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F40 CEM Locomotive and M1 Passenger Car Impact Test

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14. ABSTRACT
An impact test with a F40 locomotive and a M1 passenger car was conducted to evaluate the performance of the vehicles under dynamic conditions. The locomotive was retrofitted with crash energy management (CEM) components – including a push-back coupler (PBC), deformable anti-climbers, and a sliding lug connected to the draft pocket with a set of shear bolts. The impact test was performed in November 2021 at the Transportation Technology Center in Pueblo, Colorado. The M1 passenger car, backed by two empty hopper cars, was impacted by the CEM-equipped locomotive at 32.8 mph. The impact-initiated deformation on one set of anti-climbers, activated the PBC, and sheared all the shear bolts.

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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, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

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, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °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 (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	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 (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

Inches	0	1	2	3	4	5

Centimeters	0	1	2	3	4	5	6	7	8	9	10	11	12	13

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

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

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Executive Summary

Researchers conducted an impact test between an EMD F40 passenger locomotive equipped with crash energy management (CEM) components and an M1 series passenger car backed by two empty freight cars. This test was performed to evaluate the performance of the CEM components under dynamic conditions. Researchers retrofitted the CEM locomotive with a push-back coupler (PBC), deformable anti-climbers, and shear bolts. This test was performed in November 2021 at the Transportation Technology Center in Pueblo, Colorado.

The locomotive and M1 passenger car impacted at 32.8 mph. The locomotive and M1 passenger car couplers were closed at impact, preventing the possibility of coupling; however, the locomotive was lodged into the cab end of the M1 passenger car by the force of the impact. The vehicles had to be pulled apart after the test. The locomotive sustained structural damage to its front plate beyond the expected deformation of the CEM components. The impact caused the crushing of one set of anti-climbers, the activation of the PBC, and the shearing of the sliding lug bolts. The M1 passenger car sustained significant damage at the impact end of the vehicle (cab area) and the carbody buckled approximately three-quarters of the length of the car back from the impact point. Aside from this damage, the interior of the M1 passenger car was relatively unharmed inboard of the cab area, except for deformation of the flooring.

Future work will include the final test in this program, which will be a full-scale, train-to-train impact. This test will evaluate the performance of the retrofit CEM components in a high-energy collision scenario.

1. Introduction

In November 2021, researchers conducted an impact test between an EMD F40 passenger locomotive equipped with crash energy management (CEM) components and a M1 passenger car backed by two empty freight cars. This test characterized the combined performance of the installed CEM components. This research program integrated three CEM components onto a locomotive to demonstrate that they could work together to mitigate the effects of a collision and prevent override. The CEM system includes a deformable anti-climber (DAC), a push-back coupler (PBC), and a sliding lug connected to the draft pocket with a set of shear bolts.

1.1 Background

The Office of Research, Development, and Technology of the Federal Railroad Administration (FRA) and the Volpe National Transportation Systems Center (Volpe) continue to evaluate new technologies for increasing the safety of passengers and operators in rail equipment. In recognition of the importance of override prevention in train-to-train collisions in which one of the vehicles is a locomotive, FRA seeks to evaluate the effectiveness of components integrated into the end structure of a locomotive specifically designed to mitigate the effects of a collision and to prevent override of one onto the other.

In recognition of the importance of override prevention in train-to-train collisions in which one of the vehicles is a locomotive,[1] and in light of the success of crash energy management technologies in passenger trains,[2] FRA seeks to evaluate the effectiveness of crashworthy components that are integrated into the end structure of a locomotive. These components are specifically designed to mitigate the effects of a collision and, in particular, to prevent override of one of the lead vehicles onto the other.[3]

In prior Volpe Center research, designs for two CEM components for retrofit onto the forward end of a locomotive, a deformable anti-climber and a push-back coupler, were developed, fabricated and tested.[4] The performance of each design was evaluated through large deformation dynamic finite element (FE) analysis. Two test articles were fabricated and dynamically tested individually by means of a rail car impact into a test wall to independently verify performance

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[1] Mayville, R.A., Stringfellow, R.G., Rancatore, R.J., Hosmer, T.P. (1995). Locomotive Crashworthiness Research: Executive Summary. DOT/FRA/ORD-95/08; Tyrell, D., Severson, K., Marquis, B., Martinez, E., Mayville, R., Rancatore, R., Stringfellow, R., Hammond, R., Perlman, A.B. (1999). Locomotive Crashworthiness Design Modifications Study, Proceedings of the 1999 IEEE/ASME Joint Railroad Conference, Institute of Electrical and Electronics Engineers. Catalog Number 99CH36340; Mayville, R., Stringfellow, R., Johnson, K., Landrum, S. (2003). Crashworthiness Design Modifications for Locomotive and Cab Car Anticlimbing Systems. US Department of Transportation, DOT/FRA/ORD-03/05.

[2] Tyrell, D., Jacobsen, K., Martinez, E. (2006). A Train-to-Train Impact Test of Crash Energy Management Passenger Rail Equipment: Structural Results. American Society of Mechanical Engineers. Paper No. IMECE2006-13597.

[3] Llana, P., Stringfellow, R. (2011). Preliminary Development of Locomotive Crashworthy Components. Proceedings of the 2011 ASME Joint Rail Conference, Paper No. JRC2011-56104.

[4] Llana, P., Stringfellow, R. (2011). Preliminary Finite Element Analysis of Locomotive Crashworthy Components. American Society of Mechanical Engineers, Paper No. RTDF2011-67006; Llana, P., Stringfellow, R. (2011). Preliminary Finite Element Analysis of Locomotive Crashworthy Components. American Society of Mechanical Engineers, Paper No. RTDF2011-67006

characteristics of the two components relative to specific requirements. The tests were successful in demonstrating the effectiveness of the two design concepts. Test results were consistent with FE model predictions in terms of energy absorption capability, force-displacement behavior, and modes of deformation.

In a follow-on program, the two CEM components were integrated into the end structure of a conventional locomotive (see Figure 1) in order to demonstrate through a series of full-scale vehicle collision tests that these components work together to mitigate the effects of a collision and prevent override.[5] Each of these tests are designed to evaluate the performance of the CEM locomotive in head-on collision scenarios in which a moving CEM locomotive (or CEM locomotive-led consist) collides with a stationary vehicle or consist. The stationary vehicle (or lead vehicle in a consist) may be a conventional locomotive, a CEM locomotive, a cab car, or a freight car. The overall objective of these tests is to demonstrate the effectiveness of a locomotive CEM system comprised of a PBC and a DAC.

In a first series of tests, the performance of the PBC was evaluated in a series of coupling tests performed at collision speeds ranging from 2 mph to 9 mph.[6] In these tests, the CEM locomotive impacted a standing M1 cab car.

In this program, two vehicle-to-vehicle collision tests were performed, one with a CEM locomotive impacting a standing conventional locomotive (V2VT1)[7] and this test with a CEM locomotive impacting a standing consist led by an M1 cab car with a trailing ballasted freight car (V2VT2).

Pre-test activities in support of V2VT1 indicated that a target speed of 21 mph ± 1 mph would meet test objectives of complete PBC stroke with shear bolt failure and energy absorption in the DAC of at least 50 percent of the design specification, with some margin for error. The actual test speed was only 19.3 mph, well less than the minimum expected speed. The various components performed as designed: the vehicles remained in-line with no derailment and no signs of override, the stroke of the PBC deformation tube appears to have been exhausted, and the DAC energy absorption levels met test targets. However, due to the low test speed, there was not enough energy to fail the shear bolts of the PBC.

1.2 Objectives

This test was intended to demonstrate the combined functionality of the PBC and the DAC as the CEM system. The research team designed the test to characterize the structural performance of the CEM components and impacted locomotive at a speed sufficient to activate all the CEM system components.

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[5] Stringfellow, R., Amar, G. (2016). Locomotive Crashworthy Components Retrofit for F40 Locomotive. Final report to the Volpe National Transportation Systems Center, Contract No. DTRS57-15-F-50013.

[6] Llana, P., Jacobsen, K., Stringfellow, R. (2019). Conventional and Crash Energy Management Locomotive Coupling Tests. DOT/FRA/ORD-19/36.

[7] Rakoczy, P., Gorhum, T. (2021). Conventional and CEM Passenger Locomotive Impact Test. DOT/FRA/ORD-21/02.

1.3 Overall Approach

1.3.1 CEM Locomotive

The F40PH locomotive is a four-axle, diesel-electric locomotive intended for passenger service. This test used a CEM-retrofitted F40 Locomotive 234 as the impacting vehicle (Figure 1); it weighs 231,825 lbs.

Figure 1. F40PH Locomotive 234

1.3.2 Stationary Consist

The stationary consist contained M1 Passenger Car 8333 backed by two empty hopper cars, BN 526308 and BN 531622 (Figure 2). The M1 passenger car was set up with the cab end toward the impact point; it weighs 80,750 lbs. The empty hopper cars weigh 59,300 lbs. and 59,950 lbs., respectively. The M1 passenger car was partially abated to remove asbestos. This involved removing the seats, flooring, and interior side paneling. The flooring was replaced by two layers of 1/2-inch-thick plywood, secured to the car frame to simulate the original car structure and rigidity.

Figure 2. M1 Passenger Car 8333 and Empty Hopper Cars

1.3.3 Test Setup

The impact test was performed in November 2021 at the Transportation Technology Center (TTC) in Pueblo, Colorado. The testing was performed by positioning the CEM locomotive uphill from the stationary consist and utilizing another locomotive to push the CEM locomotive and release it at a designated location. The CEM locomotive was then allowed to roll freely down a slight grade until it impacted the stationary consist. The release location and speed of the CEM locomotive was determined through speed trials and adjusted shortly before the test to achieve the desired impact speed. The couplers of the CEM locomotive and the M1 passenger car were aligned and closed to prevent coupling upon impact.

The two empty hopper cars had the handbrakes applied to keep the stationary consist in place and to stop motion after the impact. A string of loaded hopper cars was placed approximately 300 feet behind the stationary locomotive to arrest any remaining momentum if the brakes were not sufficient.

Before the test, speed trials were conducted using the CEM locomotive to determine the optimum release location and speed needed to achieve the desired impact speed. To achieve a more precise target speed, adjustments were made immediately before testing to account for wind speed and direction.

1.4 Scope

This report presents the test results, discusses the execution of the test, and summarizes the overall results of the test.

1.5 Organization of the Report

- Section 2 describes the test instrumentation and data collection system used in testing.
- Section 3 describes the results of the test. These results include the test details, the data measured, and a discussion of the post-test damage.
- Section 4 contains the concluding remarks.
- Section 5 contains a list of the references made in this report.
- Appendix A describes the target positions on the CEM locomotive.
- Appendix B contains the test data collected from all transducers.

2. Test Instrumentation

The test configuration and instrumentation were consistent with the specifications in the test implementation plan. Table 1 lists all instrumentation used for this testing. Additional descriptions of instrumentation are provided in the following subsections.

Table 1. Instrumentation Summary

Type of Instrumentation	Channel Count
Accelerometers	43
String Potentiometers	26
Strain Gages	62
Total Data Channels	**131**
High-Definition Video	8
High-Speed Video	7

2.1 Definition of Coordinate Axes

All local acceleration and displacement coordinate systems were defined relative to the front (lead) end of each vehicle. Positive X, Y, and Z directions are forward, left, and up, relative to the lead end of each vehicle.

2.2 CEM Locomotive Accelerometers

Tri-axial accelerometers were placed at the two ends and the center along the carbody centerline. The locomotive had longitudinal and vertical accelerometers placed on the left and right sides of its underframe at its center. Each truck was equipped with a vertical accelerometer and two longitudinal accelerometers, right and left. The locomotive's PBC was fitted with three longitudinal accelerometers, one on each side of the coupler and one on the bottom of the sliding lug. The typical scale factor calibration error for the accelerometers used is 2 percent of full scale. Table 2 summarizes all accelerometers on Locomotive 234. Figure 3 and Figure 4 show the locations of the accelerometers on the locomotive.

Table 2. CEM Locomotive Accelerometer Summary

Name	Range	Location
AMLE_X	400g	Moving vehicle, lead end, center – longitudinal
AMLE_Y	200g	Moving vehicle, lead end, center – lateral
AMLE_Z	200g	Moving vehicle, lead end, center – vertical
AMUC_X	200g	Moving vehicle, underframe center – longitudinal
AMUC_Y	200g	Moving vehicle, underframe center – lateral
AMUC_Z	200g	Moving vehicle, underframe center – vertical
AMUCR_X	200g	Moving vehicle, underframe center-right – longitudinal
AMUCR_Z	200g	Moving vehicle, underframe center-right – vertical
AMUCL_X	200g	Moving vehicle, underframe center-left – longitudinal
AMUCL_Z	200g	Moving vehicle, underframe center-left – vertical

Name	Range	Location
AMTEC_X	200g	Moving vehicle, trailing end, center – longitudinal
AMTEC_Y	200g	Moving vehicle, trailing end, center – lateral
AMTEC_Z	200g	Moving vehicle, trailing end, center – vertical
AMLT_Z	400g	Moving vehicle, lead truck – vertical
AMLTR_X	400g	Moving vehicle, lead truck, right – longitudinal
AMLTL_X	400g	Moving vehicle, lead truck, left – longitudinal
AMTT_Z	400g	Moving vehicle, trailing truck – vertical
AMTTR_X	400g	Moving vehicle, trailing truck, right – longitudinal
AMTTL_X	400g	Moving vehicle, trailing truck, left – longitudinal
AMCR_X	5,000g	Moving vehicle, coupler, right – longitudinal
AMCL_X	5,000g	Moving vehicle, coupler, left – longitudinal
AMS_X	5,000g	Moving vehicle, sliding lug – longitudinal

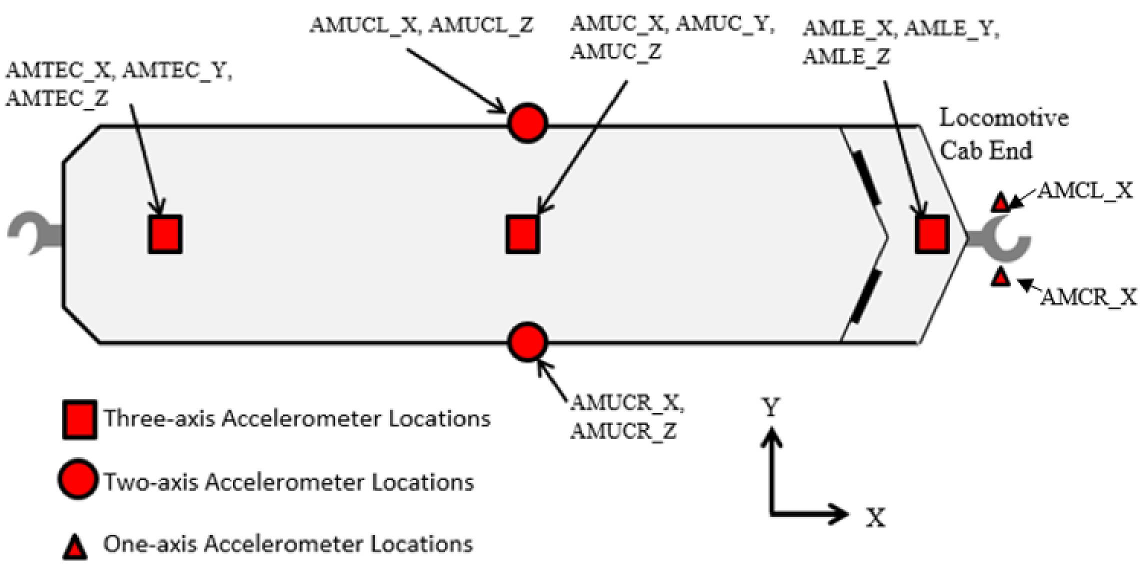

Figure 3. Top View of Accelerometer Locations on CEM Locomotive

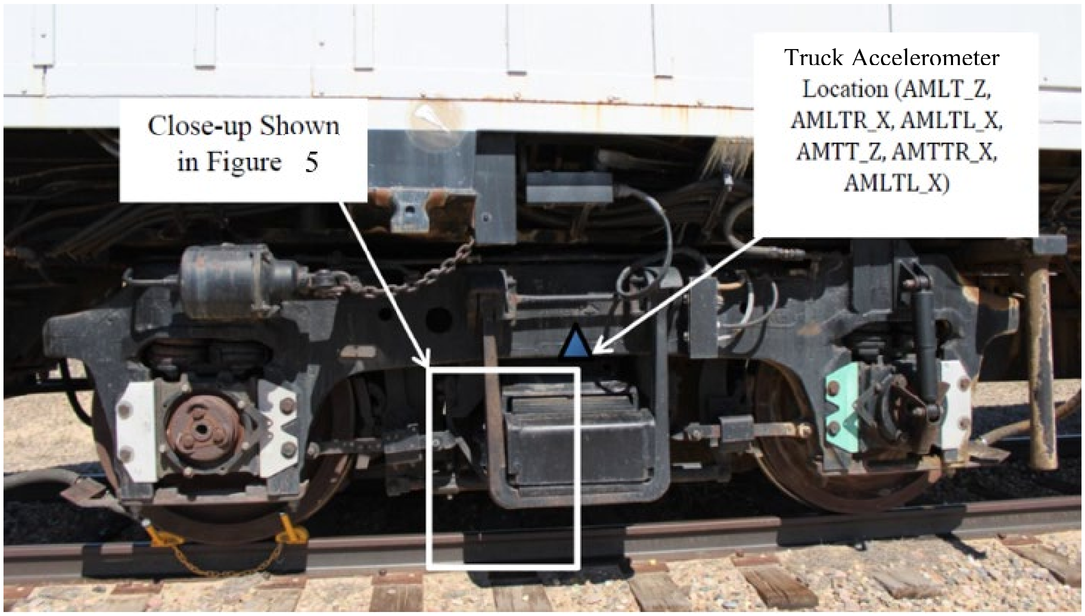

Figure 4. Accelerometer Locations on CEM Locomotive Truck

2.3 CEM Locomotive String Potentiometers

In addition to accelerometers, Locomotive 234 was instrumented with vertical string potentiometers across each truck's secondary suspension. Two string potentiometers were also fitted to the coupler of the locomotive to measure the longitudinal displacement. Two additional string potentiometers were fitted to the front of the locomotive underframe to measure longitudinal displacements. Table 3 summarizes all string potentiometers on the locomotive. Figures 5 to 10 show the locations of the string potentiometers on the locomotive. Red lines in the figures indicate the measurement and blue rectangles indicate the mounting location.

Table 3. CEM Locomotive String Potentiometer Summary

Name	Range	Location
DMLTR	± 5 inch	Moving vehicle, secondary suspension, lead truck, right
DMLTL	± 5 inch	Moving vehicle, secondary suspension, lead truck, left
DMTTR	± 5 inch	Moving vehicle, secondary suspension, trailing truck, right
DMTTL	± 5 inch	Moving vehicle, secondary suspension, trailing truck, left
DMUL	+5/-45 inch	Moving vehicle, underframe, front – longitudinal, left
DMUR	+5/-45 inch	Moving vehicle, underframe, front – longitudinal, right
DMCL	+20/-30 inch	Moving vehicle, coupler – longitudinal left
DMCR	+20/-30 inch	Moving vehicle coupler – longitudinal right
DMSL	+20/-30 inch	Moving vehicle, sliding lug – longitudinal left
DMSR	+20/-30 inch	Moving vehicle, sliding lug – longitudinal right
DMACR	+5/-45 inch	Moving vehicle, bottom DAC – longitudinal right
DMACL	+5/-45 inch	Moving vehicle, bottom DAC – longitudinal left
DMACTR	+5/-45 inch	Moving vehicle, top DAC – longitudinal right
DMACTL	+5/-45 inch	Moving vehicle, top DAC – longitudinal left

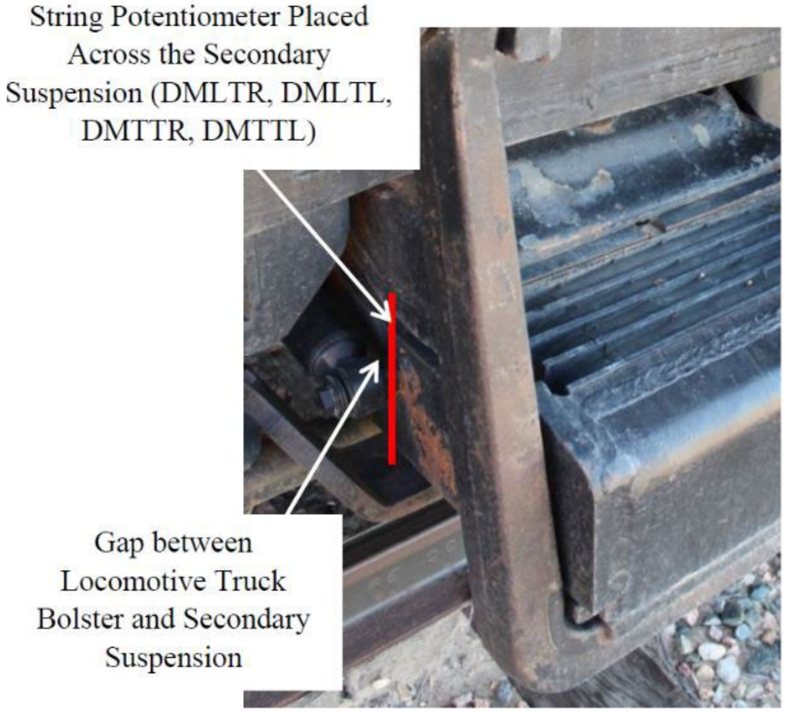

Figure 5. CEM Locomotive Truck Secondary Suspension String Potentiometer Location

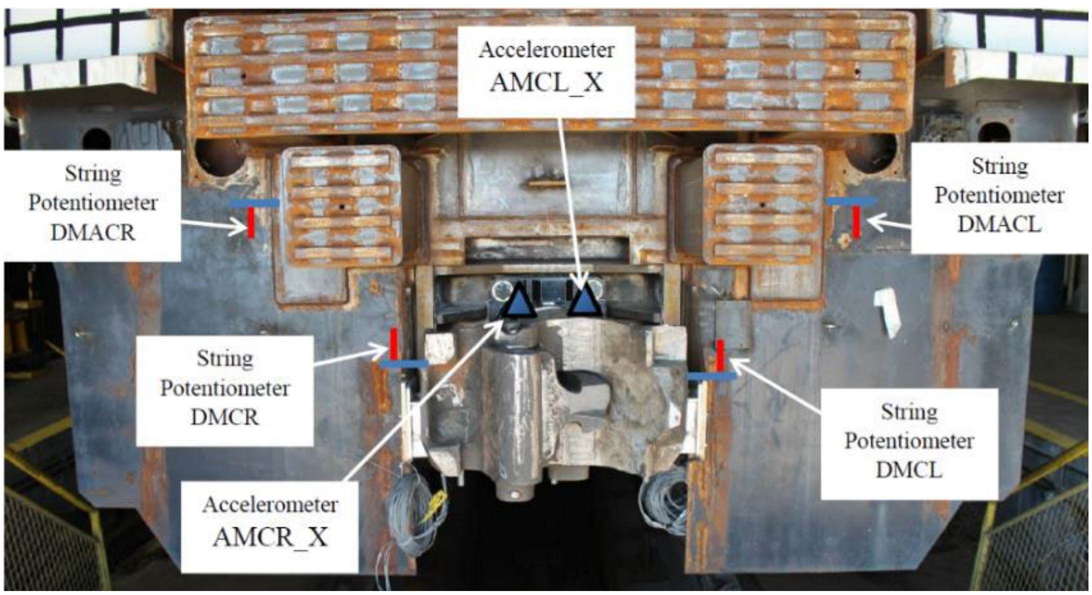

Figure 6. CEM Locomotive Coupler and Bottom DAC Instrumentation

Figure 7. CEM Locomotive Top DAC String Potentiometers

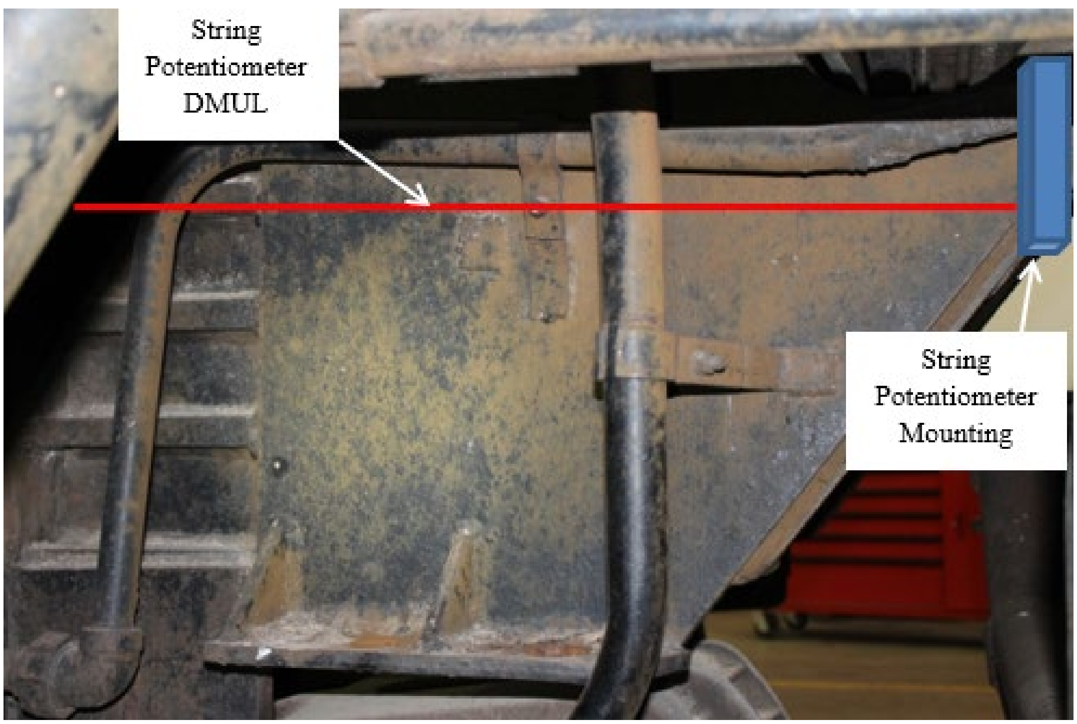

Figure 8. CEM Locomotive Underframe String Potentiometer

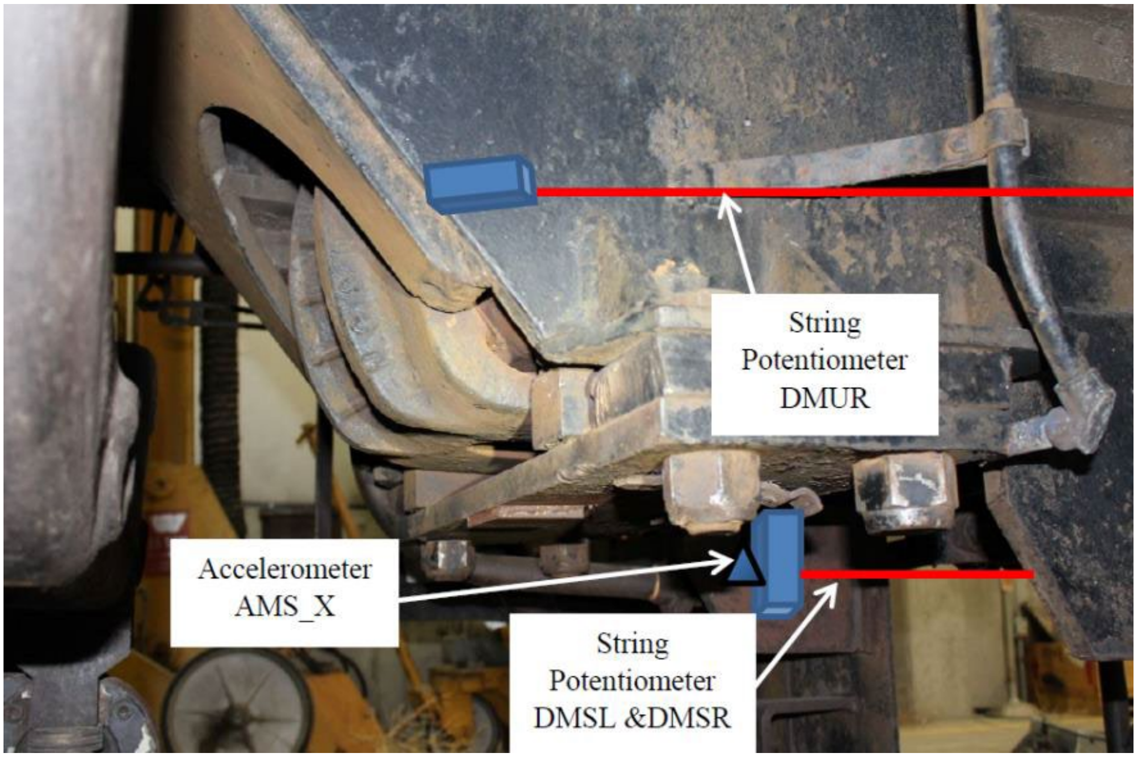

Figure 9. Right Side CEM Locomotive String Instrumentation

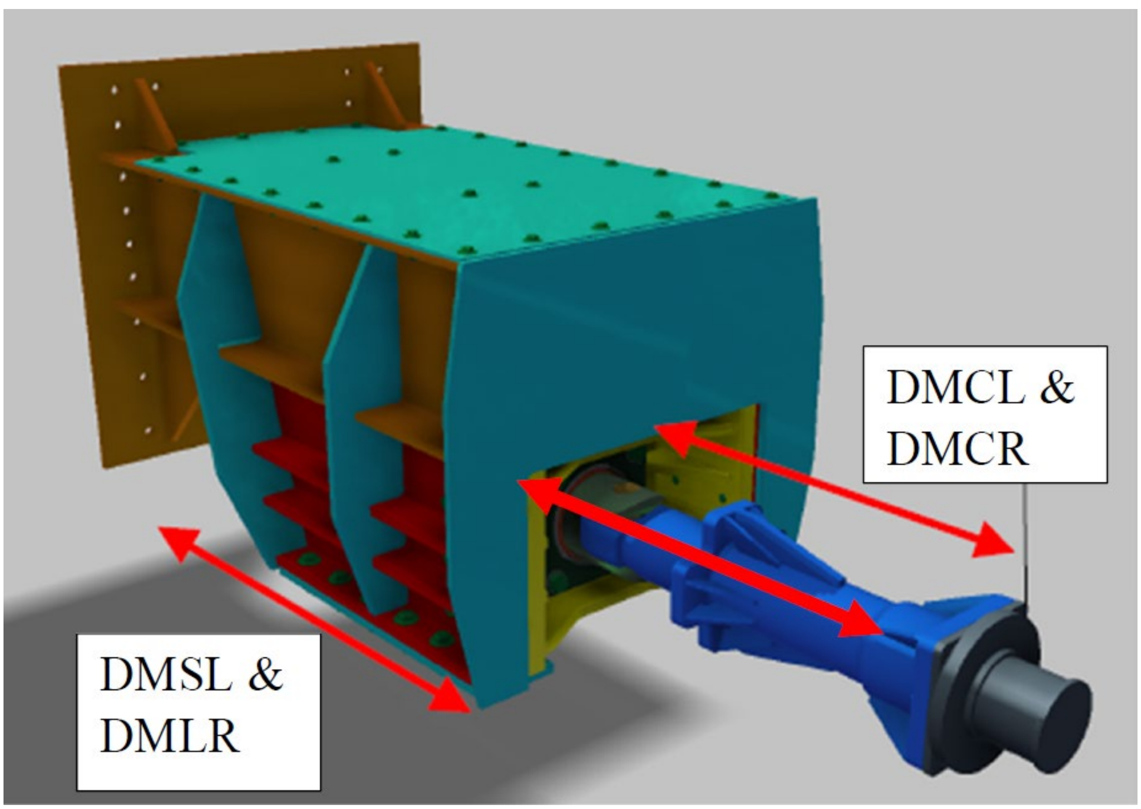

Figure 10. CEM Locomotive Coupler String Potentiometers

2.4 CEM Locomotive Strain Gages

Locomotive 234 was instrumented with 33 strain gages on the sliding lug, draft gear pocket, coupler, and center sill as shown in Table 4 and Figures 11 through 15.

Table 4. CEM Locomotive Strain Gage Summary

Name	Orientation	Location
SMCST	Longitudinal	Moving vehicle, coupler shank, above coupler carrier, top
SMCSR	Longitudinal	Moving vehicle, coupler shank, above coupler carrier, right
SMCRL	Longitudinal	Moving vehicle, coupler shank, above coupler carrier, left
SMCPR	Longitudinal	Moving vehicle, coupler shank at pin, right
SMCPL	Longitudinal	Moving vehicle, coupler shank at pin, left
SMSL1	Longitudinal	Moving vehicle, sliding lug 1, top-right front bolt hole
SMSL2	Longitudinal	Moving vehicle, sliding lug 2, top-right rear bolt hole
SMSL3	Longitudinal	Moving vehicle, sliding lug 3, bottom-right front bolt hole
SMSL4	Longitudinal	Moving vehicle, sliding lug 4, bottom-right rear bolt hole
SMSL5	Longitudinal	Moving vehicle, sliding lug 5, top-left front bolt hole
SMSL6	Longitudinal	Moving vehicle, sliding lug 6, top-left rear bolt hole
SMSL7	Longitudinal	Moving vehicle, sliding lug 7, bottom-left front bolt hole
SMSL8	Longitudinal	Moving vehicle, sliding lug 8, bottom-left rear bolt hole
SMDP1	Longitudinal	Moving vehicle, draft pocket 1, top-right front bolt hole
SMDP2	Longitudinal	Moving vehicle, draft pocket 2, top-right rear bolt hole
SMDP3	Longitudinal	Moving vehicle, draft pocket 3, bottom-right front bolt hole
SMDP4	Longitudinal	Moving vehicle, draft pocket 4, bottom-right rear bolt hole
SMDP5	Longitudinal	Moving vehicle, draft pocket 5, top-left front bolt hole
SMDP6	Longitudinal	Moving vehicle, draft pocket 6, top-left rear bolt hole
SMDP7	Longitudinal	Moving vehicle, draft pocket 7, bottom-left front bolt hole
SMDP8	Longitudinal	Moving vehicle, draft pocket 8, bottom-left rear bolt hole
SMTDR1	Longitudinal	Moving vehicle, top of draft pocket, right-front
SMTDR2	Longitudinal	Moving vehicle, top of draft pocket, right-rear
SMTDL1	Longitudinal	Moving vehicle, top of draft pocket, left-front
SMTDL2	Longitudinal	Moving vehicle, top of draft pocket, left-rear
SMCRT	Longitudinal	Moving vehicle, center sill, right-front
SMCRB	Longitudinal	Moving vehicle, center sill, right-rear
SMCLT	Longitudinal	Moving vehicle, center sill, left-front
SMCLB	Longitudinal	Moving vehicle, center sill, left-rear
SMXPR	Longitudinal	Moving vehicle, cross plate, right
SMXPL	Longitudinal	Moving vehicle, cross plate, left
SMDAR	Vertical	Moving vehicle, draft pocket back plate, right
SMDAL	Vertical	Moving vehicle, draft pocket back plate, left

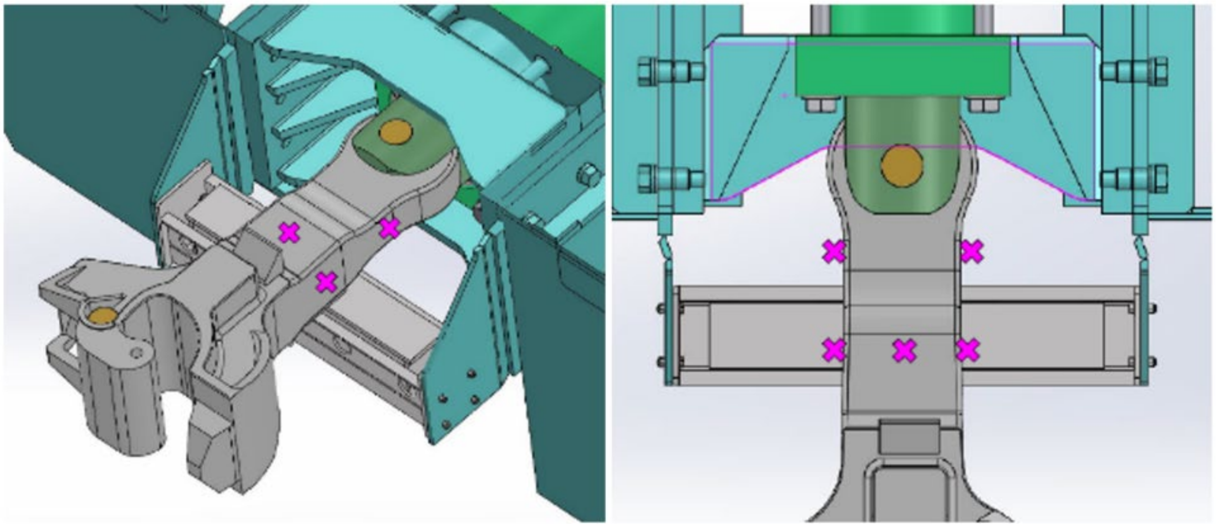

Figure 11. Strain Gage Locations on CEM Locomotive Coupler Shank

Strain gages were installed inside of the lug facing the coupler (Figure 12), 1.5 inches outboard (in front) of each top and bottom hole on both sides.

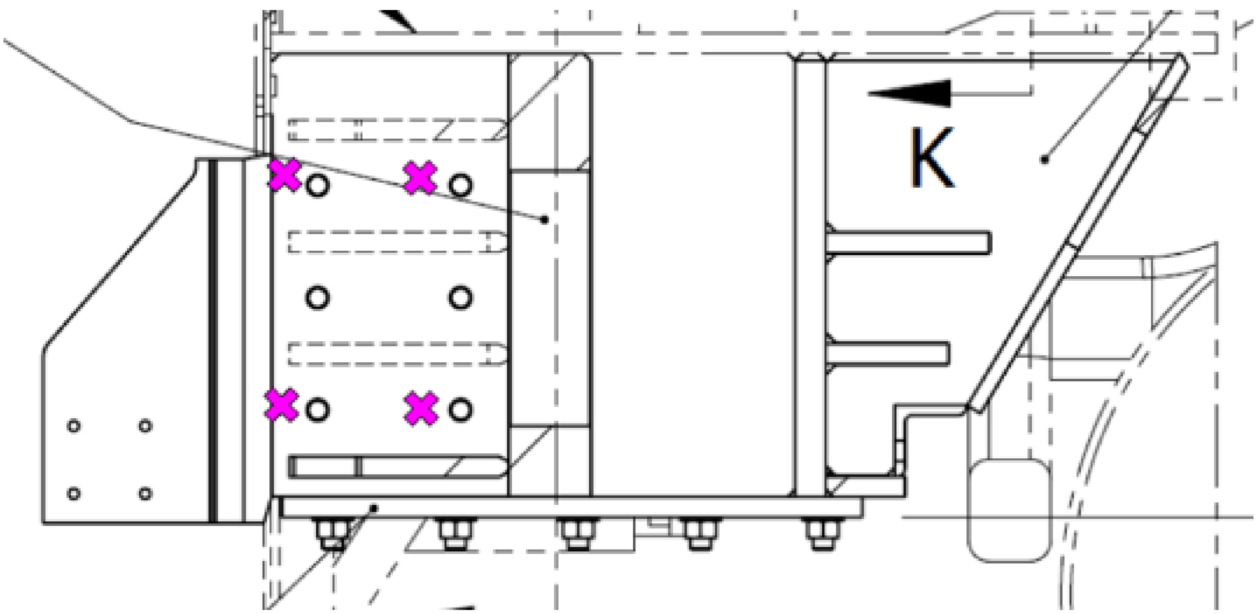

Figure 12. Strain Gage Locations on CEM Locomotive Sliding Lug

Strain gages were installed outside of the pocket facing out (Figure 13), 1.5 inches inboard of (behind) each top and bottom hole on both sides.

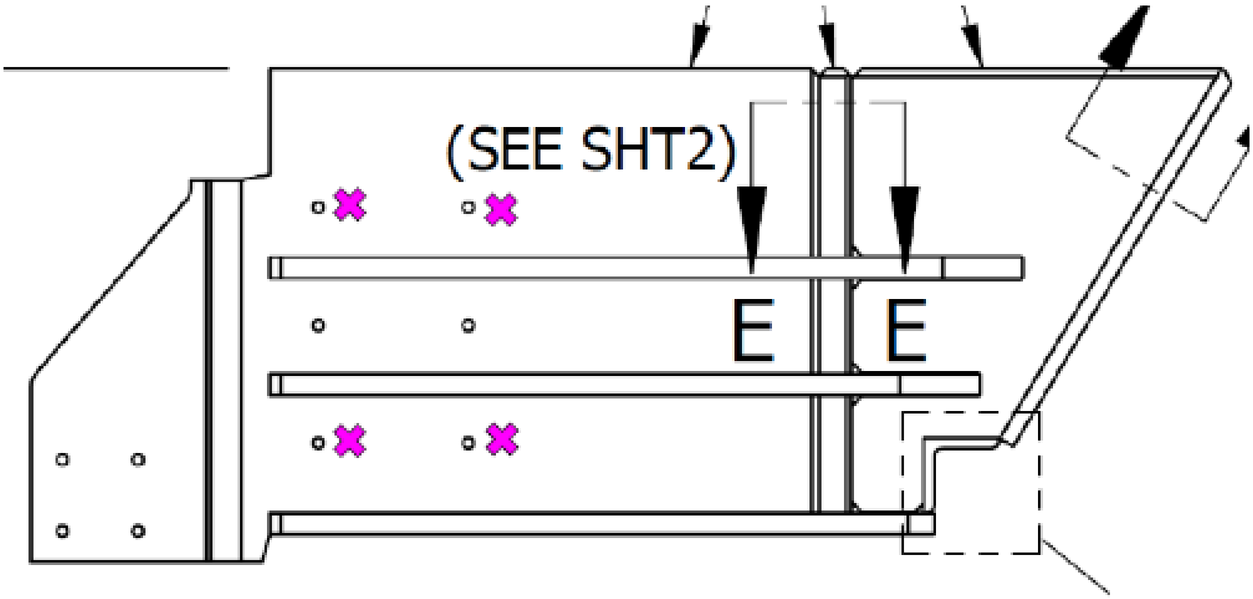

Figure 13. Strain Gage Locations on CEM Locomotive Draft Pocket

Strain gages on the draft pocket were installed on the outside, 2 inches below the connection to the underframe on the left and right sides. Strain gages on the center sill above the draft pocket were installed 2 inches below the top edge of the center sill on the left and right sides. One set of strain gages located on the center sill was placed directly above the back of the draft pocket. The second set of center sill strain gages was placed forward of the locomotive's lifting pad supports. Figure 14 shows approximate locations of these strain gages.

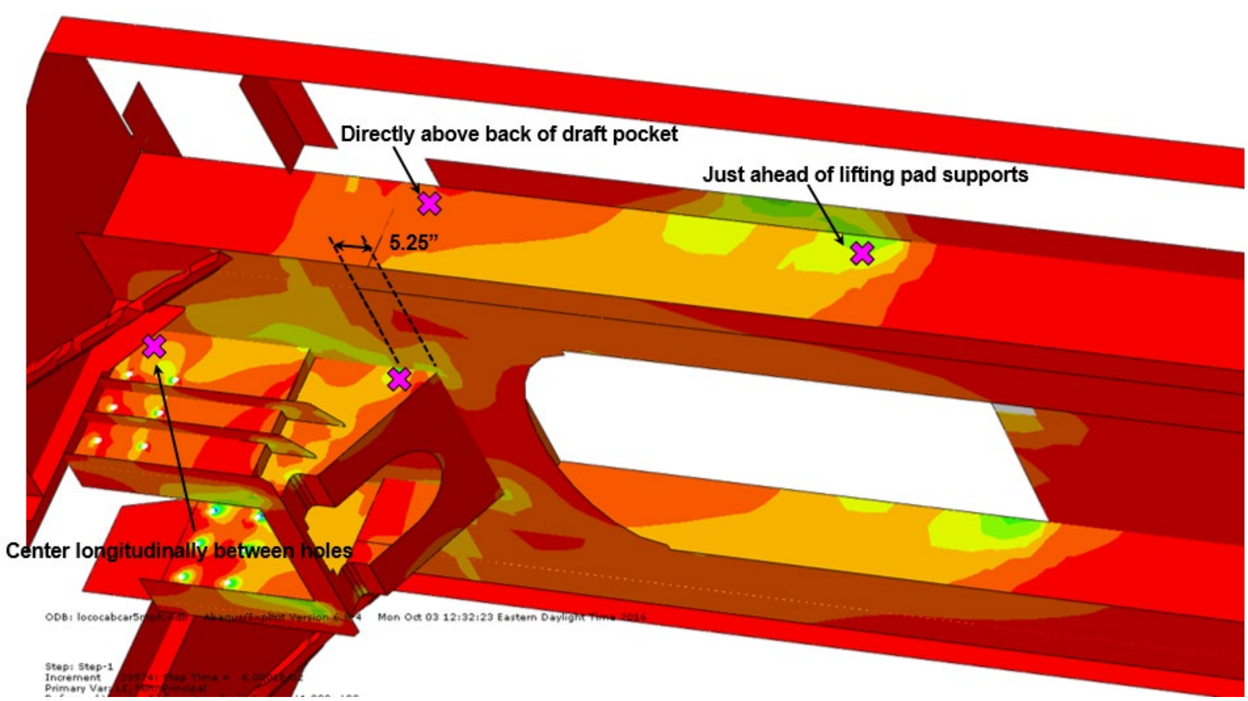

Figure 14. Strain Gage Locations on CEM Locomotive Draft Pocket and Center Sill

An additional two strain gages (SMXPR, SMXPL) were installed on the cross plate, and two strain gages (SMDAR, SMDAL) were placed at the draft gear pocket back plate. The strain gages on the draft gear pocket back plate were on each near side of the pocket, near the intersection with the cross plate, and oriented in the vertical direction. The strain gages on the cross plate were in line with the side of the pocket corners and oriented in the longitudinal direction. Figure 15 shows approximate locations of these strain gages.

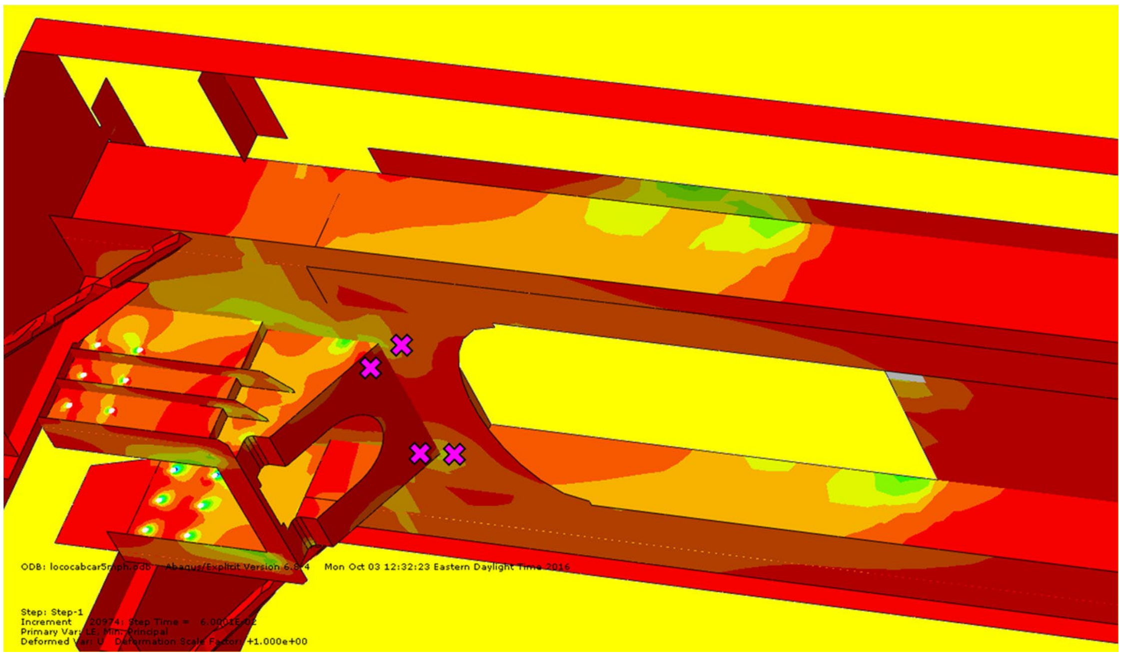

Figure 15. Strain Gage Locations on Cross Plate and Draft Gear Pocket Back Plate

2.5 CEM Locomotive Speed Sensors

Multiple speed sensors accurately measured the impact speed of the CEM locomotive when it was within 20 inches of the impact point. The speed trap is a reflector-based sensor. It uses ground-based reflectors separated by a known distance and a vehicle-based light sensor that triggers as the locomotive passes over the reflectors. The last reflector is within 10 inches of the impact point. The time interval between reflector passing was recorded and speed was calculated from reflector spacing (distance) and time. Backup speed measurements were made with a handheld radar gun.

2.6 M1 Passenger Car Accelerometers

Tri-axial accelerometers were placed at the two ends and the center along the car centerline. The car had longitudinal and vertical accelerometers placed on the left and right side of its underframe at its center. Each truck was equipped with a vertical accelerometer and two longitudinal accelerometers (right and left). The typical scale factor calibration error for the utilized accelerometers is 2 percent of full scale. Table 5 summarizes all accelerometers on the M1 passenger car. Figure 16 shows locations of the accelerometers.

Table 5. M1 Passenger Car Accelerometer Summary

Name	Range	Location
ASLE_X	400g	Stationary vehicle, lead end, center – longitudinal
ASLE_Y	200g	Stationary vehicle, lead end, center – lateral
ASLE_Z	200g	Stationary vehicle, lead end, center – vertical
ASUC_X	200g	Stationary vehicle, underframe center – longitudinal
ASUC_Y	200g	Stationary vehicle, underframe center – lateral
ASUC_Z	200g	Stationary vehicle, underframe center – vertical
ASUCR_X	200g	Stationary vehicle, underframe center-right – longitudinal
ASUCR_Z	200g	Stationary vehicle, underframe center-right – vertical
ASUCL_X	200g	Stationary vehicle, underframe center-left – longitudinal
ASUCL_Z	200g	Stationary vehicle, underframe center-left – vertical
ASTEC_X	200g	Stationary vehicle, trailing end, center – longitudinal
ASTEC_Y	200g	Stationary vehicle, trailing end, center – lateral
ASTEC_Z	200g	Stationary vehicle, trailing end, center – vertical
ASLT_Z	400g	Stationary vehicle, lead truck – vertical
ASLTR_X	400g	Stationary vehicle, lead truck, right – longitudinal
ASLTL_X	400g	Stationary vehicle, lead truck, left – longitudinal
ASTT_Z	400g	Stationary vehicle, trailing truck – vertical
ASTTR_X	400g	Stationary vehicle, trailing truck, right – longitudinal
ASTTL_X	400g	Stationary vehicle, trailing truck, left – longitudinal
ASCR_X	5,000g	Stationary vehicle, coupler, right – longitudinal
ASCL_X	5,000g	Stationary vehicle, coupler, left – longitudinal

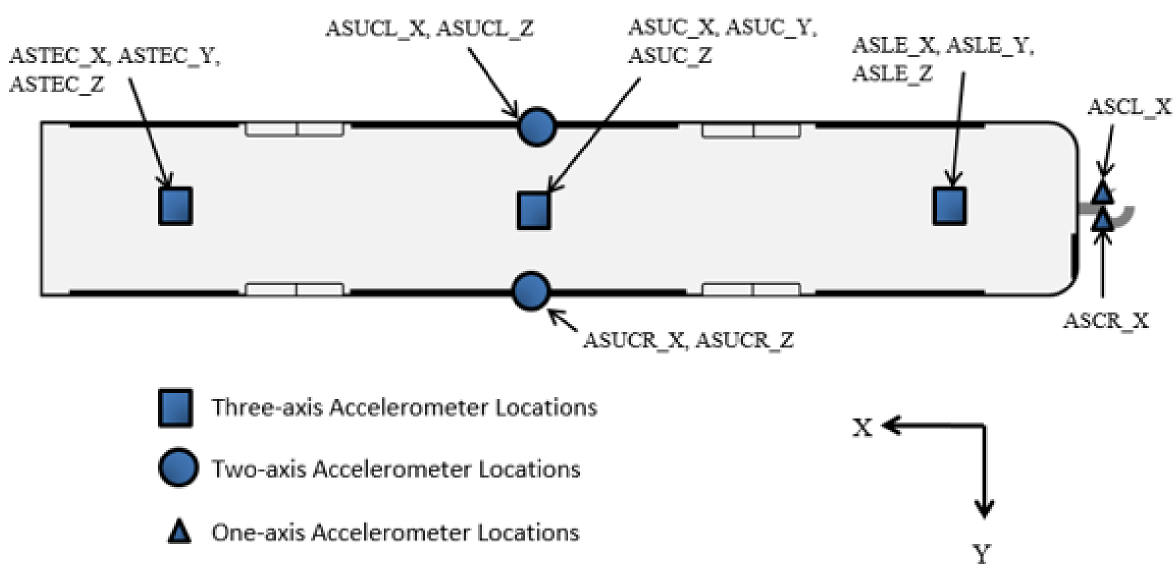

Figure 16. Accelerometer Locations on M1 Passenger Car

2.7 M1 Passenger Car String Potentiometers

The M1 passenger car was equipped with vertical string potentiometers across each truck's secondary suspension. The underframe of the car was also fitted with two string potentiometers near the coupler to measure longitudinal displacement. Two additional string potentiometers were placed between the rear end of the M1 car and the lead end of the first empty hopper car. Table 6 summarizes all string potentiometers on the M1 passenger car. Figure 17 through Figure 21 show locations of the string potentiometers.

Table 6. M1 Passenger Car String Potentiometer Summary

Name	Range	Location
DSLTR	± 5 inch	Stationary vehicle, secondary suspension, lead truck, right
DSLTL	± 5 inch	Stationary vehicle, secondary suspension, lead truck, left
DSTTR	± 5 inch	Stationary vehicle, secondary suspension, trailing truck, right
DSTTL	± 5 inch	Stationary vehicle, secondary suspension, trailing truck, left
DSUL	+5/-45 inch	Stationary vehicle, underframe, front – longitudinal, left
DSUR	+5/-45 inch	Stationary vehicle, underframe, front – longitudinal, right
DSCL	+20/-30 inch	Stationary vehicle, coupler – longitudinal left
DSCR	+20/-30 inch	Stationary vehicle, coupler – longitudinal right
DSTCL	+20/-30 inch	Stationary vehicle, trailing end coupling – longitudinal left
DSTCR	+20/-30 inch	Stationary vehicle, trailing end coupling – longitudinal right

Figure 17. M1 Passenger Car Truck Instrumentation

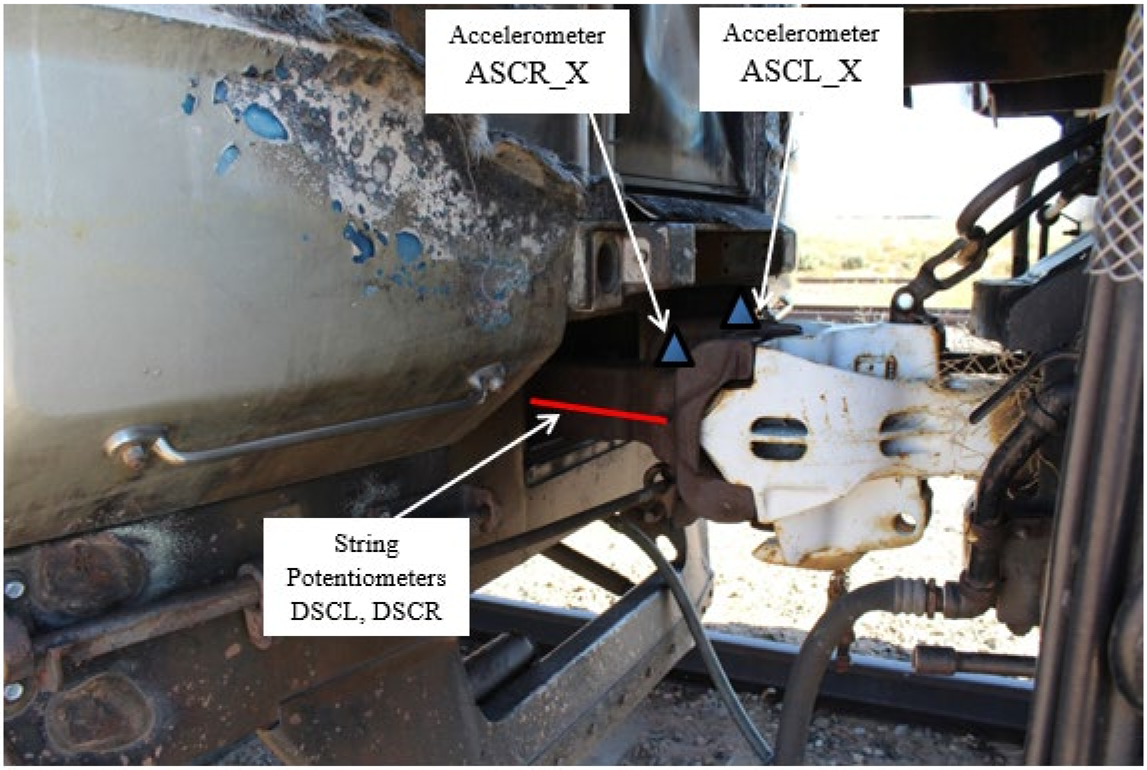

Figure 18. M1 Passenger Car Front Coupler Instrumentation

Figure 19. M1 Passenger Car Left Side Underframe String Potentiometer

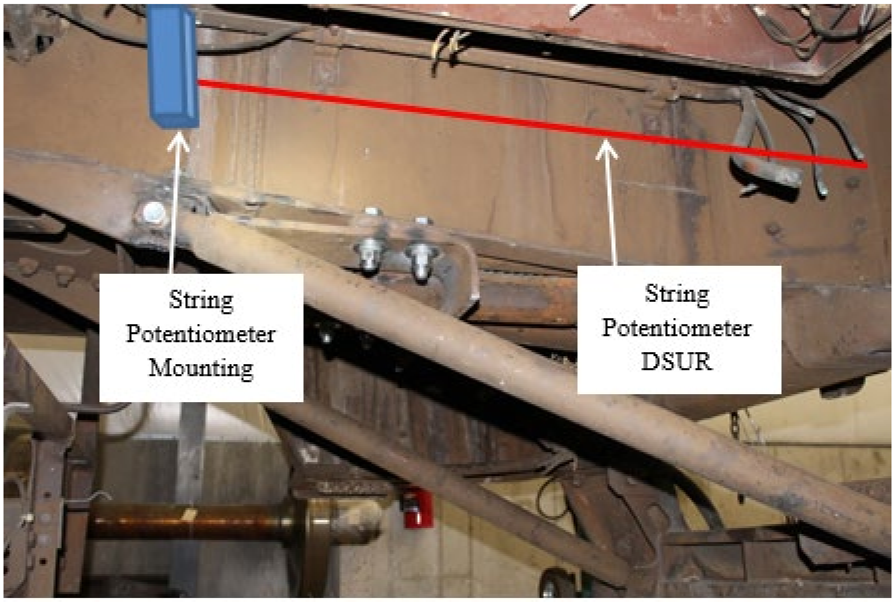

Figure 20. M1 Passenger Car Right Side Underframe String Potentiometer

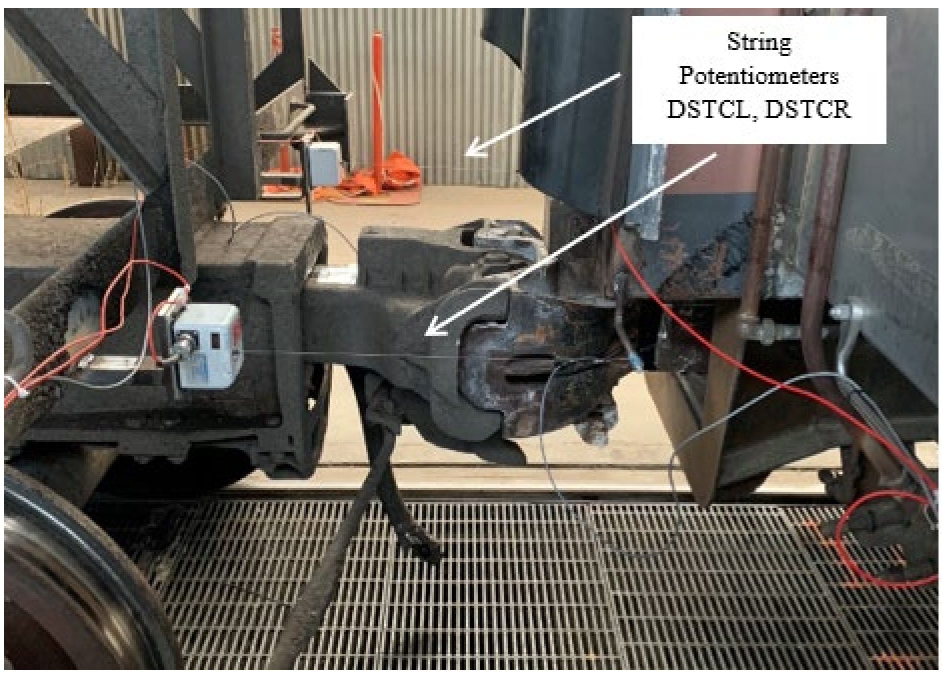

Figure 21. M1 Passenger Car Trailing End Coupler String Potentiometers

2.8 M1 Passenger Car Strain Gages

The M1 passenger car was fitted with 25 strain gages and one additional strain gage on the rear coupler. The strain gage on the rear coupler was placed on top of the coupler shank above the coupler carrier. Table 7 summarizes all strain gages on the M1 passenger car. Figure 22 through Figure 25 show approximate locations of the strain gages.

Table 7. M1 Passenger Car Strain Gage Summary

Name	Orientation	Location
SSDR1	Longitudinal	M1 car, draft sill, right, outboard of buff stop, top
SSDR2	Longitudinal	M1 car, draft sill, right, outboard of buff stop, bottom
SSDR3	Longitudinal	M1 car, draft sill, right, inboard of buff stop, top
SSDR4	Longitudinal	M1 car, draft sill, right, inboard of buff stop, bottom
SSDL1	Longitudinal	M1 car, draft sill, left, outboard of buff stop, top
SSDL2	Longitudinal	M1 car, draft sill, left, outboard of buff stop, bottom
SSDL3	Longitudinal	M1 car, draft sill, left, inboard of buff stop, top
SSDL4	Longitudinal	M1 car, draft sill, left, inboard of buff stop, bottom
SSCR1	Longitudinal	M1 car, center sill transition, right, top
SSCR2	Longitudinal	M1 car, center sill transition, right, bottom
SSCL1	Longitudinal	M1 car, center sill transition, left, top
SSCL2	Longitudinal	M1 car, center sill transition, left, bottom
SSSLFO	Longitudinal	M1 car, left side sill, front truck, outboard
SSSLFI	Longitudinal	M1 car, left side sill, front truck, inboard
SSSLTO	Longitudinal	M1 car, left side sill, trailing truck, outboard
SSSLTI	Longitudinal	M1 car, left side sill, trailing truck, inboard
SSSRFO	Longitudinal	M1 car, right side sill, front truck, outboard
SSSRFI	Longitudinal	M1 car, right side sill, front truck, inboard
SSSRTO	Longitudinal	M1 car, right side sill, trailing truck, outboard
SSSRTI	Longitudinal	M1 car, right side sill, trailing truck, inboard
SSCST	Longitudinal	M1 car, front coupler shank, above carrier, top
SSCSR	Longitudinal	M1 car, front coupler shank, above carrier, right
SSCRL	Longitudinal	M1 car, front coupler shank, above carrier, left
SSCPR	Longitudinal	M1 car, front coupler shank, pin, right
SSCPL	Longitudinal	M1 car, front coupler shank, pin, left
SSRCST	Longitudinal	M1 car, rear coupler shank, above carrier, top

Strain gages on the draft sill were installed 3 inches outboard and 10 inches inboard of the buff stop, 2 inches away from the top and bottom edges on the left and right sides. Strain gages at the transition to the center sill were installed 1 inch away from the top and bottom edges on the left and right sides.

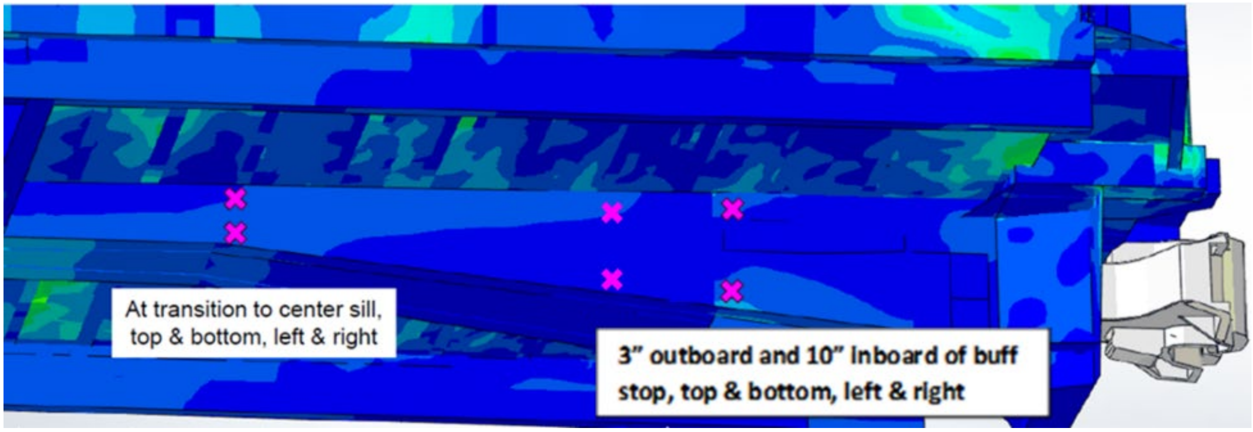

Figure 22. Strain Gage Locations on the M1 Passenger Car Center Sill

Outboard strain gages on the side sill were installed 3 inches outboard of the truck connection on the left and right side of both trucks, centered vertically on the side sill. Inboard strain gages on the side sill were installed 3 inches inboard of the truck connection on the left and right side of both trucks, centered vertically on the side sill.

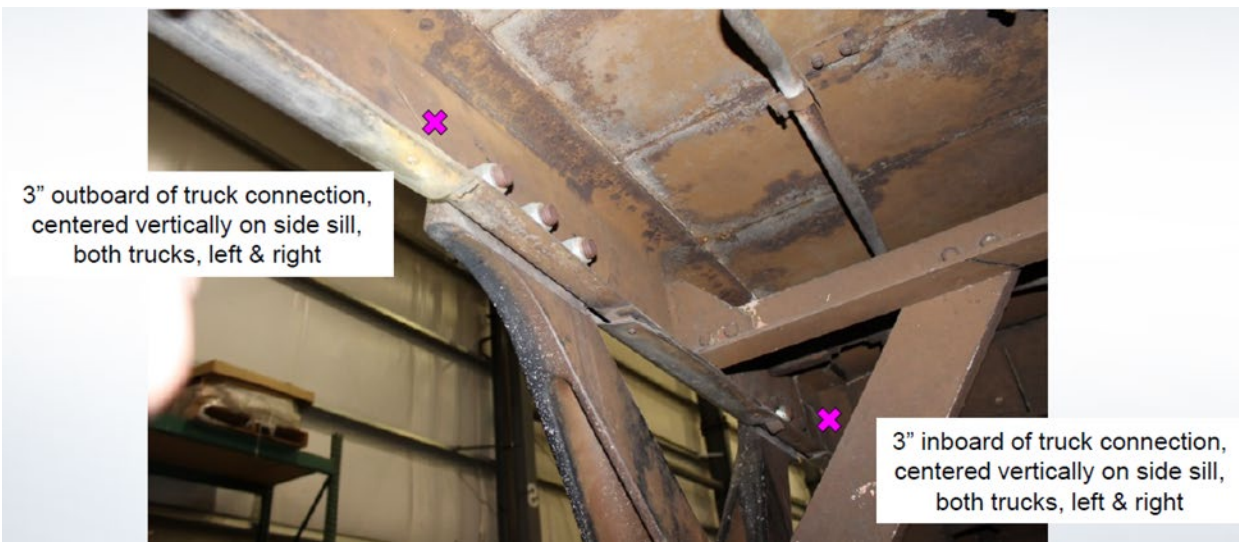

Figure 23. Strain Gage Locations on the M1 Passenger Car Side Sill

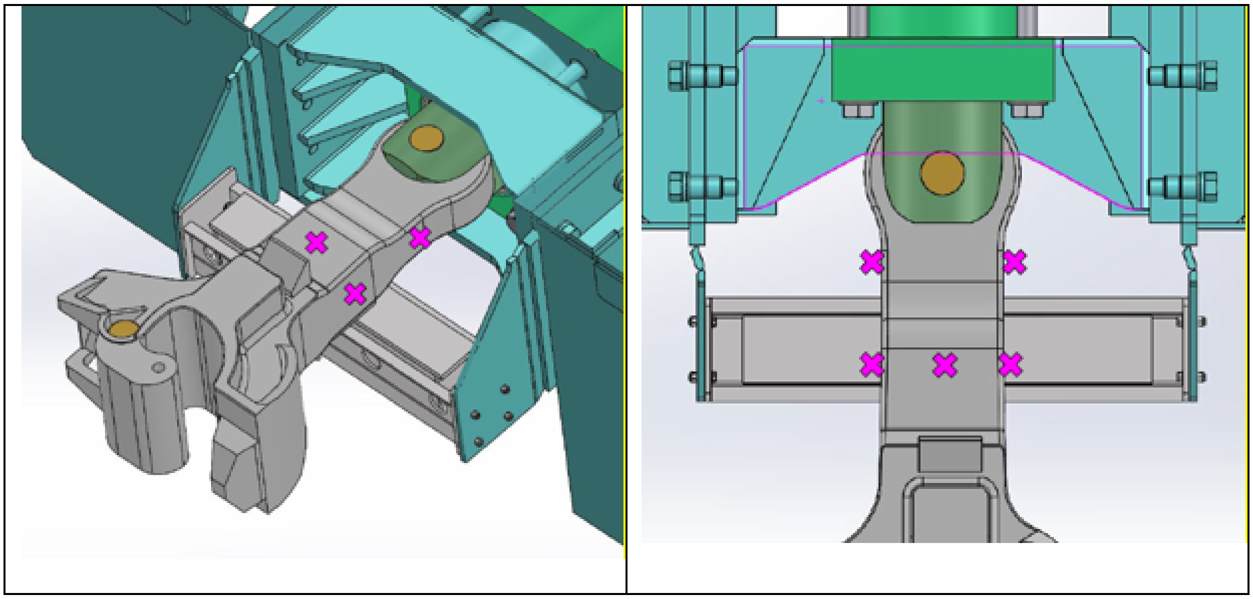

Figure 24. Strain Gage Locations on the M1 Passenger Car Front Coupler

Figure 25. Strain Gage Location on the M1 Passenger Car Rear Coupler

2.9 Empty Hopper Car String Potentiometers

The hopper cars were fitted with string potentiometers between the rear end of the first hopper car and the lead end of the second hopper car. Table 8 summarizes all string potentiometers between the first and second hopper cars. Figure 26 shows the locations of the string potentiometers.

Table 8. Hopper Car String Potentiometer Summary

Name	Range	Location
DHTCL	+20/-30 inch	First hopper trailing end coupling – longitudinal left
DHTCR	+20/-30 inch	First hopper trailing end coupling – longitudinal right

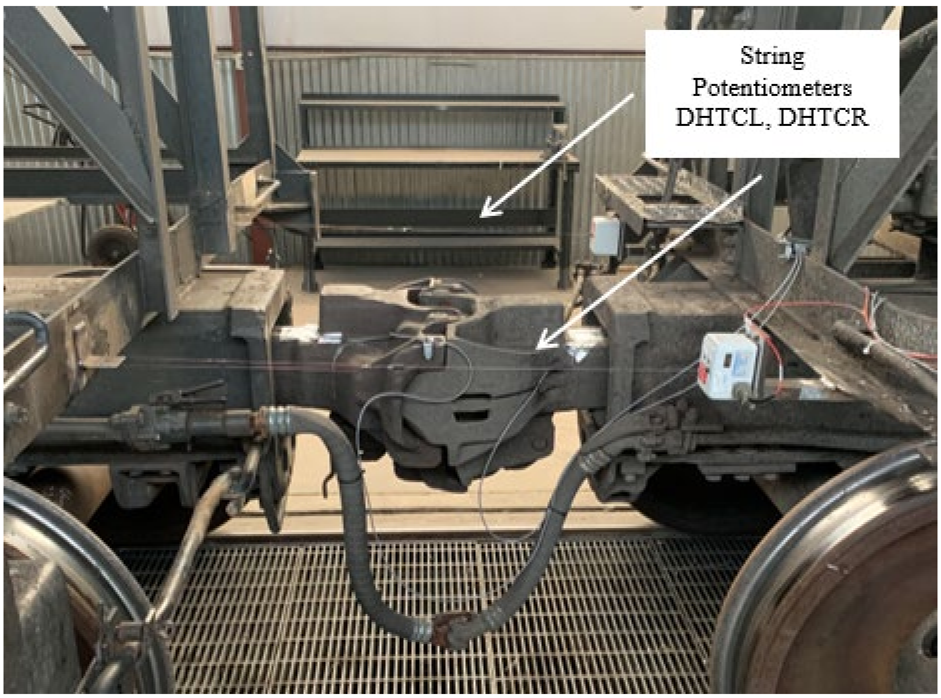

Figure 26. String Potentiometer Locations between First and Second Hopper Car

2.10 Empty Hopper Car Strain Gages

The hopper cars were fitted with three uniaxial strain gages. A single strain gage was installed on top of the coupler shank above the coupler carrier for the first hopper car's front coupler, the first hopper car's rear coupler, and the second hopper car's front coupler. Table 9 summarizes all strain gages on the hopper cars. Figure 27 and Figure 28 show the locations of the strain gages.

Table 9. Hopper Car Strain Gage Summary

Name	Orientation	Location
SHFCST	Longitudinal	First hopper car, front coupler shank, above carrier, top
SHRCST	Longitudinal	First hopper car, rear coupler shank, above carrier, top
SH2FCST	Longitudinal	Second hopper car, front coupler shank, above carrier, top

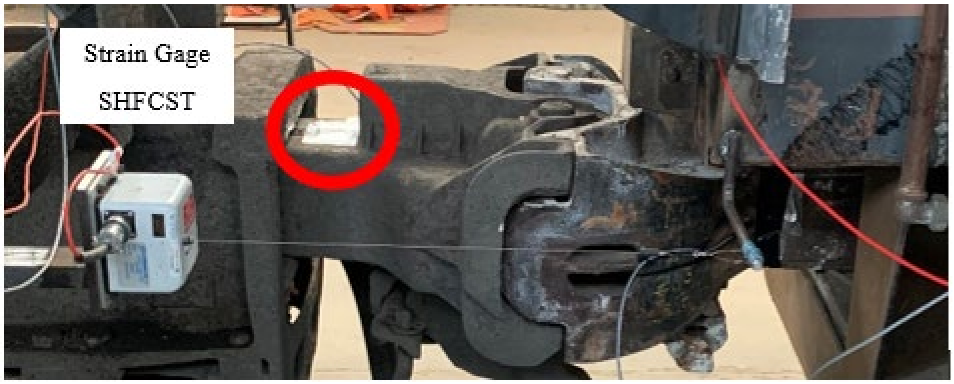

Figure 27. Strain Gage Location on First Hopper Car Front Coupler

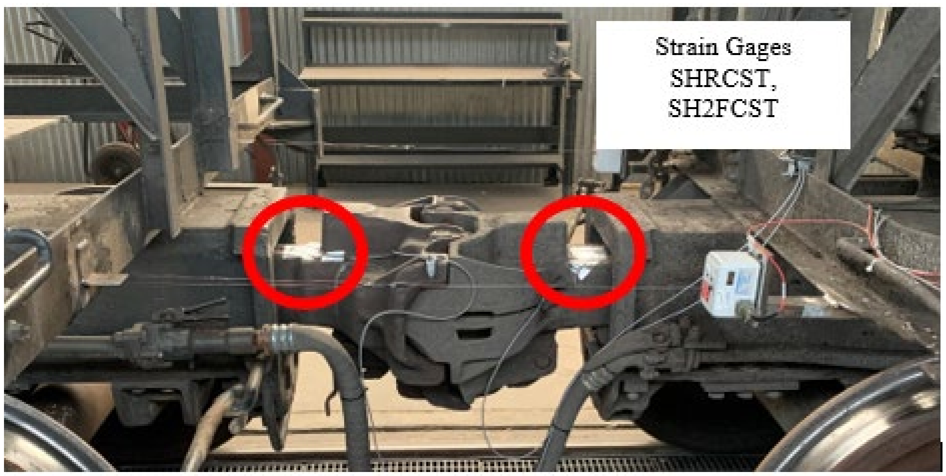

Figure 28. Strain Gage Locations on First Hopper Car Rear Coupler and Second Hopper Car Front Coupler

2.11 Real-Time and High-Speed Photography

Seven high-speed and eight real-time, high-definition video cameras documented the impact event. Figure 29 and Figure 30 show schematics of the setup positions of the high-speed and high-definition cameras. All high-speed cameras are crashworthy and rated for peak accelerations of 100g. Technicians aligned and sighted the cameras when the vehicles were positioned at the impact point prior to the start of the test. Two flashes were installed on the CEM locomotive and M1 passenger car, and they were triggered at the same time as the data acquisition systems. Flashes were visible from the high-speed cameras and were used to confirm the time of trigger and to evaluate any trigger time discrepancies between vehicles.

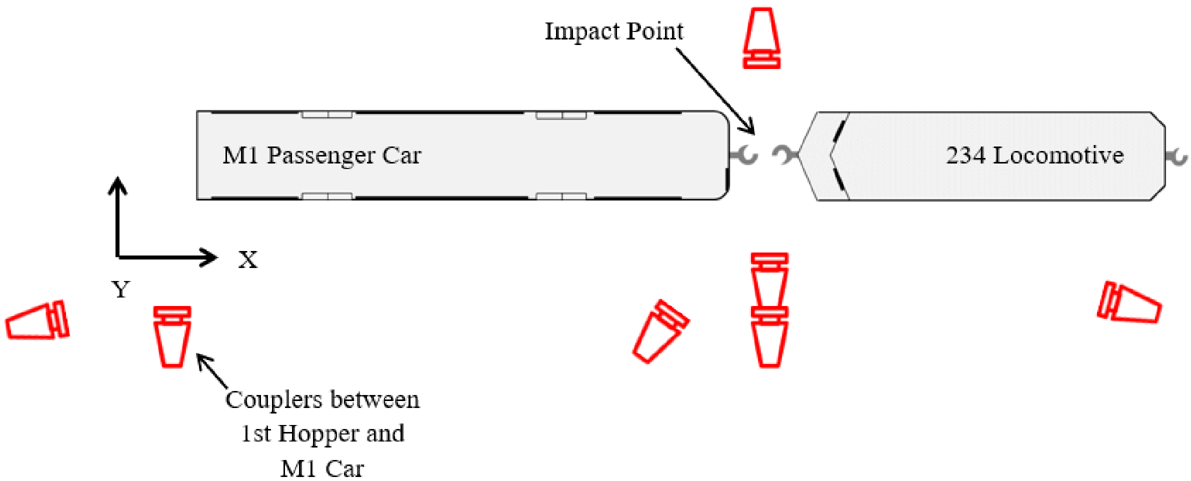

Figure 29. High-Speed Camera Locations

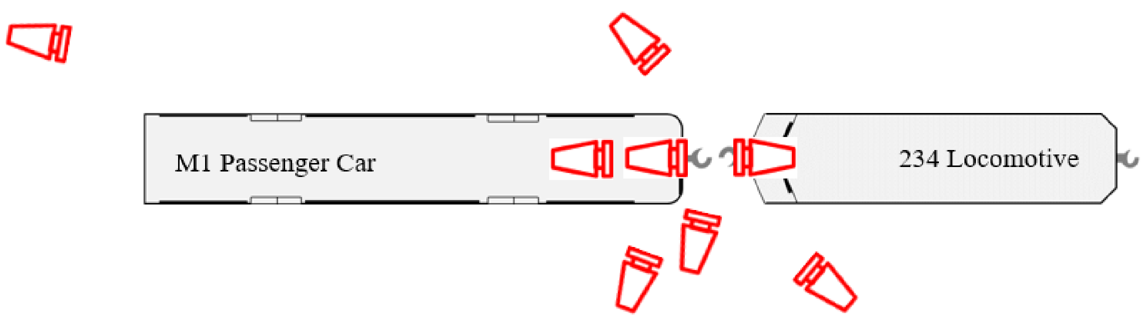

Figure 30. High-Definition Camera Locations

Drones were also used to document the impact. Three drones provided the following views: directly above the impact point (top view), an isometric view of the impact point looking northeast as the locomotive approached, and a chase view with the drone following the locomotive as it approached and impacted the stationary consist.

2.12 Data Acquisition

A set of eight-channel, battery-powered, onboard data acquisition systems recorded data from instrumentation mounted on both the CEM locomotive and the M1 passenger car. These systems provided excitation to the instrumentation as well as analog anti-aliasing filtering of the signals, analog-to-digital conversion, and recording of each data stream.

The data acquisition systems were GMH Engineering DataBRICK3 units. Data acquisition was in compliance with the appropriate sections of SAE J211.[8] Data from each channel were anti-alias filtered at 1,735 Hz, and then sampled and recorded at 12,800 Hz. Data recorded on the DataBRICK3s were synchronized to time zero at initial impact. The time reference came from closure of the tape switches on the front of the test vehicle. Closure of the tape switches occurred

[8] SAE International. (2007). SAE J211/1 Standard. 1995. Instrumentation for Impact Test – Part 1: Electronic Instrumentation. Warrendale, PA: SAE International.

at the initial contact of the impacting vehicles. Each DataBRICK3 was ruggedized for shock loading up to at least 100g. Onboard battery power was provided by GMH Engineering, comprised of 1.7-amp-hour, 14.4-volt NiCad packs. Tapeswitch model 1201-131-A provided event initial contact time.

Software in the DataBRICK3 units was used to determine zero levels and calibration factors rather than relying on set gains and expecting no zero drift. The DataBRICK3 units were set to record 1 second of data before initial impact and 7 seconds of data after initial impact.

3. Results

As described in Section 1, this test program included a November 2021 impact test between a F40 locomotive equipped with CEM components and a M1 passenger car backed by two empty hopper cars. The target impact speed was 33 mph. Handbrakes were applied on the empty hopper cars. Ambient conditions are summarized in Table 10.

Table 10. Summary of Ambient Conditions

Wind Speed	Gust Speed	Wind Direction	Temperature
11 mph	14 mph	NE	35°F

3.1 Test Details

The actual impact speed for the test is shown in Table 11, as are the approximate impact forces and energy levels based on accelerometer data.

Table 11. Summary of Test Results

Target Impact Speed	Actual Impact Speed	Approximate Peak Impact Force	Approximate Impact Energy
33 mph	32.8 mph	8,000,000 lbs.	8,300,000 ft.-lbs.

3.2 Measured Data

The data collected were processed for zero offset corrections and filtering. To ensure the data plotted and analyzed contained only impact-related information and excluded electronic offsets or steady biases, an offset adjustment procedure was developed. The offset was determined by averaging the data collected before the impact. The offset was then subtracted from the entire dataset for each channel. This post-test offset adjustment was independent of the pre-test offset adjustment made by the data acquisition system.

Post-test filtering of the data was accomplished using a phaseless four-pole digital filter algorithm consistent with SAE J211 requirements [1]. A 60-Hz channel frequency class filter was applied to obtain the filtered acceleration data shown in this report. A brief summary of the measured data is provided in this section. Appendix B contains plots of the time histories of the filtered data from all transducers for the test.

3.2.1 Accelerations

Longitudinal acceleration of the CEM locomotive was one of the primary measurements, and multiple accelerometers were used on this locomotive to capture that data. The CEM locomotive acceleration was used to derive the impact energy and contact force between the CEM locomotive and the M1 passenger car. The average longitudinal acceleration was obtained by averaging the accelerations measured by the longitudinal accelerometers on both vehicles. Accelerometers placed over the trucks on the locomotive exhibited high levels of noise after filtering; therefore, these accelerometers were excluded from the averages.

Figure 31 provides the average longitudinal acceleration time history as derived from the locomotive accelerometer data. Impact accelerations are shown as positive in these graphs; however, during the impact, the CEM locomotive accelerated in the negative X direction based on the established coordinate system. During the impact test, the vehicles did not couple due to the closed knuckles on the couplers, but the CEM locomotive front end was lodged into the cab end of the M1 passenger car from the force of the impact. The vehicles had to be pulled apart after the completion of the test.

All acceleration data are reported in Appendix B.

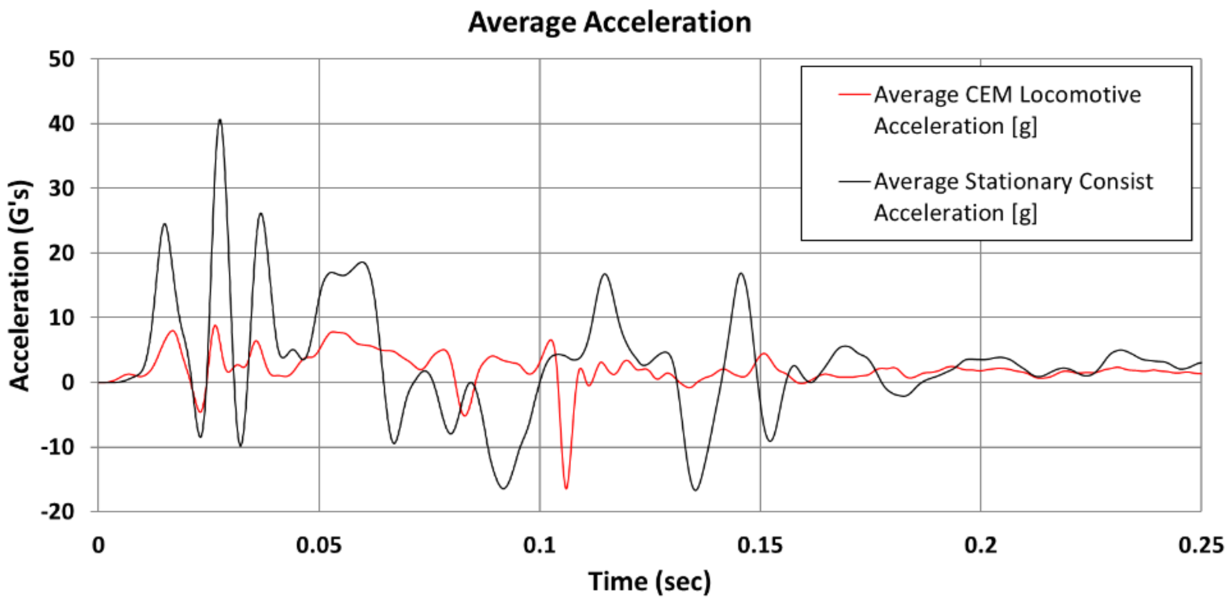

Figure 31. Longitudinal Average Acceleration

3.2.2 Displacements

Figure 32 shows the displacement of the locomotive and M1 passenger car couplers. DMCL_X and DMCR_X represent the left- and right-side displacements on the CEM locomotive's coupler, respectively. DSCL_X and DSCR_X represent the displacements of the M1 passenger car's coupler, respectively. According to the established coordinate system, the coupler moving into the draft pocket was reported as a negative displacement for both the CEM locomotive and the M1 passenger car. The severity of the impact caused the cab end of the M1 passenger car to be crushed, its coupler forced back, and eventually the M1 car's center sill to be collapsed. This caused the coupler head to pivot and the draft system to fail. The draft system damage and the damage to the string potentiometers on the M1 passenger car explain the unusual displacement readings for DSCL_X and DSCR_X.

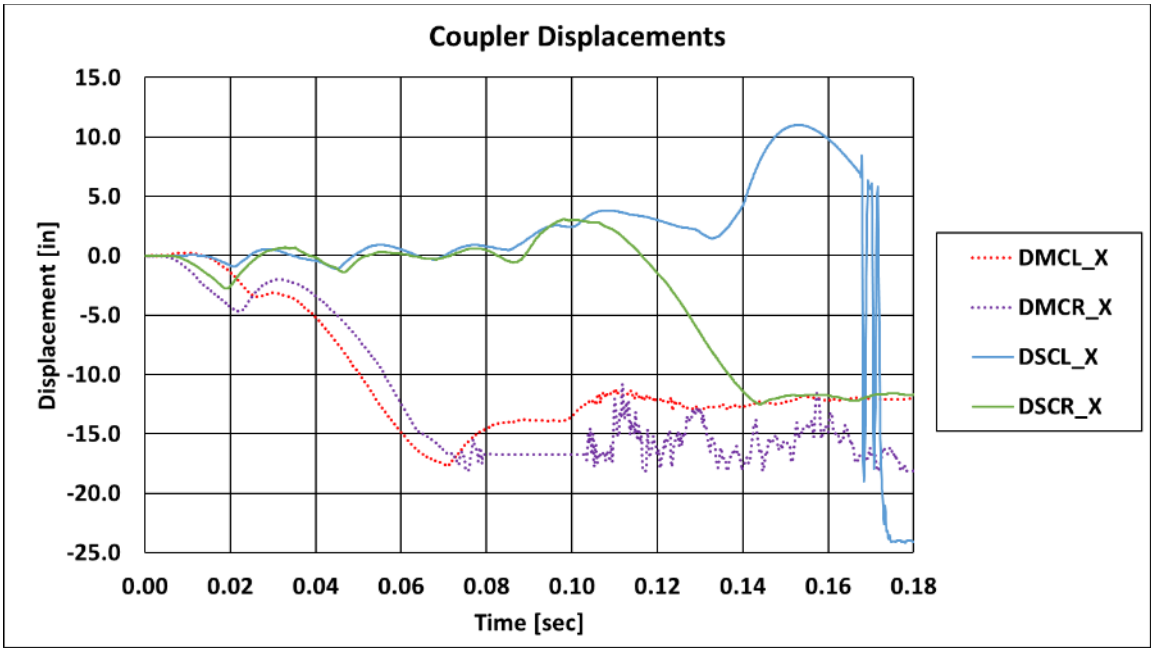

Figure 32. Impacting Coupler Displacements

Figure 33 shows measured longitudinal displacements of the locomotive's anti-climbers. The bottom set of anti-climbers were engaged at the impact and deformed. The measured displacements (DMACR and DMACL) included bending of the front plate and crush displacements of the tubes. The deformation on both sides was fairly symmetrical. The top anti-climber experienced negligible deformation over the course of the impact and did not activate; thus, its displacements were nearly zero.

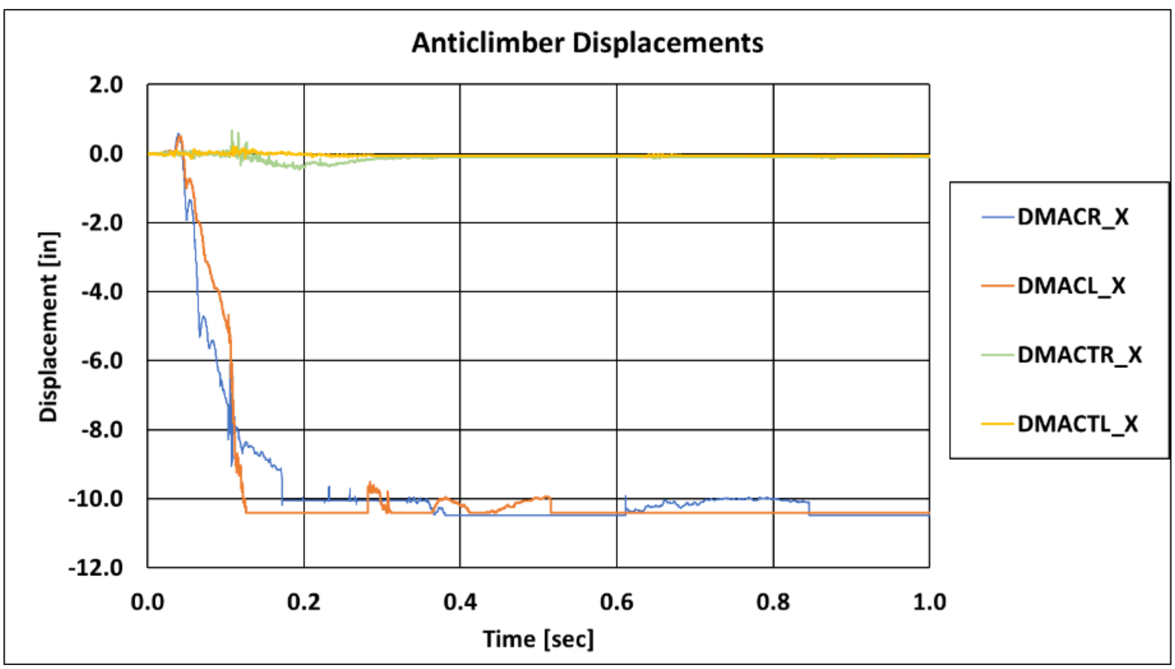

Figure 33. Anti-climber Displacements

The sliding lug bolts were sheared during impact. Measured displacements of the sliding lug are displayed in Figure 34.

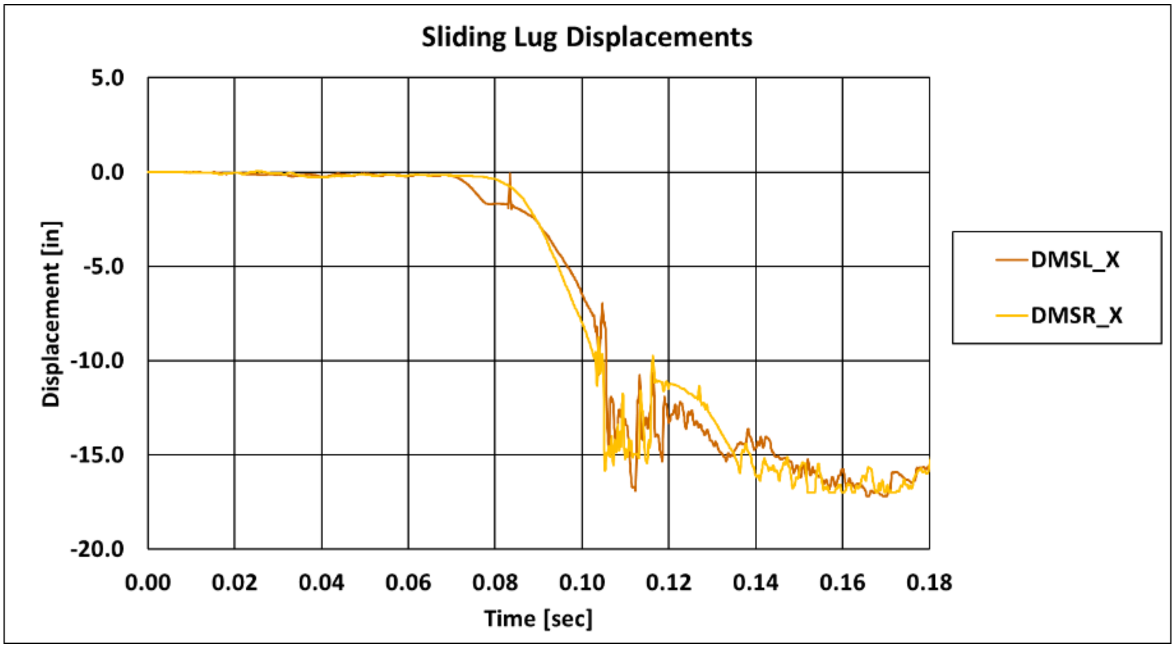

Figure 34. Sliding Lug Displacements

Appendix B includes all measured displacements.

3.2.3 Strains

The CEM locomotive was equipped with 33 strain gages, and another 26 strain gages were on the M1 passenger car. An additional 3 strain gages were placed on the coupler shanks of the first hopper car (front and rear coupler) and the second hopper car (front coupler). Strain gage data from both the CEM locomotive and stationary cars are grouped according to their positions in the vehicles. Figure 35 to Figure 46 show the strain gage data for all instrumented vehicles. During the impact, the cables connected to several strain gages were hit by debris or severed, resulting in a loss of useful data after various lengths of time. This effect was particularly noticeable on the CEM locomotive's sliding lug and coupler and the M1 passenger car's front and rear coupler strain gages. The SSRCST (M1 car, rear coupler shank, above carrier, top) channel did not provide any usable data during the test despite passing checkouts and having no visual evidence of damage to the transducer or cables. Its data have been excluded from the report. Plots below show data from the first 250 milliseconds of impact, which covers the duration of the initial impact. The data acquisition setup resulted in positive strains representing compression and negative strains representing tension.

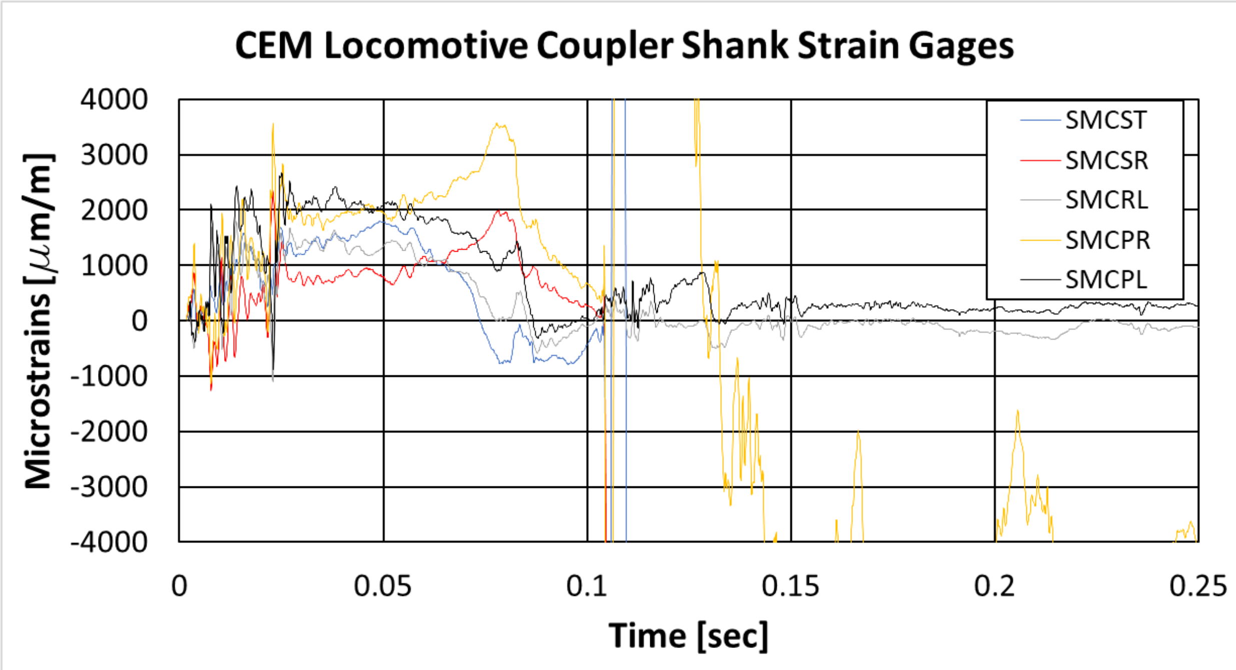

Figure 35. CEM Locomotive Coupler Shank Strain Results

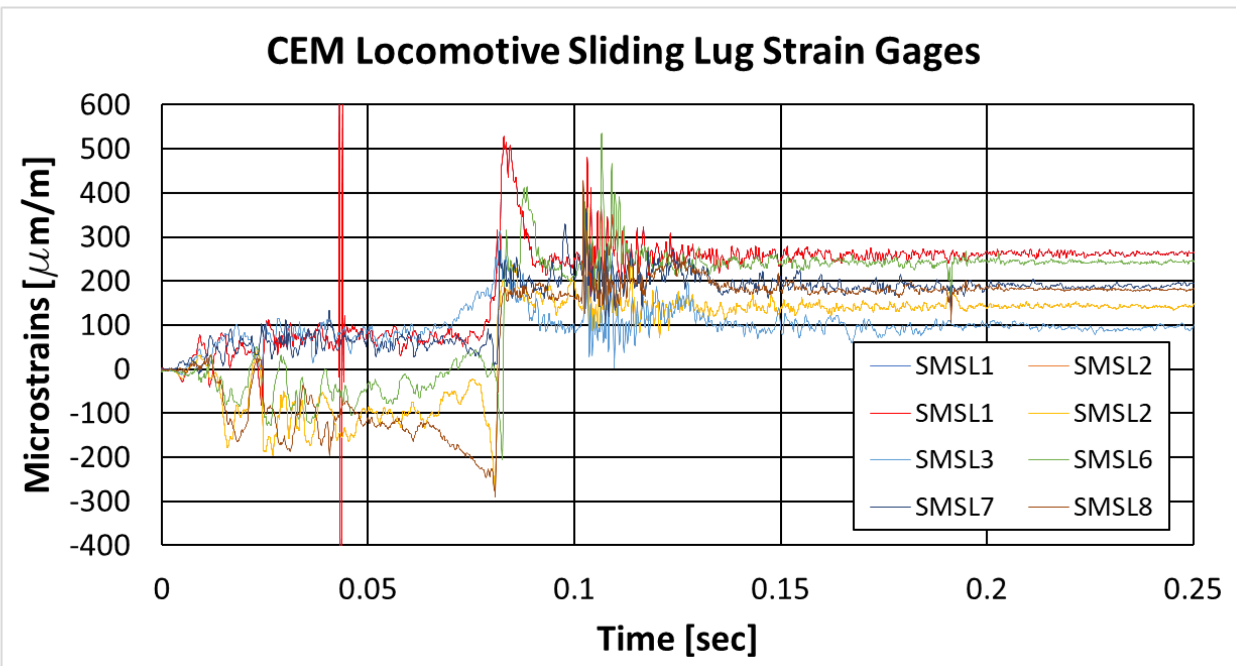

Figure 36. CEM Locomotive Sliding Lug Strain Results

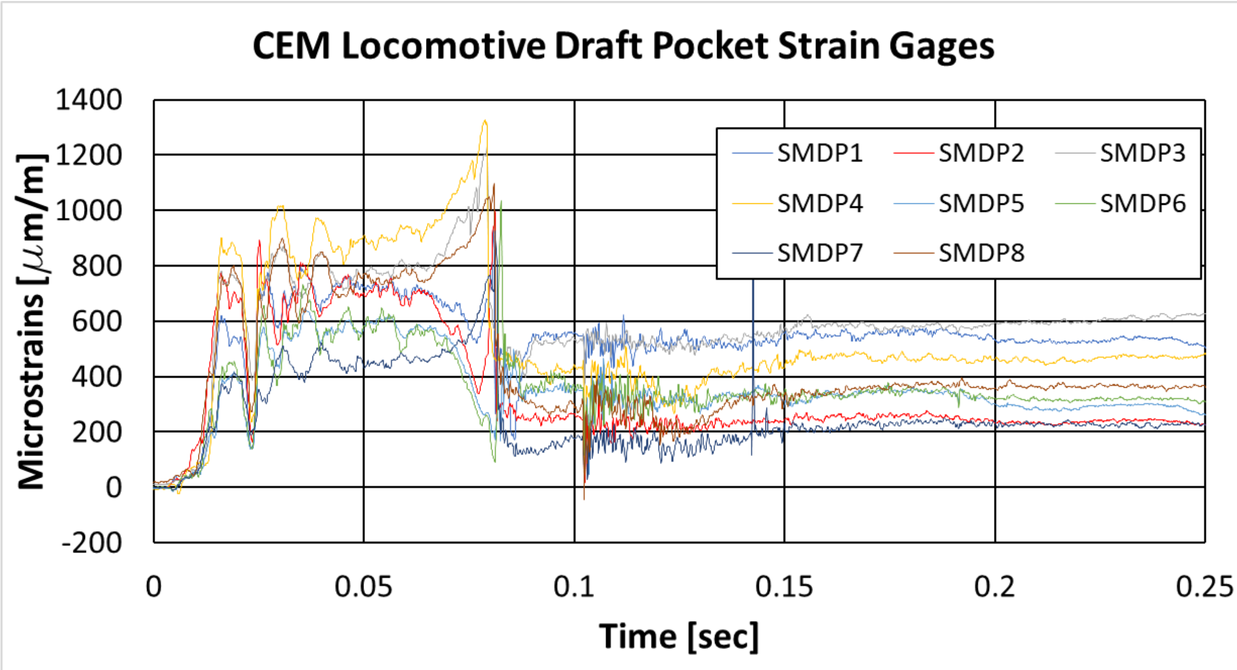

Figure 37. CEM Locomotive Draft Pocket Strain Results

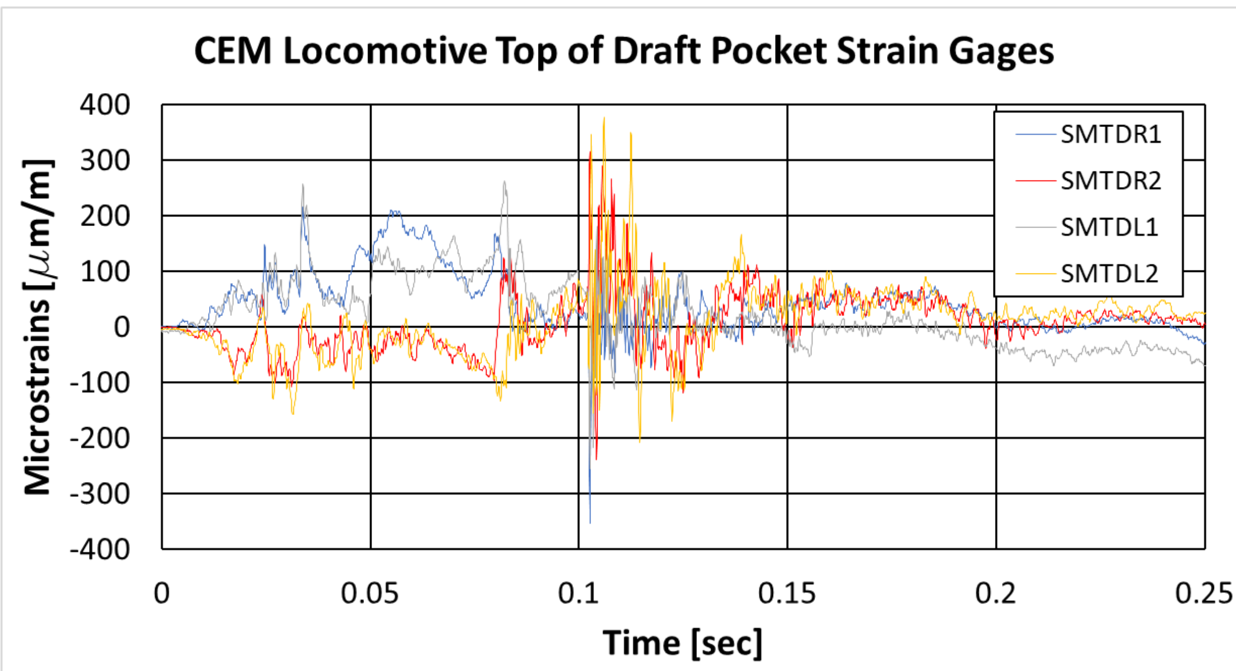

Figure 38. CEM Locomotive Top of Draft Pocket Strain Results

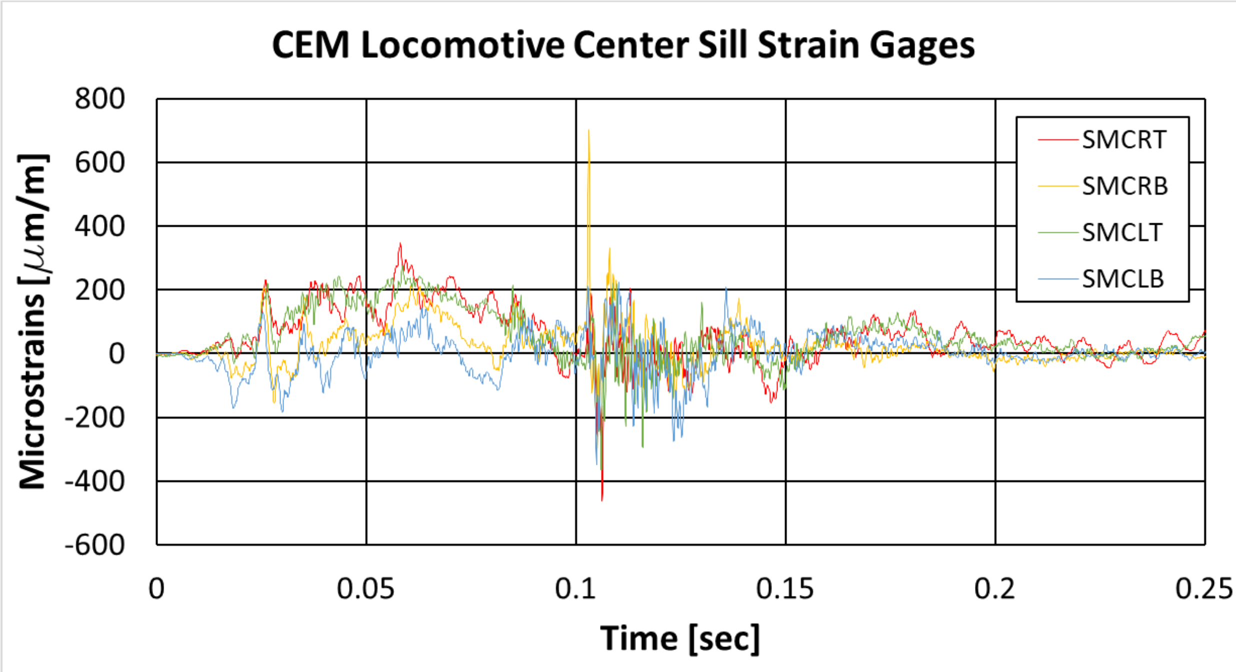

Figure 39. CEM Locomotive Center Sill Strain Results

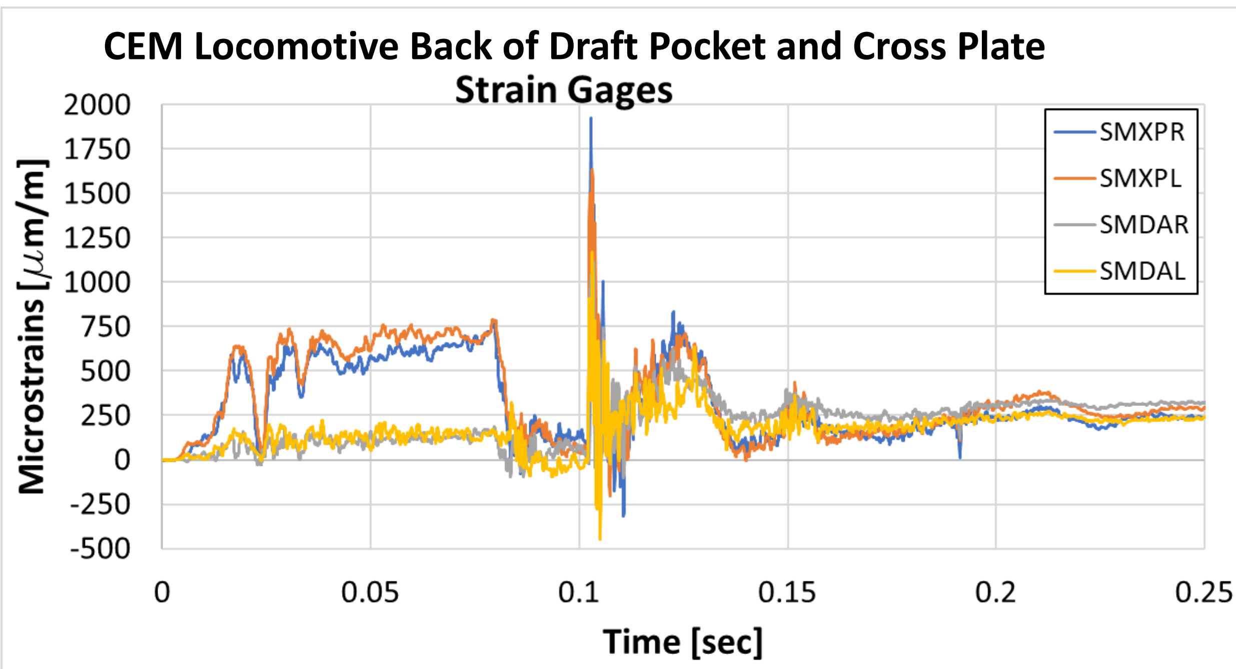

Figure 40. CEM Locomotive Back of Draft Pocket and Cross Plate Strain Results

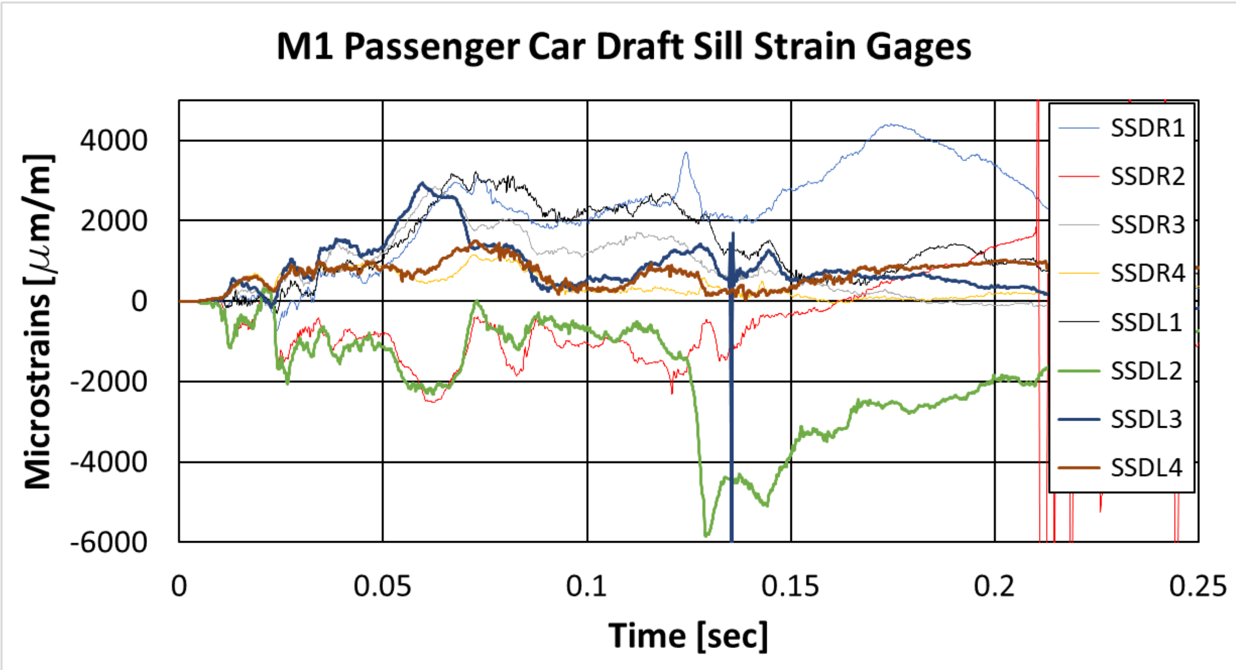

Figure 41. M1 Passenger Car Draft Sill Strain Results

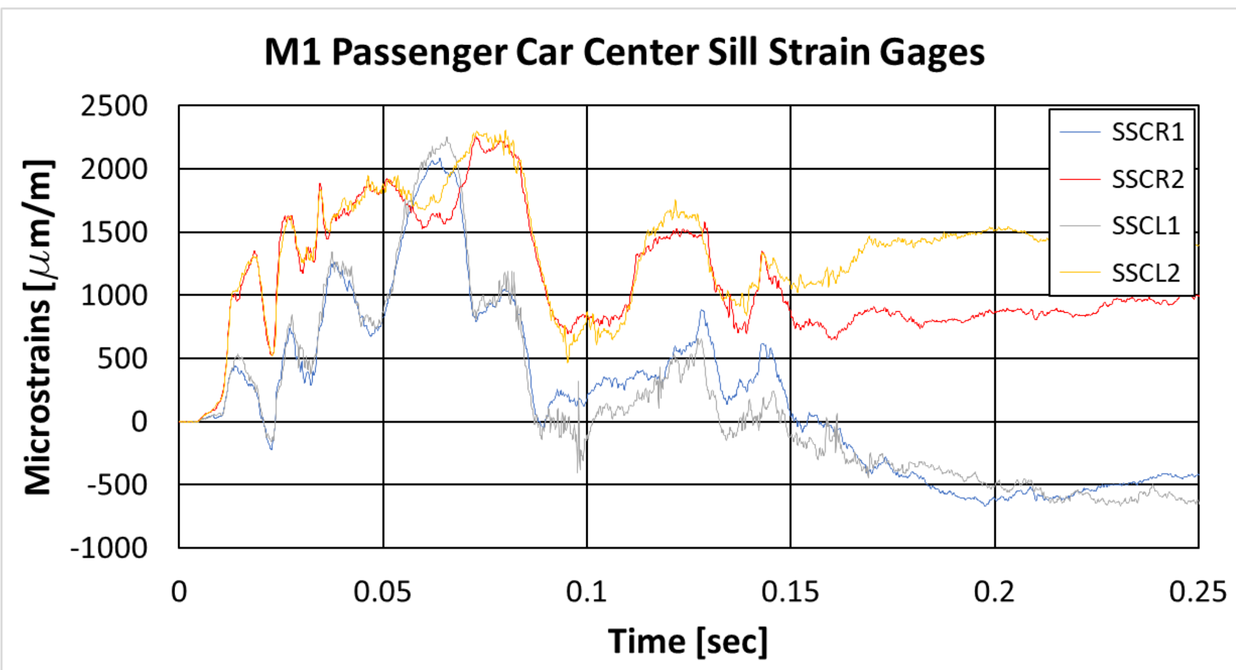

Figure 42. M1 Passenger Car Center Sill Strain Results

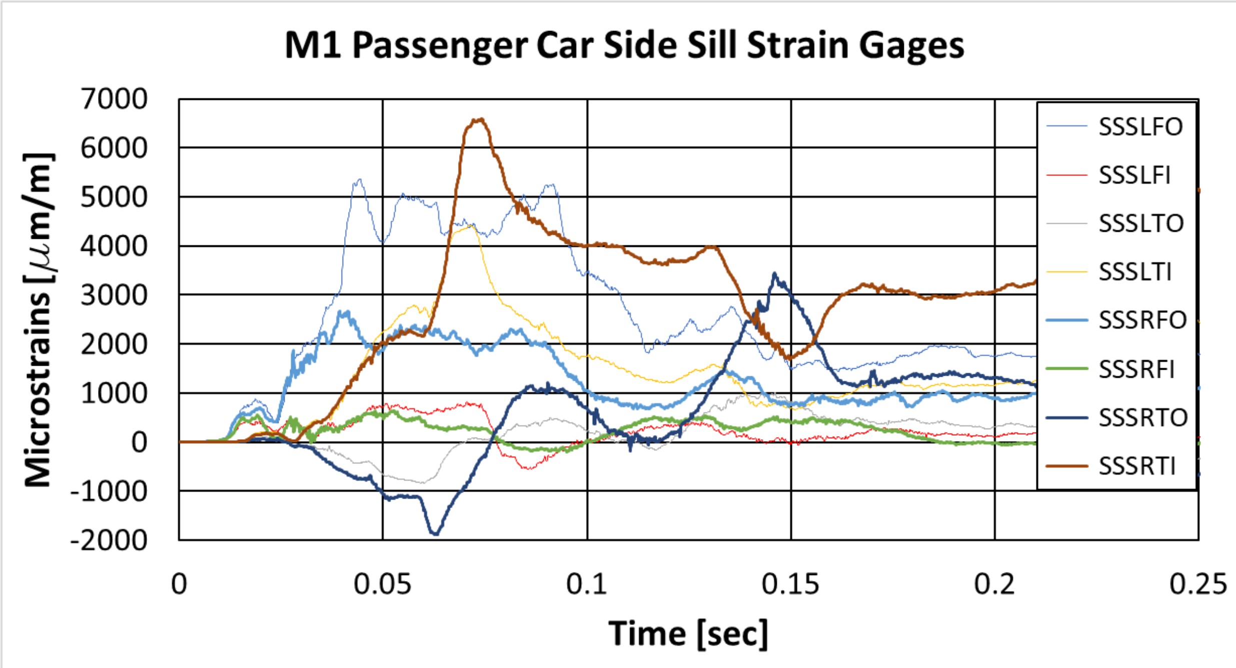

Figure 43. M1 Passenger Car Side Sill Strain Results

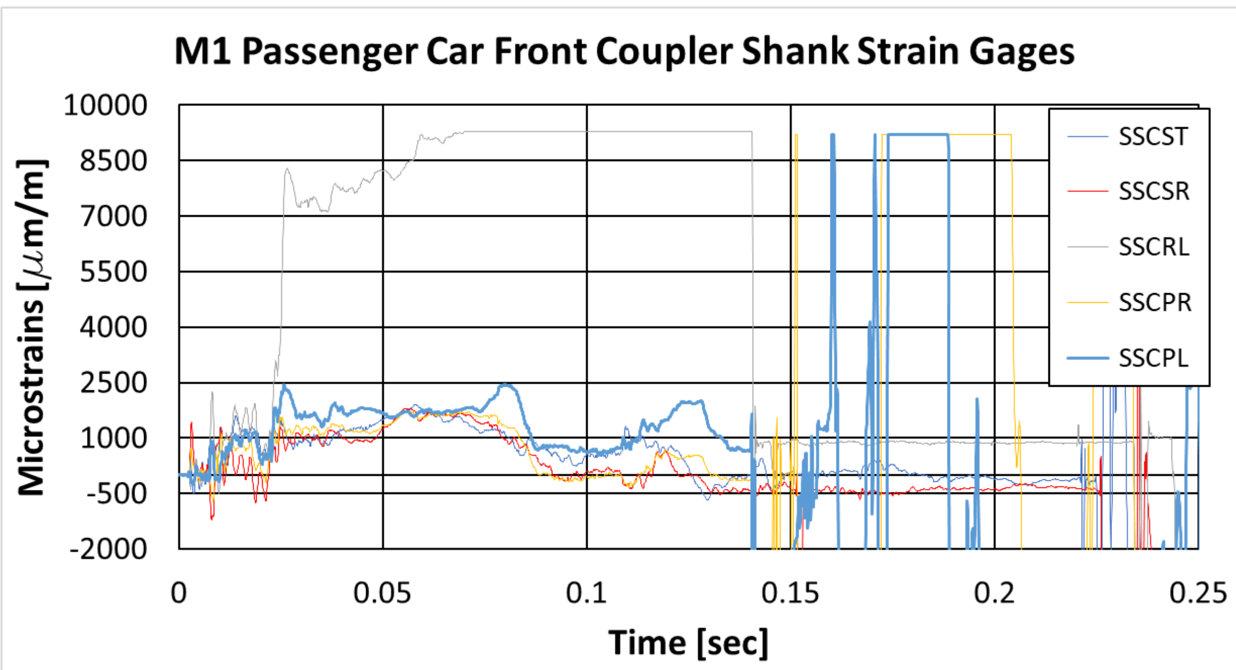

Figure 44. M1 Passenger Car Front Coupler Shank Strain Results

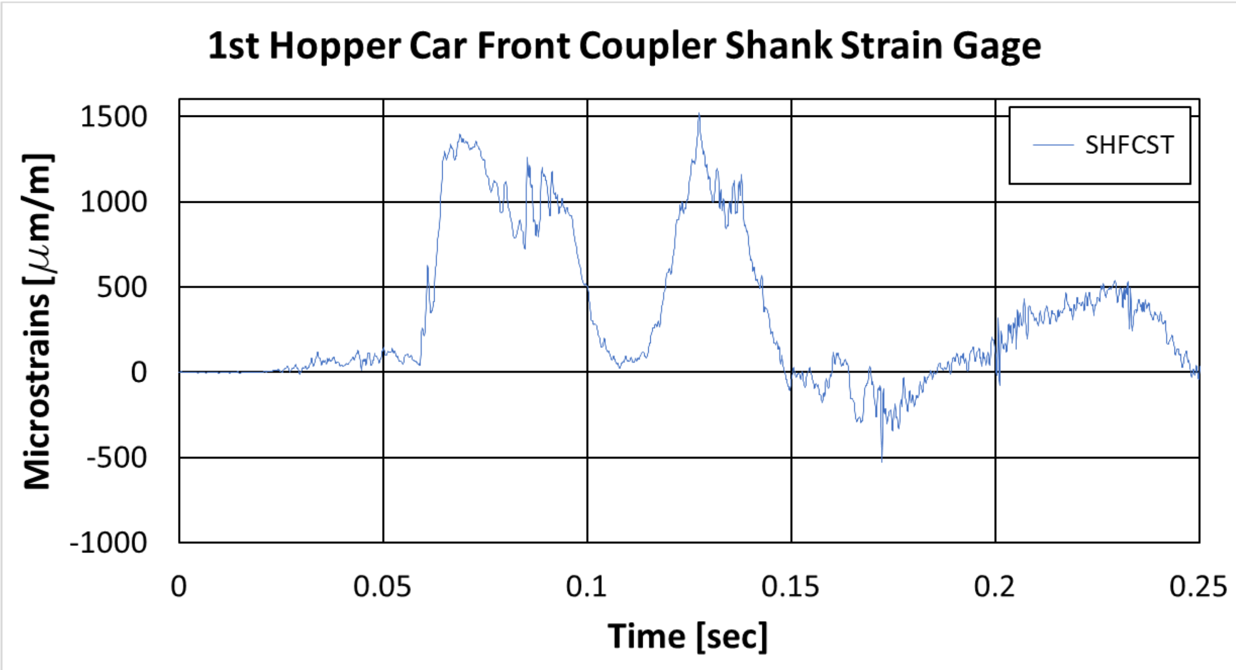

Figure 45. First Hopper Car Front Coupler Shank Strain Results

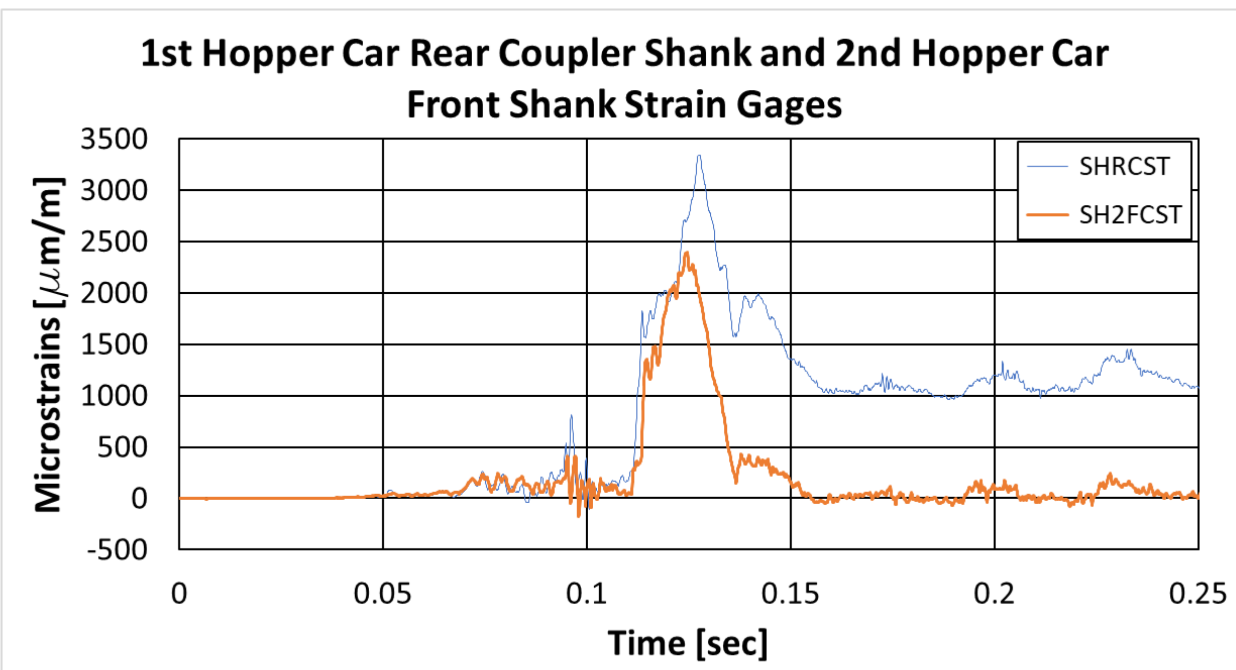

Figure 46. First Hopper Car Rear Coupler Shank and Second Hopper Car Front Shank Strain Results

3.2.4 Forces

Impact forces between the CEM locomotive and the stationary consist can be calculated as a product of the average acceleration and mass of the corresponding vehicle. Figure 47 shows the time history of the vehicle impact forces.

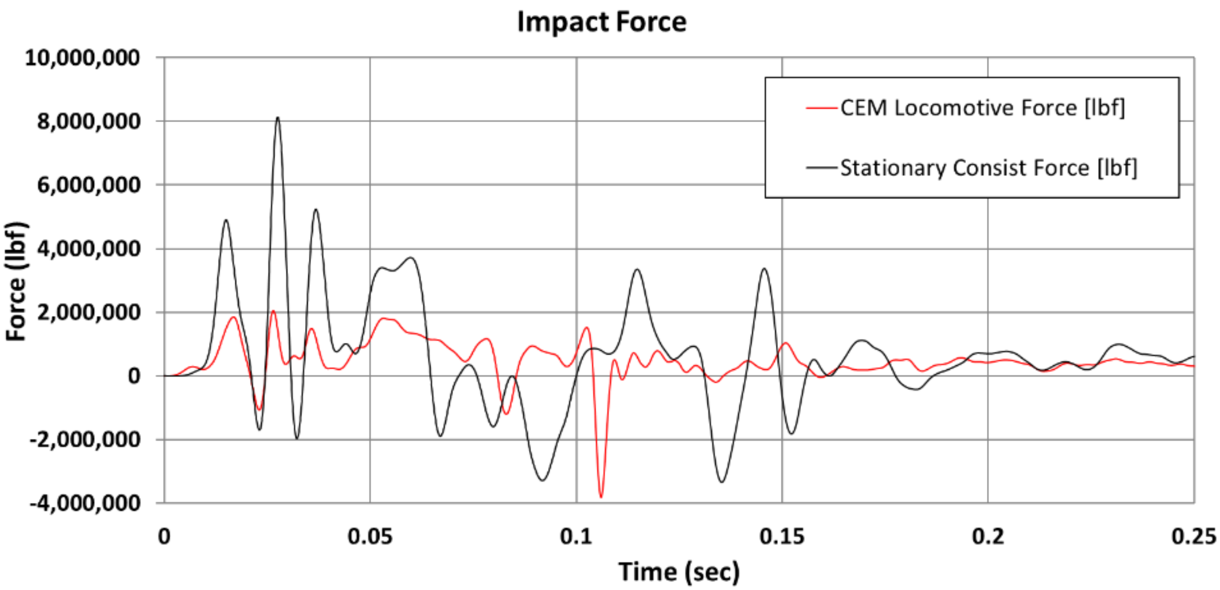

Figure 47. Impact Force

The force was calculated by multiplying vehicle weight and average carbody acceleration. The average acceleration was calculated as described in Section 3.2.1 and was taken from longitudinal accelerometers mounted on the underframe of each vehicle. The peak impact force was approximately 8 million lbf for the stationary consist and 2 million lbf for the CEM locomotive.

3.2.5 Energies

Energy balance is the summary of the energy transfer during the impact. The total energy at the beginning of the impact is equal to the kinetic energy of the CEM locomotive. After the first impact, all vehicles moved forward on the track until they stopped. The dissipated energy accounted for CEM component deformation, braking, and other energy losses. Because the energies should balance, the dissipated energy was obtained by subtracting the kinetic energies from the total energy. Figure 48 shows the energy balance for the initial impact.

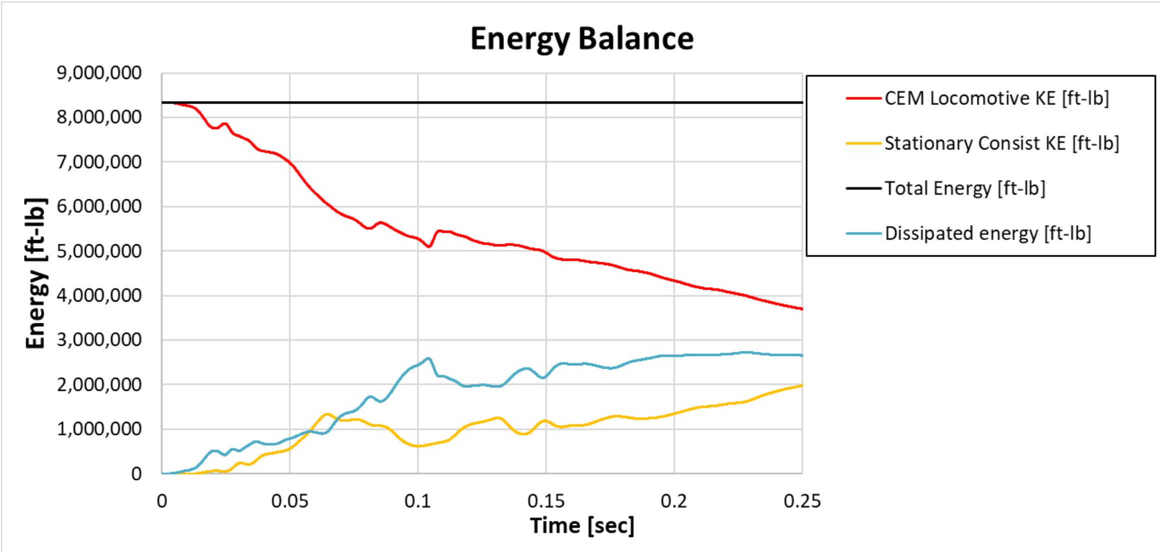

Figure 48. Energy Balance

3.3 Post-Test Damage and CEM Activation

During the impact, the various components of the CEM system were activated. The PBC was activated and exhausted its stroke, and the bottom anti-climbers were engaged and crushed. These anti-climbers and their crush tubes were deformed by the impact. The upper anti-climber appeared to have made slight contact with the M1 passenger car; however, it was still intact after the test. The deformation of the upper anti-climber and its crush tubes was negligible. The impact activated the shear bolts and deformed one bolt hole in the draft pocket. The CEM components after the test are shown in Figure 49 through Figure 53.

Figure 49. Crushed Bottom Anti-climbers

Figure 50. Activated PBC

Figure 51. Sliding Lug after Test

Figure 52. Activated Shear Bolt after Test

Figure 53. Deformed Bolt Hole in Draft Pocket

The locomotive and M1 passenger car couplers were closed at impact, preventing the possibility of coupling; however, the locomotive was lodged into the cab end of the M1 passenger car by the force of the impact. The vehicles had to be pulled apart after the test to assess damage to each vehicle. The impact damaged the front plate of the locomotive, bending it back toward the rear of the vehicle. No other structural damage on the locomotive was noted. The cab end of the M1 passenger car was severely damaged during the impact. Damage to the coupler, draft gear system, and occupational area of the carbody occurred. Also, the carbody buckled approximately three-quarters of the length of the car back from the impact point. Aside from the damage to the cab end of the car, the interior of the M1 passenger car was relatively unharmed except for deformation of the flooring. The damage of each vehicle is shown in Figure 54 through Figure 59.

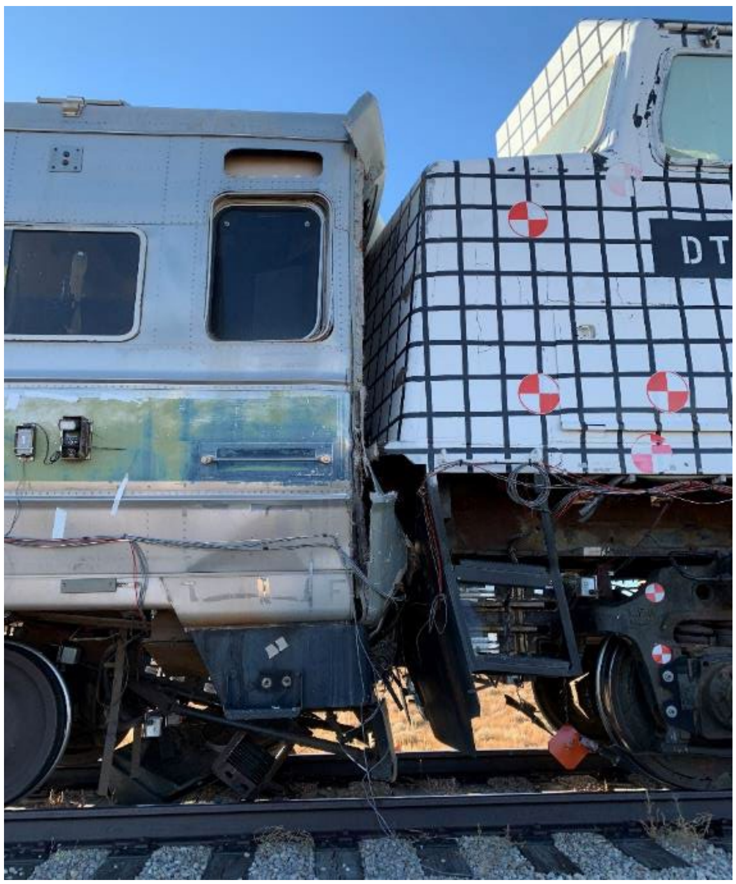

Figure 54. CEM Locomotive and M1 Passenger Car Intertwined after Test

Figure 55. Buckled M1 Passenger Car

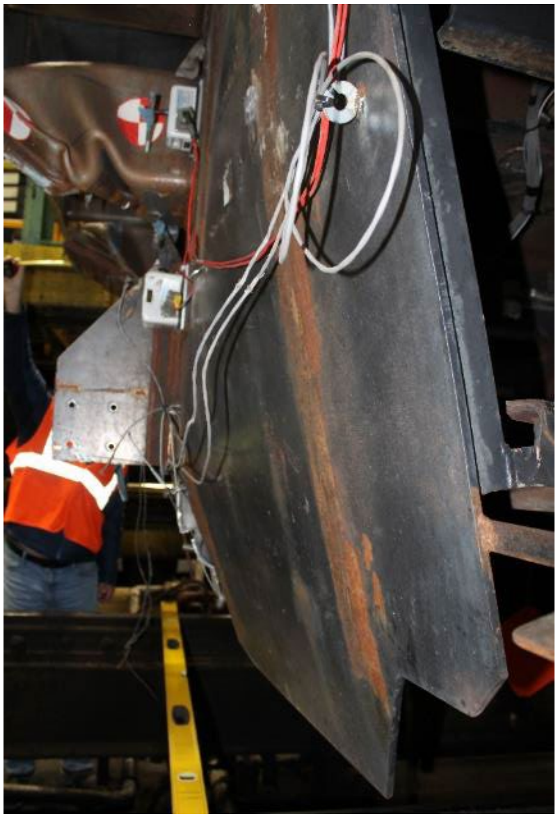

Figure 56. CEM Locomotive Bent Front Plate

Figure 57. M1 Passenger Car Impact End (Cab) Exterior

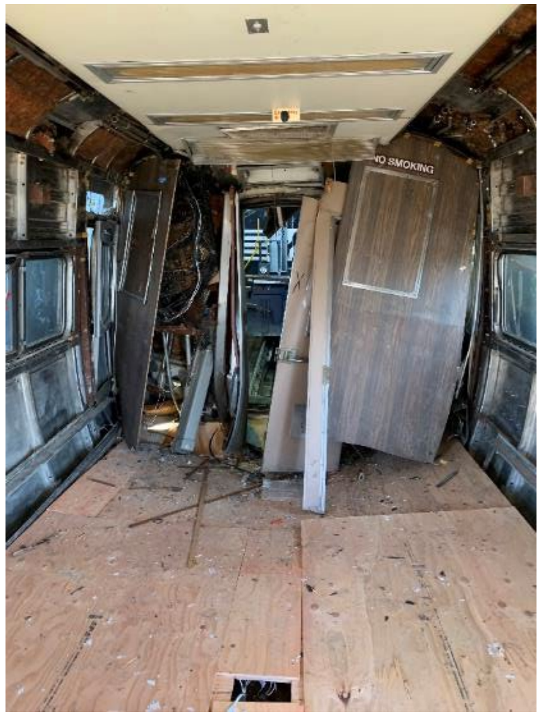

Figure 58. M1 Passenger Car Impact End (Cab) Interior

Figure 59. M1 Passenger Car Trailing End Interior

4. Conclusion

This report documents the impact test conducted by TTCI between a locomotive retrofitted with CEM components and a M1 passenger car backed by two empty hopper cars. This test was intended to evaluate the combined performance of the CEM components, including the push-back coupler, the deformable anti-climbers, and the shear bolts and sliding lug. This impact test was conducted in November 2021 at TTC near Pueblo, Colorado.

The stationary M1 passenger car and two hopper cars were impacted by the 231,825-lb locomotive at 32.8 mph. The locomotive and M1 passenger car couplers were closed at impact preventing the possibility of coupling; however, the locomotive was lodged into the cab end of the M1 passenger car by the force of the impact. The vehicles had to be pulled apart after the test.

The cab end underframe of the M1 passenger car came into contact with the lower set of deformable anti-climbers during the impact, causing them to partially crush. The upper anti-climber made slight contact with the M1 passenger car however it is still intact. The deformation of the upper anti-climber and its crush tubes was negligible. The push-back coupler was activated and exhausted its stroke. The impact also activated the shear bolts and deformed one bolt hole in the draft pocket. The total impact energy was close to 8 million ft.-lbs.

The test confirmed that the PBC, the anti-climbers, and the shear bolts in the sliding lug were activated, prevented override, and absorbed the impact energy as intended.

Data collected in this test will be used to validate the computer models and to prepare for the final impact test in the program. The final test will be a full-scale train-to-train impact to evaluate the performance of the retrofit CEM components in a high-energy collision scenario.

Abbreviations and Acronyms

CEM	Crash Energy Management
DAC	Deformable Anti-Climber
FRA	Federal Railroad Administration
PBC	Push-Back Coupler
TTC	Transportation Technology Center
Volpe	Volpe National Transportation Systems Center

Appendix A. Target Positions

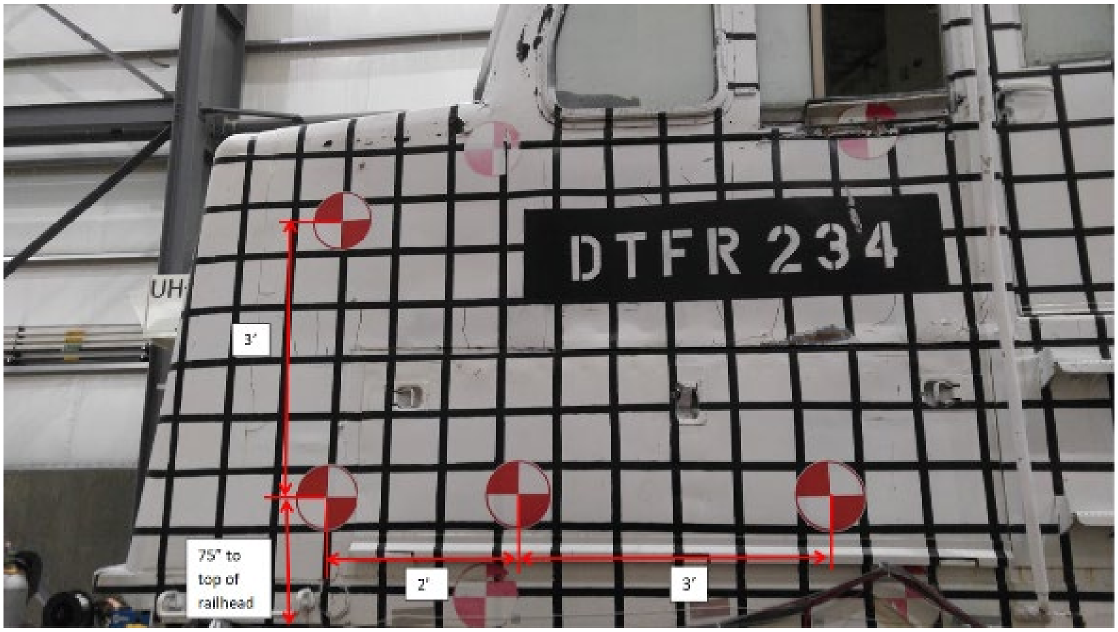

Figure A1. Target Spacing for CEM Locomotive

Appendix B. Test Data

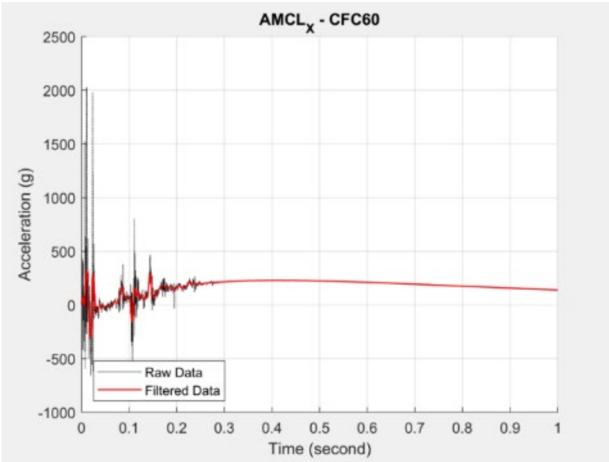

Figure B1. AMCL_X Accelerometer Data

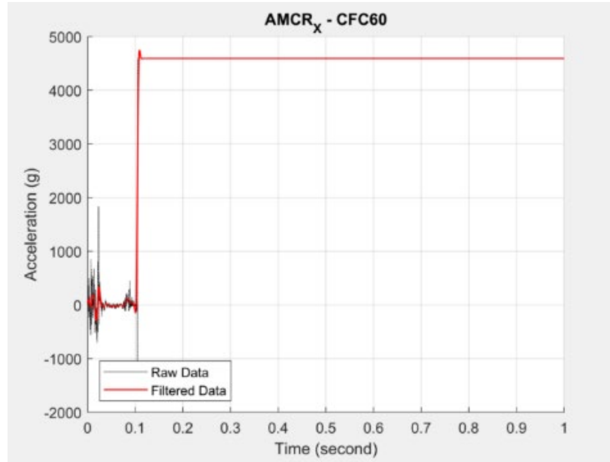

Figure B2. AMCR_X Accelerometer Data

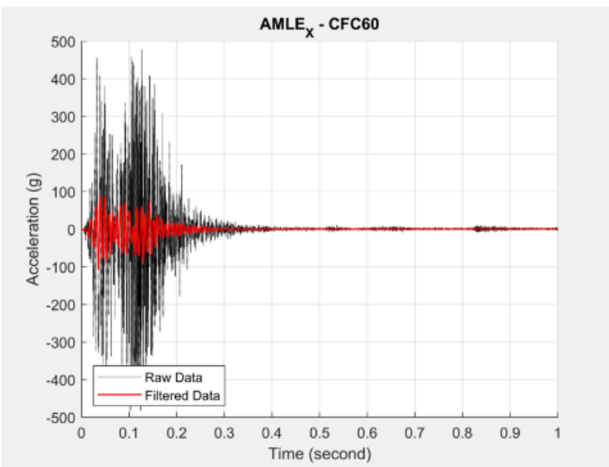

Figure B3. AMLE_X Accelerometer Data

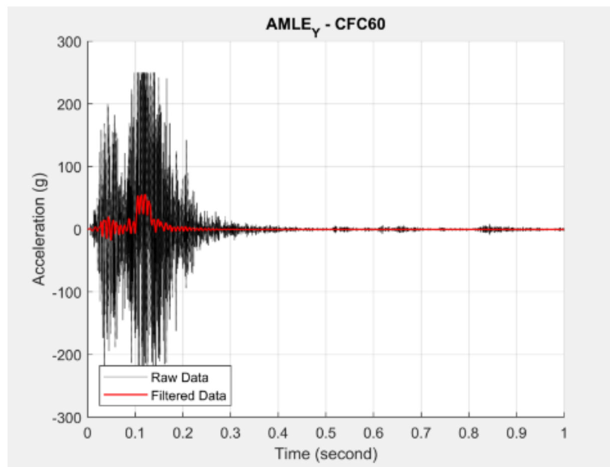

Figure B4. AMLE_Y Accelerometer Data

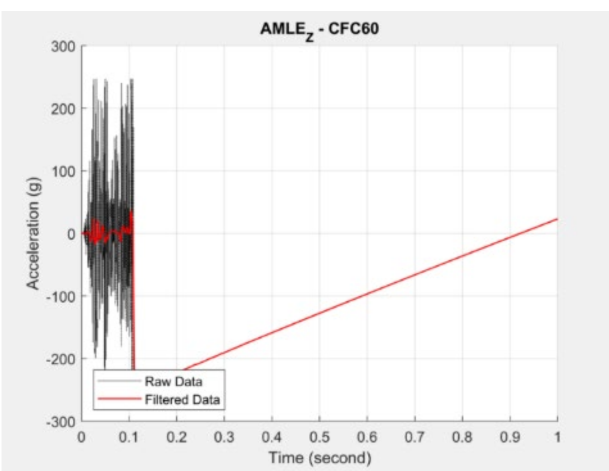

Figure B5. AMLE_Z Accelerometer Data

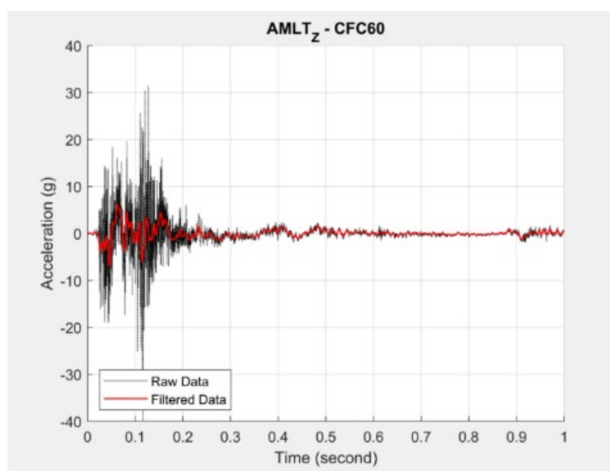

Figure B6. AMLT_Z Accelerometer Data

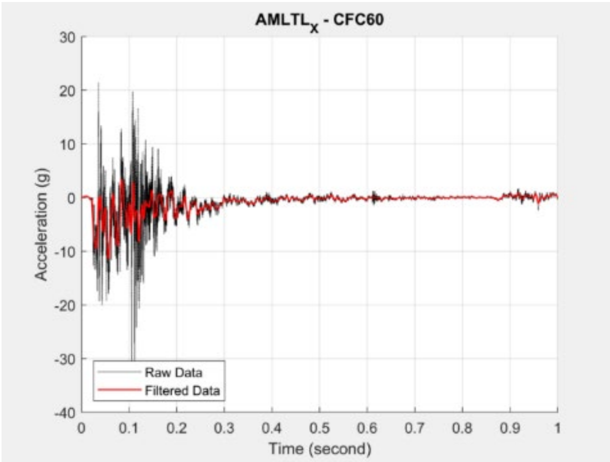

Figure B7. AMLTL_X Accelerometer Data

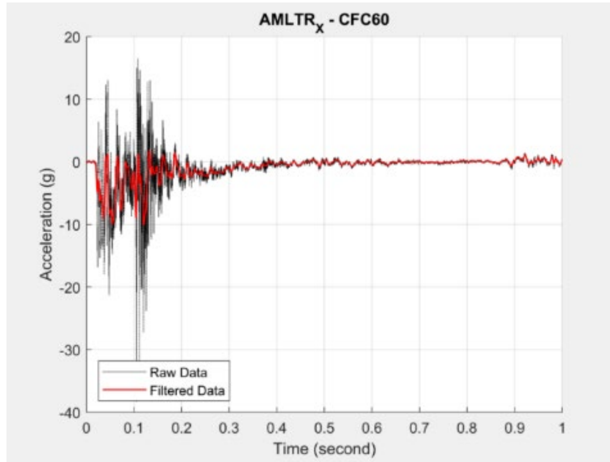

Figure B8. AMLTR_X Accelerometer Data

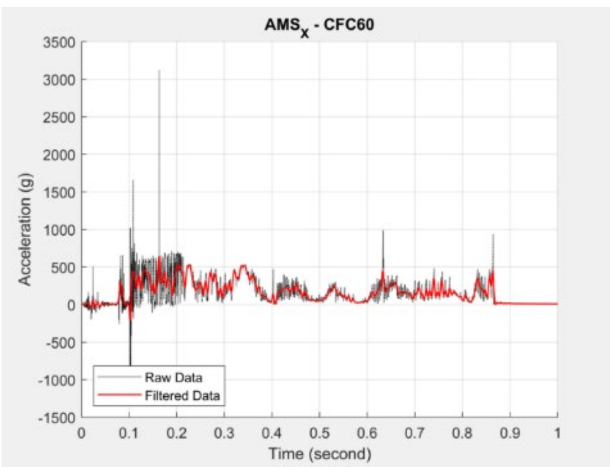

Figure B9. AMS_X Accelerometer Data

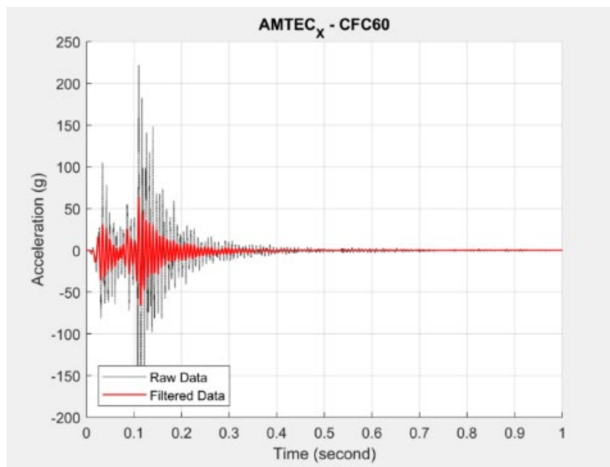

Figure B10. AMTEC_X Accelerometer Data

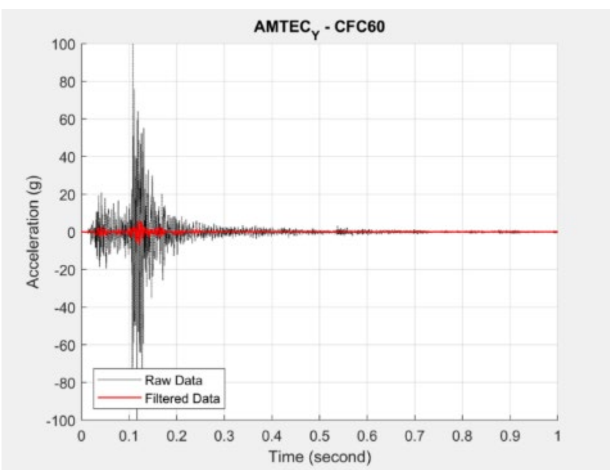

Figure B11. AMTEC_Y Accelerometer Data

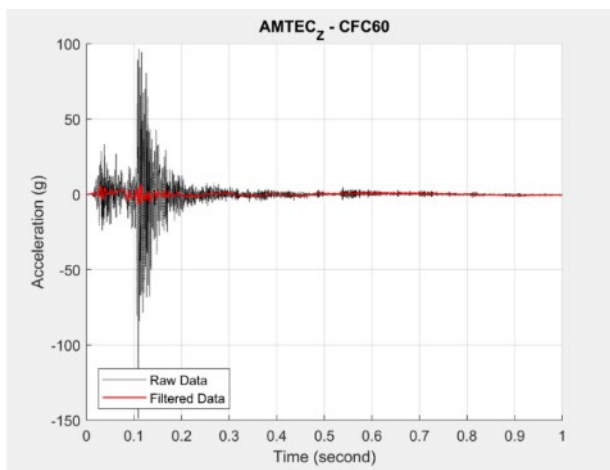

Figure B12. AMTEC_Z Accelerometer Data

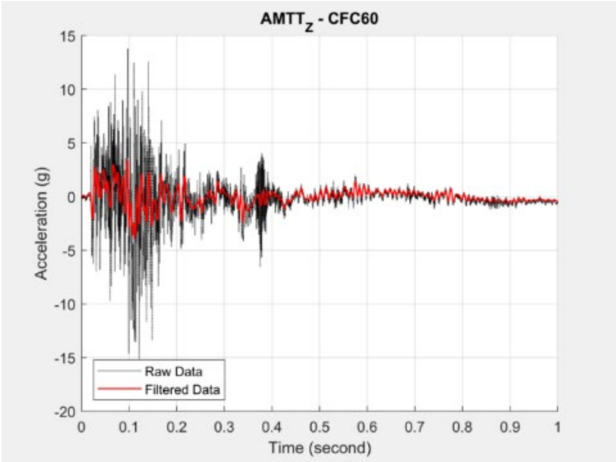

Figure B13. AMTT_Z Accelerometer Data

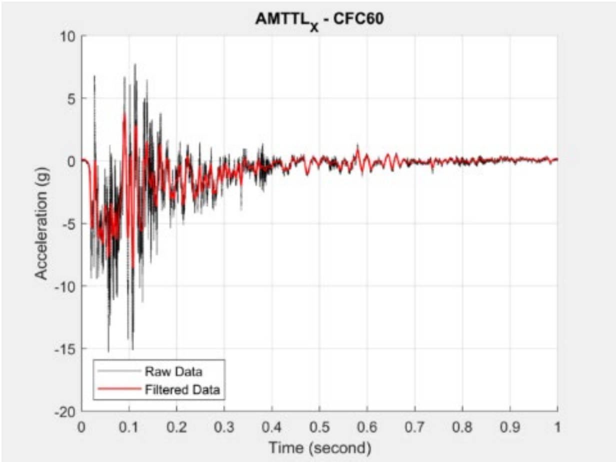

Figure B14. AMTTL_X Accelerometer Data

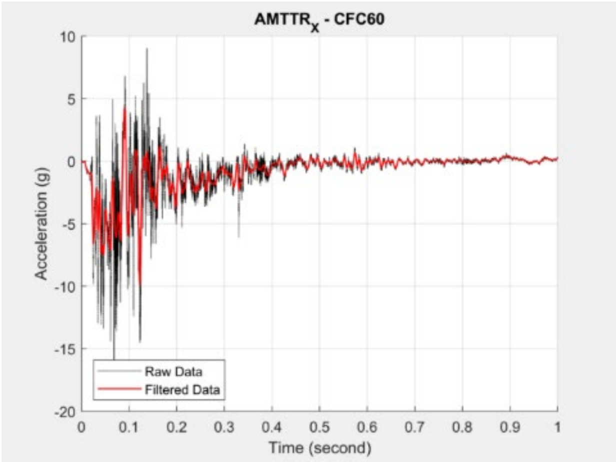

Figure B15. AMTTR_X Accelerometer Data

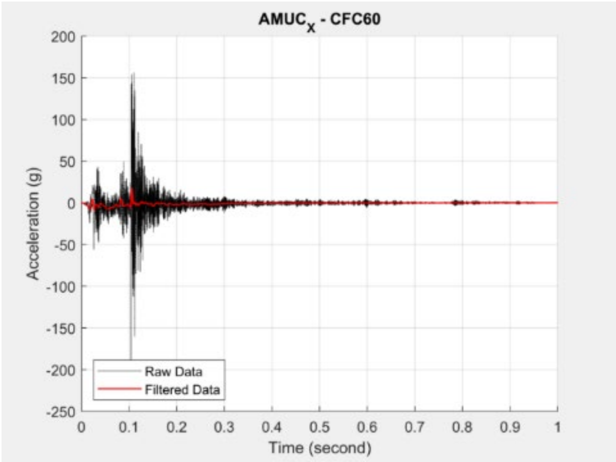

Figure B16. AMUC_X Accelerometer Data

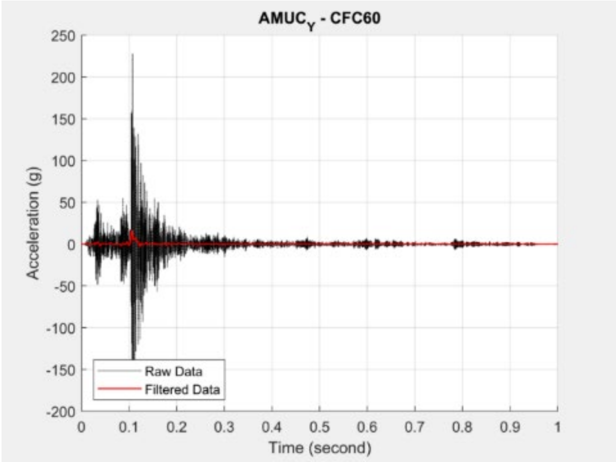

Figure B17. AMUC_Y Accelerometer Data

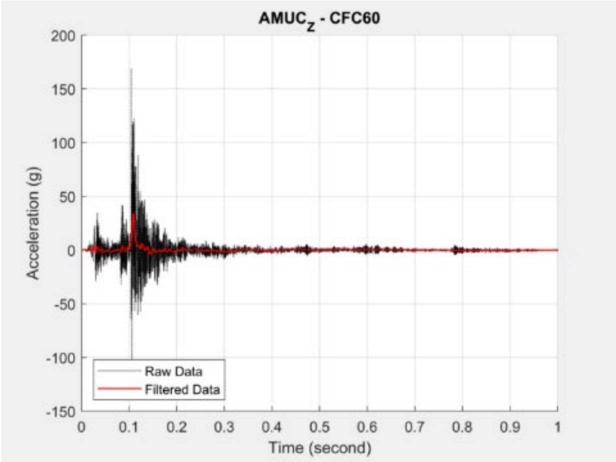

Figure B18. AMUC_Z Accelerometer Data

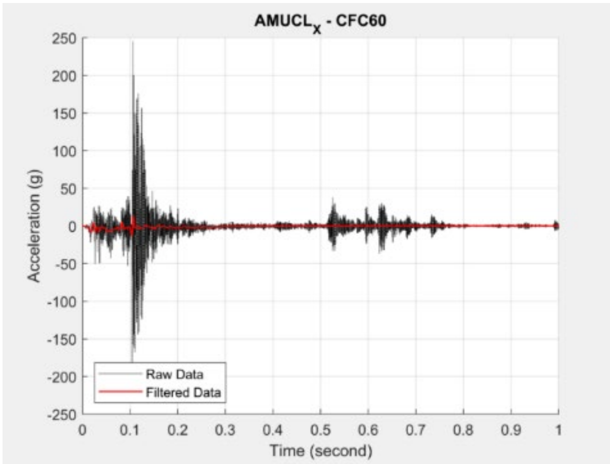

Figure B19. AMUCL_X Accelerometer Data

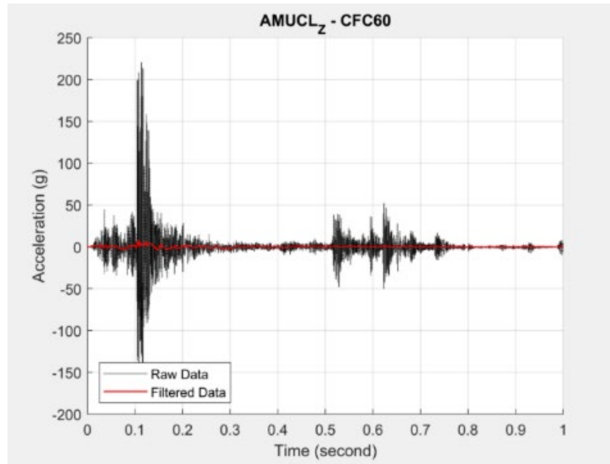

Figure B20. AMUCL_Z Accelerometer Data

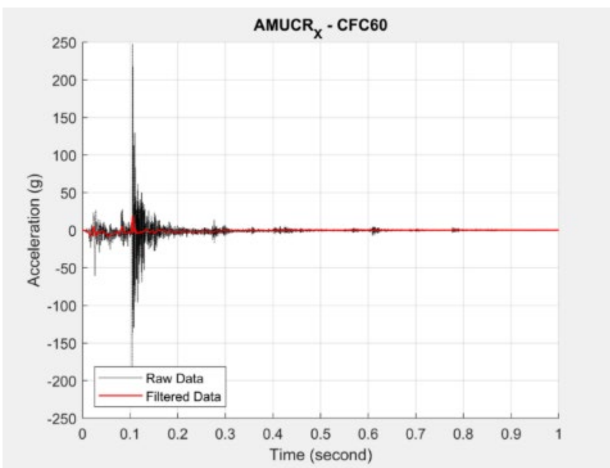

Figure B21. AMUCR_X Accelerometer Data

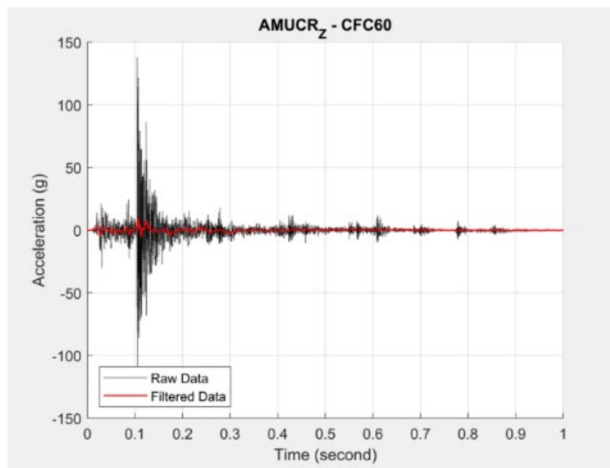

Figure B22. AMUCR_Z Accelerometer Data

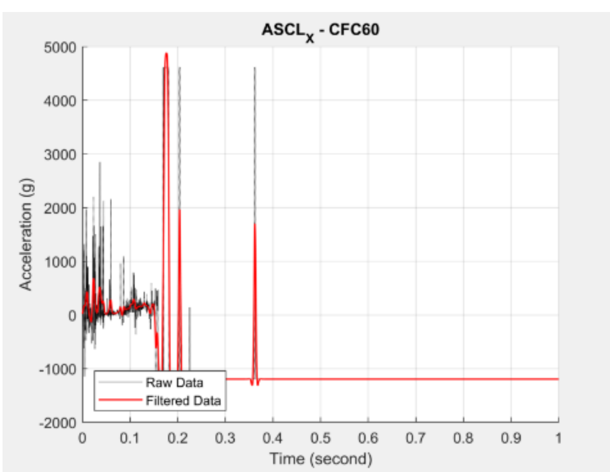

Figure B23. ASCL_X Accelerometer Data

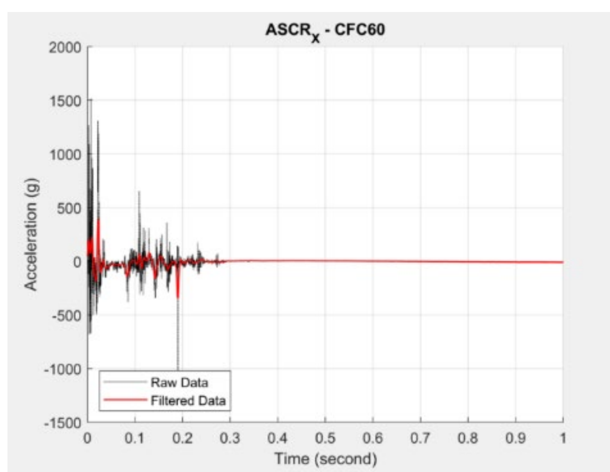

Figure B24. ASCR_X Accelerometer Data

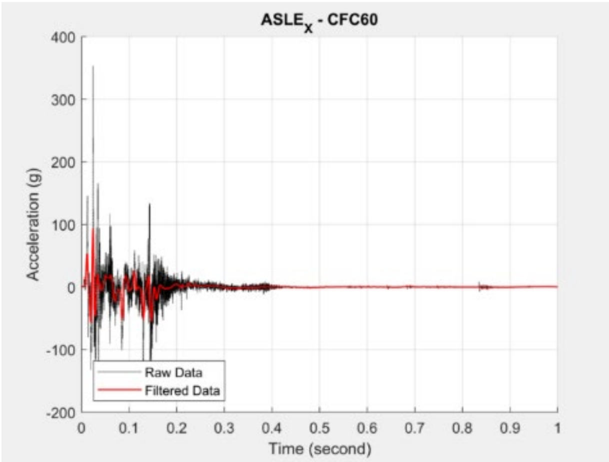

Figure B25. ASLE_X Accelerometer Data

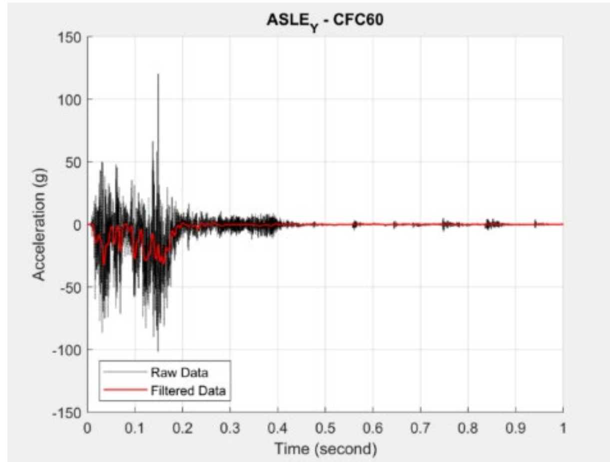

Figure B26. ASLE_Y Accelerometer Data

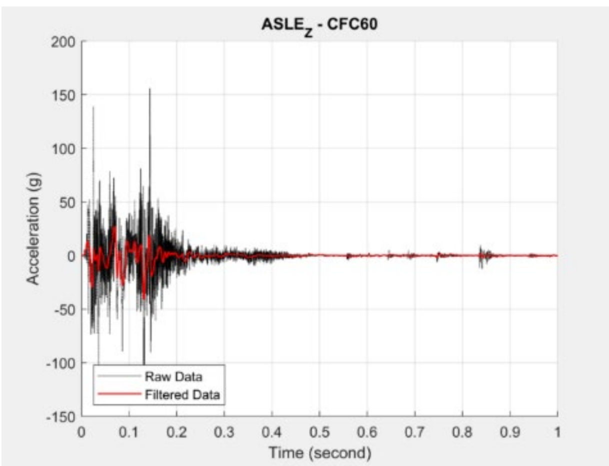

Figure B27. ASLE_Z Accelerometer Data

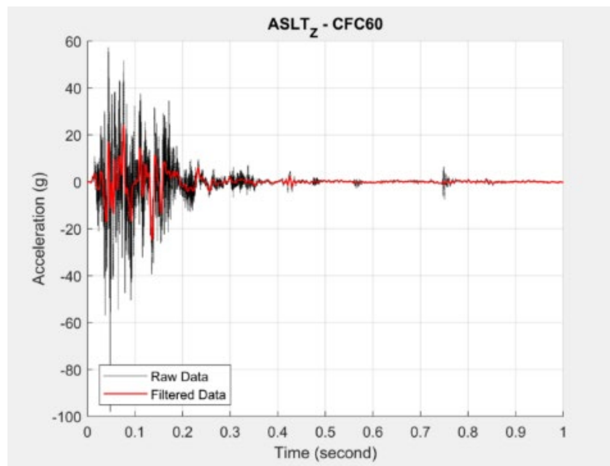

Figure B28. ASLT_Z Accelerometer Data

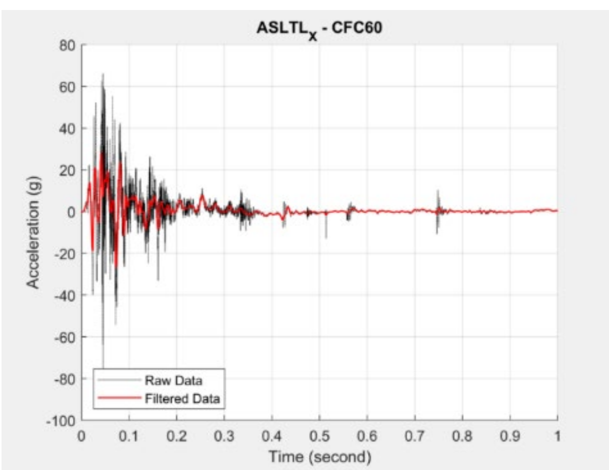

Figure B29. ASLTL_X Accelerometer Data

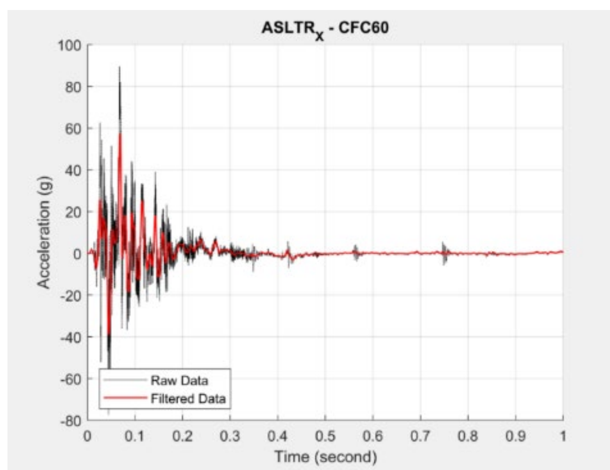

Figure B30. ASLTR_X Accelerometer Data

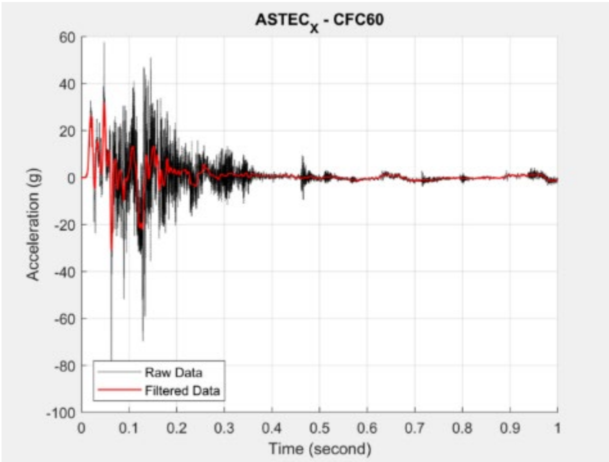

Figure B31. ASTEC_X Accelerometer Data

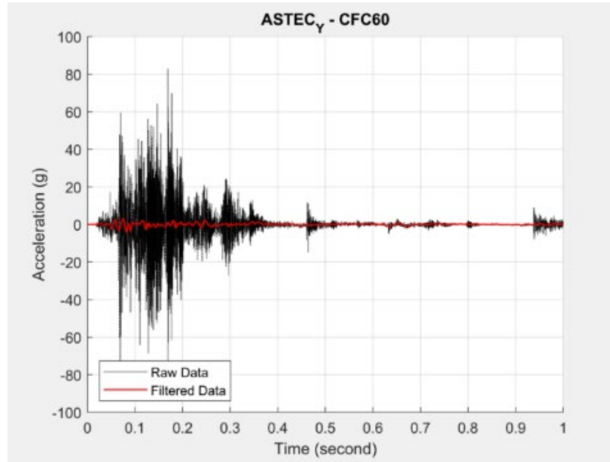

Figure B32. ASTEC_Y Accelerometer Data

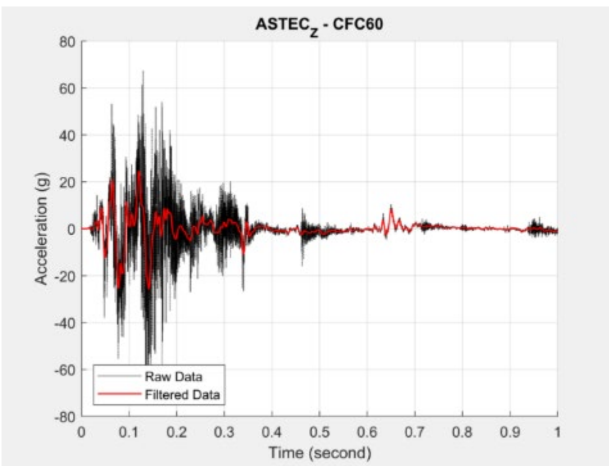

Figure B33. ASTEC_Z Accelerometer Data

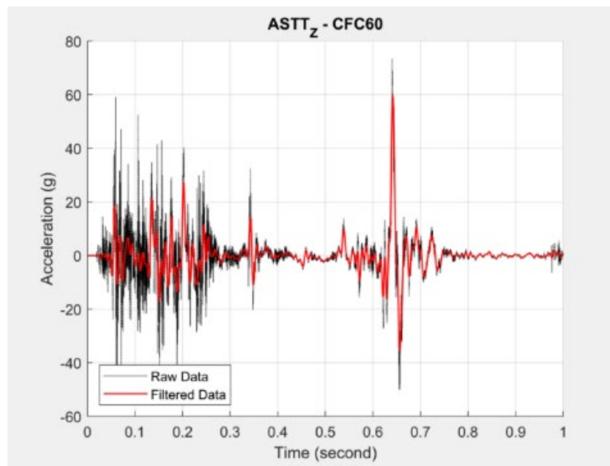

Figure B34. ASTT_Z Accelerometer Data

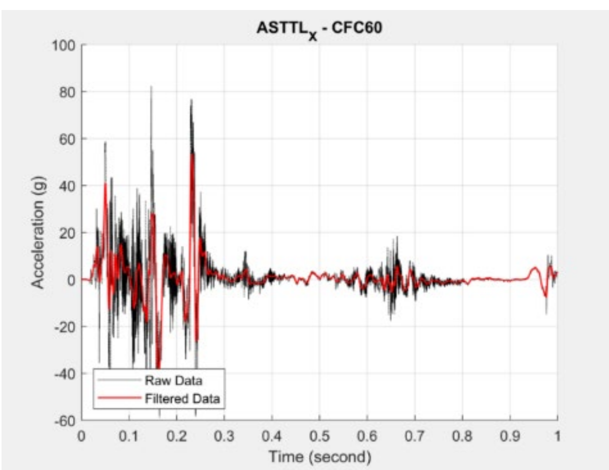

Figure B35. ASTTL_X Accelerometer Data

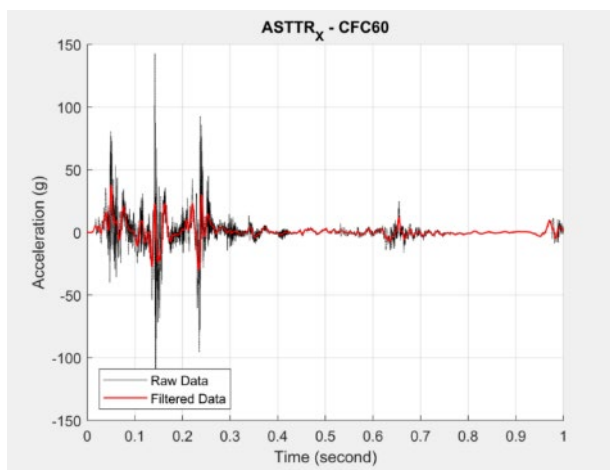

Figure B36. ASTTR_X Accelerometer Data

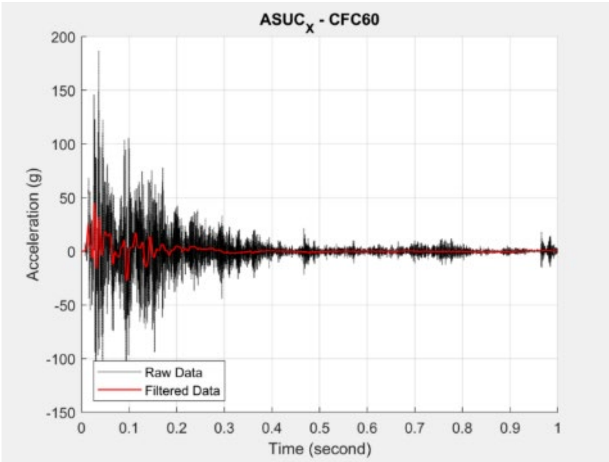

Figure B37. ASUC_X Accelerometer Data

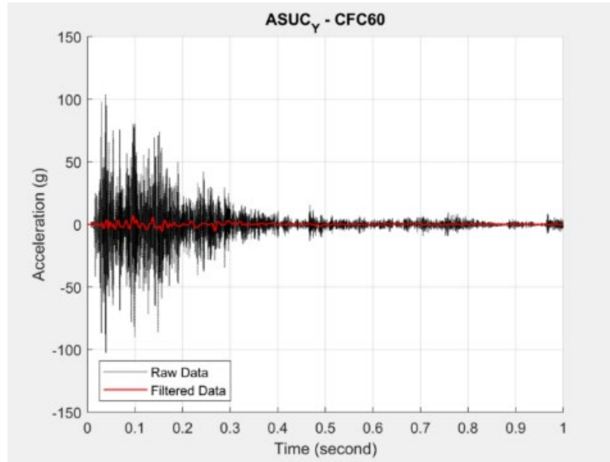

Figure B38. ASUC_Y Accelerometer Data

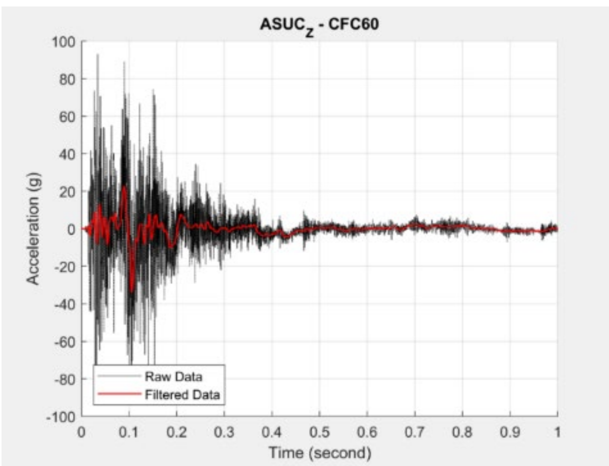

Figure B39. ASUC_Z Accelerometer Data

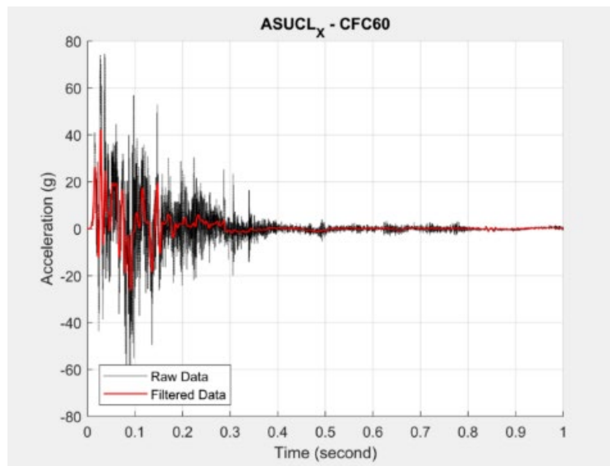

Figure B40. ASUCL_X Accelerometer Data

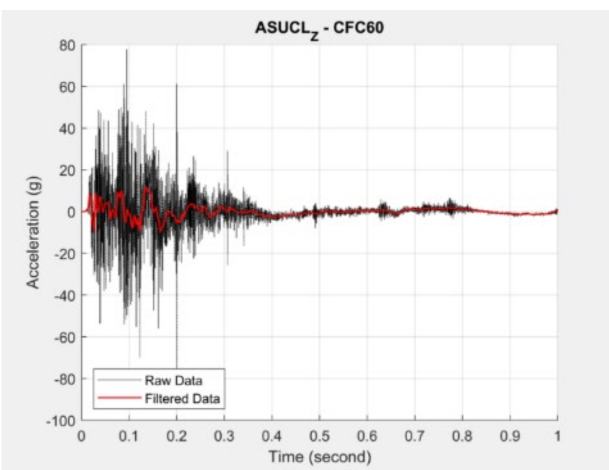

Figure B41. AMUCL_Z Accelerometer Data

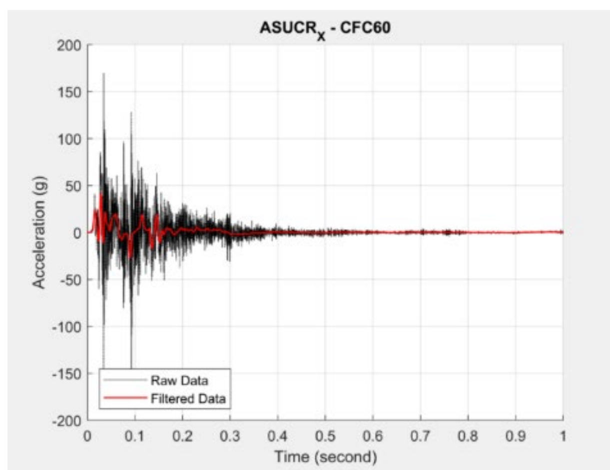

Figure B42. ASUCR_X Accelerometer Data

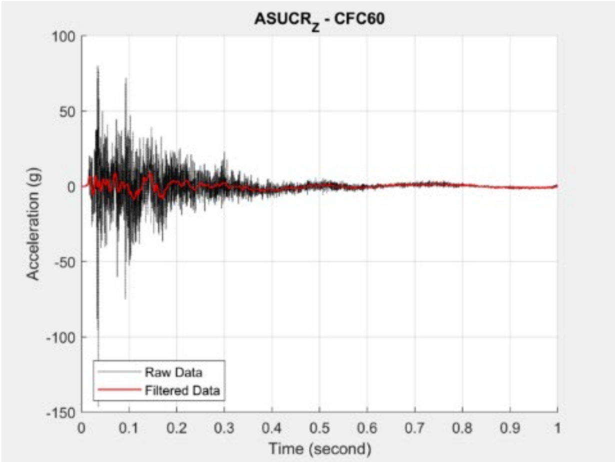

Figure B43. ASUCR_Z Accelerometer Data

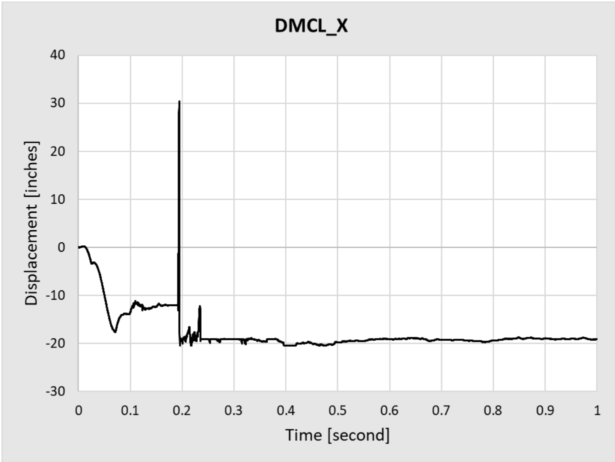

Figure B44. DMCL_X Displacement Data

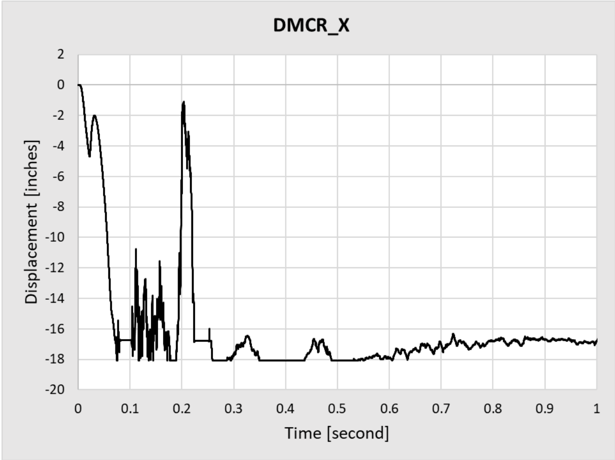

Figure B45. DMCR_X Displacement Data

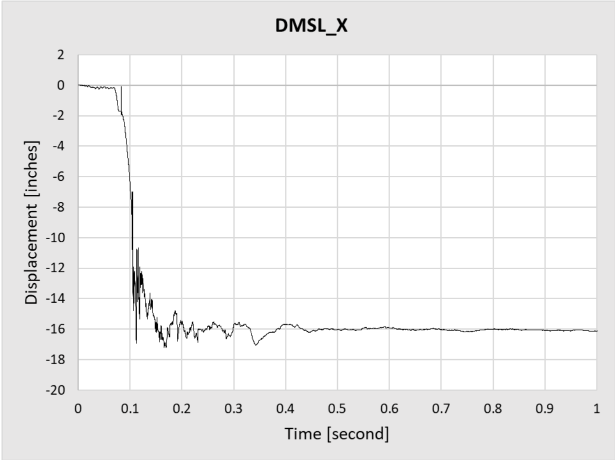

Figure B46. DMSL_X Displacement Data

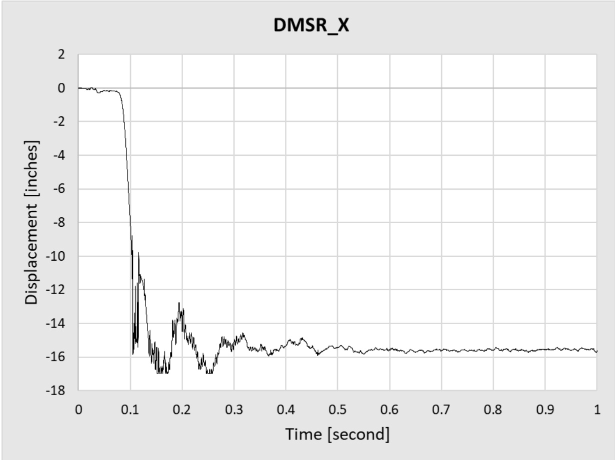

Figure B47. DMSR_X Displacement Data

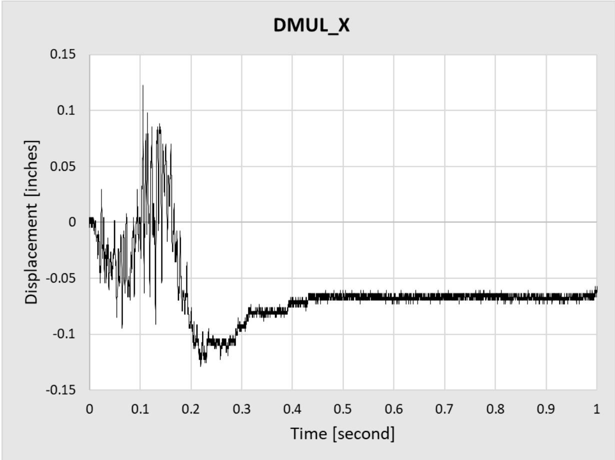

Figure B48. DMUL_X Displacement Data

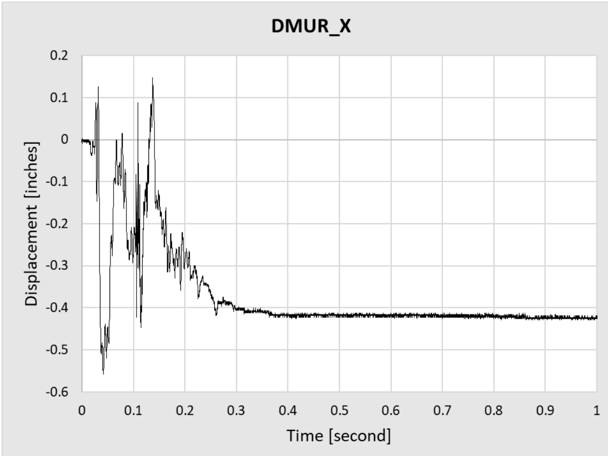

Figure B49. DMUR_X Displacement Data

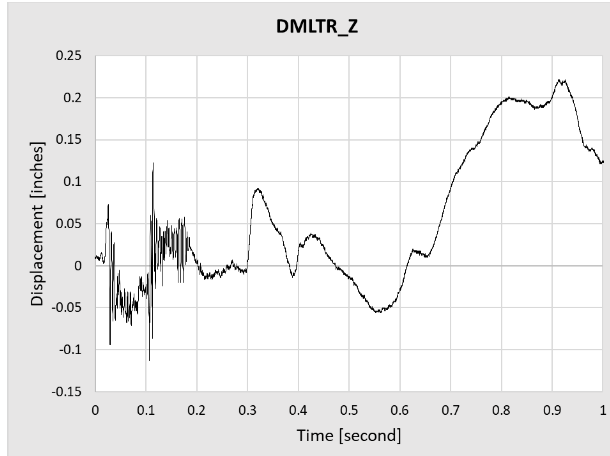

Figure B50. DMLTR_Z Displacement Data

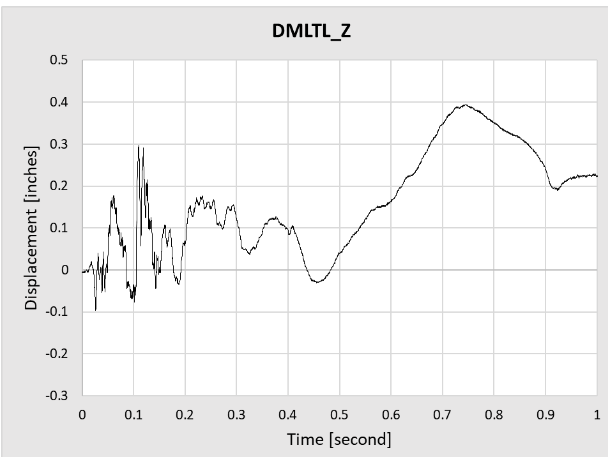

Figure B51. DMLTL_Z Displacement Data

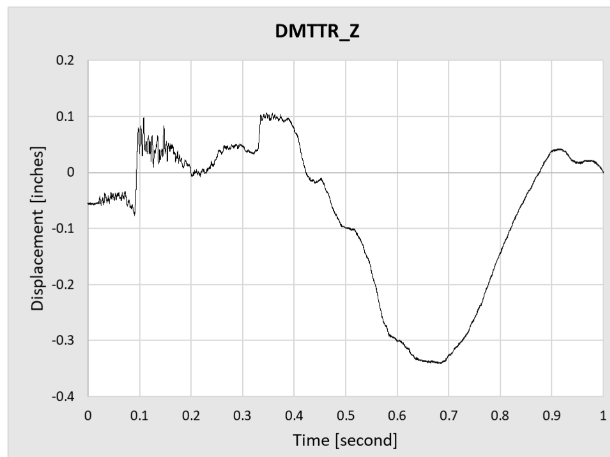

Figure B52. DMTTR_Z Displacement Data

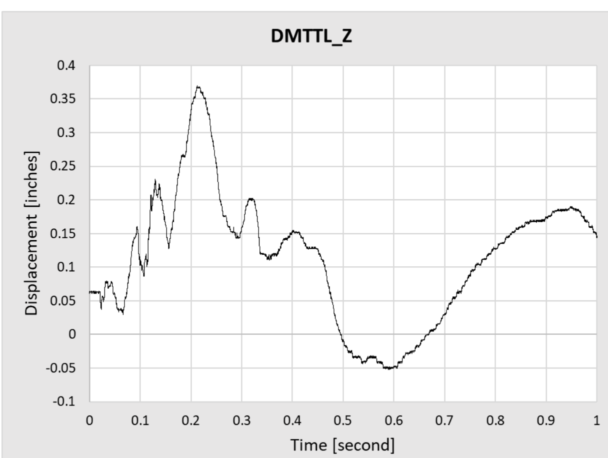

Figure B53. DMTTL_Z Displacement Data

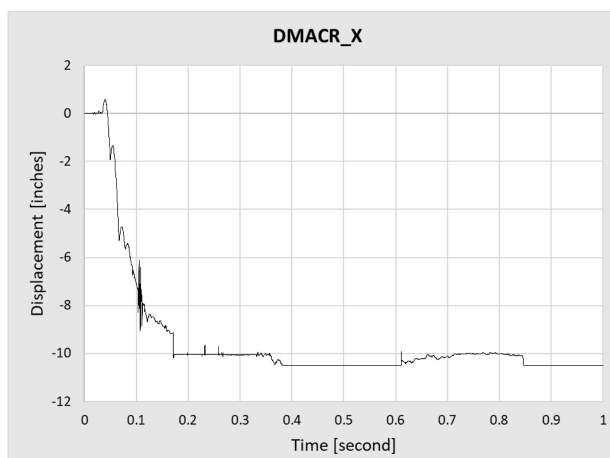

Figure B54. DMACR_X Displacement Data

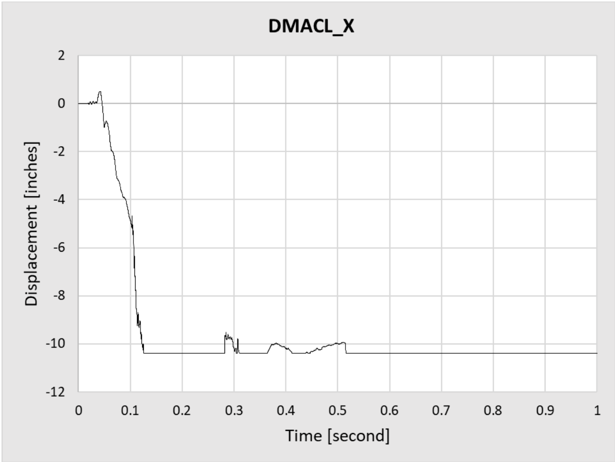

Figure B55. DMACL_X Displacement Data

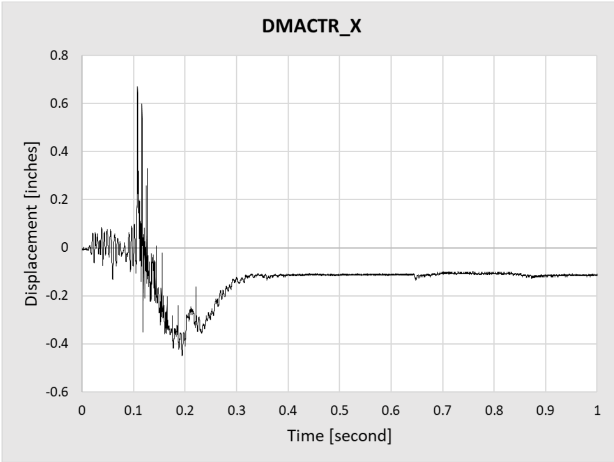

Figure B56. DMACTR_X Displacement Data

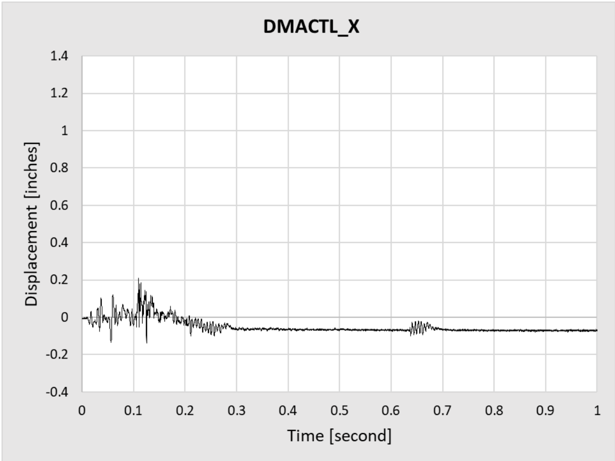

Figure B57. DMACTL_X Displacement Data

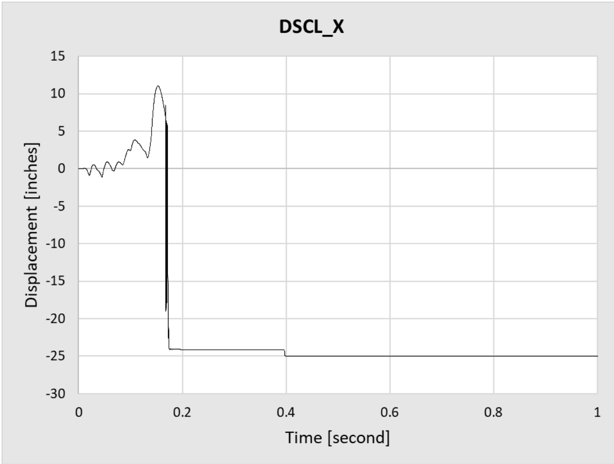

Figure B58. DSCL_X Displacement Data

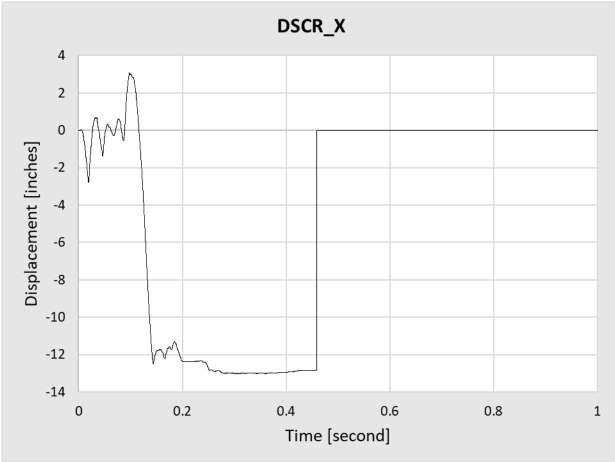

Figure B59. DSCR_X Displacement Data

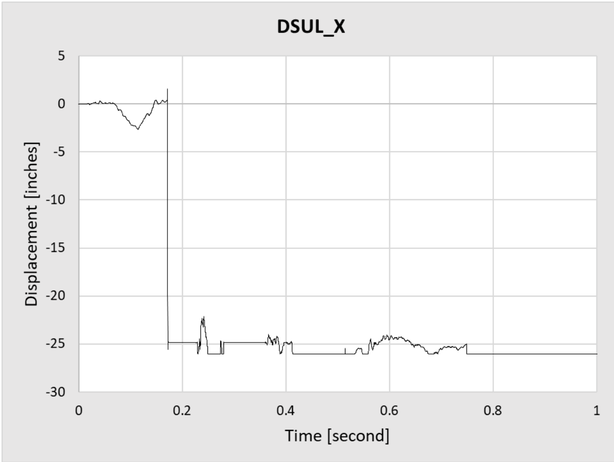

Figure B60. DSUL_X Displacement Data

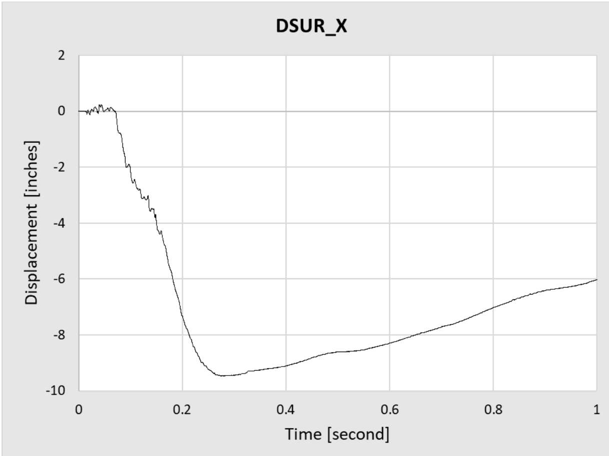

Figure B61. DSUR_X Displacement Data

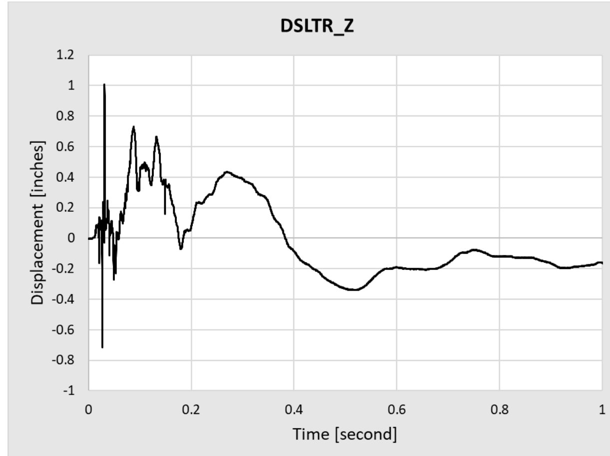

Figure B62. DSLTR_Z Displacement Data

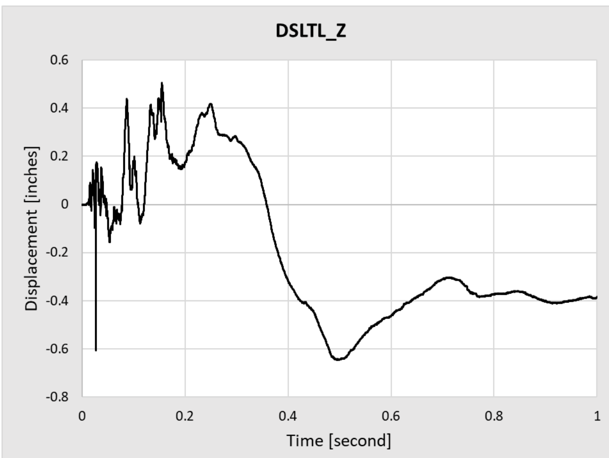

Figure B63. DSLTL_Z Displacement Data

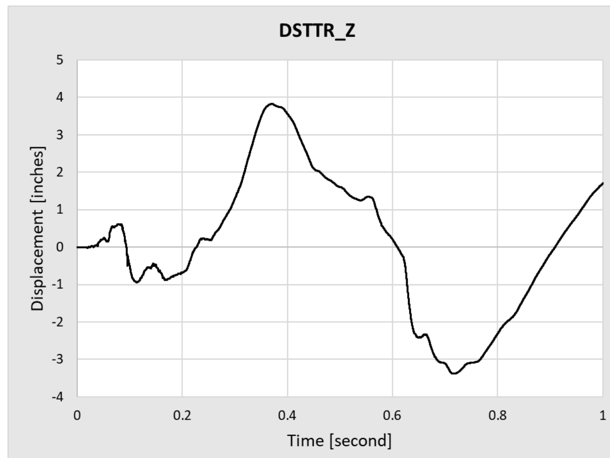

Figure B64. DSTTR_Z Displacement Data

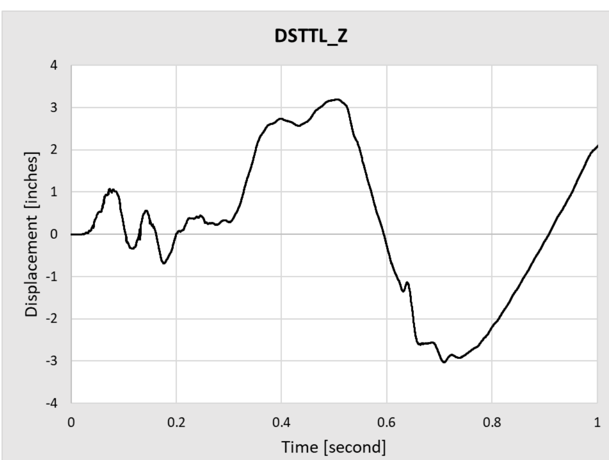

Figure B65. DSTTL_Z Displacement Data

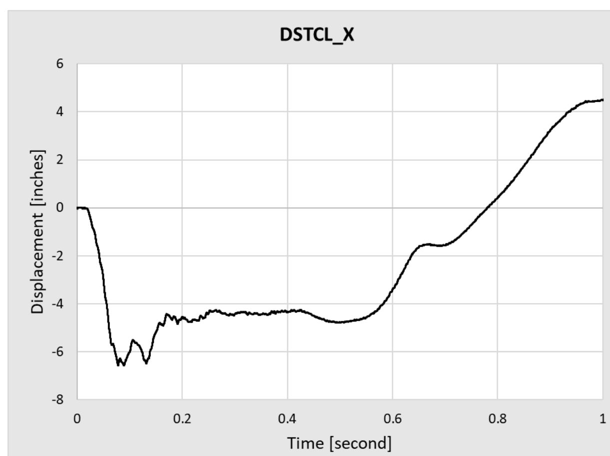

Figure B66. DSTCL_X Displacement Data

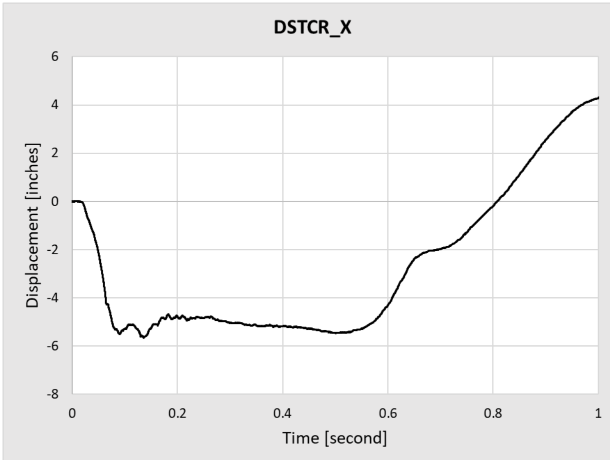

Figure B67. DSTCR_X Displacement Data

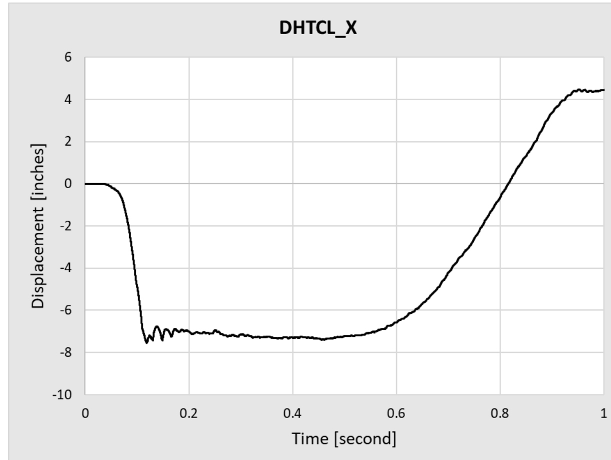

Figure B68. DHTCL_X Displacement Data

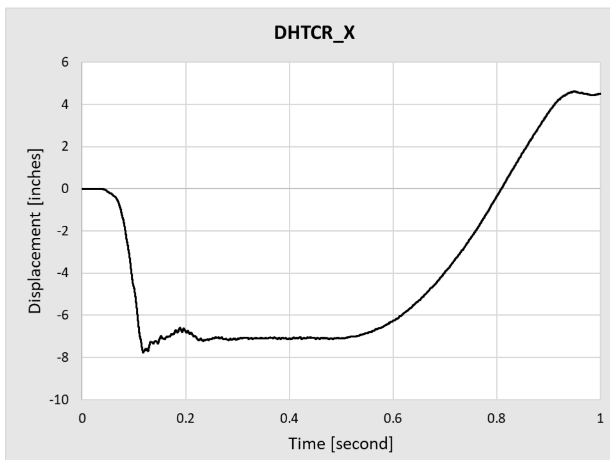

Figure B69. DHTCR_X Displacement Data