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Full-Scale Locomotive Dynamic Crash Testing and Correlations: C-39 Type Locomotive Colliding with a Loaded Hopper Car (Test 7)

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13. ABSTRACT (Maximum 200 words)

This report presents the results of a locomotive and three loaded hopper car consist traveling at 29 miles per hour colliding with a stationary consist of 35 loaded hopper cars. The details of test instrumentation, LS-DYNA finite element simulation, conducting of the test, and correlations between the simulation results and test data are presented. The test was fully instrumented and included high-speed video of the collision event. The test resulted in the override of the locomotive over the hopper car consist.

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1 inch (in)	=	2.5 centimeters (cm)	1 millimeter (mm)	=	0.04 inch (in)
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1 yard (yd)	=	0.9 meter (m)	1 meter (m)	=	3.3 feet (ft)
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1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)	10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres
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1 fluid ounce (fl oz)	=	30 milliliters (ml)	1 liter (l)	=	1.06 quarts (qt)
1 cup (c)	=	0.24 liter (l)	1 liter (l)	=	0.26 gallon (gal)
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, ft^3)	=	0.03 cubic meter (m^3)	1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
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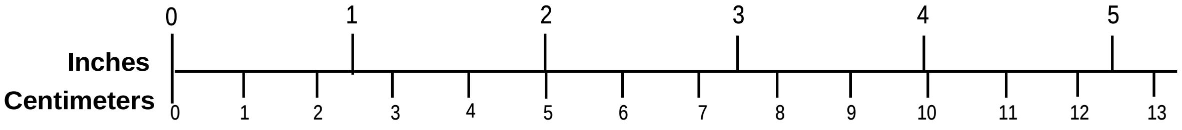

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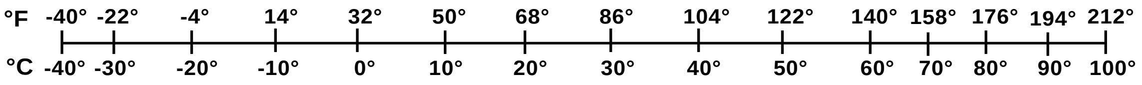

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Acknowledgments

This report presents the test data and analysis of a full-scale collision test involving a C-39 type locomotive and a hopper car in a stationary consist. Foster-Miller, Inc., performed this work under contract DTFR53-01-D-0029 Task Order 0001 from the Federal Railroad Administration (FRA) funded under the Locomotive Crashworthiness Research Program.

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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 accidents involving locomotives and other rail or highway vehicles. This report presents a full-scale collision test between a C-39 type locomotive and a hopper car in a stationary consist. The test measurements included structural damage, decelerations, and strains at critical locations. This report correlates the dynamic finite element model (FEM) predictions with the test results. The simulations reasonably predicted the overall collision dynamic sequences and damages to the locomotive.

This test was similar to a previous test, Test 1, when a locomotive modified to represent a SD-70 MAC, which has collision posts, was subjected to an in-line collision with a loaded hopper car in a consist. In this first test, the locomotive speed was approximately the same as in the present test. The SD-70 type locomotive (with collision posts) overrode the hopper car just as in the present test, with the C-39 locomotive (without collision posts); the collision posts did not significantly alter the end result.

In this test, a C-39 with three trailing cars, collectively moving at 29.8 miles per hour (mph), rear-ended a hopper car in a stationary consist of 35 loaded cars. The locomotive overrode the hopper car, whose rear and sidewalls were completely damaged. The different heights of the locomotive underframe and the hopper sill beam and the coupler/draft gear system failure were principal causes of the override. Damage to the anticlimber and locomotive front was massive with the draft gear failing. The cab was not intruded because the locomotive rode over the hopper car. The fuel tank of the locomotive was damaged and breached in the collision.

The principal lessons from this test were:

- Even at low speeds (~30 mph), the locomotive can override stationary vehicles.
- Hopper car provided no significant resistance to locomotive override.
- Pilot plate and draft gear formed a ramp that allowed the locomotive to ride up on top of the comparatively weaker hopper structure.
- Damage to the anticlimber and locomotive front, including the collision posts, was massive: the anticlimber failed, the draft gear pocket sheared off, and the fuel tank was breached.

1. Introduction

1.1 Background

FRA initiated a program on improved crashworthiness of locomotives with the ultimate objective of developing S-580 standards on the basis of analysis and testing. A previous collision test between SD-70 type locomotive and a hopper car in a consist resulted in the override of the locomotive on the hopper car. A similar test with C-39 type locomotive rear-ending a hopper car in a consist was the subject of evaluation in this report.

The Phase II testing program involved the following collision scenario: the striking, or bullet, consist included a C-39 locomotive and three fully loaded hopper cars and the target consists included a stationary hopper car in a consist of 35 loaded cars. The bullet consist target speed was 32 mph, to match the collision speed attained in Test #1.

This test involved a locomotive subjected to an in-line collision with a loaded hopper car. This type of collision actually occurred at Carlisle, OH, in 2001.

1.2 Objectives

The following lists the specific objectives of the program:

1. Define test requirements with details of the collision scenario, test equipment, measurements, and instrumentation. The measurements should include the dynamic strains in structural posts and the deceleration levels on the cab floor.
2. Evaluate crew injuries because of intrusion, high decelerations, and secondary impacts on the crew.
3. Develop a finite element simulation for the colliding cars in the consist.
4. Correlate the finite element simulation results with the test data on the locomotive structure.

1.3 Organization of the Report

Section 2 describes the overall approach of the current task. This section first presents test procedures, instrumentation, and measurements, including the locations. A brief description of the model development and analysis is then given, followed by details of the basis of the correlations between the test and simulation.

Sections 3 gives detailed descriptions of the full-scale test, its associated simulation, and correlations of the test and simulation results. Test setup and damages to locomotive and other vehicular structures are given, followed by a brief description of the corresponding simulation model. The sections then present correlations of measured and predicted parameters, including the overall collision sequences, accelerations, and strains at predetermined locations.

Finally, Section 4 presents a brief discussion of this crashworthiness test and conclusions.

2. Technical Approach

The simulation and correlations were performed by Foster-Miller, Inc., who also prepared the test requirements document based on a primary analysis. The full-scale test was conducted by Transportation Technology Center, Inc. (TTCI).

The correlations made between the simulation results and test data included dynamic sequence, accelerations, strains, damage to the structure. The test had sufficient photographic, video, and sensor data to support the comparisons.

2.1 Simulation Method

During the test, a total of 5 seconds (s) of data were recorded, starting 1 s before the initial impact and continuing for 4 s after the initial impact. The computer simulations of the crash event were carried out for the first 1 s after initial impact, which was found to be sufficient to capture the major damage in the locomotive structure. The total number of nodes was approximately 40,000 with each node having six degrees of freedom.

HyperMesh^{TM} [1], a multipurpose computerized mesh generator and modeling tool, generated geometry and mesh models for pre-processing. LS-DYNA [2], a dynamic structural analysis finite element program, performed the simulation and post-processing calculations.

The advantages of LS-DYNA included the following:

- It was most suitable for analyzing structures in a single process by combining the dynamic modeling of the locomotive consist as a whole with embedded detailed models of the lead locomotive and the objects it collided into, including standing car consists.
- Simulations permitted visualization of the collision process in the early stages where:
  - Most significant locomotive structural deformations, movements, and decelerations occurred.
  - Three dimension interactions of various components of the locomotive, including the cab and the interior’s influence on crew survivability.
- Models could be developed with detailed representation of the locomotives, rail vehicles, and other potential colliding objects, such as inter-modal ISO containers, hopper cars, and vehicles.

The computer time required to simulate 1 s of data for collision events was generally 15–24 hours on a single 3.0-gigahertz Pentium PC with 1 gigabyte of memory and 250 gigabytes of disk space.

FEMs were developed for the following vehicles:

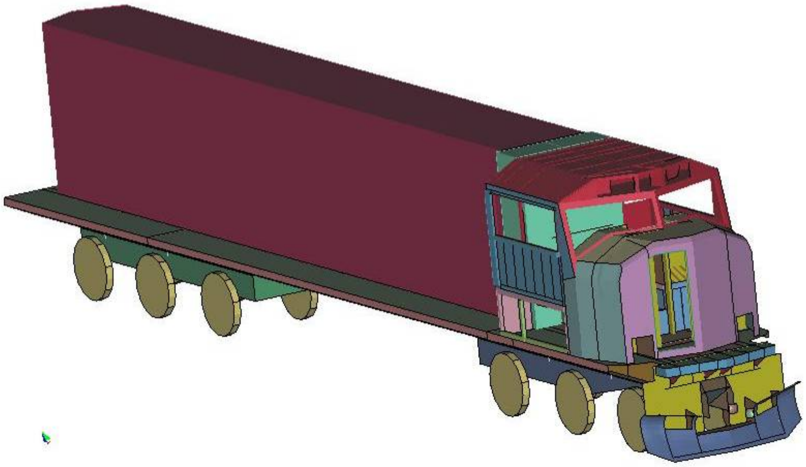
- Locomotive
- Loaded hopper cars
- Track system

The models had the following characteristics:

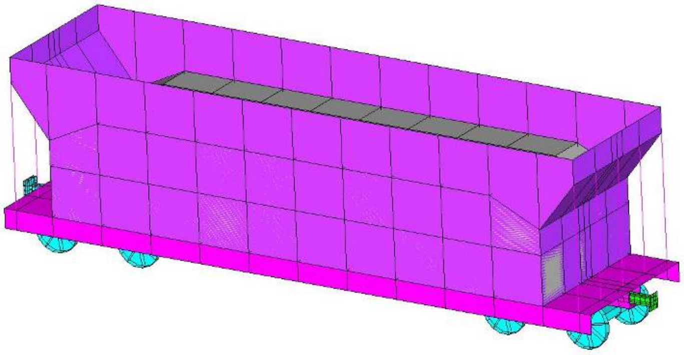
- Appropriate basic structural and mechanical components (including the locomotive, trailing cars, separate bogies and suspension, and draft gear) using shell, plate, beam, and solid finite elements.
- Masses in all directions.
- A simplified model simulated the test scenarios. The model was defined to represent the entire moving consist and the first three hopper cars of the stationary target consist and a maximum of four vehicles in each consist at the front end of the collision point. Additional masses, suspension, and draft gear stiffness in the remainder of the model represented the 35 hopper car consist.
- A realistic nonlinear spring rate between the vehicles to represent the effects of draft gear deformations, travel stops, and clearances.
- Nonlinear material property for all deformable structures, with elastic, elasto-plastic, and fully ductile (if 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.

2.2 Description of the Model

Figure 1(a) shows the FEM of the bullet locomotive and Figure 1(b) shows the detailed model of the first three hopper cars in the stationary consist. The model combined all the remaining cars into a single mass/stiffness system equivalent to the remaining 26 cars. The entire locomotive consist has ~50,000 degrees of freedom.



(a) Locomotive



(b) Hopper Car

Figure 1. FE Models

Figure 2 shows the consists for of the Test 7 scenario. The entire finite element collision model had over 30,000 elements.

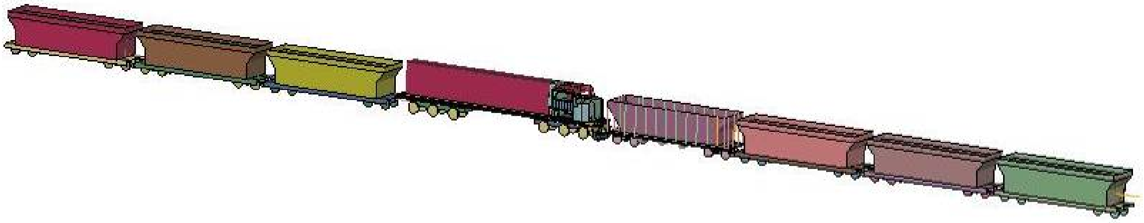


Figure 2. Test 7 Consists

2.2.1 Structures and Dimensions

The locomotive used in the test was a modified C-39. Appropriate sheet metal thicknesses, masses, and inertias in the model represented the actual locomotive used in the real test. The locomotive weighed 380,000 pounds (lb). The model contained three loaded hopper cars (each weighing ~260,000 lb) coupled to the rear of this locomotive.

Foster-Miller modeled the standing hopper consist (each car weighing ~260,000 lb) as a four car consist. Extra weight and a stiff spring were added to the last car to account for the resistance supplied by the remaining 31 cars used in the actual test, thus representing 35 hopper cars.

2.2.2 Test Consists and Equipment

Sharma & Associates, Inc., in Hinsdale, IL, built the locomotive using a modified C-39. This locomotive was manufactured before S-580 standards (no collision posts). Sharma & Associates, Inc., modified the locomotive to include anticlimber and floating bolsters.

The loaded hopper cars came from the existing stock at TTC.

2.2.3 Test Procedures and Instrumentation

The dynamic impact tests employed an active locomotive to push the test consist (locomotive and three loaded hopper cars). The active locomotive disengaged the consist at a predetermined location to let it strike the stationary consist.

TTCI determined the release distance and the speed of the moving consist at release point from a series of speed calibration runs carried out before the test. TTCI measured the speed of the moving consist at impact using a laser speed trap and a standard radar gun.

The contact of tape switches on the front of the locomotive triggered all the instrumentation on board the vehicles. The tape switches were closed by the contact of the locomotive with the stationary vehicle. The data was then saved for 1 s before the trigger and 4 s after the trigger, for a total of 5 s worth of data at a rate of 12,800 hertz (Hz) and saved onto modular data bricks located on board the vehicles. The data was downloaded from the data bricks to a computer after the test was completed. An SAE J211 [3] filter digitally filtered acceleration data after test data collection at frequencies of 25 and 60 Hz.

The test used strain gauges, accelerometers, and string potentiometers to characterize the behavior of the vehicles during the collisions. TTCI installed the following measurement devices:

- Strain gauges on the underframe, and windshield posts measured the impact loads on these components.
- 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 two vehicles.
- String potentiometers between the locomotive and first hopper car measured the relative three-dimensional displacements of the two vehicles during the collision.

The tests used five high-speed film cameras and six standard video cameras to record the impact test.

2.2.4 Test Measurements

TTCI measured the geometries of the vehicles, the weights of the moving and the stationary consists and the positions of all the transducers before the test.

The following items were measured for the test.

Test Locomotive Speed

A laser speed trap and an off-board handheld Doppler radar speed gun (± 0.1 mph) measured the speed of the test locomotive just before impact.

Longitudinal Strain on the Underframe

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

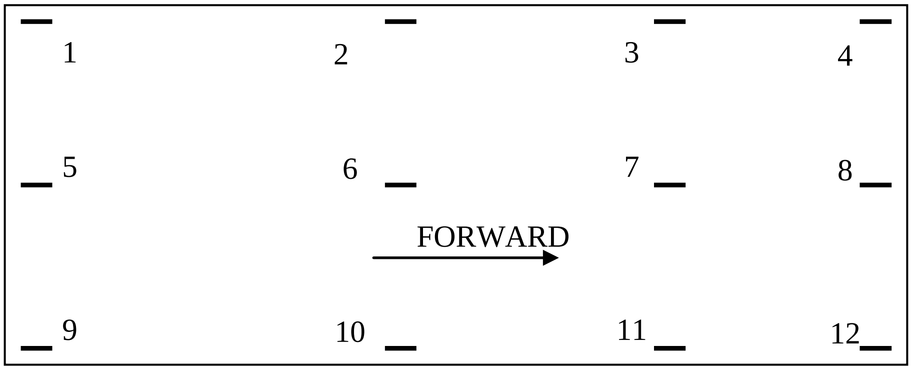


Figure 3. Locations of Strain Gauges on the Underframe

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.

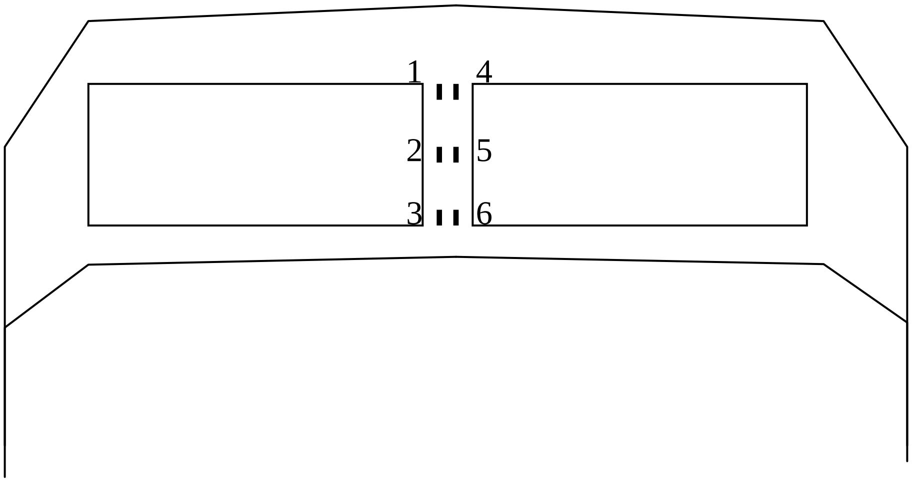


Figure 4. Location of Strain Gauges on Center Post of the Windshield

Additional Strain Measurements

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

Acceleration

The test recorded acceleration measurements on the cab floor of the locomotive and on the first two moving hopper cars. TTCI placed a triaxial accelerometer on the floor of the cab near the driver's seat to measure the gross and flexible motions of cab floor. Triaxial accelerometers at center-sill and at the centerline (axially and laterally) of the first two hopper cars in the moving consist measured the gross and flexible motions of the hopper cars. Additional triaxial accelerometers were placed at various other locations to record more data for the three test scenarios.

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

Table 1. Typical 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
First moving hopper car	Three axis	Longitudinal	X
		Lateral	Y
		Vertical	Z
Second moving hopper car	Three axis	Longitudinal	X
		Lateral	Y
		Vertical	Z
First stationary hopper car	Three axis	Longitudinal	X
		Lateral	Y
		Vertical	Z
Second stationary hopper car	Three axis	Longitudinal	X
		Lateral	Y
		Vertical	Z
Locomotive, above event recorder	Three axis	Longitudinal	X
		Lateral	Y
		Vertical	Z

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

Photography and Video

Five high-speed film cameras and six standard video cameras recorded the collision. Camera coverage was selected to provide views of both the left and right sides of the vehicles, overhead views, and an overall view of the impact. Figure 5 gives the locations videos with respect to the collision location simulation

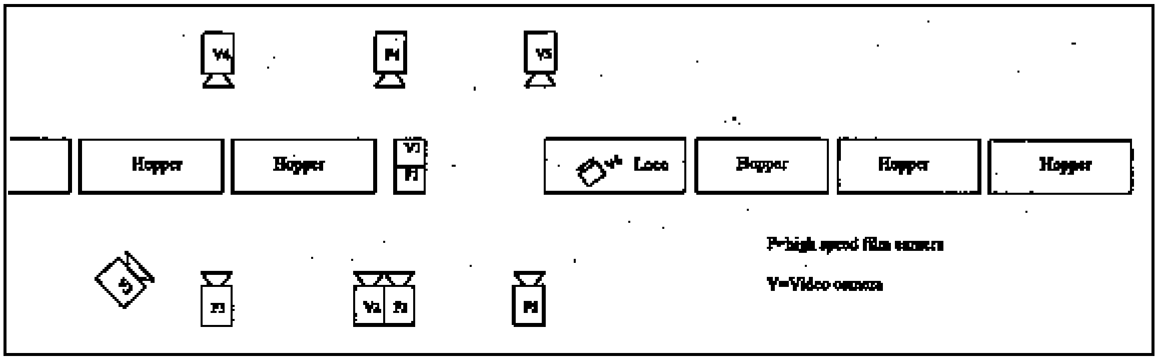


Figure 5. Video Camera Positions

2.2.5 Boundary Condition and Constraints

Foster-Miller simulated the interaction between the structures (locomotive and hopper cars) and ground as friction force. The friction coefficient in the transverse direction of the wheels was assigned to be 0.6, whereas in the rolling direction, it was taken as 0.3.

To improve the simulation of the contact between the locomotive and the stationary hopper car, the model simulated some parts in greater detail (e.g., the front axle of the front locomotive truck). The spring rate of the couplers was tailored to provide the correct impact momentum to the locomotive. Modeling of these contact interfaces was important for a proper simulation.

2.2.6 Loading Condition

The loads applied in the simulations include the initial moving consist velocities and gravity forces. The locomotive velocity immediately before impact in the actual test was the initial simulation velocity value.

2.3 Correlation of Simulation and Test Results

This report compares the simulation results 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. The accelerations calculated from simulations were filtered similarly to the collected test data using an SAE J211 filter at 25 and 60 Hz.

2.3.1 Dynamic Event Sequence Correlation

Foster-Miller compared the dynamic event sequence obtained from the collision simulation with photographic and video information from the test. The following dynamic events were used for the test and simulation correlations:

- Deformation to major structural components.
- Relative positions of the locomotive and impacted target vehicles.
- Component failure.

2.3.2 Acceleration Correlations

TTCI collected acceleration data at certain locations for comparison with simulation data. The acceleration of the corresponding nodes on the model created simulated output for comparison with test data. In areas without fine mesh modeling, nodes were identified to closely match the accelerometer location. A selected filter first filtered the simulated accelerations and then converted to the unit of g's (acceleration due to gravity). Sign conventions for the accelerations were as follows:

- Longitudinal: positive was forward acceleration.
- Lateral: positive was rightward acceleration.
- Vertical: positive was downward acceleration.

Table 2 describes the nodes identified for simulation accelerations and shows the simulation values for comparison with measured test data accelerations.

Table 2. Node Locations Identified for Acceleration

Location	Node Flagged	Comparison
Locomotive floor	Near driver'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

2.3.3 Strain Correlations

Table 3 lists the locations for strain correlation. Positive values show tension, and negative values show compression.

Table 3. Strain Locations for Correlation

	Identified Location	Vectors	Strain Gauges in Test
Underframe	6	Longitudinal	Standard
	8	Longitudinal	Standard
Center post of windshield	1	Vertical	Standard
	6	Vertical	Standard

3. Locomotive Colliding with Loaded Hopper Car

3.1 Test Setup and Collision Damage

The striking consist moved with a velocity of 29.8 mph with C-39 locomotive in lead and three trailing loaded hopper cars. The stationary consist, which was in line, had 30 loaded hopper cars. Figure 6 shows the test setup; Figures 8 and 9 show the vehicles of interest before impact. Figure 9 shows the alignment of the locomotive and hopper car before impact.

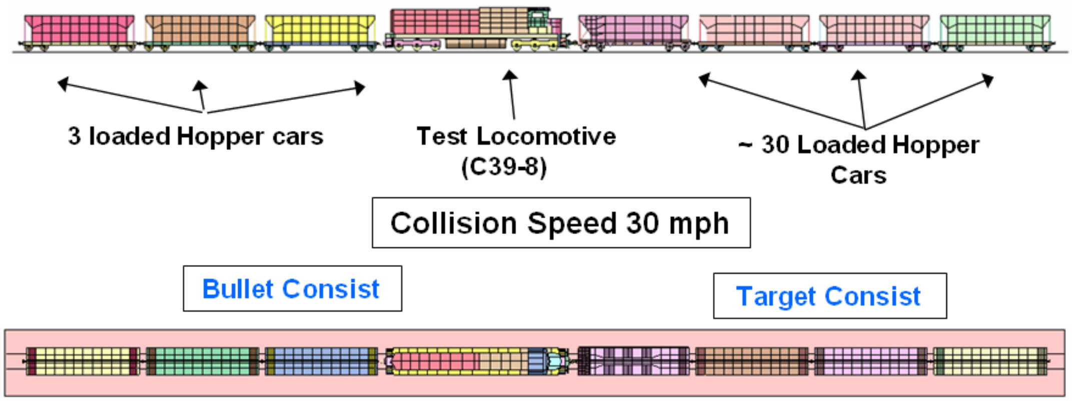


Figure 6. Test Setup

Figure 7. Locomotive and Bullet Consist before Impact

Figure 8. Hopper Car and Target Consist before Impact Test

Figure 9. Alignment of Locomotive and Covered Hopper Car at Point of Impact

Table 4. Rolling Stock Weights in the Moving and Stationary Consists

	Moving Consist Weight (lb)	Stationary Consist Weight (lb)
Locomotive	382,274	
First Hopper Car	261,775	
Second Hopper Car	261,600	
Third Hopper Car	258,825	
Loaded Hopper Car 1		270,375
Loaded Hopper Car 2		263,175
Loaded Hopper Car 3		262,025
Loaded Hopper Car 4		8,463,000
Total Weight	1,174,474	9,258,775

Table 4 presents the rolling stock weights in the moving and stationary consists used in the tests. Figures 10–16 provide images from the high-speed video and a description of the dynamic sequence of events.

Figure 10. Initial Contact of Collision

The initial contact between the moving locomotive and the stationary hopper car occurred at the couplers. The draft gears then fully compressed and forced downward as the draft gear housings failed.

Figure 11. Locomotive Coupler Failure

The pilot plate was forced downward because of the coupler/draft gear movement, which in turn, deformed the locomotive underframe and compressed the suspension of the front bogie.

Figure 12. Locomotive Nose and Anticlimber Collided with Hopper Car

As the locomotive continued forward, the anticlimber collided with the rear structural supports of the hopper car. Next, the top of the locomotive nose collided with the top rear of the hopper car.

Figure 13. Locomotive Intruded into Hopper Car

Then, the locomotive nose pushed into the interior of the hopper car. The pilot plate, coupler/draft gear, and front bogie of the locomotive shoved the end of the hopper car toward the center of the car.

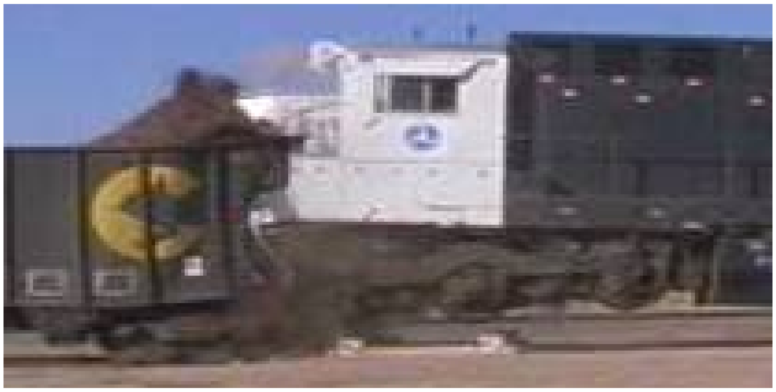


Figure 14. Locomotive Began to Override Hopper Car

The front of the locomotive began to rise because of the anticlimber and associated bracing overriding the hopper's car bogie and main sill.

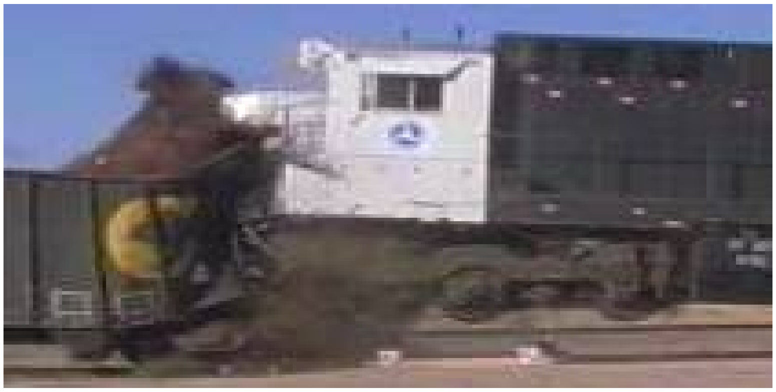


Figure 15. Locomotive Truck Contacted Hopper Sill

As the locomotive continued forward, the front nose continued to rise and to displace the ballast of the hopper car. The locomotive's front bogie contacted the hopper car's sill, overrode the sill, and climbed into the interior of the hopper car.

Figure 16. Locomotive Came to Rest Atop Hopper Car

The rear and side walls of the hopper car were destroyed as the locomotive moved into and above the hopper car. The fuel tank was breached during the collision.

Figures 17–19 show the damages and final positions of the locomotive and the hopper car.

Figure 17. Locomotive after Collision

Figure 18. Damage to Locomotive

Figure 19. Hopper Car after Collision

3.2 Correlations of the Collision Results

3.2.1 Dynamic Event Sequence Correlation

Figure 20 shows the dynamic sequence correlations between the test and the simulation captured at time equaling 0.06, 0.39, and 1.01 s. The dynamic sequence as captured from the high-speed video was in agreement with the simulations from the finite element analysis.

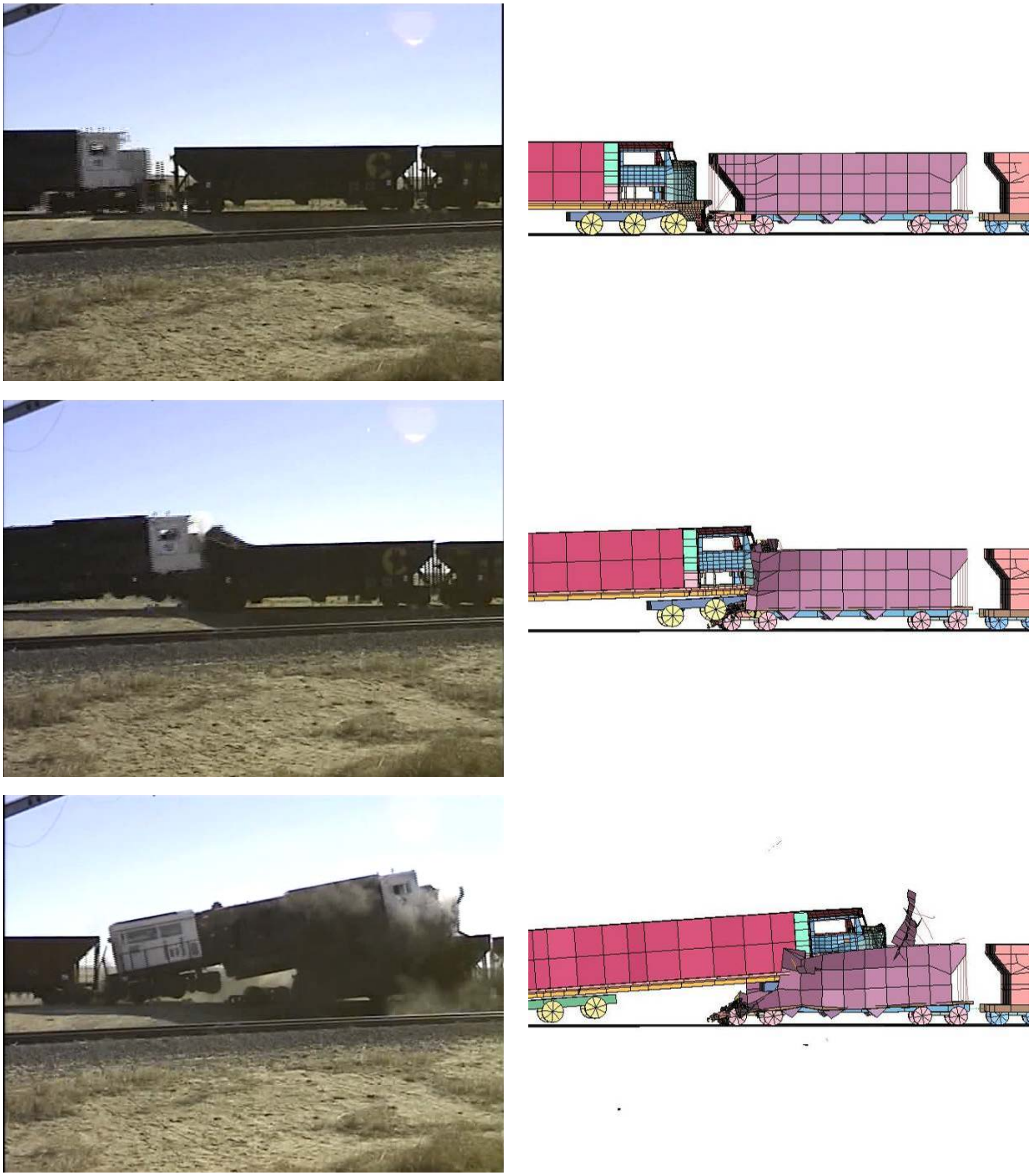


Figure 20. Kinematic Comparison between Test and Simulation

The simulated finite element collision sequence progressed as follows:

- Initial contact with the draft gear occurred. The draft gear compressed to its limit and failed.
- The contact forced the center sill of the hopper car into the locomotive draft gear box. The anticlimber of the locomotive destroyed the vertical beams on the rear side on impact end of the hopper car.
- As the moving consist continued forward, the plow on the front of the locomotive made contact with the front bogie of the hopper car. The side beams on the underframe of the hopper car began to buckle downward. The short hood of the locomotive crushed into the upper portion of the hopper car. The plow of the locomotive continued and pushed the hopper car bogies forward as shown in Figure 21.

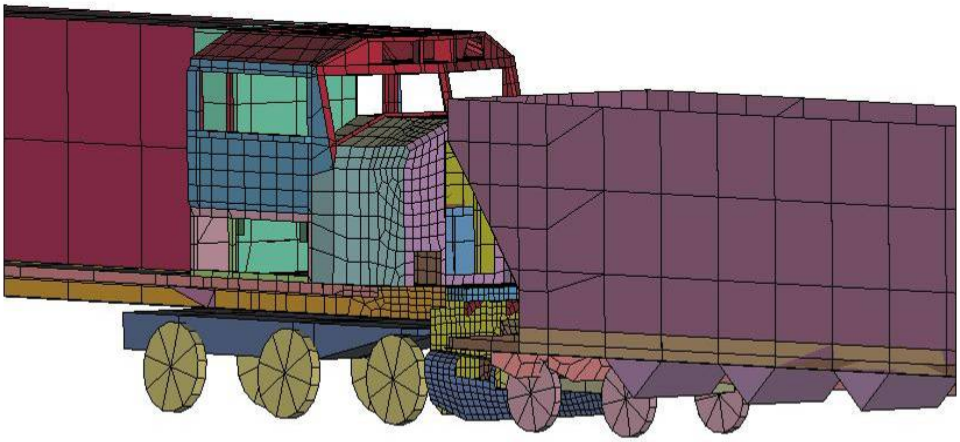


Figure 21. Initial Contact of Locomotive with Hopper Car

- The locomotive continued forward into the hopper car, pushing it slightly forward. The locomotive continued to move forward with deceleration because of collision forces and braking. Eventually, the inertia of the remaining cars in the stationary consist restrained the hopper car from movement.
- The substantial forward momentum of the locomotive combined with the downward buckling of the hopper car underframe lifted the front of the locomotive. The locomotive continued to ascend higher above the hopper car while tearing the hopper car’s sidewalls. The locomotive stopped with its lead truck resting inside and toward the top of the hopper car (see Figure 22).

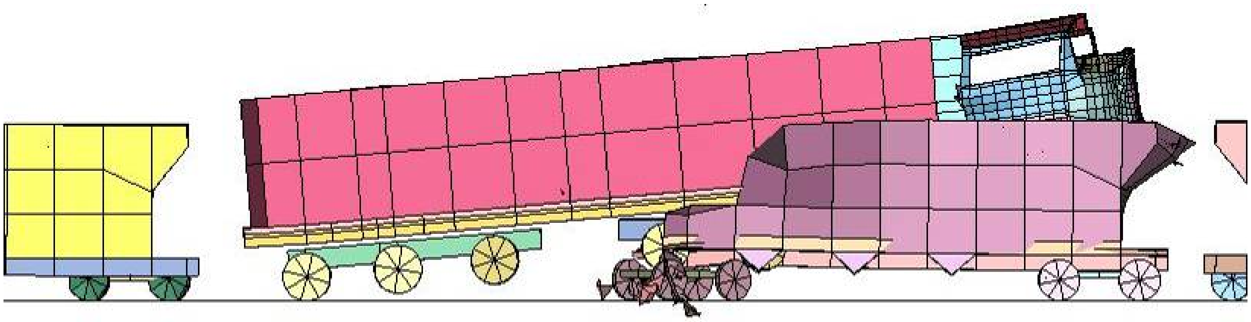


Figure 22. Locomotive Overriding Hopper Car

Figure 23 illustrates the damage to the locomotive and hopper car from the simulated collision.

Figure 23. Locomotive and Hopper Car Damage from Simulation

The agreement between the actual dynamic sequences (from high-speed video) and the finite element analysis simulation (computer generated) was reasonable as shown in Figure 20. The damages seen in the simulations were also in reasonable agreement.

3.2.2 Acceleration Correlation

Foster-Miller compared accelerations in the FEM with those measured from the test. During the test, instrumentation collected accelerations from the locomotive floor, the first two moving hopper cars behind the locomotive, and the first two leading stationary hopper cars at the sill level.

Figure 24 and Figure 25 show acceleration correlations between test vehicles, and the filtering sequence were at 25 and 60 Hz. Table 5. shows the comparison of peak accelerations.

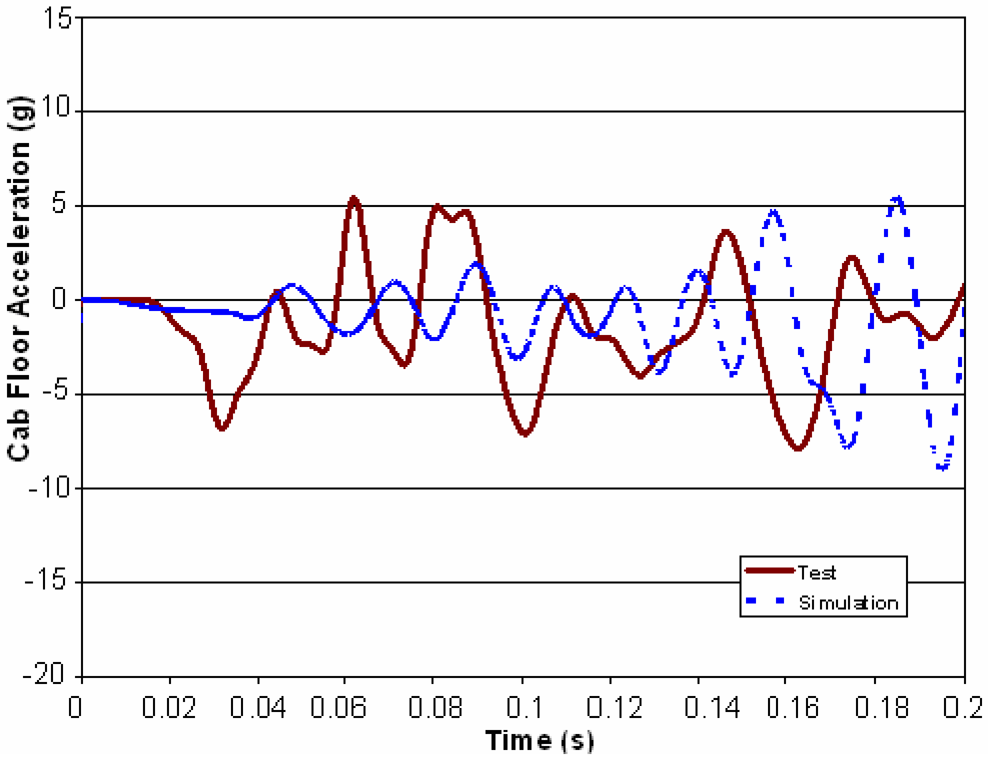


Figure 24. Locomotive Cab Floor Longitudinal Acceleration Filtered at 25 Hz

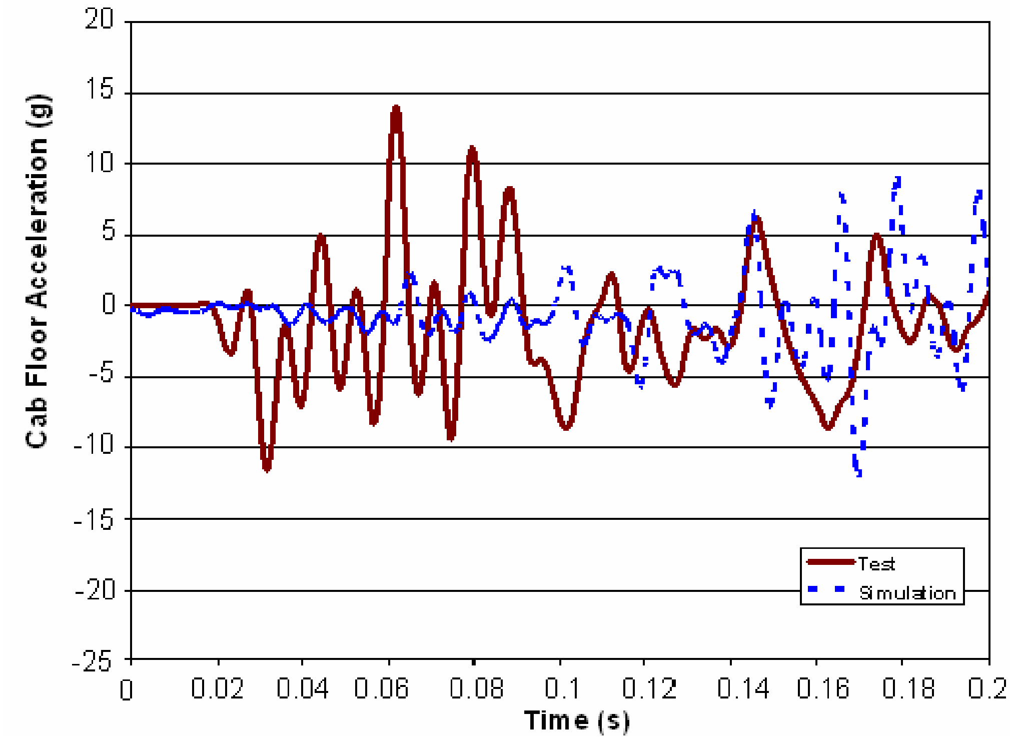


Figure 25. Locomotive Cab Floor Longitudinal Acceleration Filtered at 60 Hz

Table 5. Acceleration Comparison for Test 7

Filter Frequency	Locomotive Cab Floor (g)	
	Test	Simulation
25 Hz	7.9	9
60 Hz	11.5	12.2

As shown in the previous figures, the time histories of predicted longitudinal accelerations of the locomotive cab floor were in agreement with the test results.

3.2.3 Strain Correlations

The correlations between the simulation and the test used strain data for the center windshield posts of the locomotive. The underframe and windshield post did not suffer any significant damage from the collision.

The simulation results also showed the absence of damage to these structures.

Table 3 describes element locations and the identified strains chosen for correlation. Figure 26 and Figure 27 show the windshield strain correlations.

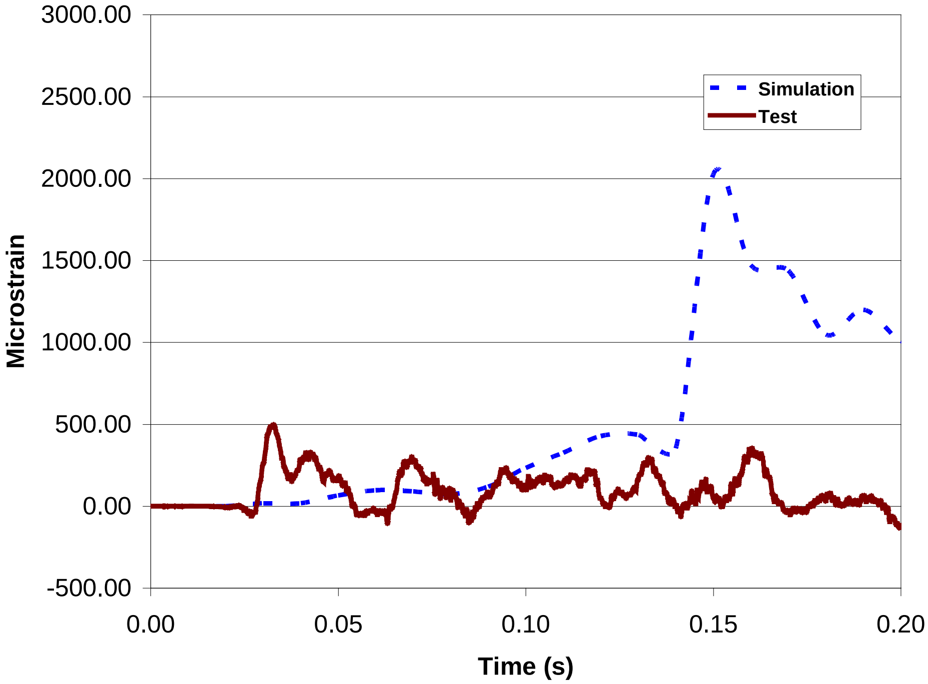


Figure 26. Windshield Strain–Location 5

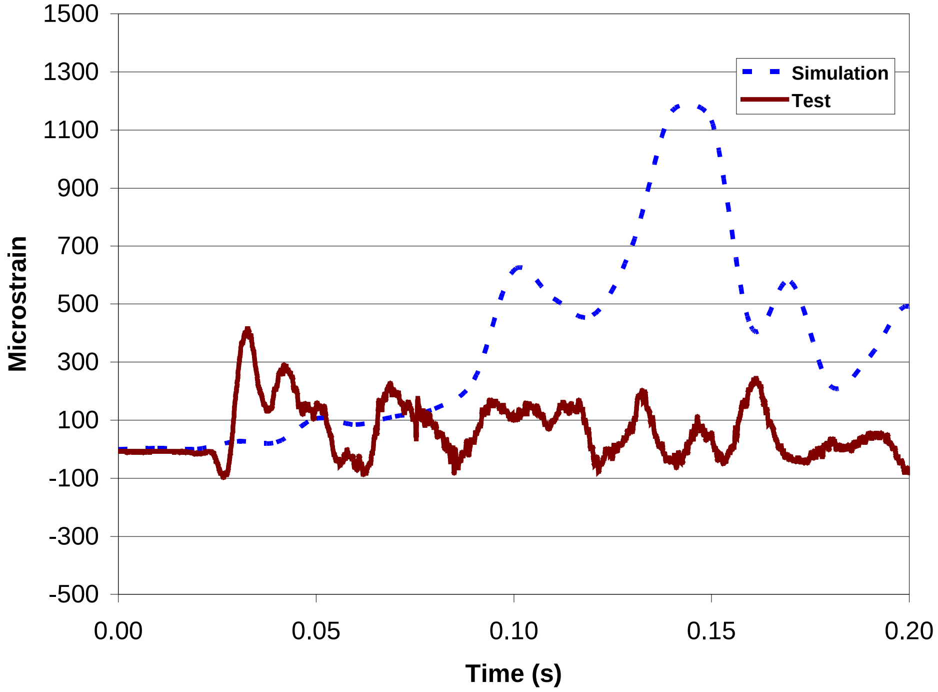


Figure 27. Windshield Strain–Location 2

The largest measured strain on the windshield area was 200 microstrain and occurred on the right beam of the windshield (location 5).

3.3 Assessment

The dynamic sequences predicted by the simulation agreed with the test sequence. The test and the simulation showed the important phenomenon of the locomotive override on the hopper car. The substantial forward momentum of the locomotive, combined with the downward buckling of the hopper car underframe and caused the override of the locomotive.

The peak accelerations of the locomotive predicted by the simulation agreed well from the beginning of the simulation through 0.1 s. Other correlations were unsatisfactory.

4. Conclusions

Analysis of the simulation predictions and actual test results leads to the following conclusions:

Structural Damage

- Damage to the locomotive front was massive in this test, including the draft gear pocket shearing off and the anticlimber failure. No intrusion into the cab occurred because of the locomotive override onto the hopper car.
- The locomotive fuel tank was breached during the override of the hopper car. This situation could result in a fuel spill, increasing the risks of a fire and a hazardous materials spill.
- In a similar previous test, under akin impact conditions between a SD-70MAC locomotive and a loaded hopper car consist and a stationary, loaded hopper car consist, the collision resulted in locomotive override. The collision posts in the SD-70 played no role once override took place.

Correlation between Simulation and Test Results

- The simulation reasonably predicted the overall collision dynamic sequence and damages to the locomotive in this test scenario. The model accurately predicted the massive damage to the cab front.
- The predicted peak deceleration levels for all scenarios showed reasonable agreement with test data, although the peaks in the simulations did not occur at the same times as those in the last.. The deceleration level imposed on the locomotive was an important indicator of the injury potential due to the secondary collision between the crew and interior, as shown in the present test.
- The time histories in the test and in the simulations do not show good agreement. The tests show reduced damping and high frequency content. Peak values of acceleration and strains generally occur within 0.1–0.2 s after impact, in the simulation and the test.
- The simulation predicted the locomotive override on the hopper car under certain assumptions. The small height difference between the locomotive draft gear and the hopper sill could be a factor contributing to the override. A frame-by-frame inspection of the high-speed photography revealed that the locomotive frame started rising up into the back of the hopper car, tearing apart the side and rear walls of the hopper car, and eventually riding up to the hopper car front.

5. References

1. *HyperMesh User's Manual*, Version 6.0. (2004). 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*, (Rev. 2003). Society of Automotive Engineering.

Abbreviations and Acronyms

FEM	finite element model
FRA	Federal Railroad Administration
Hz	hertz
lb	pound(s)
mph	mile(s) per hour
s	second(s)
TTC	Transportation Technology Center
TTCI	Transportation Technology Center, Inc.