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Transportation

**Federal Railroad
Administration**

Locomotive Fuel Tank Structural Safety Testing Program: Passenger Locomotive Fuel Tank Side Impact Load Test

Office of Research
and Development
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Final Report
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13. ABSTRACT (Maximum 200 words)

This report represents a passenger fuel tank load test simulating a Side Impact Collision. The test is based on the Federal Railroad Administration's (FRA) requirements for locomotive fuel tanks in the Title 49 Code of Federal Regulations (CFR), Part 238, Appendix D. This test covers Section (a) (3) of Appendix D, which states that in a side impact collision by an 80,000-pound Gross Vehicle Weight tractor/trailer at the longitudinal center of the fuel tank, the fuel tank shall withstand, without exceeding the ultimate strength, a 200,000-pound load (2.5g) distributed over an area of 6 inches (in) by 48 in (half the bumper area) at a height of 30 in above the rail (standard DOT bumper height).

This report presents the test data, which showed that the resulting displacement of the tank sidewall corresponding to a maximum side impact load of nearly 300 kilopounds was approximately 0.5 in. This comprised of mostly elastic deformation and very little plastic deformation. Upon unloading, no local residual plastic deformation was noticeable to the naked eye although plotted test data revealed a small residual plastic deformation of 0.1 in. No crack or tank breach was observed near the side impact load application zone or elsewhere in the tank. Therefore, from the FRA regulatory perspective, the tank is considered to have satisfied the structural integrity requirement set forth in 49 CFR Part 238, Appendix D, Section (a) (3).

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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

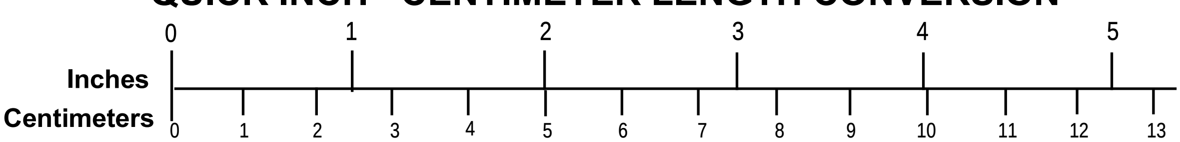
VOLUME (APPROXIMATE)

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 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

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Acknowledgments

This report discusses full-scale passenger fuel tank test simulating a side impact loading condition. Foster-Miller/QinetiQ North America performed this work under contract DTFR53-07-00003 Task Order 004 from the Federal Railroad Administration (FRA) for the Locomotive Fuel Tank Safety Improvement Program.

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Contents

Illustrations

Executive Summary

As a part of the Federal Railroad Administration (FRA) Fuel Tank Safety Improvement Program, the structural integrity of an Electro-Motor Diesel, Inc. (known as EMD)-F59 PHI passenger locomotive fuel tank was evaluated under the side impact load case. The quasi-static load test was performed in a custom-designed fuel tank test fixture located at the Foster-Miller/QinetiQ North America (QNA) Transportation Research Center in Fitchburg, MA. This report presents the details of the test setup, instrumentation, methodology, and results. Correlations of test results with those obtained from finite element analysis (FEA) using ABAQUS are also shown.

The results of side impact load test reveal that the supplied F59 PHI tank is capable of withstanding quasi-static load as specified by the Title 49 Code of Federal Regulations (CFR) Part 238, Appendix D, Section (a) (3), which states that in a side impact collision by an 80,000-pound (lb) gross vehicle weight tractor/trailer at the longitudinal center of the fuel tank, the fuel tank shall withstand, without exceeding the ultimate strength, a 200,000-pound load (2.5g) distributed over an area of 6 inches (in) by 48 in (half the bumper area) at a height of 30 in above the rail (standard Department of Transportation bumper height).

Test results showed that the sidewall of the tank safely resisted the applied maximum load of 317,000 lb without fracture or cracking. The tank exhibited evidence of undergoing very little local plastic deformation in the contact region with the side-impacting bumper. The rest of the tank was practically undamaged, including the tank attachment fixtures. Hence, from the FRA regulatory perspective, it may be concluded that the tank has passed the structural integrity requirement set forth in 49 CFR Part 238, Appendix D, Section (a) (3).

1. Introduction

1.1 Background

Ensuring the structural integrity of locomotive fuel tanks in railroad accidents is crucially important to improving the safety of train crews and passengers. Damage to tanks and associated fuel system components can lead to leaks, potential fires, and cause pollution, resulting in loss of property as well as passenger injuries. The FRA Fuel Tank Safety Improvement Program was being pursued to address these safety concerns.

FRA specified the loads a typical fuel tank must withstand for safety under minor derailment (MD), jackknife derailment (JD), and side impact. Full-scale tests to validate passenger fuel tank strength to safely resist these loads following derailment have not been performed to date, except for a few tests on freight locomotive tanks by Foster-Miller/QNA at its Transportation Research Center in Fitchburg, MA.

1.2 Objectives

Foster-Miller/QNA performed this test with following objectives:

(a) Simulate the side impact loading condition on the F59 PHI passenger locomotive fuel tank by using the full-scale fuel tank test fixture located at the Transportation Research Center,

(b) Instrument the test setup with load cell and transducers for displacement measurement,

(c) Determine the load versus displacement data, identifying salient points related to plastic yielding, peak load, and corresponding displacements,

(d) Determine the unloading behavior of the tank when the load is removed,

(e) Identify the permanent deformation in the tank sidewall and cracking, if any, and

(f) Correlate the test data with those obtained from FEA and explain reasons for discrepancy, if any.

2. Technical Approach

2.1 Test Condition

All primary locomotive fuel tanks are required to resist certain loading conditions without failure per FRA regulations that reference American Association of Railroads (AAR) Standard S-5506. These regulations originated through collaborative efforts of AAR and FRA and were introduced in 1995 as Recommended Practice RP-506 for new manufacture. These guidelines have been used by industry after that time. In 2007, they became the AAR Standard S-5506 and were subsequently referenced in 49 CFR Part 238. These requirements incorporate application of three static load conditions that are applied by railhead surfaces to the tank exterior, representing exposure to three different accident scenarios, namely MD, JD, and side impact. This report covers the test condition involving the side impact loading case only.

This test covers Section (a) (3) of Appendix D of 49 CFR Part 238 which states that "in a side impact collision by an 80,000-pound Gross Vehicle Weight tractor/trailer at the longitudinal center of the fuel tank, the fuel tank shall withstand, without exceeding the ultimate strength, a 200,000-pound load (2.5g) distributed over an area of 6 × 48 in (half the bumper area) at a height of 30 in above the rail (standard DOT bumper height)." This represents one of the severe loading cases of a grade-crossing accident scenario in which the front bumper of a heavy road vehicle or tractor trailer hits near the longitudinal center of one side of the locomotive fuel tank, shown in Figure 1.

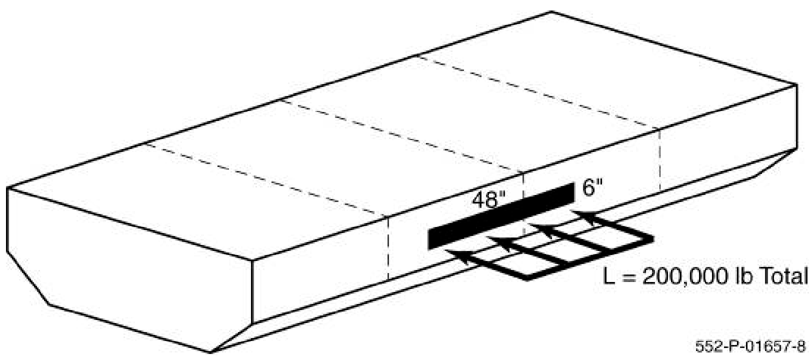

Figure 1. Schematic of FRA Side Impact Load Applied to the Tank Sidewall

2.2 Test Fixture

The testing outlined in this document was performed by using the full-scale fuel tank test fixture illustrated in Figure 2.

The fixture was designed and developed by Foster-Miller/QNA to test a fuel tank in all standard derailment configurations, and is located at its Transportation Research Center. The modular nature of the fixture allows for different tank types to be tested in multiple load configurations with minimal modifications to the fixture.

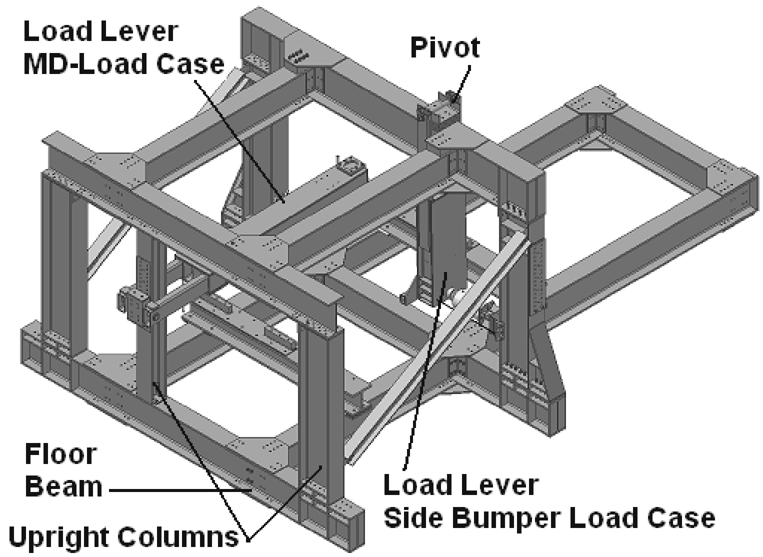

Figure 2. Locomotive Fuel Tank Test Fixture

The test fixture was designed to enable application of all three types of FRA derailment load conditions to a wide range of full-size production locomotive fuel tanks. The tanks are tested upside-down relative to their position in actual locomotives. Movable support beams are used to reposition tanks relative to the loading levers, which incorporate a segment of actual rail or bumpers for contact with the tank. The levers swing in large-radius arcs, to closely reflect the translational movement of the railhead or bumper into the tank implied by the regulations. Use of widely spaced supports and stiff arms assures stability of the fixture under the unpredictable crushing behavior that might occur when large deflections (of several inches) are produced on the tank walls. The test fixture is, therefore, designed to be capable of stable operation under the extreme loading conditions.

The tank mounting brackets are also accommodated, because these are part of the tank attachment system and are also subjected to the impact loads. The tests tax these important components as they must function satisfactorily under the required load conditions. Figure 3 shows the test fixture and fuel tank configuration for application of FRA side impact load to the F59 passenger locomotive fuel tank.

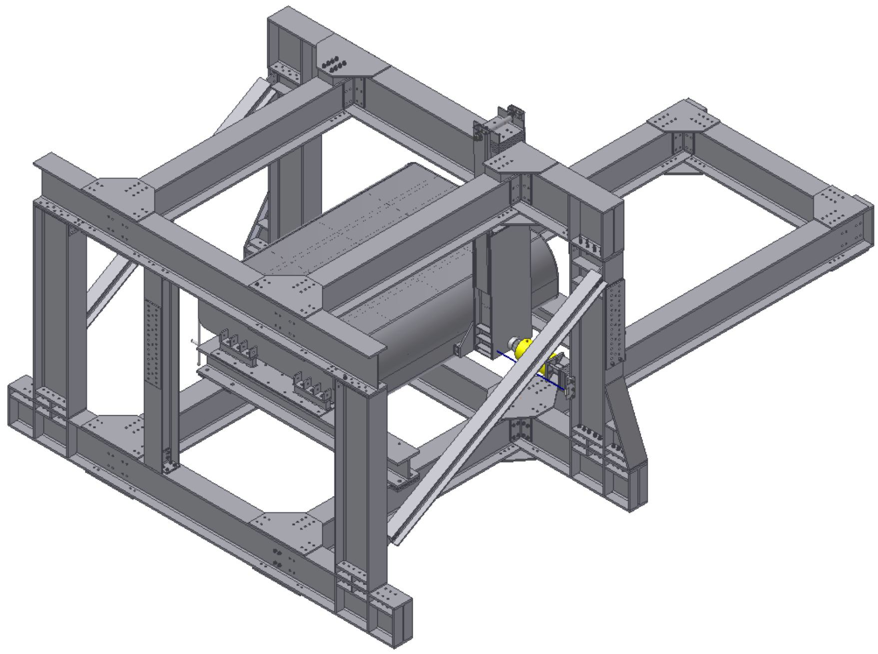

Figure 3. Test Fixture and F59 Tank Configuration for Side Impact Load Case

Shakedown testing was conducted to prove out the integrity of test fixture, instrumentation, and to refine test procedures. Additionally, a separate calibration test was performed for the evaluation of pivot joint reaction force of the load lever.

2.3 Fuel Tank Load and Displacement Measurement Method

For the side impact load case, the fuel tank is mounted near the middle portion of the test fixture and anchored down to the transverse floor beams at both ends. The load lever is positioned at the longitudinal middle of the tank on one side. It is suspended from an upper transverse beam such that its lower end containing a bumper (6 in deep and 48 in long) touches the tank sidewall at the desired height, as shown in Figure 3. For side impact load application, an Enerpac servohydraulic actuator is used that is positioned horizontally between an upright column and lower end of the load lever having its axis coincide with the midplane of the bumper.

The pressure transducer output of the hydraulic pump unit provides the magnitude of applied load during a test. For tank displacement measurement, one string potentiometer (string pot) was connected to the lever in the plane of loading. Two more string pots were connected to the backside (opposite to the loading sidewall). One was attached near one end of the tank and the other near the middle. In the event of likely rigid-body displacement (lateral sliding along the loading direction) of the tank because of applied side impact load, the difference of readings between that of the string pot attached to the load lever and the average reading of the back-face string pots provides the tank displacement under side impact load application.

2.4 Test Article

The test article used in this testing program is a F59 PHI passenger locomotive fuel tank. This was reported to have been manufactured using corrosion-resistant (COR-TEN) steel material. Its overall shape and major external dimensions are shown in Figure 4. The interior construction details including baffle configurations and wall thicknesses are shown in Figure 5.

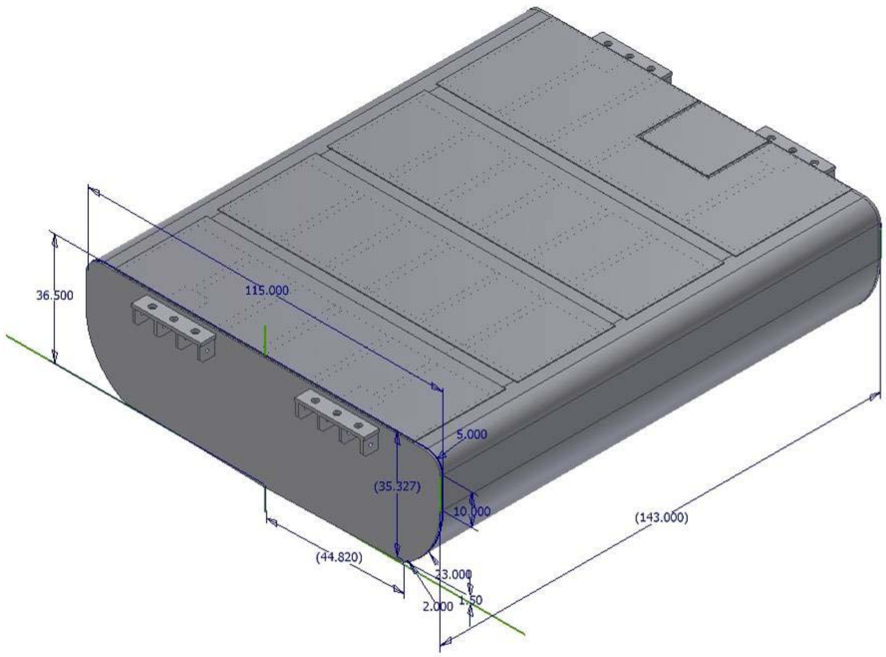

Figure 4. External Dimensions of F59 PHI Passenger Locomotive Tank

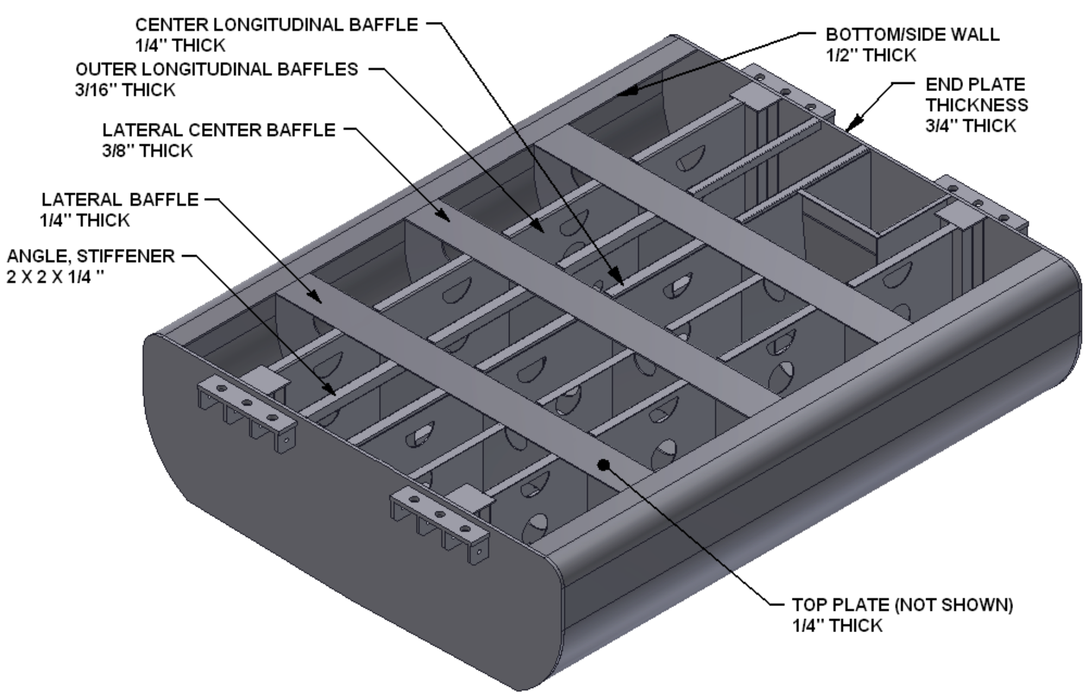

Figure 5. F59 Tank Interior Details Including Component Wall Thicknesses

The side impact load is intended to be applied at the middle of one side of the fuel tank with the bumper touching one side plate covering a 6 × 48-inch band. The bumper is configured to straddle both sides of the three-eighths-inch-thick lateral center baffle, supported by a 0.5-inch-thick sidewall. This is expected to permit evaluation of the tank structural integrity under worst case side impact conditions.

2.5 Test Instrumentation and Data Acquisition

All test data for the fuel tank structural improvement program were acquired through National Instruments (NI) signal conditioners integrated to a high-end PC (Figure 6) using Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) version 8.2.1 software (NI, 2008a). LabVIEW is a powerful graphical programming environment for measurement and automation developed by NI for applications to test and measurement.

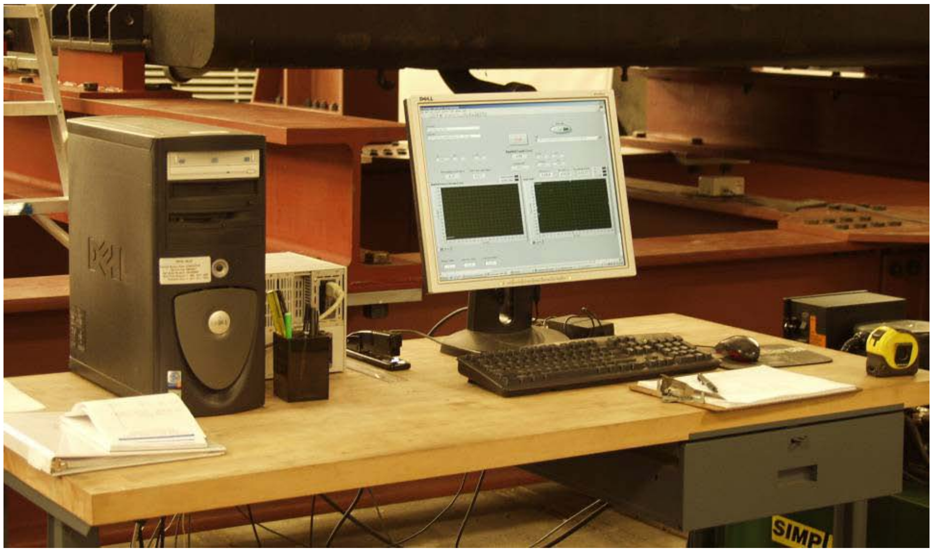

Figure 6. Test Control and Data Acquisition System Setup

In addition, the following instrumentation was used in this test:

Instrumentation for measurement of applied load

Load is applied through an Enerpac hydraulic cylinder with a maximum capacity of 10,000 pounds per square inch (psi). To determine the applied piston load, a calibrated Setra 201 pressure transducer with a maximum pressure rating of 10,000 psi was used. This permits continuous monitoring of pressure as well as applied piston load data by using LabVIEW software for acquisition and recording for later processing.

Instrumentation for measurement of tank deformation

To measure the tank sidewall horizontal deformation because of side impact load applied by the load lever, a Celesco string potentiometer was attached to the load lever as shown in Figure 7. Two additional Celesco string pots were attached to the unloaded (back face) sidewall of F59 tank. One string pot was attached near one end of tank and the other to the (back face) sidewall near the location of lateral center baffle. This arrangement of string-pot mountings permitted measurement of the overall tank horizontal displacement due to sliding motion and/or bending in the horizontal plane under side impact load. The string potentiometer attachments to the back face sidewall of the inverted tank are shown in Figure 8. All three string potentiometers were connected to one NI SCXI-1121 signal conditioning module (NI, 2008b) for automated data acquisition by using LabVIEW.

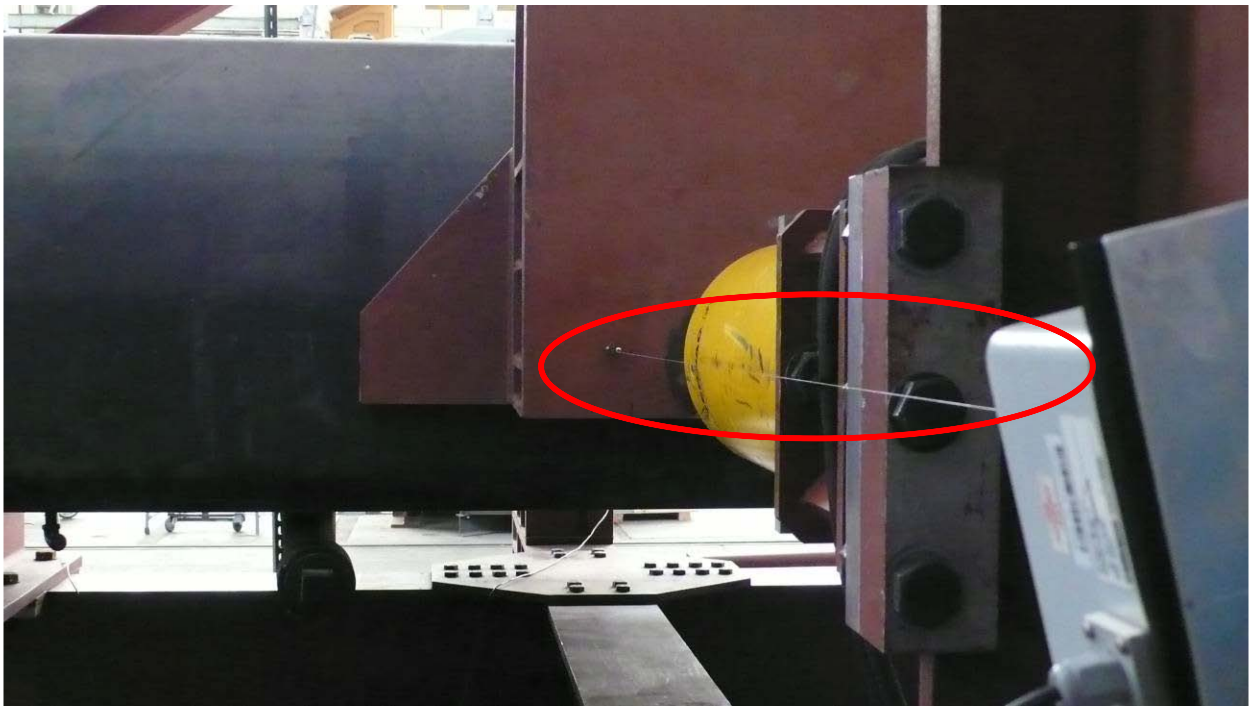

Figure 7. F59 Tank Loading Face String Potentiometer Attachment to Load Lever

Figure 8. Two String Potentiometer Attachments to the Unloaded Sidewall of the Tank

As mentioned, all data were acquired through NI signal conditioners integrated with the high-end PC by using LabView version 8.2.1 with NI-Daq 4.3 software (NI, 2008a) that permitted data acquisition, real-time display, and recording for later analysis. The test control and data acquisition system was shown in Figure 6.

2.6 Test Methodology

The test preparation and methodology for conducting side impact load test comprised the following steps:

- The F59 tank was positioned over the test fixture in an inverted position.
- Two transverse floor beams were anchored down to the test fixture per the computer-aided design (CAD) and the inverted tank was mounted over them with the help of tank-attachment fixtures located at both ends of the tank.
- The load lever was repositioned relative to the tank so that while anchored and suspended from an upper transverse beam, the bumper attached to its lower end just made contact with one sidewall of the tank, as required for FRA side impact load case. This was determined from the CAD drawing of test setup shown in Figure 3.
- The hydraulic actuator was positioned between the lower-end back face of the load lever and an upright column of the test fixture as shown in Figure 9. Before commencement of the test, the actuator piston was at its minimum travel position and just made contact with the back surface of the load lever under unloaded condition.

- One string potentiometer was attached between the back face of the load lever and an upright column of the test fixture as shown in Figure 7.
- Two more string pots were attached to the opposite-side unloaded sidewall of the tank as shown in Figure 8. One of them was attached near one end of tank and the other was attached near the location of central transverse baffle of the tank. These two string pots were meant to measure average sliding displacement, if any, of the tank because of side impact load.
- The hydraulic hoses of the actuator were connected to the power pack, and the output of all transducers, such as load cell, pressure transducer, and string potentiometers, was connected to the NI data acquisition hardware.
- The output of NI-Daq modules was connected to the high-end PC loaded with LabVIEW version 8.2 software for real-time display of all transducer output data and for recording all data to the hard drive.
- To start the test, all transducers were reset to show zero output without load application.
- Hydraulic power pack was started and its pressure increased in steps to apply the desired load by the actuator on the load lever that was transmitted to the sidewall of tank through the "bumper."
- The applied load was gradually raised up to and beyond the required maximum of 200 kilopounds (kip), as the test condition stated. All transducer output data were automatically recorded at a sampling rate of 1 kilohertz onto the hard disk of the PC.
- After the maximum load application up to about 300 kip, the actuator load was gradually reduced to zero and the residual displacement of the tank sidewall and the unloaded position of load lever were recorded.
- The F59 tank sidewall was photographed after completion of unloading (Figure 10). Hardly any noticeable residual deformation was in the tank sidewall even though a peak SI load well above the required 200 kip was applied.

Figure 9. Configuration of Servohydraulic Actuator for Side Impact Load Application

Figure 10. A Closeup View of Tank Sidewall and the Load Lever following Complete Unloading

3. Test Results and Discussions

The test procedure outlined in Section 2.6 was followed to conduct the side impact load test. During the test, the side impact load experienced by one sidewall of inverted F59 tank was continuously monitored and recorded. The load point horizontal displacement was measured from the output of a string potentiometer connected to the back face of the load lever, coinciding with the initial line of contact with the tank sidewall. The variation of applied actuator load, representing side impact load, and consequent horizontal displacement of the load lever in contact with tank sidewall is shown in Figure 11. The output of two string potentiometers—representing horizontal displacements or sliding motion/bending in horizontal plane of the tank due to application of side impact load—is also plotted. The load lever displacement behavior with variation in applied side impact load is shown in Figure 12. The effective load point deformation of the tank sidewall is computed by subtracting the average value of the two string pot outputs, SP-2 and SP-3 (attached to the unloaded sidewall) from that of SP-1 (attached to the back face of load lever). This effective load point deformation of tank sidewall versus the applied SI load is shown in Figure 13.

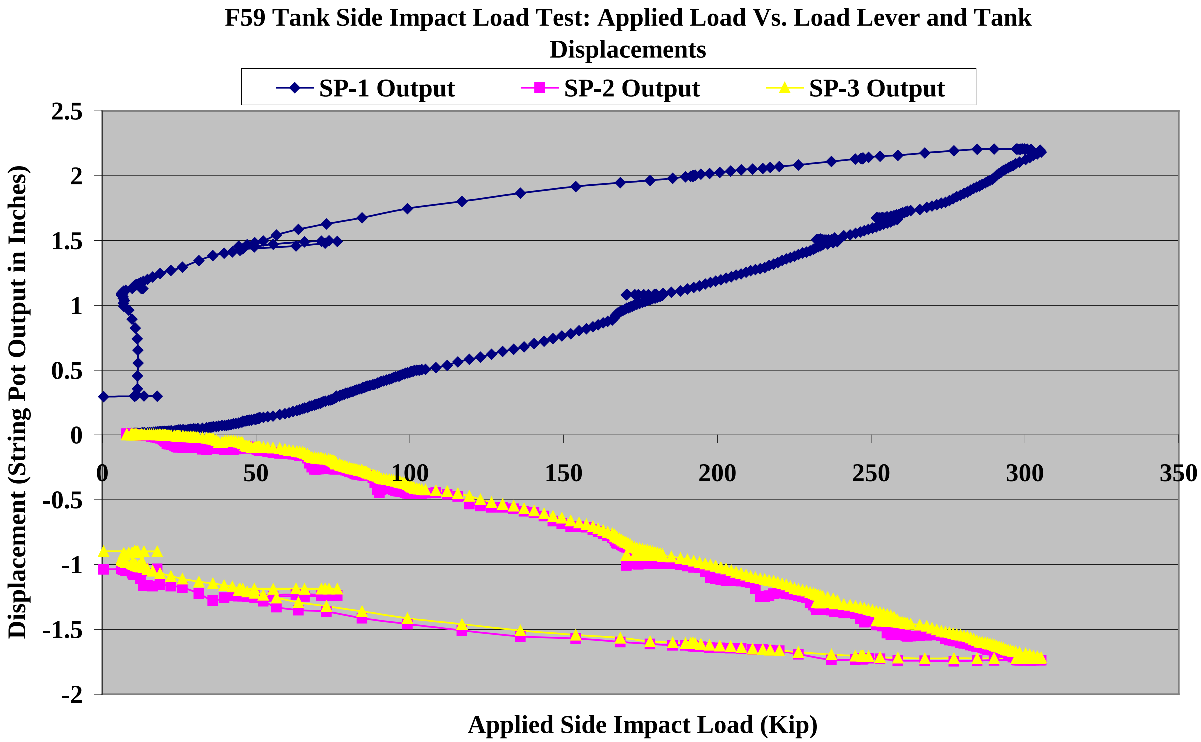

Figure 11. Applied Side Impact Load vs. Load Lever and Tank Unloaded-Sidewall Displacements

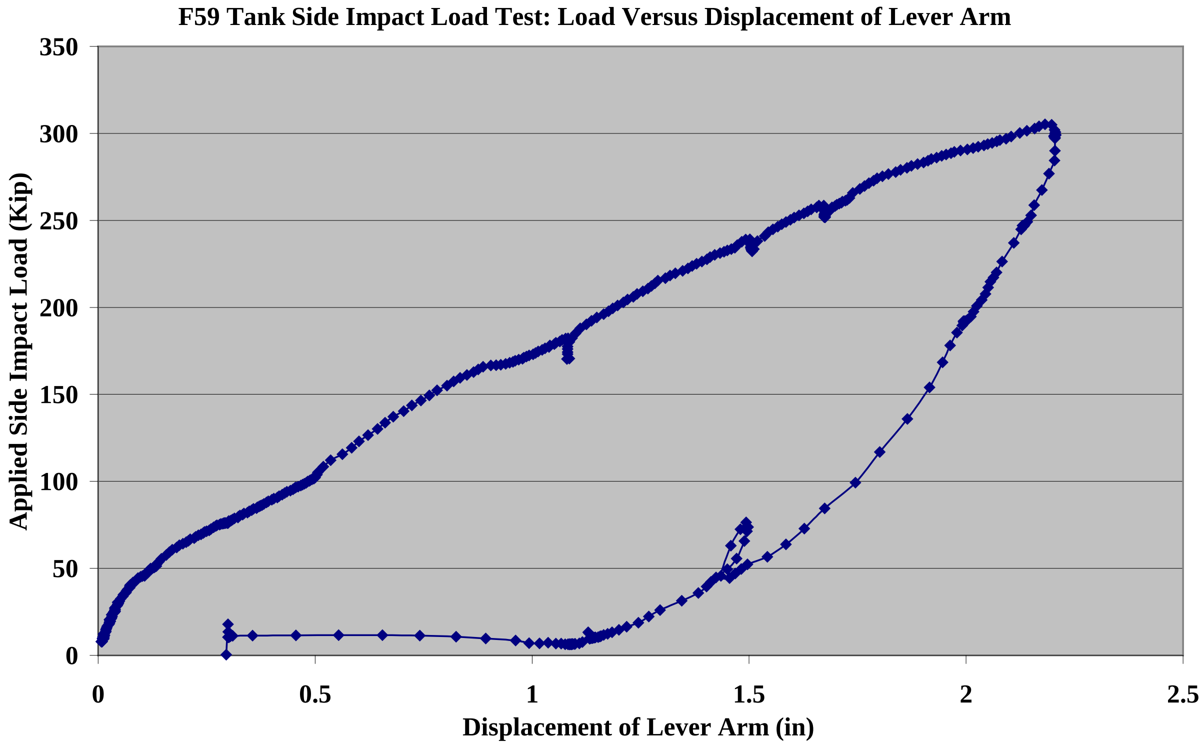

Figure 12. Variation of Load Lever Displacement with Applied Side Impact Load

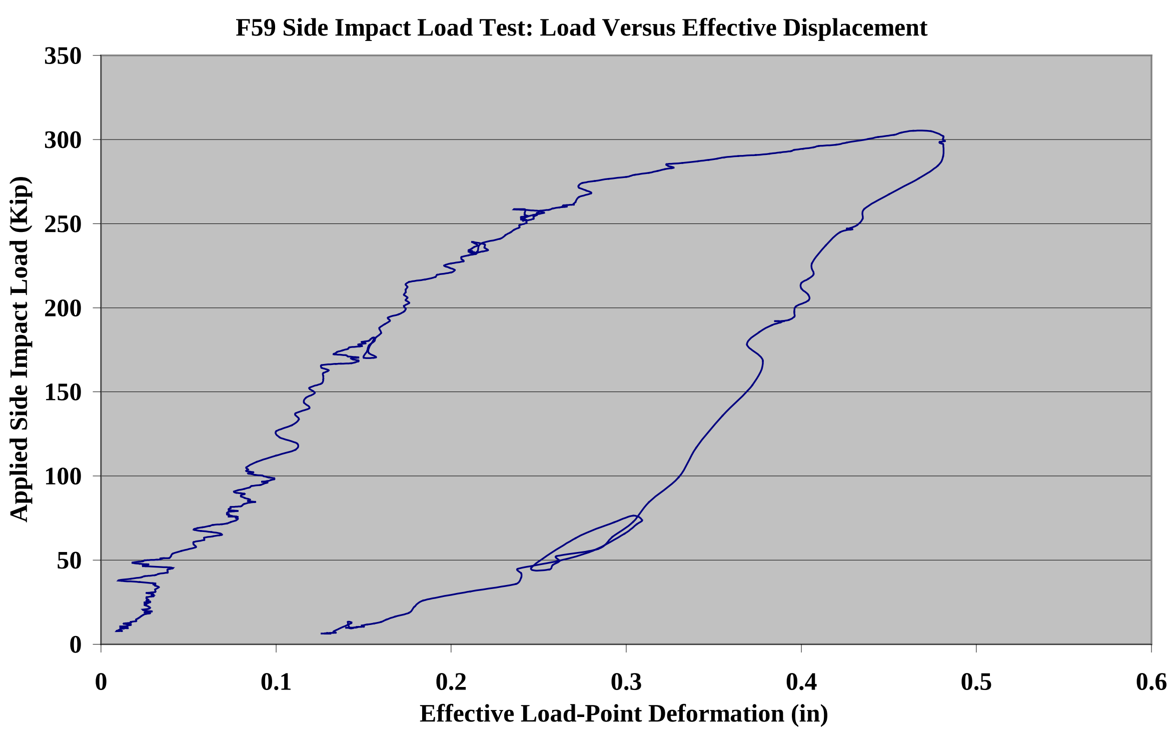

Figure 13. Effective Load Point Deformation of Tank Sidewall with Applied Side Impact Load

Following FRA guidelines for test conditions outlined in Section 2.1, the magnitude of applied quasi-static side impact load was increased gradually to 200 kip and beyond up to a maximum value of about 300 kip. From the test results shown in Figures 11–13, it is observed that:

- The applied side impact load and corresponding displacement of the load lever exhibit an almost linear relationship. The horizontal displacement of the tank (unloaded) back sidewall increased with increased applied load on tank front sidewall, although there were signs of intermittent "slip and stick" of the tank during this process. One likely reason for this sliding motion of tank under horizontal loading condition could be the existing gap between the oversized holes in tank attachment brackets and the large fastener bolts used for anchoring the tank. Despite adequate tightening of the nuts over large washers, there seems to have been appreciable sliding along the direction of loading.
- Effective local deformation of the tank sidewall with side impact load point is shown in Figure 13. The peak side impact load of slightly over 300 kip caused elastoplastic deformation in the tank sidewall of about 0.5 in. Upon unloading, the residual plastic deformation on the sidewall is seen to be only about 0.12 in. This confirmed the barely visible slight depression in the sidewall after unloading and removal of load lever.
- The tank sidewall at the point of loading as well as all other walls were found to be undamaged owing to side impact load, and no breach was detected anywhere in the tank.

On the basis of these test results, the F59 PHI passenger locomotive tank is considered to demonstrate adequate strength and structural integrity against applied FRA side impact load without any failure or breach in its walls. Furthermore, the applied side impact load versus load lever displacement behavior offers clear indication of greater-than-statutory side impact load bearing capacity of the tank.

4. Results of Simulation and FEA

4.1 Mechanical Properties Evaluation of F59 Tank Material

Foster-Miller/QNA carried out coupon-level testing to obtain reliable material properties, especially true stress versus true strain tensile data for the components of the tank. These data were necessary as material input parameters for FEA of the side impact load case. Material testing was performed by fabricating F59 tank component specimens, machined to the American Society for Testing Materials (ASTM) specifications, and applying tensile load in an Instron test machine. The load was monotonically increased slowly (quasi-static loading) from its initial value of zero to its final value just before breaking, so that the cross-section necking area and the corresponding tensile force could be measured for the computation of true stress. Through the examination of the tensile stress in the specimen as a function of the strain, material properties such as the elastic modulus, yield stress, ultimate stress and percent elongation at or near break condition of the coupons were obtained. Additionally, to represent sheet metal in ABAQUS, linear isotropic plasticity material model was used. This material model required the true stress versus true strain relationship as input parameters for the postyield segment of the stress–strain curve. That necessitated generation of tensile properties data on small samples of plate materials obtained from various sheet metal components of F59 PHI tank.

4.1.1 Test Sample Preparation and Testing

Initially, small-size plates were cut from different components of F59 tank, such as the top, bottom, and side plates, central and outer longitudinal baffles, and transverse central baffle. The end plates, which were 0.75-inch thick were identical to those of SD-70 tank tested previously so were not tested. Depending on the plate thickness of the retrieved material from components, tensile test coupons were fabricated per ASTM standards. For those plates having 0.25-inch thickness or less, tensile test coupons were fabricated according to ASTM-E8 Standard for subsize (SS) coupons. These SS test coupons were machined to be 6 in long to allow for the use of an extensometer for accurate measurement of strain and percent elongation. The coupons were tested in a calibrated Instron 1332 servohydraulic test machine. For consistency, the test machine crosshead-separation speed was maintained constant at 0.044 in/min and the data rate was 300 samples per minute. An MTS extensometer with 1.0-inch range of travel was used to continuously monitor and record percent elongation of the gage section almost up to the breaking point. This feature of the test was useful in computation of “true stress versus true strain” deformation behavior of the material beyond nominal ultimate stress point, which provided the necessary plastic strain component input into the ABAQUS FEA model.

4.1.2 Tensile Test Results

Two or three identical coupons were tested in tension up to or near breaking point and the results were found to be consistent. Figure 14 shows a sample tensile stress versus strain curve, plotted in terms of engineering stress versus engineering strain. The results of all three test coupons tested showed that the average engineering yield stress of the material was 65,957 psi, the corresponding ultimate stress was 72,810 psi, and the average percent elongation at break was 21.7.

The test data were then used to compute the corresponding true stresses and true strains, on the basis of the actual cross-section area of the specimen, including necking, in the postyield regime associated with higher rate of elongation. Assuming that zero change occurs to the total volume of the specimen gage section during the tensile test, the relationship between true and engineering stresses and strains can be derived as:

$\sigma_T = \sigma_E\ (1 + \epsilon_E)$ (1)

$\epsilon_T = \ln\ (1 + \epsilon_E)$ (2)

where σ_E and ϵ_E are engineering stresses and strains, respectively, and σ_T and ϵ_T are true stresses and true strains, respectively.

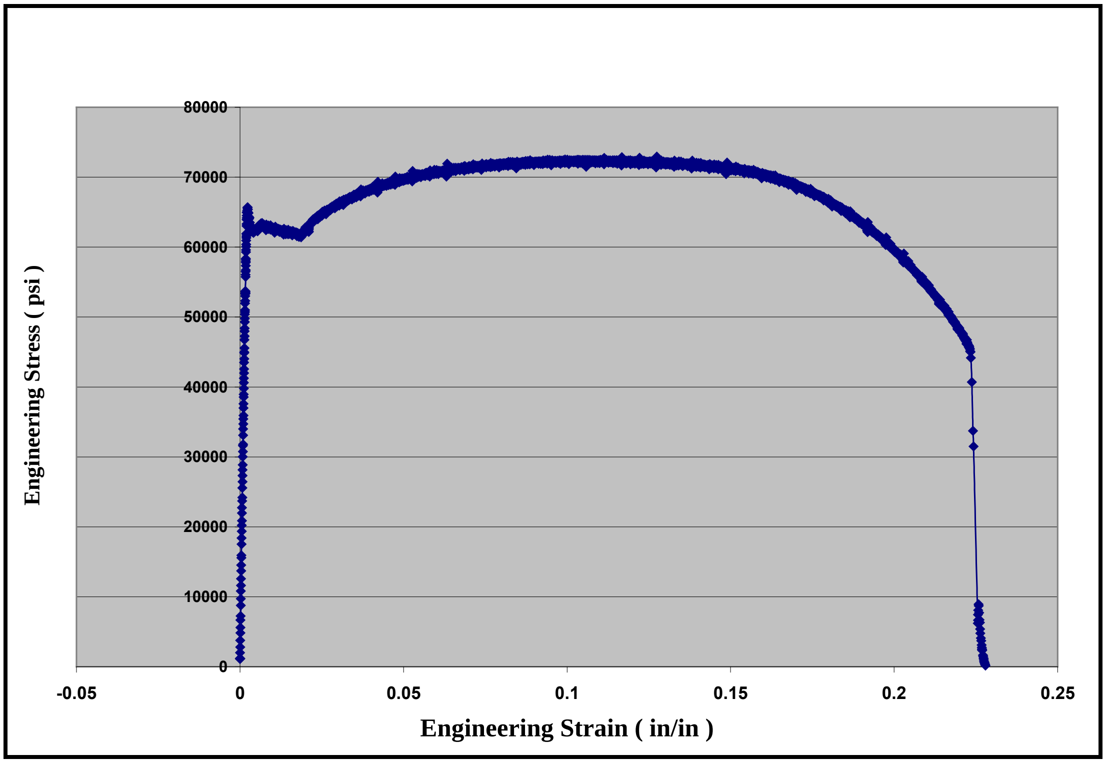

Figure 14. Tensile Stress vs. Strain Curve for Tank Top Plate Material

The computed true stress versus true strain data derived from the test data of a sample tensile test coupon is shown in Figure 15. In this figure the last point of the curve represents the true stress at the necking region of the gage section, accurately computed by measuring actual cross-sectional dimensions of an unbroken specimen and with the known magnitude of applied load close to the termination of test. For a failed specimen, the reconstituted cross-section necking area and the magnitude of tensile load just before its sudden drop at break were considered to compute the true stress, which offered the last data point of the test. Because the true stress magnitudes from necking and associated reduction in cross-section area increase beyond the ultimate stress point up to the breaking point, the interim true stress values were interpolated corresponding to true strain values. The tensile test data of the top plate suggest that its material is likely to be an enhanced-strength quenched and tempered steel, COR-TEN B-QT70, or high-strength low-alloy (HSLA) steel such as ASTM A656.

The results of all the tensile coupon tests performed on materials retrieved from different components of the tank are included in Appendix A – Summary of F59 Tank Material Tensile Properties Data.

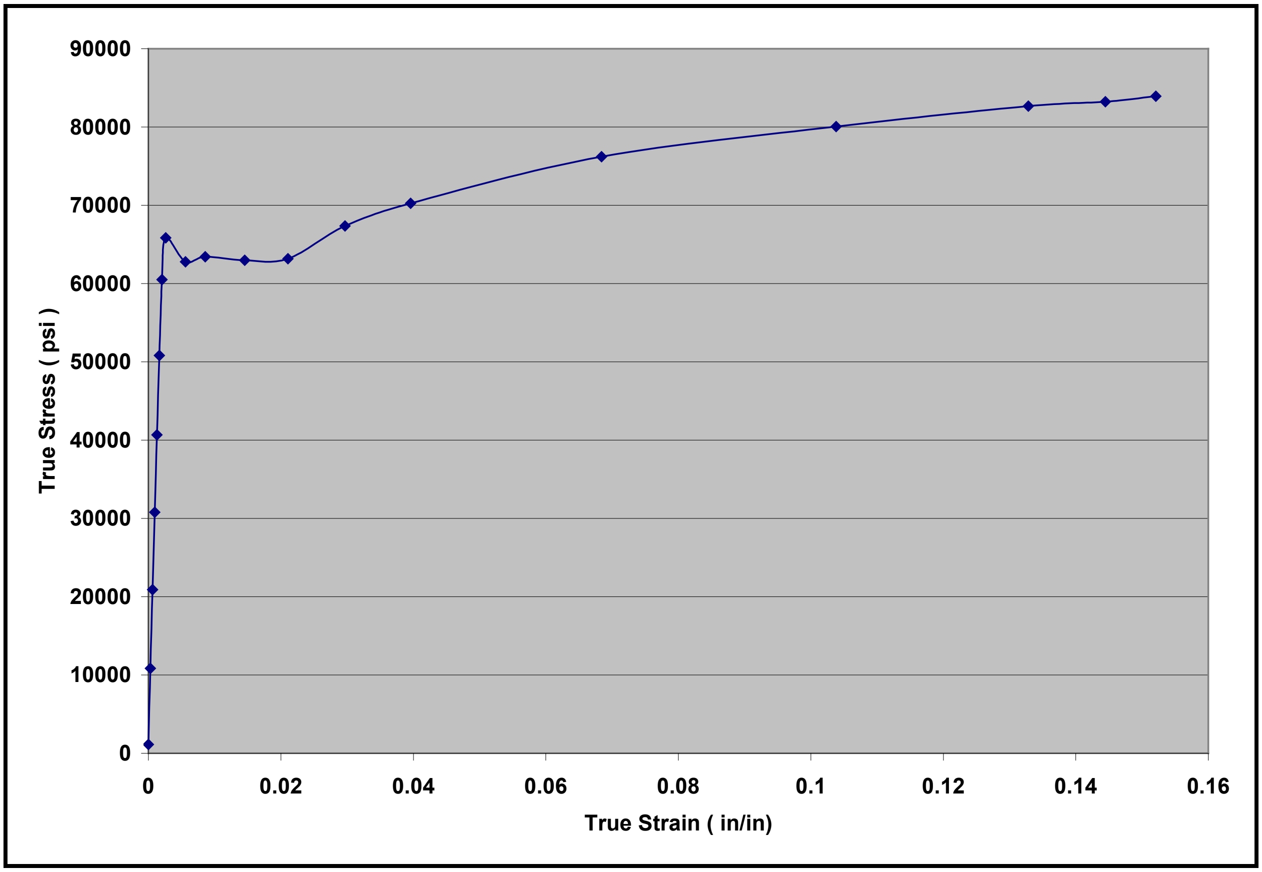

Figure 15. Extracted True Stress vs. True Strain Data for Tank Top Plate Material

4.2 FEA for Side Impact Load Case

A static finite element model (FEM) was developed in ABAQUS to model the side impact load case using 85749 shell and solid elements and kinematic constraints. The full model and the model with the outer wall elements removed are shown in Figure 16 (a) and (b). Material properties used in the model were the same as those used in the JD FEM, as shown in the table below.

Component	Thickness (in)	Likely Material	Modulus (Msi)	Yield Stress (ksi)	Source
Top plate	0.25	HSLA steel	30.5	65.9	Test
Bottom plate	0.491	CORTEN-B-QT70	29.4	70.4	Test
Side plates	0.491	CORTEN-B-QT70	29.4	70.4	Test
End plates	0.75	CORTEN-B	29.7	51.6	Test (SD-70)
Rail	N/A	High-strength steel	30.0	110.0	Handbook
Transverse baffles	0.3705	AISI 1030 or CORTEN-A	29.5	50.9	Test
Longitudinal baffle (outer)	0.1825	CORTEN-A	28.7	50.1	Test
Longitudinal baffle (center)	0.2265	Cast iron	13.0	31.0	Test

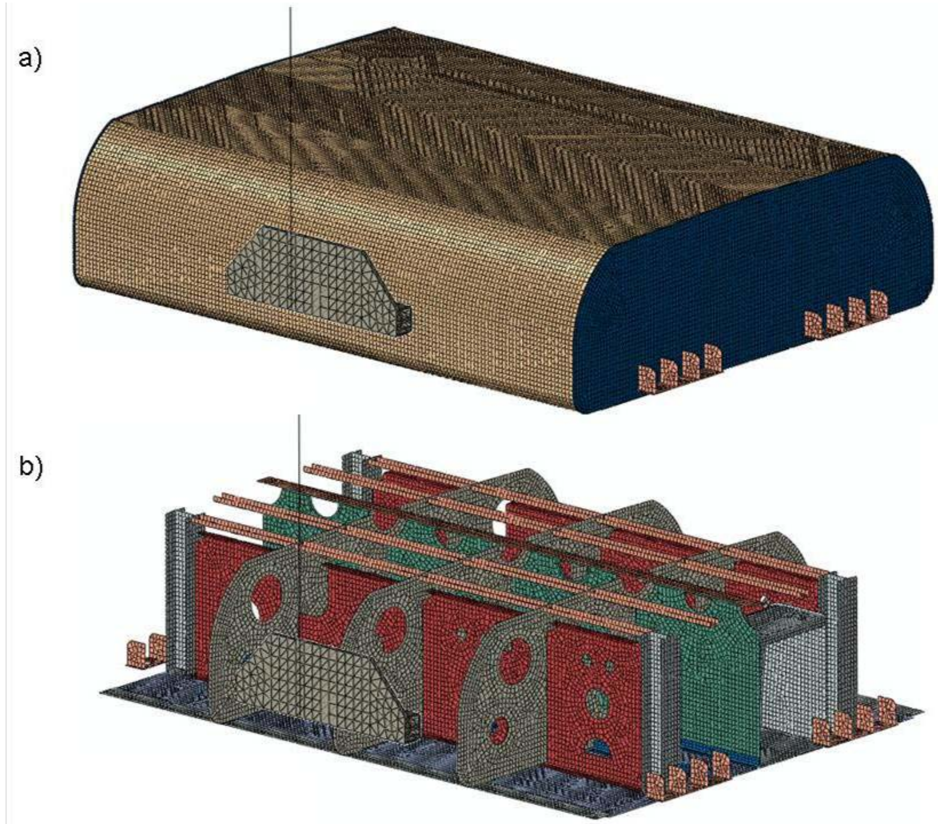

Figure 16. FEM of F59 Tank under Side Impact Loading: (a) Inverted Tank and a Bumper Attached to the Load Lever and (b) a Cutaway View of Tank Internal Structure

FEM predictions of deformation and von Mises stress in the F59 tank under side impact loading are shown in Figure 17. The load/displacement history, analogous to that of the experiment, was also determined in the FEM. These results are shown along with the experimental data in Figure 18.

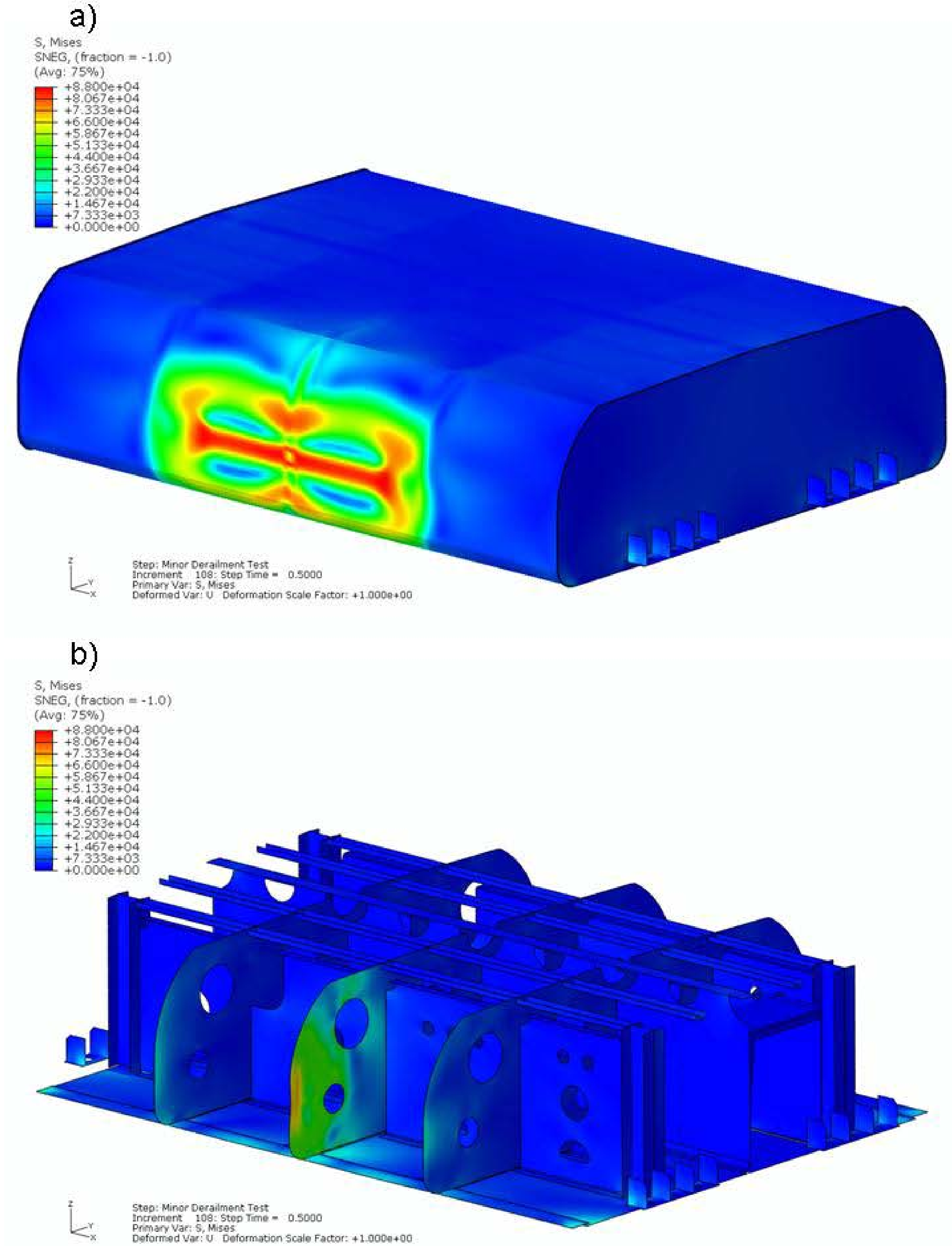

Figure 17. Von Mises Stress Contours Corresponding to Applied Maximum Side Impact Load: (a) in the Sidewall of F59 Tank and (b) in the Internal Structures

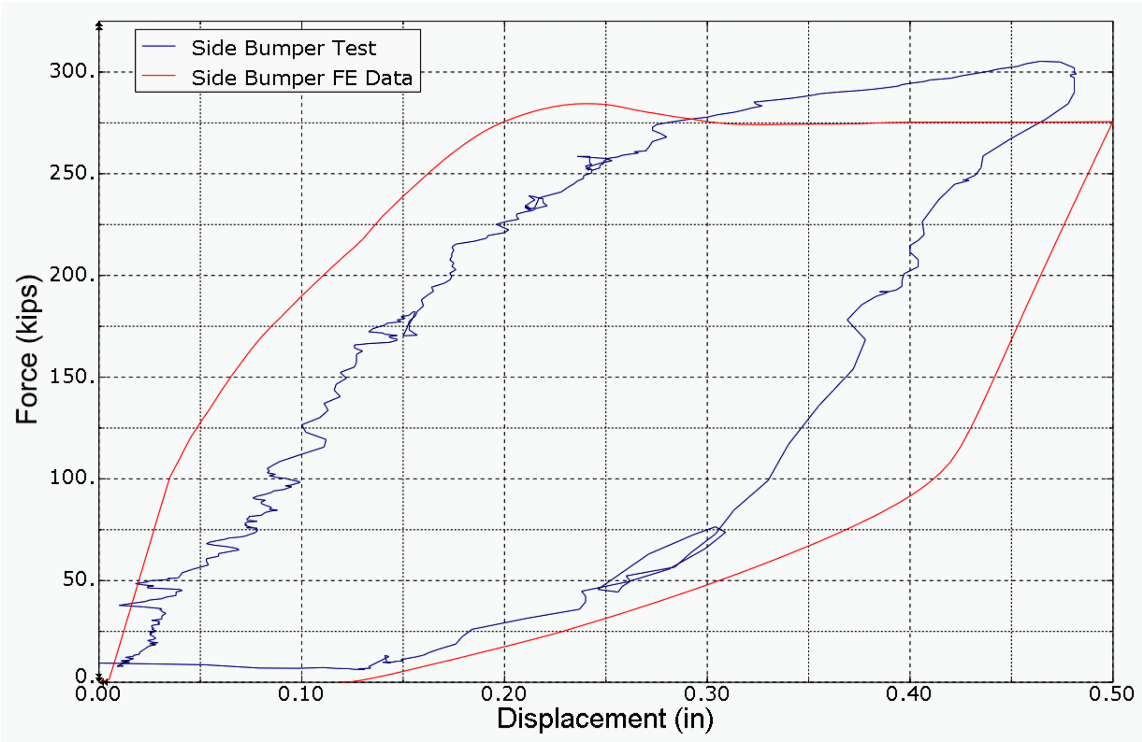

Figure 18. FEM and Experimental Force vs. Displacement Data

The test data in this case were postprocessed to assess the effects of tank slipping in the test setup. Therefore, the resulting data are seen to be very nonlinear, especially during the loading part. Taking this into account, as can be seen in Figure 18, it is conceivable that the actual tank deformation response would have been stiffer had it not slipped during loading. Accounting for this artifact, the FEM results may be considered to generally agree with the experimental data. However, some variations can be identified between the two sets. First, the FEM seems to be stiffer initially, up to about 0.04 in of deformation. This discrepancy is most certainly due to initial slipping and settling of the tank in the test. Second, after about 0.25 in of deflection, the FEM softens slightly and, thereafter, offers a very low-stiffness plastic response. This most likely occurs because the central transverse baffle directly behind the fuel tank sidewall and at the center of the side-impacting bumper is found to have buckled and is capable of offering only lower stiffness through bending. This can be seen in the cutaway detail shown in Figure 19. The unloading part of FEM results also differ from those of the test, showing a faster elastic recovery and a small lateral shift for the FEM result. However, upon complete unloading, the residual plastic deformation of nearly 0.12 in agrees with the measured value from the test.

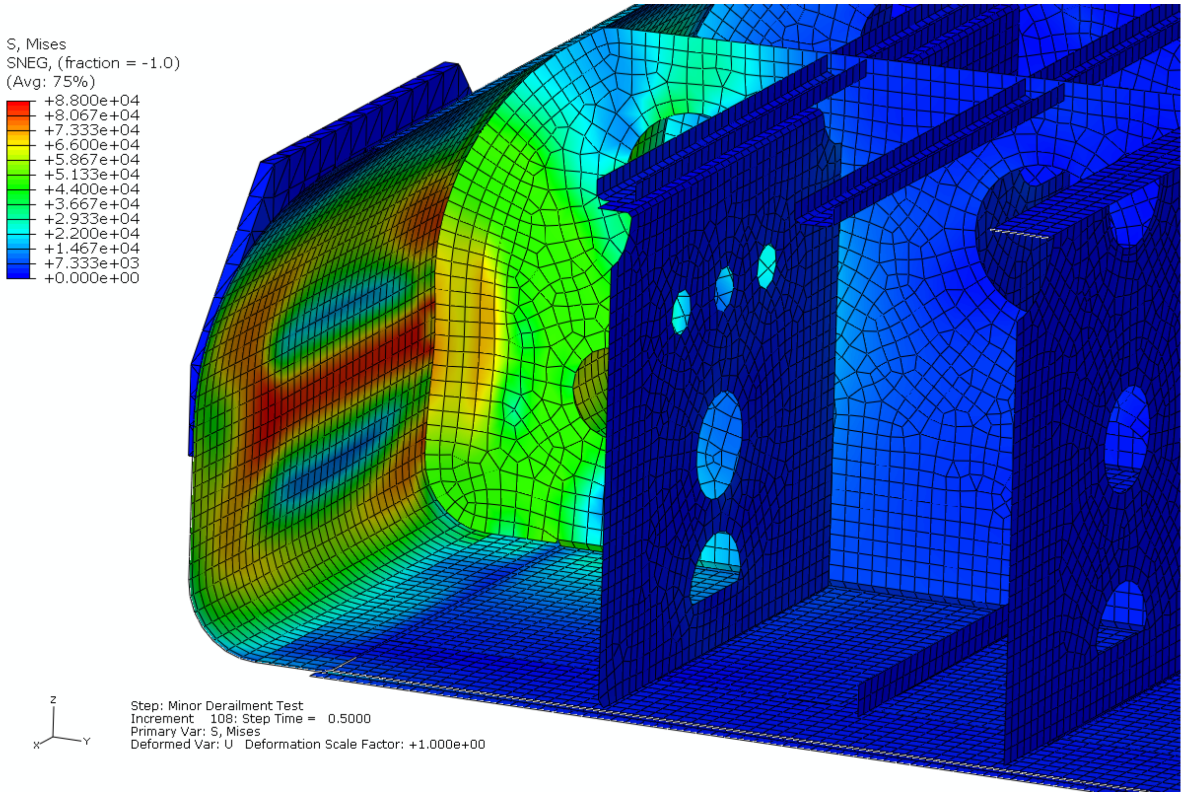

Figure 19. Detail of Cutaway FEM Results Showing von Mises Stresses in the Buckled Transverse Baffle Directly behind the Side Impact Bumper

5. Conclusions

The F59 PHI passenger locomotive fuel tank was subjected to simulated quasi-static side impact load at Foster-Miller/QNA's full-scale fuel tank test facility. It was observed that the effective horizontal deformation of the sidewall of the inverted tank, corresponding to a maximum side impact load of 317 kip, was 0.5 in. This comprised both elastic and plastic components of the tank sidewall deformation. Upon unloading, the local residual plastic deformation of the sidewall at the bumper location was found to be approximately 0.12 in, with no cracks or breach observed within the plastically deformed zone or elsewhere. Despite the applied side impact load being more than 50 percent of the statutory test load, the residual plastic deformation or the 'permanent set' was negligibly small and not discernible to the naked eye. Hence, from the FRA regulatory perspective, the tank was deemed to have passed the structural integrity requirement and be considered safe against side impact load (FRA, 2005) under 49 CFR Part 238, Appendix D, Section (a) (3).

6. References

1. National Instruments. (2008a). LabVIEW Version 8.2.1 w/ NI-Daq 4.3 http://www.ni.com/labview/.

2. National Instruments. (2008a). Data Acquisition Model SCXI-1121/1120tb. http://sine.ni.com/nifn/cds/view/main/p/sn/n24:SCXI/lang/en/nid/1036/ap/daq.

3. Requirements for External Fuel Tanks on Tier I Locomotives, Section (a) (3), Appendix D to Part 238, 49 CFR Ch. II (10-1-05 Edition), Federal Railroad Administration, Department of Transportation, 2005.

Appendix A.
Summary of F59 Tank Material Tensile Properties Data

F59 Tank Materials Tensile Properties Data

1. Outer Longitudinal Baffle Plate

Nominal plate thickness =	0.1825 in
Coupon	F59-C1/2
Young's modulus, E =	28.7×10^6 psi
UTS =	69,432 psi
Elongation at UTS =	10.4 percent
Elongation at break =	22 percent
True stress at yield =	50,081.8 psi
True strain at yield =	0.001745

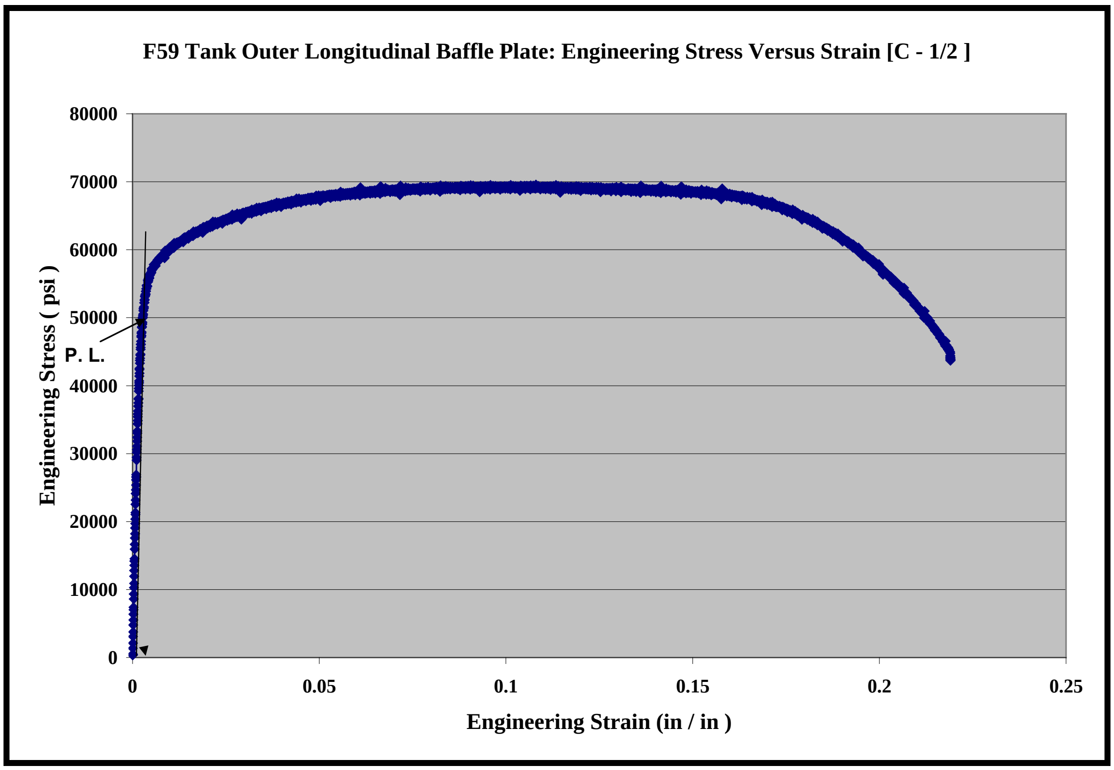

Figure A1. Engineering Stress vs. Strain Curve for Outer Longitudinal Baffle Plate

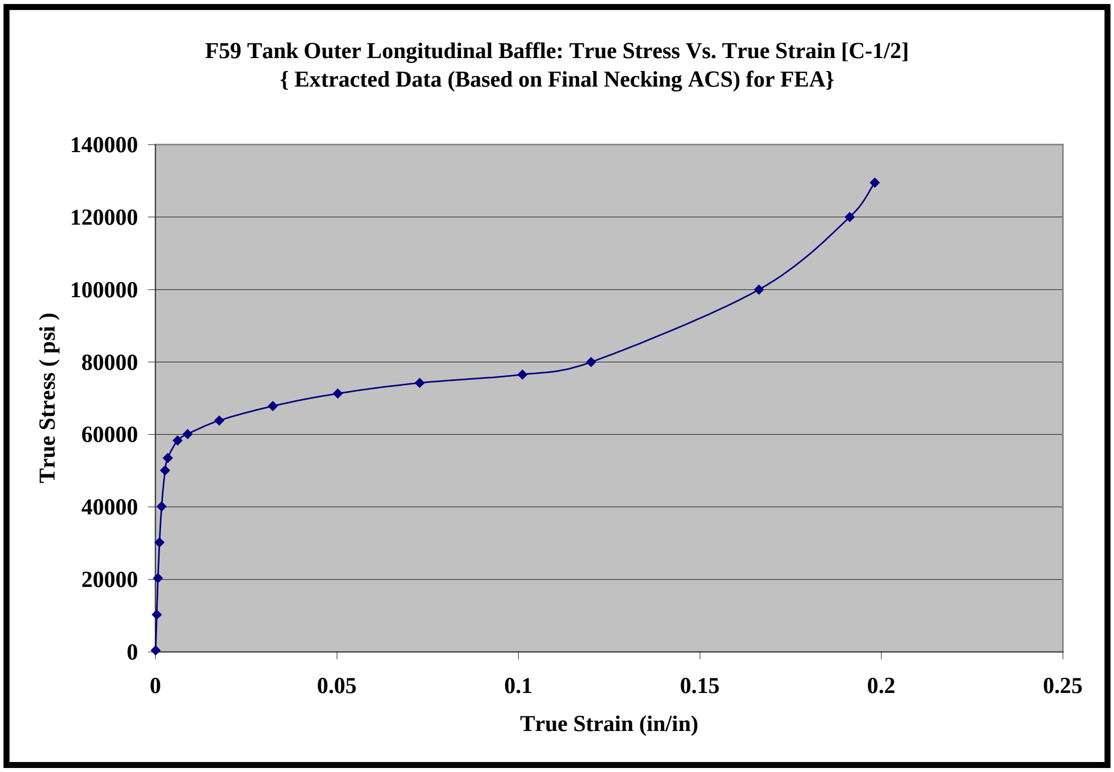

Figure A2. True Stress vs. True Strain Curve for Outer Longitudinal Baffle

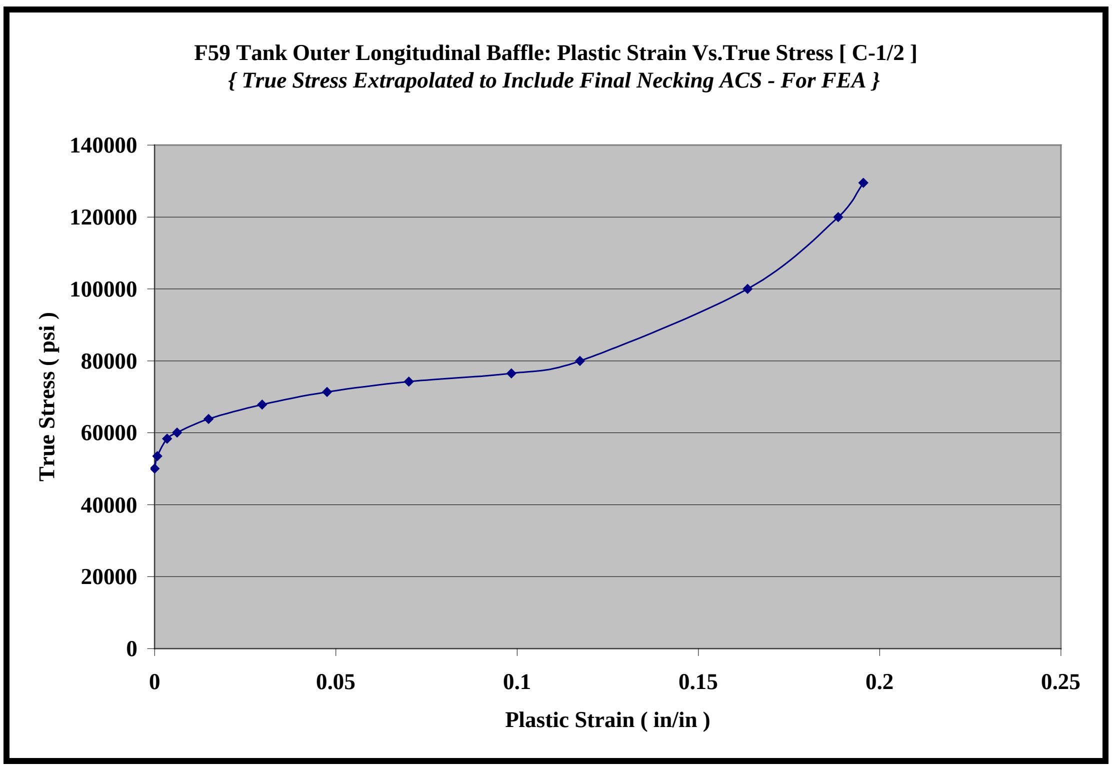

Figure A3. True Stress vs. Plastic Strain Curve for Outer Longitudinal Baffle

2. F59 Tank Central Longitudinal Baffle Plate

Nominal plate thickness =	0.2265 in
Coupon	F59-C2/1
Young's modulus, E =	13.0×10^6 psi (average value of 2 coupons tested)
UTS =	53,669 psi
Elongation at UTS =	16.75 percent
Elongation at break =	29.2 percent
True stress at yield =	31,014.8 psi
True strain at yield =	0.00238

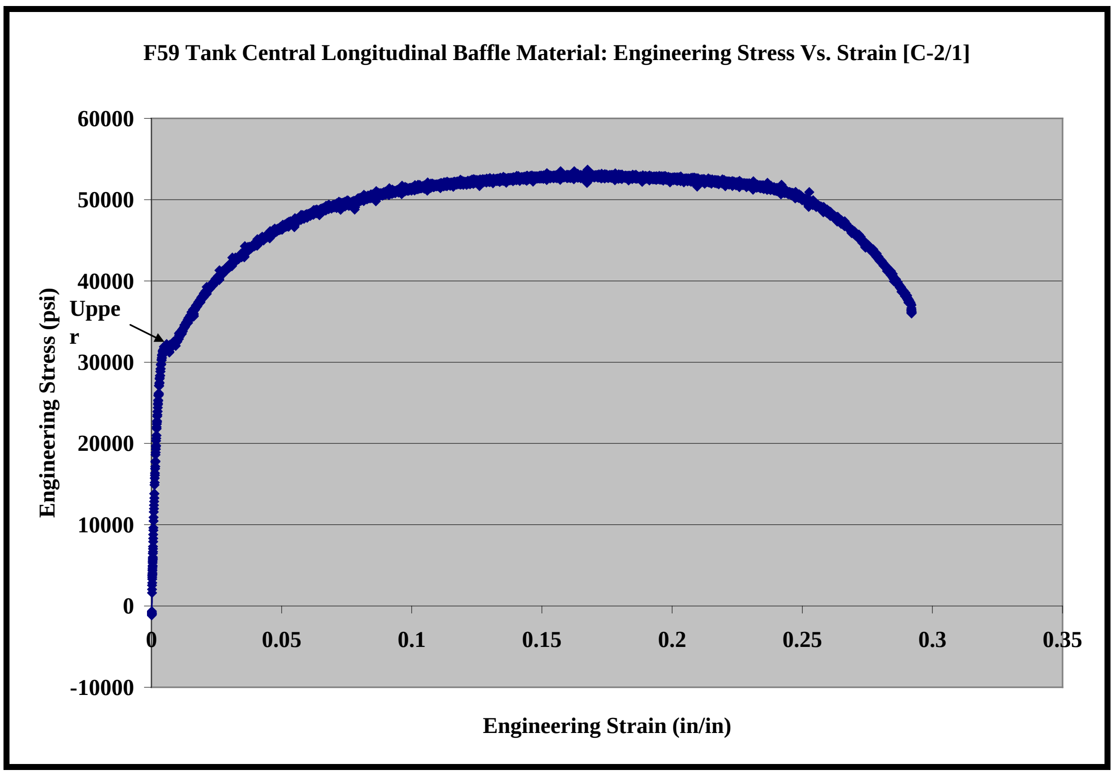

Figure A4. Engineering Stress vs. Strain Curve for Central Longitudinal Baffle Plate

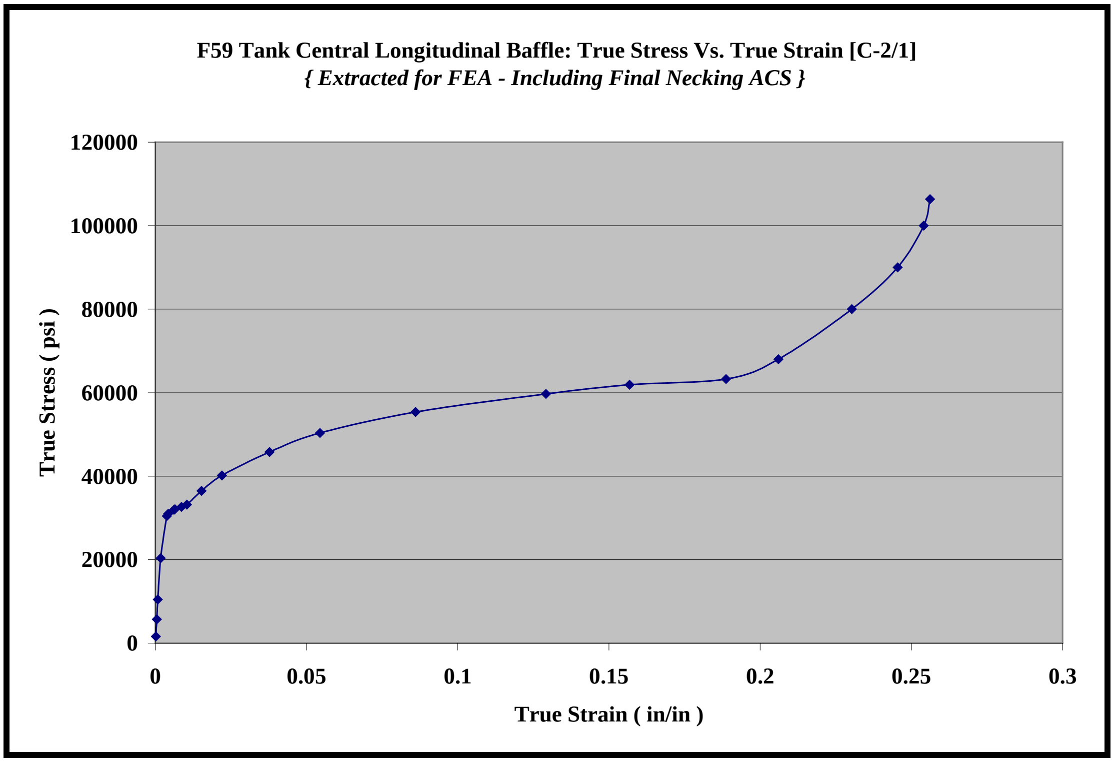

Figure A5. True Stress vs. True Strain Curve for Central Longitudinal Baffle

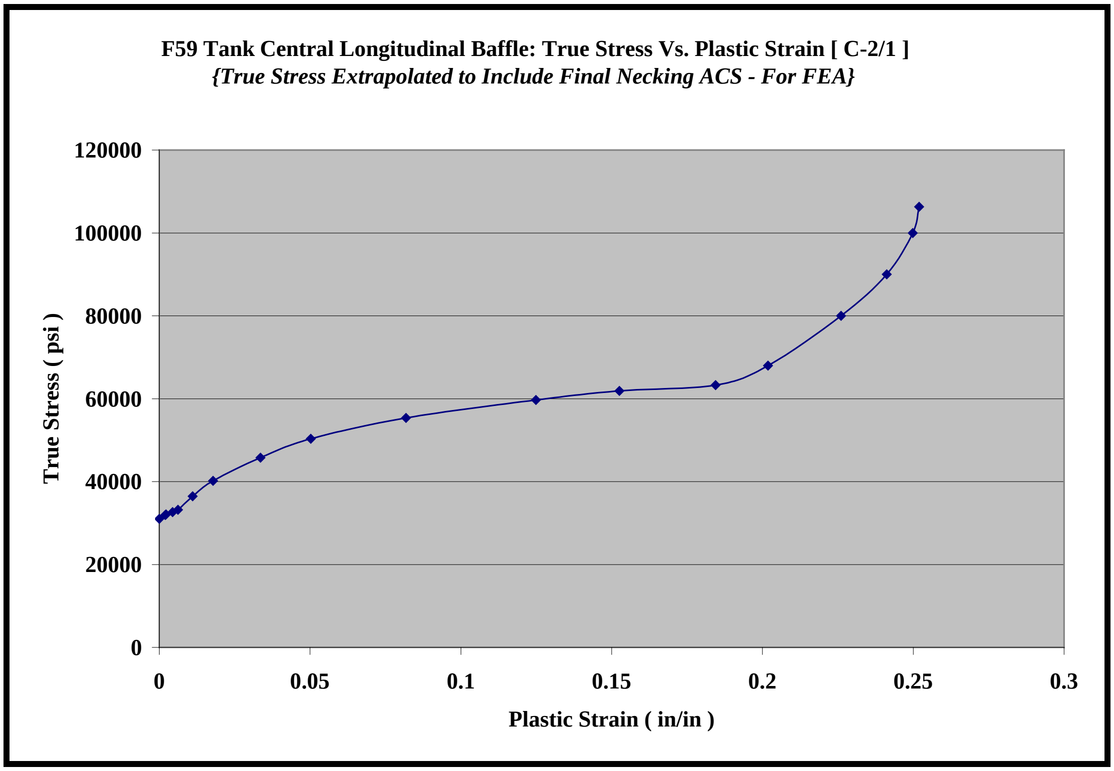

Figure A6. True Stress vs. Plastic Strain Curve for Central Longitudinal Baffle

3. F59 Tank Central Transverse Baffle Plate

Nominal plate thickness =	0.3705 in
Coupon	F59-C3/1
Young's modulus, E =	29.513×10^6 psi
UTS =	69,475 psi
Elongation at UTS =	19.2 percent
Elongation at break =	37.9 percent
True stress at yield =	50,891.81 psi
True strain at yield =	0.001671

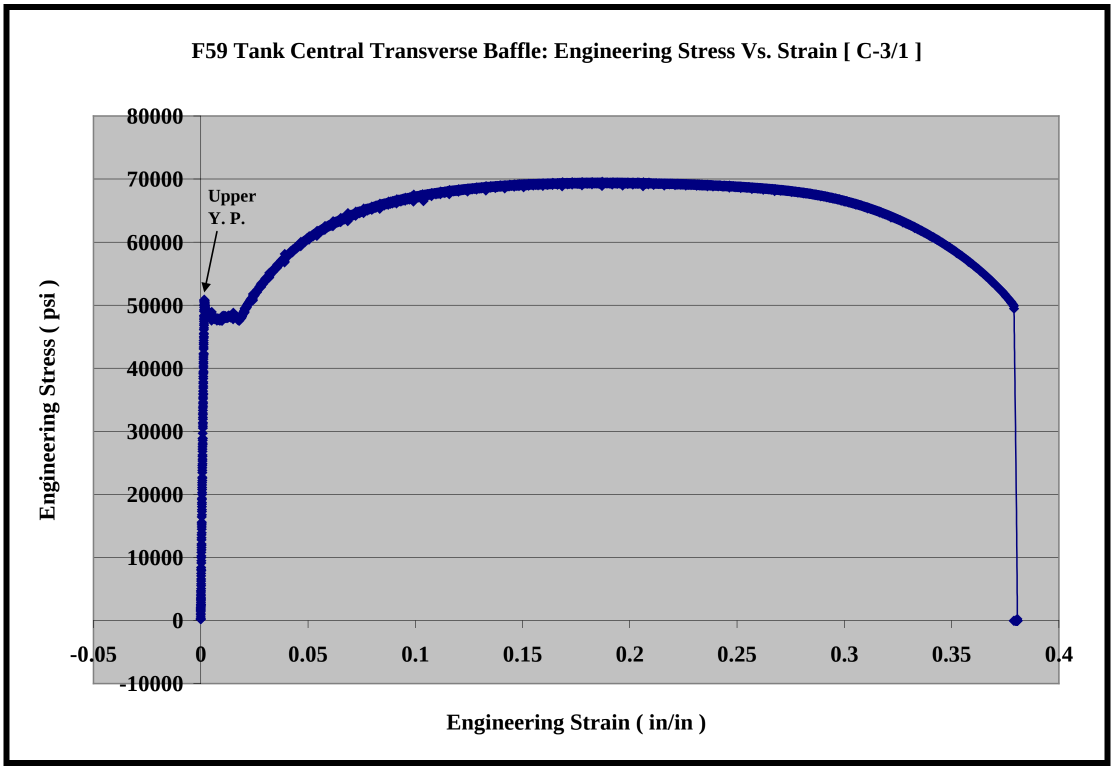

Figure A7. Engineering Stress vs. Strain Curve for Central Transverse Baffle Plate

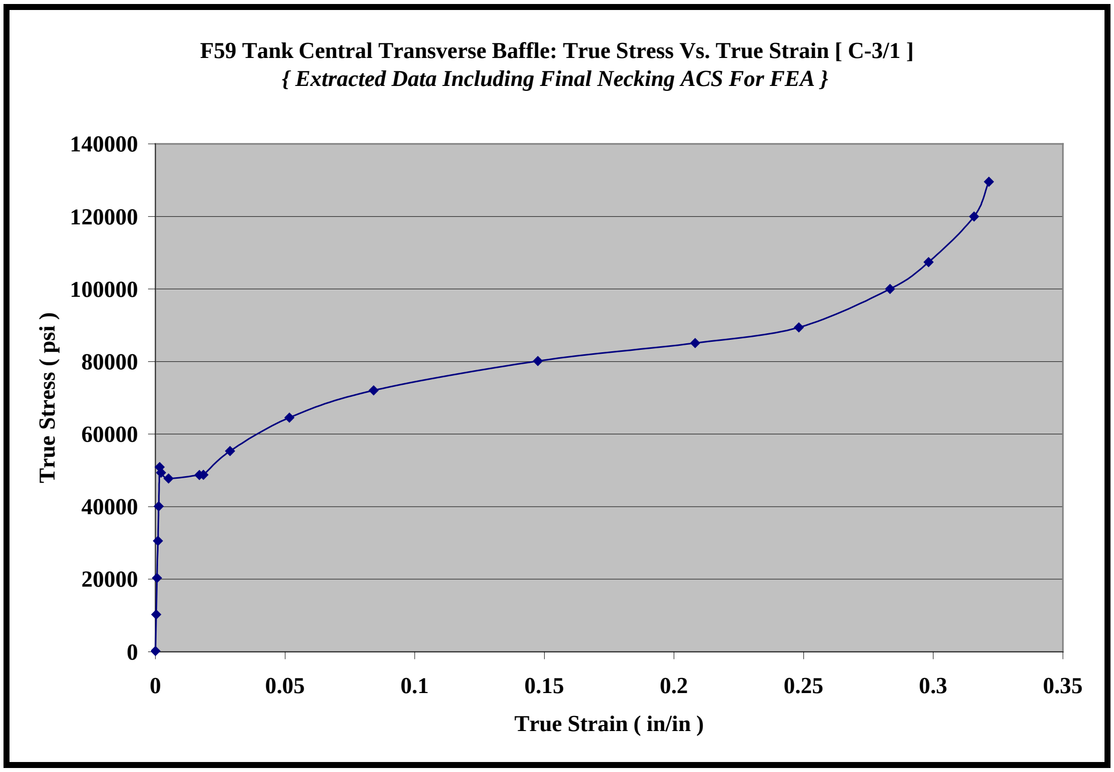

Figure A8. True Stress vs. True Strain Curve for Central Transverse Baffle

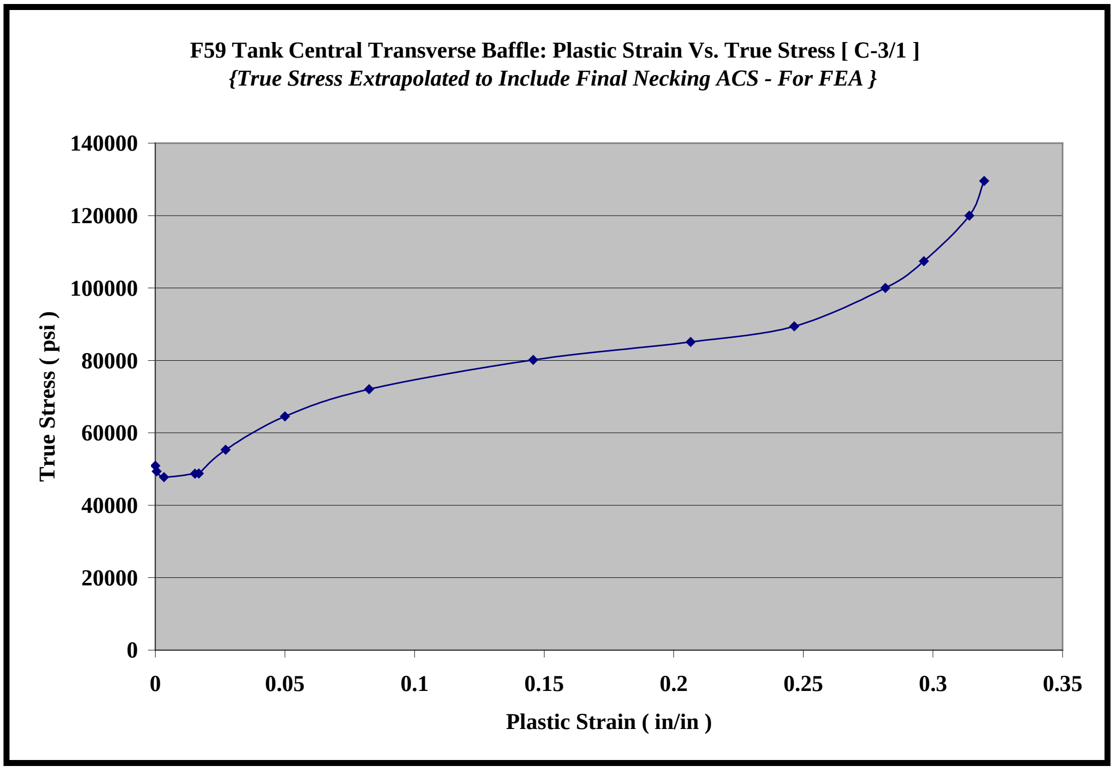

Figure A9. True Stress vs. Plastic Strain Curve for Central Transverse Baffle

4. F59 Tank Top Skin Plate

Nominal plate thickness =	0.25 in
Coupon	F59-1-1
Young's modulus, E =	30.517×10^6 psi
UTS =	72,935 psi
Elongation at UTS =	14 percent
Elongation at break =	24.6 percent
True stress at yield =	65,834.65 psi
True strain at yield =	0.0023617

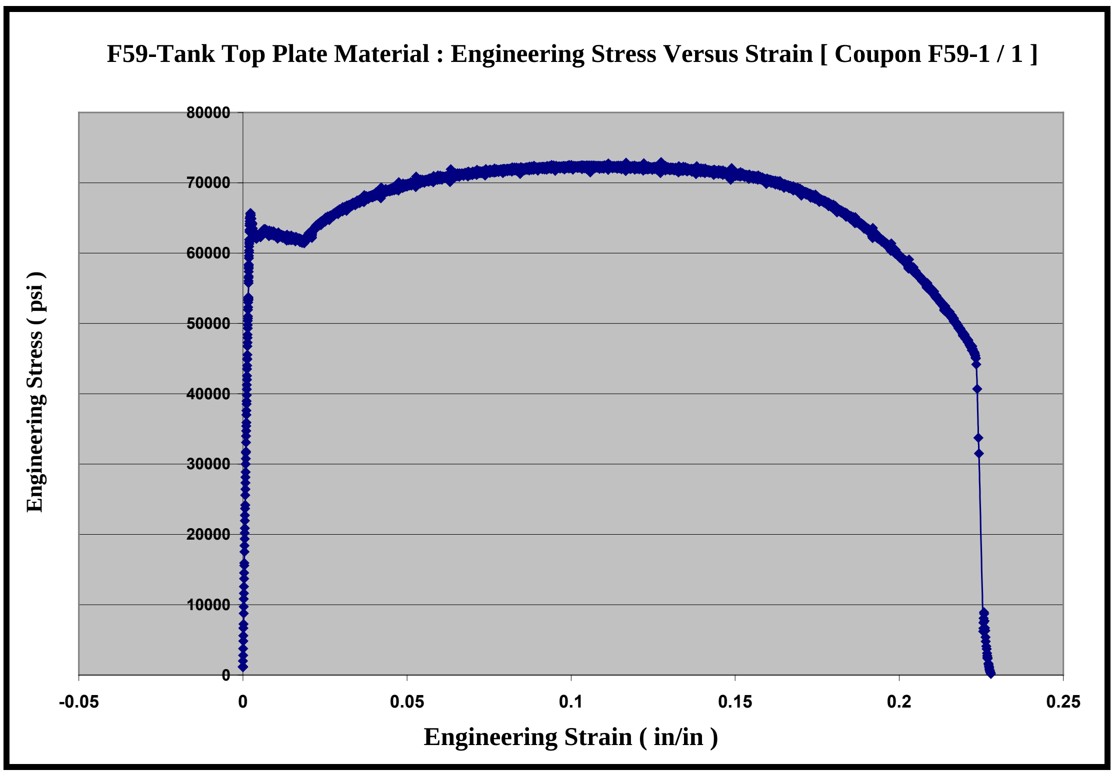

Figure A10. Engineering Stress vs. Strain Curve for F59 Tank Top Plate

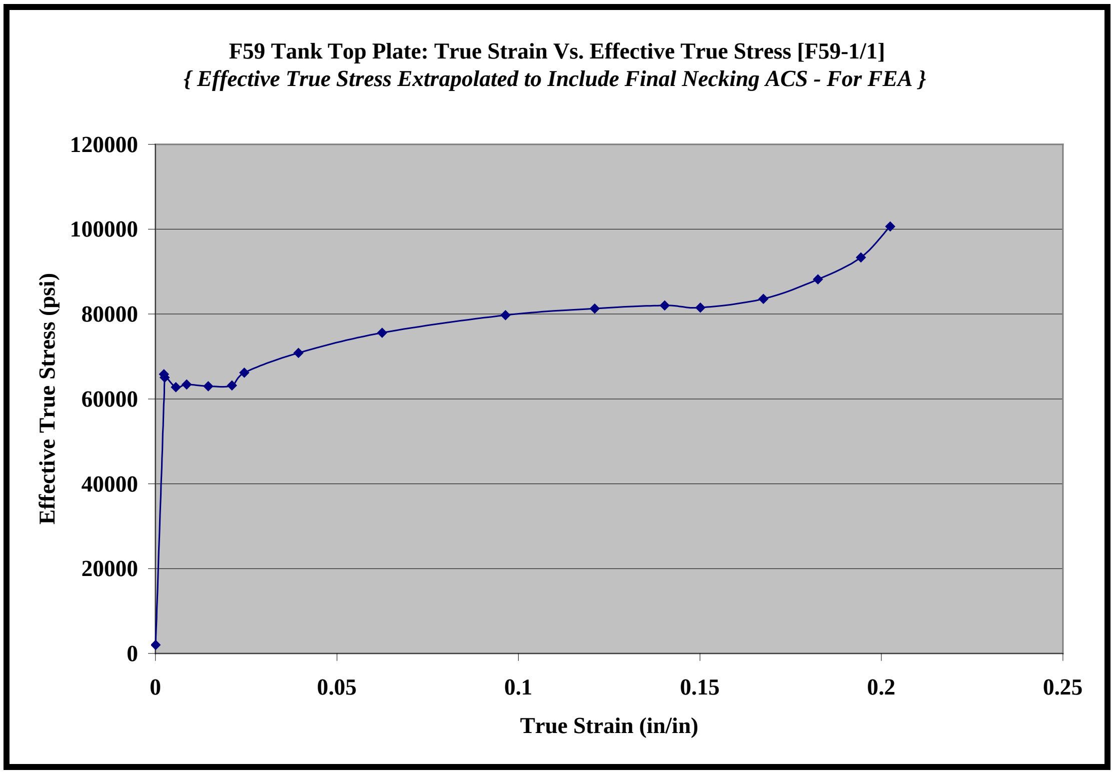

Figure A11. True Stress vs. True Strain Curve for F59 Tank Top Plate

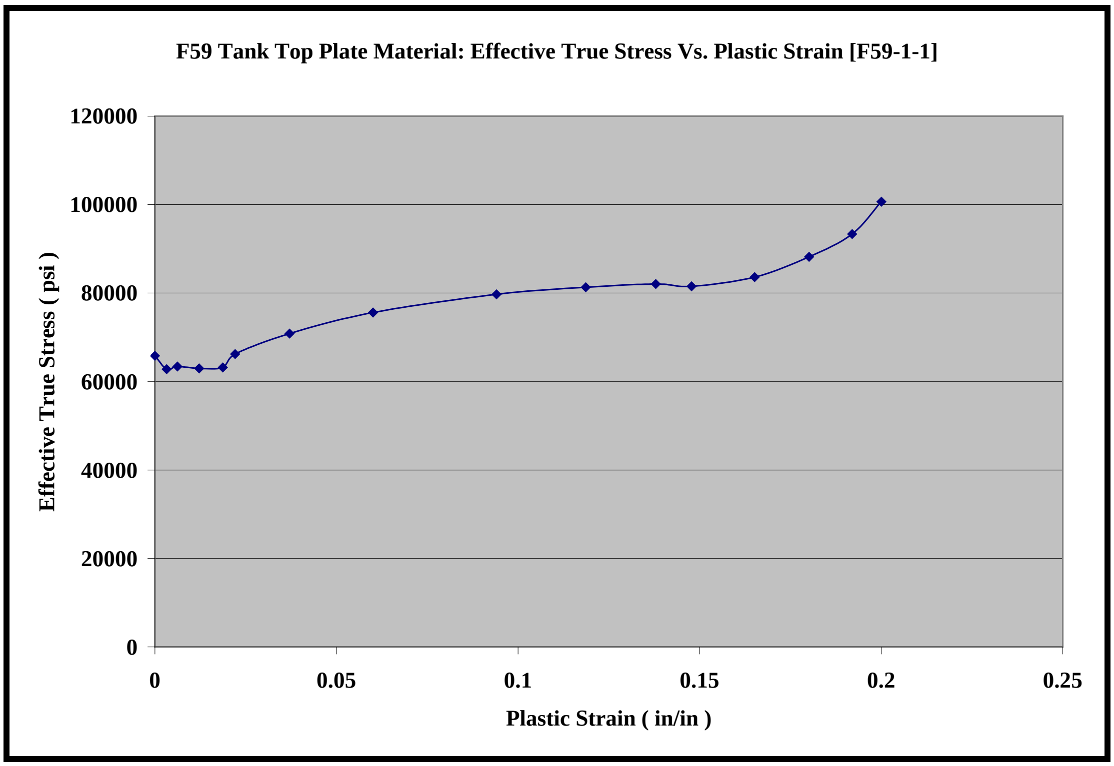

Figure A12. True Stress vs. Plastic Strain Curve for F59 Tank Top Plate

5. F59 Tank Bottom and Side Plate

Nominal plate thickness =	0.491 in
Coupon	F59-4-2
Young's modulus, E =	29.422×10^6 psi
UTS =	88,662 psi
Elongation at UTS =	5.45 percent
Elongation at break =	25.1 percent
True stress at yield =	70,400 psi
True strain at yield =	0.002542

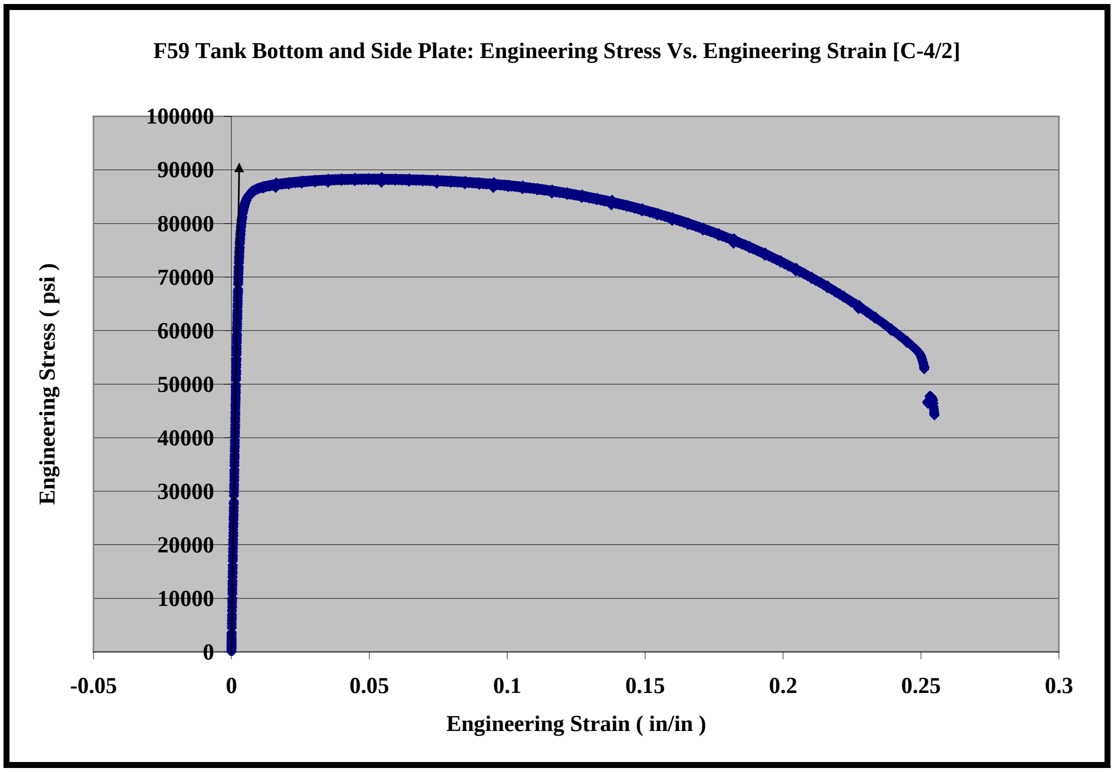

Figure A13. Engineering Stress vs. Strain Curve for F59 Tank Bottom and Side Plate

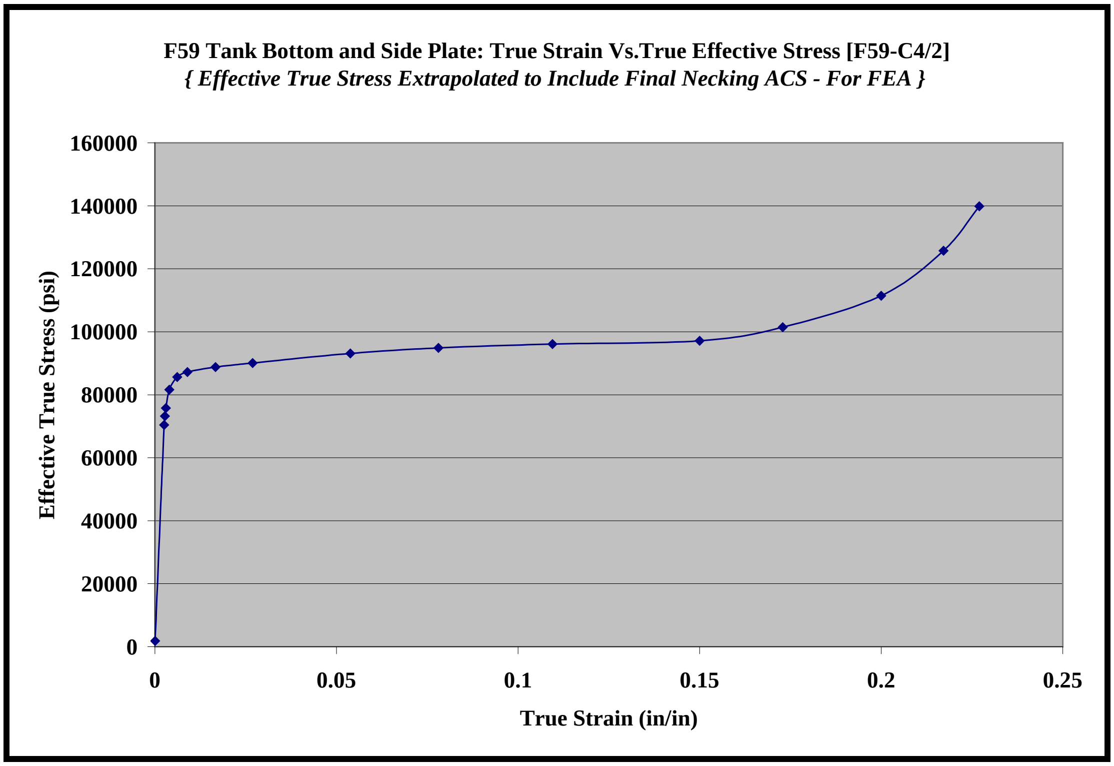

Figure A14. Effective True Stress vs. True Strain Curve for F59 Tank Bottom and Side Plate

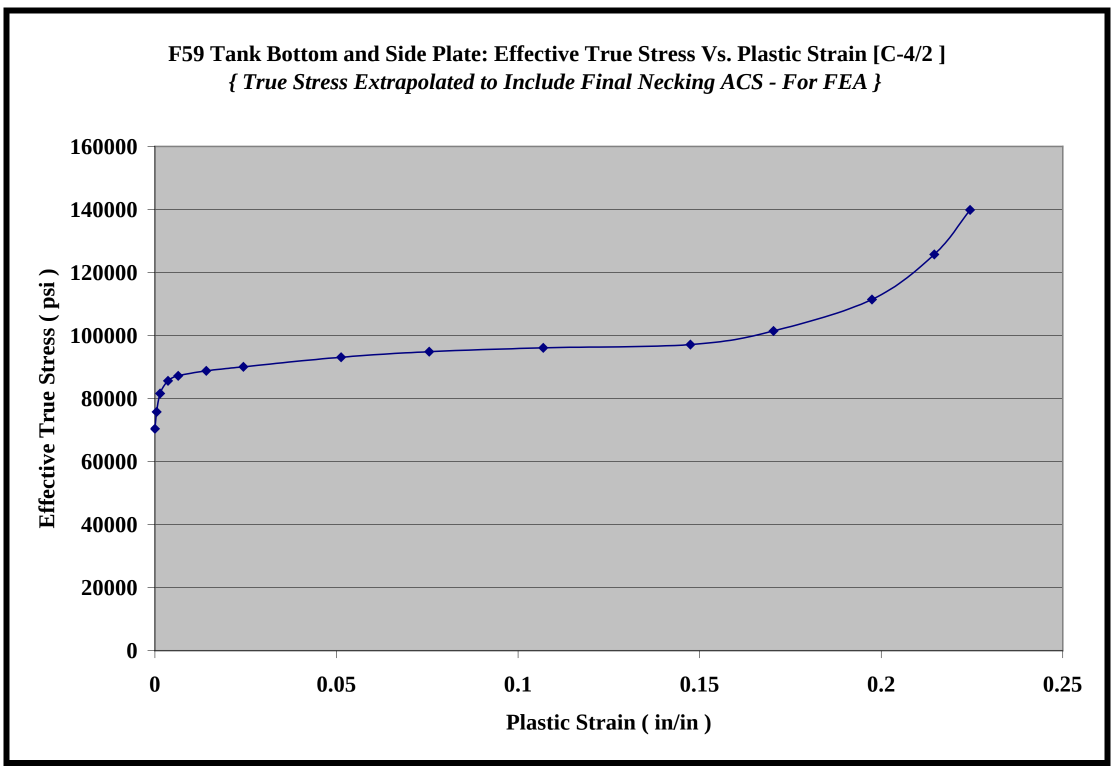

Figure A15. True Stress vs. Plastic Strain Curve for F59 Tank Bottom and Side Plate

6. F59 Tank End Plate

Assumed same material as SD70 tank

Nominal plate thickness =	0.75 in
Coupon	(SD70)-5/2
Young's modulus, E =	29.7×10^6 psi
UTS =	73,546 psi
Elongation at UTS =	11.34 percent
Elongation at break =	21.6 percent
True stress at yield =	51,581 psi
True strain at yield =	0.00171

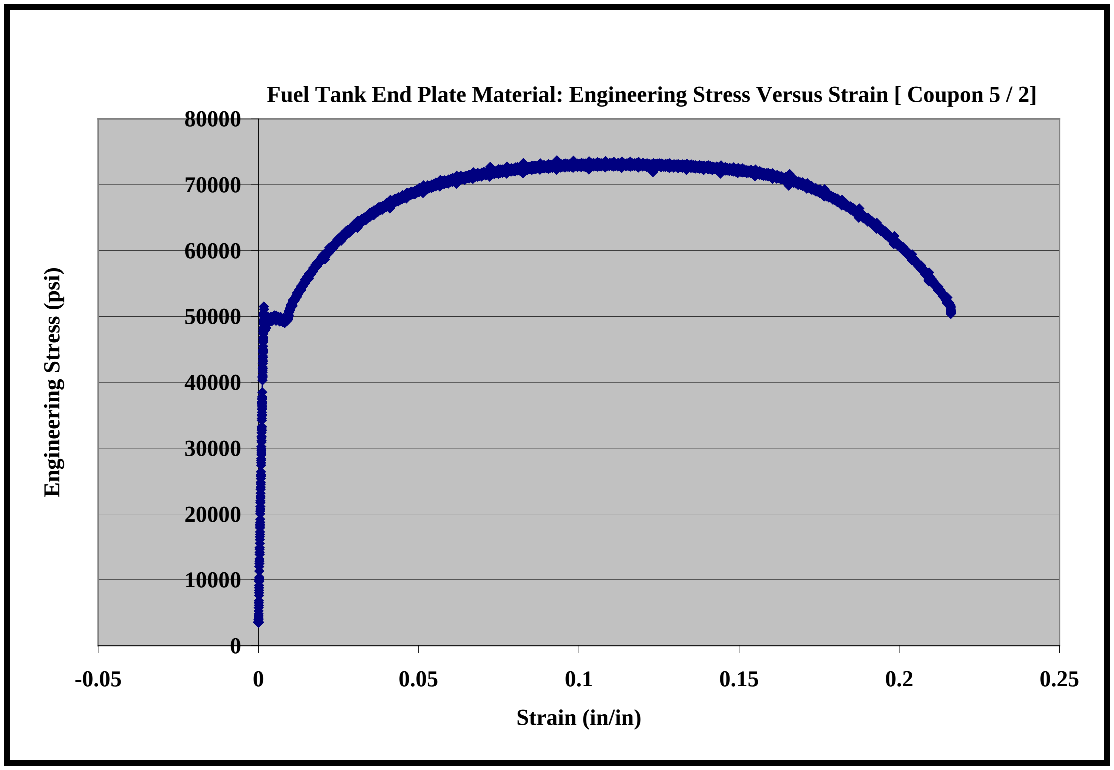

Figure A16. Engineering Stress vs. Strain Curve for Fuel Tank End Plate

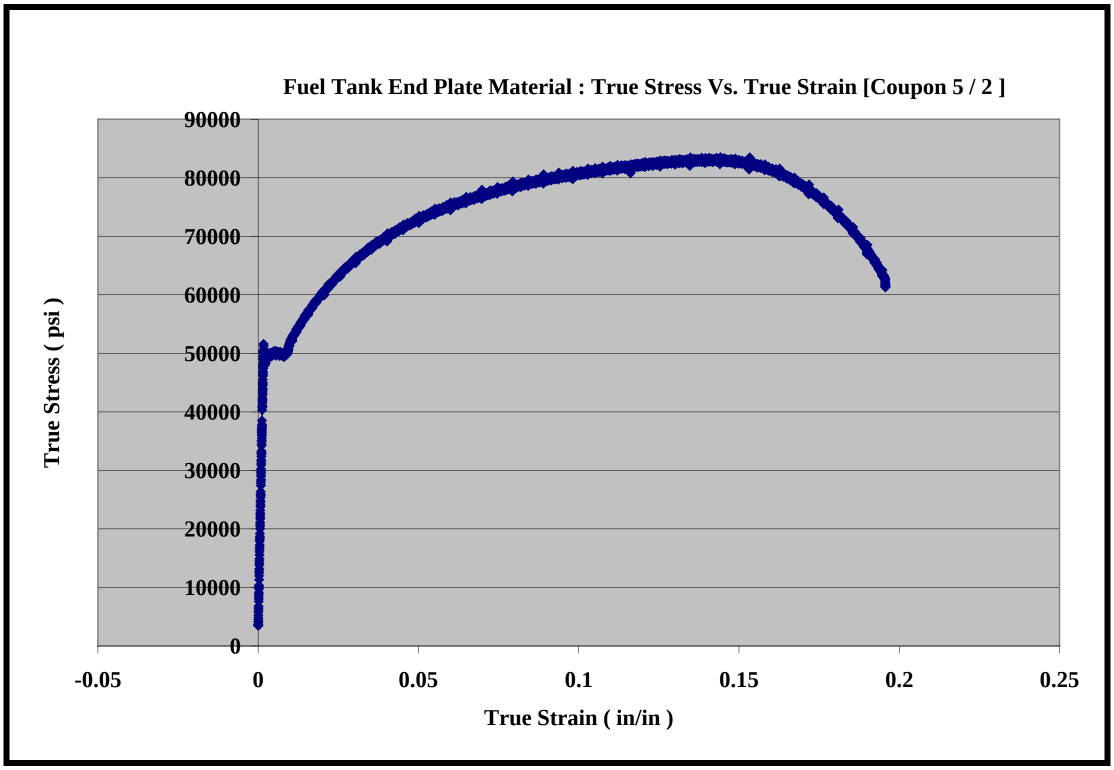

Figure A17. True Stress vs. True Strain Curve for Fuel Tank End Plate

Table A1. Summary of F59 Tank Materials Properties from Tensile Test Data

Component	Thickness (in)	Material	Modulus (Msi)	Yield Stress (ksi)	Ultimate (Msi)
Top plate	0.25	HSLA Steel	30.50	65.90	72.93
Bottom plate	0.491	CORTEN-B-QT70	29.40	70.40	88.66
Side plates	0.491	CORTEN-B-QT70	29.40	70.40	88.66
End plates	0.75	CORTEN-B	29.70	51.60	73.54
Transverse baffles	0.3705	AISI 1030/CORTEN-A	29.50	50.20	69.47
Longitudinal baffle (outer)	0.1825	CORTEN-A	28.70	50.10	69.43
Longitudinal baffle (center)	0.2265	Cast iron	13.00	31.90	53.70

Notes:
COR-TEN A refers to corrosion-resistant steel material of thickness less than 0.5"
COR-TEN B refers to same material with thickness in the range of 0.5" to 2.0"
QT70 represents thermomechanically processed (quenched and tampered) COR-TEN steel material to raise the yield stress from 50 to 70 ksi.

Abbreviations and Acronyms

CAD	computer-aided design
CFR	Code of Federal Regulations
EMD	Electro-Motive Diesel, Inc.
FEA	finite element analysis
FEM	finite element model
FRA	Federal Railroad Administration
HSLA	high-strength low-alloy
in	inch
JD	jackknife derailment
kip	kilopound
ksi	kilopound per square inch
MD	minor derailment
Msi	million pound per square inch
NI	National Instrument
psi	pound per square inch
SS	subsize