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Full-Scale Tank Car Rollover Tests – Survivability of Top Fittings and Top Fittings Protective Structures

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13. ABSTRACT (Maximum 200 words)

Full-scale rollover crash tests were performed on three non-pressure tank carbodies to validate previous analytical work and determine the effectiveness of two different types of protective structures in protecting the top fittings. The tests were performed with three different tank cars: 1) an unprotected base case car, 2) a base case car with an added protective skid weldment, and 3) a base car with an added protective bolt-on sleeve on the unloading nozzle with a reinforcing cone. Test conditions such as the impacting speed and angle were controlled by pivoting the carbodies in a fixture about a fixed axis and the fittings (or protective structures) impacted a concrete target pad. Before each test, proper test conditions and parameters were determined by Dynamic Finite Element analysis.

These tests establish that the skid and bolt-on sleeve concepts are efficient and practical methods for protecting top fittings on non-pressure cars from failure (and lading release) during rollover derailments. The demonstrated concepts can be developed into application-specific designs by tank car builders and implemented on tank cars as appropriate.

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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

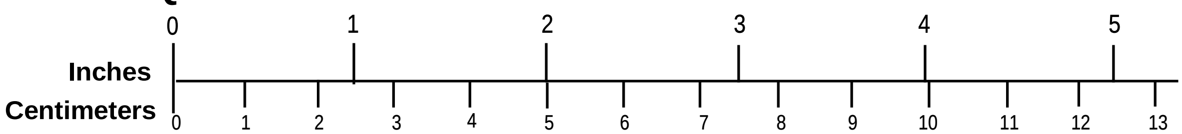
VOLUME (APPROXIMATE)

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

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

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

Railroad tank cars are usually equipped with fittings, which often protrude outside the tank envelope and are used for loading and unloading as well as other functions. These fittings can hit the ground or other objects during a rollover derailment and under derailment conditions in an unprotected state (particularly on non-pressure cars), fittings are unlikely to survive. Damaging them would likely result in a release of lading and possibly pose a public hazard. The structural response of these fittings to impact conditions should be studied and concepts should be developed for protecting them.

Dynamic Finite Element Analysis (FEA) illustrated that these fittings are susceptible when an appropriately-equipped tank car encounters rollover derailment conditions. This earlier analytical work was used to develop and evaluate several structural concepts for protecting top fittings from rollover, and this report describes the full-scale rollover testing of these concepts with actual tank cars.

In these tests, a deflective skid weldment and a bolt-on sleeve with reinforcing cone were evaluated against an unprotected top fitting. The weldment is a robust (heavy) concept that is designed for severe impacts, and the bolt-on sleeve is a moderate (lighter) concept for nominal impacts.

The skid weldment consisted of two large longitudinal sheets (which were tapered to prevent snagging) and two smaller lateral sheets welded to the tank with intermediate pads. On the other hand, the bolt-on sleeve was a weldment with an energy absorbing ring feature around its circumference. It was fastened to the fittings with the existing fastener holes used for the cover plate. A reinforcing cone was attached from the unloading nozzle to the tank shell to reduce the stresses at the nozzle-to-tank connection. Prior analytical work had indicated that the nozzle to tank connection was a critical area that needed reinforcement.

In the tests, each of three tank carbodies was placed in an engineered rollover fixture with the carbody pinned at the bolsters of one side of the car, though the carbody was allowed to rotate freely about this constraint. Non-pressured cars were used for testing because they do not employ the extensive structure and protective bonnets associated with pressured cars, which makes it more likely that derailed non-pressured cars will suffer damage to their fittings. The carbodies were filled with water to simulate the lading.

Hydraulic jacks were used to push the carbody to the point where it rolls over by gravity; the test setup was designed so that the fittings would impact a concrete target pad at a desired impact speed. Data was collected by a high-speed video camera along with sets of strain gages and accelerometers. This method provided a controlled, comparable, and repeatable method of testing, with the following results:

- The unprotected fittings were completely destroyed and the lading was rapidly released as a result.

- The deflective skid structure protected the fittings at the industry agreed upon test speed of 18 miles per hour (mph) with no resulting lading release.

- The bolt-on sleeve with reinforcing cone was successful in protecting the fittings at the agreed upon speed of 12 mph with no lading being released..

These tests have established that the deflective skid and bolt-on sleeve concepts are both effective and practical when used to protect top fittings on non-pressure cars from failure (and lading release) during rollover derailments. These concepts can be developed into application-specific designs by tank car builders and implemented on tank car designs, as appropriate.

1 Introduction

1.1 Background

Tank cars are usually equipped with a wide range of fittings—including manways, liquid/vapor valves, pressure relief devices, vacuum relief devices, unloading valves, sample lines, gauging devices, and bottom outlets—that allow efficient loading and unloading operations and provide for the safe handling and transportation of lading. They are generally installed on either the top or bottom of the car based on the intended function of the device, and come in various forms depending on the application. The fittings generally project out of the envelope of the tank for easy access and are designed to provide safe operation under normal operating conditions.

If a serious derailment causes the tank to be thrown off its trucks, it is possible that the entire weight and momentum of the tank might crush one or more fittings against the ground or an outside object. If such an incident occurs, it is unlikely that the fitting will survive structural failure or the connection between the device and the tank will fail, which would cause a loss of lading or a hazardous material (hazmat) leak. The safety and environmental implications of such an event are tremendous. The Minot, ND, incident of January 8, 2002, is a case in point. Several of the less severely damaged derailed cars leaked all of their anhydrous ammonia over many hours after their top fittings were damaged in the derailment. The leaked chemicals (along with the lading from the completely ruptured cars) produced a large toxic plume, resulting in one fatality and the evacuation of thousands of nearby residences.

The structural resilience of the most common fittings on tank cars in derailment and rollover conditions should be evaluated, and this need extends beyond the purely analytical work that was done in the past. Performing full-scale rollover tests of various tank cars can complement already performed analytical investigations [1, 2] and they can validate the analytical results obtained from previous work. Three general service non-pressure cars were used in three rollover simulation tests with:

- A base case tank car with no fittings protection,
- A deflective skid protective structure added to the base case car, and
- A bolt-on sleeve type protective structure installed on a tank car.

1.2 Objectives

The objectives of this test effort were to:

1. Demonstrate a repeatable method for testing tank car fittings and protections for fittings.
2. Compare the performance of unprotected top fittings with fittings that are protected by two different methods in rollover scenarios.
3. Determine strains, forces, and deflections that are experienced by the fittings, local tank shell, and protective structure during a rollover.
4. Calibrate the analytical models based on the test results.

1.3 Scope

Prior analysis, simulations and concept development resulted in several conceptual designs for protecting top fittings on non-pressure cars. They were classified as:

1. Robust (and heavy) designs that would protect fittings under severe impact scenarios, and

2. Moderate (and lighter) designs that would protect fittings under nominal impact scenarios.

In this effort, a base case unprotected tank was tested, as well as one concept each from the "Robust" and "Moderate" categories. Based on effectiveness, suitability, and practicality, a "Robust" top skid concept and a "Moderate" bolt-on sleeve were chosen for testing. Both concepts were intended to be sacrificial, i.e., the protective structure could fail as long as the fittings themselves were protected and no lading was released.

2 Test Articles

The base case and skid tests used ACF built DOTX 14007 and DOTX 14144 model tank cars, which are nearly identical and are 20,954-gallon general service cars of DOT class 111A100W1. These cars have a light weight of 65,700 pounds (lbs), a load limit of about 249,300 and 250,700 lbs, respectively, and a truck center spacing of 38’9”. The cars are equipped with separate manways, unloading nozzles, and safety valves.

The bolt-on sleeve test employed a Richmond Tank Car-built OWIX 15047, which is DOT class 111A100W1 car with a 20,800 gallon capacity, a light weight of 69,300 lbs, and a load limit of 263,000 lbs. This car has a truck center spacing of 38’-2⅝” and is equipped with a separate manway, unloading nozzle, and safety valve.

To prepare all three cars for testing, holes were cut in the bolster flanges and a section of steel round stock was welded in the hole centered about the flange. These bars acted as the pivot when they were engaged in the bearing provision in the tank support fixture. An additional reinforcing structure connected the round bar to the tank and bolster flange. This was done to alleviate high bearing stresses in the bolster flange as the tank was pivoted with its full weight on the bearings. The taut wire method was used to ensure adequate alignment of the bars at each bolster.

Refer to Section 4.3 for a description of the instrumentation that was added to the three test articles.

2.1 Base Case

Except for the modifications mentioned above, the only changes made to the base case car body were removing the ladder and the platform from the impact side of the car. Figure 1 shows the non-impacting side of the base case car after modification. Figure 2 shows a close-up of the top fittings.

Figure 1 Base Test Article

Figure 2. Top Fittings – Base Case Test Article

2.2 Deflective Skid Concept

To protect the fittings during the rollover scenario described in Section 3A, a protective skid was designed with the aid of dynamic FEA modeling (see Section 6). The skid consisted of two long longitudinal plates and two transverse plates. Gussets were used where the plates joined. Both longitudinal plates had sloped ends to reduce the chance of catching objects in the event of a derailment and to reduce longitudinal forces.

The skid was composed of a 1-inch thick ASTM A588 steel plate welded to the tank shell surface with intermediate ½-inch thick ASTM A588 steel pads between the skid and the tank shell. Full-length welds were used throughout. The skid was large enough to allow all fittings to be placed inside its boundaries, if desired, and the focus of impact for this test was centered about the safety valve (Figures 3, 4, and 5). The skid weight including pads is approximately 4,500 lb.

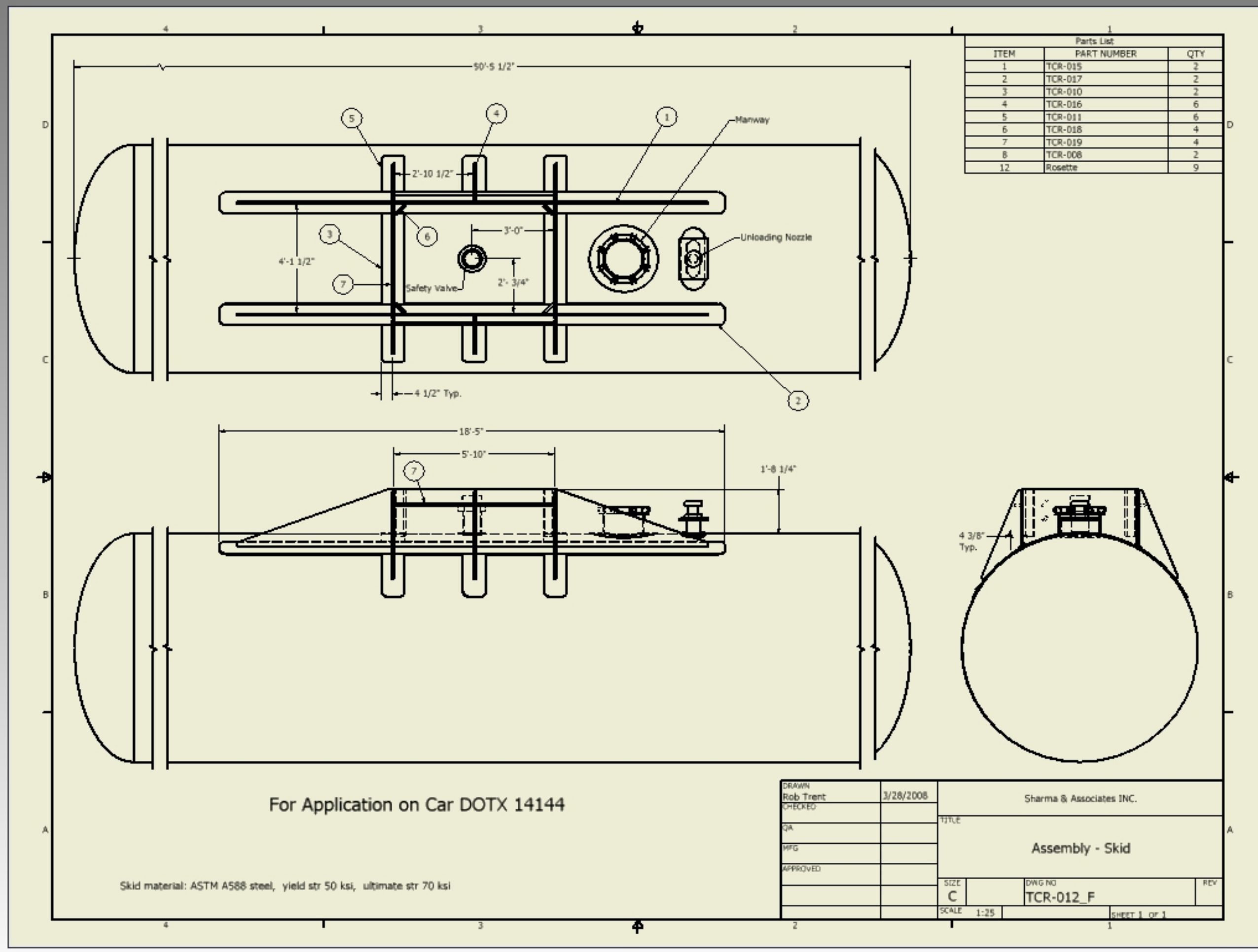


Figure 3. Drawing – Skid Assembly

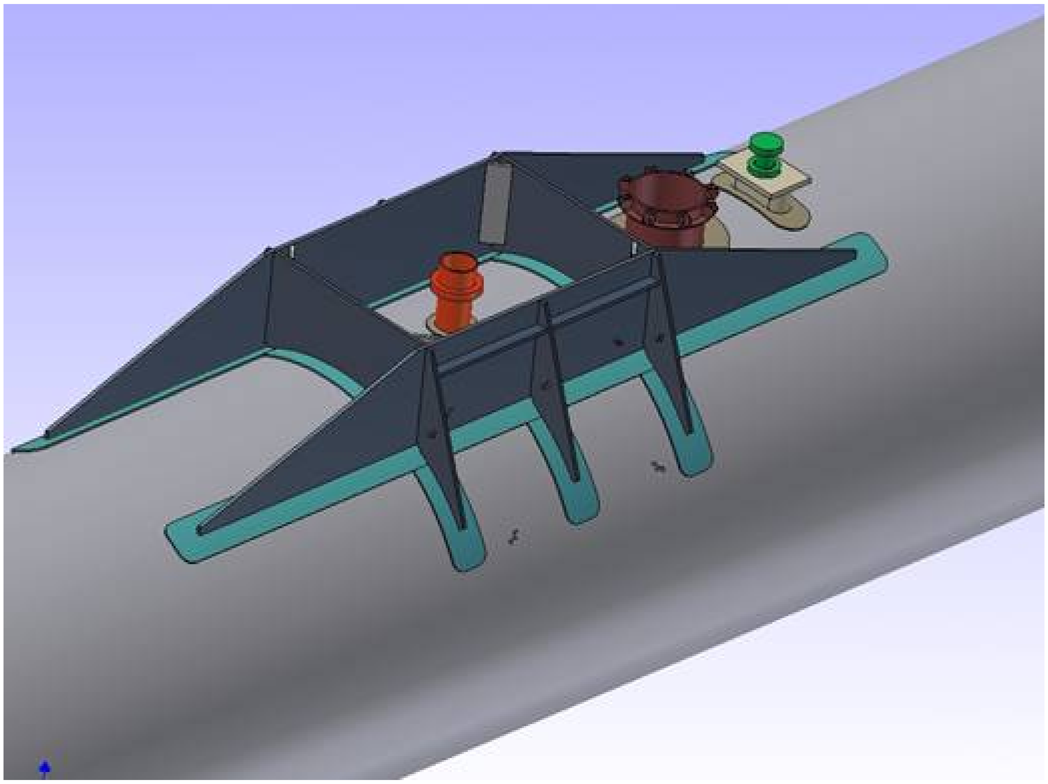


Figure 4. Deflective Skid Concept

Figure 5. Deflective Skid – Pre-Test

2.3 Bolt-On Sleeve with Cone Concept

The bolt-on protective sleeve assembly with a welded-in reinforcing cone structure was designed with the aid of dynamic FEA modeling (see Figures 6 and 7). Prior analytical work had shown that outside of the fittings, the connection between the nozzle and the tank was a weak link when rollover derailments occur. This bolt-on sleeve concept addresses both the fittings and the tank interface by utilizing both a sleeve and a cone for protection and reinforcement.

The reinforcing cone has a 45-degree slope and was fabricated out of ½-in thick ASTM A517 Gr. F steel plate. It extends $7^{11}/_{16}$ 7-11/16 inches above the top center of the tank shell and is welded with continuous full penetration welds. It connects to the tank shell through a ½-inch thick steel ASTM A516 Gr. 70 steel pad.

Instead of the existing 18-in diameter unloading nozzle, the 20-in diameter manway was converted into an unloading nozzle for use in this test. This modification, which was consistent with the current standard size unloading nozzle, was agreed upon by a committee consisting of Sharma & Associates (SA), Federal Railroad Administration (FRA), and industry representatives.

The bowl assembly consists of two ¾-in thick steel plates formed into semitubes and welded together to create the sleeve, a base plate, and a ½-in thick reinforcing rim assembly to increase deformation resistance and act as an energy absorber. The bowl fastens to the cover plate of the unloading nozzle through 1-inch diameter 20 grade 8 bolts (see Figure 8). The weight of the cone and pad is approximately 570 lb. The weight of the sleeve is approximately 500 lb.

The clearance between the inner surface of the protective sleeve (at the ID) and the outermost surface of the fittings, if they were placed inside this bowl, is 7 inches.

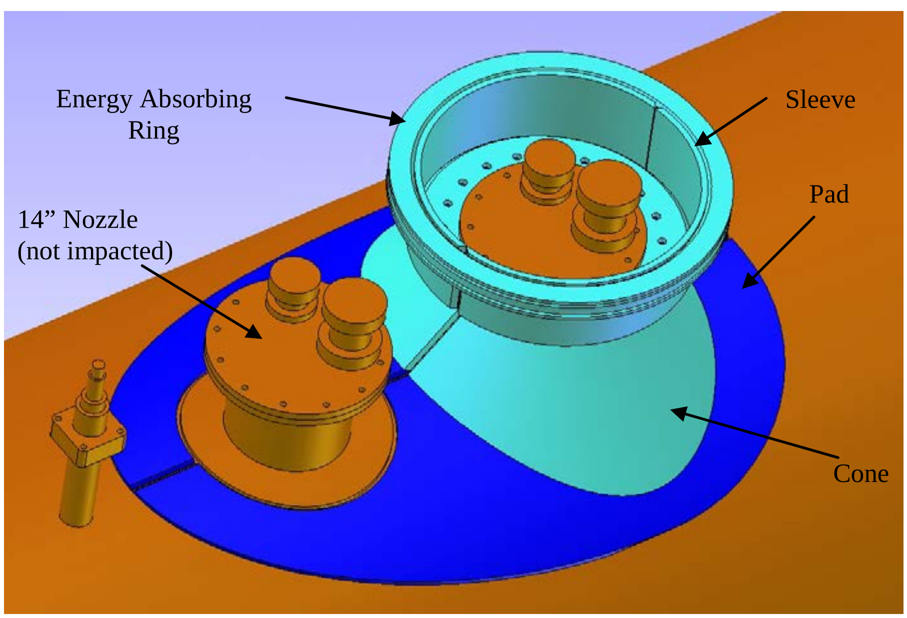


Figure 6. Sleeve and Cone – View 1 (shown with valves inside bowl for scale)

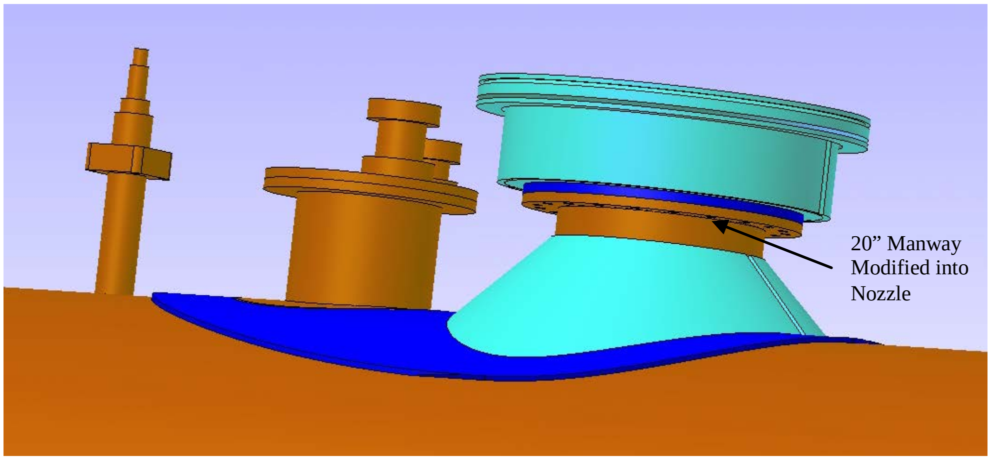


Figure 7. Sleeve and Cone – View 2

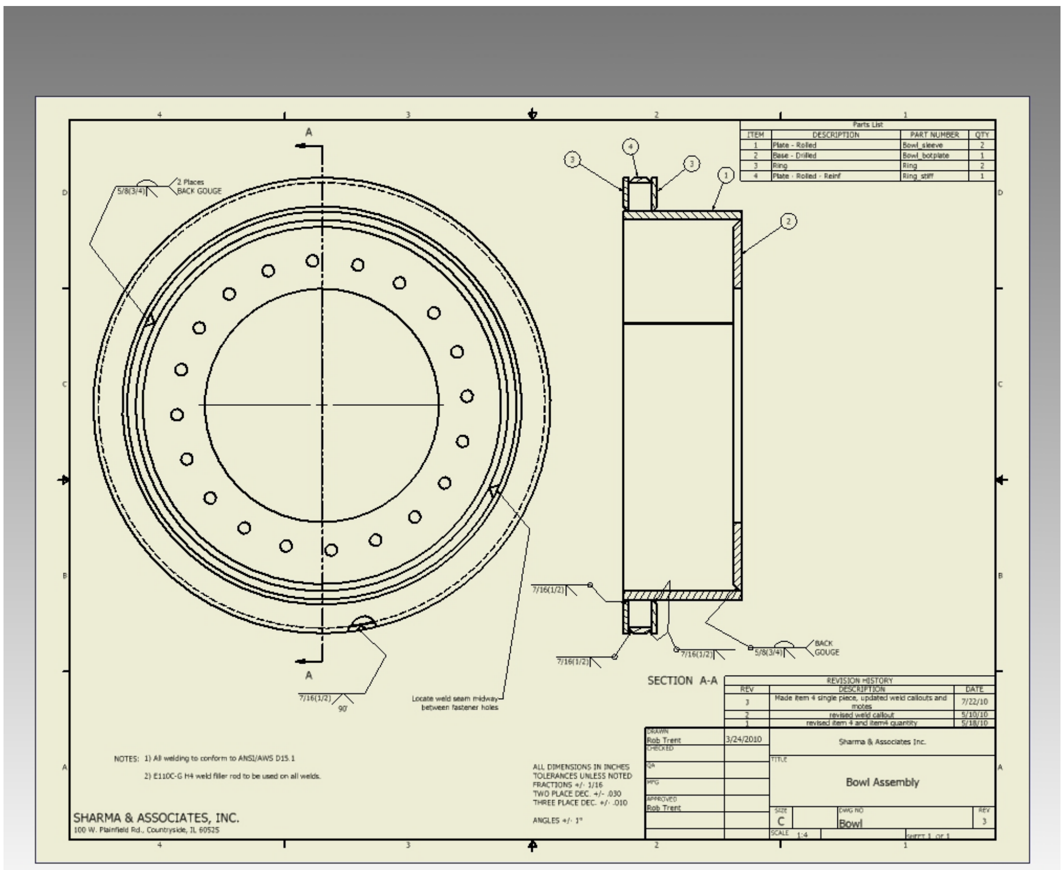


Figure 8. Bolt-On Sleeve Assembly Drawing

3 Test Description

In each test, a full-scale tank car was placed into a fixture which rolled each loaded untrucked carbody about a fixed pivot. The tanks were filled with water to a two percent outage. The carbodies were pushed to the point of imminent rotation and then rotated under the force of gravity until impact. A concrete surface target stopped the car rotation and it was the subject of impacts by the top fittings or protective structures. Also, the vertical location of the concrete target surface could be adjusted for different impact speeds (as agreed upon by SA, FRA, and the tank car manufacturers). The tank shell, fittings, and protective structure (when applied) were instrumented with strain gages and accelerometers that recorded the stresses and forces on materials. This type of arrangement controls impacts and provides repeatable test conditions.

A high-speed video was taken of each rollover test to record the events, capture the deformation sequence, and determine the velocity at impact. Post-test analysis of the test articles determined deflections, damage to the structure, and compromises to tank integrity leading to loss of car lading.

The following rollover tests were performed:

Test 1. DOTX 14007 with minimal changes (i.e. the “base case”)

Test 2. DOTX 14144 (sister car to DOTX 14007) with a deflective skid attached

Test 3. OWIX 15047 with a protective bolt-on sleeve and cone attached

3.1 Test 1 – Base Case

The base case test provided a reference for the other two tests, validated the FEA modeling of the unprotected car, and verified the functioning of the test setup. This case focused on the impact of the safety valve, which was outfitted with a wire rope attached to its outer end and fastened to a point on the tank car with slack. This prevented the valve from flying too far when impact occurred. The fixture was elevated above the impact surface to an impact angle of about 45 degrees between the fittings and the target surface (see Figures 9 and 10). Two 8-inch thick sacrificial concrete impact blocks were stacked above the concrete target foundation to produce a desired impact speed of 24 mph as measured at the top impact point of the safety valve. These blocks were positioned so they would only impact with the safety valve. A second single 8-inch thick concrete block was positioned to only impact with the manway. The unloading nozzle was free to impact the base concrete pad. A steel plate was used between the base pad and the sacrificial pads in order to protect the base pad (see Figure 11).

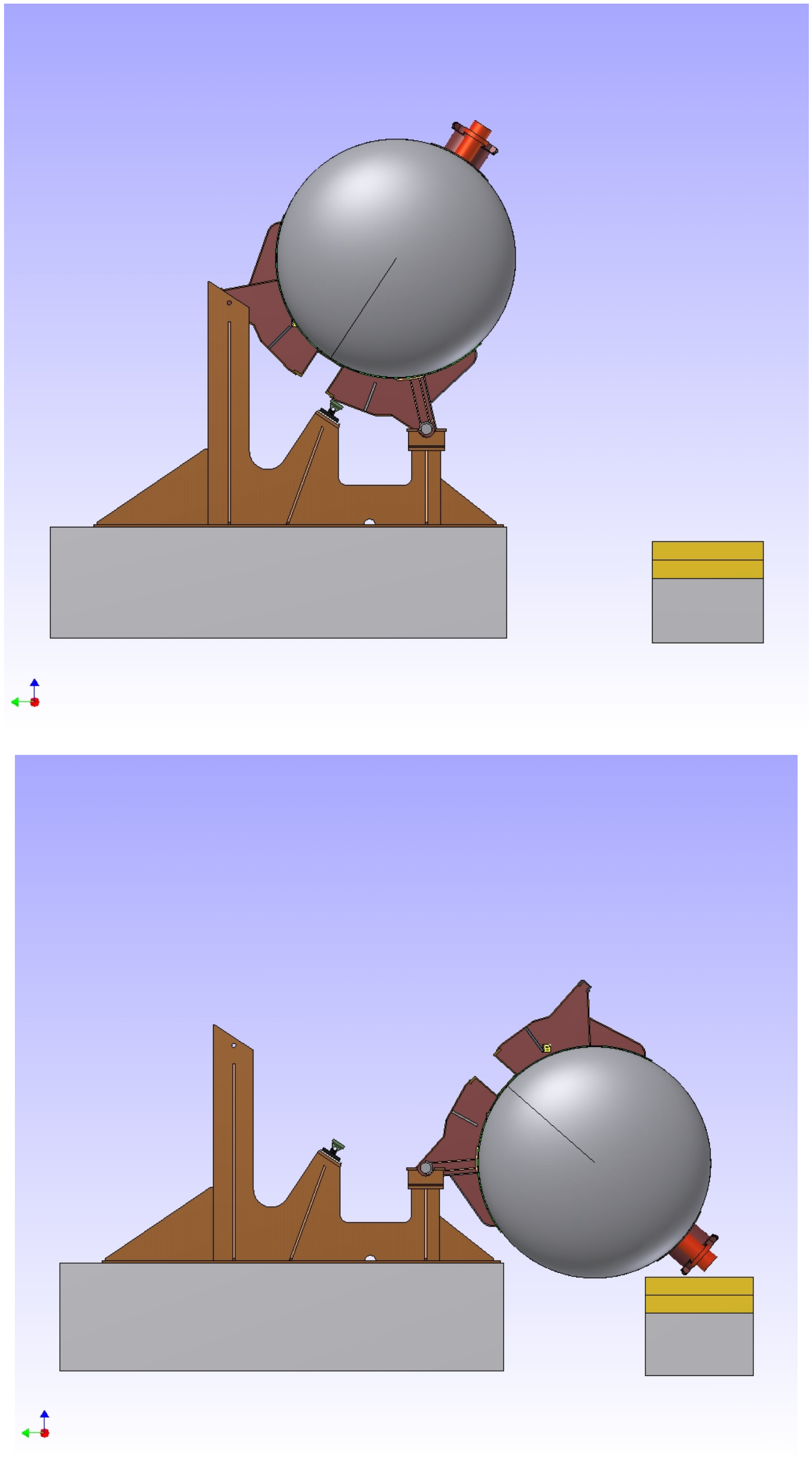


Figure 9. Base Case Test

Figure 10. Base Case – Tank Carbody in Test Fixture

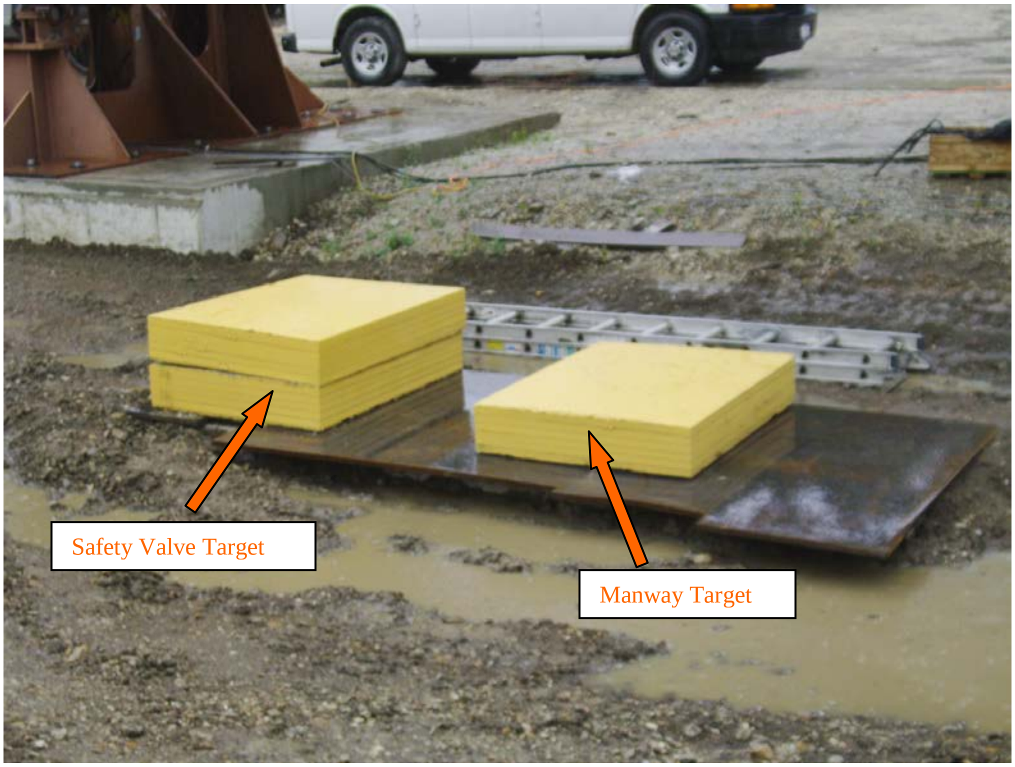


Figure 11. Concrete Target Pads – Base Case

3.2 Test 2 – Deflective Skid

The next test was performed on a car which was identical to the base case car except it had a deflective skid attached. Prior to performing this test, FRA decided that an impact speed of 18 mph was appropriate for this case, which meant that a stack of sacrificial concrete target blocks with a total height of 28 inches was placed above the target foundation. One 20 -in block and another 8-in block were used; the 8-in block on top received an impact similar to the base case test. The resulting angle of impact was 27 degrees between the tank vertical plane and the target surface (see Figures 12 and 13).

Figure 12. Concrete Target Pads – Skid Case

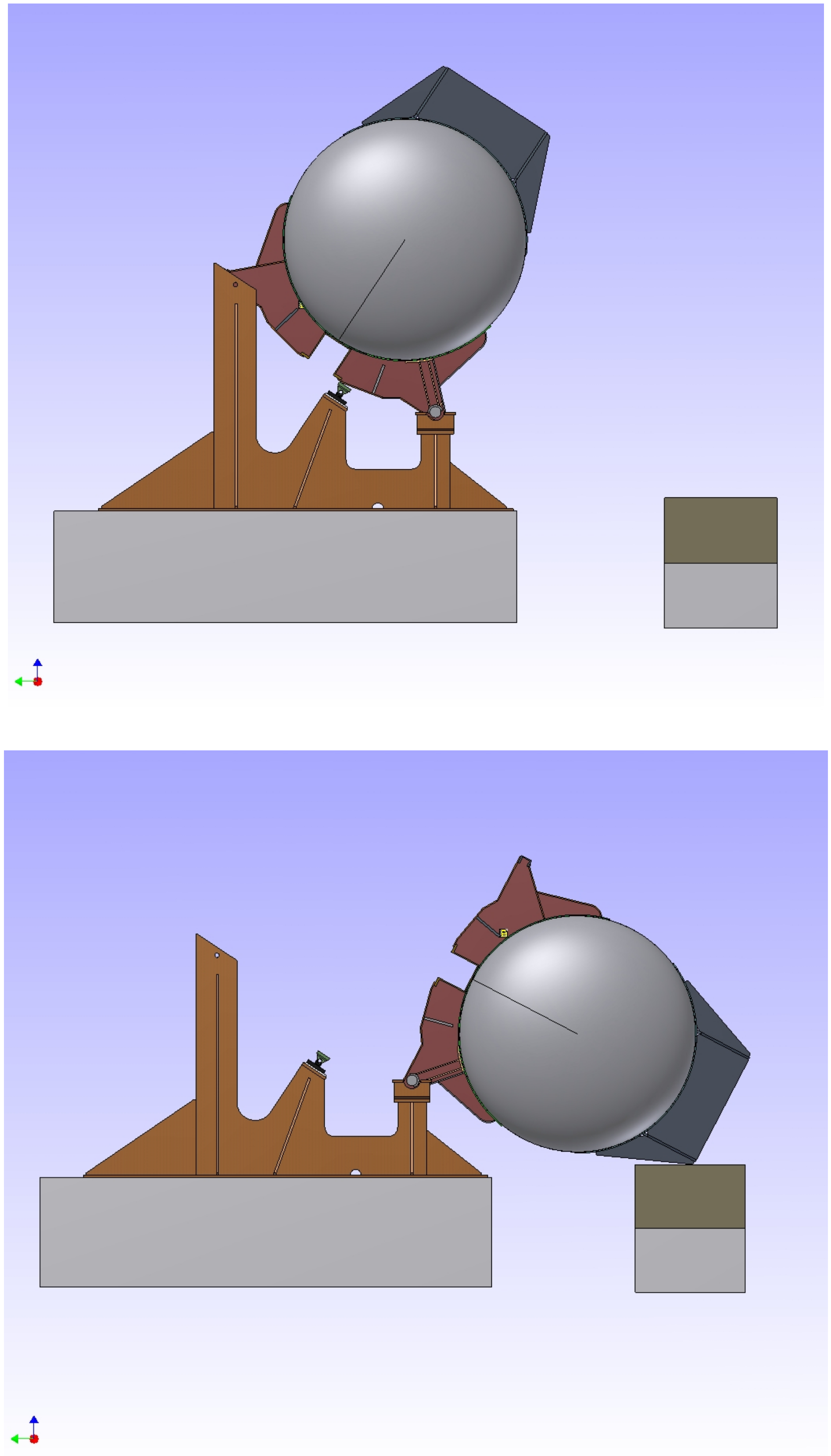


Figure 13. Skid Case Test

3.3 Test 3 – Bolt-On Sleeve with Cone

For the final test, in which a car was equipped with a bolt-on sleeve and a cone attachment, FRA decided that an impact speed of 12 mph was appropriate. To achieve this speed, the target was raised significantly above the height used in the previous tests; ground fill was added at the impact site and compacted to serve as a base for the new concrete target (see Figures 14 and 15). The target had inclined impact surface to maintain the same impact angle used in the earlier test. Two 8-inch thick sacrificial concrete blocks were placed on top of the main concrete pad.

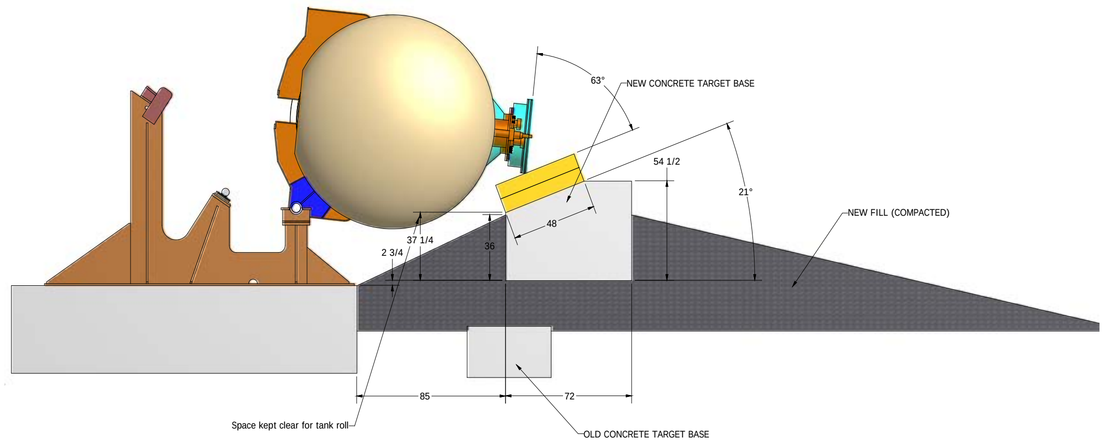


Figure 14. Layout of Bolt-On Sleeve Test

Figure 15. Photograph of Bolt-On Sleeve – Pre-Test

4 Test Apparatus

S&A designed and conceptualized the overall test setup with effectiveness and practicality in mind. Once the test concept was finalized, individual elements of the test apparatus were designed and fabricated. The test apparatus had the following elements:

- Two fabricated tank support fixtures
- A concrete support base
- A concrete target area
- A hydraulic system
- Instrumentation

Test Fixtures

Two fabricated fixtures, one at each bolster, supported the tank car body. They were designed using the appropriate modeling tools, and the structural adequacy of the fixtures was confirmed using ANSYS finite element software. The frames were fabricated at a local manufacturing facility and SA ensured that the frames were fabricated properly.

The fixtures were anchored with concrete bases that were poured at each fixture location and the bases were large enough to accommodate a range of tank car sizes for future testing. Plain pivot bearings were provided integral with the fixtures so they can accept a shaft that is welded perpendicular to each carbody bolster web. These bearings were made from steel tube stock and had lower and upper halves. After the shaft was placed in the lower-half bearing, the upper-half bearing was bolted to secure the tank body in position in the fixture (see Figures 16 and 17).

A 75-ton hydraulic cylinder was mounted on each fixture with a clevis eye and roller attached (see Figure 18). The roller exerted force on the bolster flange to roll the tank car body about the pivot bearing.

4.1 Hydraulic System

The hydraulic system consisted of the following components:

- An electric induction pump (20L)
- Two 75-ton double acting cylinders
- Two 2½-inch pressure gauge, 0-10,000 psi ½
- Appropriate high pressure piping, including valves, hoses, couplers, etc.

The single pump powered both cylinders through a setup of manifolds and valves. The symmetry of the tank car body provided for uniform cylinder extension speed.

Figure 16. Bearing to accept pivot shaft

Figure 17. Pivot Shaft

Figure 18. Hydraulic Cylinder and Rollers

4.2 Instrumentation

For all three test cases, a dynamic FEA analysis was performed to select appropriate locations for the mounting of strain gages. Locations on or near the fittings or protective structures and far enough away from steep strain gradients were selected. Several locations on the tank shell were also instrumented with strain gauges to determine the stresses at these locations and to obtain data to compare with the simulations. The bondable gauges could record up to 200,000 microstrain. These strain gauges use specially annealed constantan foil with a tough high-elongation polyimide backing to enable measurements of large post-yield strains. Strain gauges were bonded to the test specimen surfaces using an automatic strain gauge bonding system, which simultaneously applied pressure and heat to the gauges being bonded. For all three tests:

- An accelerometer was mounted on the tank shell between the manway and the safety valve to record forces experienced during impact.
- A tilt sensor was installed to obtain a trace of the angular movement of the tank.
- A high-speed camera pointed at the safety valve was used to record the impact.

4.2.1 Test 1 – Base Case

In Test 1, a total of 17 rosettes and 7 single grid gages were used (see Figure 19). To accommodate all 60 channels, three data collection systems were used. These consisted of a Somat eDAQ-lite, a GMH and a custom built DAQ system. The Somat was used for the strain channels acquiring data around the safety valve. The GMH box was used for other strain channels, and the custom DAQ box recorded the tilt sensor and the accelerometer.

4.2.2 Test 2 – Deflective Skid

In Test 2, a Somat eDAQ-lite data acquisition system was used to collect data on all 31 channels used. A total of nine rosettes were used (see Figures 20 and 22). A ribbon switch was installed on the target to provide a pulse to record the time of impact.

4.2.3 Test 3 – Bolt-On Sleeve with Cone

In Test 3, a Somat eDAQ-lite data acquisition system was used to collect data on all 31 channels used. A total of eight rosettes and three single strain gages were used (see Figure 21). A ribbon switch was installed on the target to provide a pulse to record the time of impact. See Figure 23 for a sample photo of the strain gauges being bonded.

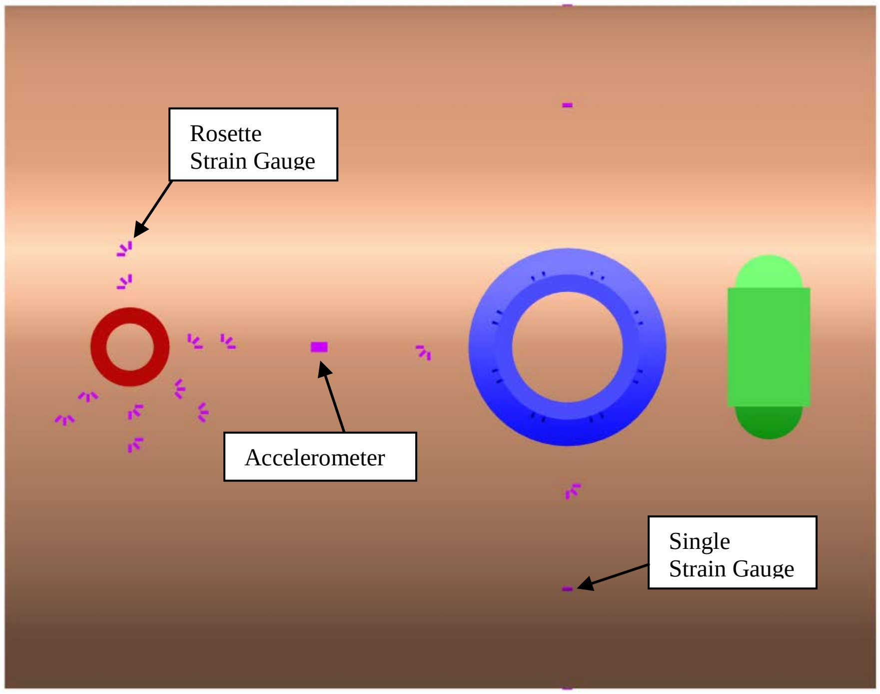


Figure 19. Strain Gage Instrumentation – Base Case

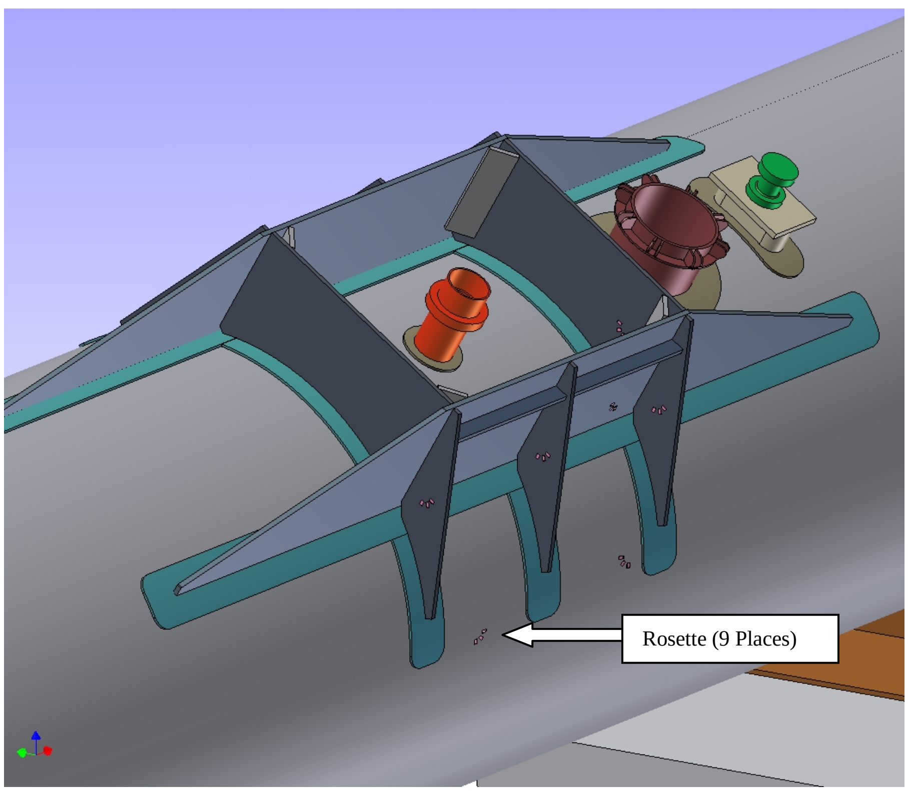


Figure 20. Strain Gauge Instrumentation – Skid Case

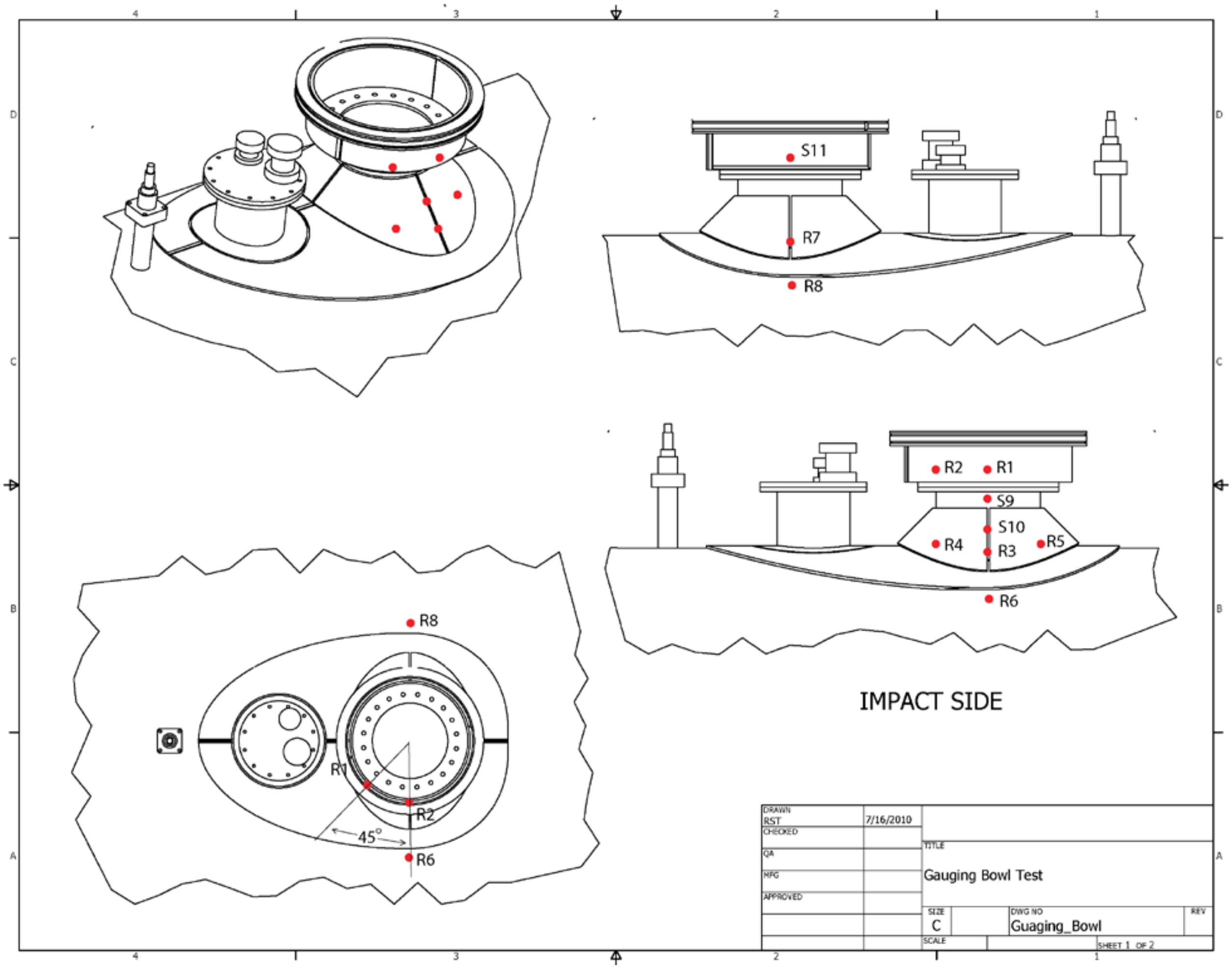


Figure 21. Strain Gauge Instrumentation – Sleeve Case (R = rosette, S = single gage)

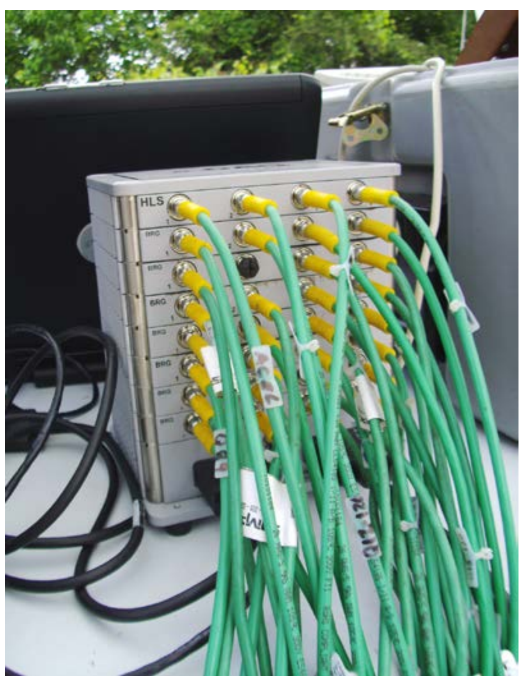


Figure 22. Somat e-DAQ Lite data acquisition system

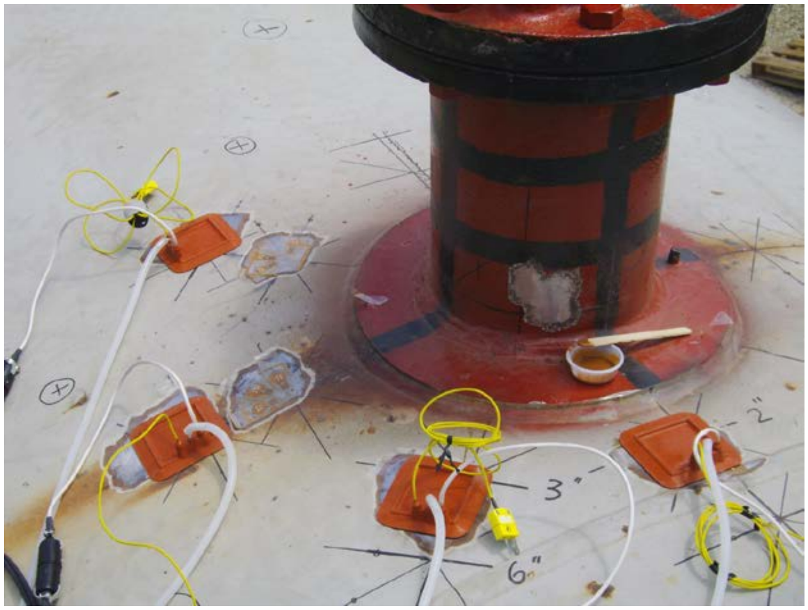


Figure 23. Strain Gages being bonded to Tank Shell

4.3 Video

A digital high-speed camera (3,000 frames/second) was used to capture the fittings as they impacted the concrete target. Standard digital movie cameras also captured the overall image and a close up of the test and impact area.

5 Test Results

For all three tests, the test apparatus performed as designed. The hydraulic system pushed the tank car body about its pivot until the force of gravity took over and the car rolled over onto the target pad.

5.1 Test 1 – Base Case

In this test, the initial impact occurred between the safety valve and the top sacrificial concrete block, followed by an impact between the manway and the adjacent single block, and then a final impact between the unloading nozzle and the base pad. The safety valve deformed, bent relative to its attachment on the tank shell, sheared off the tank shell, became momentarily "pinched" between the tank shell and the top concrete block, and then flew outward away from the tank as far as the valve's tether would allow. The top concrete block was pushed out approximately 15 feet and broken into one large and several smaller pieces. The manway cover was broken off, as was the unloading nozzle (see Figures 24 through 26). The tank shell deformed inward in the vicinity of the fittings varying up to 3½ inches. This damage resulted in a rapid release of the lading (water).

The high-speed video indicated that the impact speed was 24 mph with the accelerometer recording forces of approximately 10 g's perpendicular to the tank surface and 10 g's lateral. Sample strain gauge data are presented in Appendix A. Generally, the data agrees in magnitude and shape with the strain data obtained from the LS-Dyna simulation of the scenario.

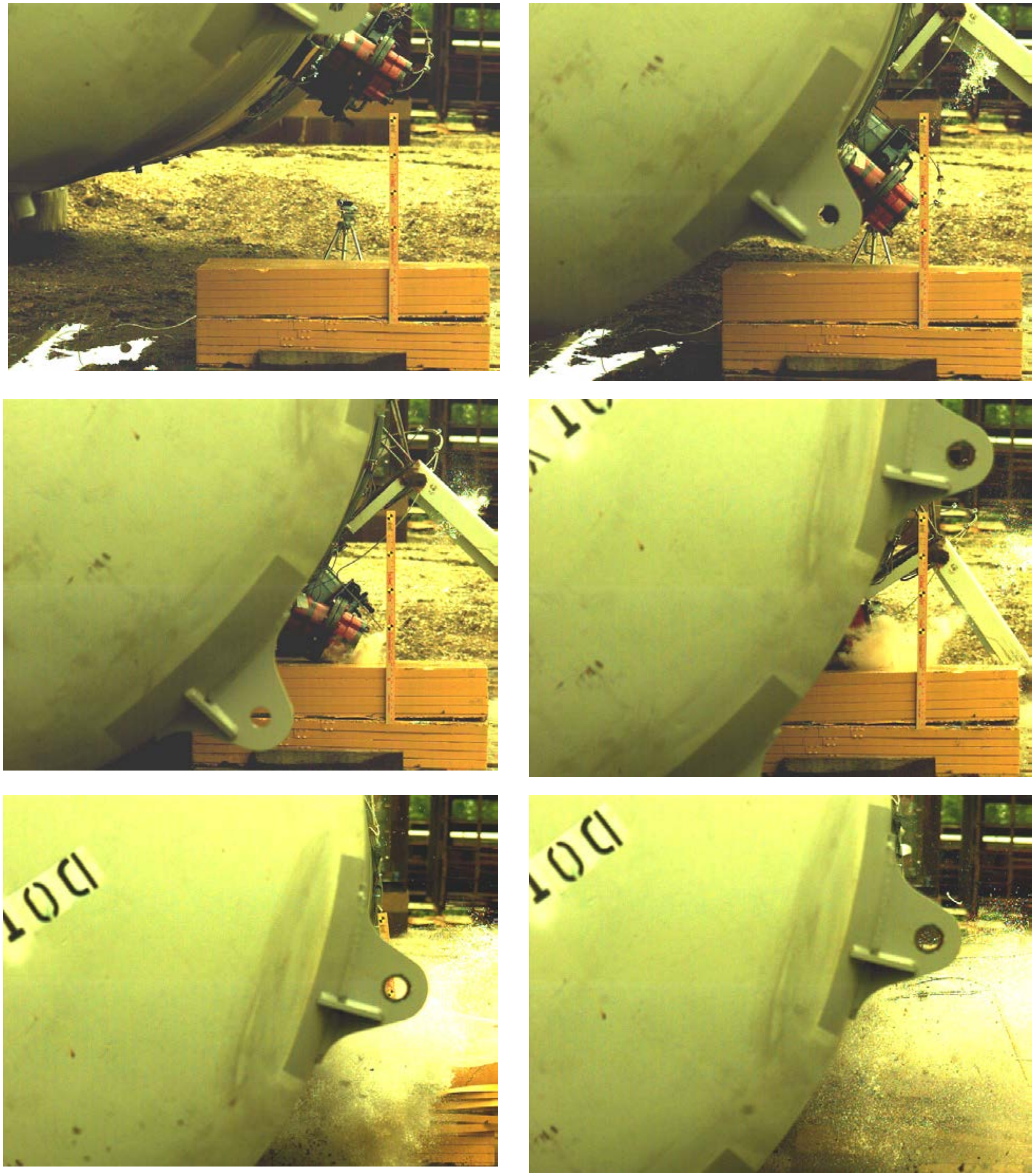


Figure 24. Views from High Speed Camera – Base Case

Figure 25. Base Case – Post-Test (View 1)

Figure 26. Base Case – Post-Test (View 2)

5.2 Test 2 – Deflective Skid

When the deflective skid hit the concrete blocks, it crushed the top 8-inch block and cracked the lower 20-inch block (Figure 27). High-speed video indicated that the impact speed was 17.6 mph, while the accelerometers recorded unfiltered maximum impact accelerations of 10 g perpendicular to the tank surface and 12 g lateral. The skid performed as expected in protecting the top fittings. There was no release of lading at the points of interest. However, there was a slight secondary leak due to a seal issue (which was unrelated to the test setup and procedure).

The skid saw inward deformation along its longitudinal leading edge, with a maximum deformation of about 2⅞ inches toward the tank center perpendicular to the sheet. The B-end (west end) lateral plate buckled slightly. Section 6 provides a comparison of actual test deflection versus deflection from the simulations. The skid itself survived without fracture and succeeded in protecting the fittings from any damage (Figure 28). All horizontal welds were inspected with the magnetic particle method and no cracks were found. The ends of the fillet welds at the impact side gussets had ¼-inch long cracks due to a very thin amount of parent material ripping off the tank shell pads (see weld inspection report).

It should be noted that the skid was intended to be a sacrificial and protective structure, so deformations or cracking are not considered failures. Sample strain gauge data are presented in Appendix A.

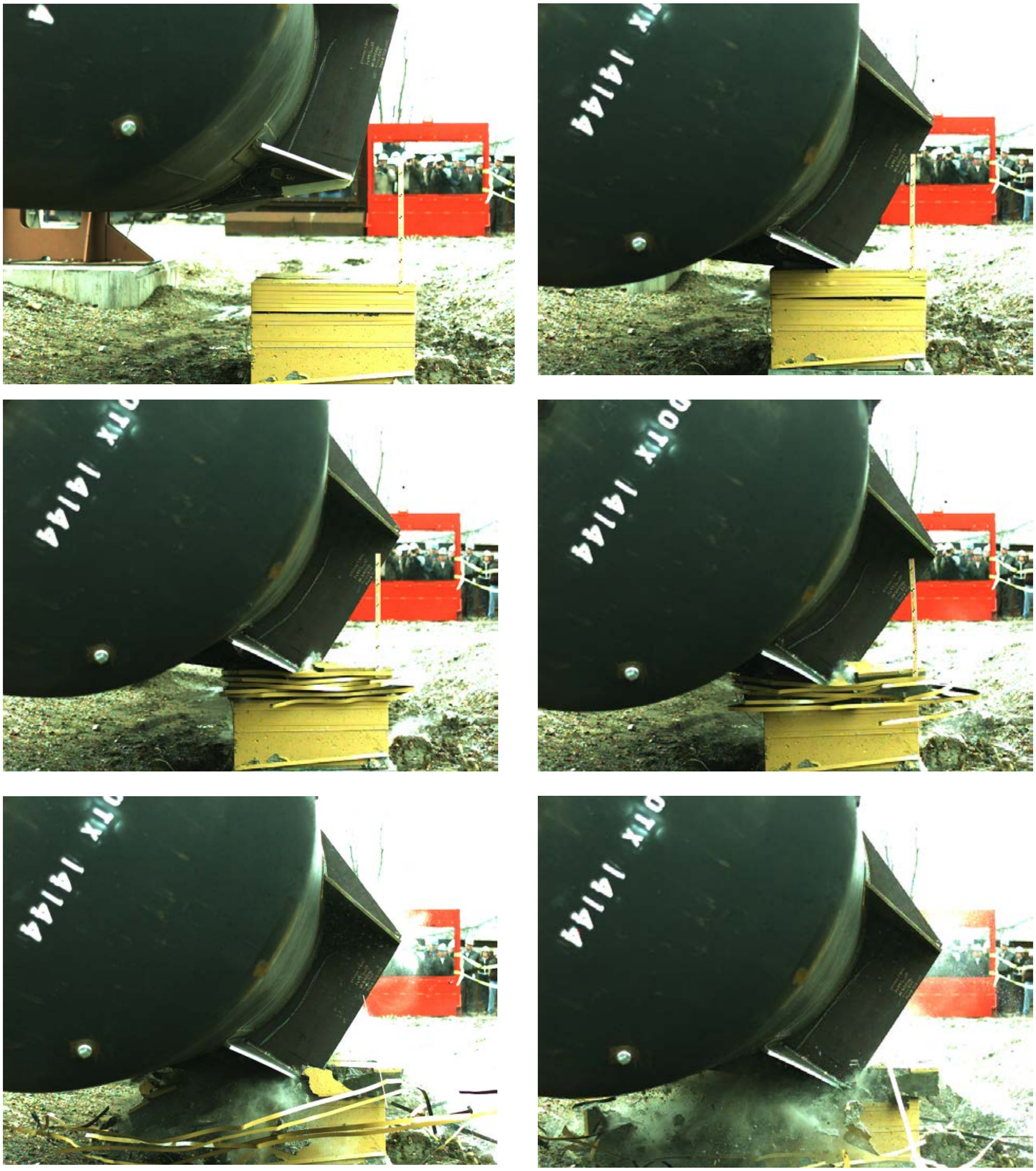


Figure 27. Views from High-Speed Camera – Skid Case

Figure 28. Skid Case – Post-Test

5.3 Test 3 – Bolt-On Sleeve with Cone

Upon impact, the protective sleeve assembly sheared completely through both 8-inch thick concrete sacrificial blocks (see Figures 29 and 30). The protective sleeve assembly's hollow ½-inch thick buffer feature ("ring") was crushed along the impact side (see Figure 31) and the sleeve deformed inward ⅞ inch at the inner diameter. In the area around the top fittings, the tank shell and pad deformed inward about 5 inches (see Figure 32). The impact speed was 12 mph. Accelerometers recorded unfiltered maximum accelerations of 6 g's perpendicular to the tank surface and 9 g's lateral. The small ⅞-inch deformation of the sleeve indicates that the protective space envelope of the fittings located inside the sleeve would not have been breached. There was a 7-inch clearance between the inside of the sleeve and what would have been the outer fiber of the nearest fitting. No damage was found on the 20 grade-8 bolts or on any welds. No release of lading occurred.

Sample strain gauge data are shown in Appendix A.

Figure 29. Sleeve Case – Post-Test (View 1)

Figure 30. Sleeve Case – Post-Test (View 2)

Figure 31. Sleeve Case – Crushing of Ring (Tank Lifted)

Figure 32. Sleeve Case – Inward Deflection of Tank Shell

6 FEA Modeling

When the test events described earlier are simulated, it is best to use a finite element solver with an explicit integration mechanism, since the tests involve complex contact algorithms, nonlinear material models, and dynamic modeling capabilities. LS-Dyna 3D is an explicit finite element solver that meets these requirements and is used for impact simulations and crash-worthiness analyses. SA used LS-Dyna 3D for all the simulations reported here.

For these simulations, the tank car models were created using Pro-Engineer or Inventor (3D CAD applications) and imported to Hypermesh®, a finite element modeler. Geometry for the models was built either from drawings or from field measurements obtained for the tank cars described above. The tank car body models included the stub sills, end sills, bolsters, and the top fittings or protective structures.

Dynamic FEA simulations using LS-Dyna 3D software were conducted prior to performing the actual tests. These simulations were used to develop the designs of the protective structures and provide some confidence that they would survive the impact scenarios.

Shell element models were created to accurately represent the test article cars. Solid elements were used to fill the inside of the tank and lading material properties to simulate the weight of the water used as lading in the tests. Semifluid material properties were used to allow the water to deform.

Appropriate material models were used for each of the structural materials used in the car and the protective structures, based on the yield stress, ultimate stress, and elongation properties. In some cases, the material properties were derived from tensile tests and then added into the models. Appropriate material models and material properties were also selected for the concrete and soil materials. This was done after a thorough review of available material models for concrete and soil, given that failure of the concrete elements also had to be modeled for a realistic simulation.

The model had the tank car body pinned in a fixture and it was free to rotate. There is no initial velocity. The tank was subjected to gravitational force and accelerates under gravity until impact occured.

Post-test, the models were validated in each case to correlate the measured deflected shape, strains, and accelerations with the values from the simulations. Where appropriate, material properties, initial conditions, etc. were tuned so that the model better reflected test performance.

6.1 Test 1 – Base Case

Figures 33 and 34 display screen images of the simulation shortly after impact and the results are very close to what occurred during the physical test. The safety valve breaks off and is projected out away from the tank. The top concrete pad breaks and is also projected out away from the tank by the force it receives from the tank body. The damage to the unloading nozzle components and the manway is also similar to what was observed in the actual test.

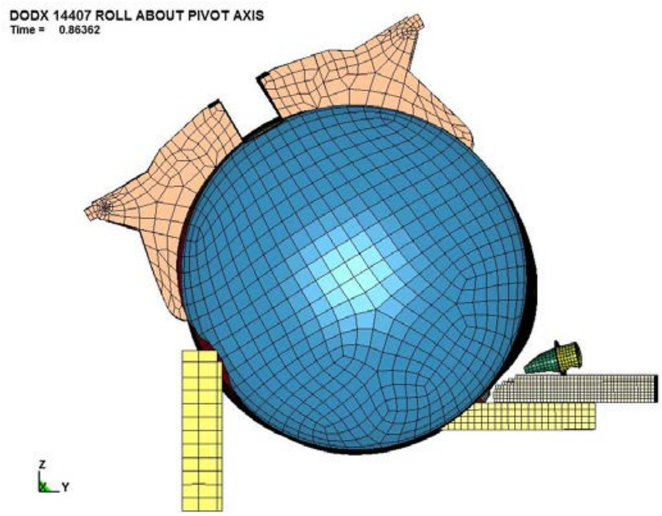


Figure 33. Base Case Simulation – View 1

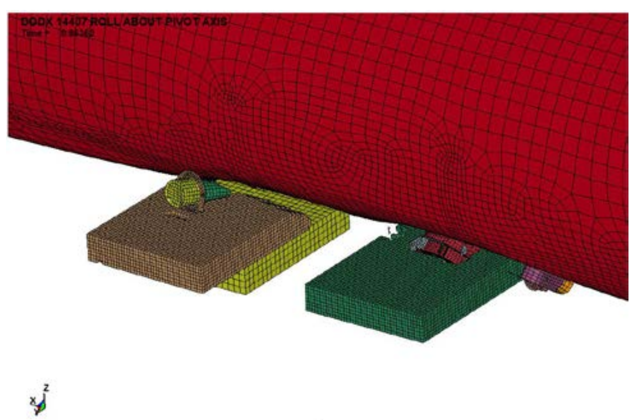


Figure 34. Base Case Simulation – View 2

6.2 Test 2 – Deflective Skid

Figure 35 shows the LS-Dyna model for this test and Figure 36 shows the deflection obtained from the model compared with what was recorded during the actual test. The deflections are of the same order of magnitude, but the actual test structure experienced less deflection. This difference is most likely due to the difficulty of accurately modeling the concrete properties and the soft soil under the concrete. This soil, which was quite wet due to heavy rain prior to the test, caused the concrete base to sink almost two inches during the actual test.

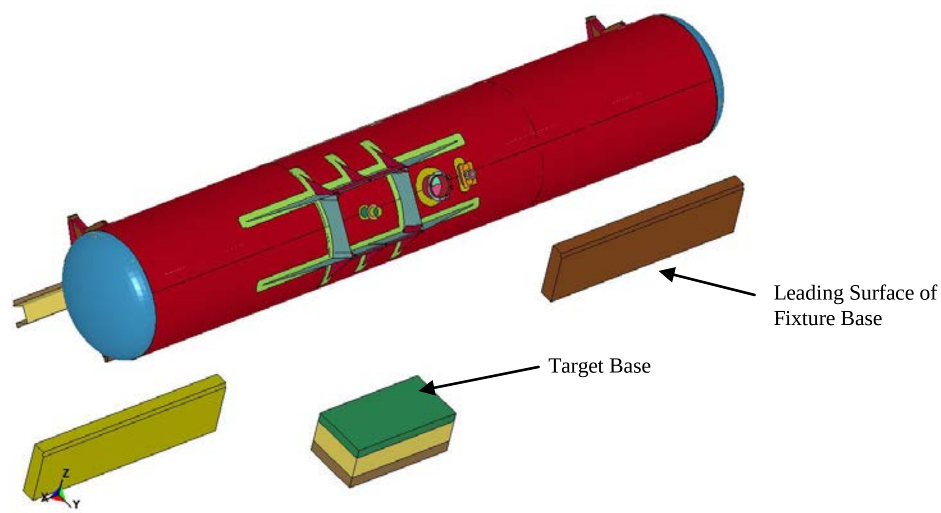


Figure 35. Skid Simulation Model

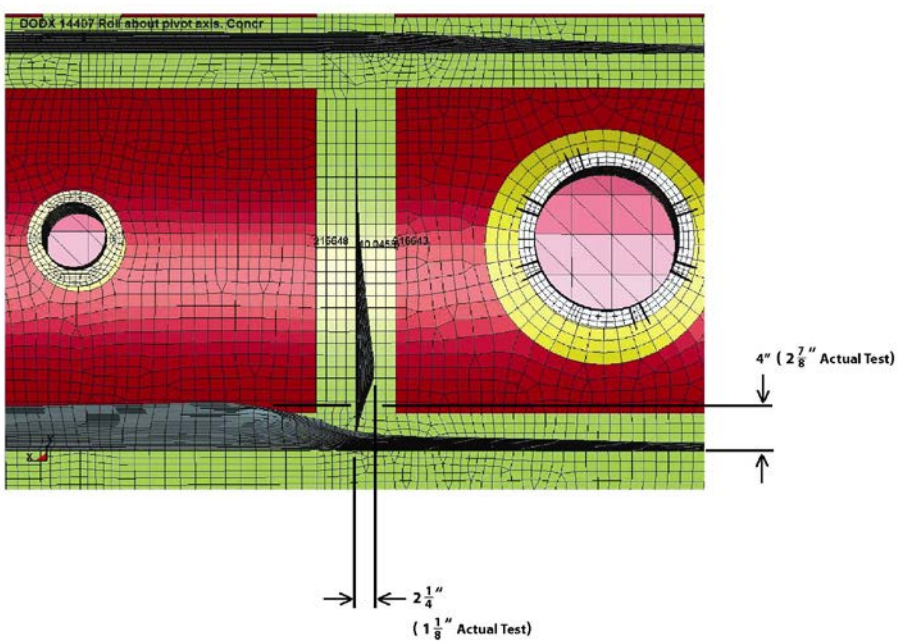


Figure 36. Skid Deformation (bending of longitudinal plate & buckling of lateral plate)

6.3 Test 3 – Bolt-On Sleeve with Cone

Figure 37 shows the results of the LS-Dyna simulation for the sleeve case, and they are very similar to what occurred in the actual test. The energy absorbing ring feature is crushed at the impact side for approximately 26 inches of length (versus about 21 inches in the actual test), and the inner diameter of the sleeve is deformed inward by about 1¼ inch (versus ⅞ inch in the actual test; see Figure 38). Figure 39 compares the crushing of the energy absorbing ring feature, in the model, with what happened in the actual test. The small differences between the model and the actual test are most likely due to the difficulty of accurately modeling the concrete properties and the soft soil under the concrete.

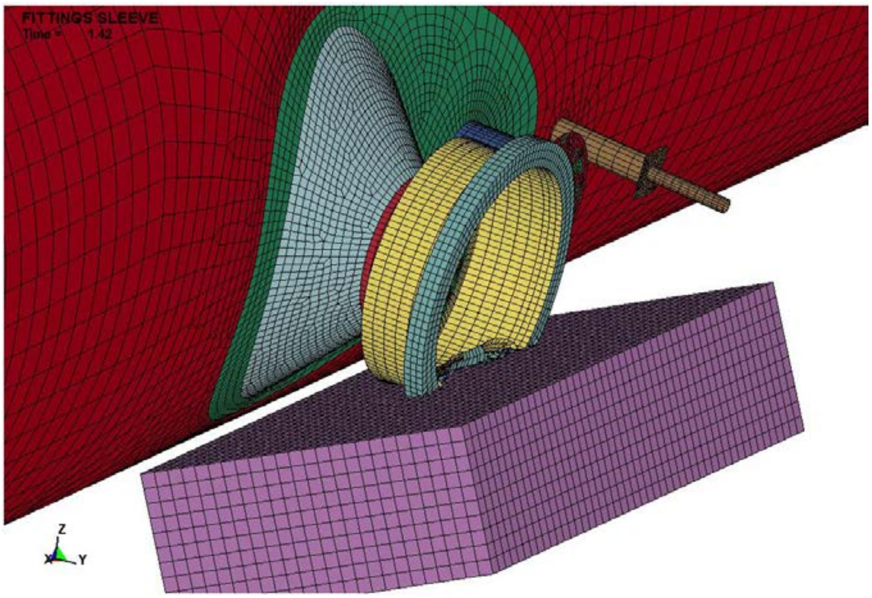


Figure 37. Bolt-On Sleeve Case Simulation

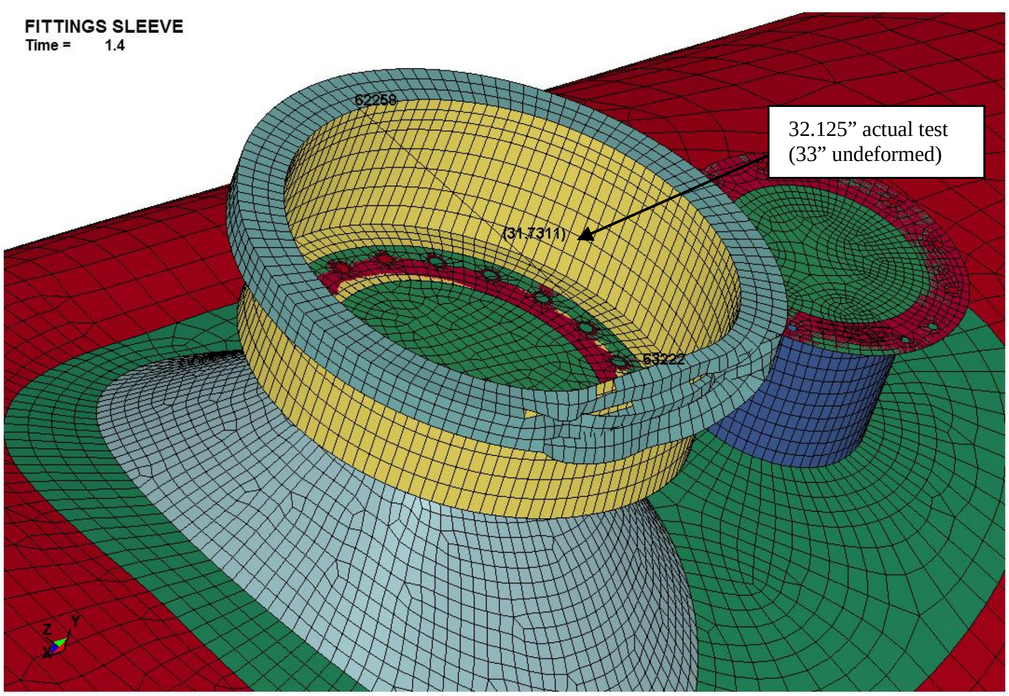


Figure 38. Sleeve Deflection

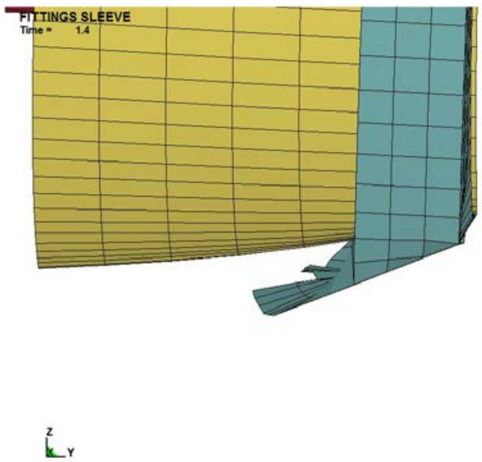


Figure 39. Crush of Ring – Model versus Actual

7 Conclusions

Three full-scale tank carbody rollover tests evaluated the survivability of the following top fittings under these rollover derailment conditions:

- A base case with unprotected top fittings,
- A case with a deflective skid weldment protecting the top fittings, and
- A case with a bolt-on sleeve and cone protecting the top fittings.

The test methods were designed to provide a controlled and repeatable means of testing tank cars in rollover scenarios. The results compared the relative effectiveness of the different types of protection.

- The base case top fittings were destroyed as expected in the rollover test and the lading was released.
- The deflective skid type protection protected the top fittings from an 18-mph impact and no lading was released.
- The bolt-on sleeve and cone type protection survived a 12-mph impact and no lading was released.

The tests helped to validate the LS-Dyna modeling of the corresponding tank geometry with a moderate allowance for variations based on concrete and soil material.

It has been clearly established that the deflective skid and bolt-on sleeve concepts are effective and practical methods for protecting top fittings on non-pressure cars from failure (and lading release) during rollover derailments. The demonstrated concepts can be developed into application-specific designs by the tank car industry and implemented on tank car designs, as appropriate.

Thus, tested and validated concepts for fittings protection are available to the tank car industry. Depending on the type of service and nature of the lading (hazardous or not), a “moderate” or “robust” level of protection may be chosen and adapted to specific tank car designs. If implemented, these concepts could improve the safety of railroad operations, particularly with regard to hazmat safety, by reducing the risks of lading release under rollover derailment conditions.

8 Recommendations

This study tested and validated non-pressure car fittings protection concepts, and it is recommended that similar studies be conducted on pressure tank car fittings and their connections to tank car structures. Pressure tank cars typically carry more dangerous hazardous materials than non-pressure tank cars. The potential effects of a lading release from a pressure tank car make understanding protective fittings rollover behavior critical.

It is also recommended that the "industry standard" top fittings protective structure design being developed be evaluated using this test method.

References

1. Trent, R., Prabhakaran, A., and Sharma, V. "Survivability of Railroad Tank Car Top Fittings in Rollover Scenario Derailments." Report No. DOT/FRA/ORD-06/11. 2007. Washington, DC: U.S. Department of Transportation.

2. Trent, R., et al. "Survivability of Railroad Tank Car Top Fittings in Rollover Scenario Derailments – Phase 2." Report No. DOT/FRA/ORD-07/03. 2009. Washington, DC: U.S. Department of Transportation.

Appendix A Sample Test Data

Base Case

The following images compare sample strain plots obtained from the LS-Dyna simulation with plots obtained from the actual test's strain gauge instrumentation. Note that the time scales used in LS-Dyna are different and not comparable to those used with the actual test instrumentation. Figure A1 shows the strain gauge locations for the base case.

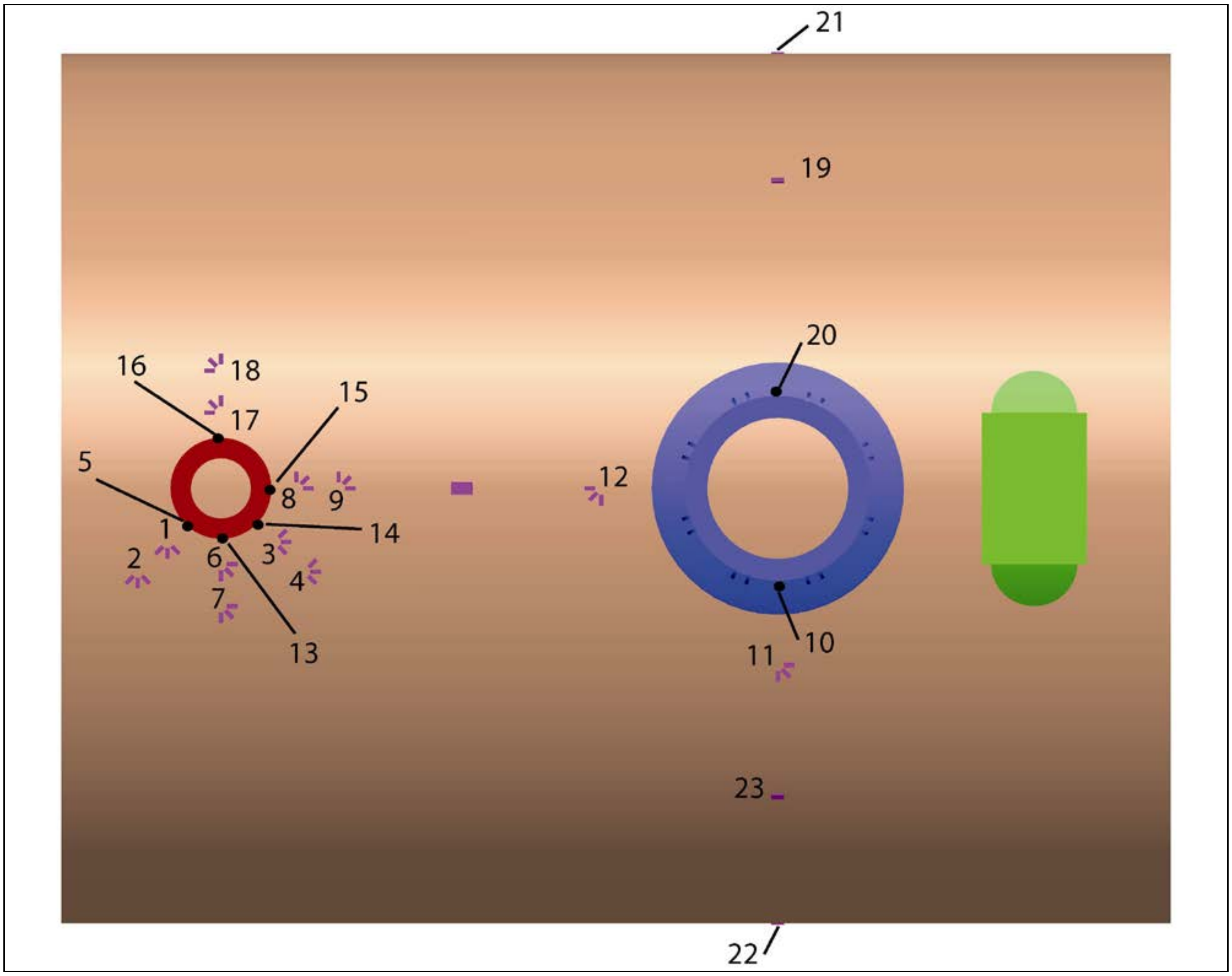
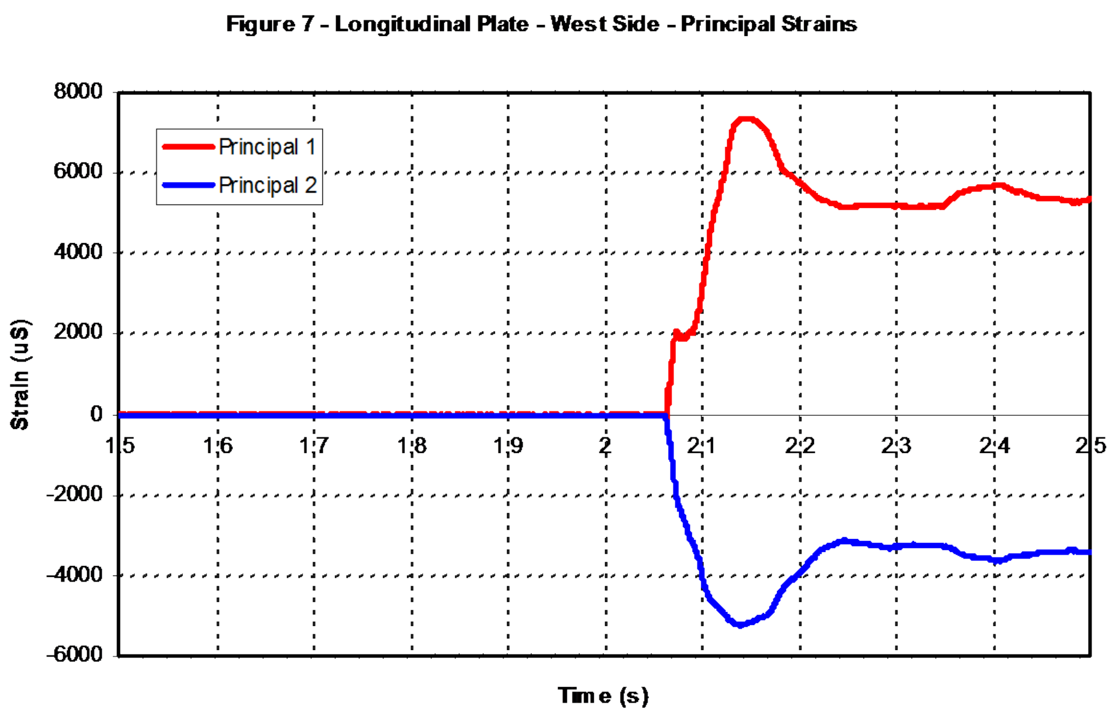


Figure A-1 Strain Gauge Locations – Base Case

Principal Strains from LS-Dyna Base Case Simulation Location #7



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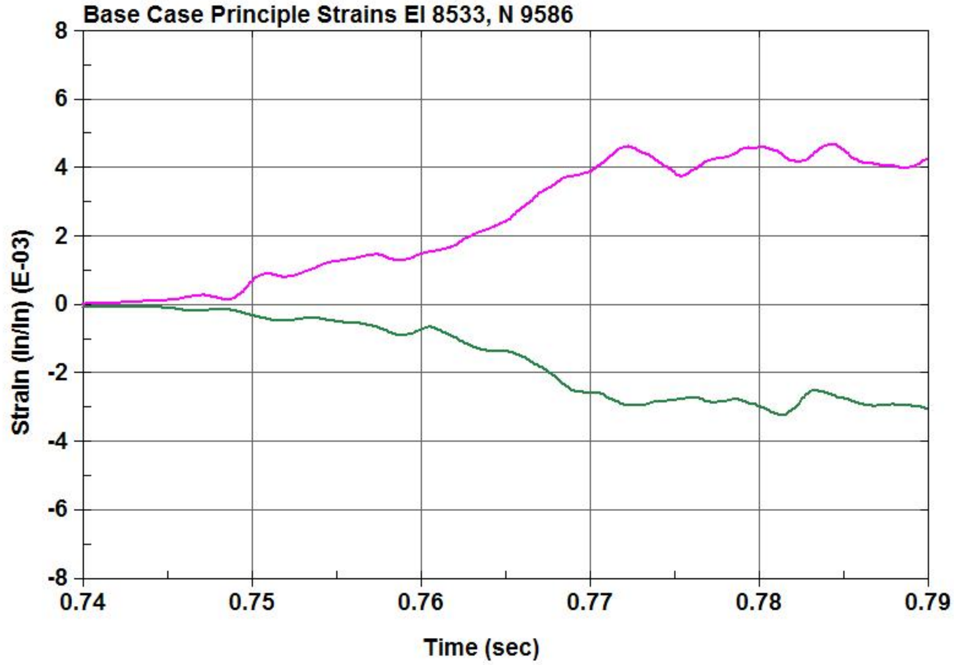
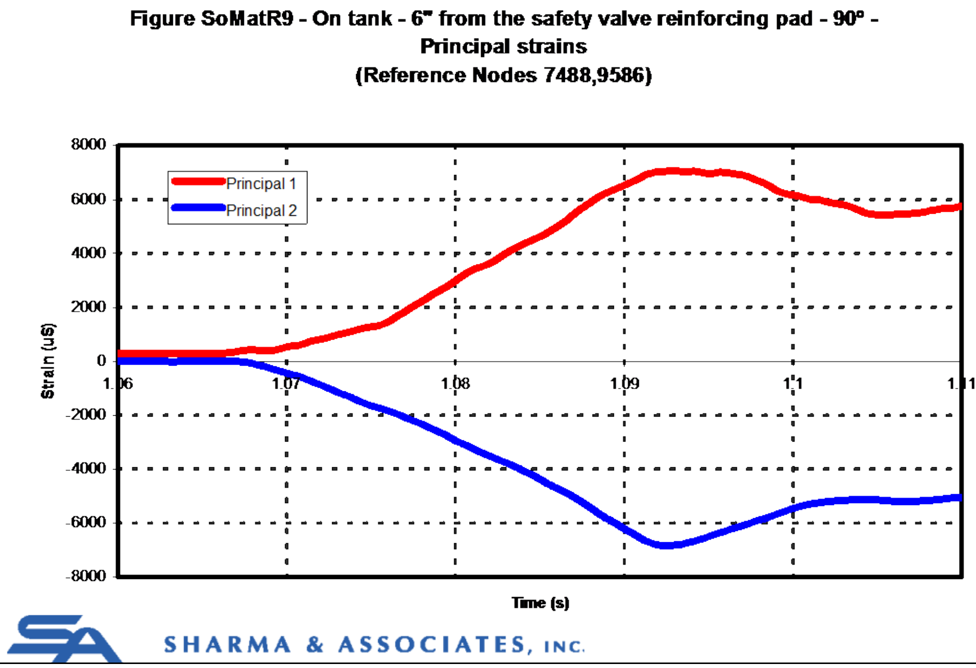
Principal Strains from Actual Base Case Test Location #7

Figure A-2 Principal Strains from Base Case Test and Base Case Simulation for Location #7

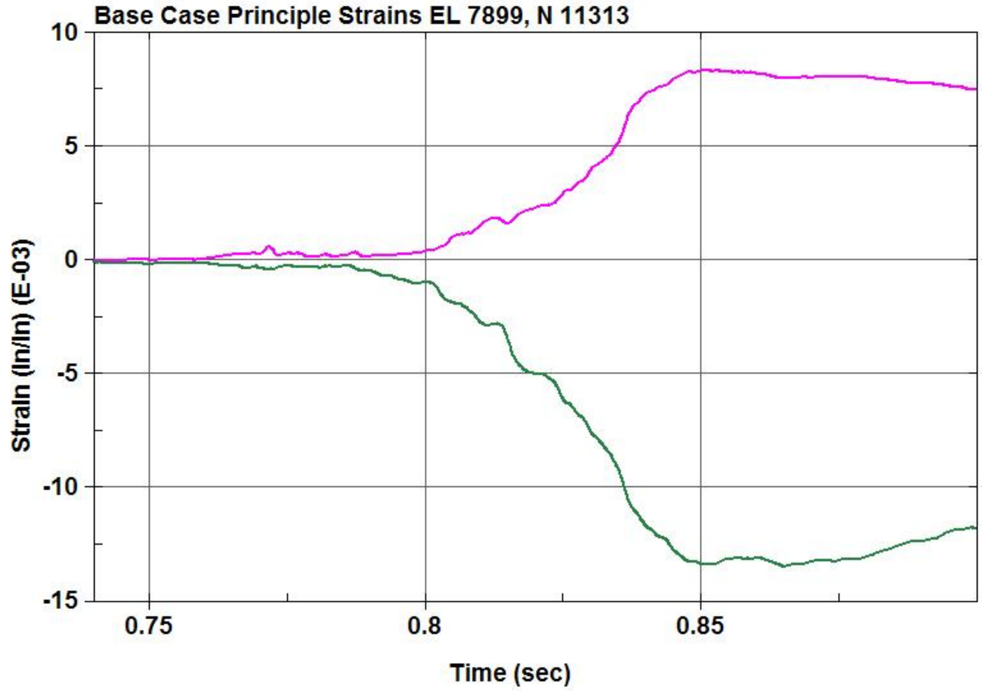


Principal Strains from LS-Dyna Base Case Simulation Location #9

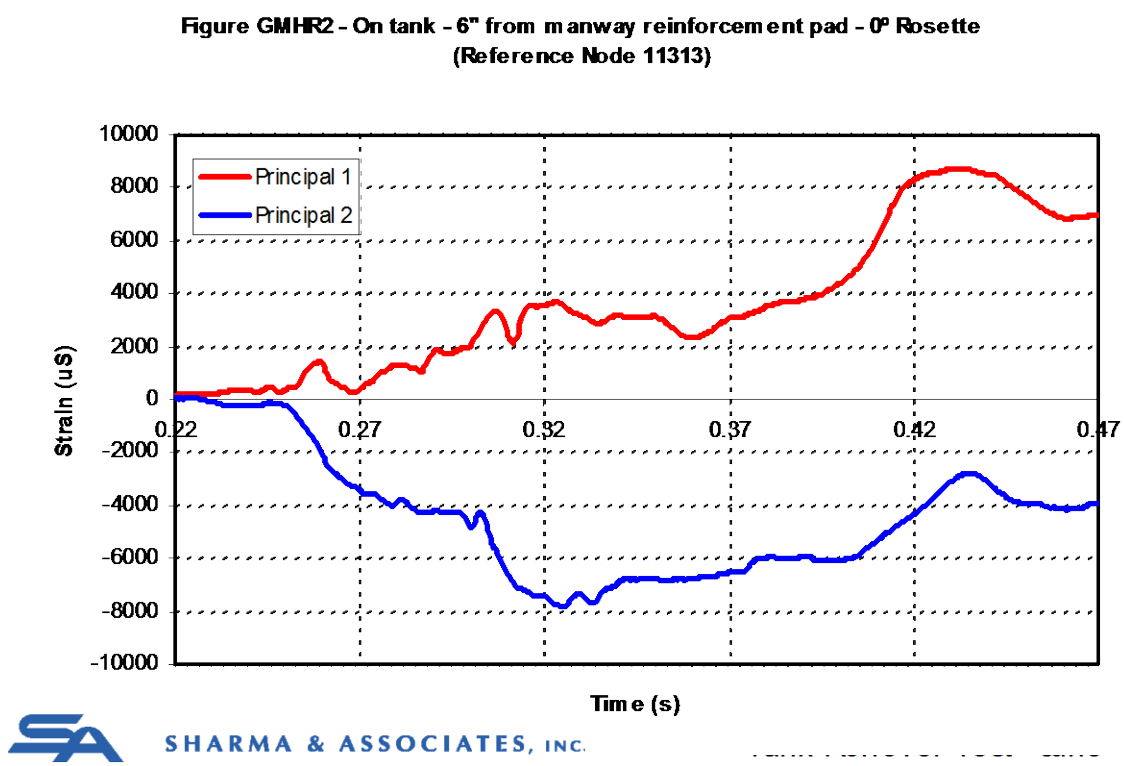


Principal Strains from Actual Base Case Test Location #9

Figure A-3 Principal Strains from Base Case Test and Base Case Simulation for Location #9

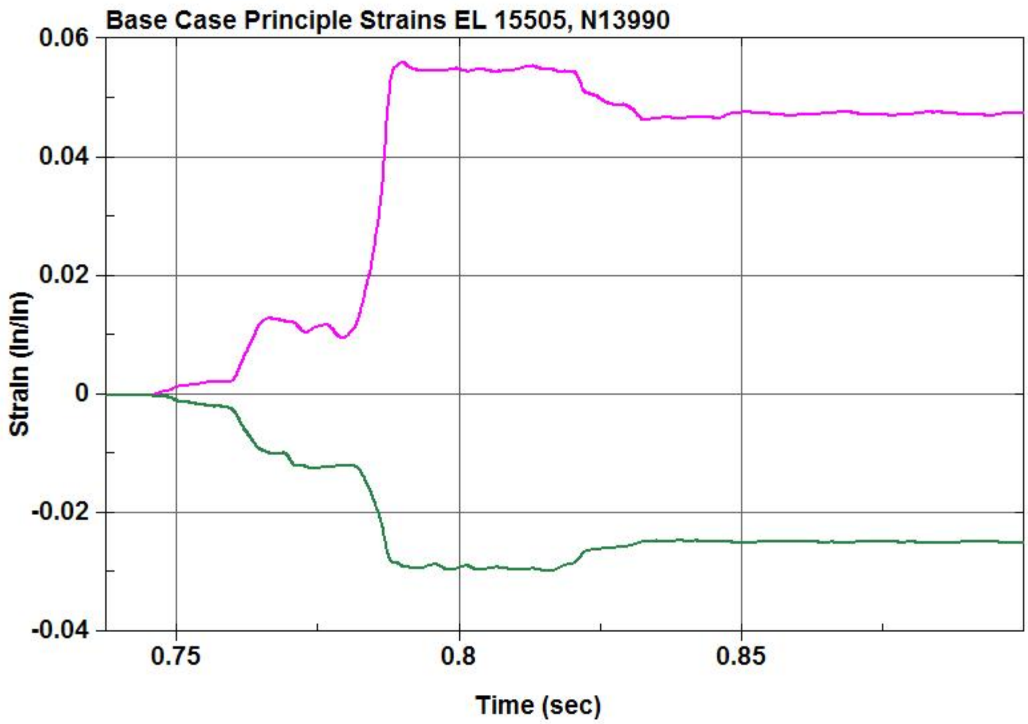


Principal Strains from LS-Dyna Base Case Simulation Location #11

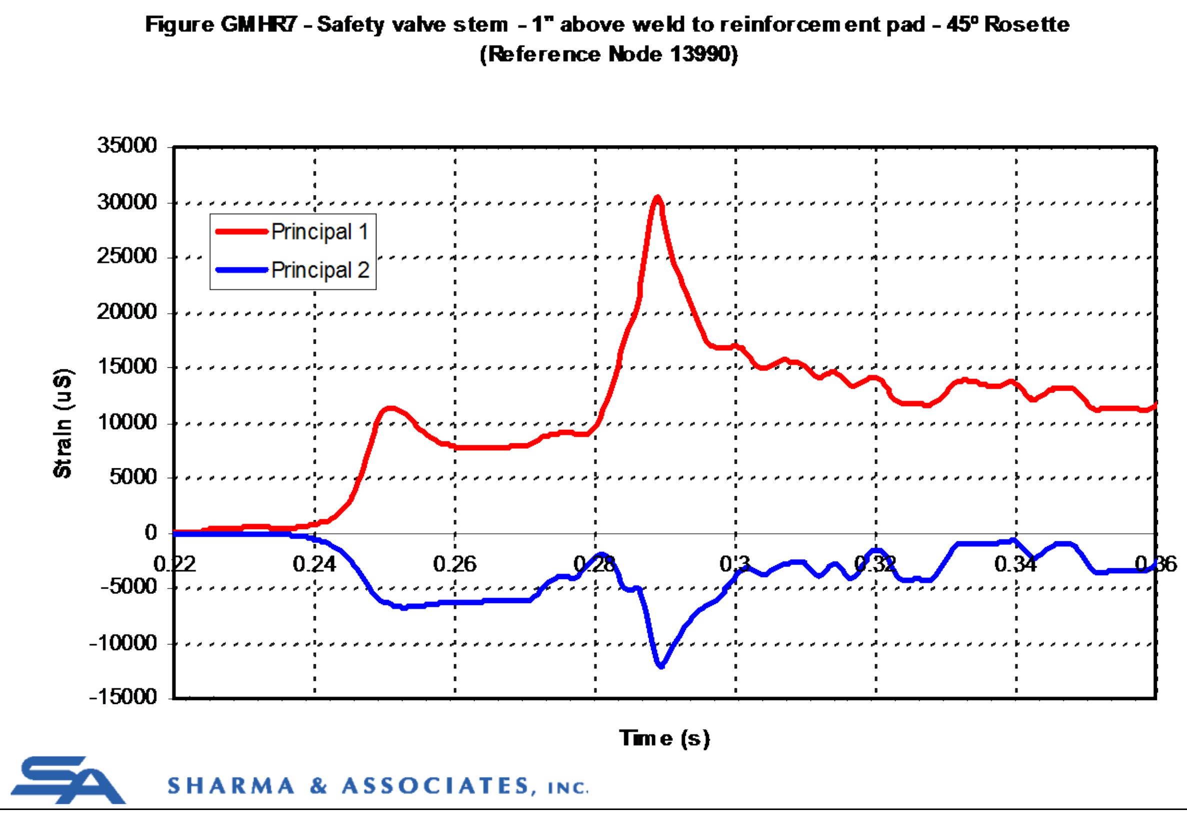


Principal Strains from Actual Base Case Test Location #11

Figure A-4 Principal Strains from Base Case Test and Base Case Simulation for Location #11

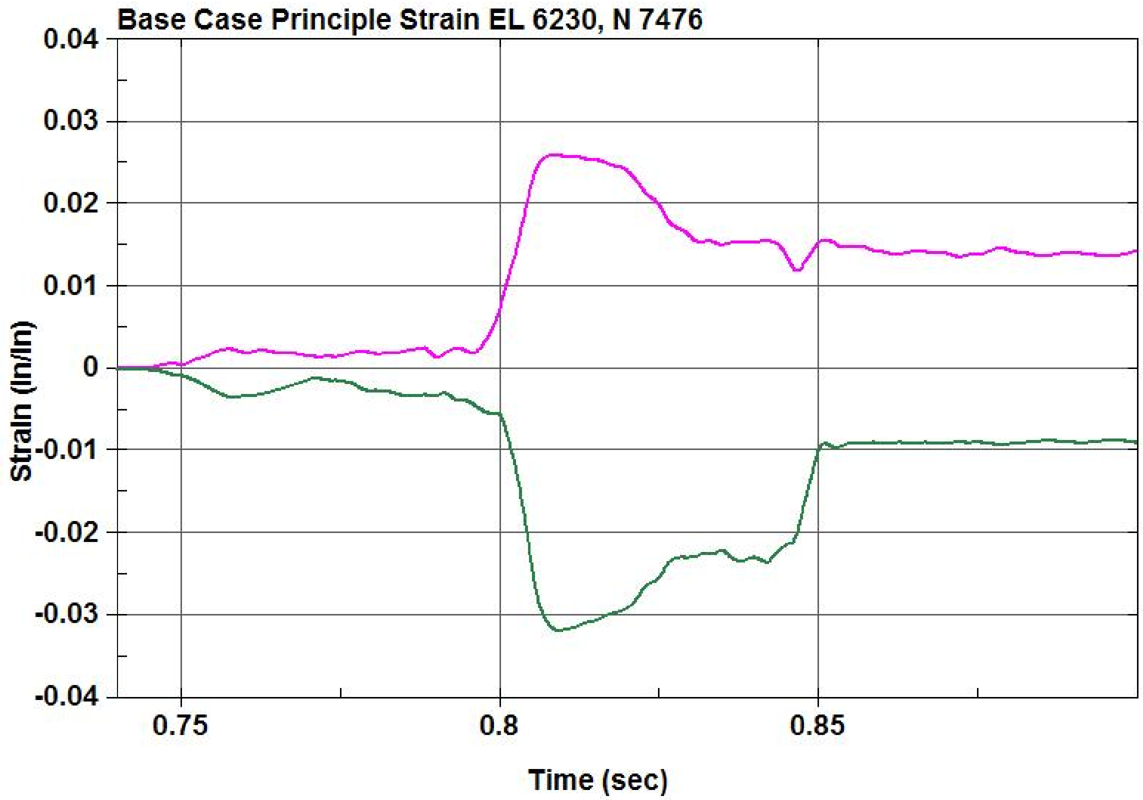


Principal Strains from LS-Dyna Base Case Simulation Location #14

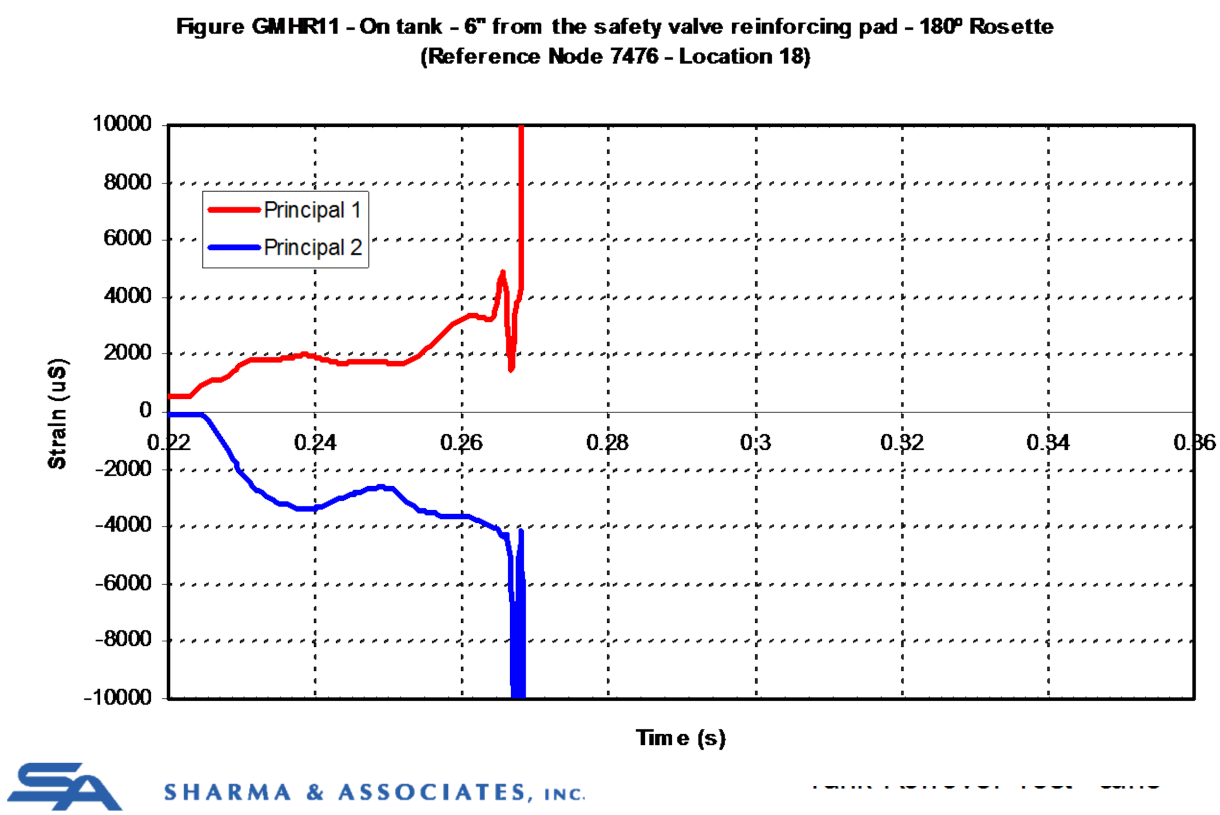


Principal Strains from Actual Base Case Test Location #14

Figure A-5 Principal Strains from Base Case Test and Base Case Simulation for Location #14

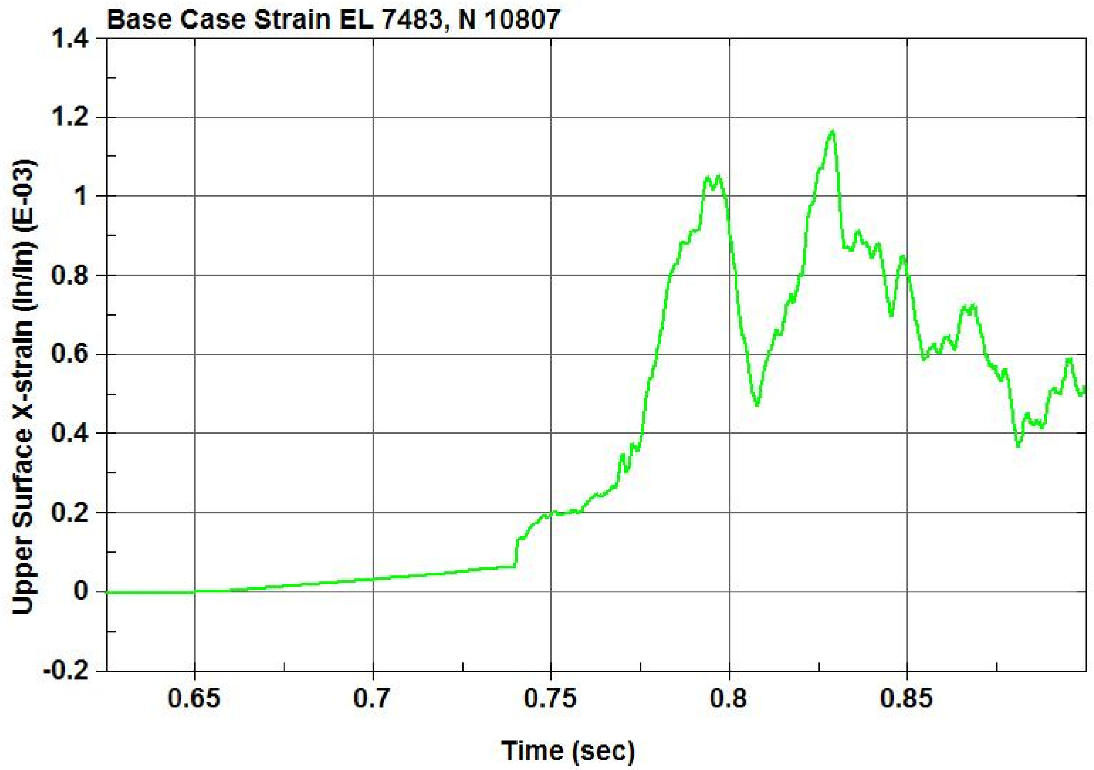


Principal Strains from LS-Dyna Base Case Simulation Location #18

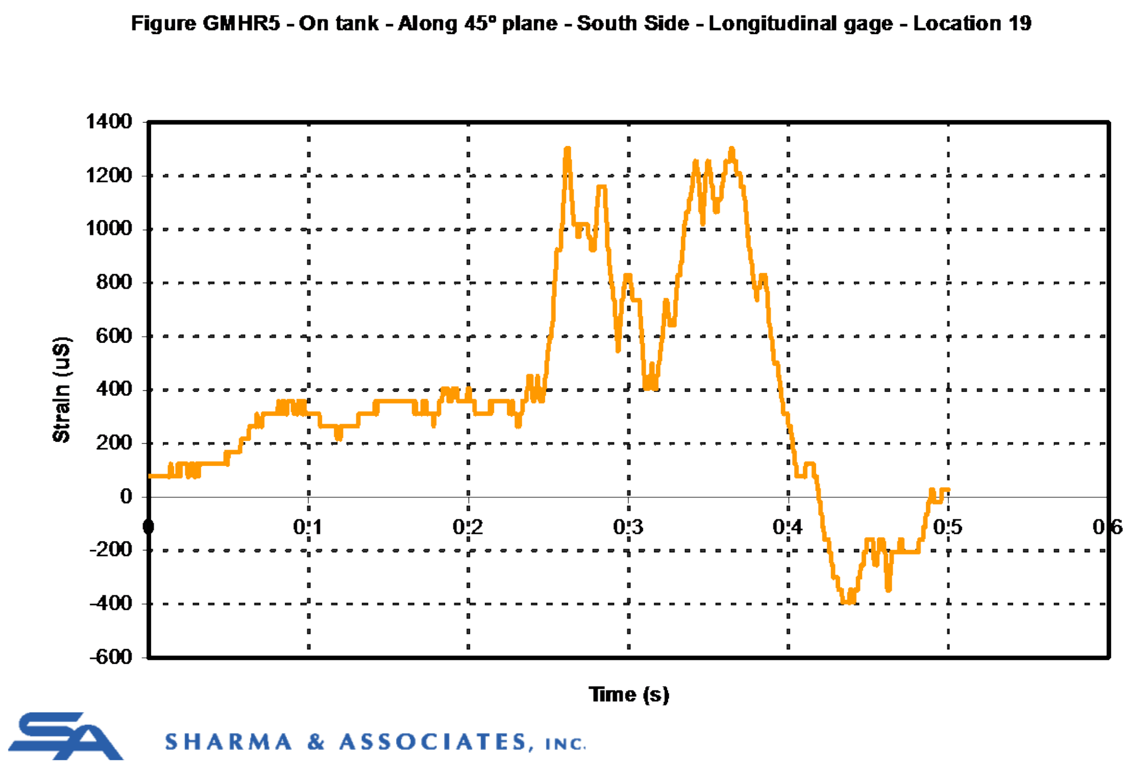


Principal Strains from Actual Base Case Test Location #18

Figure A-6 Principal Strains from Base Case Test and Base Case Simulation for Location #18



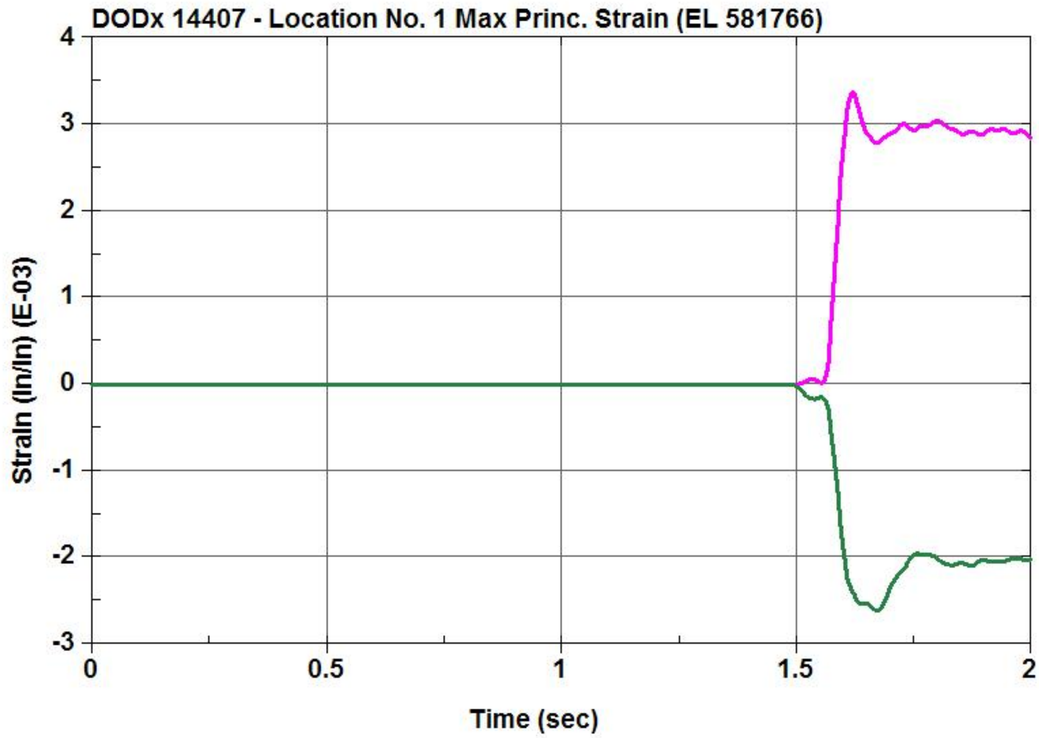
Principal Strains from LS-Dyna Base Case Simulation Location #19



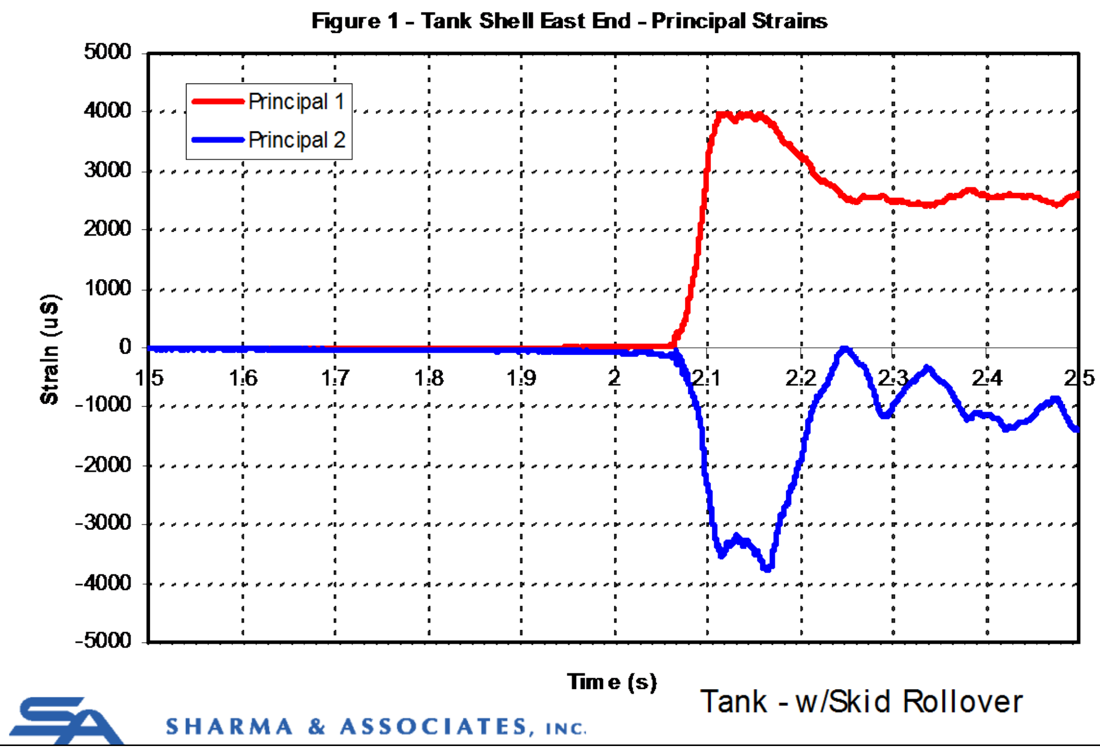
Principal Strains from Actual Base Case Test Location #19

Figure A-7 Principal Strains from Base Case Test and Base Case Simulation for Location #19

Skid Case

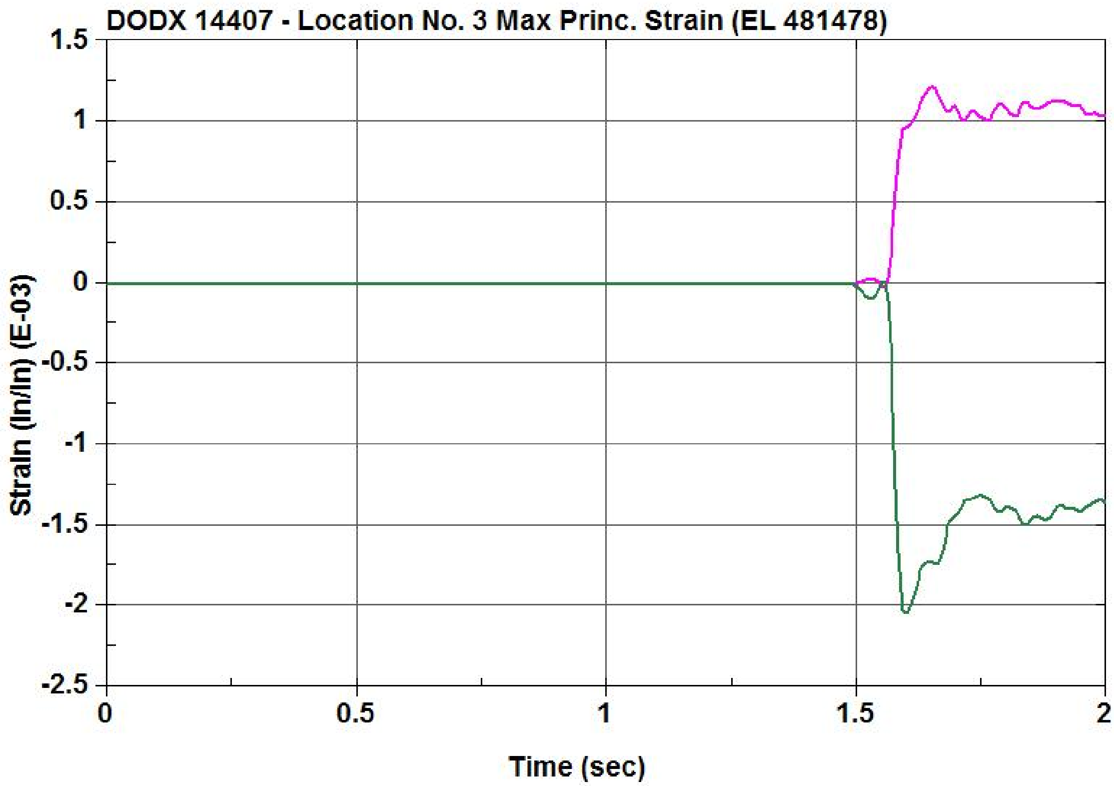


Principal Strains from LS-Dyna Skid Case Simulation Location #1

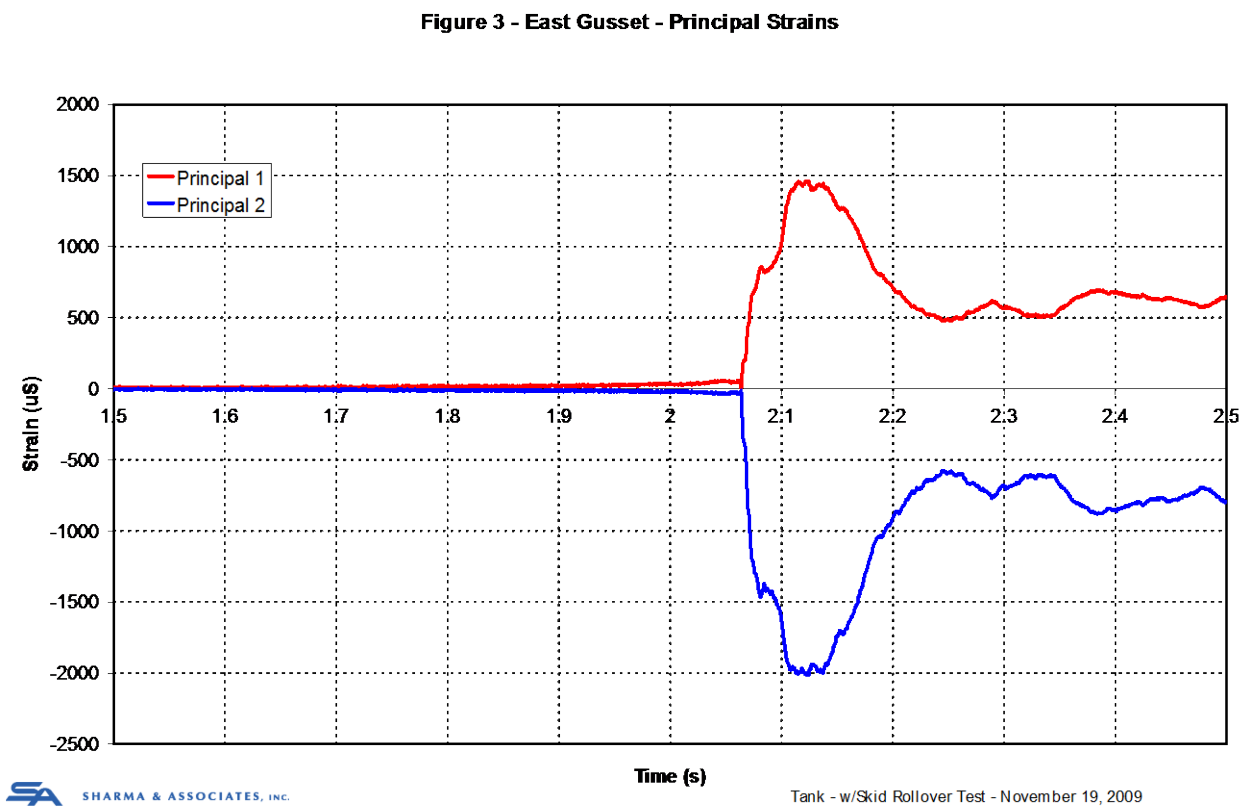


Principal Strains from Actual Skid Test Location #1

Figure A-8 Principal Strains from Skid Test and Skid Test Simulation for Location #1



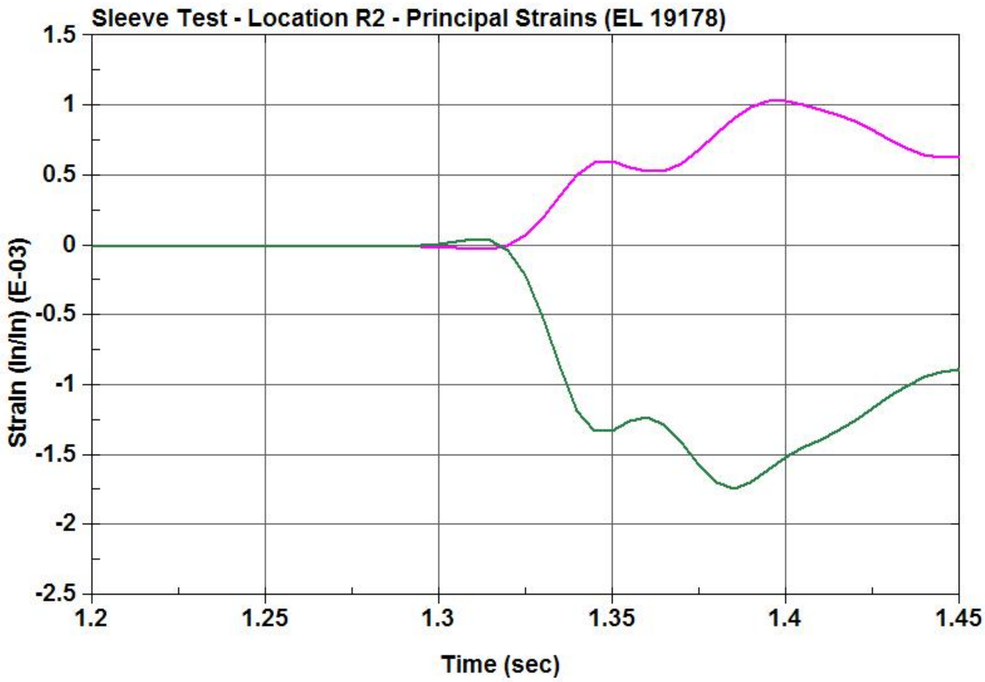
Principal Strains from LS-Dyna Skid Case Simulation Location #3



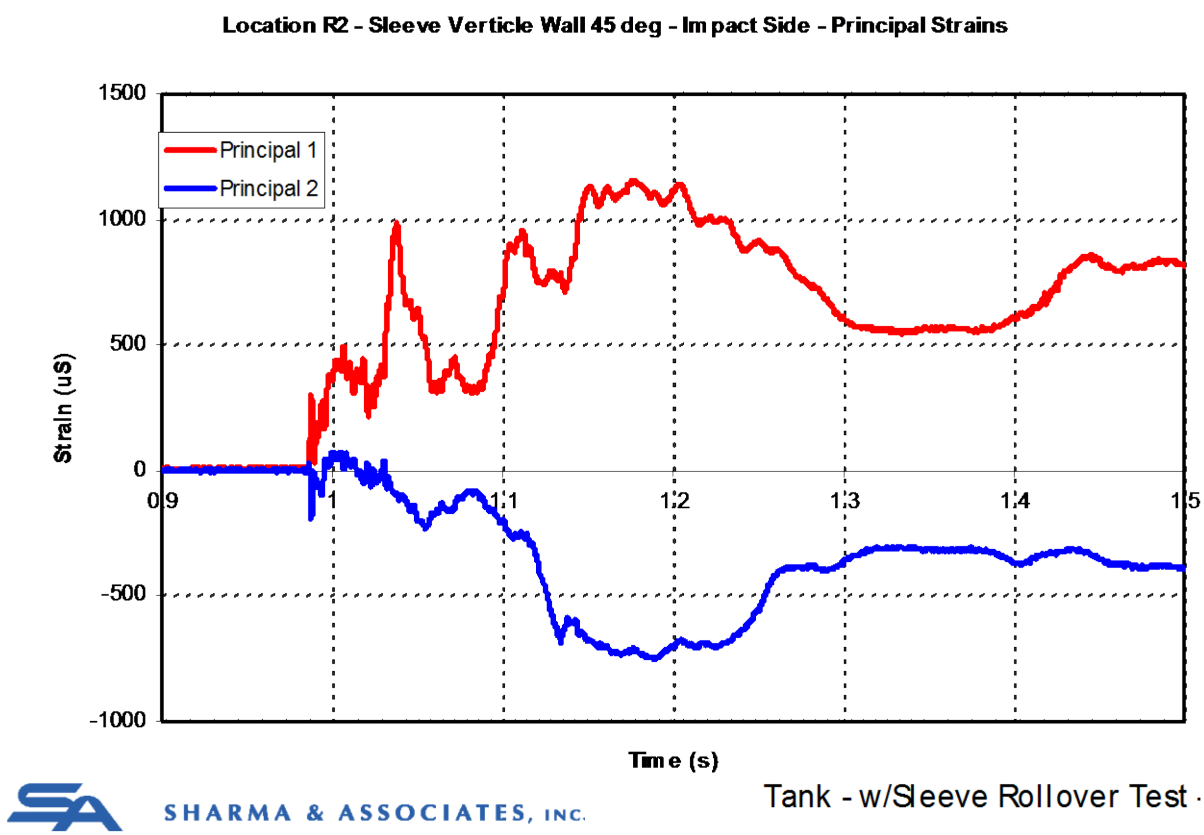
Principal Strains from Actual Skid Test Location #3

Figure A-9 Principal Strains from Skid Test and Skid Test Simulation for Location #3

Sleeve Case

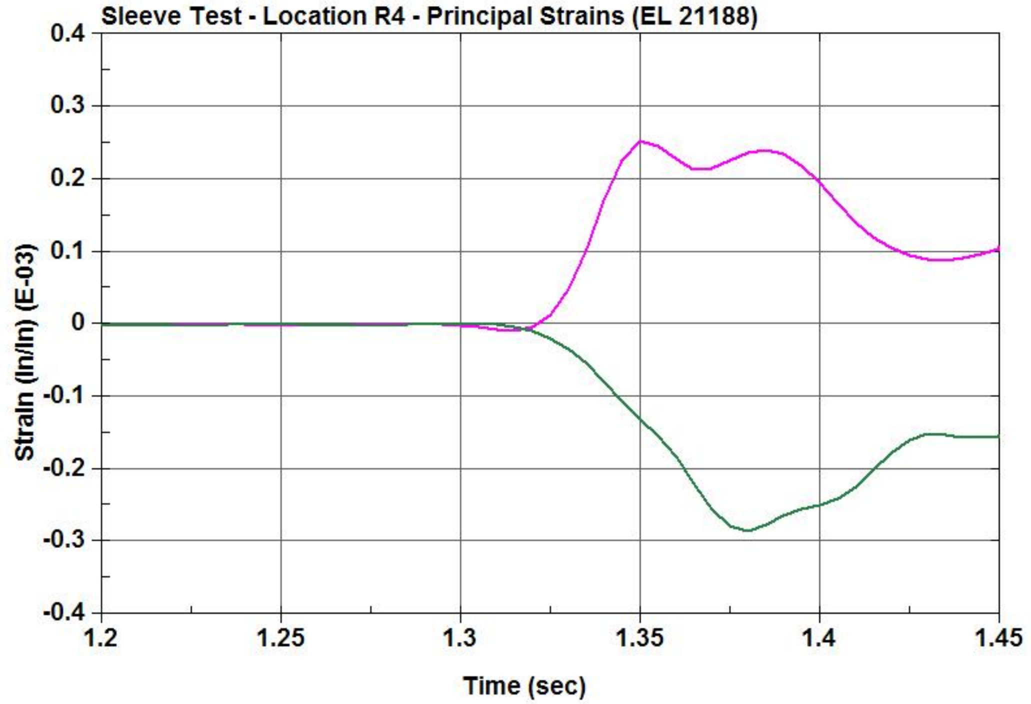


Principal Strains from LS-Dyna Sleeve Case Simulation Location R2

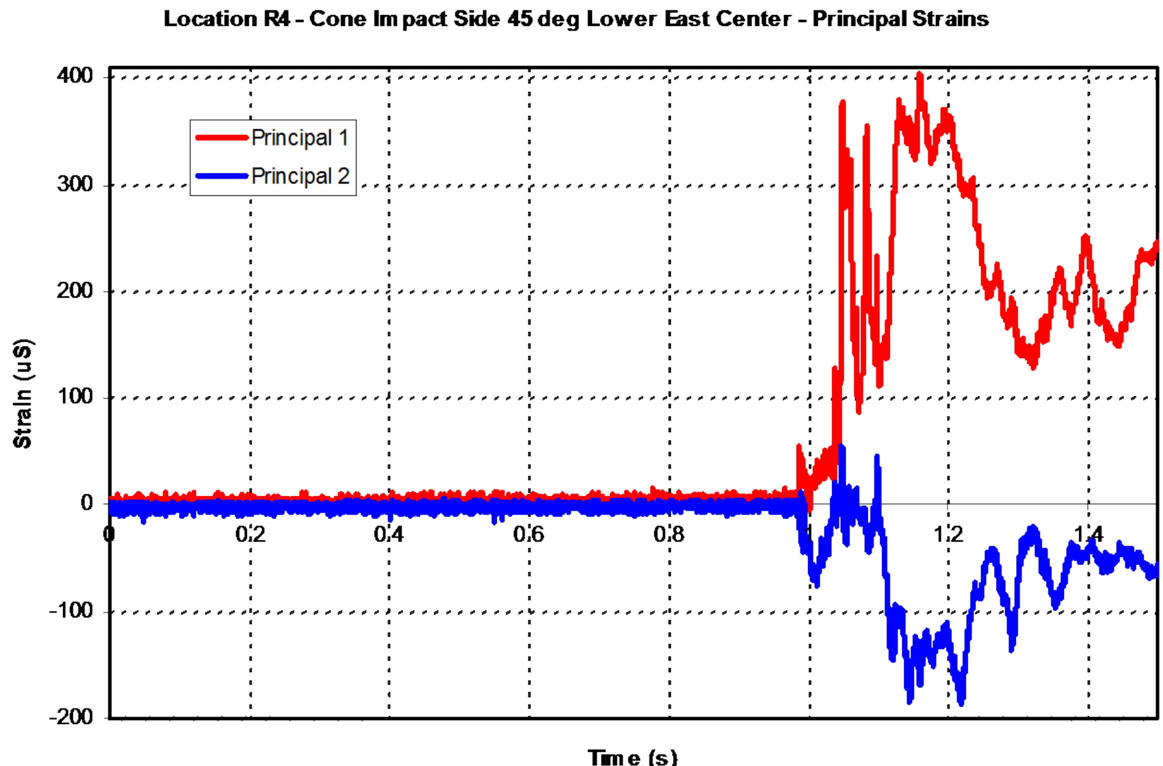


Principal Strains from Actual Sleeve Case Test Location R2

Figure A-10 Principal Strains from Sleeve Test and Sleeve Test Simulation for Location R2



Principal Strains from LS-Dyna Sleeve Case Simulation Location R4



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Principal Strains from Actual Sleeve Case Test Location R4

Figure A-11 Principle Strains from Sleeve Test and Sleeve Test Simulation for Location R4