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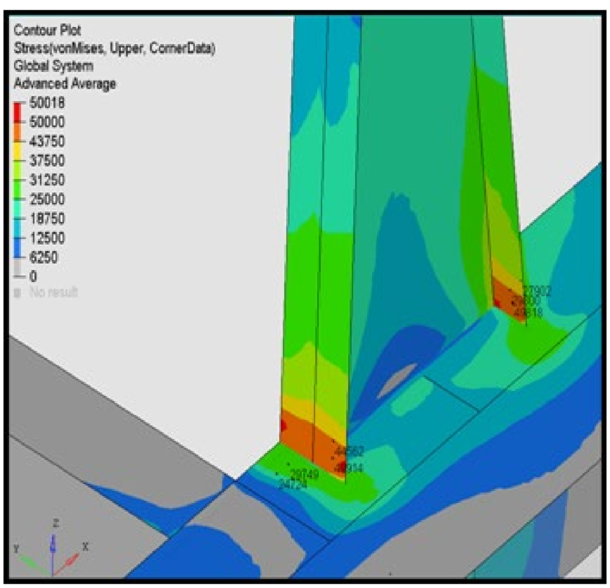
Federal Railroad
Administration

Office of Research,
Development and Technology
Washington, DC 20590

Test Evaluation of Retrofit Collison Post Design for Legacy Locomotives



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14. ABSTRACT
Legacy locomotives, such as narrow-nose designs manufactured before 1990, were not required to comply with crashworthiness requirements. Therefore, these locomotives afford less crew protection in case of train collisions. In this project, collision posts that offer additional crash protection were fabricated and installed on a legacy locomotive underframe. Structural tests conducted with the upgraded underframe using appropriate loads showed that the maximum stresses were within acceptable limits. Further, the measured strains correlated well with the expectations from design simulations, thereby validating the robustness of the retrofit design.

15. SUBJECT TERMS
Crashworthiness, collision post, freight locomotives, S-580

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 CONVERSION

°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

Updated 6/17/98

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Executive Summary

Legacy locomotives, such as narrow-nose designs manufactured before 1990, were not required to comply with crashworthiness standards now required on all locomotives in mainline freight operations. Therefore, such locomotives, many to remain in service in the foreseeable future, afford less crew protection in case of train collisions. The objective of this project was to fabricate, test, and validate a collision post (CP) design which meets AAR S-586 crashworthiness requirements (circa 2001) for retrofitting legacy locomotives.

During a previous phase of this project (FRA report DOT/FRA/ORD-19/41), Sharma & Associates, Inc. (SA) designed multiple CP concepts and investigated the crashworthiness of a sample legacy locomotive with these designs using finite element analysis. The study concluded that it was possible to comply with the crashworthiness standards defined in Subpart D of Title 49, Code of Federal Regulations, Part 229 by retrofitting legacy locomotives with CPs featuring tapered I-beam sections. SA recommended that the selected retrofit collision post be tested for compliance with the Association of American Railroads' S-580 Standard.

In this phase, SA procured a legacy locomotive underframe, including the narrow nose and cab area. Researchers removed the superstructure to facilitate access to the attachment area and allow the underframe to fit in the loading test frame.

Once the underframe structure and geometry details were established and before fabricating the CPs, the research team evaluated the design for form and fit using a computer-aided design process.

Additionally, researchers reviewed their design with a major locomotive re-manufacturer to increase the likelihood of implementation. The re-manufacturer expressed no reservations about the design and the accessibility to the short hood for installing the CPs. As this final review identified no issues, the team proceeded with collision post fabrication.

Two prototype collision posts with the recommended tapered I-beam design were fabricated and welded to a locomotive underframe structure. Thirteen strain gauges and three potentiometers were applied to the collision post and the frame.

Researchers tested the post at the SA test facility for four load cases: 50, 100, 150 and 200 kips. The maximum load to be applied in S-580 is 200 kips. A SOMAT data acquisition system was used to collect the data.

Test results showed that the CP design complied with requirements of the AAR S-580 (2001) specification, i.e., the maximum stress measured was below the tensile strength.

1. Introduction

1.1 Background

North American freight locomotives are currently designed and built to the crashworthiness requirements defined in Subpart D of Title 49, Code of Federal Regulations Part 229, and Association of American Railroads (AAR) S-580 standards.

One of the requirements is that the short hood section of locomotives must have two collision posts (CPs) of an appropriate strength. Earlier versions of the S-580 Standard (1989, 1994, and 2001 versions) required each CP to withstand a 200,000-lb. load at 30 inches above the deck and a 500,000-lb. load applied at the deck height.

The current version of the standard, effective 2005, requires each CP to withstand the following (AAR S-580 Standard, 2014):

- A 750,000-lb. load applied over the bottom 10 percent of the overall height of the CP at the base at any angle in the horizontal plane in the range of ±15° of the longitudinal axis of the locomotive (P_s).
- A 500, 000-lb. load, 30 inches above underframe applied at any angle in the range of ±15° of the longitudinal axis of the locomotive such that a moment of 15 million inch-lbs develops at the base of the post (P_{m-1}).
- The current standard also requires a load applied at a vertical location greater than 30 inches above the top of the underframe such that the moment of 15 million inch-lbs is at the base of the post (P_{m-2}). The load is applied at an angle in the range of ±8° of the longitudinal axis of the locomotive.

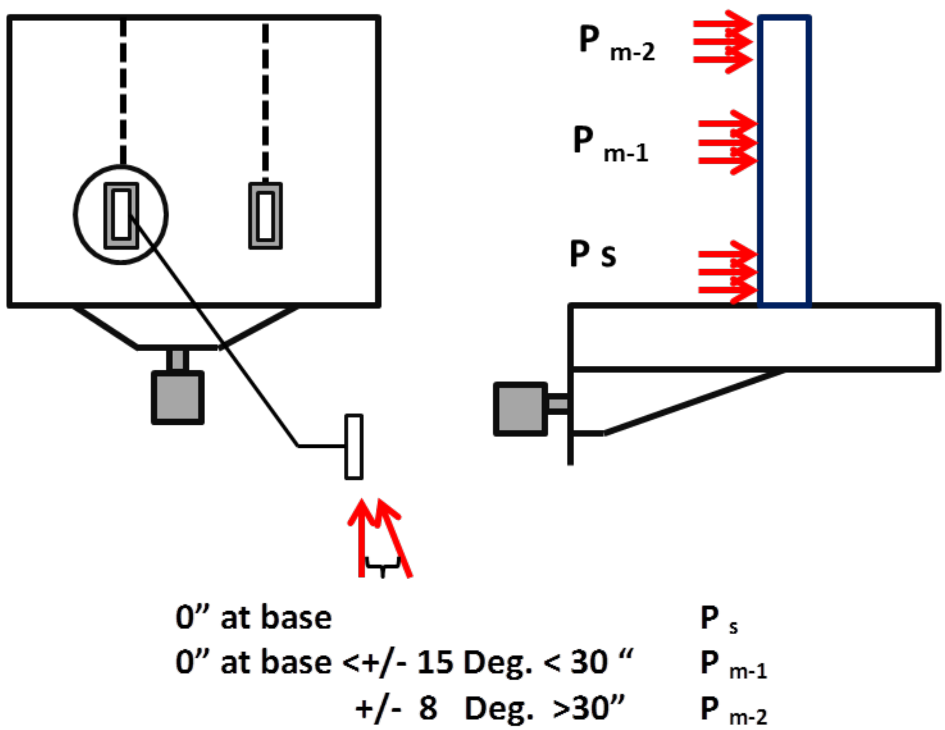

Figure 1. CP Loading Conditions
Courtesy: Schematic of Collision Post Loads, AAR MSRP Section M, S-580

The locations and orientations of the applied loads on the collision post are shown in Figure 1. Legacy locomotives, such as narrow-nose designs manufactured before 1990, did not have to comply with these crashworthiness requirements. Therefore, these older locomotives afford less crew protection in case of train collisions. Older locomotives have generally been relegated to non-lead locomotive service in Class I railroads; however, shortline railroads have purchased narrow-nose locomotives retired from Class I service for use as mainline locomotives on their systems. As a result, these locomotives are likely to remain in the North American fleet for the foreseeable future and pose risk to locomotive cab occupants.

1.2 Objectives

1. Evaluate the effectiveness of the proposed CP design by testing for 2001 AAR S-580 crashworthiness requirements.
2. Measure strains and deflections for the specific S-580 load case tested.
3. Validate the analytical model used to analyze alternate CP designs.

1.3 Overall Approach

Finite element analysis (FEA) of the baseline collision posts, as well as modified designs to improve the crashworthiness performance of CPs in a legacy locomotive, was carried out as part of the Phase II deliverable of this project. (See Phase I via the FRA eLibrary.) In addition to the two baseline designs, three alternate designs of the CPs were evaluated per 2001 S-580 requirements. Based on the results of this evaluation, the design featuring two collision posts with tapered I-beam cross-sections connected by a C channel was recommended and tested as the retrofit. Figure 2 shows the recommended CP design.

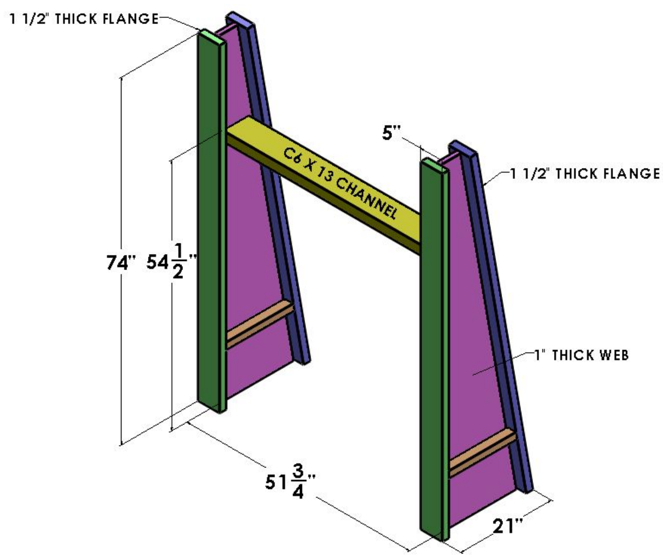

Figure 2. Tapered I-Beam CPs

Sharma & Associates Inc. (SA) acquired a representative, narrow-nose, legacy locomotive for structural testing of the collision posts. Figure 3 shows the locomotive purchased for the test.

Figure 3. Narrow-Nose Test Locomotive

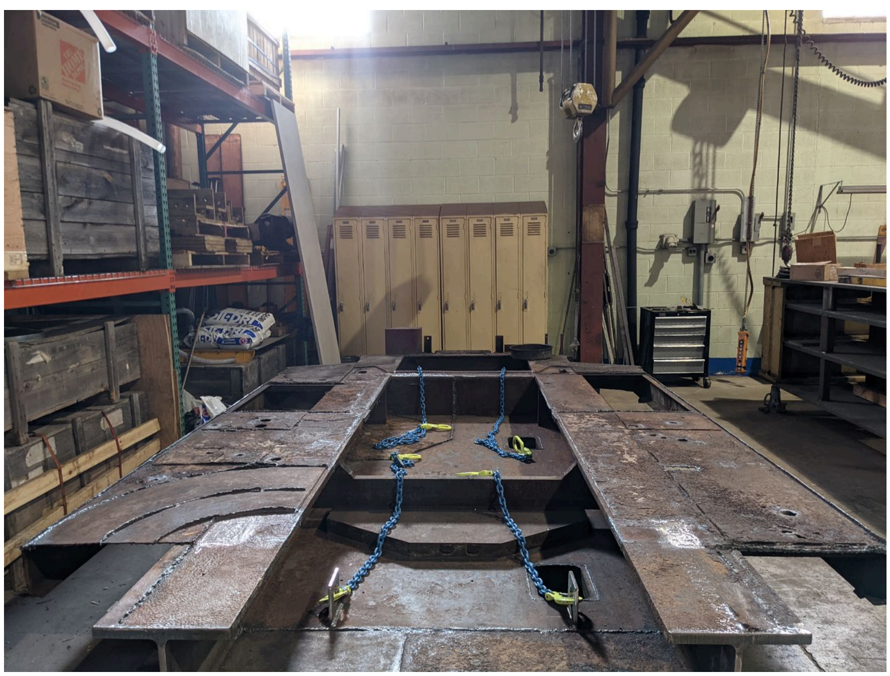

Figure 4. Locomotive Underframe

The locomotive was of the same SD-40 vintage that was evaluated using FEA for Phase I. The cab superstructure (which does not contribute appreciably to CP performance) was removed and the section of the underframe (UF) below the cab was used as the base underframe specimen upon which the CPs were mounted. Figure 4 shows the underframe after the cab superstructure and the existing collision posts were removed.

1.4 Scope

The scope of the project was limited to static testing of the collision post by applying a 200,000-lb. load at a height of 30 inches above the deck, as required by the 2001 AAR S-580 specification. The intent was to ensure the collision post could withstand the applied load and comply with the 2001 AAR S-580 requirement. The results from this testing were then used to validate the FEA model. Testing for the other load case in the AAR S-580 specification, i.e., application of 500,000 lbs at the base of the CP, was not in the project scope. S-580 calls for an analysis only for this load case, for which results can be obtained from the validated FEA model.

In the current version of S-580, the load magnitudes for the collision post are considerably higher, as noted in the Background section, and are meant to address the design requirements of the present-day locomotives. The underframe of the legacy locomotives, e.g., 1960s and 70s vintage, were designed using steel with much lower yield strength. Therefore, qualifying the legacy locomotives to the current version of the AAR S-580 specification was not within the scope of the project.

In line with the objectives outlined above, this report describes the test procedure to evaluate the collision post design for compliance with the aforementioned specific load case in the 2001 AAR S-580 specification.

The report includes a discussion of the test results used to validate the FEA model of the collision posts welded to the underframe of a legacy locomotive.

1.5 Organization of the Report

- Section 2 describes the test set up and instrumentation.
- Section 3 discusses the test procedure.
- Section 4 discusses results of the test. This section also discusses FEA model validation.
- The findings are summarized in Section 5.

2. Instrumentation and Test Setup

SA fabricated the collision posts as per the design dimensions shown in Figure 2 and Figure 5. The CPs were installed on the underframe, as shown in Figure 5. Figure 6 shows the CPs welded on to the underframe.

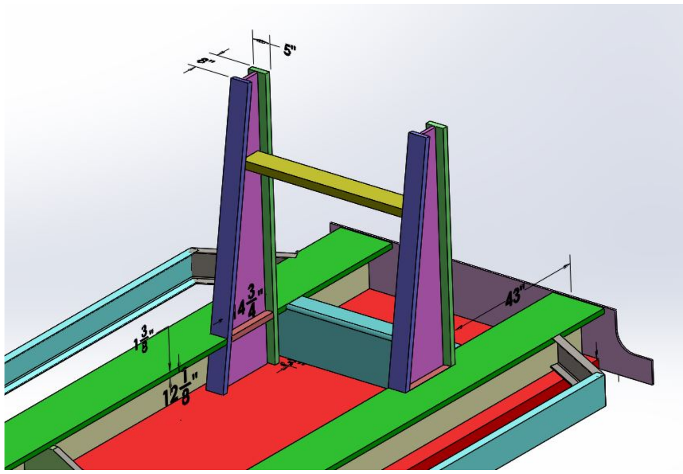

Figure 5. CP Located on Underframe

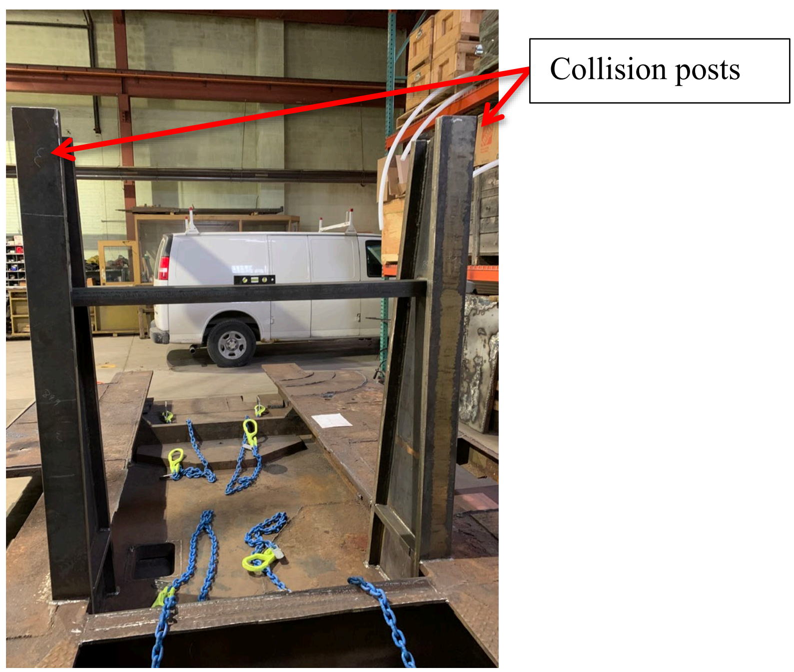

Figure 6. CPs Welded to Underframe

2.1 Strain Gauge Instrumentation

The CPs were strain-gauged at high-stress locations identified through FEA. The FEA model simulated the test setup. The locations and orientations of the strain gauges were selected based on the predicted stresses from an applied load of 200 kips, 30 inches above the top of the deck. Figure 7 shows the node locations and node numbers from the FEA model. Initially, 10 strain gauge locations were selected.

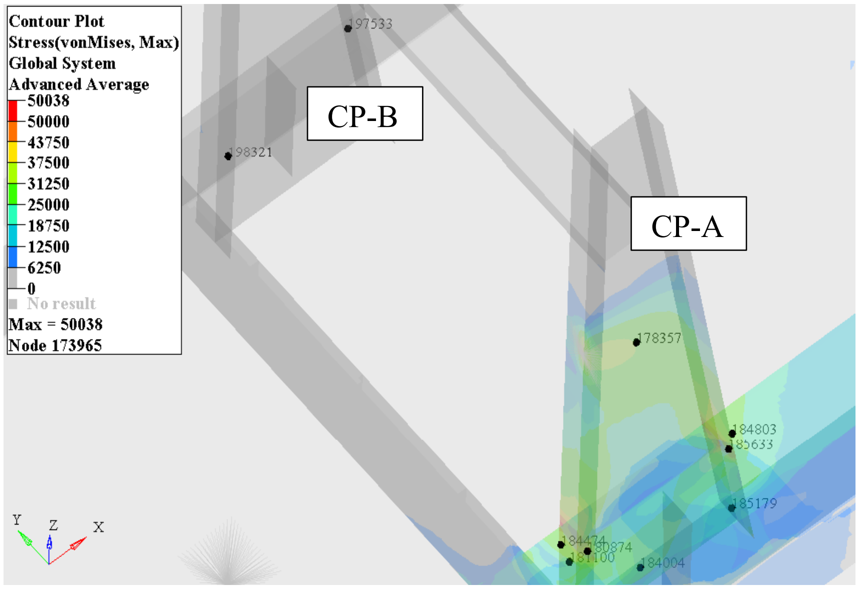

Figure 7. FEA Nodes for Strain Gauge Locations

SG #	Node ID	Location
SG_1	180874	CP-A
SG_2	178357	CP-A
SG_3	185633	CP-A
SG_4	185179	CP-A
SG_5	184004	CP-A
SG_6	181100	CP-A
SG_7	184474	UF (CP-A)
SG_8	184803	UF (CP-A)
SG_9	198321	UF (CP-B)
SG_10	197533	UF (CP-B)
SG_11	180865	CP-A
SG_12	184448	UF (CP-A)
SG_13	184819	UF (CP-A)

After analyzing the strains from an initial shakedown test in the laboratory, SA added three more rosettes. The gauges 1, 7, and 8 were located close to the weld for measuring the hot spot stresses. The additional gauges 11, 12, and 13 were 1 inch away from gauges 1, 7, and 8, respectively, to capture the nominal stresses. There were 11 strain gauges on or near the CP identified as “A” and two strain gauges on the underframe near the “B” CP. The locations of all the gauges are listed in Figure 7, along with the node identification (ID) numbers from the finite element (FE) model. The collision post on which the load was applied is identified as CP-A and the other collision post as CP-B in the figure. There were seven strain gauges on CP-A and four strain gauges on the underframe near CP-A. There were two strain gauges on the underframe near CP-B.

There were rectangular rosettes (3-channels per rosette) at 11 locations, and 2 uniaxial strain gauges at 2 locations for a total of 35 channels on both CPs. Refer to Figure 8 for a picture of the strain-gauged CP.

Appendix A shows pictures of individual strain gauges on the collision posts. Figure A-2 through Figure A-11 show close-up views of these strain gauges. The three additional rosettes are shown in Figure A-2, Figure A-8, and Figure A-9, respectively.

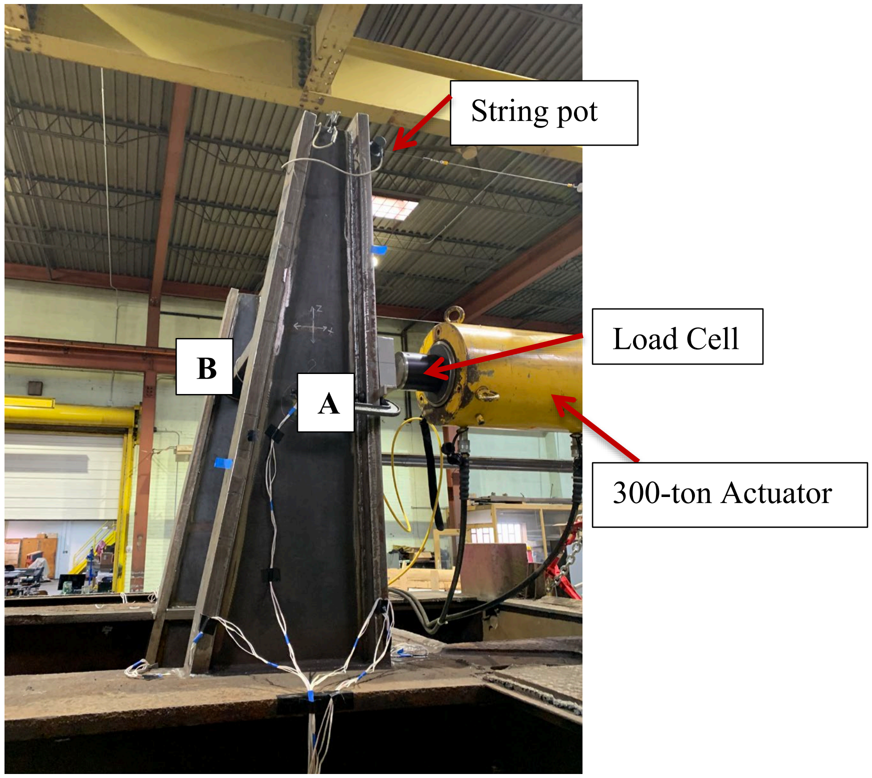

Figure 8. Instrumented CP

2.2 Test Setup

After researchers installed the strain gauges on the collision posts and the underframe, the assembly was mounted on the test load frame. A 3D model representation of this setup is shown in Figure 9. A 300-ton Enerpac hydraulic cylinder (Model CLRG-30012) was used to apply the load on one of the CPs, as shown in the figure.

A 400-kip load cell was placed between the cylinder and collision post to record the applied load. The load was applied 30 inches above the deck across the entire width and over 10 percent of the height of the collision post. A 2x6x5-inch steel block was placed between the load cell and the face of the CP to distribute the load. The magnitude of the applied load was controlled manually through a valve connected to a hydraulic pump. The CP test setup on the load frame in the SA laboratory is shown in Figure 10. The hydraulic cylinder was supported by a longitudinal beam attached to another transverse beam in the load frame, as shown in the figure. The longitudinal beam was supported by a vertical post.

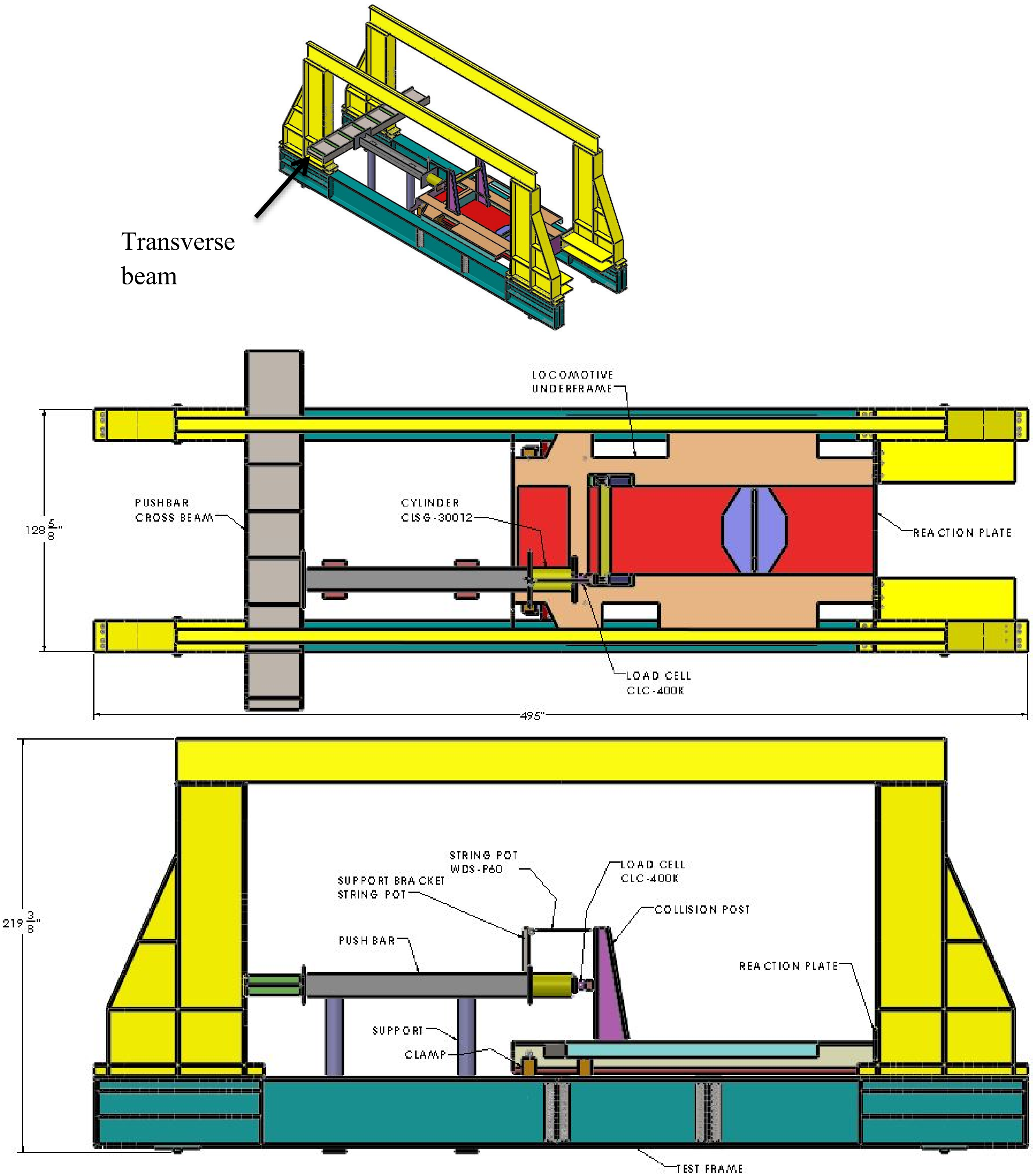

Figure 9. CP Test Setup

A close-up view of the string potentiometers, the 300-ton actuator, and the load cell is shown in Figure 11. The collision post on which the load was applied was identified as "CP-A" and the other post as "CP-B" in this report. As shown in the figure, string potentiometers ("string pots") attached 59.25 inches above the deck to measure the longitudinal deflections of the two CPs. A third string pot measured longitudinal and vertical displacements of the locomotive underframe, as shown in Figure 12.

The string potentiometers were used to monitor the deflections at these locations to identify potential issues, if any, early on during the incremental load applications and ensure safety during the tests. The load applied on the CP at the front end was reacted at the back end of the underframe. To react the applied load, the rear end of the underframe was welded to the reaction plate at the back. A rear view of the load frame and the back of the reaction plate is shown in Figure 13.

The strain gauges, string potentiometers, and load cell were connected to a SOMAT data acquisition system. The SOMAT data collection software was used to set up the channels, sampling rates, and analog filters. The data was collected at 100 samples per second. The data collection software allowed the test data to be exported to .CSV files for further processing.

Table 1 shows the list of instrumentation used in the test. All the gauges, load cells, and string potentiometers were in a calibrated condition at the time of the test with valid calibration certificates.

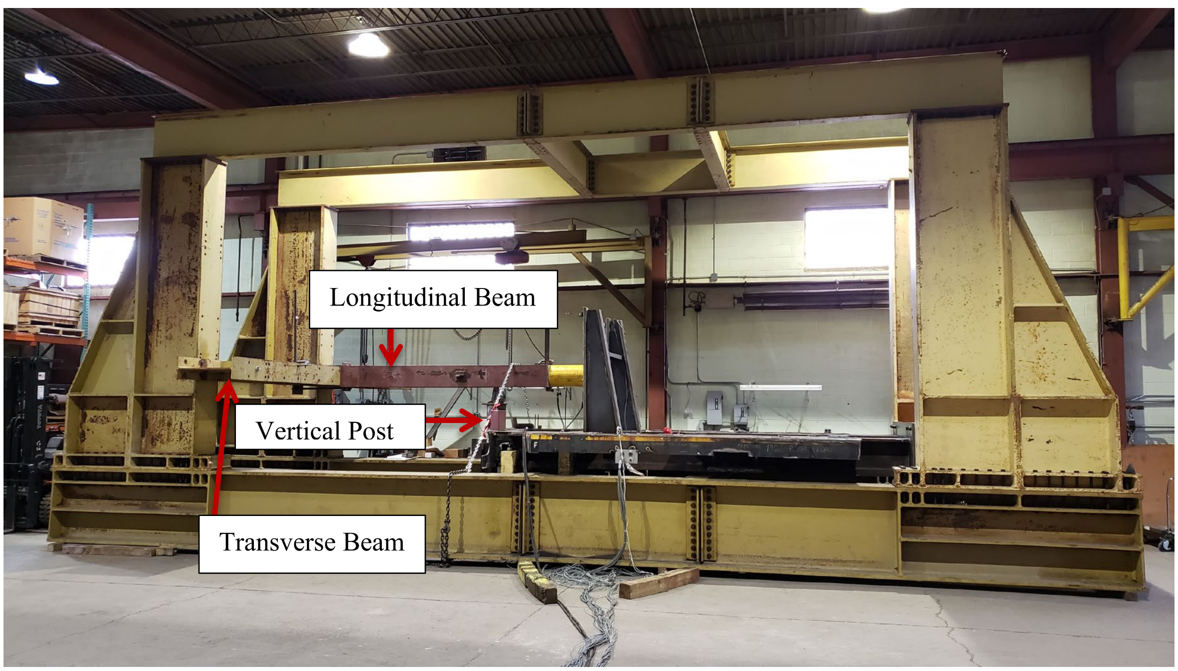

Figure 10. CPs on Load Frame

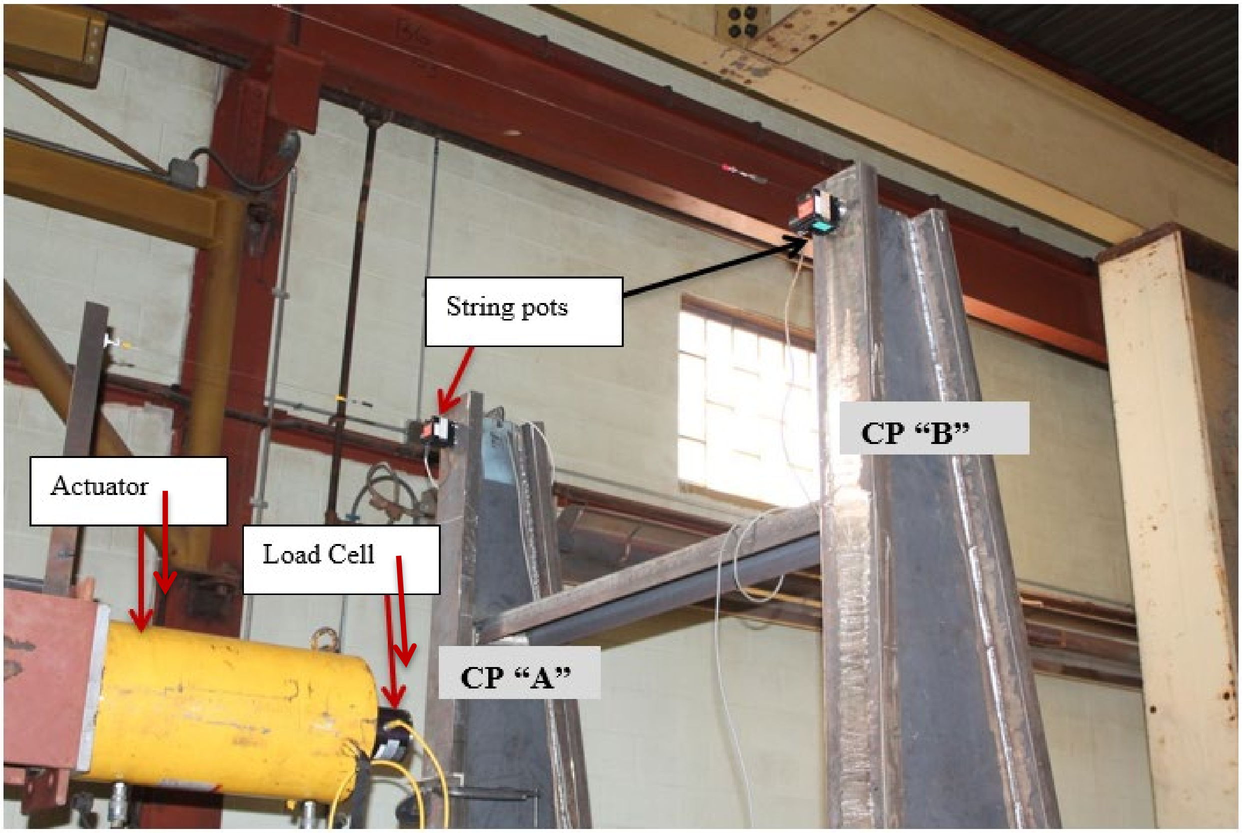

Figure 11. Close-up View of the CPs

Figure 12. Longitudinal String Potentiometer on the Underframe

Table 1. Instrumentation List

Name	Quantity	Type	Precision	Manufacturer	Model
Data Acquisition System	2	eDAQLite	±0.1%	HBM	SoMat
Strain Gages	11	Stacked Rosette	±0.001%	KYOWO	KGFS-3-350-D17-11 L10M3S
Strain Gages	2	Uniaxials	±0.00015%	HBM	K-CLY4-6/350
Displacement Transducers	3	String pots	±1.0%	Micro-Epsilon	WDS-300-P60-CR-P
Load Cell	1	400 kips	±0.1%	BLH-Nobel	C2P1 400K
Actuator	1	600 kips	-	Enerpac	CLRG 300-12

Figure 13. Reaction Plate on Load Frame

3. Test Description

The collision post design requirement in AAR S-580 (2001) states: *"A minimum of 2 collision posts, located on the underframe longitudinal (center sills) shall be designed to withstand a longitudinal force of 200,000 lb. each at 30" above the deck and 500,000 lb. each at the underframe deck without exceeding the ultimate strength of the material."* The test load case was a load of 200,000 lb. applied on the flange of the collision, 30 inches above the deck, as shown in Table 2.

Table 2. Test Load Case

Load Location	Net Force (kips)	Angle (deg)	Comment
30" above deck (44" from underframe)	200	0 (perpendicular to CP flange)	AAR S-580 (2001)

The measured values were compared to the predicted stresses as part of the FEA model validation.

<u>Test Procedure</u>

The testing procedure consisted of the following steps:

- The loads were applied in four steps as indicated below.
- Initialized zeros in all gauges, spring pots and load cells
- Applied load for Test 1 was 50 kips, which was 25 percent of the full load. The load increment was 50 kips for the subsequent three tests.
- The stresses and deflections at the intermediate steps were monitored to ascertain that the measured values were reasonable.
- To ensure personnel safety during the tests, the engineer at the laboratory visually inspected the CPs, the locomotive underframe, and the test fixture after each load step.
- The test engineer inspected for any visual indication of cracks at the welded joints of the CPs and the integrity of the fixture mountings after each load step.

Load Step 1:

- Apply load of 50 kips on CP-A and record strains and deflections.
- Reduce the load back to zero (or an acceptable minimum load not exceeding 2 percent of the applied load) and record the strains and deflections.

- Visually inspect the collision posts and the underframe for any visible deformations or cracks. If no visible cracks or failure of the CPs and underframe are present, proceed to the next step.

Load Step 2:

- Apply load of 100 kips and record strains and deflections.
- Reduce the load back to zero (or an acceptable minimum load not exceeding 2 percent of the applied load), and record the strains and deflections.
- Perform visual inspection of the collision posts and the underframe. If no visible cracks or failure of the collision posts and underframe, proceed to the next step.

Load Step 3:

- Apply load of 150 kips and record strains and deflections.
- Reduce the load back to zero (or an acceptable minimum load not exceeding 2 percent of the applied load), and record the strains and deflections.
- Perform visual inspection of the collision posts and the underframe. If no visible cracks or failure of the collision posts and underframe are present, proceed to the next step.

Load Step 4:

- Apply the full load of 200 kips and record strains and deflection.
- Reduce the load back to zero (or an acceptable minimum load not exceeding 2 percent of the applied load), and record the strains and deflections.
- Process the test data for comparison to FEA results at the strain gauged locations.

Pass/Fail Criteria:

The S-580 criterion requires that the collision post must withstand the applied load without exceeding the ultimate strength of the post and its attachment to the underframe.

4. Test Results

The SA team conducted a shakedown test to ensure the gauges and data collection system functioned as intended. The maximum load applied during this test was 100 kips, which was 50 percent of the full load. The measured strain values were converted to von Mises stresses and compared with the predicted stresses from the FEA model. There was sufficient correlation between them to proceed with the testing.

Appendix B shows stress plots from the FEA model developed specifically to simulate the test setup. The material for collision post was A572 Grade 50 steel. The material for the underframe was tested to evaluate the material characteristics. An accredited material testing laboratory performed tensile testing of three samples from the underframe. The average yield strength for the steel plate samples was 29.8 ksi, and the average tensile strength was 61 ksi. The tested material characteristics for the underframe were used in the FEA model. The stresses from this model were compared with the test results.

The team performed the official test with FRA representatives witnessing via video link. The test steps listed in Section 3 were followed and the data were collected at each load step, i.e., 25 percent for Step 1, 50 percent for Step 2, 75 percent for Step 3, and 100 percent of full load for Step 4.

The test engineer in the SA laboratory monitored strains during the test, not to exceed 1,800 µS. The FE model had predicted a maximum strain of 1,700 µS.

In addition to Step 4 at 100 percent load, correlation plots for Steps 1 to 3 at the intermediate load steps are provided for completeness.

4.1 Gauge Linearity Check

The string potentiometers and strain gauges were checked for linearity as the applied load increased from 0 to 200 kips. As shown in Figure 14, the string potentiometers exhibited good linearity over the range of the applied load. The longitudinal displacement of CP-A was highest in response to the applied load on this post. The linearity plot for some of the critical strain gauge locations, along with the corresponding correlation coefficient R^2, is shown in Figure 15.

All the strain gauges plotted had good linearity – except for the 45° channel of strain gauge 1. This channel stayed linear until the applied load reached 150 kips. The correlation coefficient R^2 for strain gauge SG_1_45, an indicator of the linearity, was 0.914, excluding the strain reading at 200 kips and 0.734, when the strain at the 200-kip load was included. The actual measured load was 200.444 kips for load step 4. The non-linear behavior of the strain gauge at SG 1 indicated there was some local yielding on the front flange of the CP due to bending.

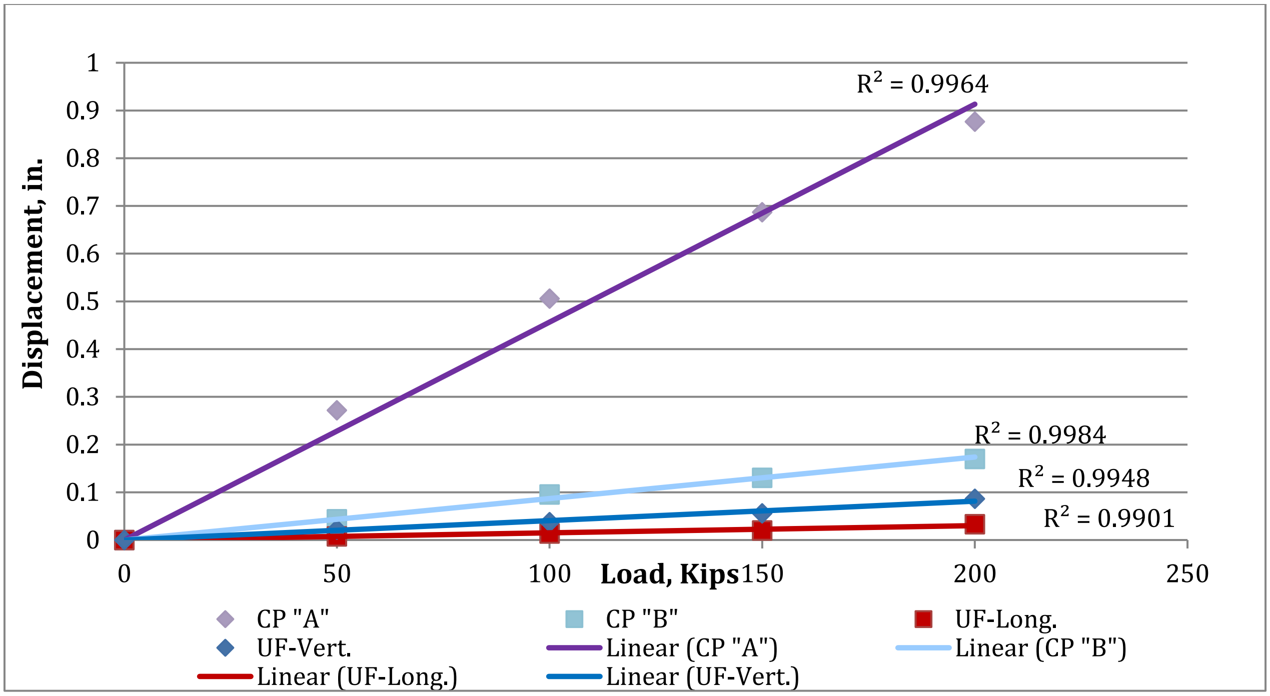

Figure 14. Linearity Plot for String Potentiometers

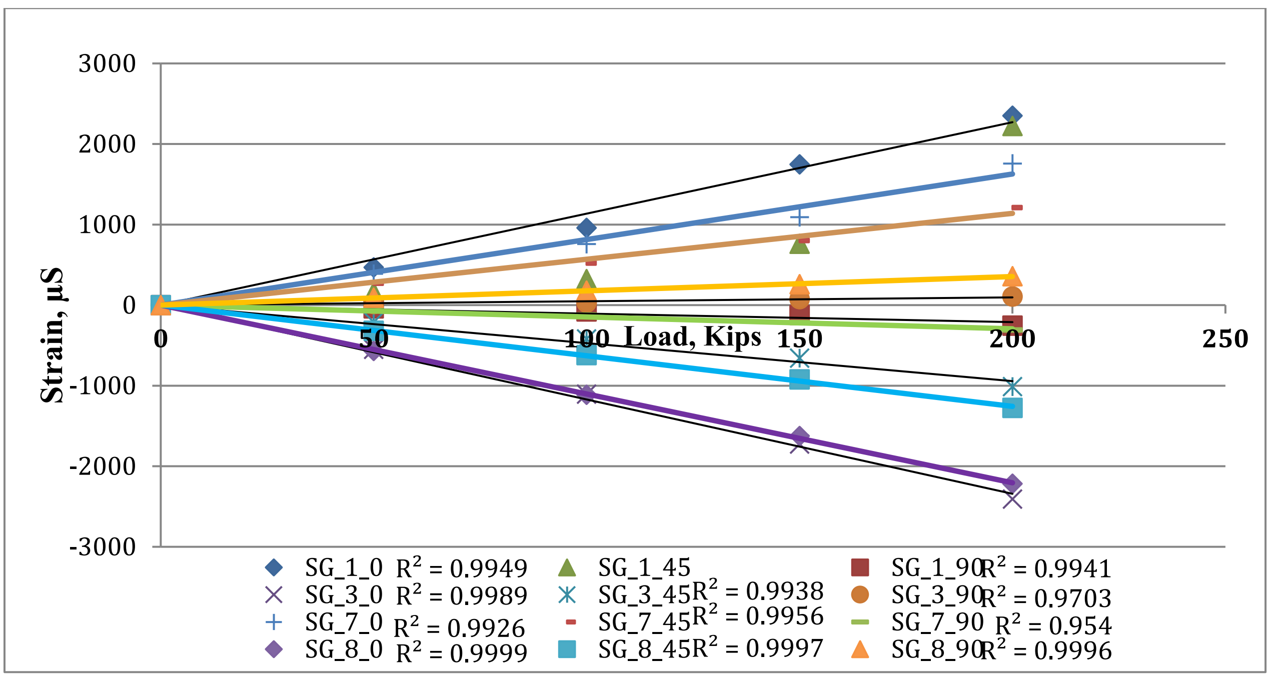

Figure 15. Strain Gauge Linearity

4.2 Discussion of Step 1 Results

The comparison of the measured stresses from Step 1 with the predicted stresses from the FEA model is provided in Table 3. Figure 16 shows the correlation plot between the FEA predicted stresses and measured stresses from the test. The least squared fit had an R^2 value of 0.73. Strain gauges 8 and 13 noted on the plot were on the underframe behind the back flange of CP-A, as shown in Figure 18. Though the measured stresses at these locations were higher than the FEA predictions, the stresses were well below the material yield strength of 30 ksi for the underframe material. For locations with low stress, e.g., strain gauges 4, 9, 10, and 12 with measured stresses below 10 ksi, percentage differences between the measured and predicted stresses were high.

Table 3. Stress Comparison at 25% of Full Load, FEA vs. Test

Gauge #	VM Stress from FEA, ksi	VM Stress from Test, ksi	% Difference	Node # from FEA Model
1	14.4	13.4	-8%	180874
2	6.3	8.1	21%	178357
3	13.3	15.7	15%	185633
4	3.1	4.8	36%	185179
5	5.6	5.5	-2%	184004
6	7.1	7.2	2%	181100
7	12.9	12.4	-4%	184474
8	10.0	17.3	42%	184803
9	0.7	1.6	55%	198321
10	0.7	0.3	-174%	197533
11	11.9	10.7	-11%	180865
12	8.2	4.1	-98%	184448
13	7.9	12.0	34%	184819

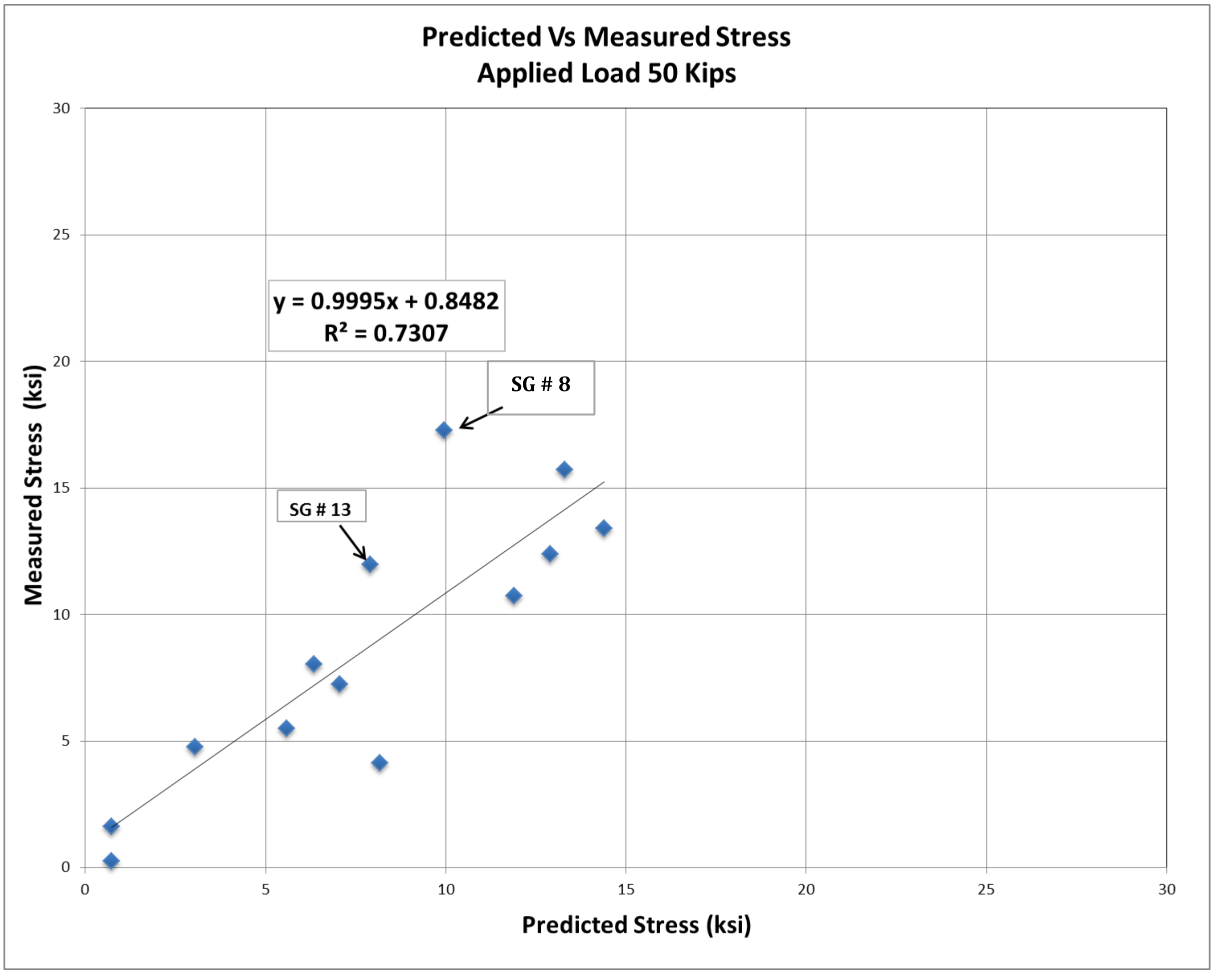

Figure 16. Correlation Plot for Load Step 1

4.3 Discussion of Step 2 Results

The comparison of the measured stress from Step 2 with the predicted stress from the FEA model is provided in Table 4. Figure 17 shows the correlation plot between the predicted stresses and the measured stresses for this load case. Similar to Step 1, strain gauges 8 and 13 had predicted stresses not matching well with the measured values. The correlation was also poor for strain gauges 4, 9, 10, and 12, with low measured stresses as noted in the previous test. The R^2 value for the trend line was 0.81, slightly higher than the previous case.

As shown in Figure 19, the maximum measured stress of 31.5 ksi in the collision post was at location 3 on the back flange, near the weld where the post was welded to the underframe. On the underframe, the maximum stress was behind the CP at location 13. The stresses around strain gauge locations 3, 8, and 13 on the back side were compressive due to the bending moment from the force applied on the front face of the CP, 30 inches above the deck.

Table 4. Stress Comparison at 50% of Full Load, FEA vs. Test

Gauge #	VM Stress from FEA, ksi	VM Stress from Test, ksi	% Difference	Node # from FEA Model
1	28.8	27.5	-5%	180874
2	12.7	15.8	20%	178357
3	26.6	31.5	16%	185633
4	6.1	9.7	37%	185179
5	11.2	10.8	-4%	184004
6	14.1	14.1	0%	181100
7	25.6	24.2	-6%	184474
8	19.8	28.4	30%	184803
9	1.5	2.9	49%	198321
10	1.4	0.7	-112%	197533
11	23.9	22.1	-8%	180865
12	16.2	8.3	-94%	184448
13	15.7	23.5	33%	184819

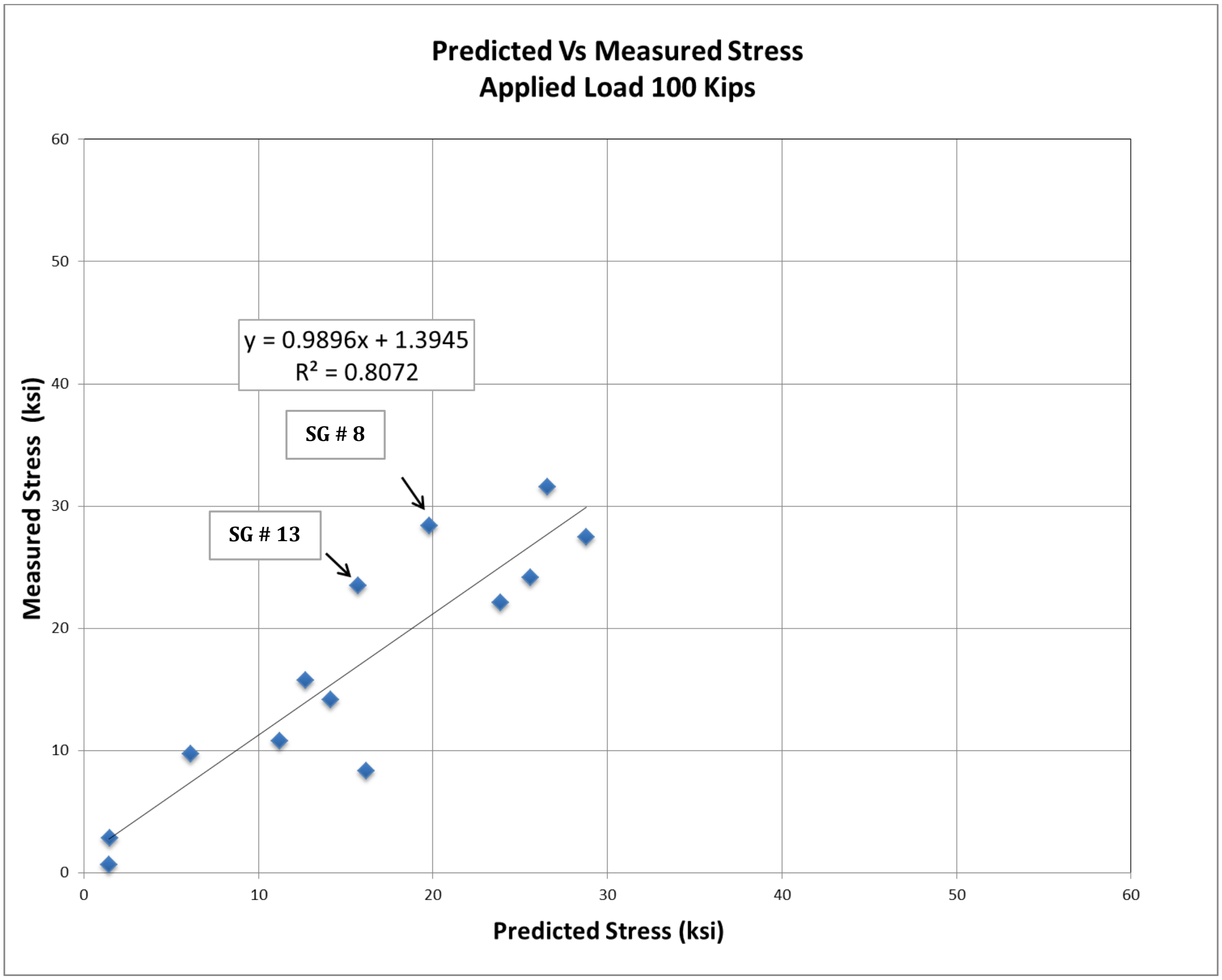

Figure 17. Correlation Plot for Load Step 2

4.4 Discussion of Step 3 Results

The comparison of the measured stress from Step 3 with the FEA predicted stress is provided in Table 5. Figure 20 shows the correlation plot between the predicted FEA stresses and measured stresses from the strain gauges for this load case. As shown in the figure, the R^2 value from the correlation plot for this test was 0.91.

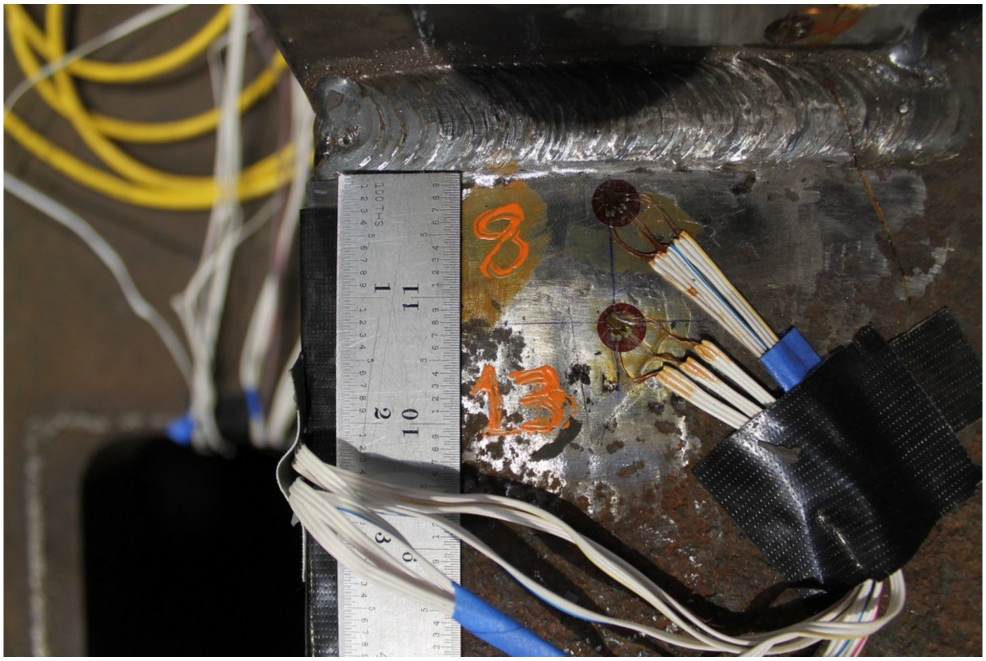

Figure 18. Strain Gauge Locations 8 & 13

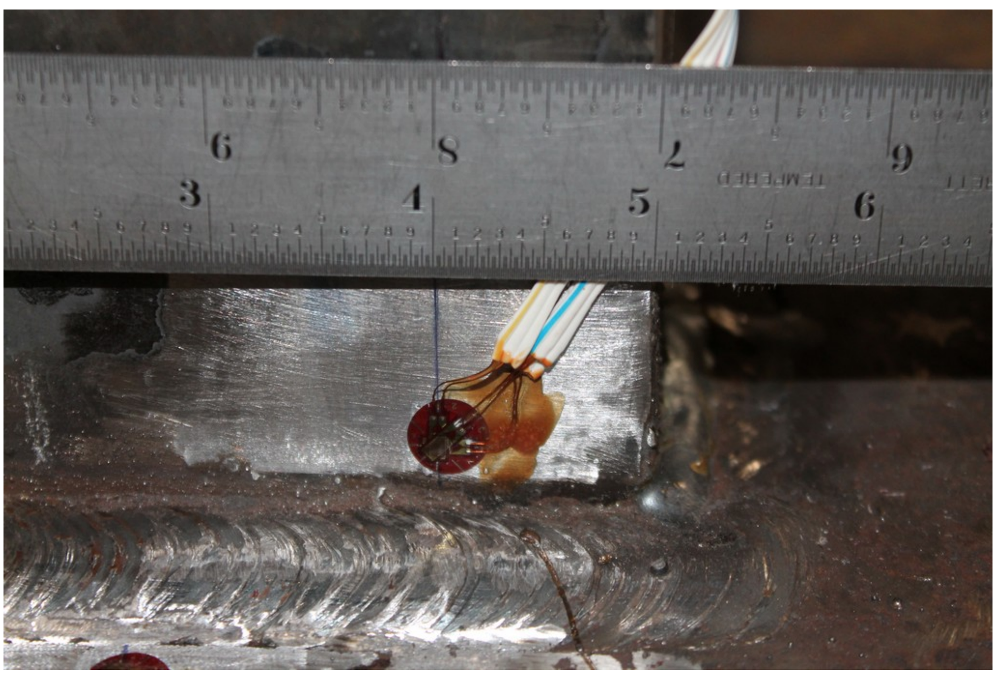

Figure 19. Strain Gauge Location 3

For this load case, as noted in the table below, the correlation for strain gauge locations 8 and 13 were much better in comparison to the previous two load cases. For the uniaxial strain gauge at location 4, the measured stress was higher than the predicted stress. This gauge was located on the back flange, as shown in Figure A-5. The stress plots from the FEA are shown in Figure 21 and Figure 22. The stress at this location was compressive, as shown in Figure 21. The compressive stress was due a bending moment from the applied load on the front face of the collision, 30 inches above the deck.

The maximum stress was reported by gauge 1 for both the FEA model and the test, as seen from Table 5. The stress near gauge 1 was tensile due to the bending moment from the applied load on the front flange, 30 inches above the deck. The correlation for location 7 was excellent, i.e., only a 0.4 percent difference, as seen from Table 5. Strain gauge 12 was 1 inch away from gauge 7, near the front face of the CP. The measured stress at location 12 was less than the FEA predicted stress, and the percentage difference between the two at this location was high. As shown in Figure 22, the actual stress gradient as measured during the test around gauges 7 and 12 was steeper than the one predicted by the FEA model.

Table 5. Stress Comparison at 75% of Full Load, FEA vs. Test

Gauge #	VM Stress from FEA, ksi	VM Stress from Test, ksi	% Difference	Node # from FEA Model
1	43.1	45.2	5%	180874
2	19.0	22.3	15%	178357
3	39.7	44.9	12%	185633
4	9.2	14.9	38%	185179
5	16.9	15.2	-11%	184004
6	21.5	20.8	-3%	181100
7	29.8	29.9	0.4%	184474
8	28.7	27.9	-3%	184803
9	2.2	3.7	41%	198321
10	2.1	1.2	-74%	197533
11	35.3	31.1	-13%	180865
12	22.3	13.7	-63%	184448
13	23.2	28.3	18%	184819

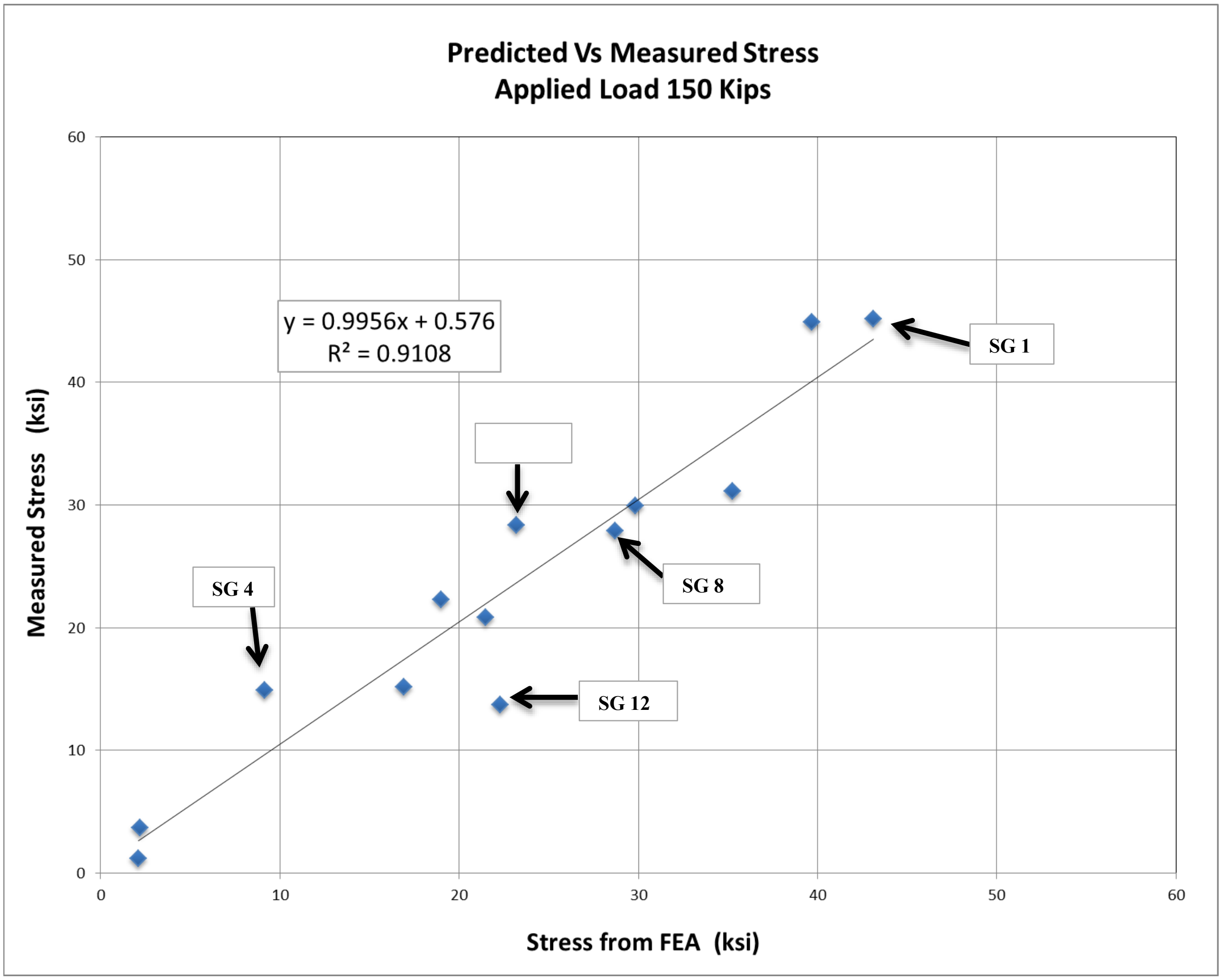

Figure 20. Correlation Plot for Load Step 3

After Step 3 was completed, a visual inspection of the collision posts and the underframe sections around them did not indicate the presence of cracks.

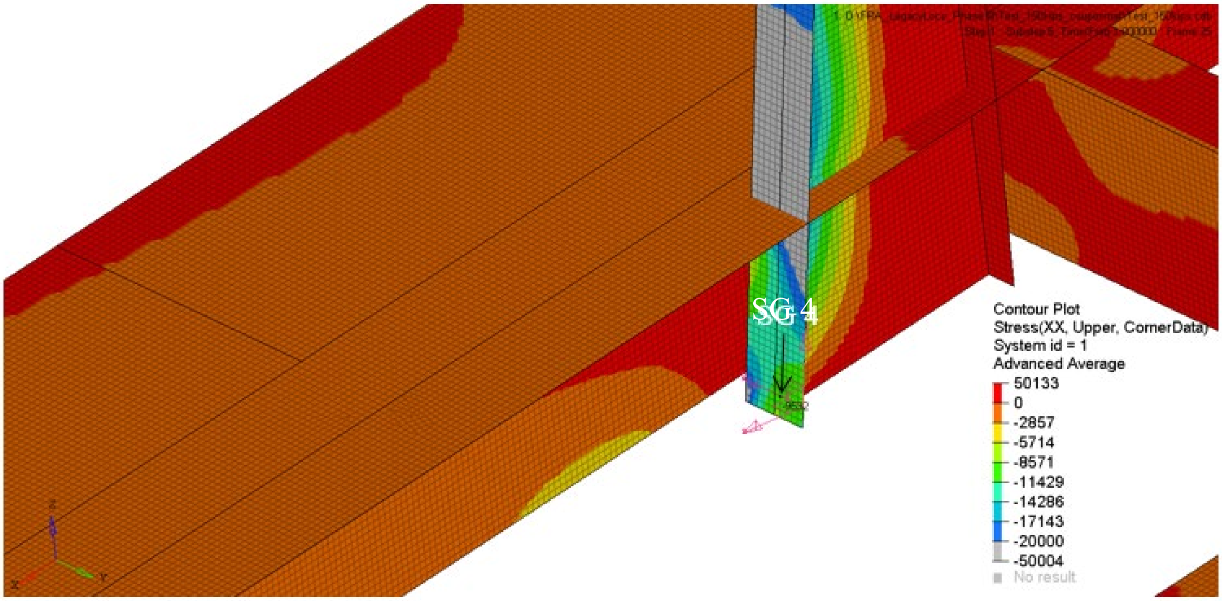

Figure 21. Directional Stress (Vertical) – Applied Load 150 Kips

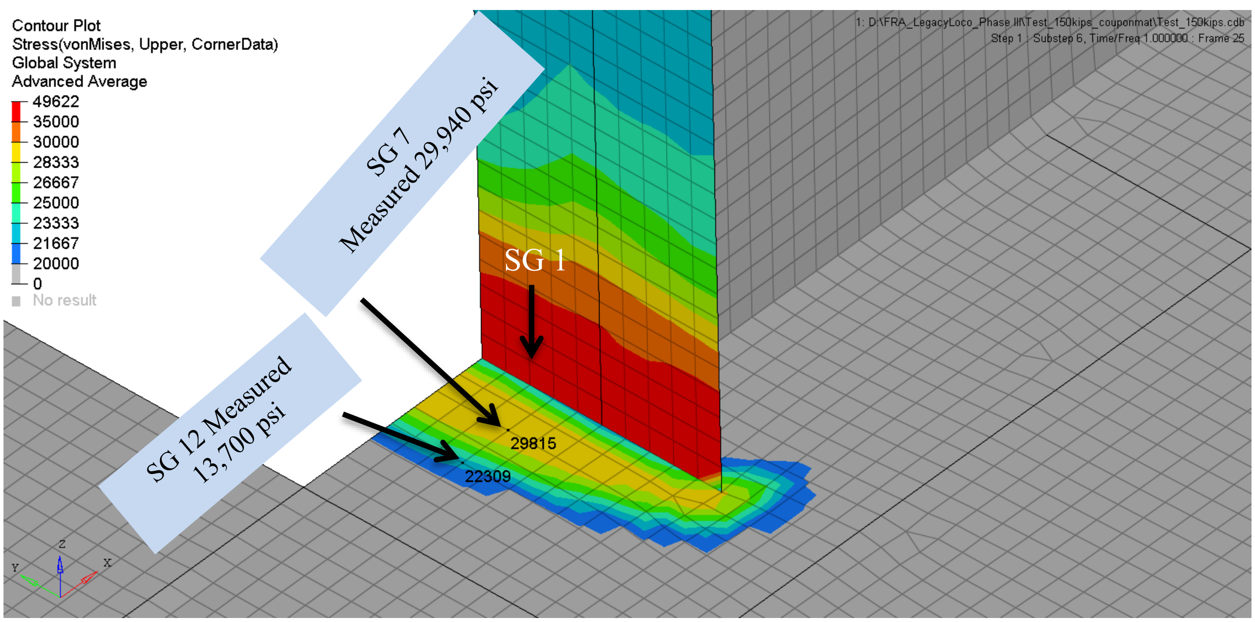

Figure 22. von Mises Stress – Applied Load 150 Kips

4.5 Discussion of Step 4 Results

The applied load on the collision post was increased to 200 kips, the maximum load as required by the AAR S-580 (2001) specification. The actual measured value was 200.444 kips. The comparison of the measured stress from Step 4 with the predicted stress from the FEA model is provided in Table 6. Figure 23 shows the correlation plot between the FEA predicted stresses and the measured stresses for this load case. The R^2 value was 0.94, as noted in the figure, showing high correlation between the predicted and measured stress values.

There were 10 strain gauges with predicted stresses matching well with the measured values in this test. Out of the remaining 3 gauges, strain gauges 9 and 10 on the underframe near CP-B measured stresses below 5 ksi, indicating these locations were not critical.

The percentage difference between the predicted and measured stresses at location 4 was 40 percent. The strain gauge at this location was a uniaxial gauge, as shown in Figure A-5. The stress plot from the FEA is shown in Figure 24. The stress was compressive, as shown in the figure.

For this load case, the correlation for strain gauges at locations 7 and 12 was very good, as seen from Table 6. In the previous load case, there was poor correlation for strain gauge 12, near the front face of the CP.

Table 6 Stress Comparison at 100% of Full Load, FEA vs. Test

Gauge #	VM Stress from FEA, ksi	VM Stress from Test, ksi	% Difference	Node # from FEA Model
1	49.9	48.4	-3%	180874
2	25.3	29.3	14%	178357
3	49.8	44.0	-13%	185633
4	12.4	20.7	40%	185179
5	22.7	20.2	-12%	184004
6	29.3	27.7	-6%	181100
7	29.8	27.9	-6%	184474
8	29.8	26.7	-12%	184803
9	2.9	4.8	38%	198321
10	2.8	1.8	-55%	197533
11	44.6	41.0	-9%	180865
12	24.7	29.1	15%	184448
13	27.9	27.3	-2%	184819

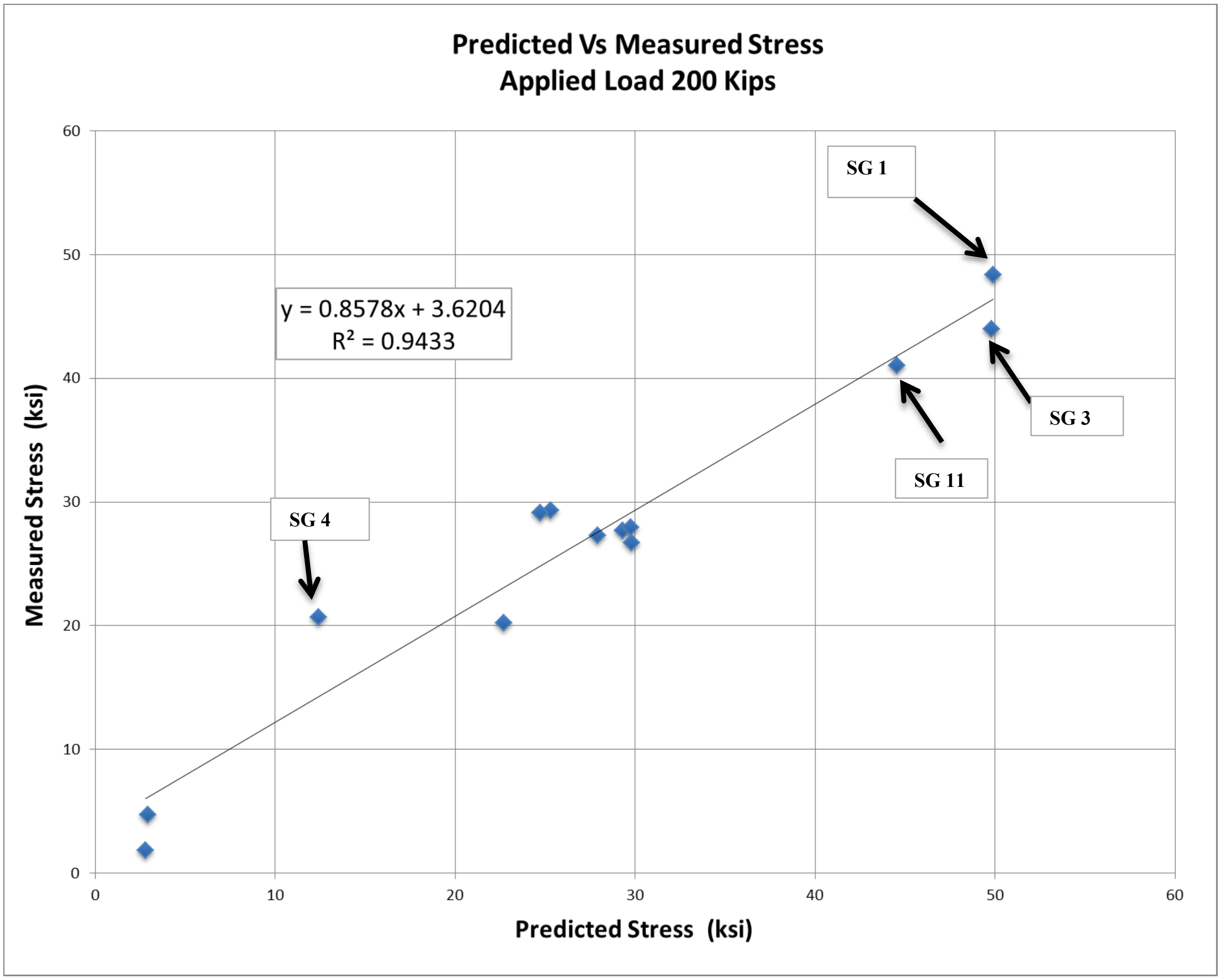

Figure 23. Correlation Plot for Load Step 4

The highest stress location was at strain gauge 1 for both the FEA model and test, as seen from Table 6. As noted in this table, locations with the second- and third-highest measured values were for gauges 3 and 11. FEA also predicted that these locations would have the second and third highest values of stress.

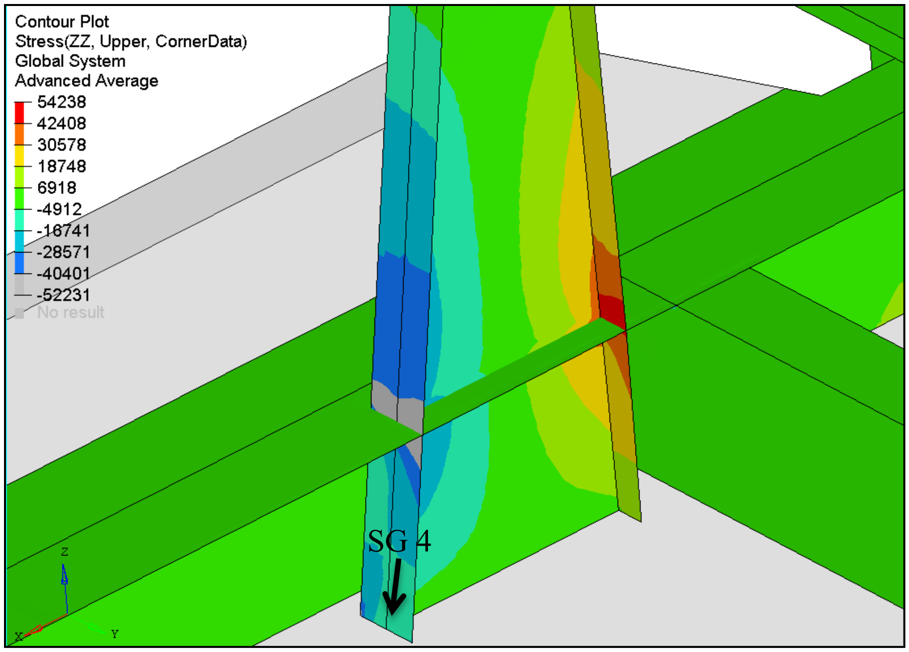

Figure 24. Directional Stress (Vertical) – Applied Load 200 Kips

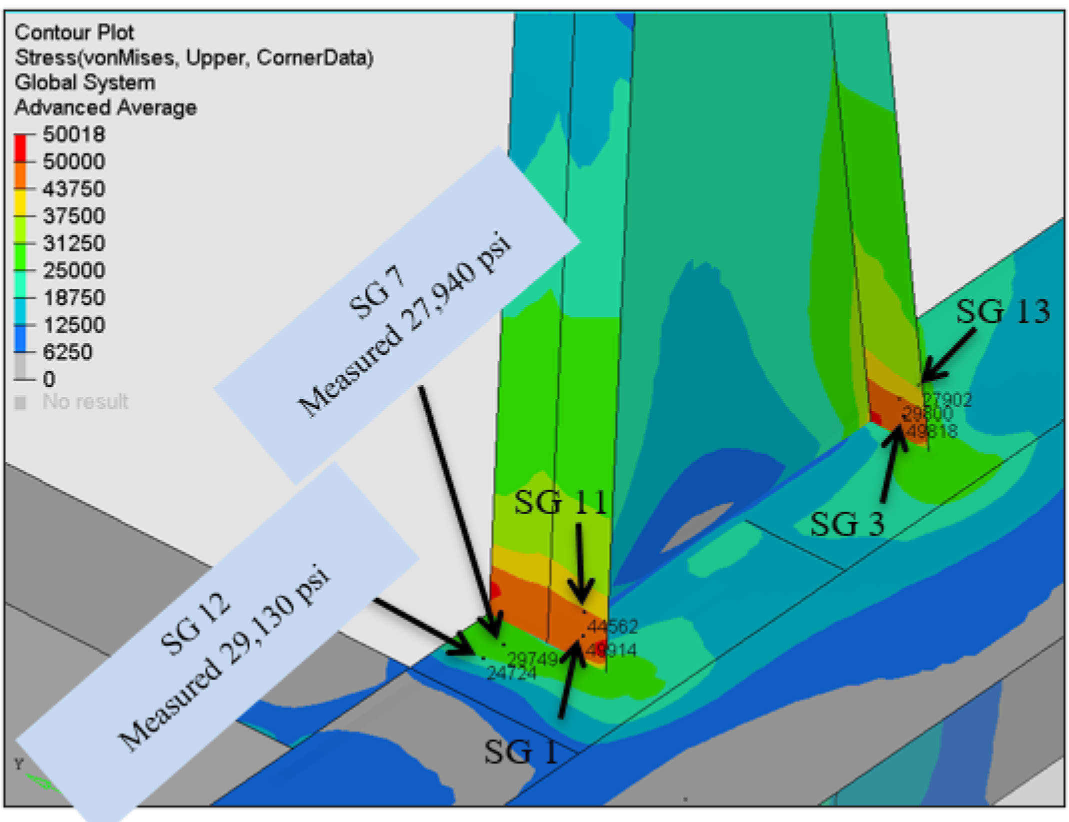

Figure 25. von Mises Stress – Applied Load 200 kips

The visual inspection of the collision posts and underframe sections nearby did not indicate any cracks after Step 4; application of the full load of 200 kips.

There were no indications of cracks on the weld around CPs. They did not fail during the maximum load case, and therefore fully complied with the requirements of the 2001 AAR S-580 specifications.

The FEA model predicted stresses showed excellent correlation with the measurements for this test.

5. Conclusion

Legacy locomotives, such as narrow-nose designs manufactured before 1990, were not required to comply with crashworthiness standards now required on all locomotives in mainline freight operations. Therefore, such locomotives, many to remain in service in the foreseeable future, afford less crew protection in case of train collisions. The objective of this project was to fabricate, test, and validate a collision post design that meets the crashworthiness requirements of AAR S-586 (circa 2001) to assist railroads as they retrofit their legacy locomotive fleets.

In Phase II of this project, SA designed and analyzed three collision post configurations to retrofit legacy locomotives. A tapered I-beam design for the CPs was recommended.

In this phase, an SD-40 legacy locomotive underframe, including the narrow nose and cab area, was procured. All superstructure was removed and cleaned to facilitate access to the attachment area and allow the underframe to be fixed in a loading frame.

Two prototype collision posts of the recommended tapered I-beam design were fabricated and welded to a locomotive underframe structure. Thirteen strain gauges and three potentiometers were applied to the CP and the frame.

The post was tested at the SA test facility for four load cases: 50, 100, 150, and 200 kips. The maximum load applied in S-580 was 200 kips. A SOMAT data acquisition system was used to collect the data.

The results of the test showed that the collision post design complied with the AAR S-580 (2001) specification requirements, i.e., the maximum stress measured was well below the ultimate strength.

The FEA model of the collision posts on the locomotive platform was validated using the strain gauge measurements from the test. The FEA model showed excellent correlation with the stress measurements from the test. Further, the measured strains correlated well with the expectations from design simulations, thereby validating the robustness of the retrofit design.

6. References

Association of American Railroads. (2014). *Manual of Standards and Recommended Practices.* Section M – Locomotive Crashworthiness Requirements, AAR S-580 Standard.

Federal Railroad Administration. (2019). Improving Collision Post Crashworthiness of Legacy Locomotives [DOT/FRA/ORD-19/41]. Washington, DC: U.S. Department of Transportation.

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AAR	Association of American Railroads
CP	Collision Post
DOT	Department of Transportation
FEA	Finite Element Analysis
FRA	Federal Railroad Administration
MSRP	Manual of Standards and Recommended Practices
SA	Sharma & Associates, Inc.
SG	Strain Gauge
UF	Underframe
VM	Von Mises

Appendix A

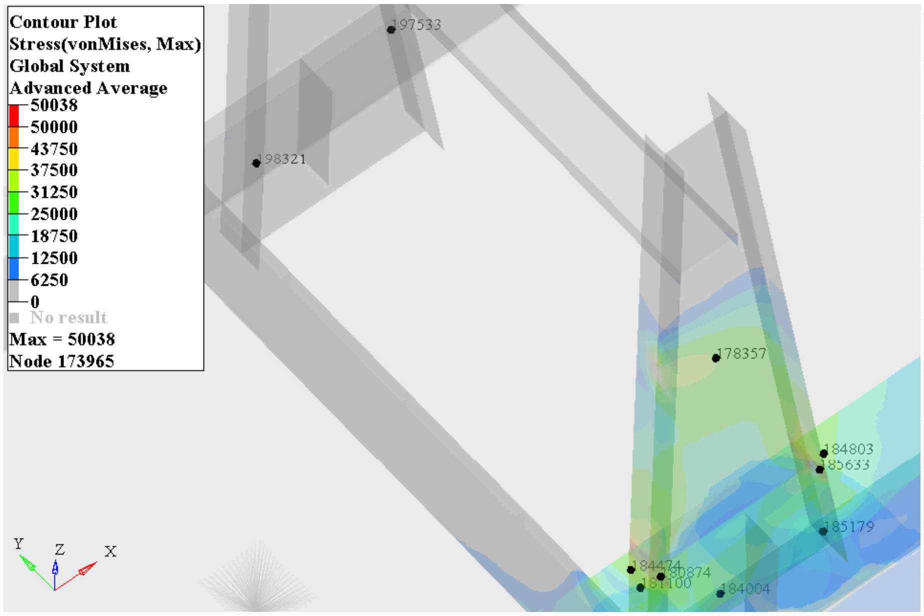

Figure A-1. FEA Nodes for Strain Gauge Locations

SG #	Node ID	Location
SG_1	180874	CP-A
SG_2	178357	CP-A
SG_3	185633	CP-A
SG_4	185179	CP-A
SG_5	184004	CP-A
SG_6	181100	CP-A
SG_7	184474	UF (CP-A)
SG_8	184803	UF (CP-A)
SG_9	198321	UF (CP-B)
SG_10	197533	UF (CP-B)
SG_11	180865	CP-A
SG_12	184448	UF (CP-A)
SG_13	184819	UF (CP-A)

Figure A-2. Strain Gauges 1 and 11

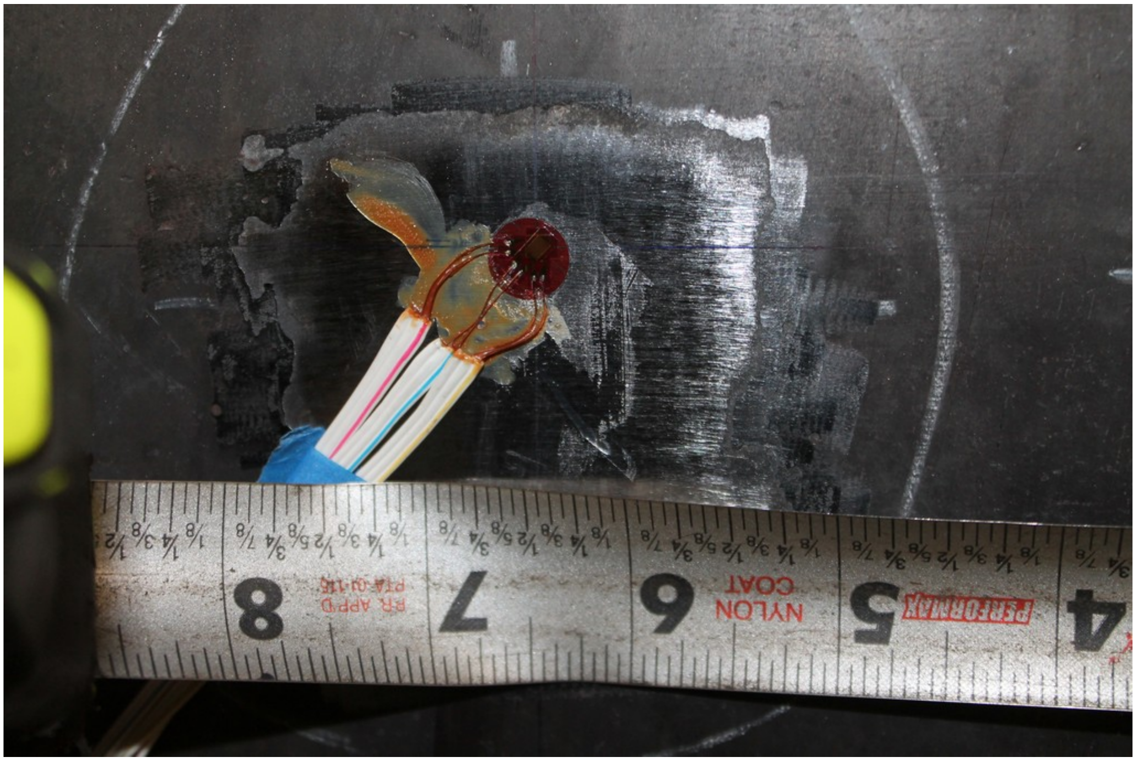

Figure A-3. Strain Gauge 2

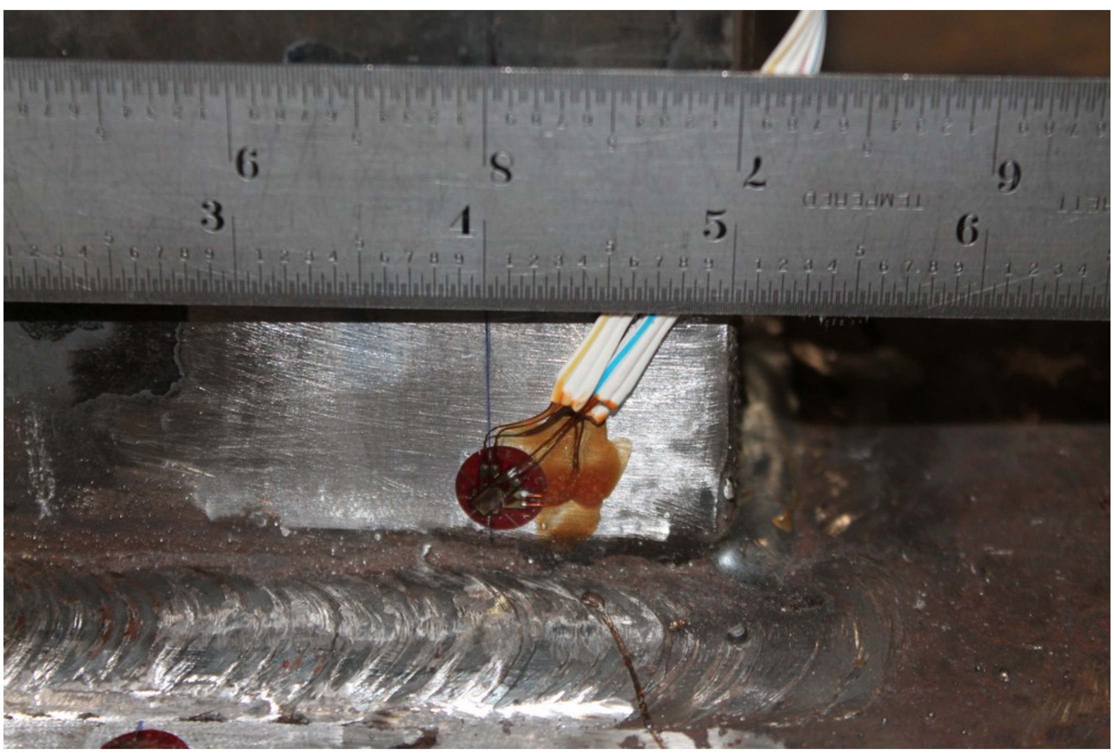

Figure A-4. Strain Gauge 3

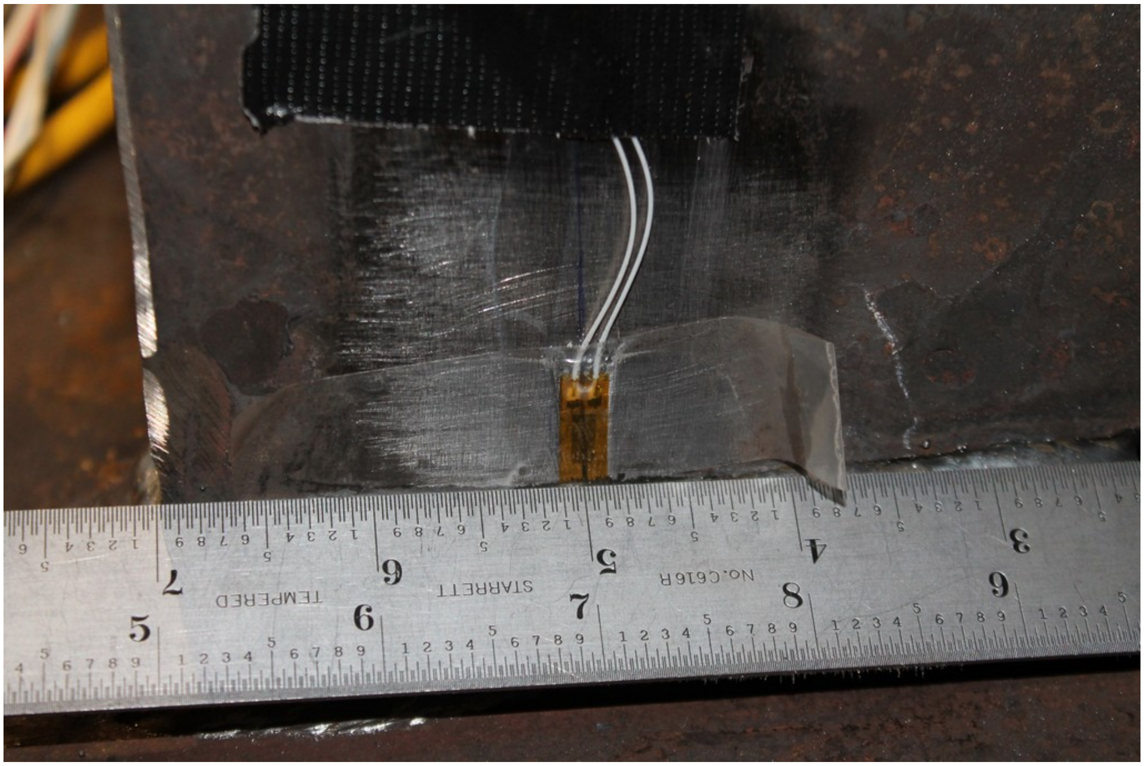

Figure A-5. Strain Gauge 4

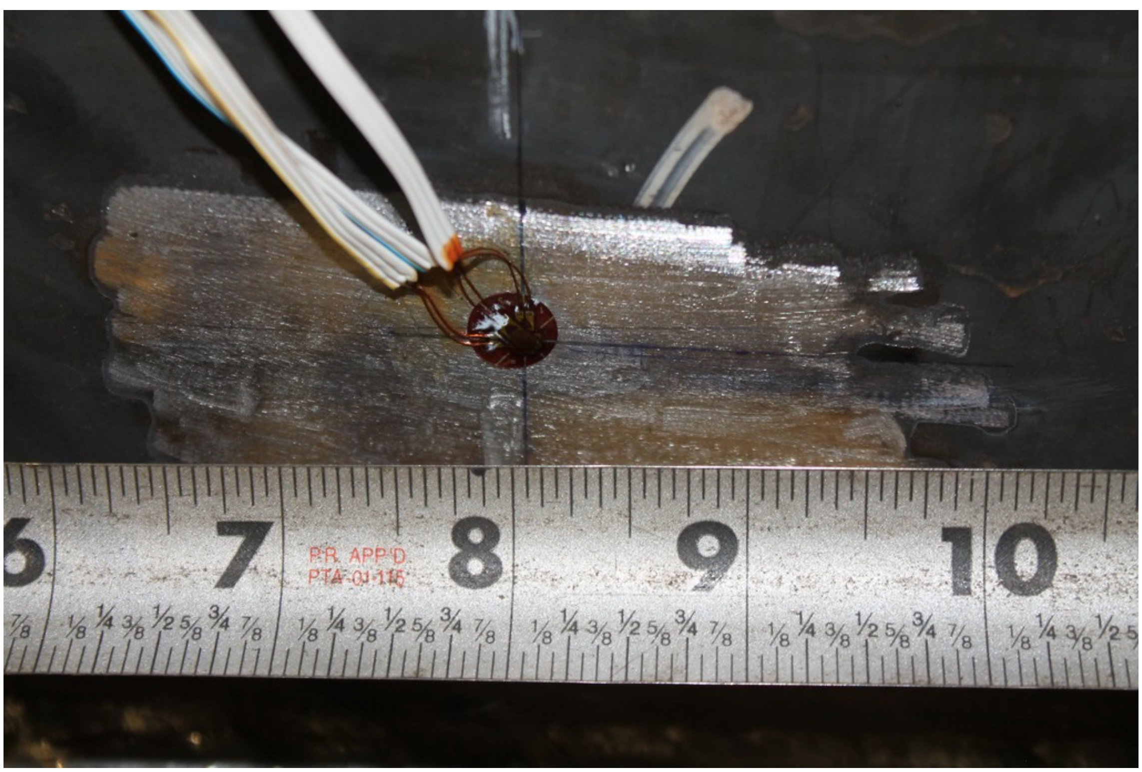

Figure A-6. Strain Gauge 5

Figure A-7. Strain Gauge 6

Figure A-8. Strain Gauges 7 and 12

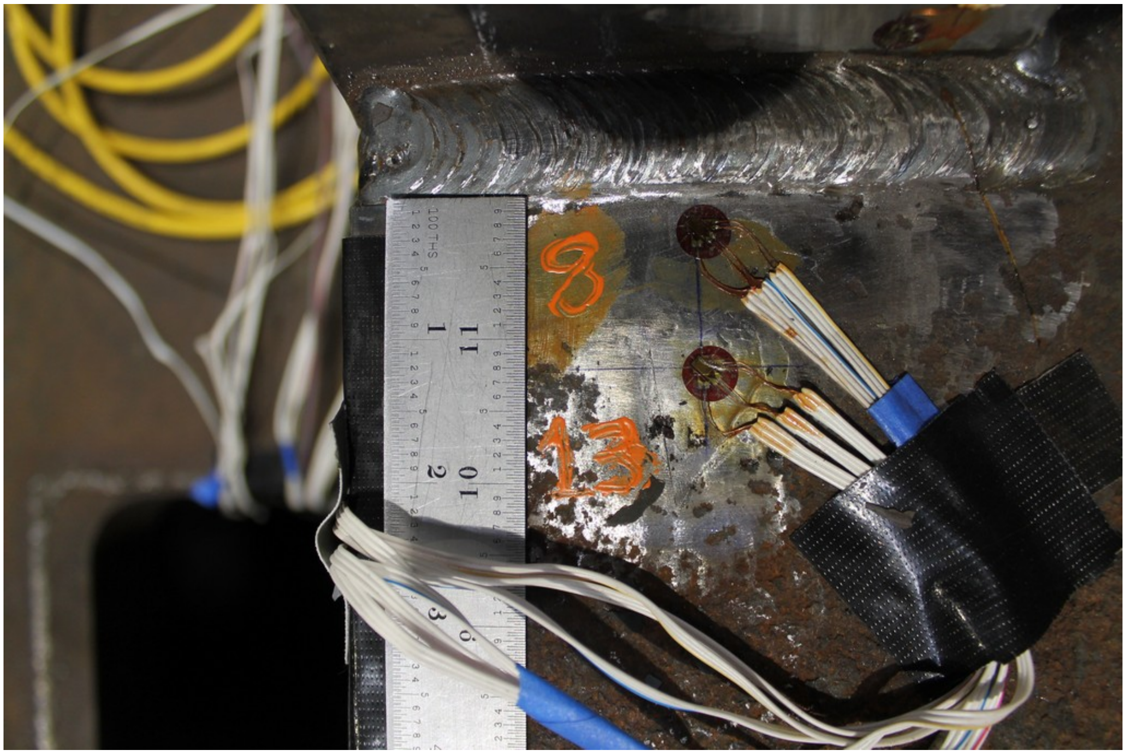

Figure A-9. Strain Gauges 8 and 13

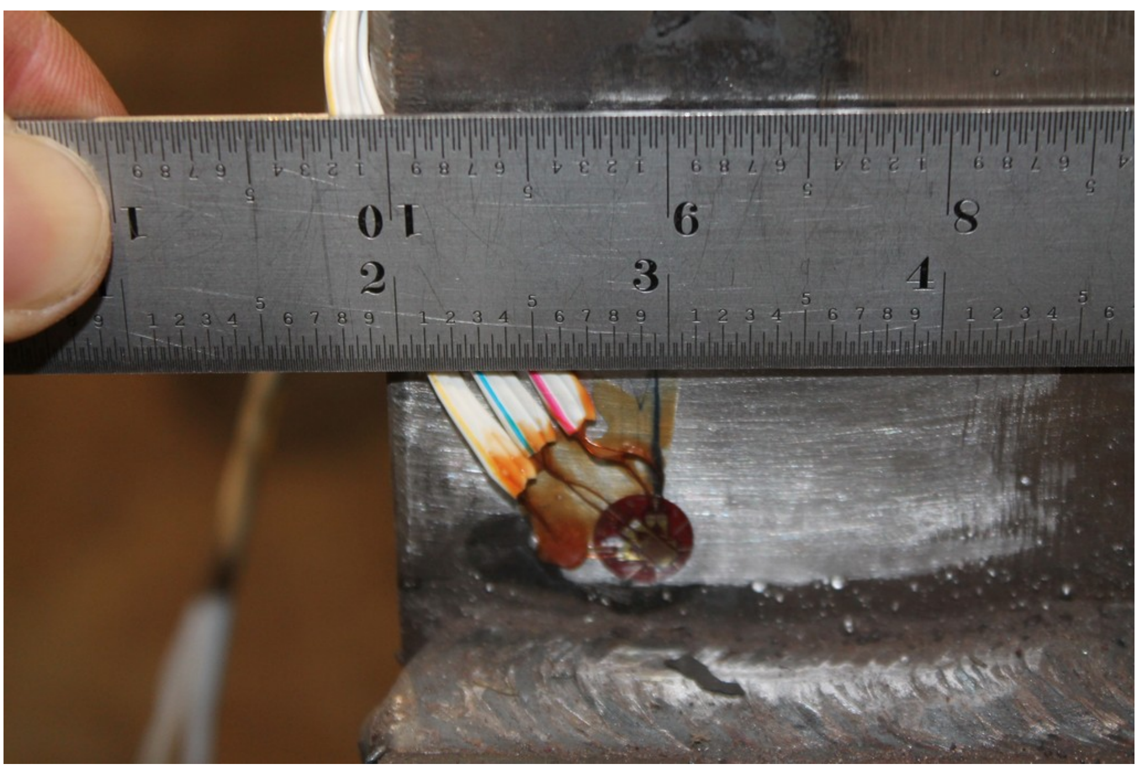

Figure A-10. Strain Gauge 9

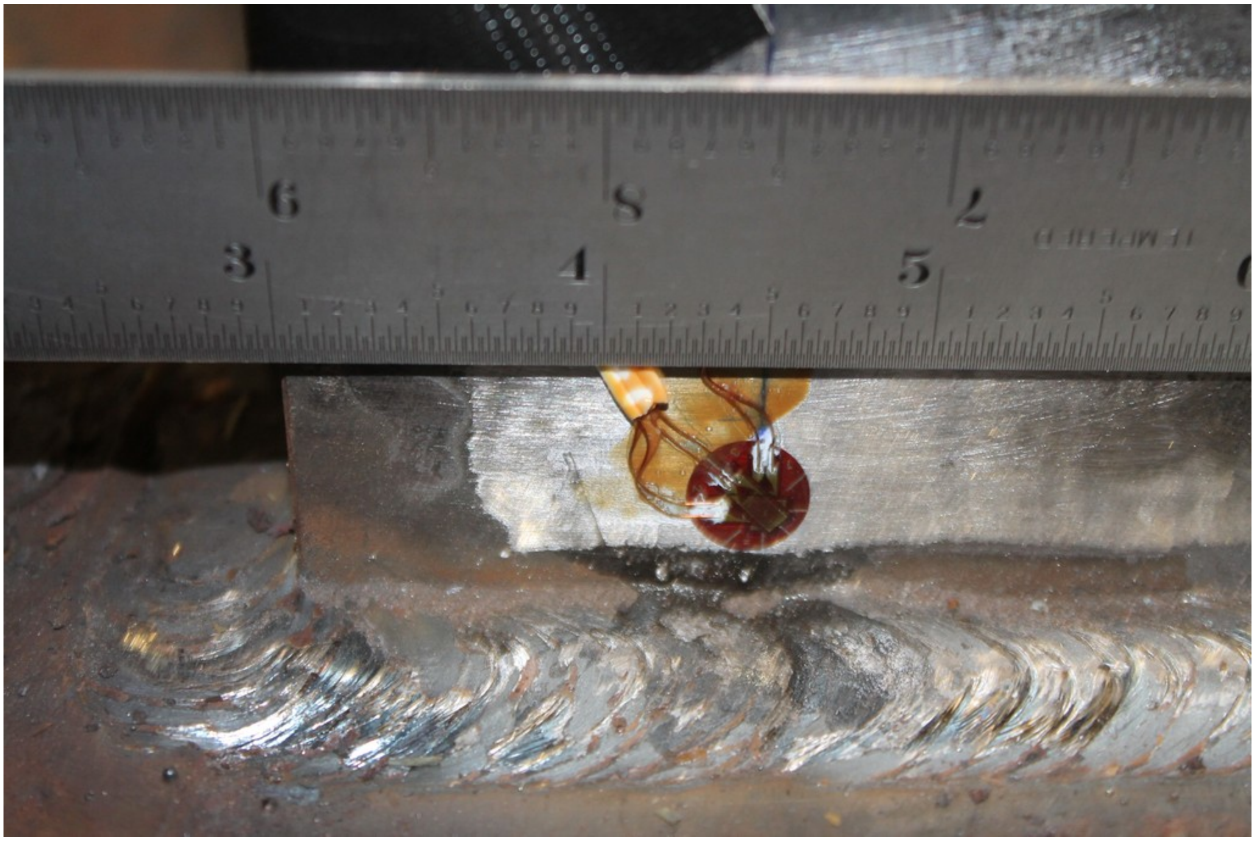

Figure A-11. Strain Gauge 10

Appendix B

FEA Plots

Applied Load 200 Kips

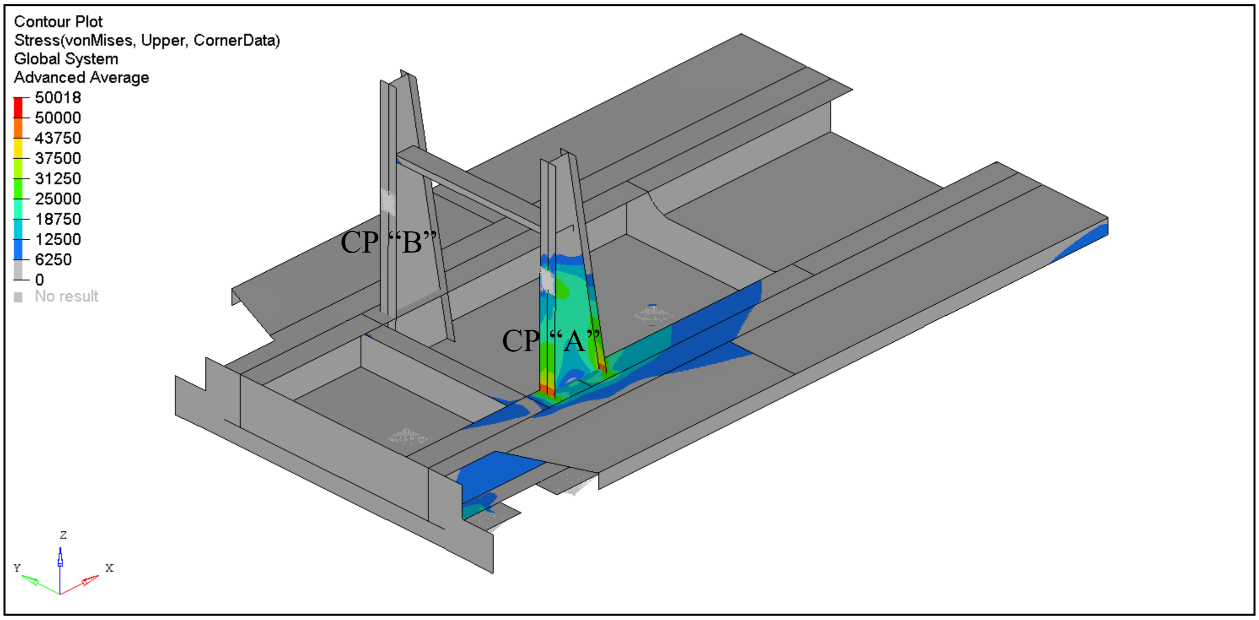

Figure B-1. von Mises Stress

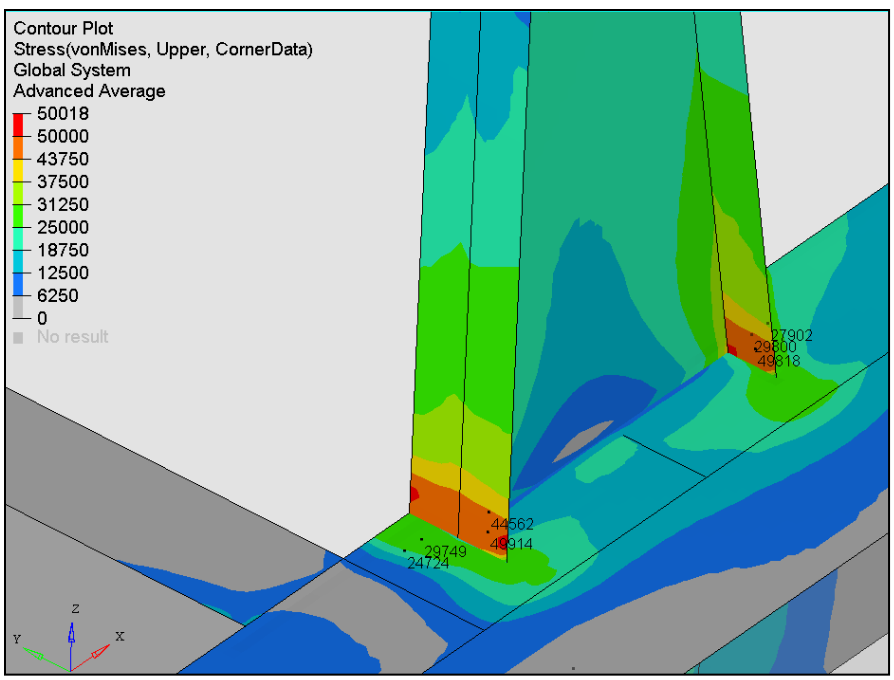

Figure B-2. Front Flange of CP-A (von Mises Stress)

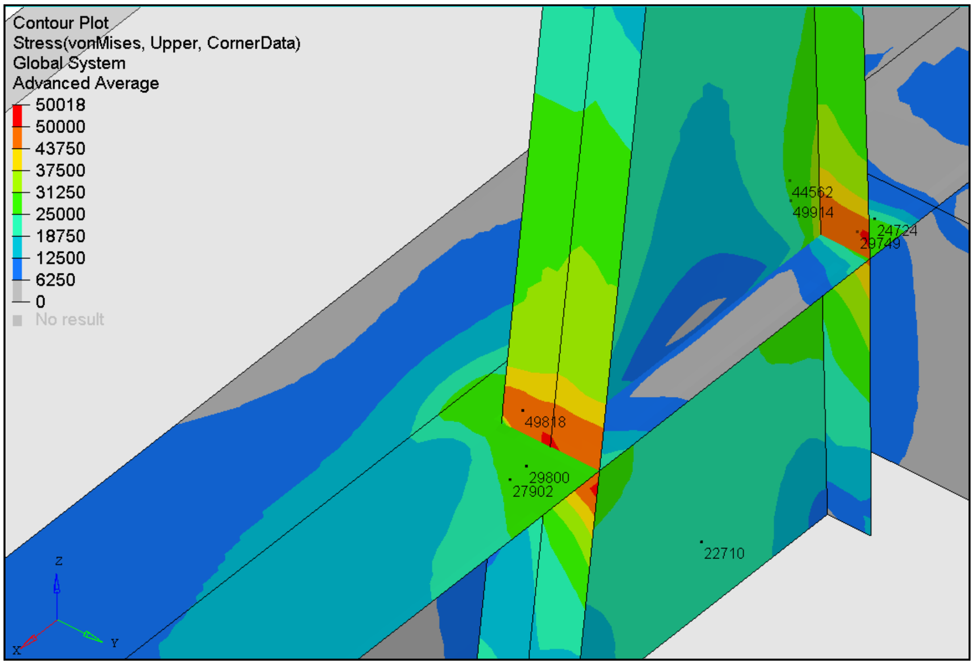

Figure B-3. Back Flange of CP-A (von Mises Stress)

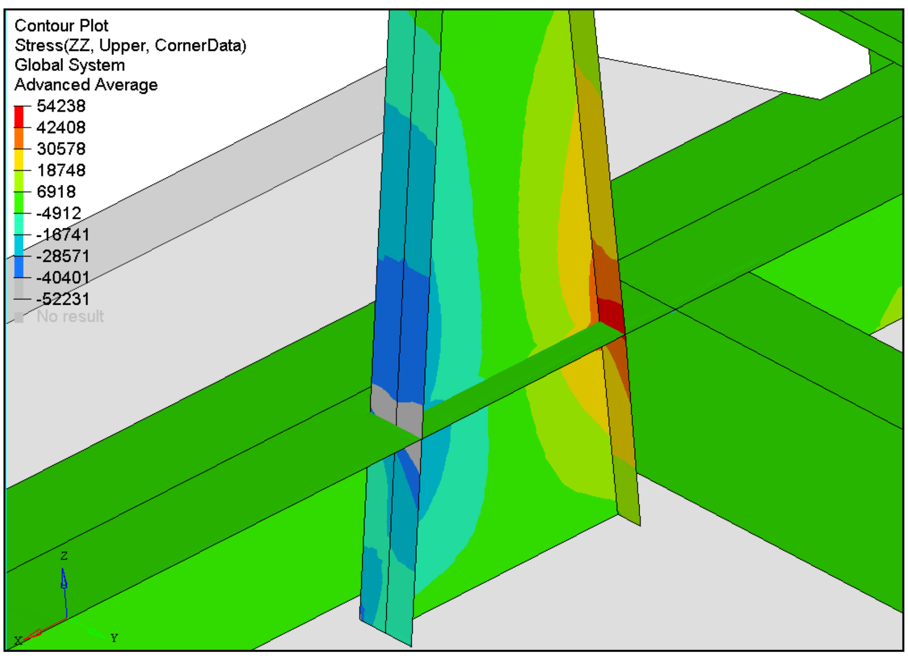

Figure B-4. Directional Stress, Vertical, CP-A