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Federal Railroad Administration

Conventional and CEM Passenger Locomotive Impact Test

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Washington, DC 20590

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Final Report
January 2021

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13. ABSTRACT Transportation Technology Center, Inc. conducted an impact test with two F40 locomotives to evaluate the performance of both vehicles under dynamic conditions. One 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 January 23, 2019, at the Transportation Technology Center in Pueblo, Colorado. The stationary locomotive was impacted by the CEM-equipped locomotive at 19.3 mph. The impact-initiated deformation on one set of anti-climbers and activated the PBC. However, the remaining impact energy was insufficient to initiate shearing in 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

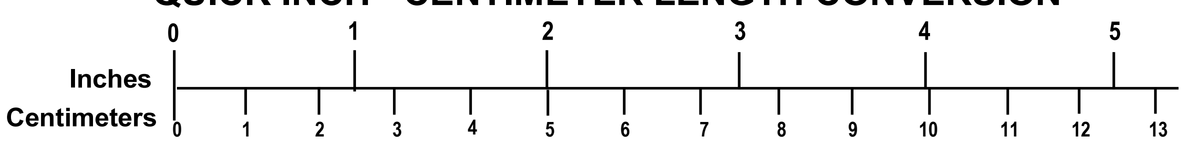
VOLUME (APPROXIMATE)

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)

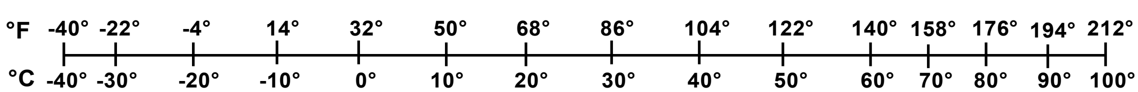
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



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

In January 2019, Transportation Technology Center, Inc. conducted an impact test between a conventional EMD F40 passenger locomotive and a locomotive equipped with CEM components to evaluate the performance of these components under dynamic conditions. The retrofitted CEM locomotive was equipped with a push-back coupler (PBC), deformable anti-climbers, and shear bolts. This test was performed on January 23, 2019, at the Transportation Technology Center in Pueblo, Colorado.

The locomotives impacted at 19.3 mph. The locomotive couplers were open at impact, with the intention that they would couple. However, the locomotives did not couple during the test. The locomotives sustained no noticeable structural damage during the test other than the expected deformation of the CEM components. The impact caused the crushing of one set of anti-climbers and the activation of the PBC. However, after these components activated, the remaining energy was not sufficient to initiate shearing in the sliding lug bolts.

Future work will include a second test using the same retrofitted CEM locomotive and an M1 cab car. For this test, the impact speed will be increased to ensure activation of all of the CEM elements. The final test in this program will be a full-scale train-to-train test to evaluate the performance of the retrofit CEM components in a high-energy collision scenario.

1. Introduction

In January 2019, Transportation Technology Center, Inc. (TTCI) conducted an impact test between a conventional passenger locomotive and a passenger locomotive equipped with crash energy management (CEM) components. This test characterized the combined performance of all the CEM components that had been installed.

This research program integrated three CEM components onto a locomotive to demonstrate that they 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.

1.2 Objectives

This test was intended to demonstrate the combined functionality of the PBC and the DAC as the CEM system. Volpe and TTCI 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.

1.3 Overall Approach

1.3.1 Stationary Locomotive

The F40PH-2CAT locomotive is a four-axle diesel-electric locomotive intended for use in passenger service. This test used F40PH-2CAT Locomotive 4117 as the stationary vehicle (Figure 1). The weight of this locomotive was measured to be 257,325 lbs.

Figure 1. F40 Locomotive 4117

1.3.2 Mobile Locomotive

The F40PH locomotive is a four-axle diesel-electric locomotive intended for use in passenger service. This test used F40 Locomotive 234 as the impacting vehicle (Figure 2). The weight of this locomotive was measured to be 232,000 lbs. This locomotive was retrofitted with the CEM system.

Figure 2. F40PH Locomotive 234

1.3.3 Test Setup

The impact test was performed on January 23, 2019, at the Transportation Technology Center (TTC) in Pueblo, Colorado. The testing was performed by positioning the mobile locomotive uphill from the stationary locomotive and allowing the mobile locomotive to roll into the stationary locomotive. The release position of the mobile locomotive was determined through speed trials and adjusted shortly before the release to achieve the desired impact speed. The couplers of both locomotives were opened and aligned to allow coupling to occur upon impact.

The stationary locomotive's air brakes were applied, and the hand brake was secured before the impact. A string of loaded hopper cars was placed approximately 200 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 mobile locomotive to determine the optimum release location for the desired impact speed. Data from the speed runs were used in calculations, accounting for wind speed and direction, in order to determine a more precise release location for the desired target speed.

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 1 of this report includes the introduction, a description of the objectives and scope of the report, as well as a description of the 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.
- Appendix B contains the test data.

2. Test Instrumentation

The test configuration and instrumentation were all 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	22
Strain gages	46
Total Data Channels	111
High Definition Video	5
High-Speed Video	6

2.1 Definition of Coordinate Axes

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

2.2 Mobile Locomotive Accelerometers

Tri-axial accelerometers were placed at the center and at the two ends along the carbody center line. 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 push-back coupler 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. Table 2 summarizes all accelerometers on Locomotive 234. Figure 3 shows the locations of the accelerometers on the locomotive.

Table 2. Mobile Locomotive Accelerometers Summary

Name	Range	Location
AMLE_X	400g	Moving Locomotive, lead end, center – longitudinal
AMLE_Y	200g	Moving Locomotive, lead end, center – lateral
AMLE_Z	200g	Moving Locomotive, lead end, center – vertical
AMUC_X	200g	Moving Locomotive, underframe center – longitudinal
AMUC_Y	200g	Moving Locomotive, underframe center – lateral
AMUC_Z	200g	Moving Locomotive, underframe center – vertical
AMUCR_X	200g	Moving Locomotive, underframe center right – longitudinal
AMUCR_Z	200g	Moving Locomotive, underframe center right – vertical
AMUCL_X	200g	Moving Locomotive, underframe center left – longitudinal
AMUCL_Z	200g	Moving Locomotive, underframe center left – vertical
AMTEC_X	200g	Moving Locomotive, trailing end, center – longitudinal
AMTEC_Y	200g	Moving Locomotive, trailing end, center – lateral
AMTEC_Z	200g	Moving Locomotive, trailing end, center – vertical
AMLT_Z	400g	Moving Locomotive, lead truck – vertical
AMLTR_X	400g	Moving Locomotive, lead truck, right – longitudinal
AMLTL_X	400g	Moving Locomotive, lead truck, left – longitudinal
AMTT_Z	400g	Moving Locomotive, trailing truck – vertical
AMTTR_X	400g	Moving Locomotive, trailing truck, right – longitudinal
AMLTL_X	400g	Moving Locomotive, trailing truck, left – longitudinal
AMCR_X	5000g	Moving Locomotive coupler, right – longitudinal
AMCL_X	5000g	Moving Locomotive coupler, left – longitudinal
AMS_X	5000g	Moving Locomotive sliding lug – longitudinal

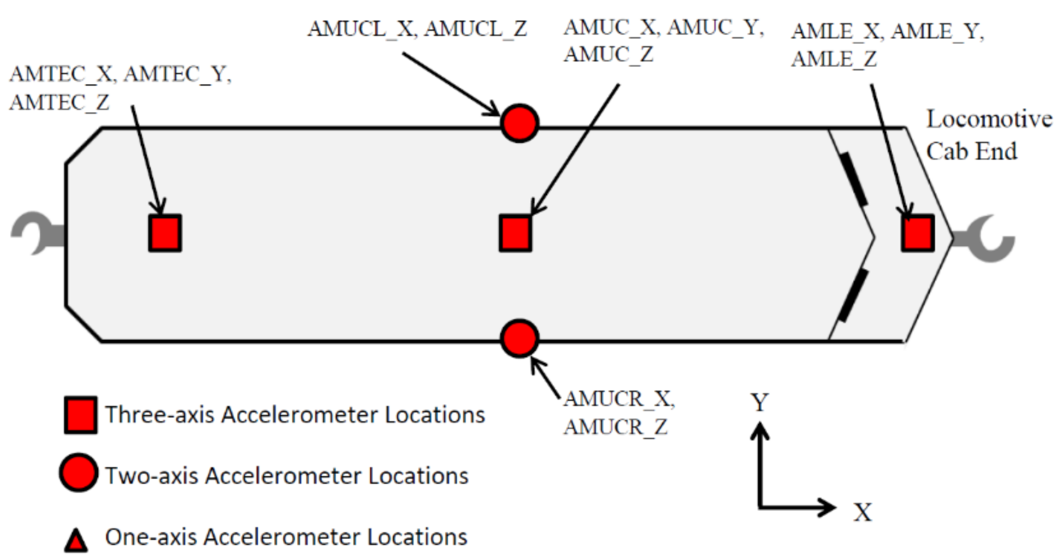

Figure 3. Accelerometer Locations on Mobile Locomotive

2.3 Mobile Locomotive String Potentiometers

In addition to accelerometers, Locomotive 234 was instrumented with 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. Figure 4 to Figure 10 show the locations of the string potentiometers on the locomotive.

Table 3. Mobile Locomotive String Potentiometers Summary

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

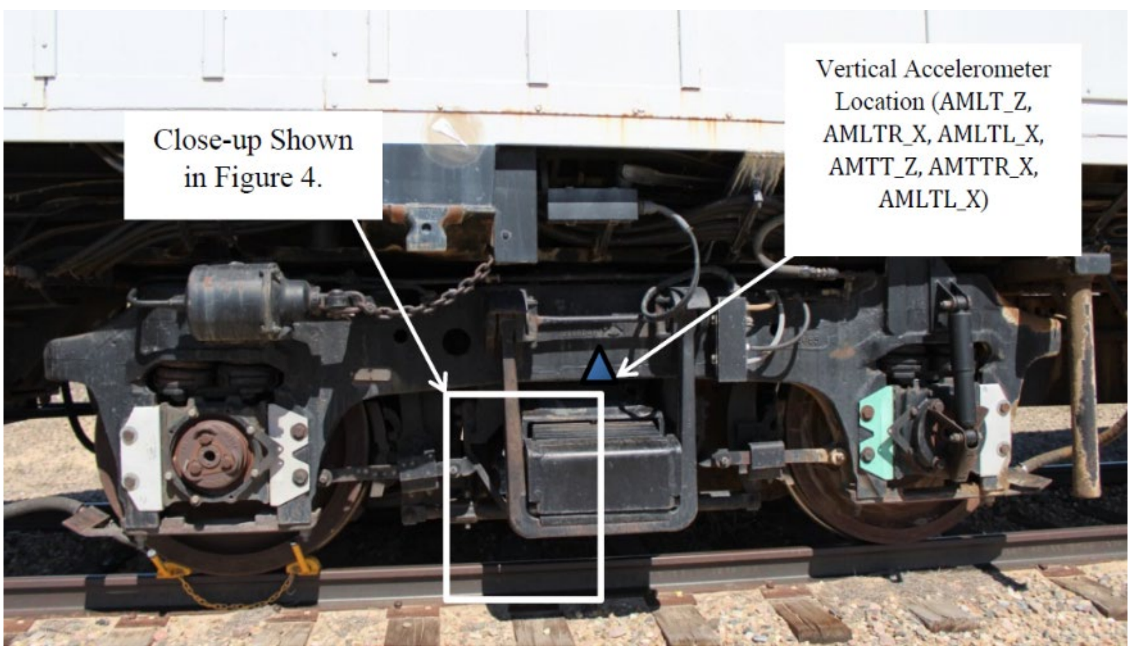

Figure 4. Locations of Accelerometers on Mobile Locomotive Truck

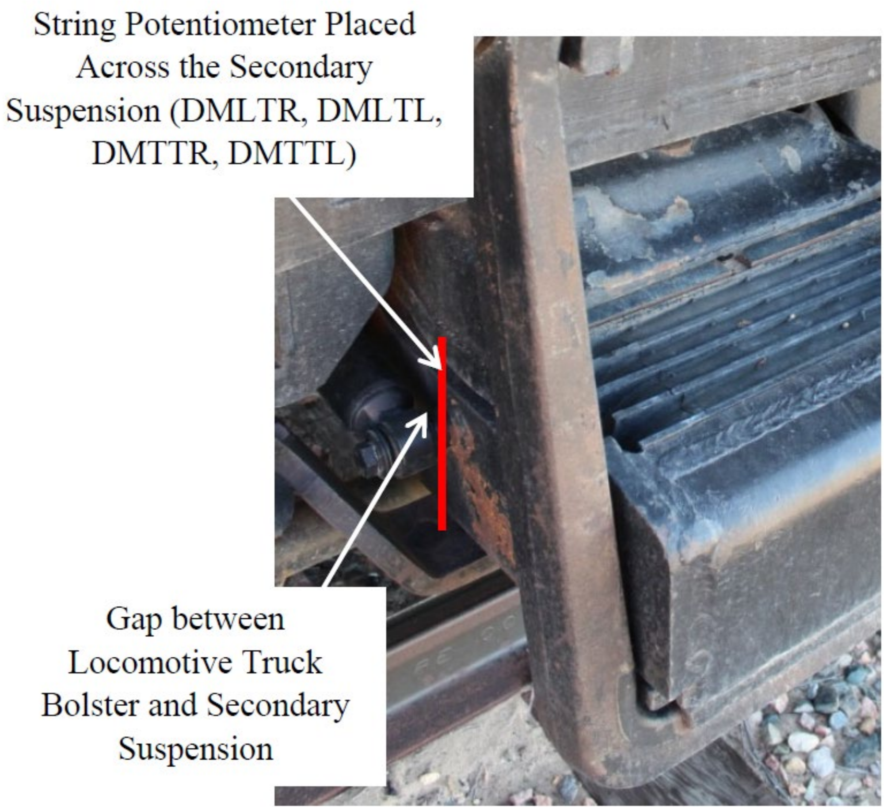

Figure 5. Mobile Locomotive Truck Secondary Suspension String Potentiometers

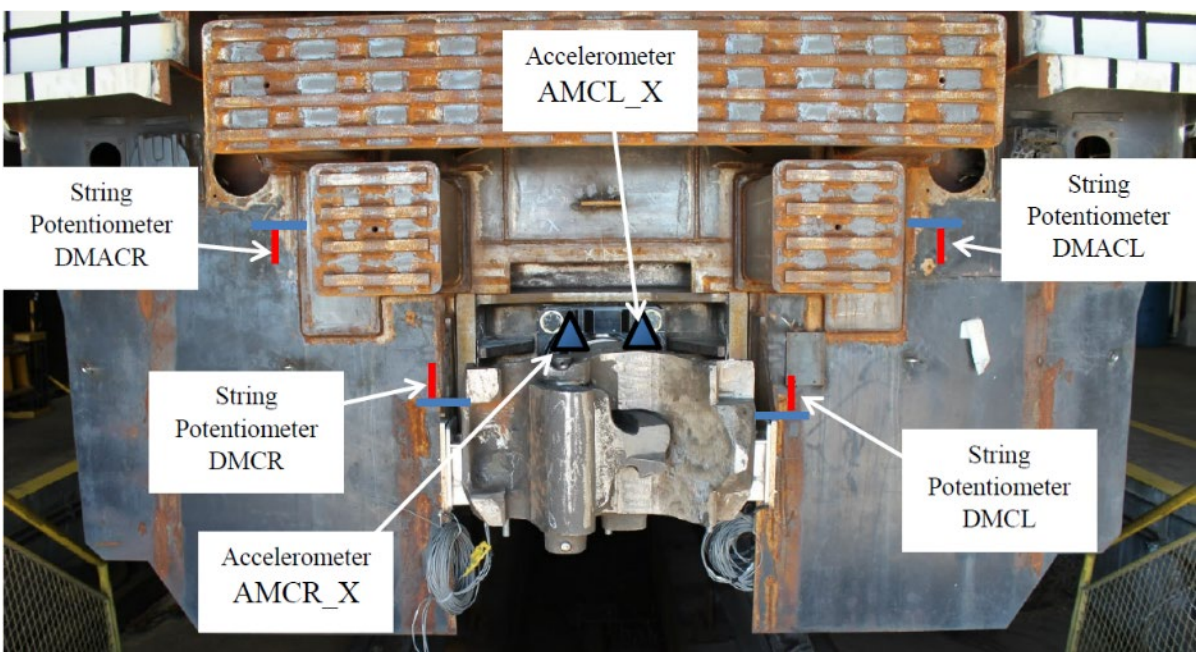

Figure 6. Mobile Locomotive Coupler Instrumentation

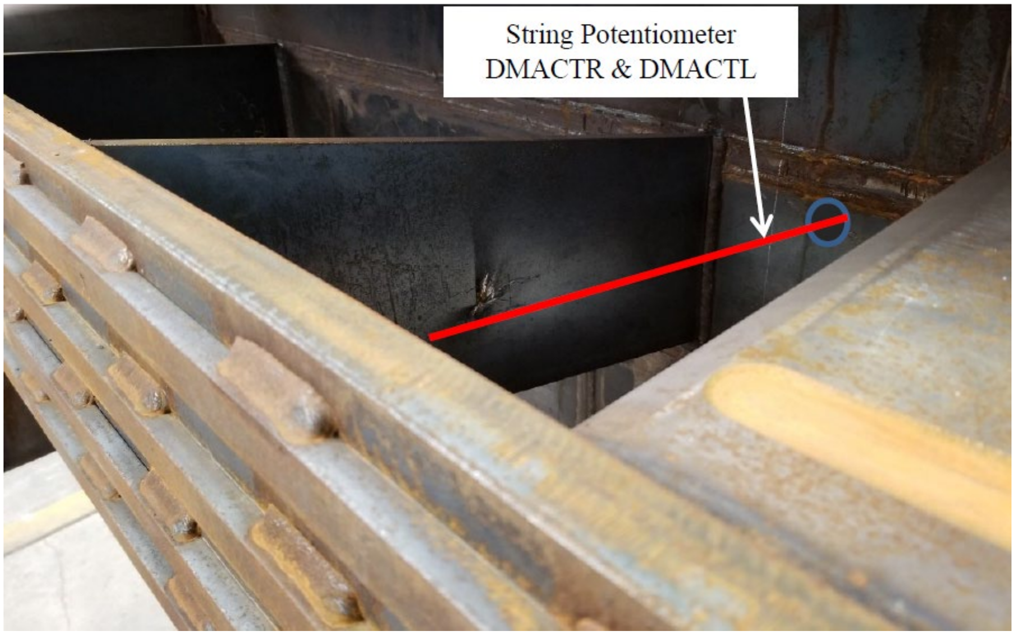

Figure 7. Mobile Locomotive Top Anti-climber String Potentiometers

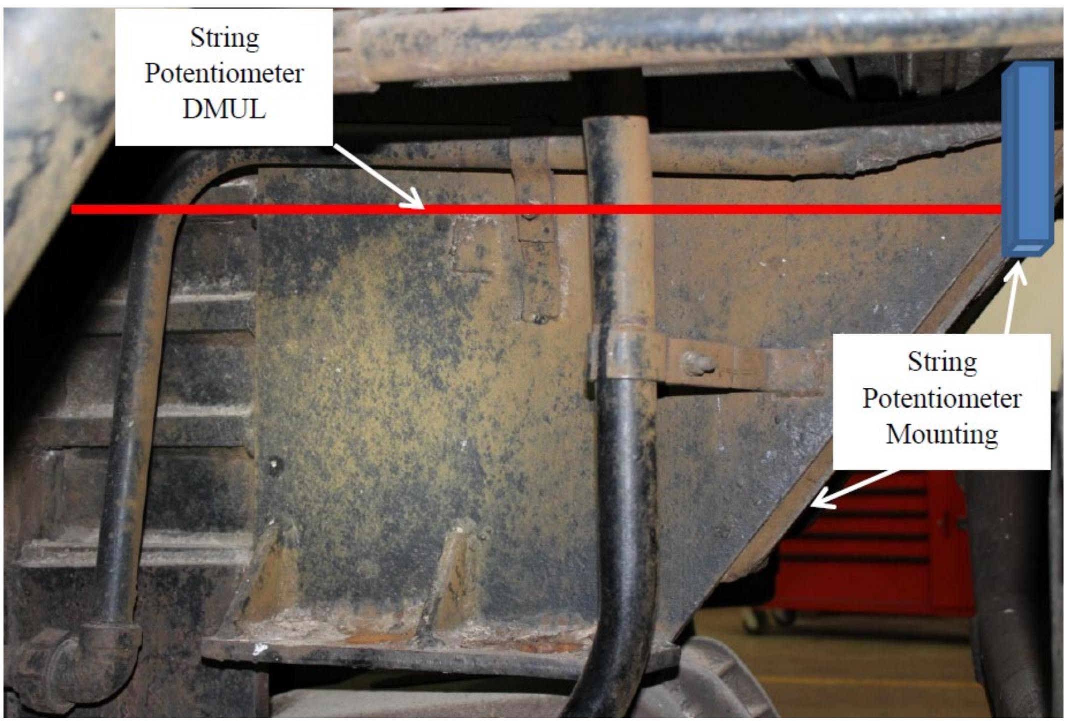

Figure 8. Mobile Locomotive Underframe String Potentiometers

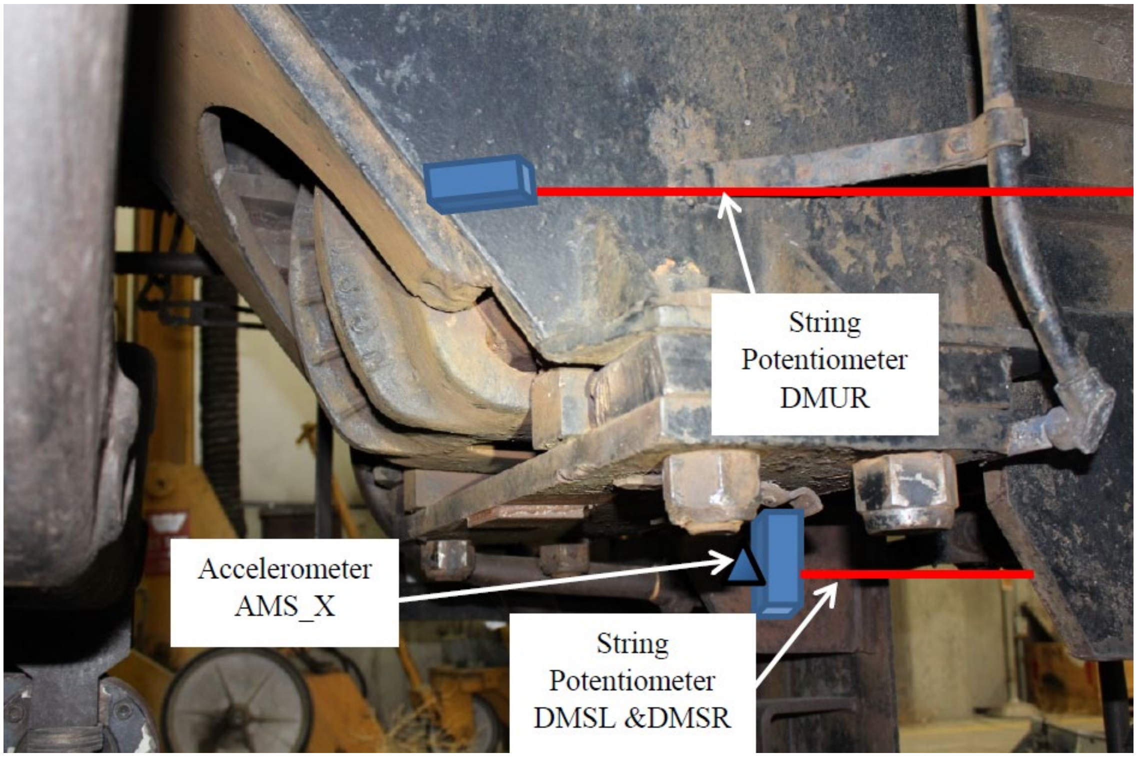

Figure 9. Right Side Mobile Locomotive String Potentiometers

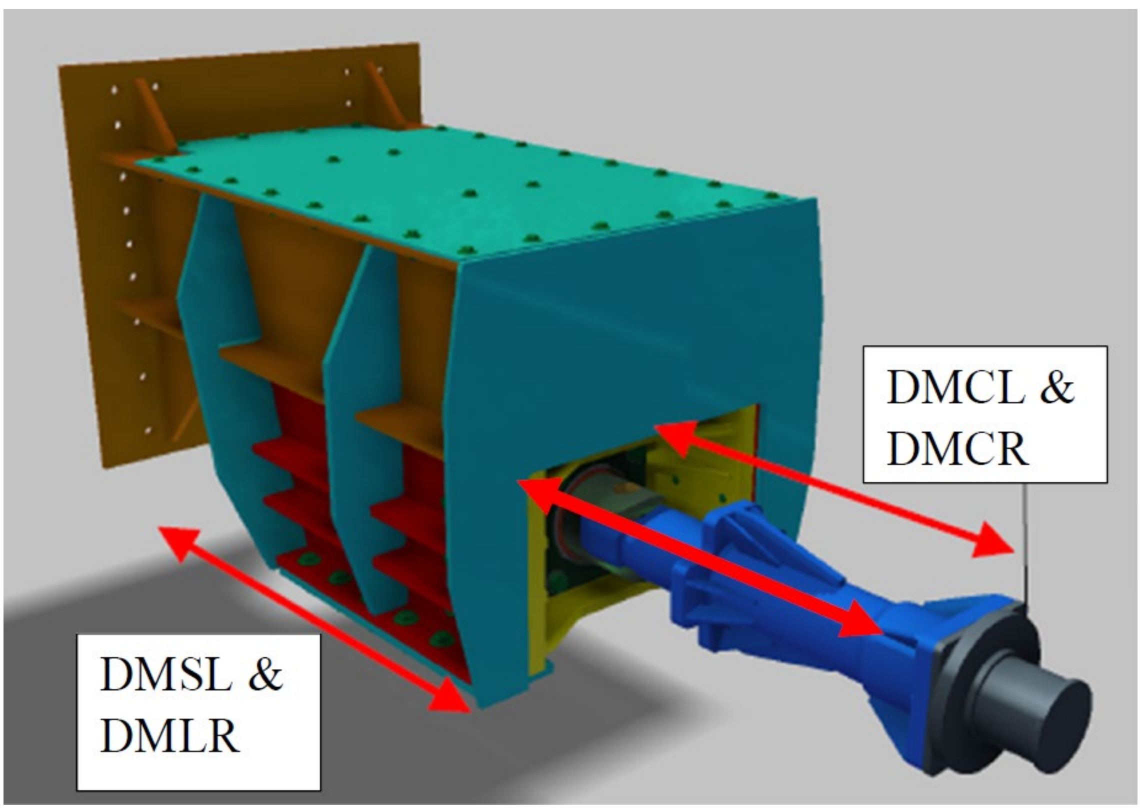

Figure 10. Mobile Locomotive Coupler String Potentiometers

2.4 Mobile 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. F40 Locomotive Strain Gage Summary

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

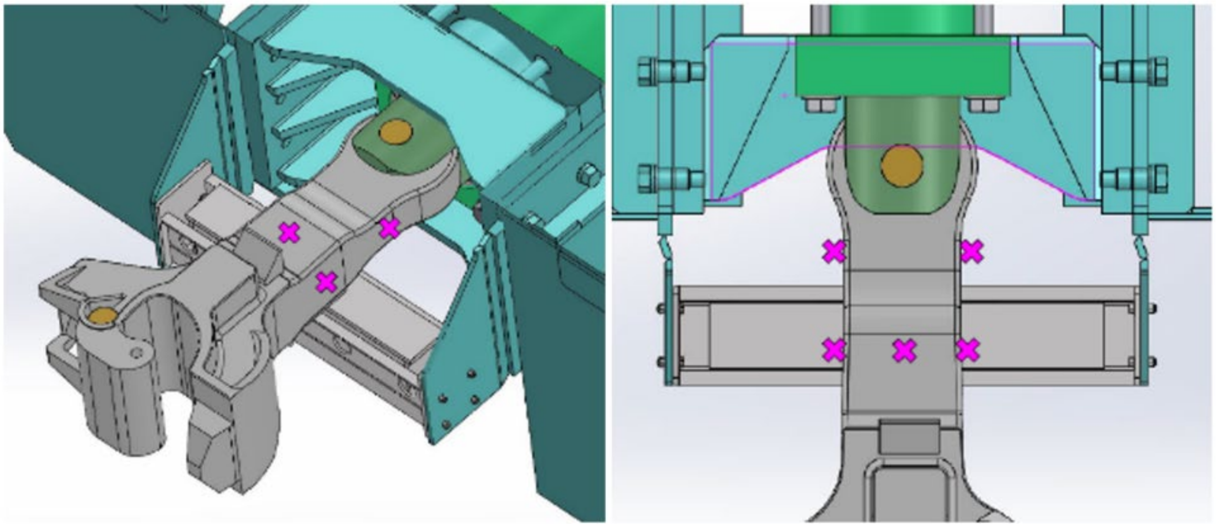

Figure 11. Strain Gage Locations on Mobile Locomotive Coupler Shank

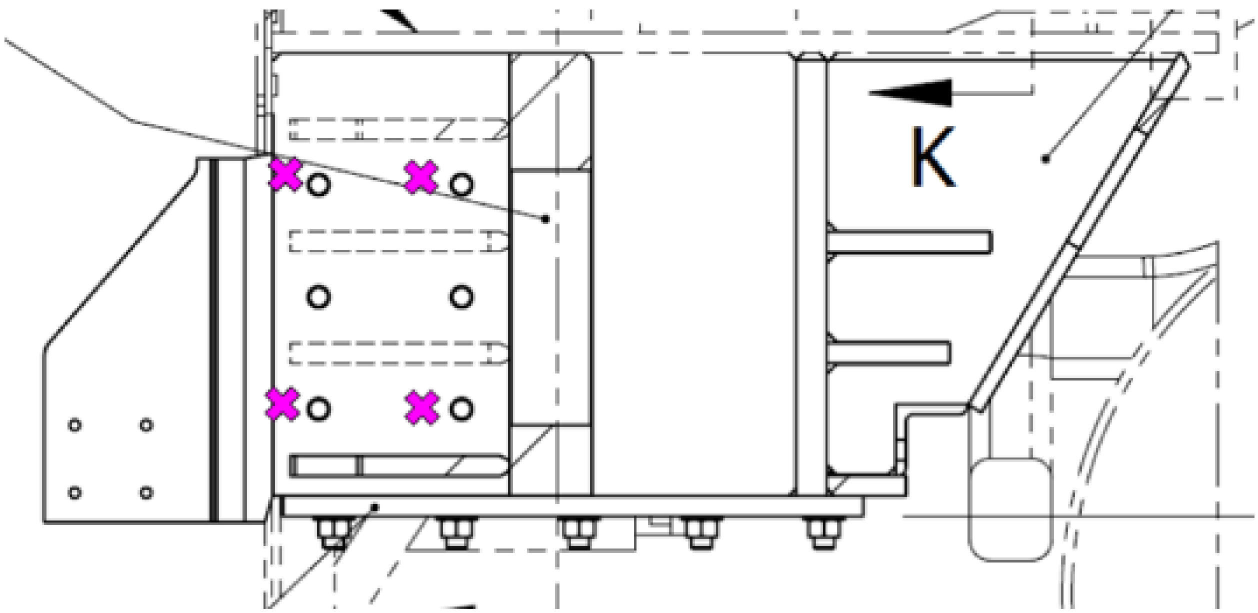

Figure 12. Strain Gage Locations on Mobile Locomotive Sliding Lug

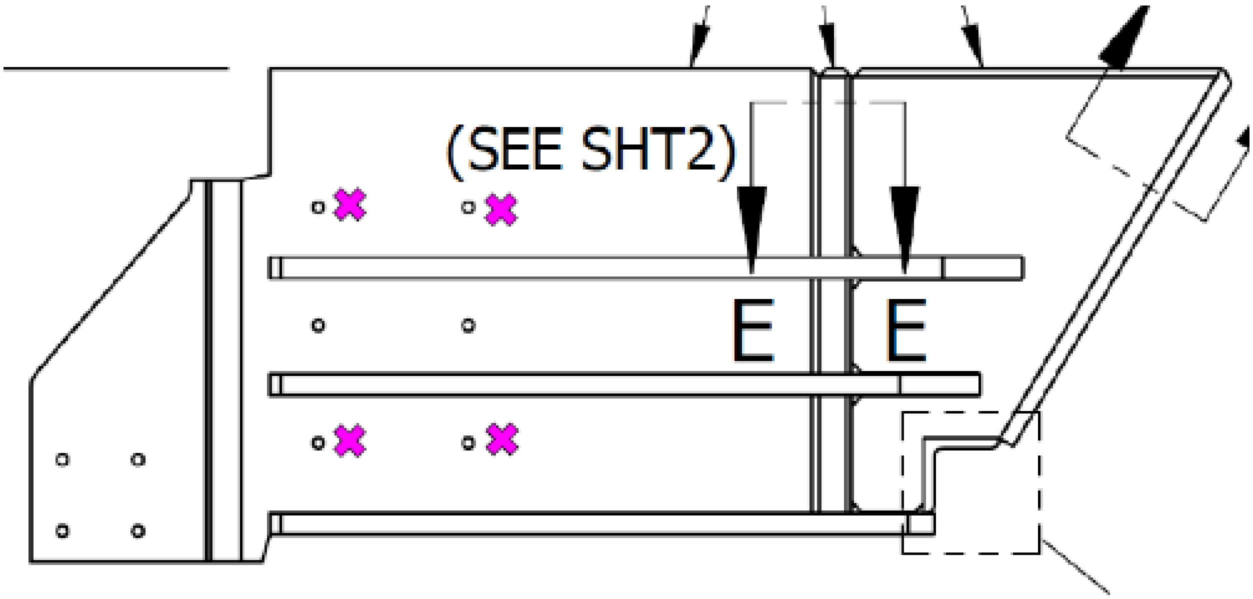

Figure 13. Strain Gage Locations on Mobile Locomotive Draft Pocket

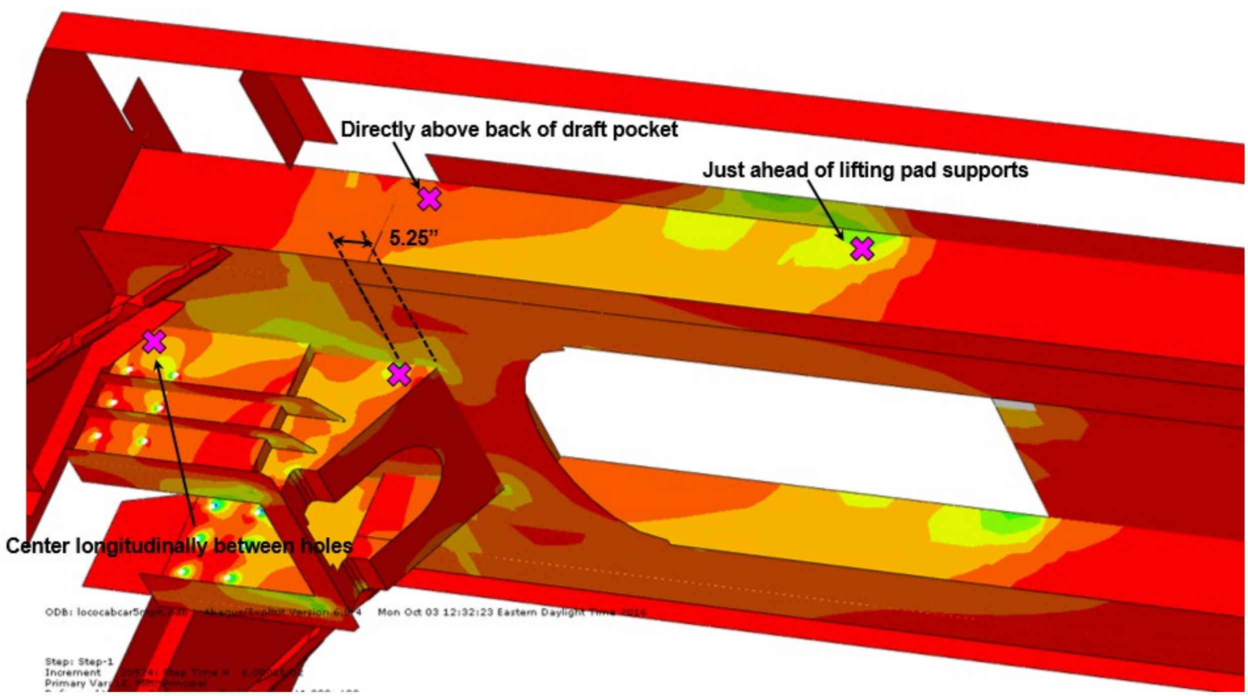

Figure 14. Strain Gage Locations on Mobile Locomotive Draft Pocket and Center Sill

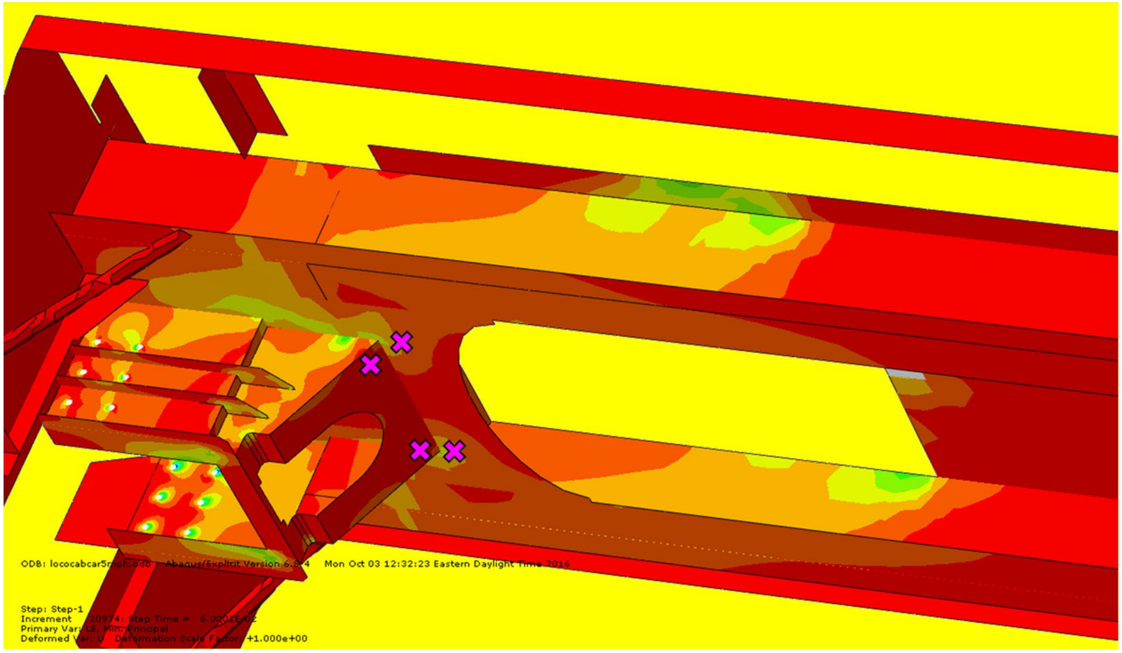

Figure 15. Strain Gage Locations on Cross-Plate and Draft Gear Pocket Back Plate

2.5 Locomotive Speed Sensors

Multiple speed sensors accurately measured the impact speed of the mobile F40 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 Stationary Locomotive Accelerometers

Tri-axial accelerometers were placed at the two ends and the center along the locomotive centerline. The locomotive had longitudinal and vertical accelerometers placed on the left and right sides of its underframe at its center. Each locomotive truck was equipped with a vertical accelerometer and two longitudinal accelerometers (right and left). The typical scale factor calibration error for the used accelerometers is 2 percent. Table 5 summarizes all accelerometers on Locomotive 4117. Figure 16 shows locations of the accelerometers.

Table 5. Stationary Locomotive Accelerometers

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, 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
ASTTR_X	400g	Stationary Vehicle, trailing truck, right - longitudinal
ASTTL_X	400g	Stationary Vehicle, trailing truck, left – longitudinal
ASCR_X	5000g	Stationary Vehicle coupler, right
ASCL_X	5000g	Stationary Vehicle coupler, left

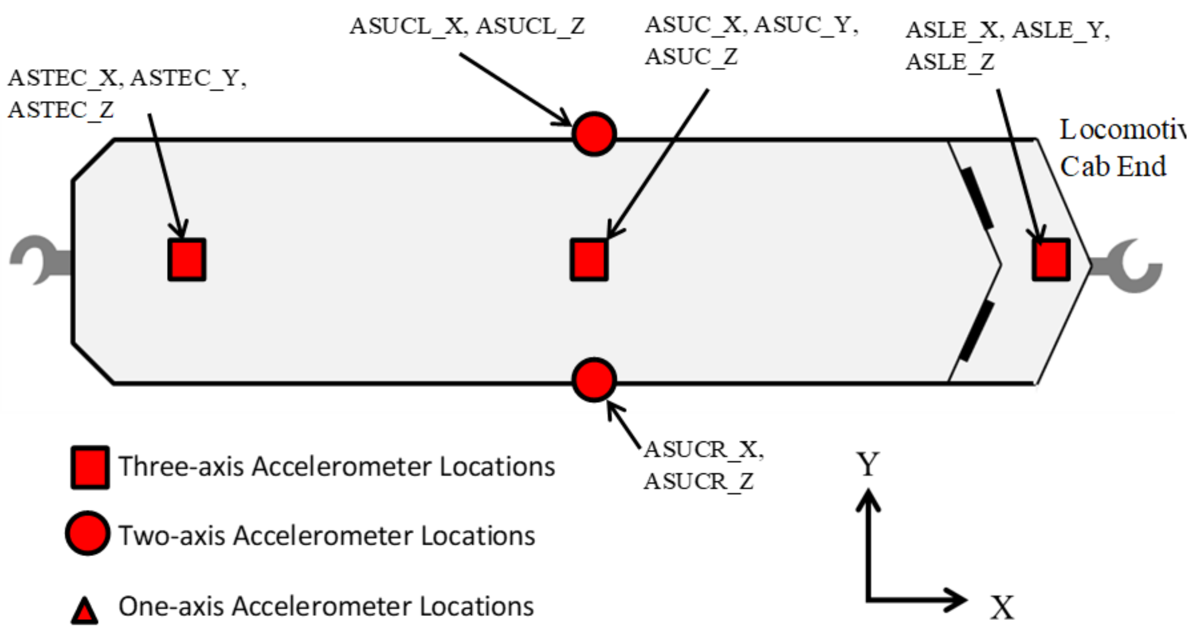

Figure 16. Accelerometer Locations on Stationary Locomotive

2.7 Stationary Locomotive String Potentiometers

In addition to accelerometers, Locomotive 4117 was instrumented with 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. An additional two string potentiometers were fitted to the front of the locomotive underframe to measure longitudinal displacements. Table 6 summarizes all string potentiometers on the locomotive. Figure 17 through Figure 21 show locations of the string potentiometers.

Table 6. Stationary Locomotive Instrumentation – String Potentiometers

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 left - longitudinal
DSUR	+5/-45 inch	Stationary Vehicle underframe, front right - longitudinal
DSCL	+20/-30 inch	Stationary Vehicle coupler – longitudinal left
DSCR	+20/-30 inch	Stationary Vehicle coupler – longitudinal right

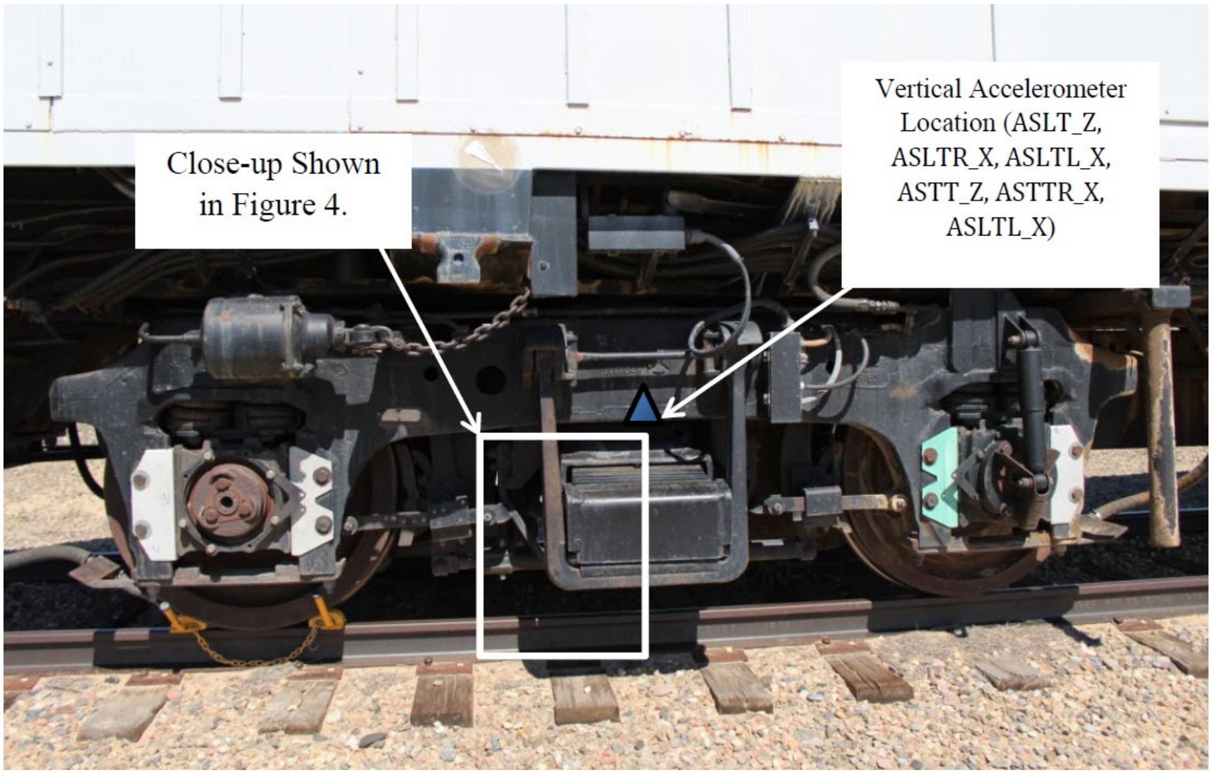

Figure 17. Accelerometers on Stationary Locomotive Truck

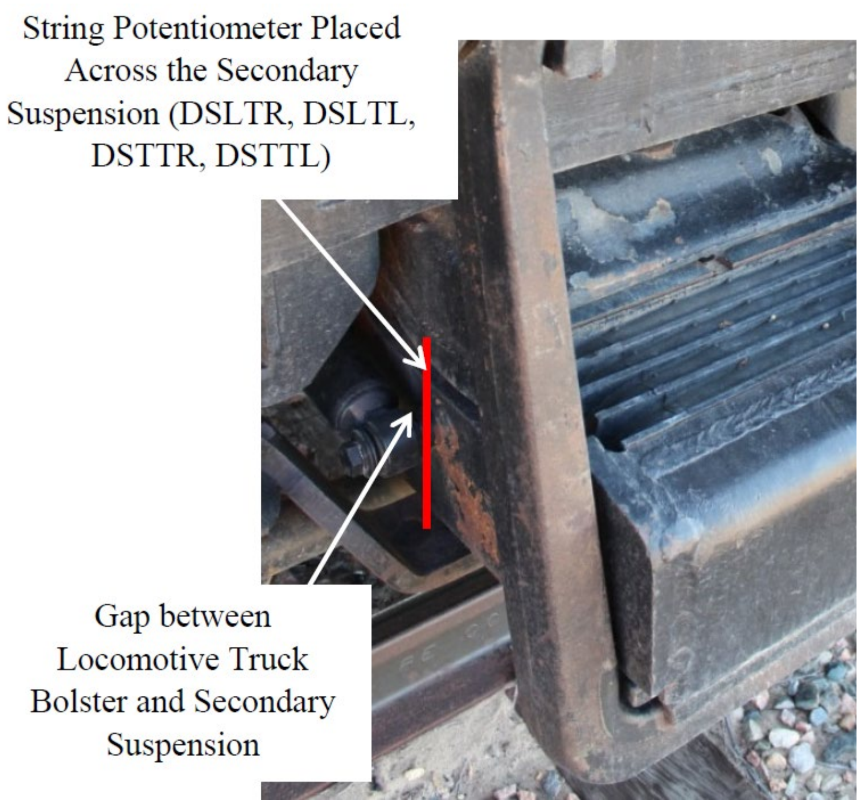

Figure 18. String Potentiometers on Stationary Locomotive Truck

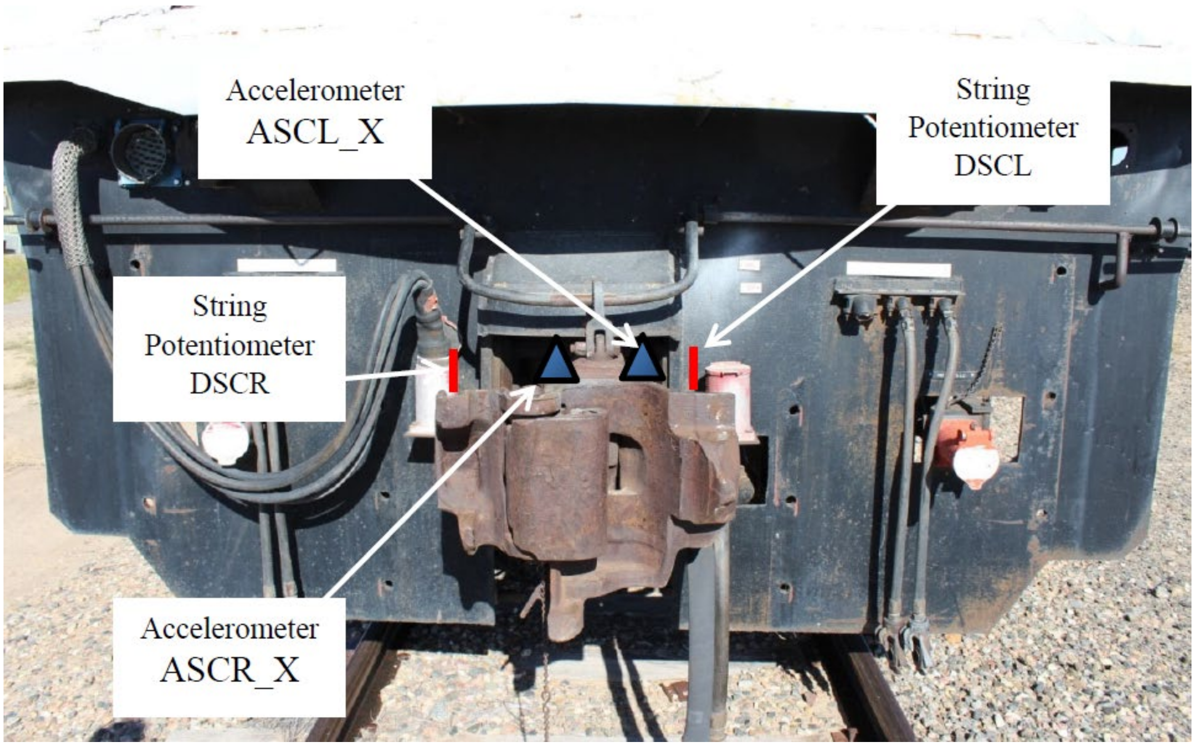

Figure 19. Stationary Locomotive Coupler Instrumentation

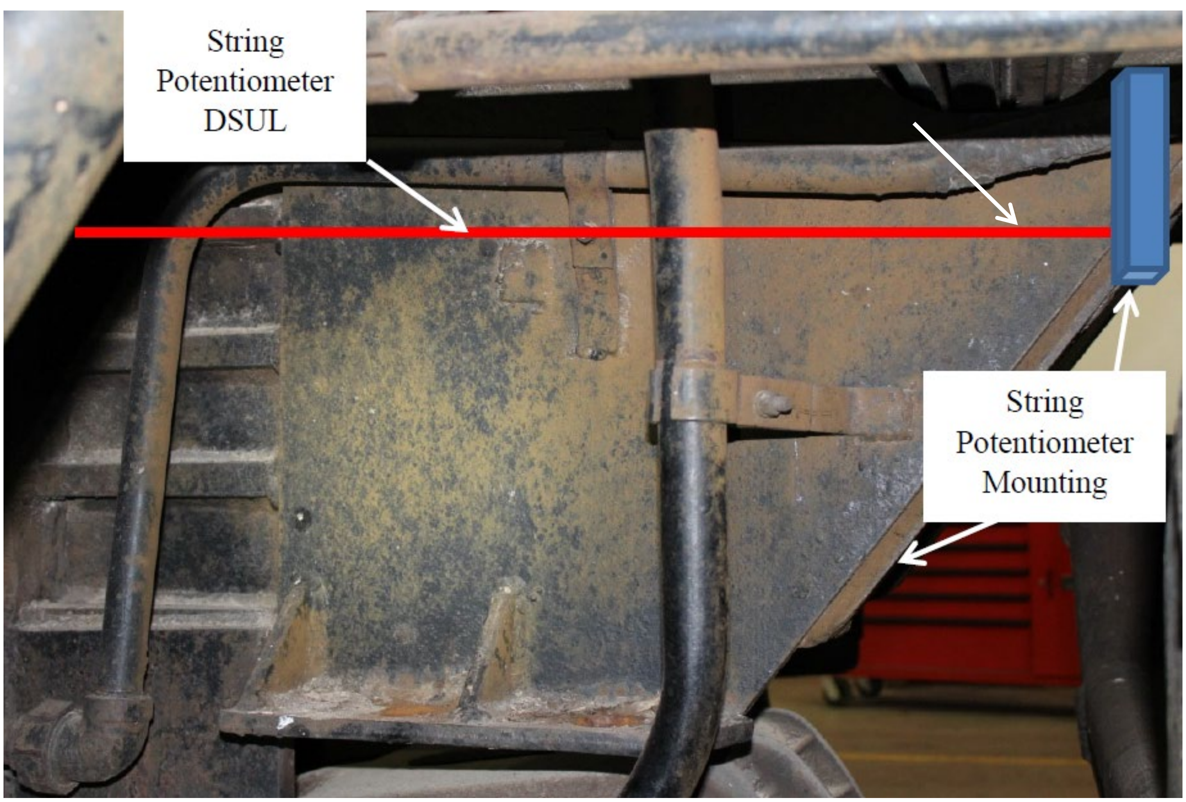

Figure 20. Stationary Locomotive Underframe String Potentiometer Left

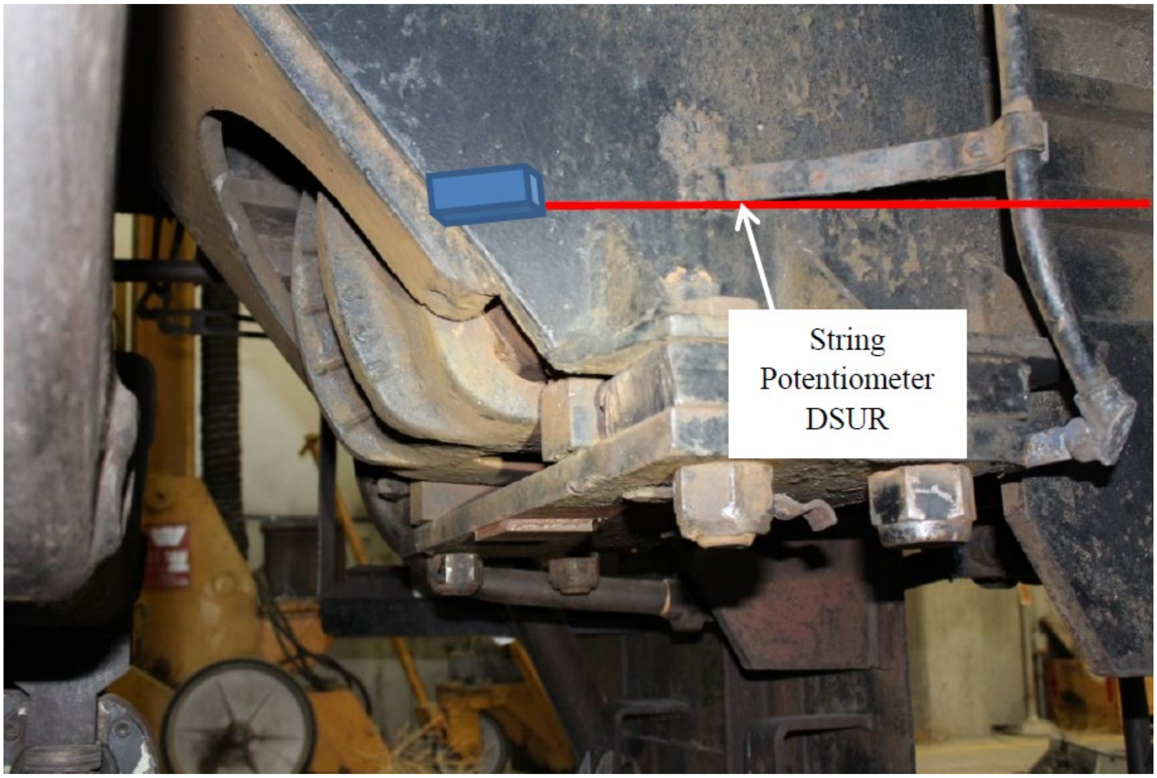

Figure 21. Stationary Locomotive Underframe String Potentiometer Right

2.8 Stationary Locomotive Strain Gages

Locomotive 4117 was instrumented with five strain gages on the coupler as well as eight strain gages on the draft pocket and center sill. Table 7 summarizes all strain gages on Locomotive 4117. Figure 22 and Figure 23 show locations of the strain gages.

Table 7. Stationary Locomotive Instrumentation – Strain Gages

Name	Orientation	Location
SSCST	Longitudinal	Stationary Vehicle, coupler shank, above coupler carrier, top
SSCSR	Longitudinal	Stationary Vehicle, coupler shank, above coupler carrier, right
SSCRL	Longitudinal	Stationary Vehicle, coupler shank, above coupler carrier, left
SSCPR	Longitudinal	Stationary Vehicle Locomotive, coupler shank at pin, right
SSCPL	Longitudinal	Stationary Vehicle, coupler shank at pin, left
SSCFR	Longitudinal	Stationary Vehicle, center sill, right front
SSCRR	Longitudinal	Stationary Vehicle, center sill, right rear (ahead of jacking pad)
SSCLF	Longitudinal	Stationary Vehicle, center sill, left front
SSCLR	Longitudinal	Stationary Vehicle, center sill, left rear (behind jacking pad)
SSXPR	Longitudinal	Stationary Vehicle, Cross plate, right
SSXPL	Longitudinal	Stationary Vehicle, Cross plate, left
SSDAR	Longitudinal	Stationary Vehicle, Draft pocket back plate, right
SSDAL	Longitudinal	Stationary Vehicle, Draft pocket back plate, left

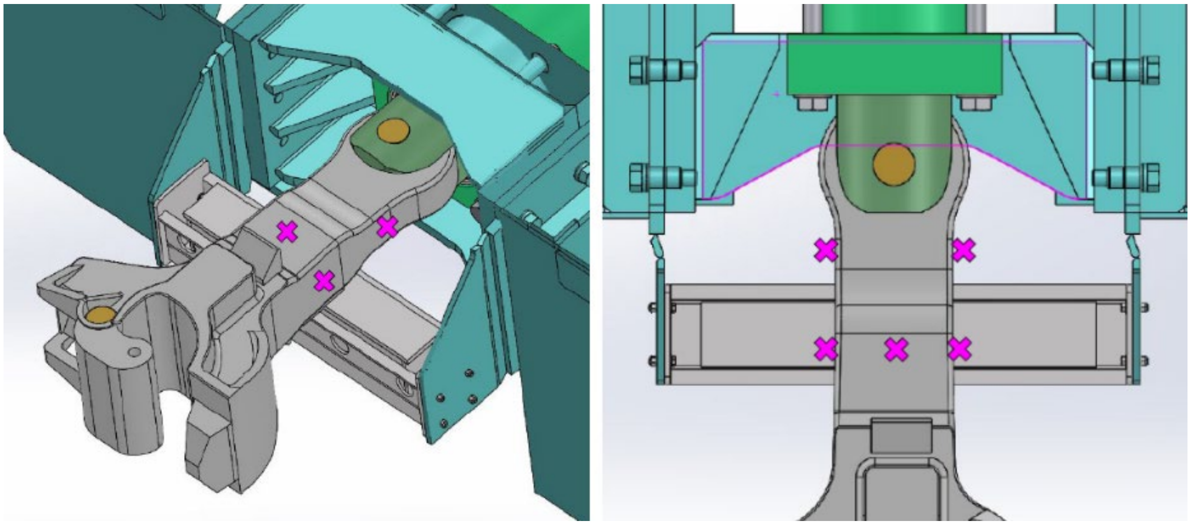

Figure 22. Strain Gage Locations on Stationary Locomotive Coupler

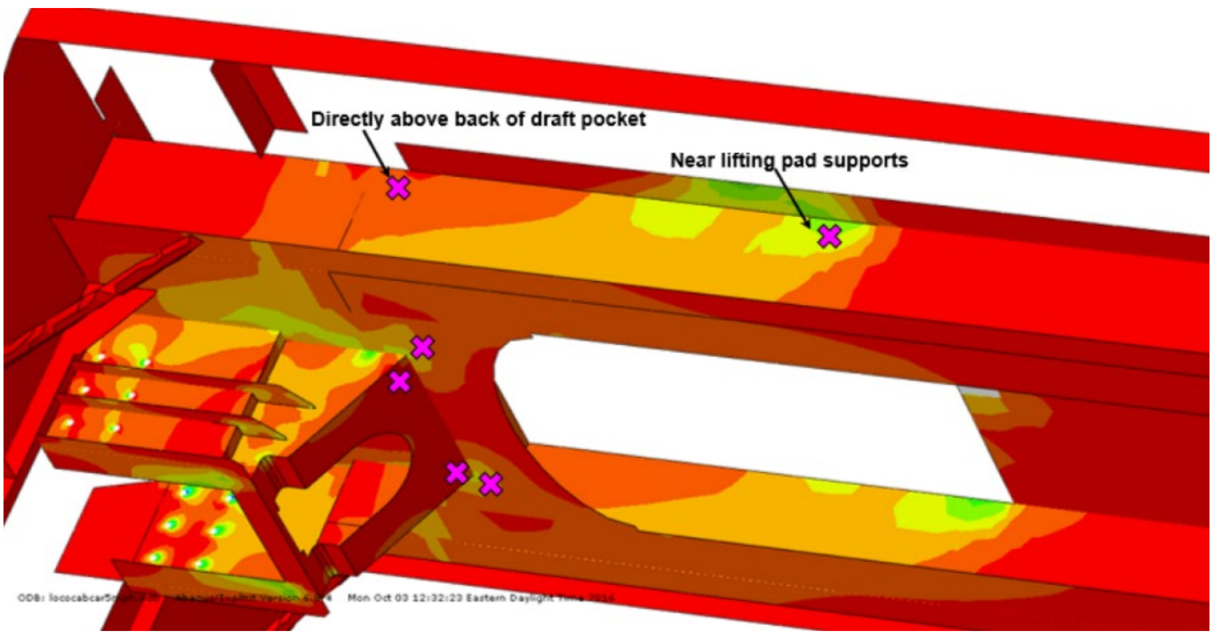

Figure 23. Strain Gage Locations on Stationary Locomotive Center Sill and Draft Pocket

2.9 Real-Time and High-Speed Photography

Six high-speed and five real-time, high-definition video cameras documented the impact event. Figures 24 and 25 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 100 g. Final alignment and sighting of the cameras was done when the locomotives were positioned at the impact point prior to the start of the test. Two flashes were installed on both locomotives, 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 both vehicles.

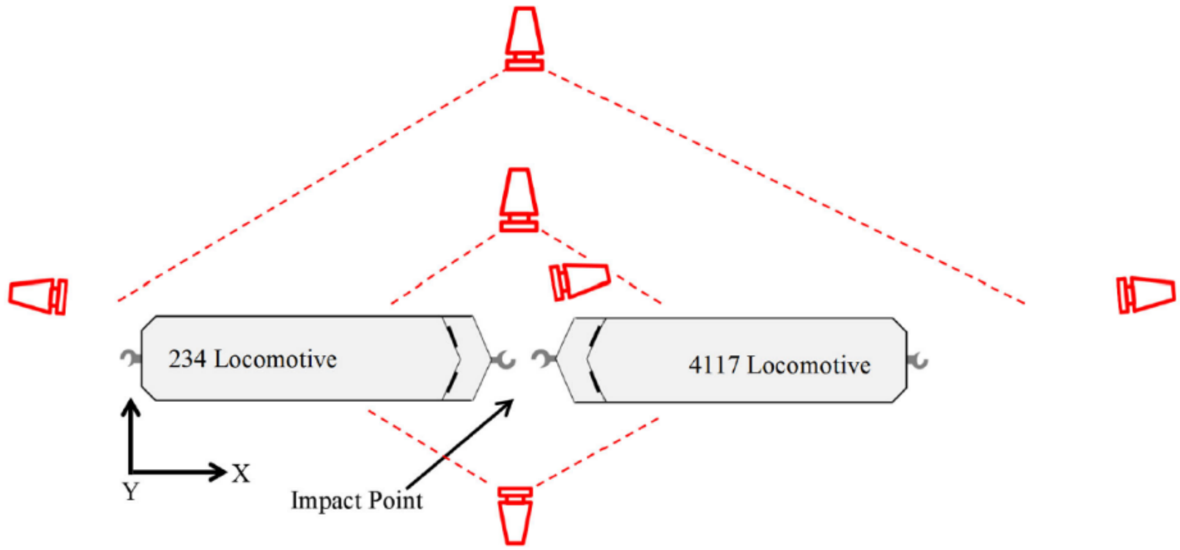

Figure 24. High-Speed Camera Locations

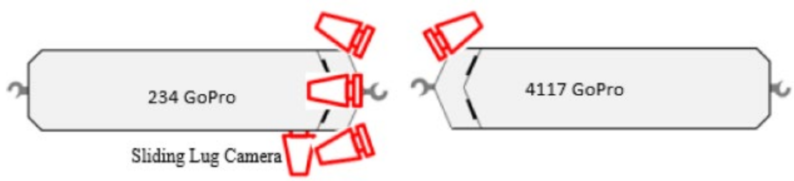

Figure 25. High Definition Camera Locations

2.10 Data Acquisition

A set of eight-channel, battery-powered, onboard data acquisition systems recorded data from instrumentation mounted on both the locomotives. 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 [1]. 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. Each DataBRICK3 was ruggedized for shock loading up to at least 100 g. Onboard battery power was provided by GMH Engineering, comprised of 1.7-amp-hour, 14.4-volt NiCad packs. Tapeswitch, model 1201-131-A tape switches, provided event initial contact time.

Software in the DataBRICK3s was used to determine zero levels and calibration factors rather than relying on set gains and expecting no zero drift. The DataBRICK3s 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 January 23, 2019 impact test between an F40 locomotive equipped with CEM components and a conventional F40 locomotive. The target impact speed was 21 mph. The stationary locomotive's hand brakes were applied. Ambient conditions are summarized in Table 8.

Table 8. Summary of Ambient Conditions

Wind Speed	Gust speed	Wind Direction	Temperature
5 mph	9 mph	SE	39°F

3.1 Test Details

The actual impact speed for the test is shown in Table 9, as are the approximate impact forces and energy levels based on accelerometer data. The last column reports the travel distance of both locomotives from the impact point to the point where both vehicles came to a complete stop.

Table 9. Summary of Test Results

Target impact speed	Actual impact speed	Approximate impact force	Approximate impact energy	Travel distance after impact
21 mph	19.3 mph	1,500,000 lbs.	2,900,000 ft.-lbs.	71 ft.

3.2 Measured Data

The data collected were processed for zero offset corrections and filtering. To ensure that 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 is independent of the pre-test offset adjustment made by the data acquisition system.

The 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 contain plots of the time histories of the filtered data from all transducers for the test.

3.2.1 Accelerations

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

Figure 26 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 an impact, the locomotives are accelerated in the negative X direction based on the established coordinate system. During the impact test, the locomotives failed to couple.

All acceleration data are reported in Appendix B.

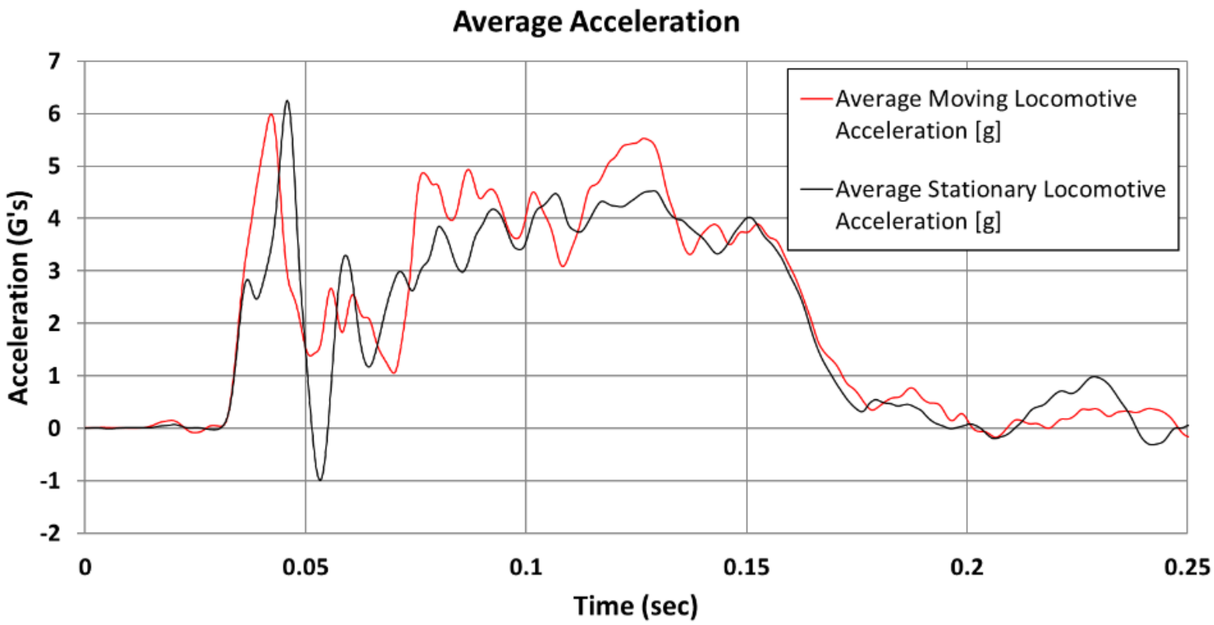

Figure 26. Longitudinal Average Acceleration

3.2.2 Displacements

Figure 27 shows the displacement of the locomotive couplers. DMCL_X and DMCR_X represent the left and right side displacements on the moving locomotive's coupler, respectively. DSCL_X and DSCR_X represent the displacements of the stationary locomotive'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 moving and stationary locomotives. The severity of the impact caused all the brackets which attached the strings to the couplers to detach, resulting in flat displacement readings after approximately 0.08 second.

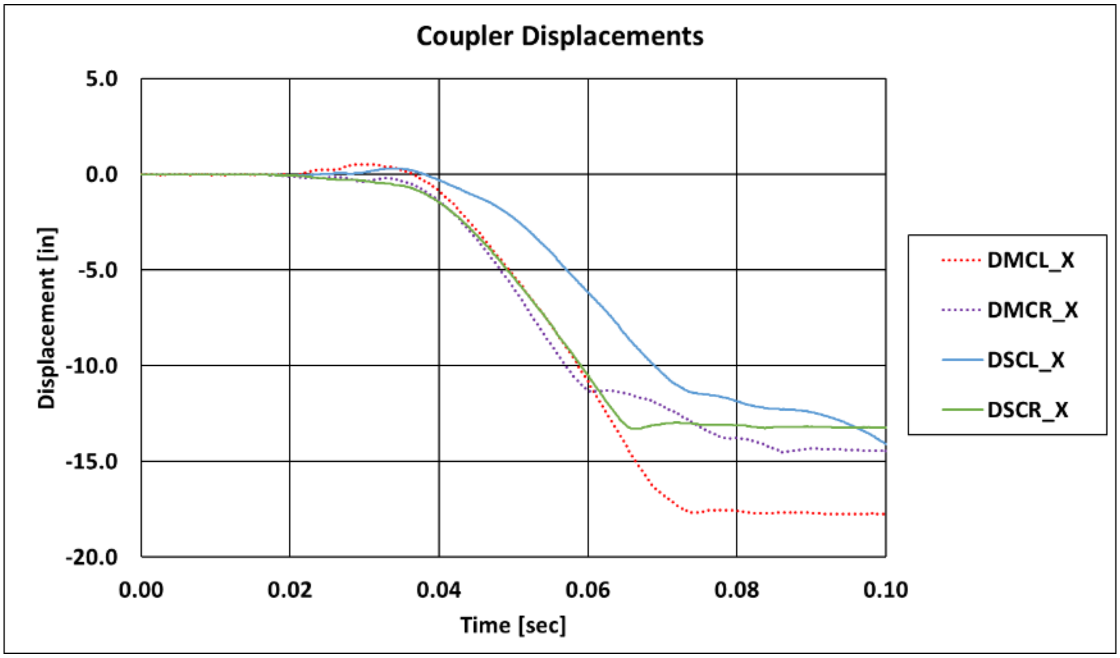

Figure 27. Coupler Displacements

Figure 28 shows measured displacements of all anti-climbers. The top anti-climber was engaged at the impact and deformed. The measured displacements (DMACTR and DMACTL) include bending of the front plate and crush displacements of the tubes. The deformation on both sides was fairly symmetrical with slightly over 1 inch of difference. Two bottom anti-climbers were not engaged; thus, their displacements are zero.

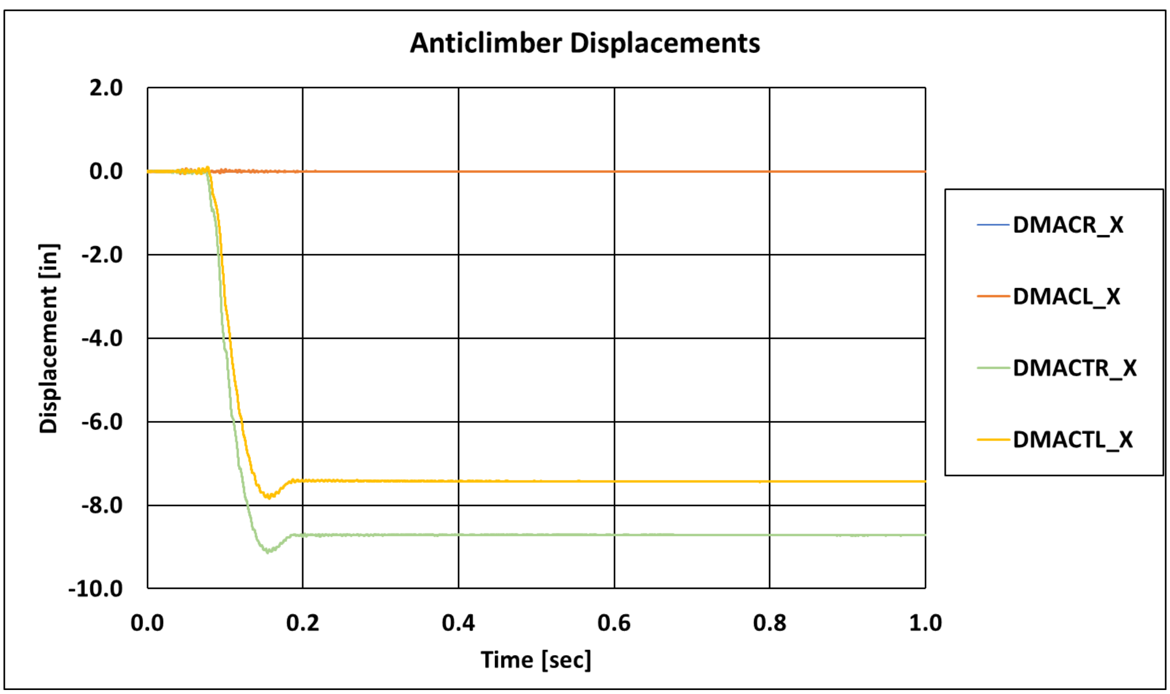

Figure 28. Anti-climber Displacements

The sliding lug bolts were not sheared; therefore, there was no displacement. Measured displacements of the sliding lug by one of the channels (DMSR) was due to impact by the coupler carrier that was detached early in the impact. All measured displacements have been plotted and included in Appendix B.

3.2.3 Strains

The moving locomotive was equipped with 33 strain gages, and another 13 strain gages were on the stationary locomotive. Strain gage data from both the moving and stationary locomotives are grouped according to their positions in the vehicles. Figures 29 to 37 show the strain gage data for both locomotives. During the impact, the cables connected to several strain gages were hit by debris or severed, resulting in a loss of useful data after approximately 70 milliseconds. This effect was particularly noticeable on the moving locomotive's coupler and sliding lug strain gages, but other strain gages showed good agreement. Plots below show data from the first 250 milliseconds of impact, which covers the duration of the initial impact.

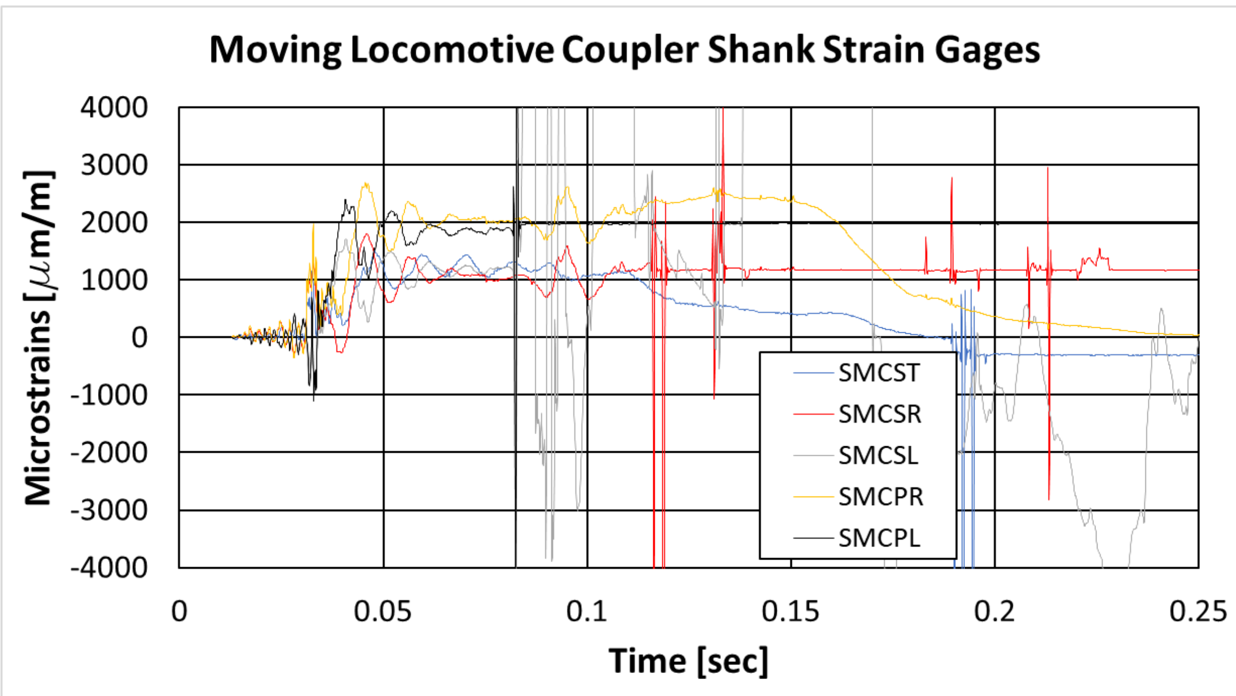

Figure 29. Mobile Locomotive Coupler Shank Strain Results

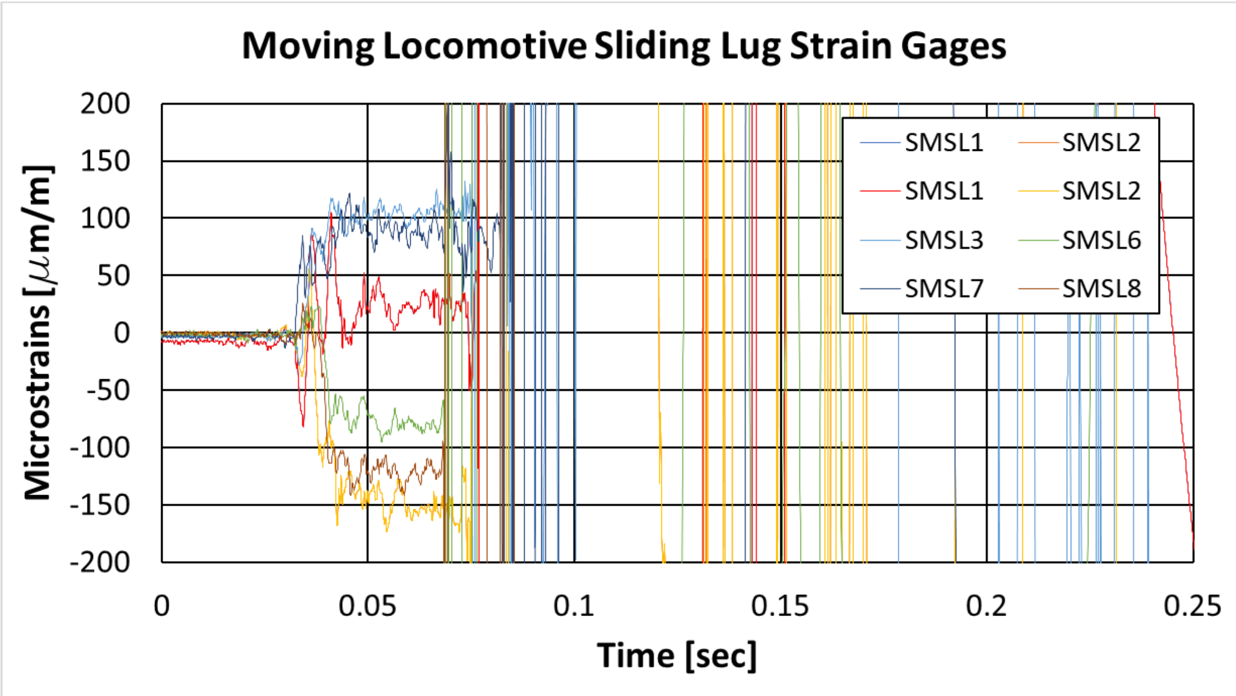

Figure 30. Mobile Locomotive Sliding Lug Strain Results

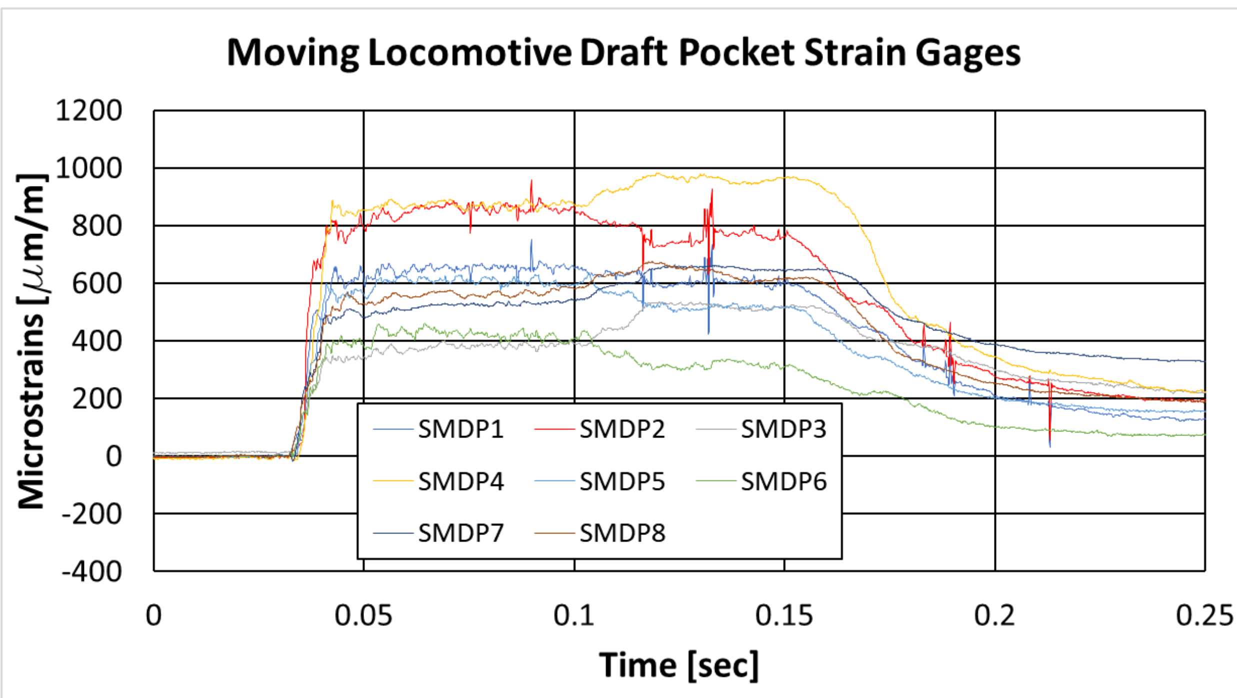

Figure 31. Mobile Locomotive Draft Pocket Strain Results

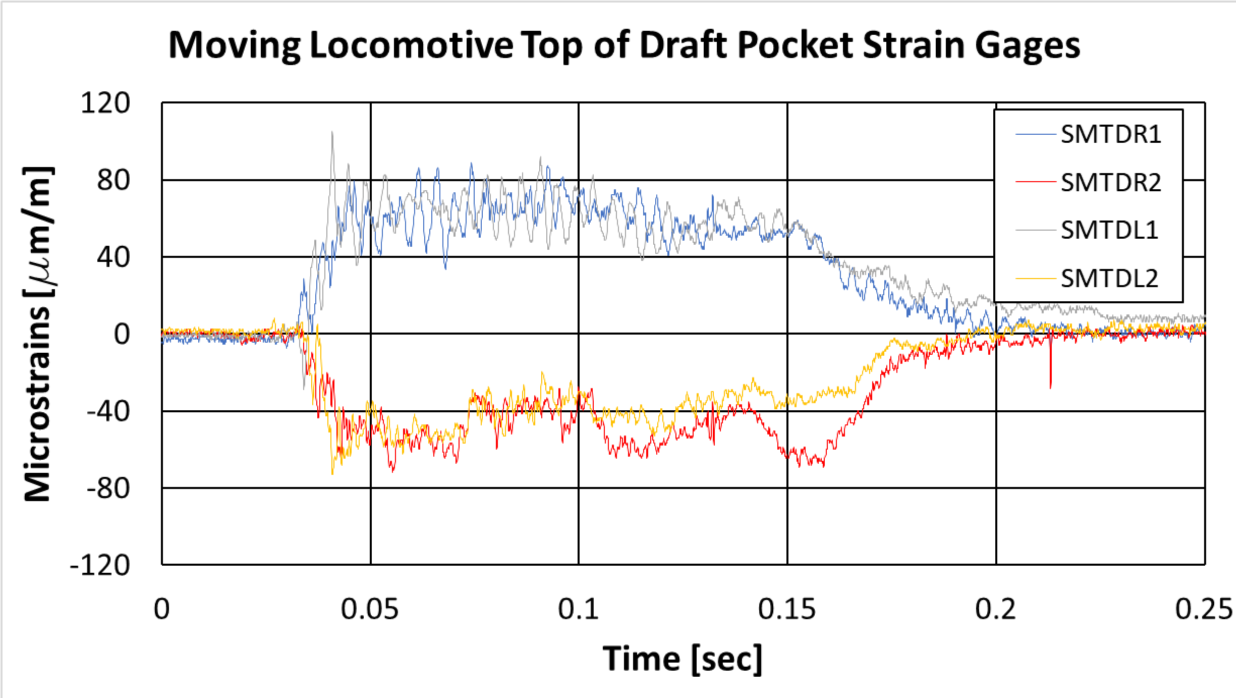

Figure 32. Mobile Locomotive Top of Draft Pocket Strain Results

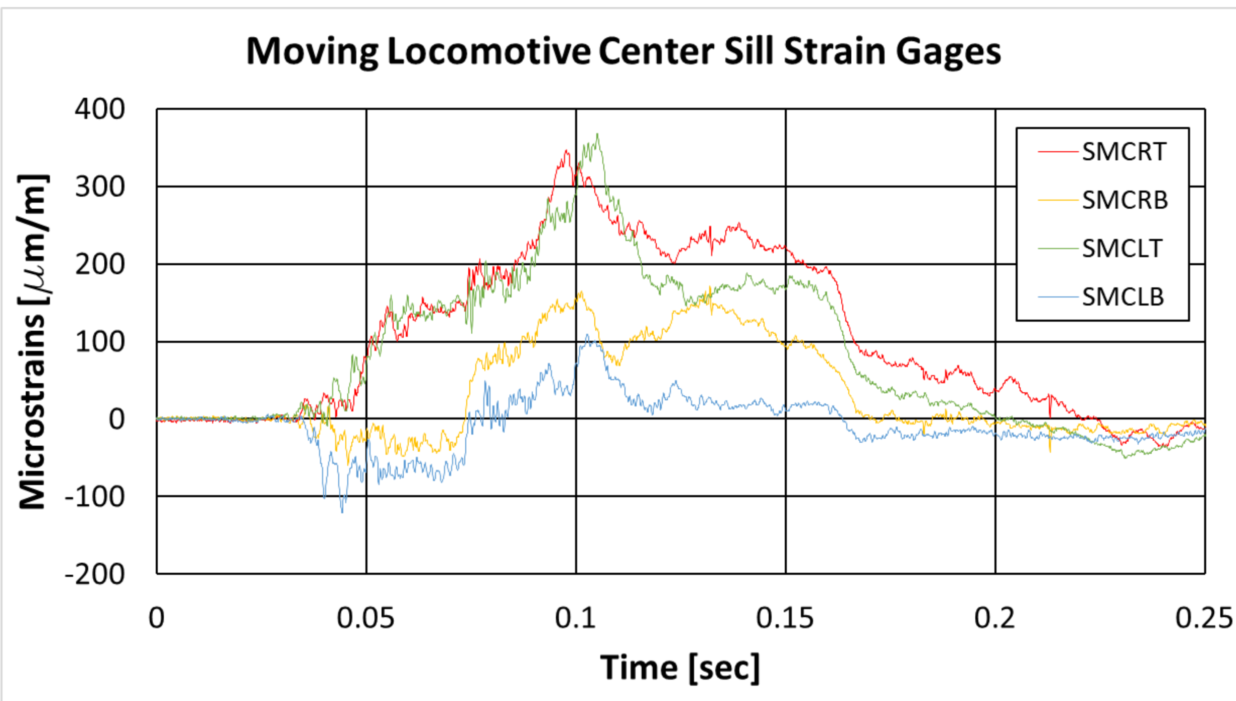

Figure 33. Mobile Locomotive Center Sill Strain Results

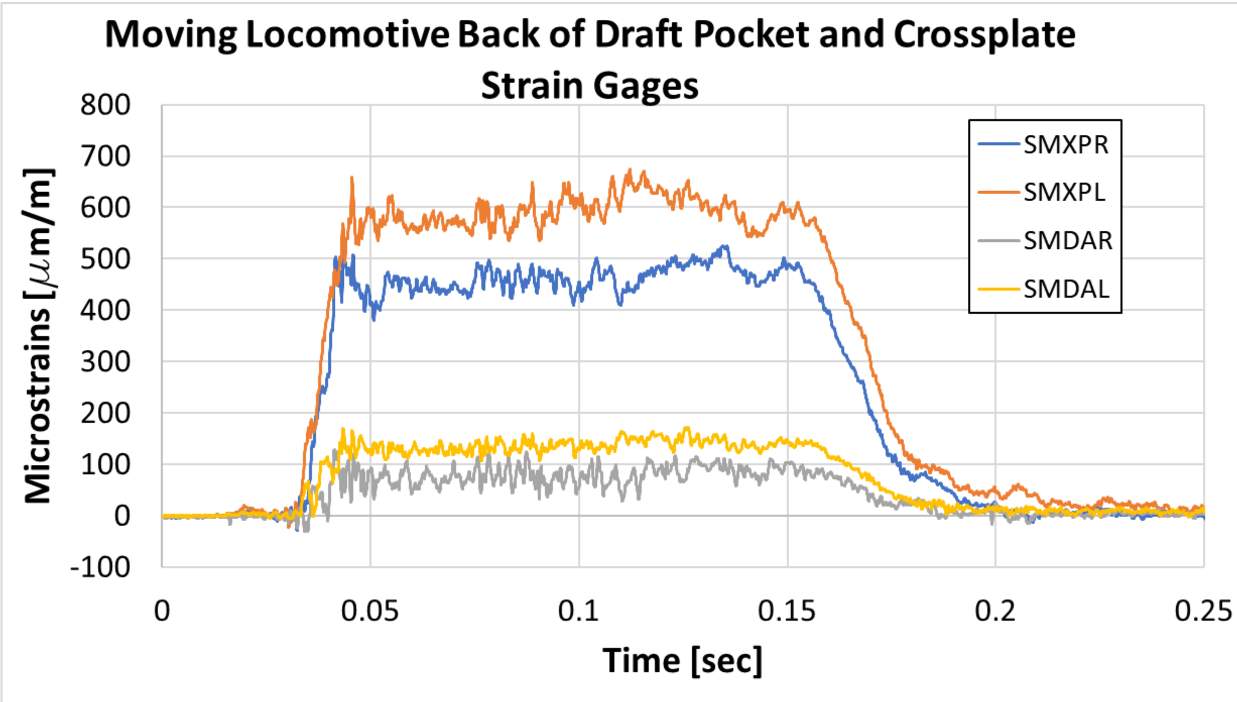

Figure 34. Mobile Locomotive Back of Draft Pocket and Crossplate Strain Results

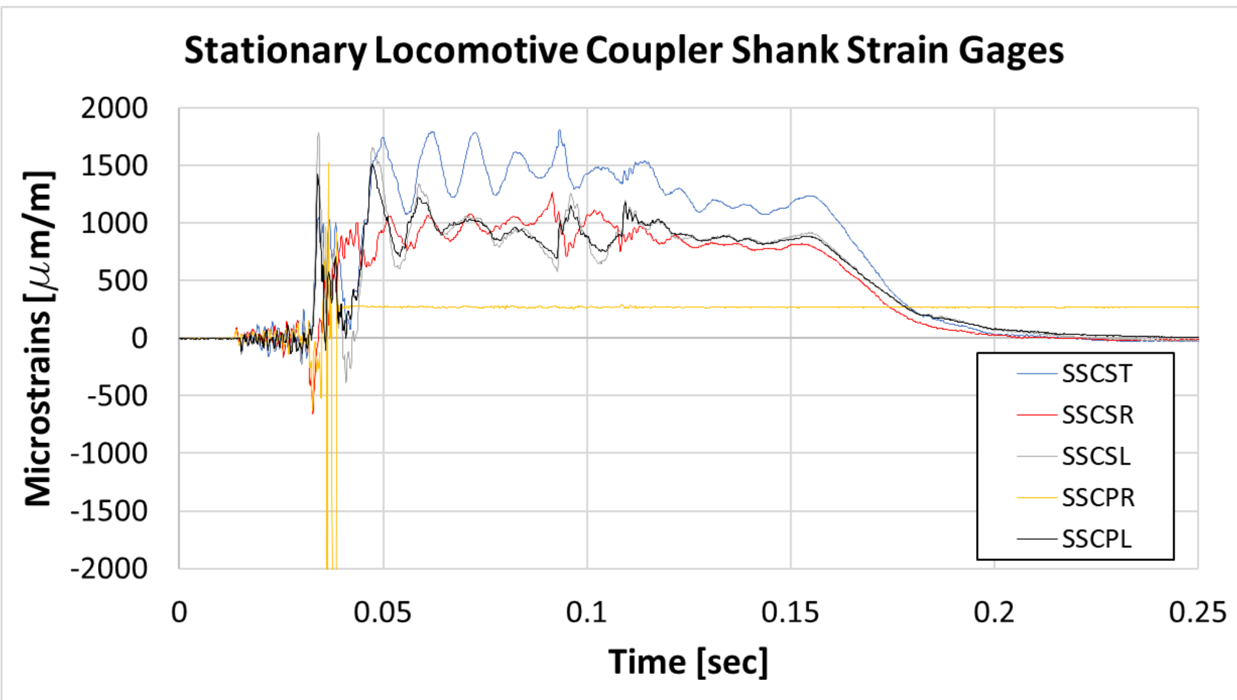

Figure 35. Stationary Locomotive Coupler Shank Strain Results

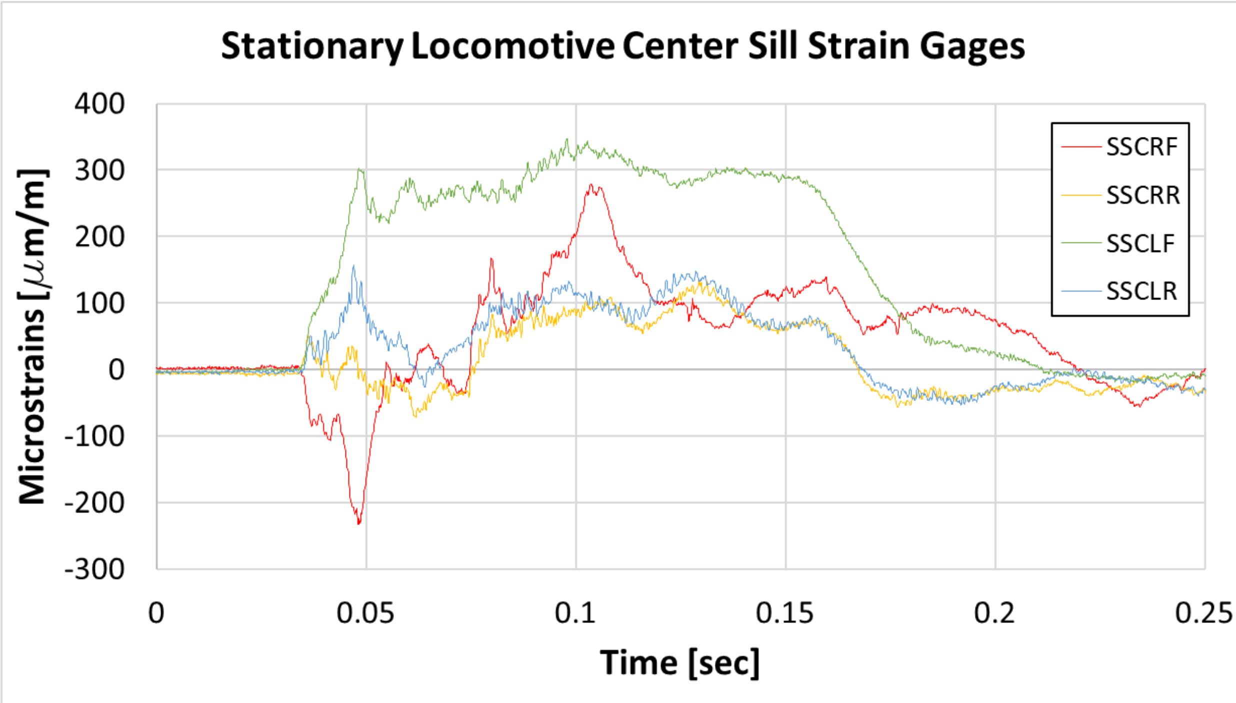

Figure 36. Stationary Locomotive Draft Sill Strain Results

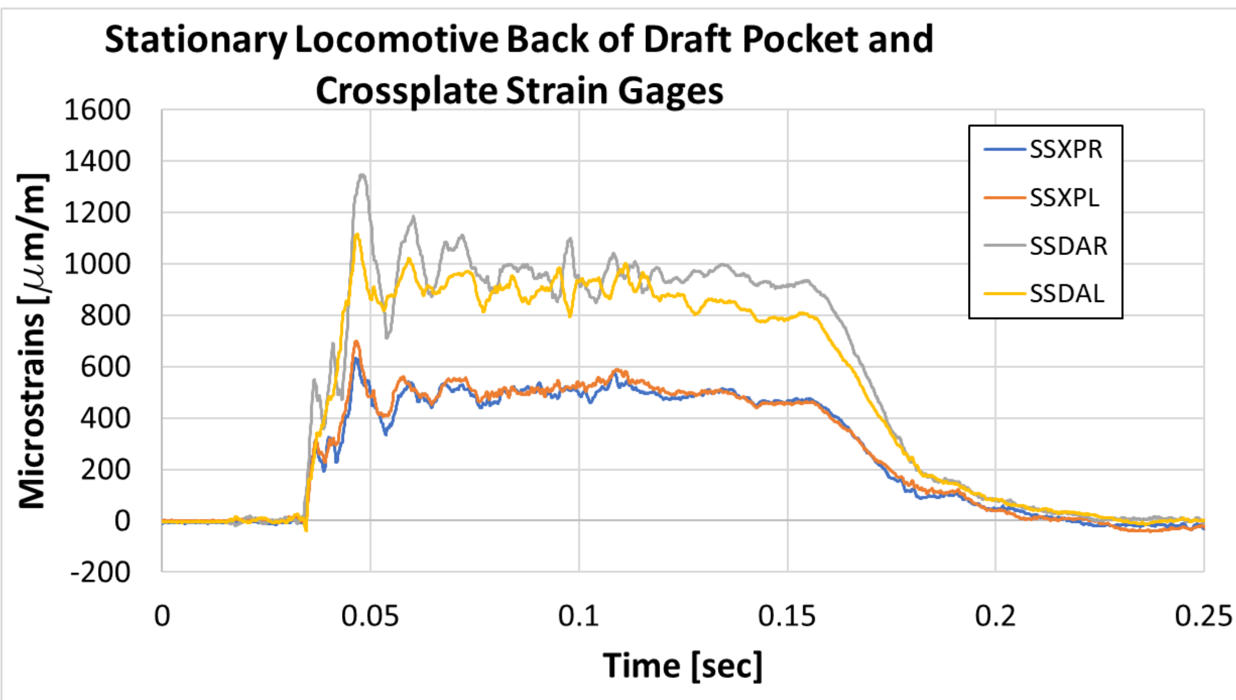

Figure 37. Stationary Locomotive Back of Draft Pocket and Crossplate Strain Results

3.2.4 Forces

Impact forces between the locomotives can be calculated as a product of the average acceleration and mass of the corresponding vehicle. Figure 38 shows the time history of the locomotive impact forces.

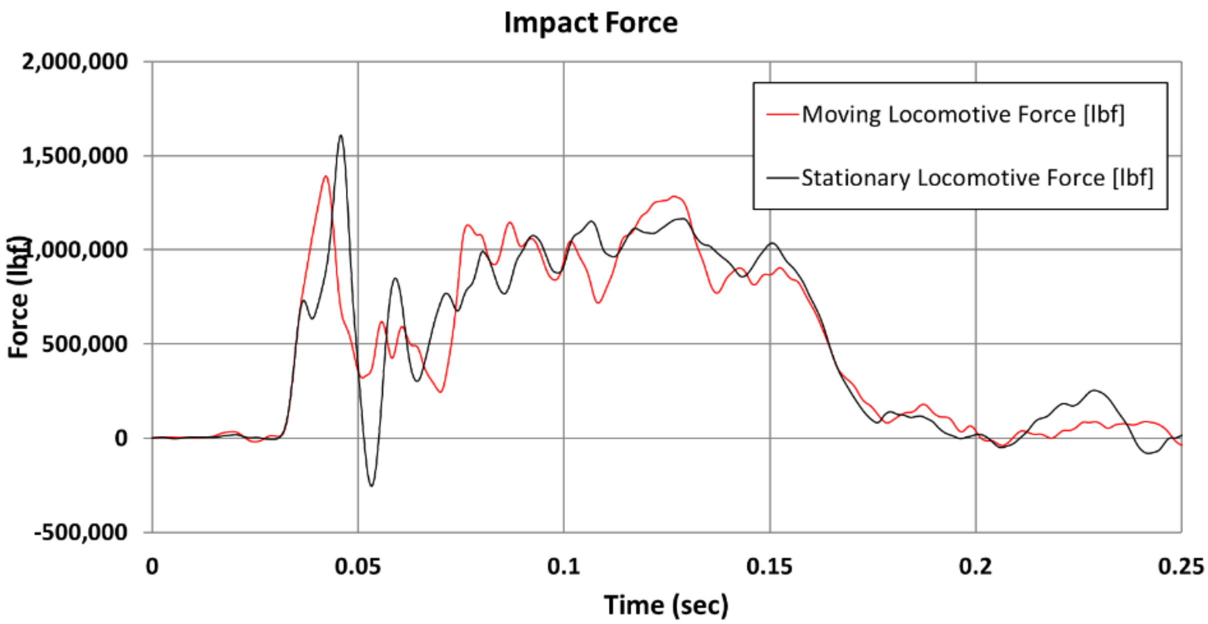

Figure 38. Impact Force

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 1,500,000 lbf for both the mobile and stationary locomotives.

3.2.5 Energies

Energy balance is the summary of the energy evolution during the impact. The total energy at the beginning of the impact is equal to the kinetic energy of the moving locomotive. After the first impact, both locomotives 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 39 shows the energy balance for the initial impact.

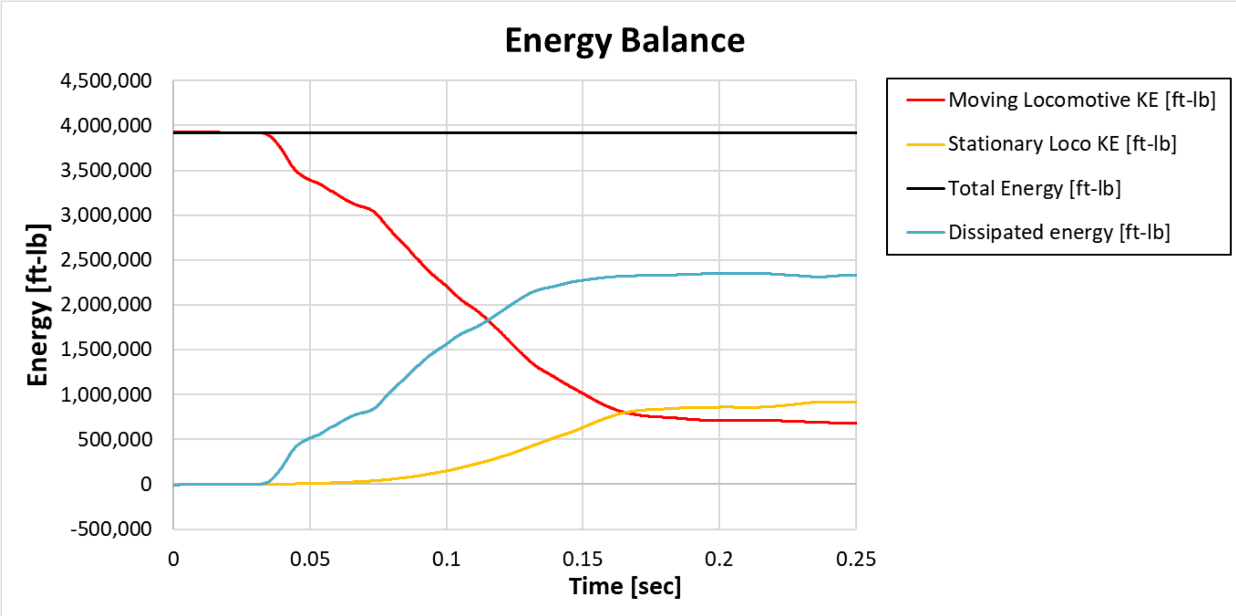

Figure 39. Energy Balance

3.3 Post-Test Damage and CEM Activation

After the impact, no structural damage was observed to have occurred on either the stationary or moving locomotives. During the impact, the PBC was activated and nearly exhausted its available stroke. In addition, the upper deformable anti-climber was engaged by the nose of the stationary locomotive. This anti-climber and its crush tubes were deformed under the impact force. The lower set of anti-climbers did not come into contact with the stationary locomotive and were intact after the test. The impact was not sufficient to activate the shear bolts, which were found to be intact after they were removed from the sliding lug. The CEM components after the test are shown in Figures 40 through 43.

Figure 40. Crushed Anti-climber

Figure 41. Activated Push-Back Coupler

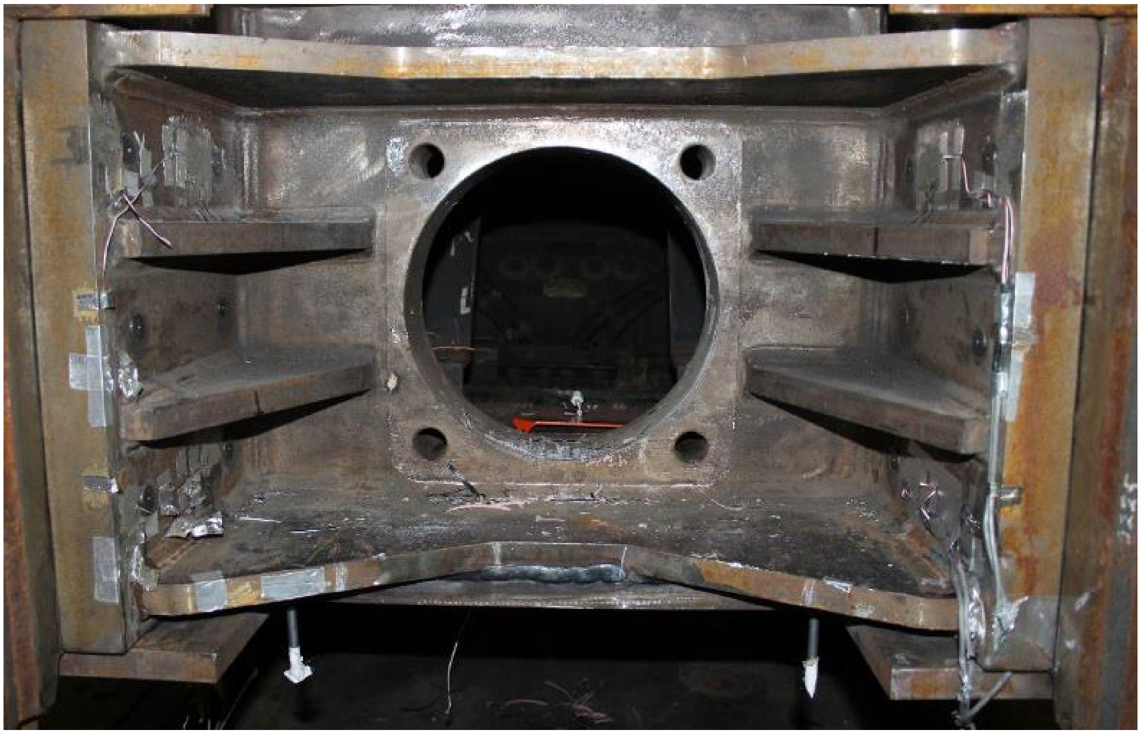

Figure 42. Sliding Lug Bolted into Draft Pocket after Test

Figure 43. Intact Shear Bolt After Test

4. Conclusion

This report documents the impact test conducted by TTCI between a passenger locomotive and a locomotive retrofitted with the CEM components. This testing 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 on January 23, 2019, at TTC near Pueblo, Colorado.

The stationary locomotive was impacted by the 232,200-lb locomotive at 19.3 mph. The locomotives did not couple during the impact.

The front of the stationary locomotive came into contact with the top set of deformable anti-climbers during the impact, causing them to partially crush. The lower set of deformable anti-climbers did not engage the stationary locomotive and did not experience any deformation. The push-back coupler was activated and nearly exhausted its available stroke. However, the remaining impact energy was not sufficient to shear the sliding lug bolts, which emerged completely intact.

The total impact energy was close to 4 million ft.-lbs. The engaged CEM components absorbed over half of the energy in first 150 milliseconds.

The test confirmed that the PBC and the anti-climbers were activated, prevented overclimbing, and absorbed the impact energy as intended. However, because of the lower than intended impact speed, the energy was not sufficient to shear the sliding lug bolts, assess the force level of the bolts, and observe the sliding-action of the lug.

Data collected in this test will be used to validate the computer model and to prepare for the next impact test with a different type of vehicle.

5. References

1. SAE International. (2007). SAE J211/1 Standard. 1995. Instrumentation for Impact Test – Part 1: Electronic Instrumentation. Warrendale, PA: SAE International. www.sae.org

Abbreviations and Acronyms

CEM	Crash Energy Management
FRA	Federal Railroad Administration
PBC	Push-Back Coupler
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)
Volpe	Volpe National Transportation Systems Center

Appendix A. Target Positions

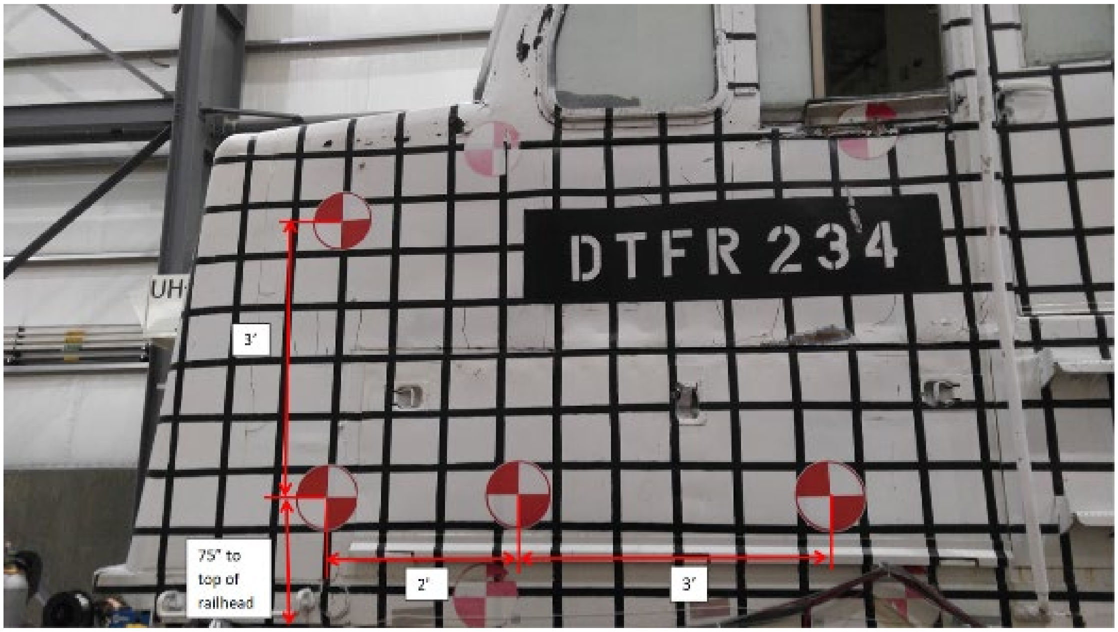

Figure A1. Target Spacing for CEM Locomotive

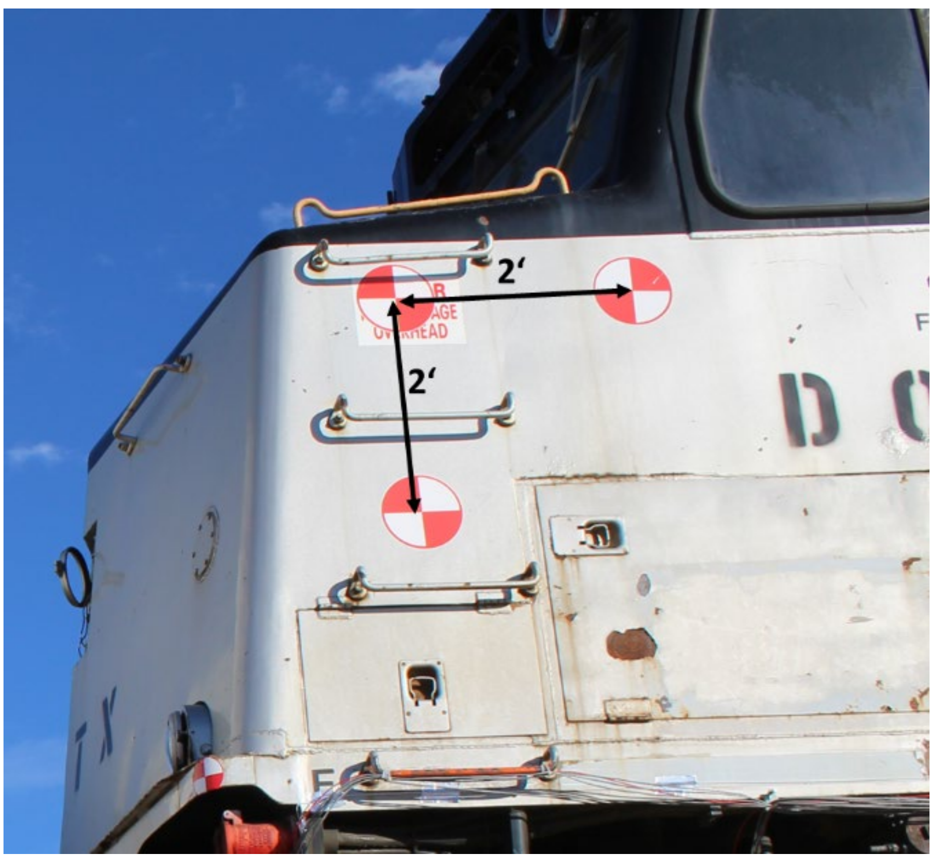

Figure A2. Target Spacing for Locomotive 4117

Appendix B. Test Data

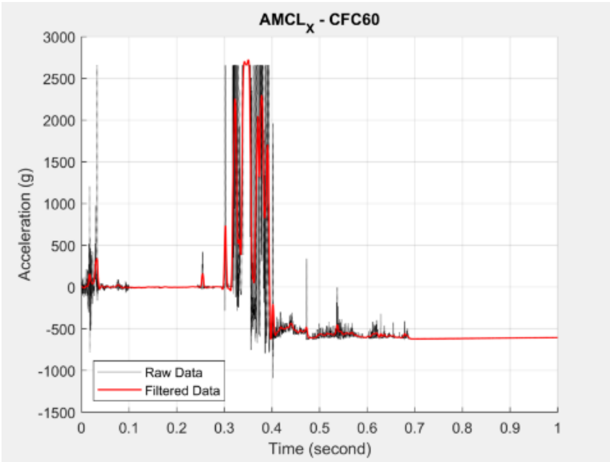

Figure B1. AMCL_X Accelerometer Data

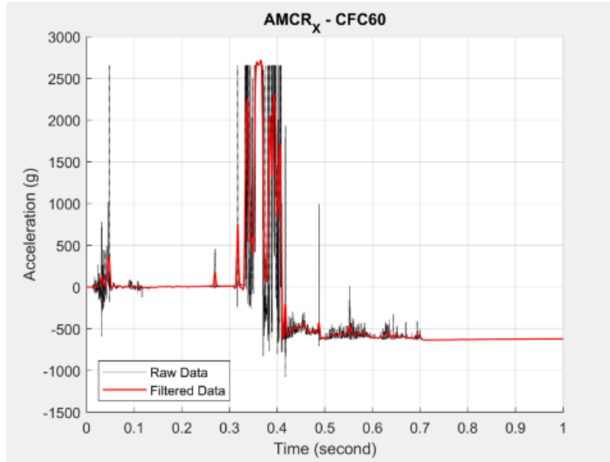

Figure B2. AMCR_X Accelerometer Data

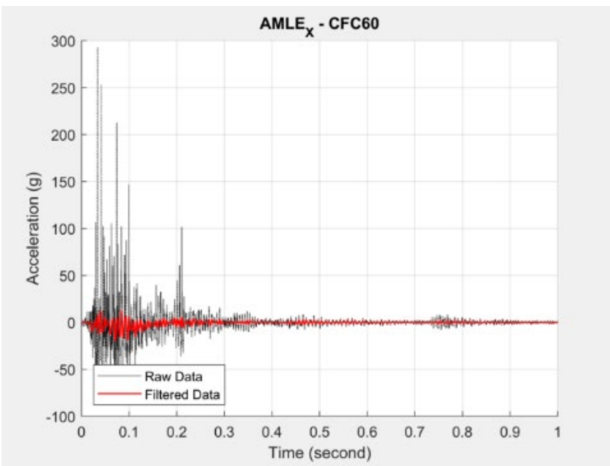

Figure B3. AMLE_X Accelerometer Data

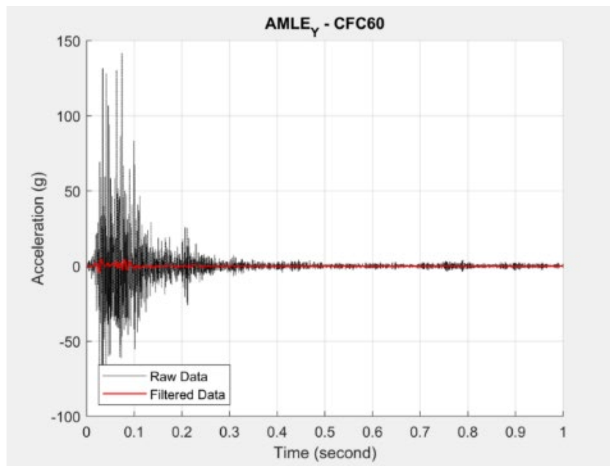

Figure B4. AMLE_Y Accelerometer Data

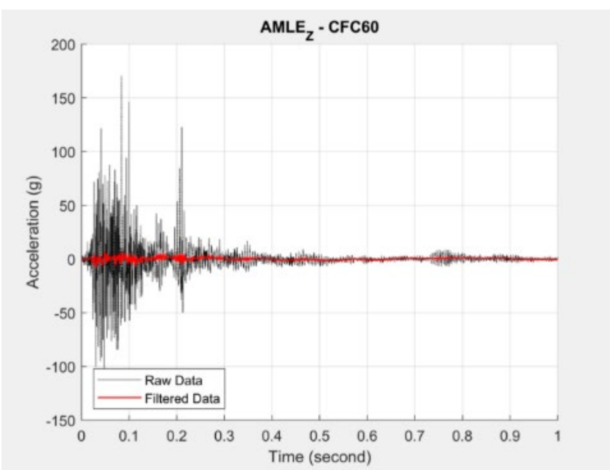

Figure B5. AMLE_Z Accelerometer Data

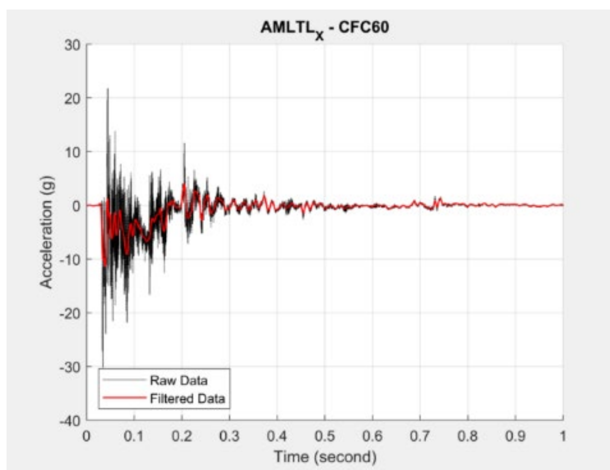

Figure B6. AMLTL_X Accelerometer Data

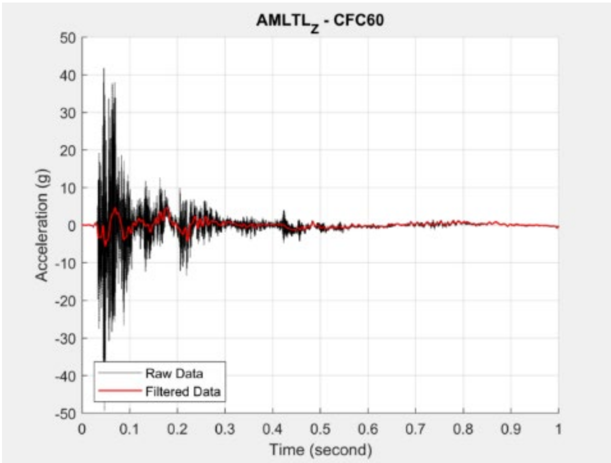

Figure B7. AMLTL_Z Accelerometer Data

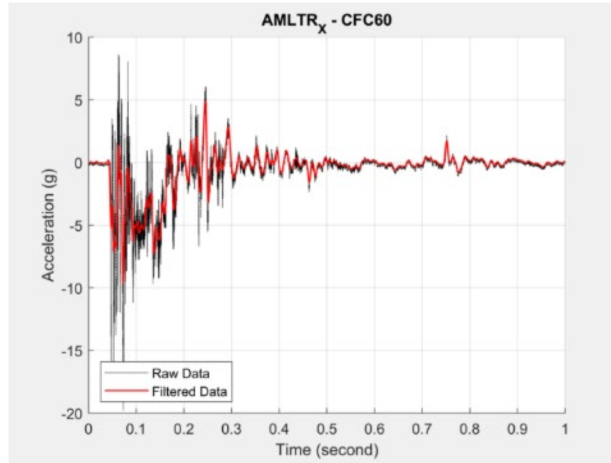

Figure B8. AMLTR_X Accelerometer Data

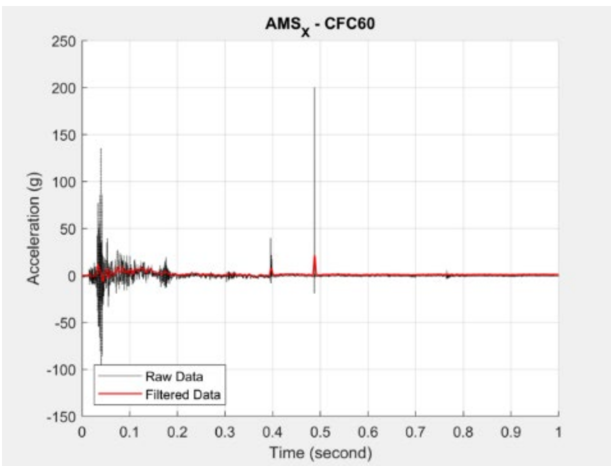

Figure B9. AMS_X Accelerometer Data

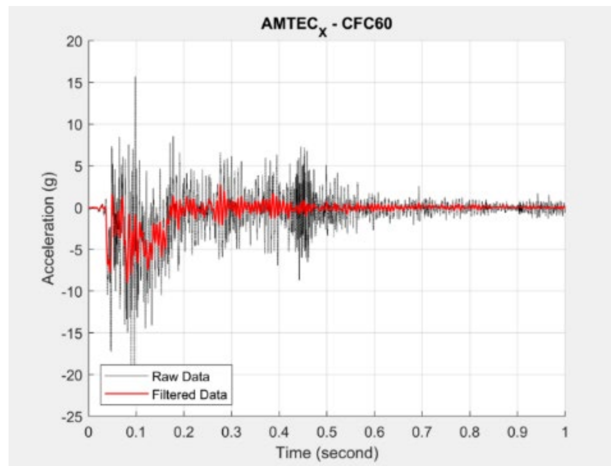

Figure B10. AMTEC_X Accelerometer Data

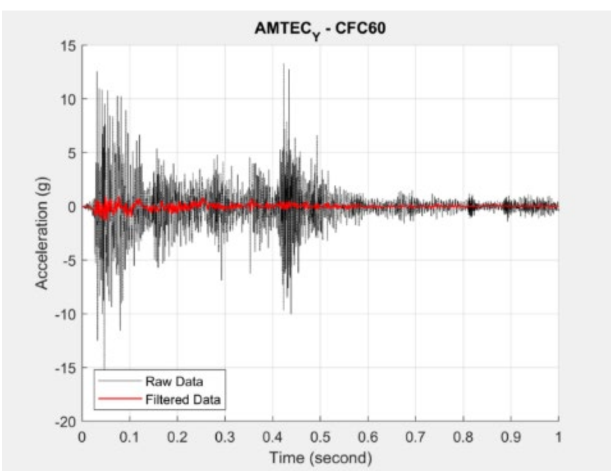

Figure B11. AMTEC_Y Accelerometer Data

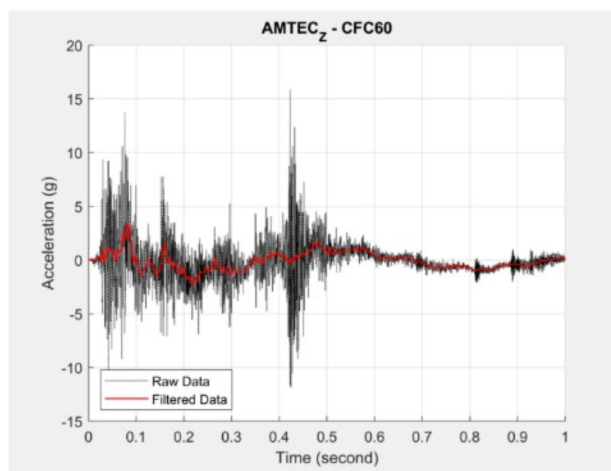

Figure B12. AMTEC_Z Accelerometer Data

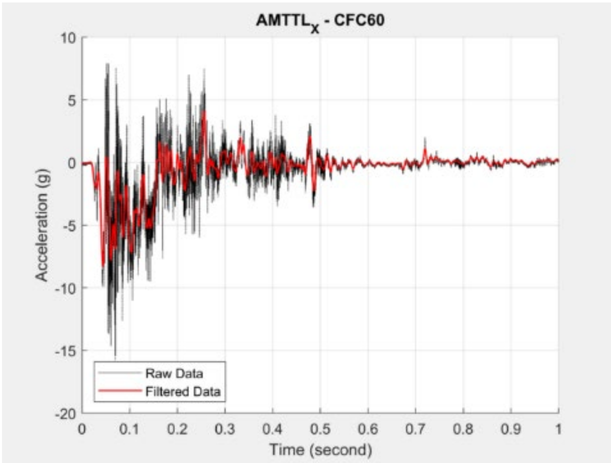

Figure B13. AMTTL_X Accelerometer Data

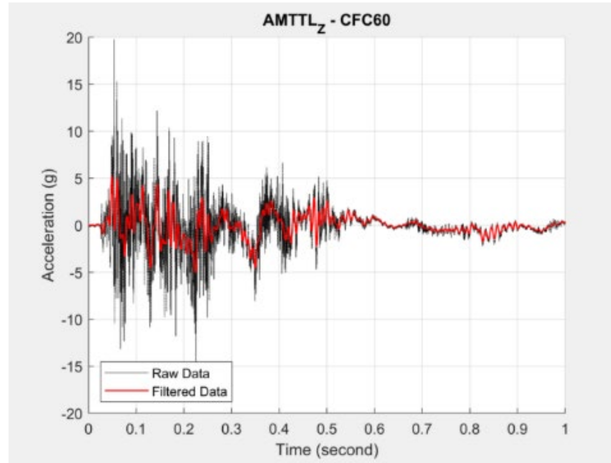

Figure B14. AMTTL_Z Accelerometer Data

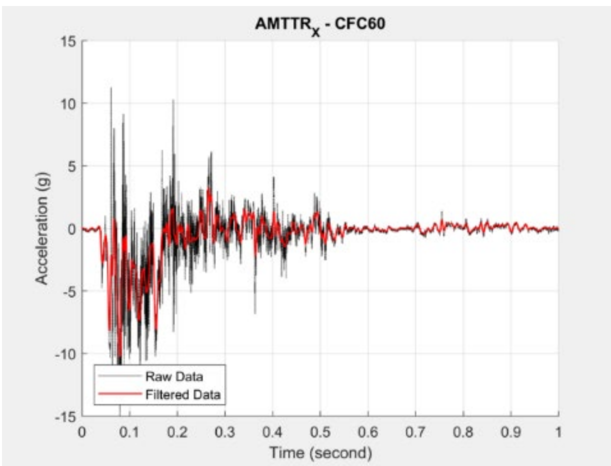

Figure B15. AMTTR_X Accelerometer Data

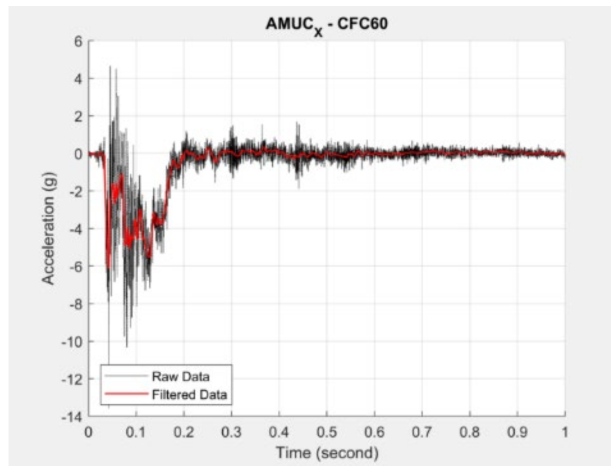

Figure B16. AMUC_X Accelerometer Data

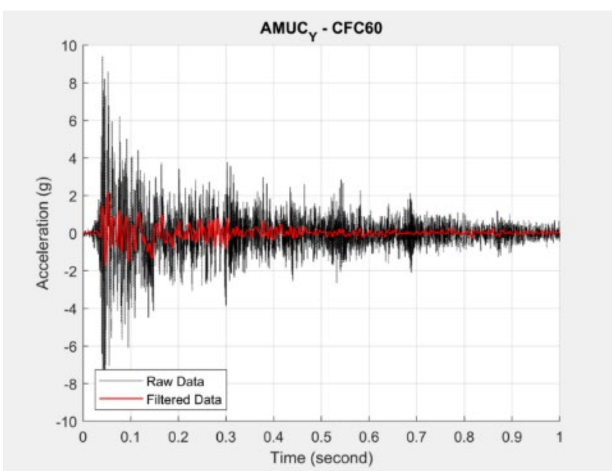

Figure B17. AMUC_Y Accelerometer Data

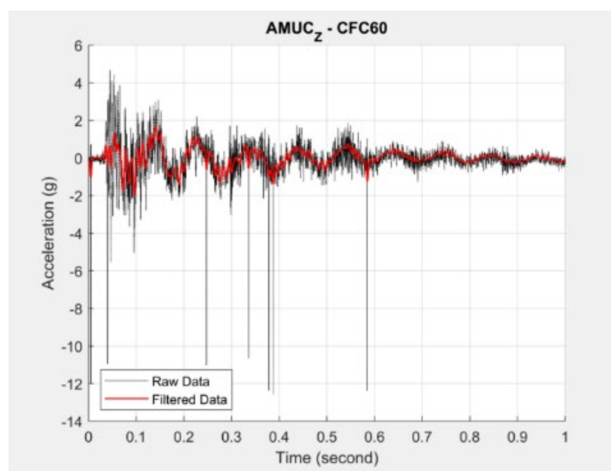

Figure B18. AMUC_Z Accelerometer Data

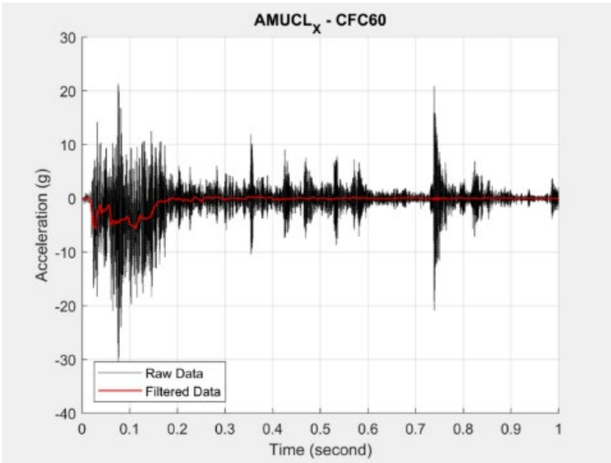

Figure B19. AMUCL_X Accelerometer Data

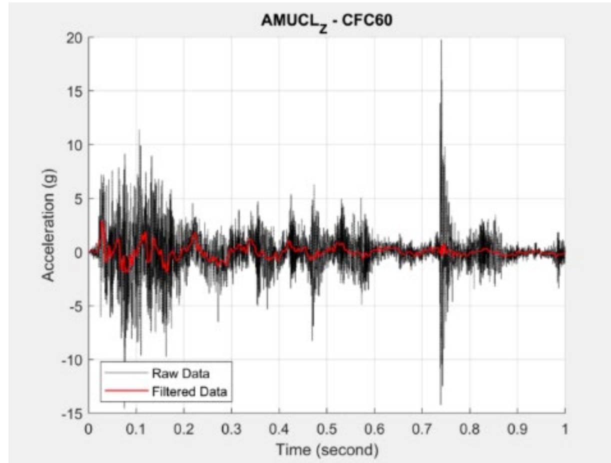

Figure B20. AMUCL_Z Accelerometer Data

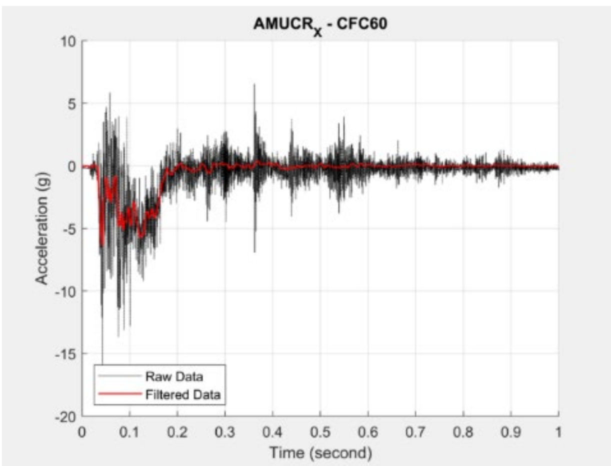

Figure B21. AMUCR_X Accelerometer Data

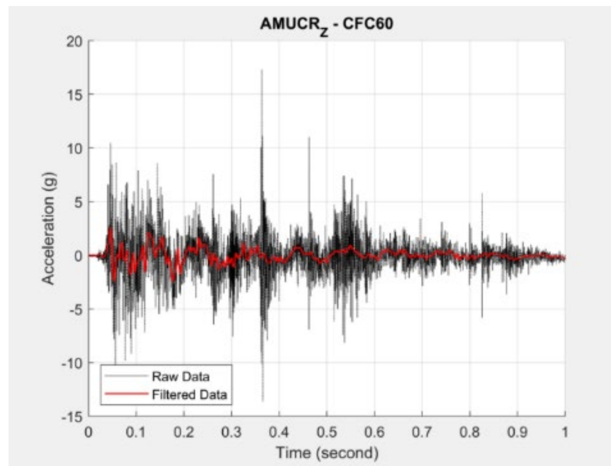

Figure B22. AMUCR_Z Accelerometer Data

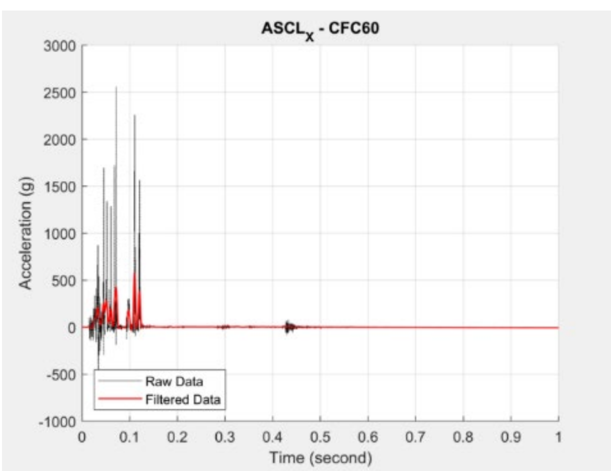

Figure B23. ASCL_X Accelerometer Data

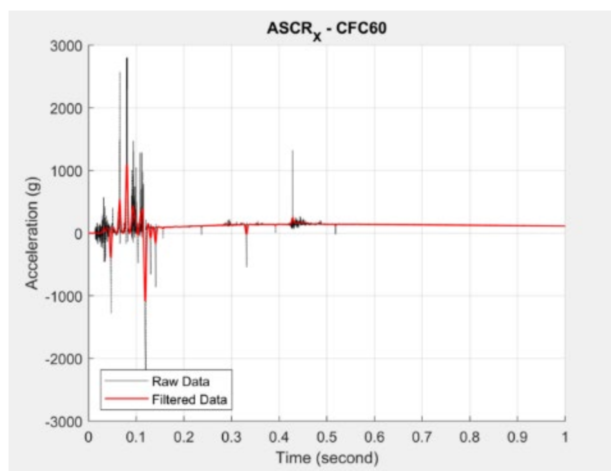

Figure B24. ASCR_X Accelerometer Data

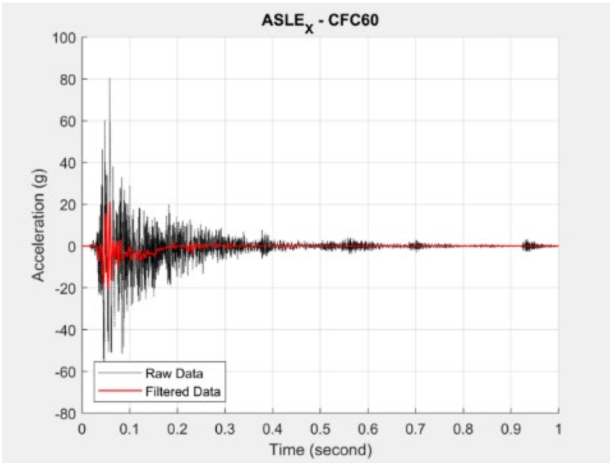

Figure B25. ASLE_X Accelerometer Data

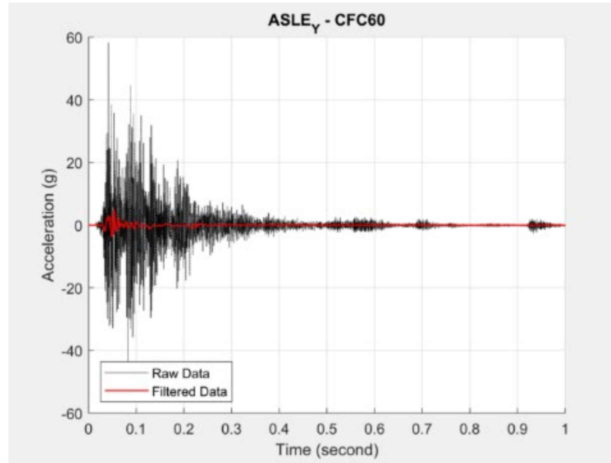

Figure B26. ASLE_Y Accelerometer Data

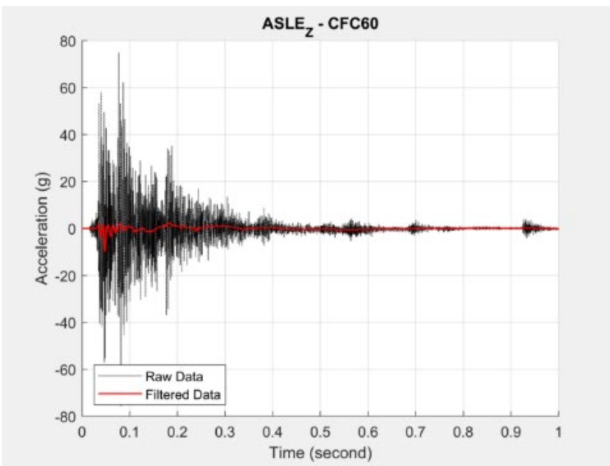

Figure B27. ASLE_Z Accelerometer Data

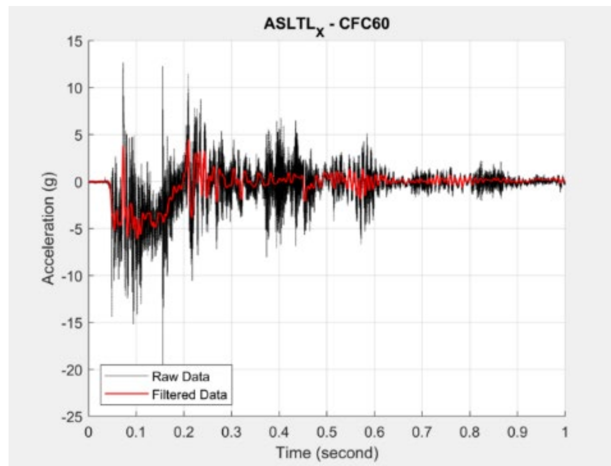

Figure B28. ASLTL_X Accelerometer Data

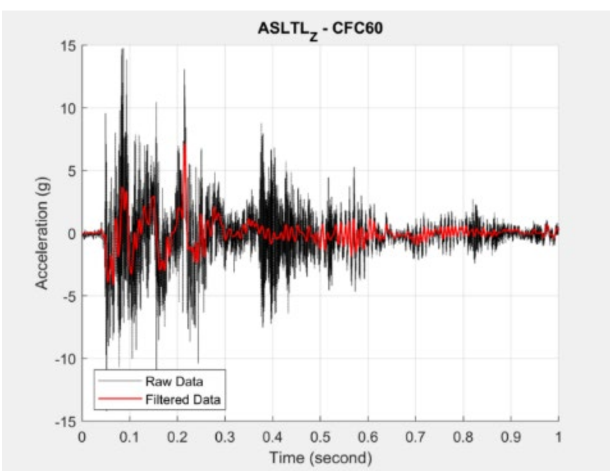

Figure B29. ASLTL_Z Accelerometer Data

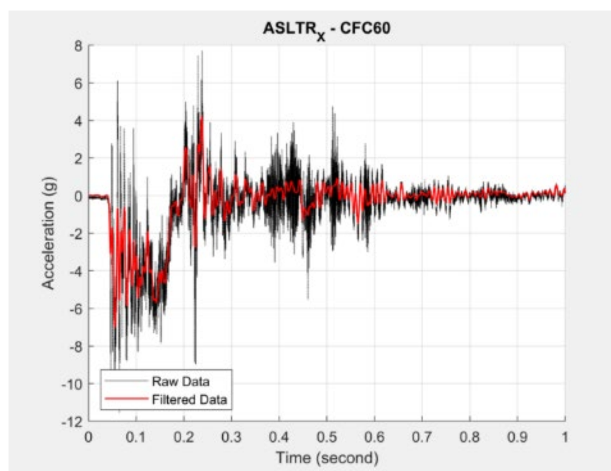

Figure B30. ASLTR_X Accelerometer Data

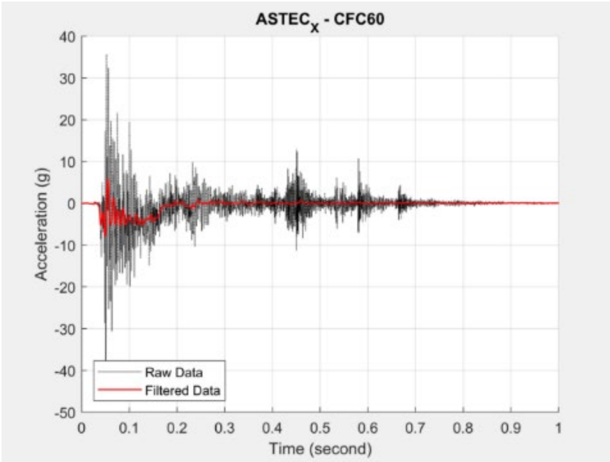

Figure B31. ASTEC_X Accelerometer Data

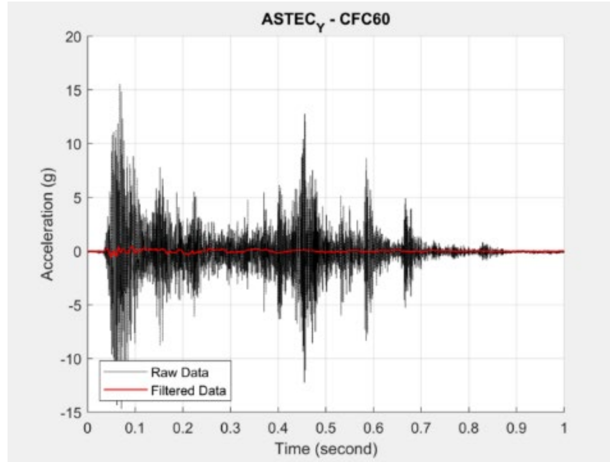

Figure B32. ASTEC_Y Accelerometer Data

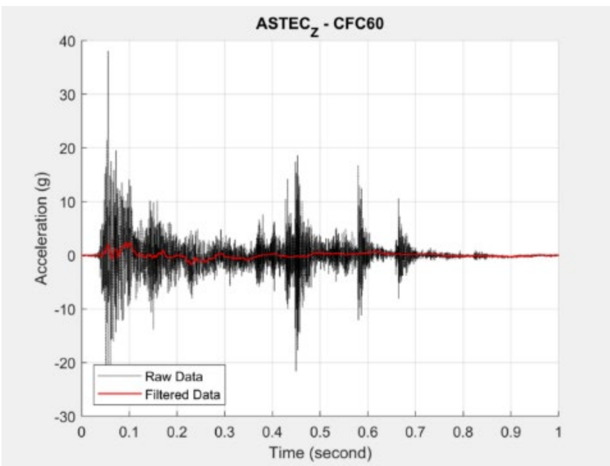

Figure B33. ASTEC_Z Accelerometer Data

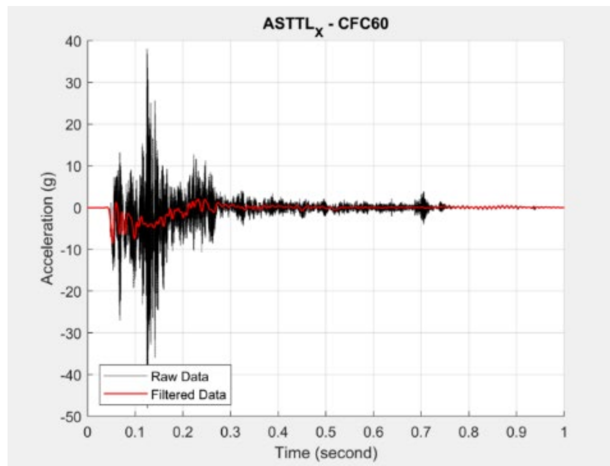

Figure B34. ASTTL_X Accelerometer Data

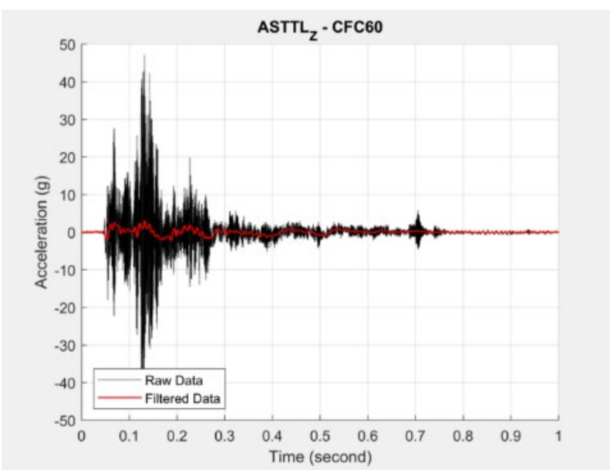

Figure B35. ASTTL_Z Accelerometer Data

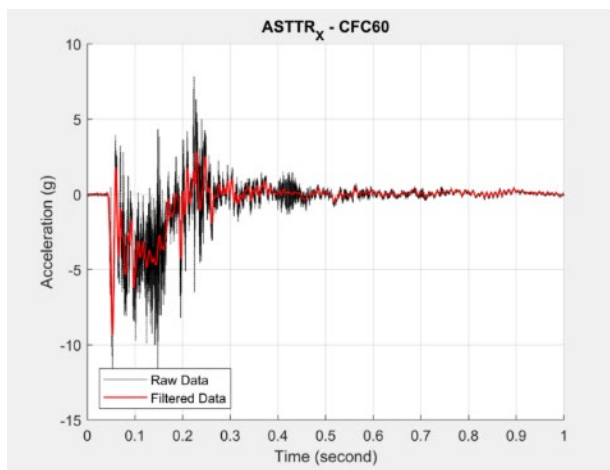

Figure B36. ASTTR_X Accelerometer Data

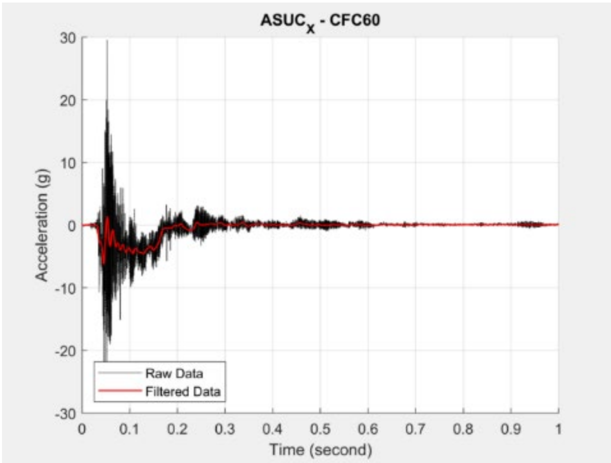

Figure B37. ASUC_X Accelerometer Data

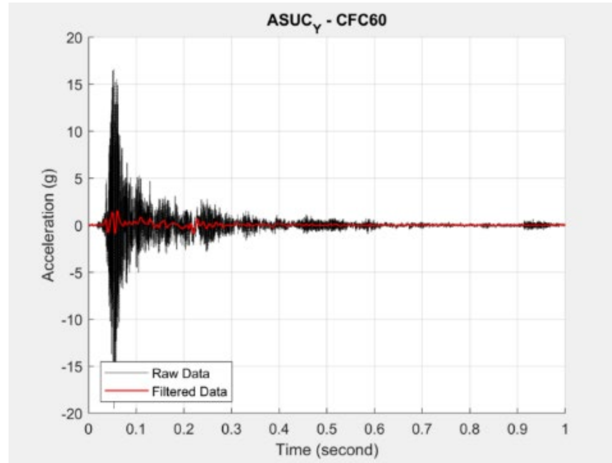

Figure B38. ASUC_Y Accelerometer Data

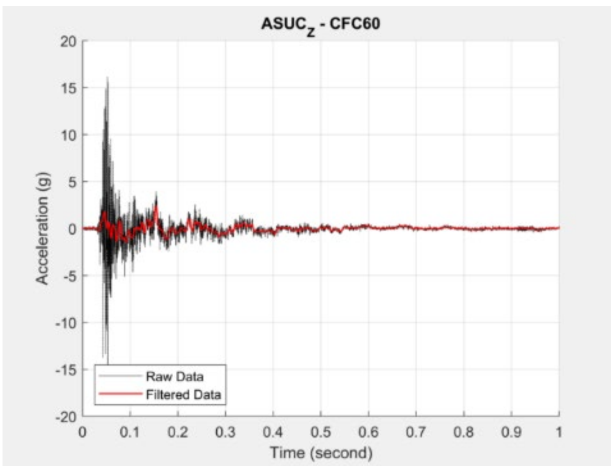

Figure B39. ASUC_Z Accelerometer Data

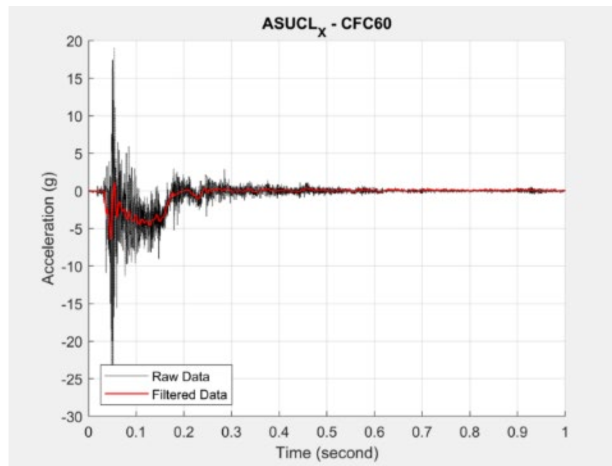

Figure B40. ASUCL_X Accelerometer Data

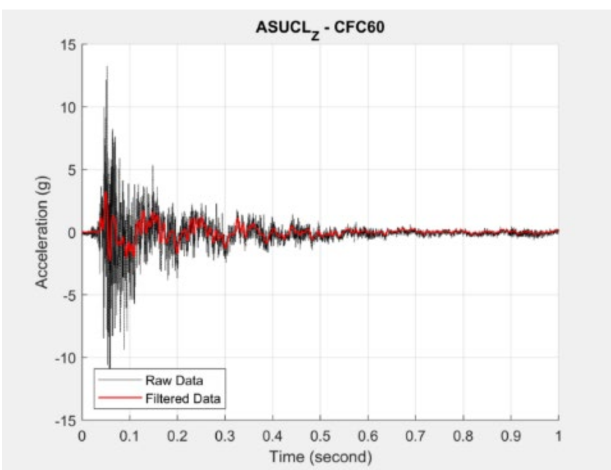

Figure B41. AMUCL_Z Accelerometer Data

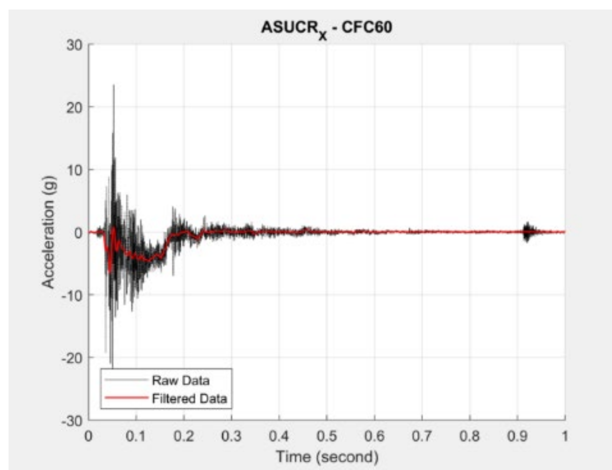

Figure B42. ASUCR_X Accelerometer Data

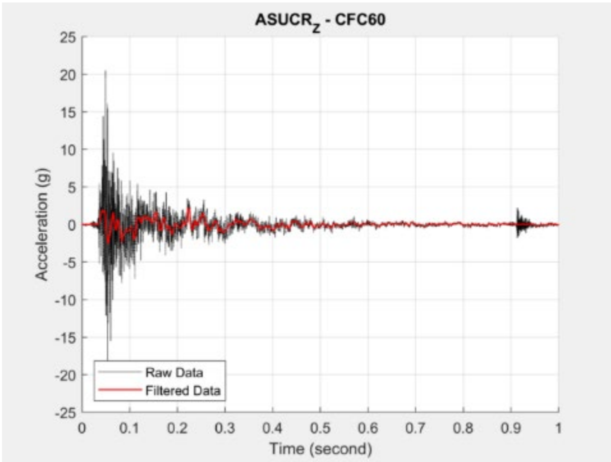

Figure B43. ASUCR_Z Accelerometer Data

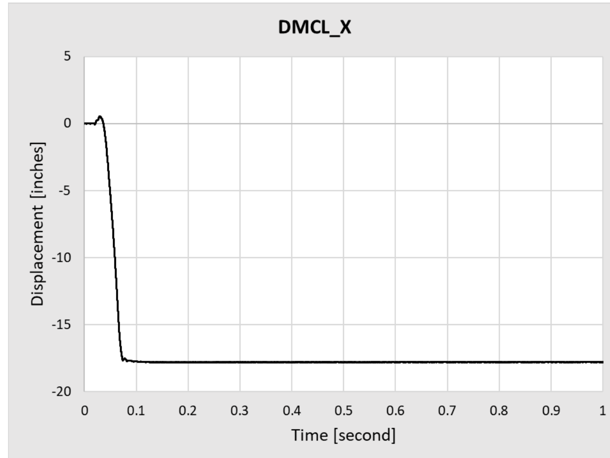

Figure B44. DMCL_X Displacement Data

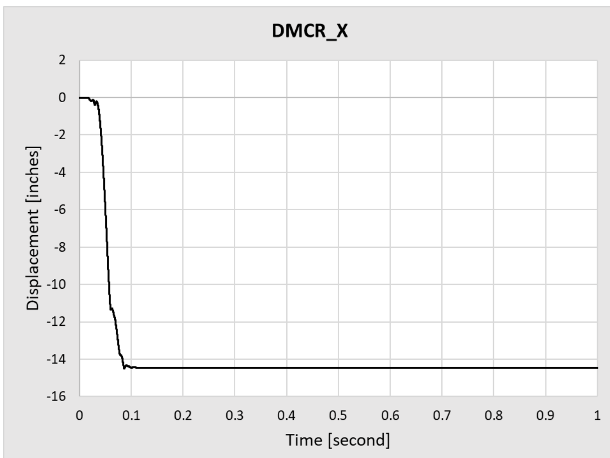

Figure B45. DMCR_X Displacement Data

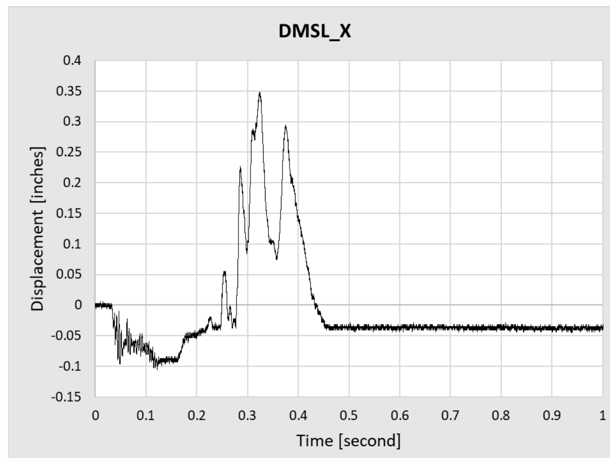

Figure B46. DMSL_X Displacement Data

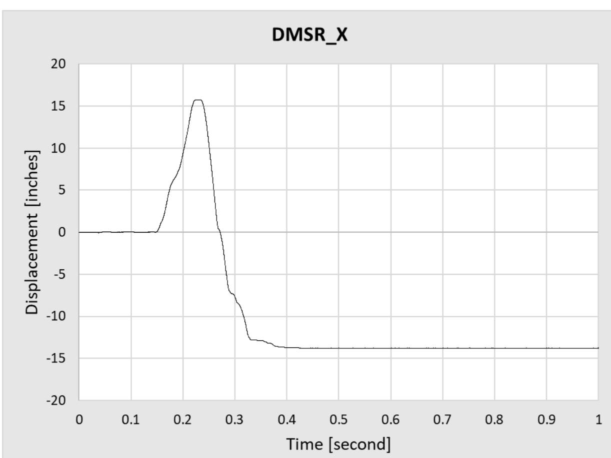

Figure B47. DMSR_X Displacement Data

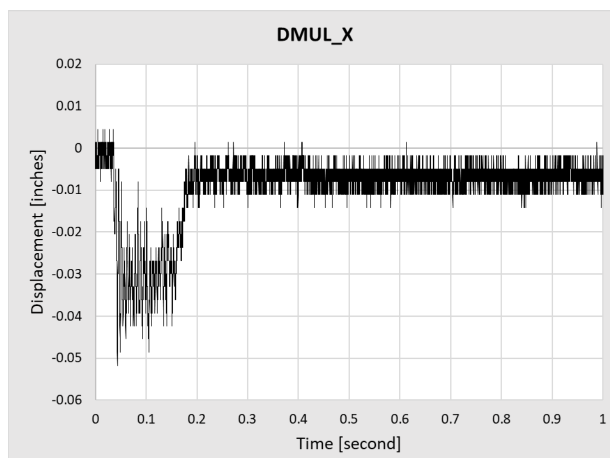

Figure B48. DMUL_X Displacement Data

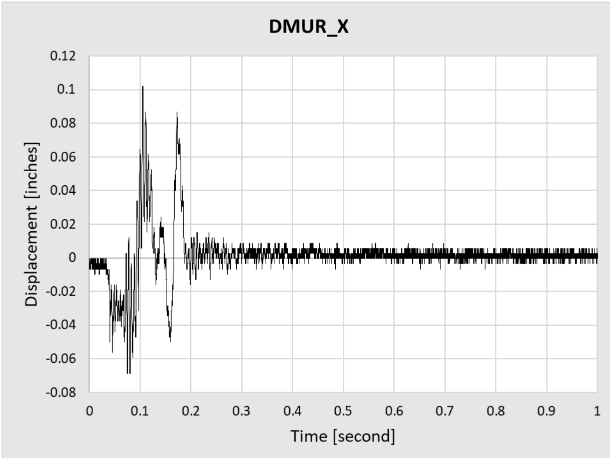

Figure B49. DMUR_X Displacement Data

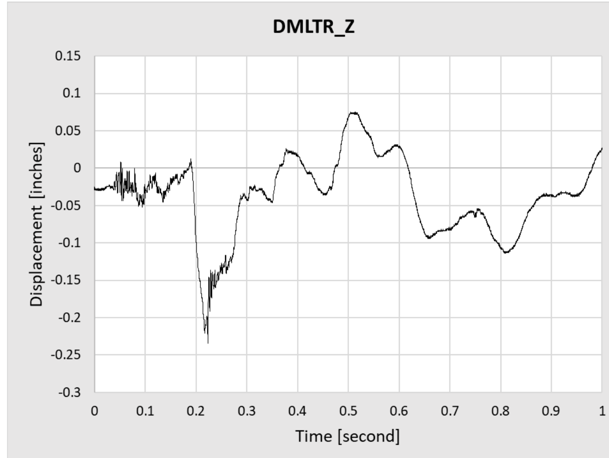

Figure B50. DMLTR_Z Displacement Data

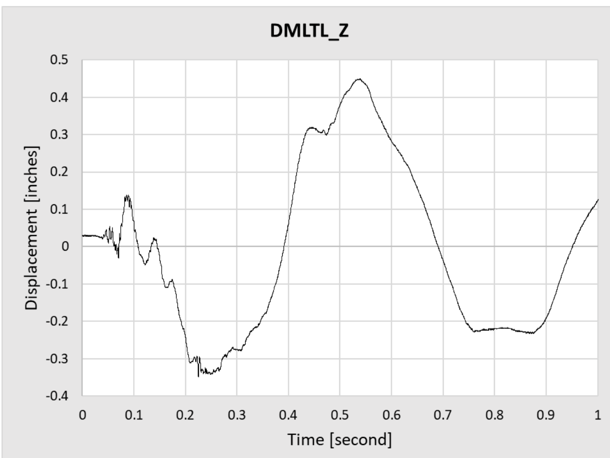

Figure B51. DMLTL_Z Displacement Data

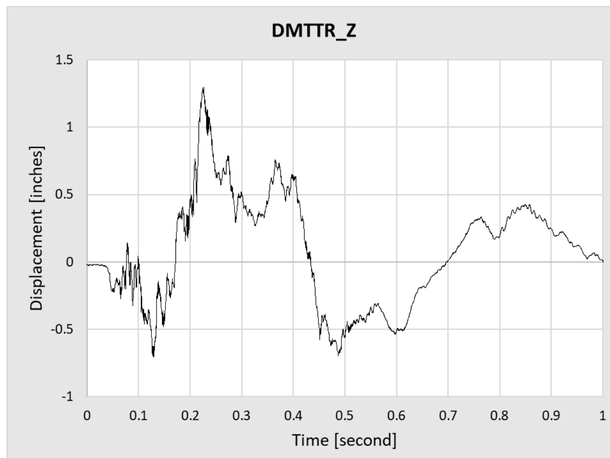

Figure B52. DMTTR_Z Displacement Data

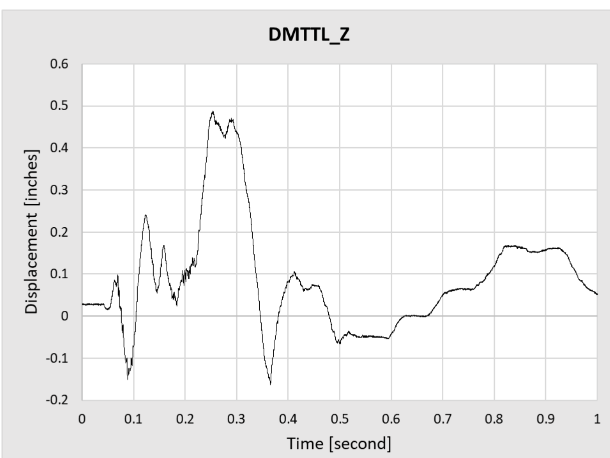

Figure B53. DMTTL_Z Displacement Data

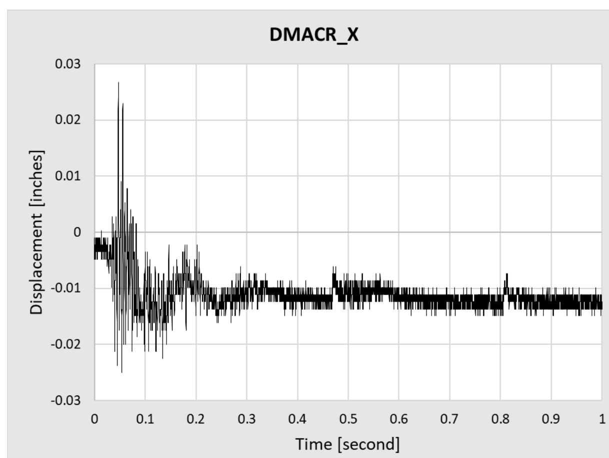

Figure B54. DMACR_X Displacement Data

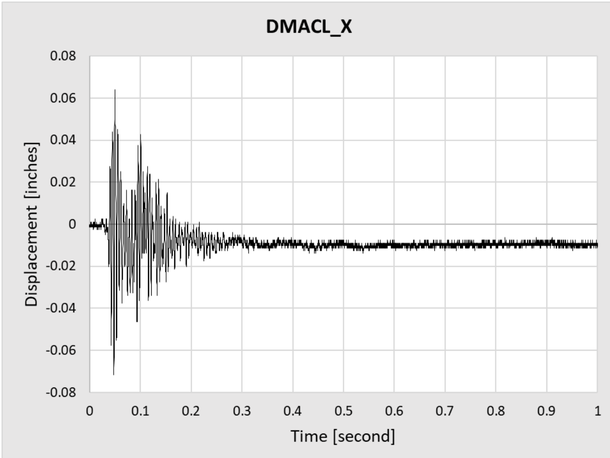

Figure B55. DMACL_X Displacement Data

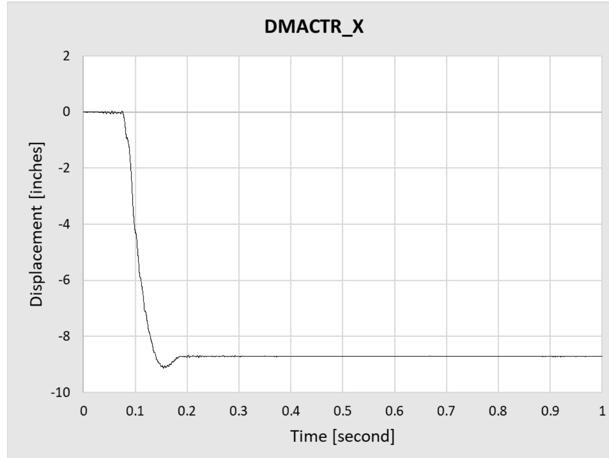

Figure B56. DMACTR_X Displacement Data

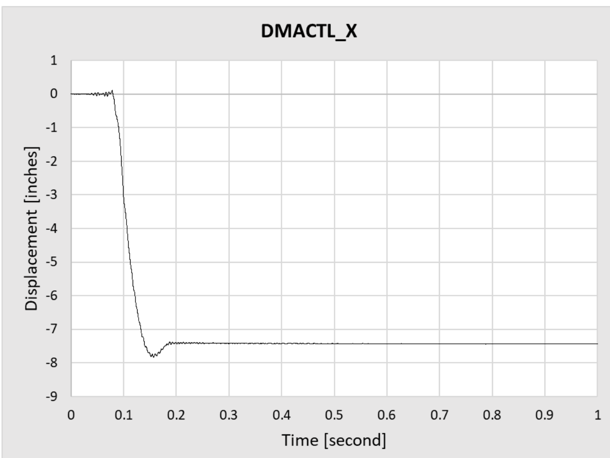

Figure B57. DMACTL_X Displacement Data

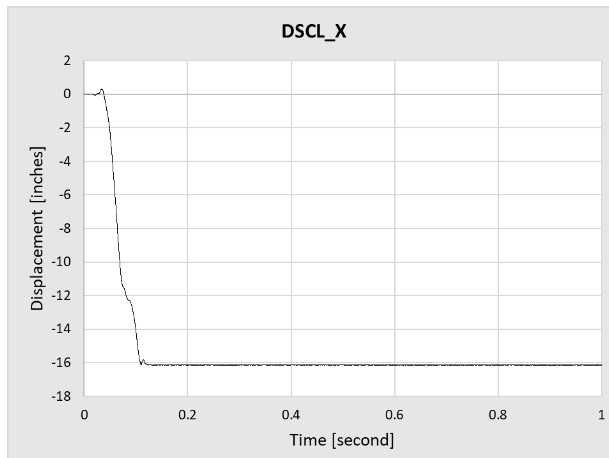

Figure B58. DSCL_X Displacement Data

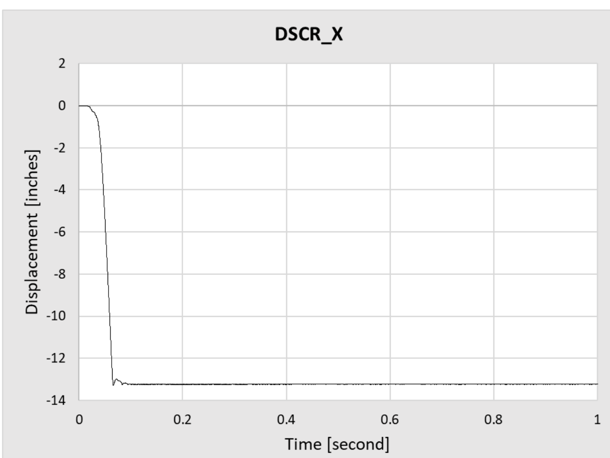

Figure B59. DSCR_X Displacement Data

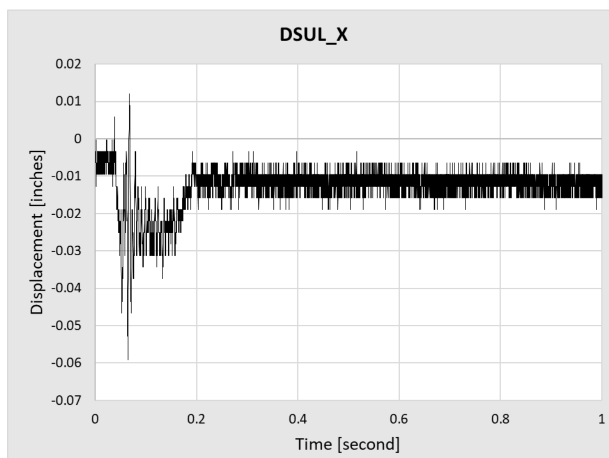

Figure B60. DSUL_X Displacement Data

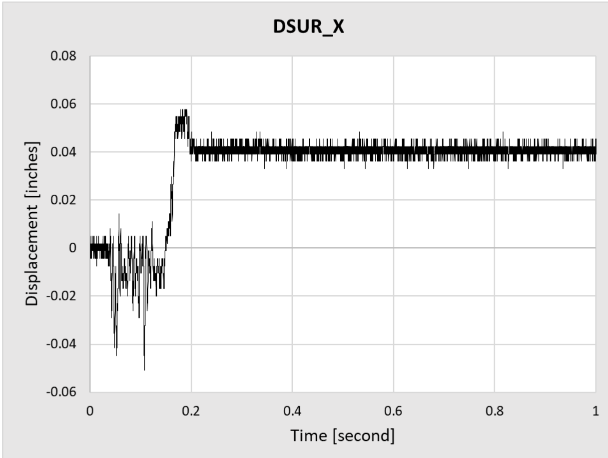

Figure B61. DSUR_X Displacement Data

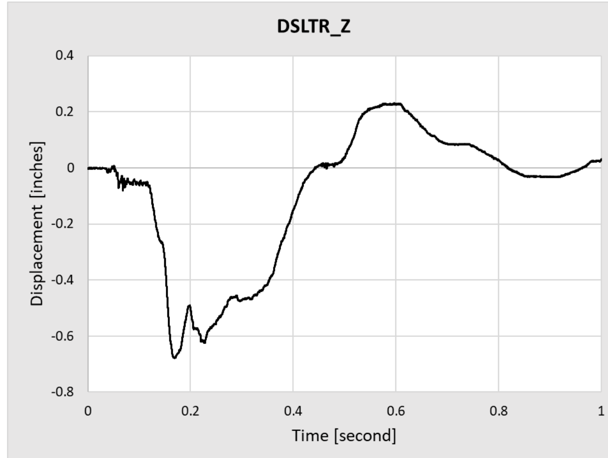

Figure B62. DSLTR_Z Displacement Data

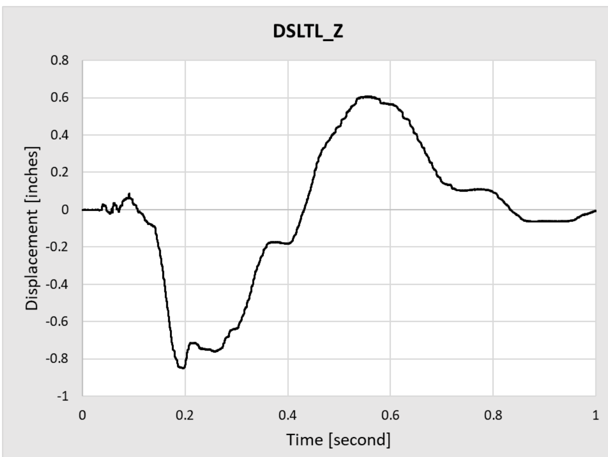

Figure B63. DSLTL_Z Displacement Data

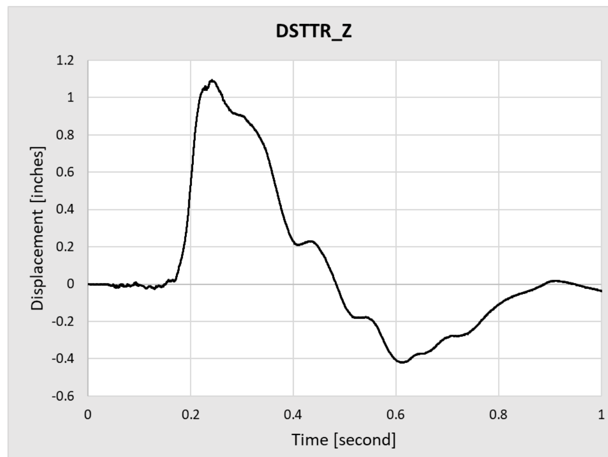

Figure B64. DSTTR_Z Displacement Data

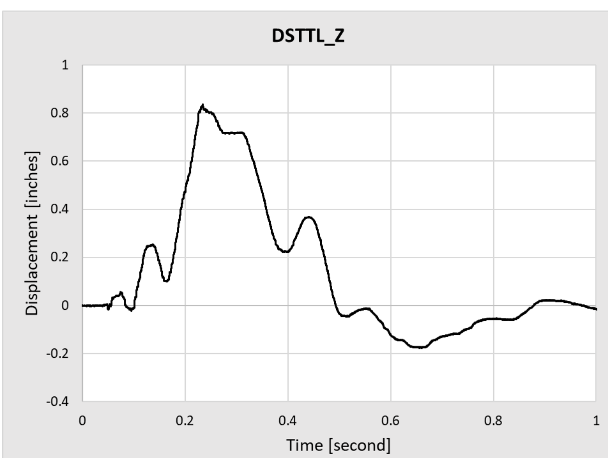

Figure B65. DSLTL_Z Displacement Data