal Strain at Location 3

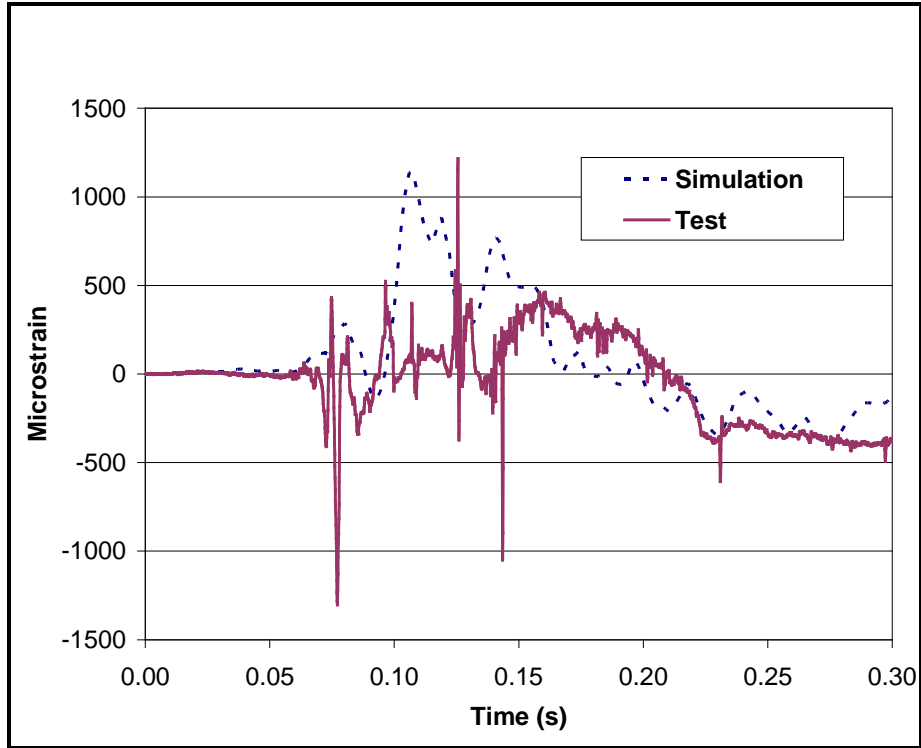


Figure 18. Right Collision Postlongitudinal Strain at Location 5

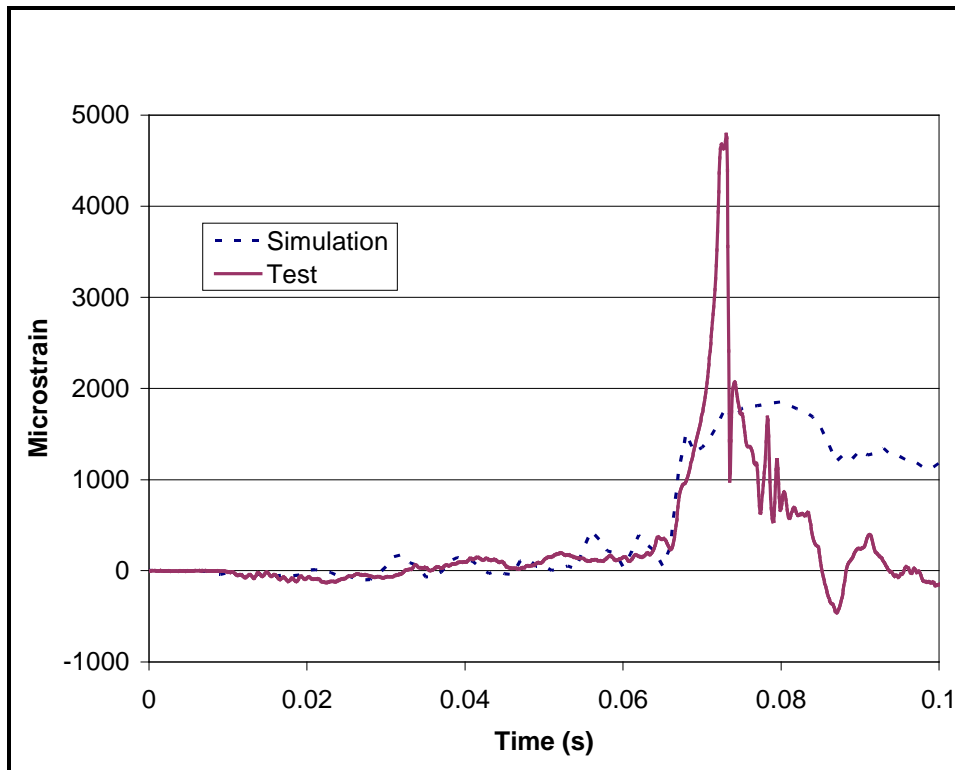


Figure 19. Right Collision Postvertical Strain at Location 8

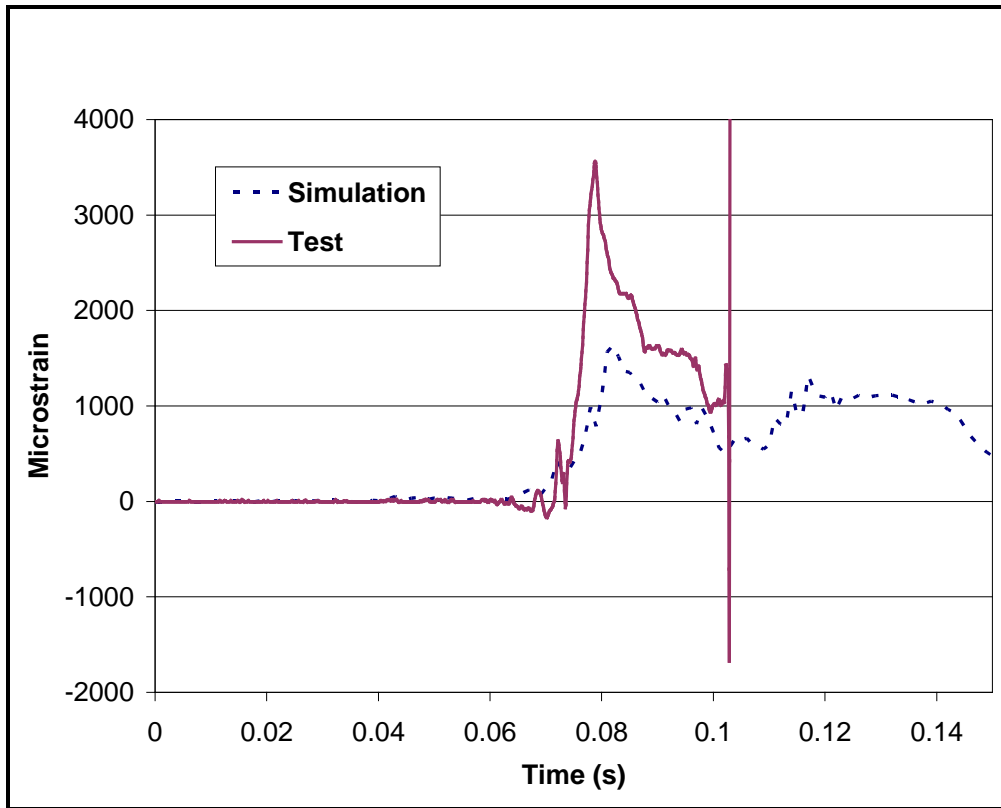


Figure 20. Right Collision Postvertical Strain at Location 10

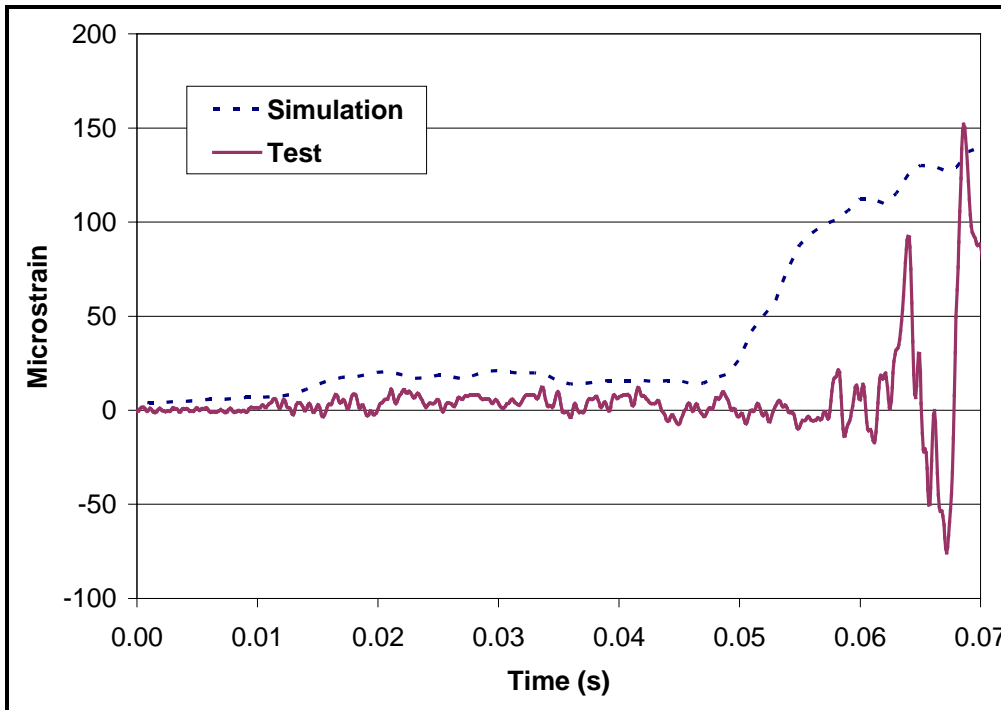


Figure 21. Left Collision Postlongitudinal Strain at Location 5

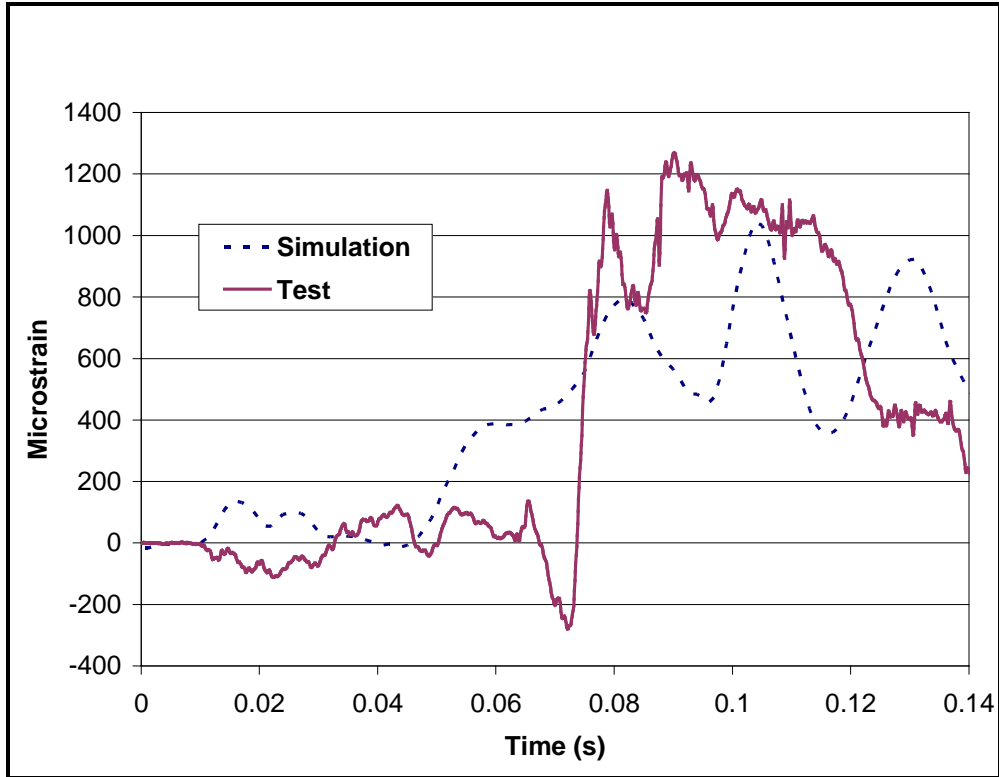


Figure 22. Left Collision Postvertical Strain at Location 8

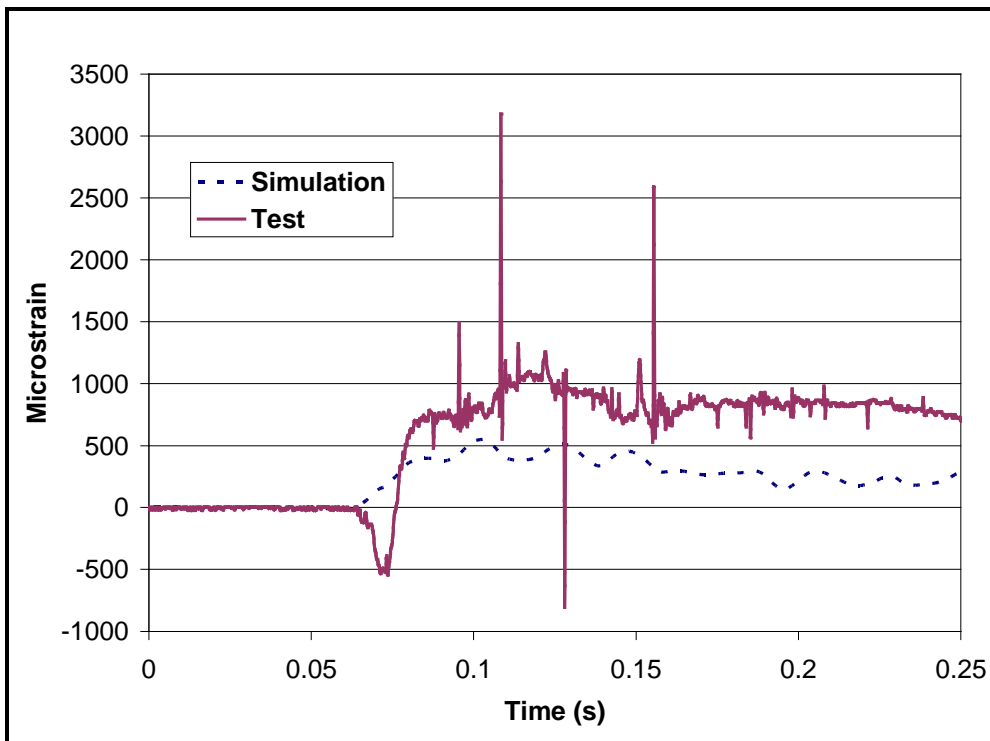


Figure 23. Left Collision Postvertical Strain at Location 10

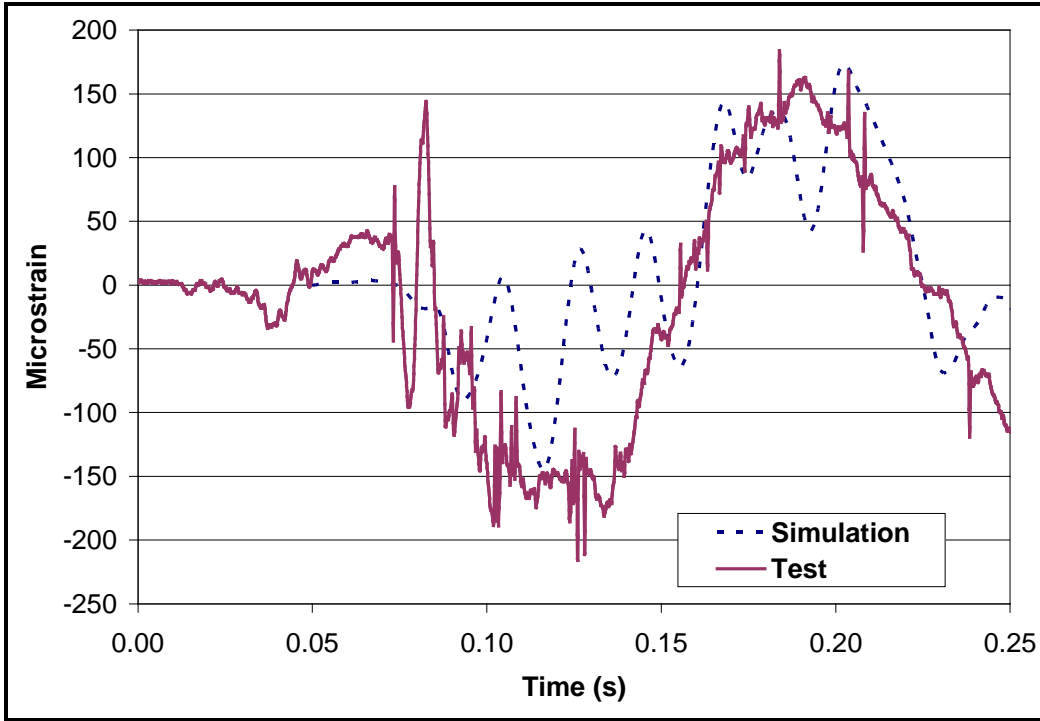


Figure 24. Underframe Longitudinal Strain at Location 6

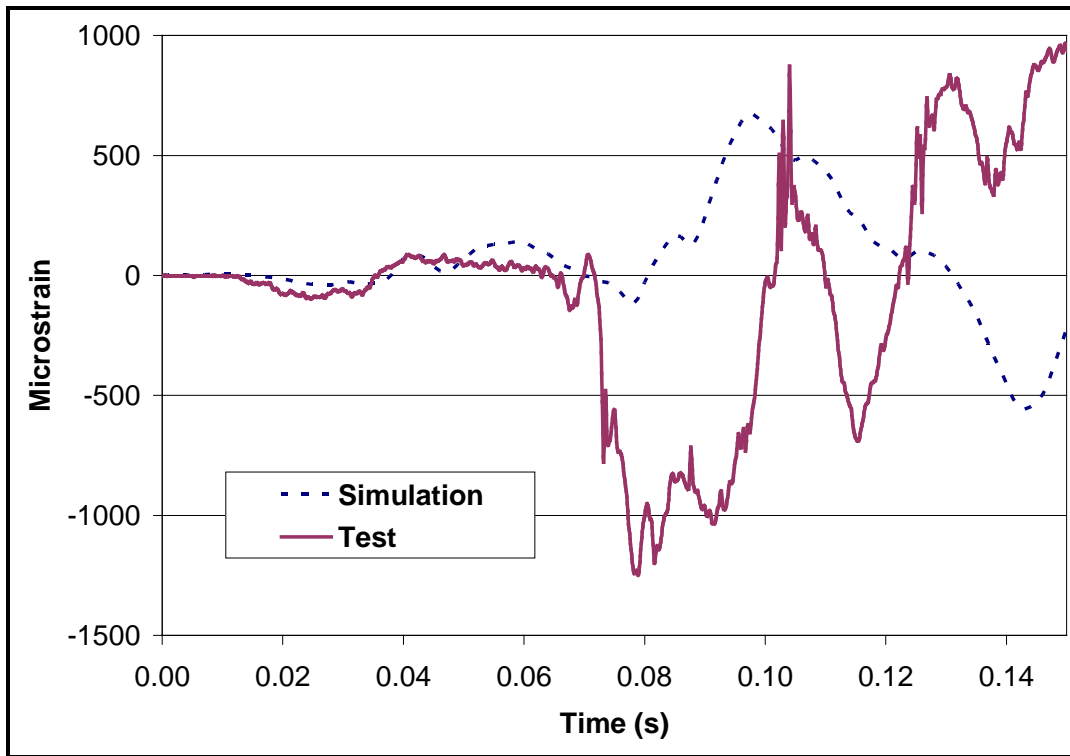


Figure 25. Windshield Postbottom Left Vertical Strain

As shown in Figure 25, simulation results sometimes compare reasonably with test data. A possible reason for disagreement is that the instrumentation was damaged due to the collision. Right collision poststrain correlations at locations 3 (Figure 17) and 10 (Figure 20) confirm the structural failure of the collision post.

The test measured maximum strain values on the right post in the vertical leg of the rosette gauge at location 8 (Figure 19). This strain gauge was at the bottom front of the collision post, (see Figure 1). The simulation also predicted the maximum strain occurring at this location.

3.2 Damage to ATD

The project team seated the ATD on the stairwell floor of the locomotive, facing rearward with its back against the interior door. Figure 26 shows the ATD before the collision, with the accelerometers positioned to measure acceleration of the head and chest and forces in the neck and femur. The test showed that most parts of the ATD suffered extensive damage.

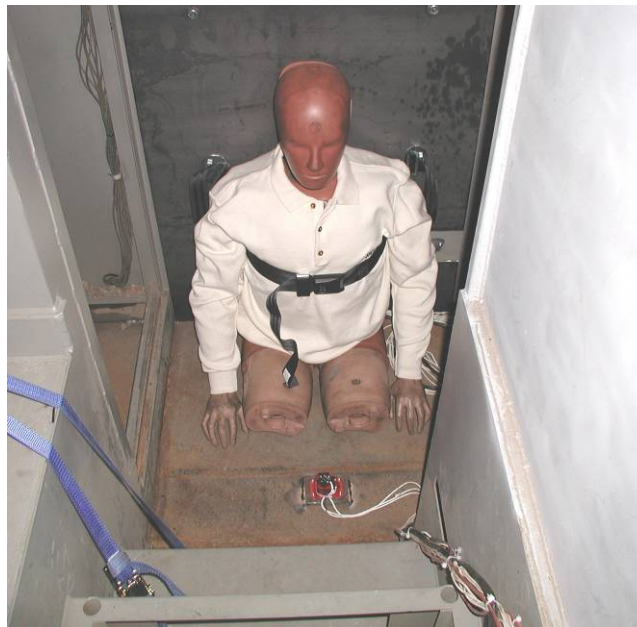


Figure 26. Test 3: ATD Position before Collision

3.3 Assessment

The FEM reasonably predicted the dynamic behavior and responses of the vehicles during the impact in the test. The dynamic sequences predicted by the simulation agree reasonably with the test. The locomotive suffered massive damage from the steel coil in the simulation and in the test. There was significant damage to the locomotive front, collision posts, and windshield posts.

The agreement of peak accelerations of the locomotive and the hopper cars predicted by the simulation and the test is not satisfactory. Strain correlations are generally inconsistent for most locations.

4. Conclusions

The analysis of the simulation predictions and the corresponding test results leads to the following conclusions:

Structural Damage and Intrusion in Cab Volume

- The test showed massive damage to the locomotive, including the short hood, collision posts, and windshield. Complete rupture occurred at the base of the right collision post. The impact significantly penetrated the cab and the firewall collapsed.

Collision Post Force

Assuming the high strain rates in the dynamic collisions can be ignored, the quasi-static load versus strain data generated by Foster-Miller at its Locomotive Test Facility can be used [5]. The quasi-static test data (both actual and linear approximation) shown in Figure 27 is from a similar collision post of an SD70-MAC.

Furthermore, strain data from strain gauge locations 3 and 5 were used to estimate the maximum load applied to the collision posts. However, during the test, strain gauge 3 on the right collision post exceeded the peak value and was therefore damaged after a peak strain of 2,500 microstrain. Using this data, the following observations are made:

- The average maximum strain seen by the right collision post using strain gauges 3 and 5, where the peak value of strain gauge 3 is used before its failure was 1925 microstrain which corresponds to approximately 1,150 kip applied on the right collision post.
- The maximum strain seen by the left collision post using strain gauges 5 (data from strain gauge 3 were not obtained) was 155 microstrain which corresponds to approximately 125 kip applied on the right collision post.
- The right collision post forces exceeded the 2003 S-580 Standard of 500 kip without any undesirable levels of deformation, causing its complete rupture.
- The load applied on the collision posts was not symmetrical because of the test configuration where the steel coil was center with the right collision post.

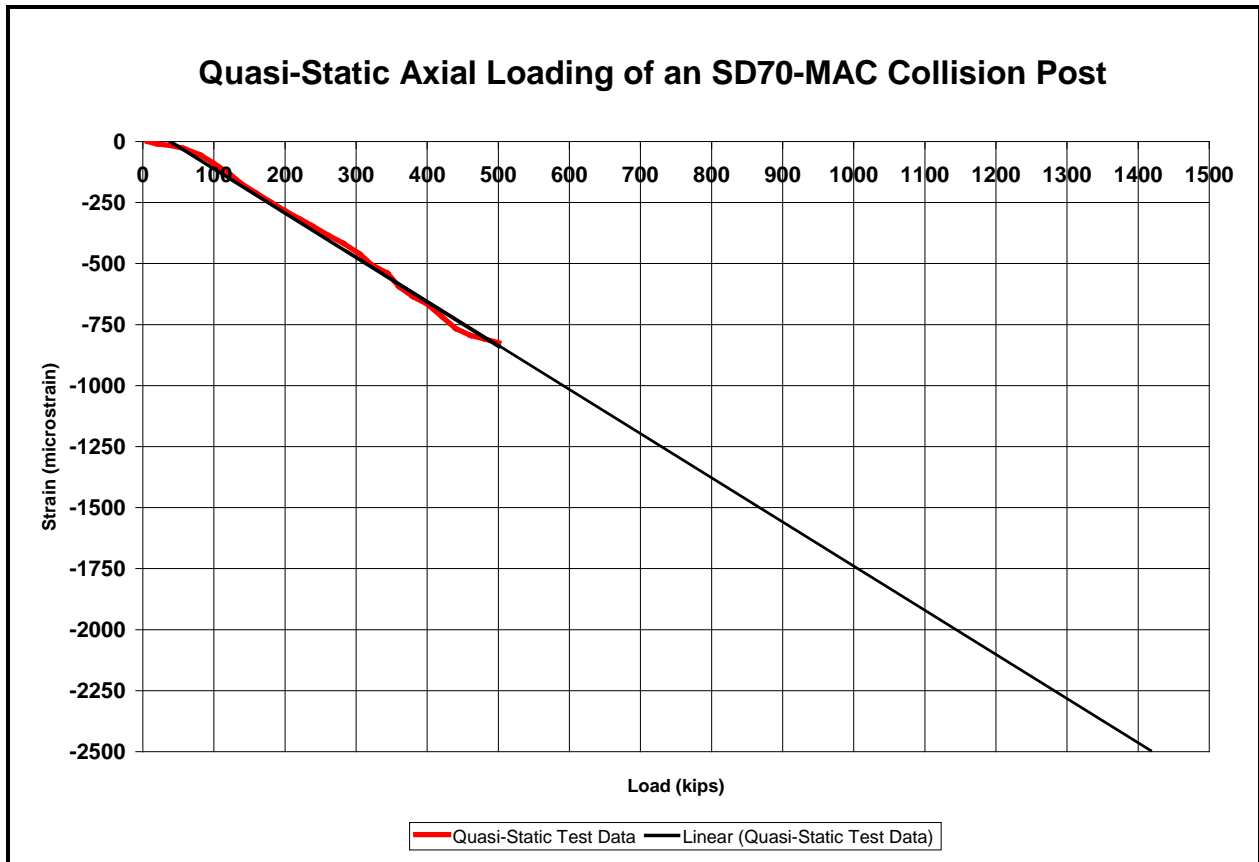


Figure 27. Quasi-Static Longitudinal Load vs. Strain of an SD70-MAC Collision Post

Correlation between Simulation and Tests

- The simulations reasonably predicted the overall collision dynamic sequences and damages to the locomotive and the massive damage to the collision posts and cab in the grade crossing scenario with the steel coil truck.
- Predicted accelerations in this test were less than significant.
- The test and simulation time histories differ in frequency. The tests generally showed reduced levels of damping and high frequency content. Peak values of acceleration and strains generally occurred within 0.1–0.2 s after impact, in the simulation and the test.

5. References

1. *HyperMesh User's Manual*, Version 2.1. (1998). Troy, MI: Altair Computing, Inc.
2. *LS-DYNA User's Manual*, Version 96.0. (2004). Livermore, CA: Livermore Software Technology Corporation.
3. *SAE J211-1: Instrumentation for Impact Test–Part 1–Electronic Instrumentation*. (2003). Society of Automotive Engineering, Rev.
4. *Federal Motor Vehicle Safety Standard No. 208*, Occupant Crash Protection, Title 49 Code of Federal Regulations, Section 571.208, Revised October 1999.
5. *Locomotive Crashworthiness: Static Strength Evaluations and Structural Improvements of SD-70-Type Locomotive*. (2006). Washington, DC: FRA.

Abbreviations and Acronyms

ATD	anthropomorphic test dummy
FEM	finite element model
FRA	Federal Railroad Administration
HIC	Head Injury Criterion
Hz	hertz
in	inch(es)
lb	pound(s)
mph	mile(s) per hour
s	second(s)
TTC	Transportation Technology Center