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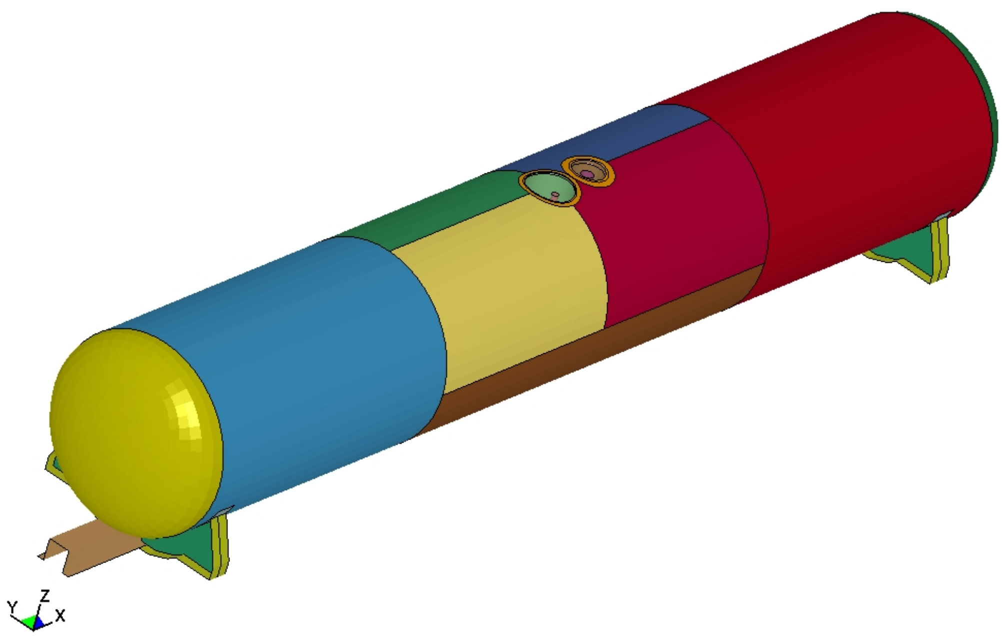
of Transportation

Federal Railroad Administration

Survivability of Railroad Tank Car Top Fittings in Rollover Scenario Derailments – Phase 2

Office of Research and Development
Washington, D.C. 20590



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Robert Trent, Anand Prabhakaran, David Brabb, Vinaya Sharma

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Sharma & Associates, Inc.
5810 S Grant Street
Hinsdale, IL 60521

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13. ABSTRACT

Phase 2 of this project is a continuation from Phase 1 and investigates the survivability of railroad tank car top fittings in rollover scenarios using Failure Element Analysis techniques. It also explores additional protective concepts intended to survive more severe impacts than those of the Phase 1 study. Three new protective concepts, a rollbar assembly using an elliptical shape to allow the car to roll with little resistance, a fabricated deflective skid, and recessed fittings, are developed and analyzed in Scenario 1 (severe rollover as in the Phase 1 study). A third scenario is simulated for the new concepts, which includes longitudinal car velocity and impact into a concrete barrier.

All three of the new protective concepts succeed at protecting the top fittings in both Scenario 1 and Scenario 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

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

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

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

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

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Figures

Executive Summary

Phase 2 of this study on the survivability of railroad tank car top fittings in rollover scenario derailments continues from the work accomplished in Phase 1. The reader should refer to the original report titled *Survivability of Railroad Tank Car Top Fittings in Rollover Scenario Derailments* for complete background information.

Railroad tank cars are commonly outfitted with an arrangement of fittings used for loading and unloading of car lading and other purposes such as pressure relief. Phase 1 of this study showed that these unprotected devices are unlikely to survive even the least severe of low speed derailments that result in a rollover of the car. The subsequent release of car contents and its safety implications to the public are critical, as exemplified by incidences such as the January 18, 2002, derailment in Minot, ND.

Phase 1 of this study identified tank car fittings that were most susceptible to derailment damage by means of a thorough investigation using multiple sources as described in the Phase 1 report. From the findings, the study focuses on top fittings of non-pressure cars, specifically those in fuel or acid service. For analysis and modeling efforts, the team selected a DOT 111A100W1 class, 30,000-gallon fuel service car based on suitability of the car and the availability of car drawings. Phase 2 continues the analysis with this same focus. The findings from this report are applicable to many other non-pressure car types with structurally similar fittings.

The geometry for the finite element models of the tank carbody and protective structure were created using Pro-engineer modeling software. The Hypermesh® preprocessor was used to mesh the models prior to converting to an appropriately formatted input file for the LS-DYNA3D program. A similar process was used to model a solid concrete barrier.

Phase 2 of the project modeled two derailment scenarios using the same numbered designations as that of the Phase 1 study. Scenario 1 (the same Scenario 1 of Phase 1 of this study) simulated a severe rollover of the tank carbody falling off its trucks with significant downward and rotational velocity. Scenario 3 adds an 18 mph longitudinal velocity to the carbody and an impact with a concrete barrier in its path. Some modification to the rotational and downward velocities was made to time the impact of the top fittings with the barrier. (Scenario 2 is unique to the Phase 1 study.)

Three additional protective concepts, Concepts 3 through 5, were developed with the goal of protecting the top fittings in more severe derailment scenarios than those investigated in Phase 1. Concept 3 adds a Rollbar assembly, which attaches attaching to the tank shell around the top fittings with its lateral members shaped elliptically and attaches to the tank sides in a smooth tangential manner to reduce impact forces during the rollover. Concept 4, adds a fabricated skid assembly surrounding the top fittings that are shaped to reduce snagging during a derailment. Concept 5 recesses the fittings into the tank body where they are unlikely to impact any object during a rollover.

The three protective concepts were modeled and simulated under both scenarios described above. All three protective concepts succeed at protecting the fittings from damage in both Scenario 1 and Scenario 3. Concept 5 adds the least amount of weight followed by Concept 3 and Concept 4. Concept 4 has the advantage of being the least costly to retrofit on existing cars. Static stress analysis was also performed on Concept 3 and a base case to benchmark strength.

1. Introduction

1.1 Background

Phase 2 of the investigation on the survivability of railroad tank car top fittings in rollover scenario derailments continues from the work accomplished in Phase 1. Please refer to the original report titled *Survivability of Railroad Tank Car Top Fittings in Rollover Scenario Derailments* for complete background information. Phase I focused on protective concepts for non-pressure cars that could be easily retrofitted to existing cars such as the 30,000-gallon fuel service car used in the analysis. Phase 1 provided a bolt-on sleeve type protective structure around the top fittings and a disc and cone reinforcement system to strengthen the fittings to tank shell interface. The analysis of these Phase 1concepts showed their effectiveness in protecting the fittings in very low speed derailment rollover scenarios.

In Phase 2, more robust concepts of protection, those that could protect the fittings in more severe accident scenarios were desired. Three new concepts of protection are explored. The first one Concept 3 adds a structural rollbar arrangement with geometry designed to minimize forces during a rollover. The second Concept 4 uses a fabricated skid to protect the fittings. The third Concept 5 incorporates the recession of the fittings arrangements down below the tank top shell surface to insure that no fittings will be directly impacted in a rollover.

1.2 Objectives

The first objective of Phase 2 was to analyze the survivability of critical top fittings and their tank connections under derailment conditions when each of the three new protective concepts are employed. These concepts were analyzed in two different derailment scenarios as described in section 1.3. This analysis used finite element techniques, including appropriate modeling of derailment scenarios as well as the modeling of relevant tank car and fittings details.

The second objective was to develop some general structural guidelines for top fittings protection from the data and knowledge obtained in Phase 1 and Phase 2 of this investigation.

1.3 Derailment Scenarios

Two different dynamic (derailment) scenarios were analyzed.

The first scenario simulated the case of a severe derailment condition, where a tank is thrown off its trucks with significant initial (rotational and downward vertical) velocity, speeds up under the influence of gravity and hits a rigid ground surface with a significant impact velocity and therefore considerable force. An initial rotational velocity of 6.3 rad/sec and an initial vertical (z direction) velocity of 164.7 in/sec were used. This scenario is similar to Scenario 1 of Phase 1 of this study.

Scenario 3 adds a longitudinal velocity component of 18 mph to the tank body. The tank body impacts a concrete barrier as described in Section 3 after the tank body is in the top down orientation. The rotational velocity is reduced to 0.15 rad/sec to allow the protective structure to remain in contact with the concrete barrier as it impacts and penetrates the barrier. The initial vertical velocity is set at 20 in/s to time the impact with the concrete barrier. In this scenario, the tank body has a rotational, vertical, and longitudinal velocity at the time of impact with the concrete barrier.

Scenario 2 was investigated and documented in Phase 1 of this study.

2. Car Description

A current model fuel service car (DOT 111A100W1) with an existing top fittings configuration was used as a starting point in this analysis. This is the same car used in Phase I of the project. The car was designed for 30,000-gallon diesel fuel service with a tank length of 56 ft, and 3 ½ in, a tank diameter of 111 ft and ¾ in, and a tank shell thickness of 7/16 inch. See Figure 1 for a schematic of the specimen tank car.

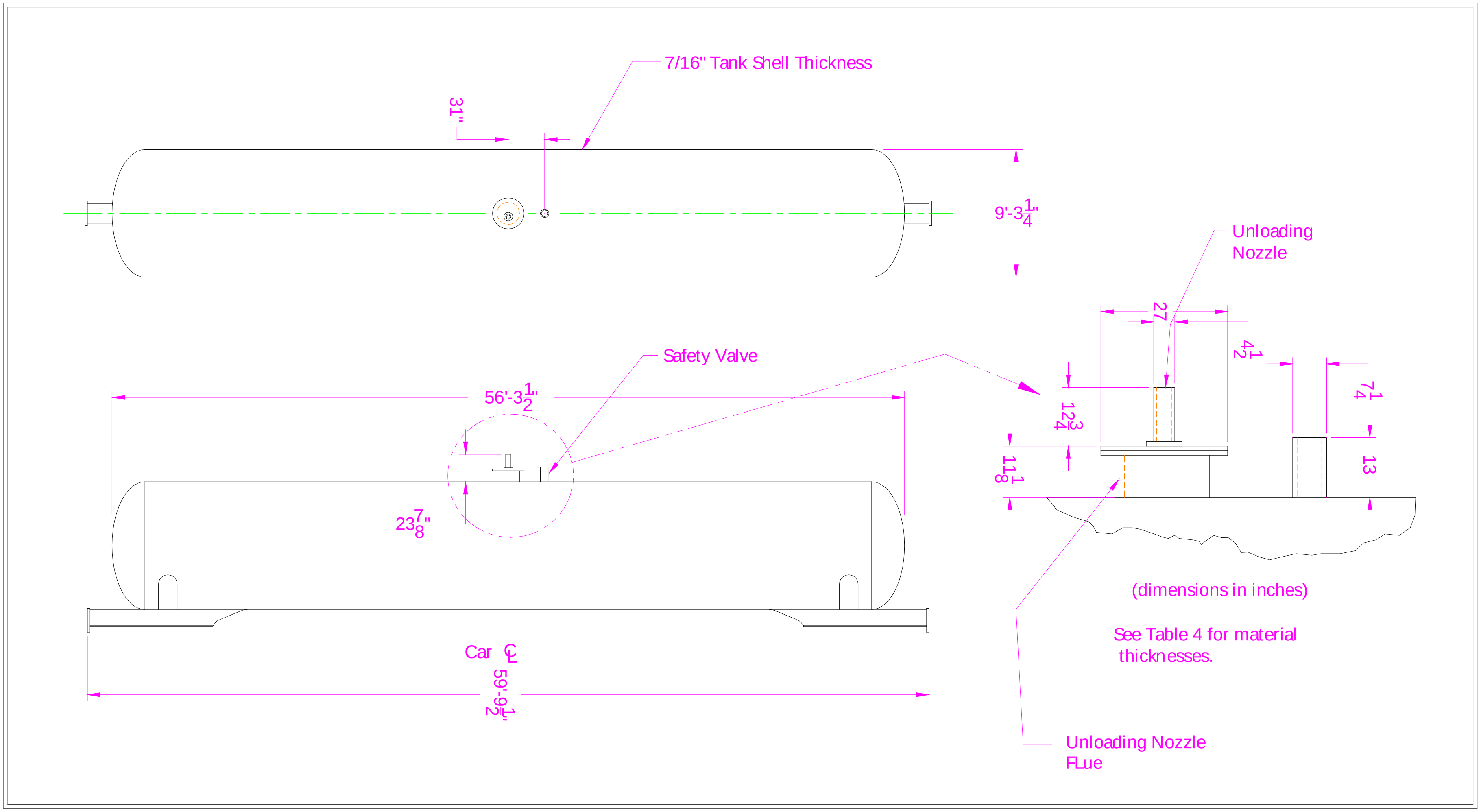


Figure 1. Schematic of Subject Tank Car (Base Case)

3. Model Description

The simulation of a rollover derailment event is best accomplished using a finite element solver with an explicit integration mechanism. Complex contact algorithms, nonlinear material models, and dynamic modeling capabilities are required for these simulations. LS-DYNA3D is an explicit finite element solver that meets these requirements and is used for impact simulations and crash-worthiness analyses. SA used LS-DYNA3D for all the simulations reported here.

To facilitate faster results from the LS-DYNA3D analysis, a new tank car model was created for Phase 2 of this study. The models were created using Pro-engineer, a 3D CAD application and imported to Hypermesh®, a finite element modeler. The geometry for the model was built from drawings obtained for the tank car described above. The tank carbody model includes: stub sills, end sills, bolsters and the top fittings. As in Phase 1, only the higher profile fittings were modeled. These include the unloading valve, unloading flue structure, unloading flue cover and safety valve.

The new tank model was meshed using all shell elements (Shell 63), used a straight in place of the tapered tank, and is absent many of the detailed underframe structural parts and separate modeling of the fasteners determined to be unnecessary for the purposes of this analysis.

All fittings components were modeled using A519 Gr 70 steel, common for non-pressure tank car fittings. The tank shell reinforcing discs around the fittings components have a TC-128 steel material callout.

The models created using the Hypermesh® preprocessor were converted to an appropriately formatted (.dyn) file for input into the LS-DYNA3D Program.

For Scenario 3, a concrete barrier, meshed mostly with 8-noded constant stress solid elements, was constructed and placed along the ground surface. The barrier had dimensions of 60 in by 28 in by 30 ft, with a mass of approximately 43,000 lb (see Figures 8 through 10). An array of nodes on the barrier is constrained to the rigid floor (ground surface) to secure the barrier. The MAT_BRITTLE_DAMAGE material card was used along with the MAT_ADD_EROSION card to produce the desired concrete properties. A high strength concrete reinforced with steel rebar was selected with an overall von Mises failure stress of 10 kilopounds per square inch (ksi). The tank body is initially oriented with the vertical centerline rotated to 140 degrees to the vertical for Scenario 3 (see Figure 9).

4. Concepts for More Robust Protection

When considering methods of protection of non-pressure tank car top fittings, it must be noted that the tank shell thicknesses of the non-pressure cars are significantly less than those of the pressure car variety. Additionally, a current Association of American Railroads (AAR) requirement exists that the connection of any protective structure to the tank must incorporate an intermediate steel plate between the protective device and the tank shell. This requirement states that the connection of the protective structure to the intermediate plate must possess 70 percent of the strength of the plate to tank interface. As a result, this connection to an already thin tank shell may become a limiting factor in the effectiveness of any protruding protective structure as it attempts to bear the full rollover forces of a loaded tank car.

Three additional concepts for protecting top fittings were developed here in Phase 2 of this study. These include:

- A rollbar weldment
- A top skid weldment
- Recessing the fittings inside the tank

These additional concepts are referred to as Concept 3, 4 and 5 respectively, continuing from Phase 1 of the study. A base case with no protective structure is simulated for Scenario 3 (case with longitudinal velocity) and described in Section 4.4. (Note that the base case for Scenario 1 was covered in the Phase 1 report.)

4.1 Rollbar Assembly

Concept 3 incorporates a fabricated rollbar assembly around the fittings with a shape designed with the intent of allowing the car to roll without imparting forces to the rollbar assembly high enough to fail the material (see Figure 2). The two transverse tubes are formed into an elliptical shape providing a smooth tangential transition off the tank surface. This protective structure is welded to the tank through ½-inch thick steel intermediate pads at each attachment to the tank. The structure is made from 8-inch outside diameter (OD) by 1-inch-thick 4140 alloy steel tube with a reported nominal ultimate strength of 100 ksi and yield strength of 70 ksi. This assembly adds 3950 lbs to the car.

4.1.1 Scenario 1

4.1.1.1 Model Description–Rollbar Assembly

The model of the rollbar assembly was created in Pro-engineer and meshed with shell elements using Hypermesh® (see Figures 3 and 4). After merging the rollbar assembly to the tank model, the file was exported to the LS-DYNA3D application for dynamic analysis.

The Failure Element Analysis (FEA model) of the rollbar assembly alone was first analyzed using the ANSYS® preprocessor, a finite element solver to confirm that existing AAR M1002 appendix E 10 structural requirements were met.

4.1.1.2 Simulation & Results–Rollbar Assembly

The simulation of the first scenario (Figure 5) shows the tank carbody falling and rotating from its initial (trucked height) position and impacting the ground surface on its body bolster structure at t=0.11 sec. The bolster deflects on the floor but does not fail as the tank car rotates. Von Mises stresses reach a high of about 60 ksi on the bolster for a duration of 0.10 sec and level off to about 12 ksi for 0.8 seconds until the bolster clears the ground surface. The tank shell impacts the ground at t=0.265 sec and continues rolling over with stresses on the tank shell reaching about 65 ksi at t=0.4 sec under the rollbar base plates. The Rollbar impacts the ground at t=0.275 sec near the point of attachment along the tank's vertical mid water line with a relatively smooth tangential transition of motion. As the car continues to roll, the stresses increase to just under 100 ksi on the Rollbar at t=0.325. A few elements at the intersection of the elliptical and support tubes of the Rollbar fail. The Rollbar however survives and successfully protects the fittings components. During this scenario, the tank experiences noticeable deflection without failure during the contact of the Rollbar structure with the ground surface. Figures 6 and 7 show the Rollbar assembly protecting the fittings during the time the fittings would otherwise be crushing on the ground surface. The floor (ground surface) is hidden in these views for clarity.

4.1.2 Scenario 3

4.1.2.1 Model Description–Rollbar Assembly

The concrete barrier was added to the model as described in section 3 (see Figures 8 and 9).

4.1.2.2 Simulation & Results–Rollbar Assembly

The simulation for Scenario 3 shows the tank carbody descending while rotating. The front longitudinal tube of the rollbar structure strikes the concrete barrier at t=0.255 sec. The lateral tube hits the concrete at t=0.26 sec and the ground (rigid wall) surface at t=0.265 sec (see Figure 10). The rollbar and tank shell body deflect as shown in Figure 11 as a result of the downward momentum of the tank carbody. The rollbar structure continues penetrating through the concrete barrier as the concrete material fails and breaks away (see Figures 12 and 13). Stresses on the rollbar material reach a maximum (von Mises) of about 80 ksi without any failure. The force between the rollbar and the concrete barrier over the duration of the simulation is plotted in Figure 14. This data has been passed through a 20 Hz lowpass filter and shows a maximum force of about 80 kips. The rollbar succeeded in protecting the fittings from impact with the ground and concrete barrier (see Figures 12 and 13).

4.2 Top Skid

Concept 4 consists of a large fabricated skid using 1" thick TC-128 steel plates with a height slightly exceeding the tallest fitting component (see Figure 15). A 20-degree bevel angle is used to avoid snagging during any longitudinal motion. Two lateral cross plates add rigidity against lateral roll over forces. These plates are augmented by four triangular gussets outboard of the longitudinal plates. The skid attaches to the tank by fillet welds thru an intermediate ½-inch-thick base plate. This assembly adds about 4500 lbs of weight to the car.

4.2.1 Scenario 1

4.2.1.1 Model Description–Top Skid

The FEA model for the skid assembly was constructed using the same method as described previously for Concept 3. The geometry and mesh were created in Hypermesh and attached to the same geometry and mesh of the tank, fittings and understructure used for Concept 3.

4.2.1.2 Simulation & Results–Top Skid

The simulation of the first scenario (Figure 16) shows the tank carbody falling and rotating from its initial (trucked height) position and impacting the ground surface on its body bolster structure at t=0.12 sec. The bolster deflects on the floor as the tank car rotates but does not fail. Von Mises stresses reach a high of about 65 ksi on the bolster for a duration of 0.10 sec and level off to about 12 ksi for 0.09 seconds until the bolster clears the ground surface. The tank shell impacts the ground at t=0.28 sec and continues rolling over with stresses on the tank shell reaching about 56 ksi @ t=0.32 sec near the bolster attachment. This level of stress exists for about 0.1 sec duration then levels off to about 25 ksi. The gussets of the skid impact the ground at t=0.30 sec. At t=0.32, some of the elements on the cross support plates fail followed by a few elements failing on the gussets of the skid at t=0.345 sec. The valve and fittings survive this scenario in spite of the minor damage imparted to the protective skid. At no point do the fittings contact the ground surface. They are successfully protected by the skid assembly. Figures 17 and 18 are views of the model showing the effectiveness of the protective skid. These views have the ground surface hidden for clarity; and are snapshots in time when the full weight of the tank is upon the skid structure.

Stresses on the tank shell reached about 56 ksi during the simulation.
The skid model (Concept 4) was also created using T-1 steel in place of the TC-128 steel. T-1 steel has a higher ultimate strength of about 110 ksi versus TC-128 at 81 ksi. In this case the simulation shows no failure points on the skid assembly.

4.2.2 Scenario 3

4.2.2.1 Model Description–Top Skid

The concrete barrier was added to the model as described in section 3 (see Figures 19 and 20).

4.2.2.2 Simulation & Results–Top Skid

In Scenario 3, the simulation is similar to that of Concept 3. The tank body falls under gravity rotating with the initial rotational velocity provided. The protective skid structure impacts the concrete barrier at t=0.22 seconds and continues penetrating through the concrete material (see Figures 21 thru 22) with minimal deflection and without failure of the protective structure. The maximum stress seen on the skid structure is about 85 ksi at the side gussets near the tank shell. The top fittings clear the concrete barrier at t=0.71 sec, are successfully protected by the structure and at no point impact the rigid ground surface (see Figure 24). Tank shell stresses reach a maximum of about 50 ksi at the interface with the support pads of the skid structure. A filtered plot of the force between the skid and the concrete barrier over time is shown in Figure 25 and shows a maximum force of about 85 kips. This agrees well with the force level seen in the Concept 3 (rollbar) analysis.

4.3 Recessed Fittings

In order to provide a greater level of top fittings protection under such severe conditions, it was decided that Concept 5 would place the fittings recessed down below the tank shell surface. This method of protection could be retrofitted to existing cars, but more likely be considered a method of protection more suitable for new car construction.

The Concept 5 design consists of an inverted unloading flue extending down into the tank space with an annular steel reinforcing plate around the tank shell cutout. An annular lip is provided at the lower end of the flue to seat the cover of the unloading flue. Unloading valves, sampling devices and other appurtenances will mount on this cover. The inner diameter is sized to allow operation, maintenance and removal of the equipment (see Figure 26). A watertight cover could be used to keep out snow, water and debris.

The material for the tank shell reinforcing discs and some fittings components had to be revised to T-1 steel to survive the impact with the concrete barrier in scenario 3 (see Table B1.)

4.3.1 Scenario 1

4.3.1.1 Model Description–Recessed Fittings

The model for Concept 5 (Recessed Fittings) was created by modifying the Concept 4 model in the local area of the fittings (see Figures 27 and 28).

4.3.1.2 Simulation & Results–Recessed Fittings

The simulation of the first scenario shows the tank body falling and rotating from its initial (trucked height) position and impacting the ground surface on its body bolster structure at t=.11 sec. Stresses reach a high of about 70 ksi on the bolster as it experiences significant deformation. The tank shell impacts the ground at t=0.26 sec and continues rolling over with stresses on the tank shell reaching about 60 ksi and about 73 ksi on the tank shell heads (see Figure 29). Both the tank and the recessed fittings survive this scenario without failure (see Figures 30 and 31). Figure 31 shows the recessed fittings and attaching shell structure viewed from within the tank after the impact. All figures have the ground surface hidden for clarity.

4.3.2 Scenario 3

4.3.2.1 Model Description–Recessed Fittings

The concrete barrier was added to the model as described in section 3 (see Figures 32 and 33).

4.3.2.2 Simulation & Results–Recessed Fittings

The simulation for scenario 3 shows the tank body falling and rotating under the applied gravity force and with the given initial velocities. The tank shell impacts the concrete barrier at t=0.31 sec in a orientation which provides direct impact to the fittings area (see Figure 34). By t=0.73 sec, the fittings have cleared the concrete barrier and reveal no failure (see Figure 35). Tank shell and head stresses generally stay below 60 ksi except for the thin material between the two recessions for the fittings. This area sees about 82 ksi (see discussion in section 6). Stresses in the fittings region are highest at the interface between the tank shell reinforcing disc and the recessed flue for both the unloading appurtenances and the safety valve. These stresses reach about 70 ksi with the Butterworth 20 hz lowpass filter and about 100 ksi unfiltered.

No elements on the concrete barrier fail in this scenario for Concept 5. This is intuitive since there are no sharp or protruding surfaces in this concept.

4.4 Base Case–Scenario 3

A base case model was created for Scenario 3 to show the results of the impact without any protective structure (see Figures 36 and 37). The model was created by taking the rollbar model and removing the rollbar and associated structure leaving the top fittings exposed. This model was simulated in the same manner as the other three concepts described previously for Scenario 3.

The animation shows that safety valve and the unloading valve begin to fail at the impact with the concrete at t=0.26 sec. The flue fails at t= 0.33 sec. Figures 38 and 39 show the failure of the top fittings. These structural failures would undoubtedly lead to release of car lading.

Note: The base case model for Scenario 1 was covered in the Phase 1 report.

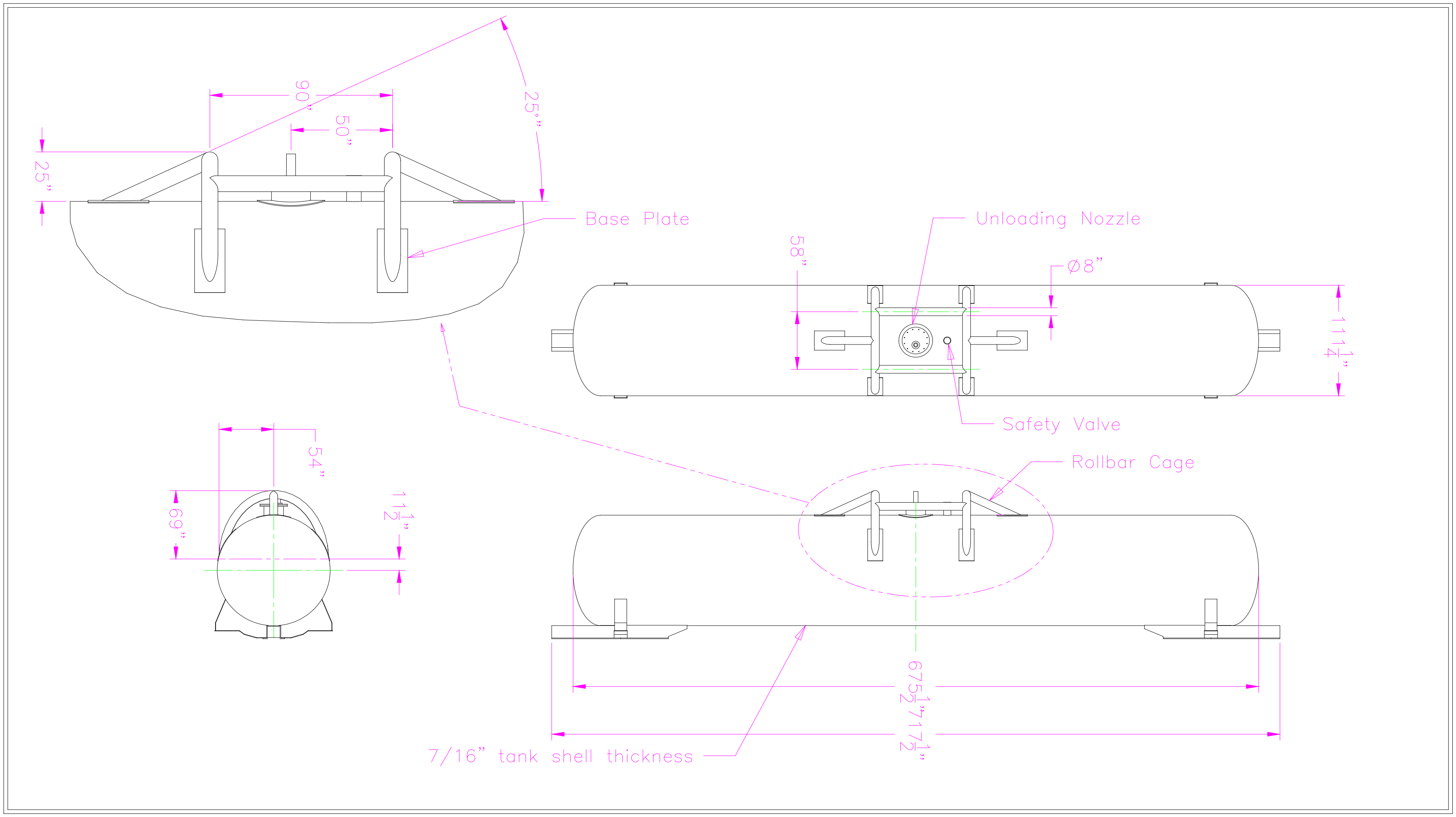


Figure 2. Schematic of Subject Tank Car with Rollbar Assembly (Concept 3)

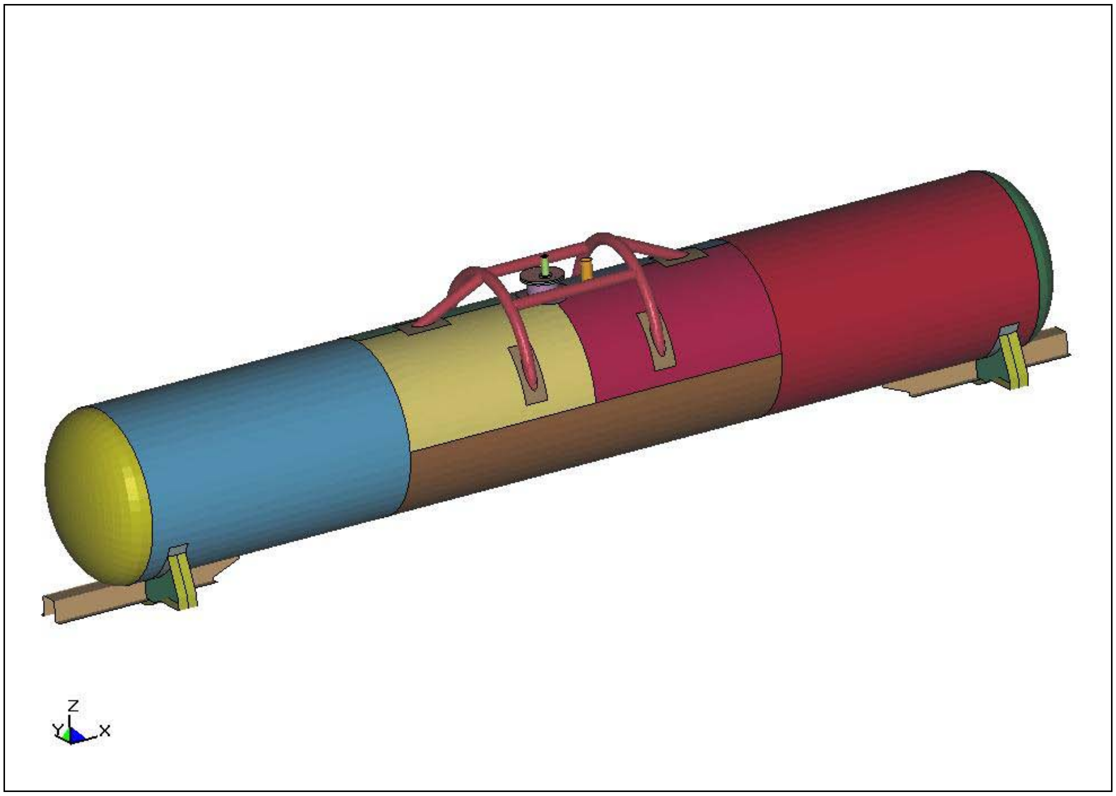


Figure 3. Model of Tank with Rollbar Assembly

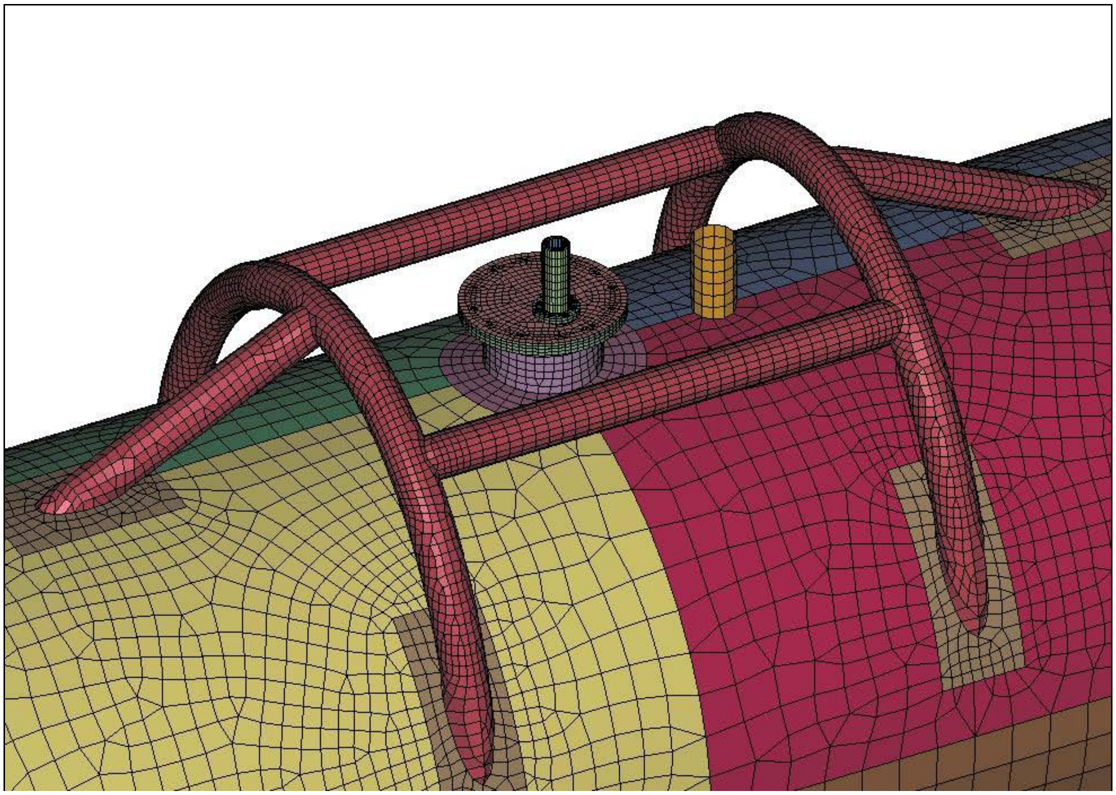
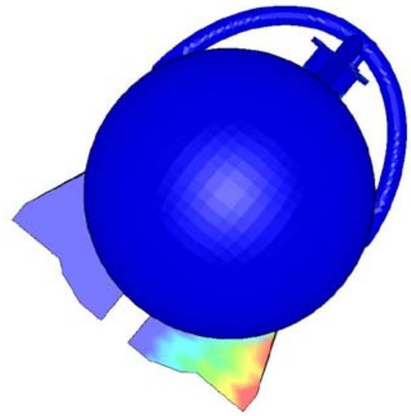
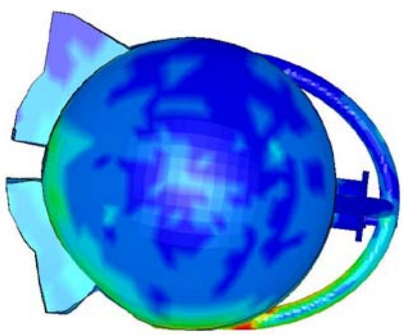


Figure 4. Finite Element Mesh on Rollbar Assembly

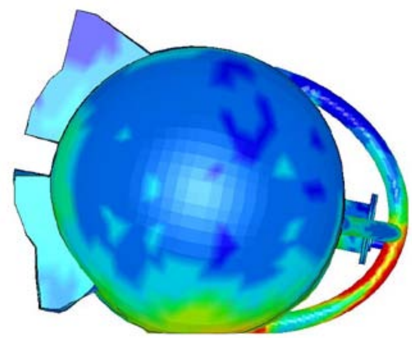
t=0 seconds



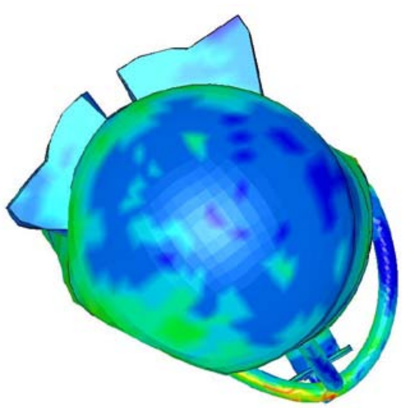
t=0.11 seconds



t=0.28 seconds



t=0.29 seconds



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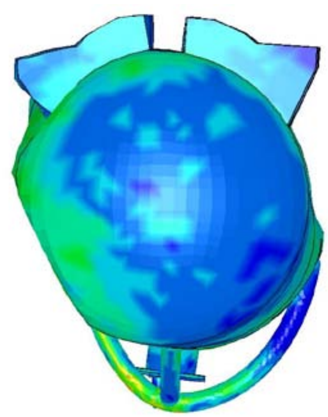

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Figure 5. Simulation Sequence (Concept 3/Scenario 1)

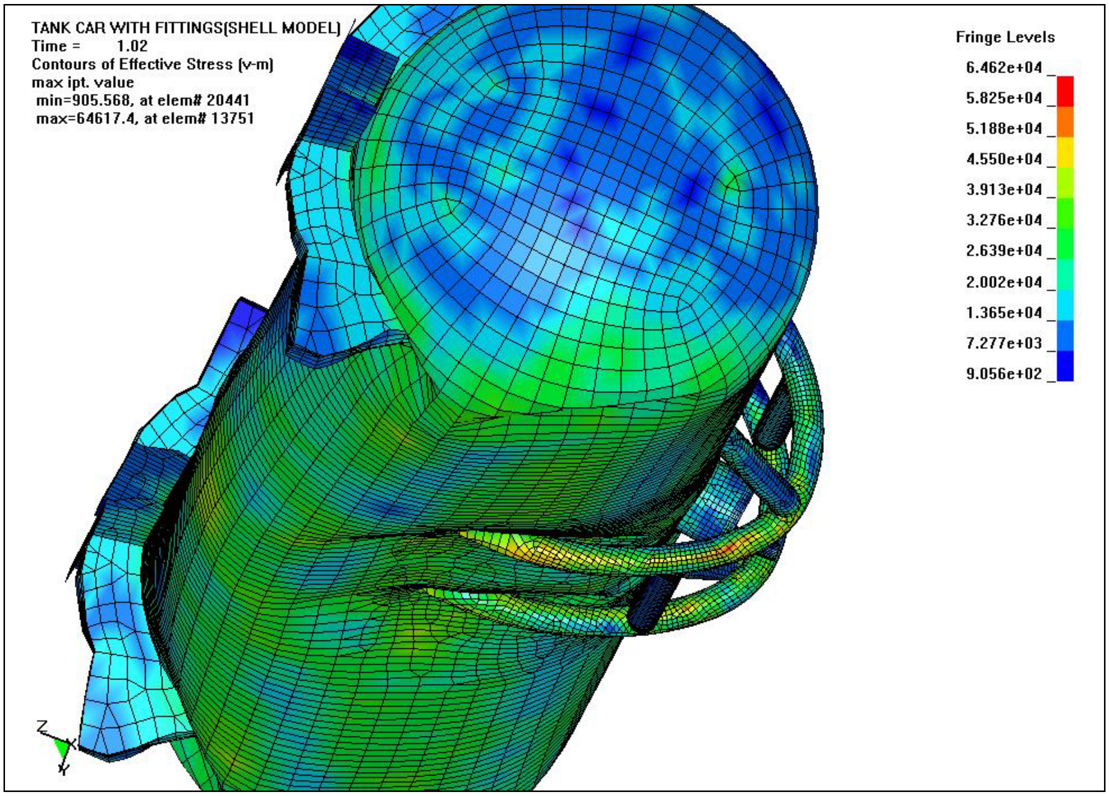

Figure 6. Concept 3 Successfully Protects Fittings (View 1)

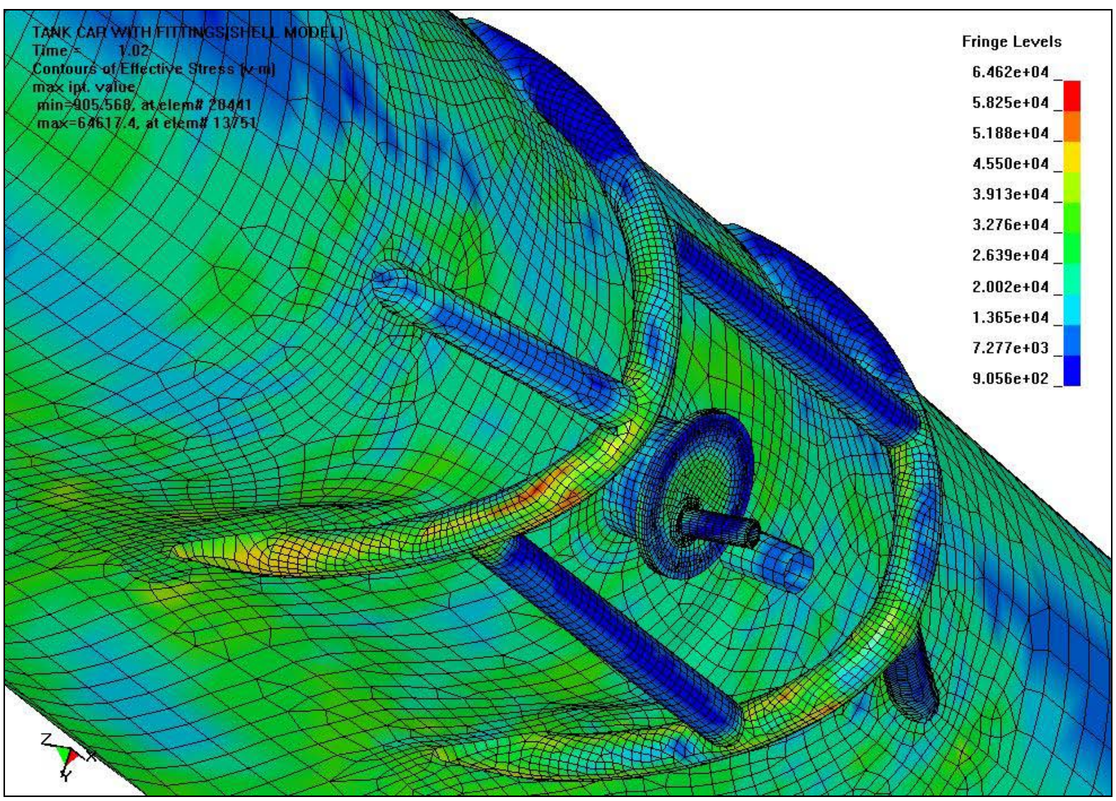

Figure 7. Concept 3 Successfully Protects Fittings (View 2)

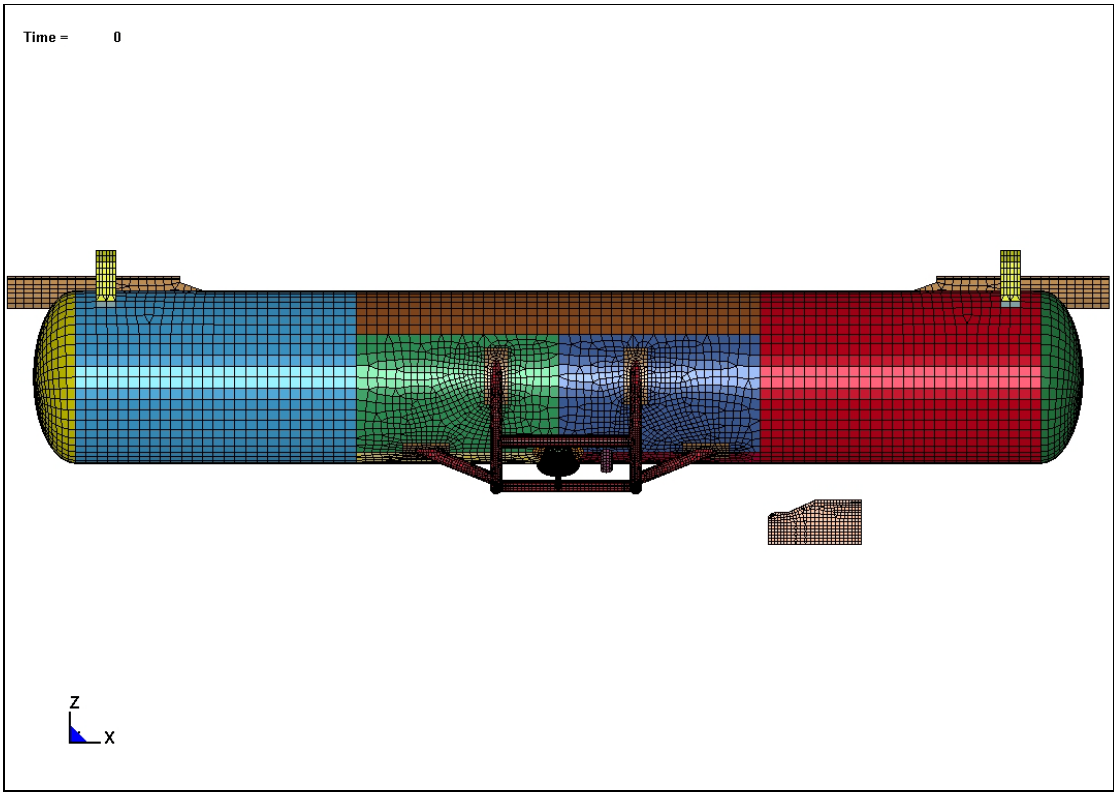

Figure 8. Concept 3 Model with Concrete Barrier (Side View)

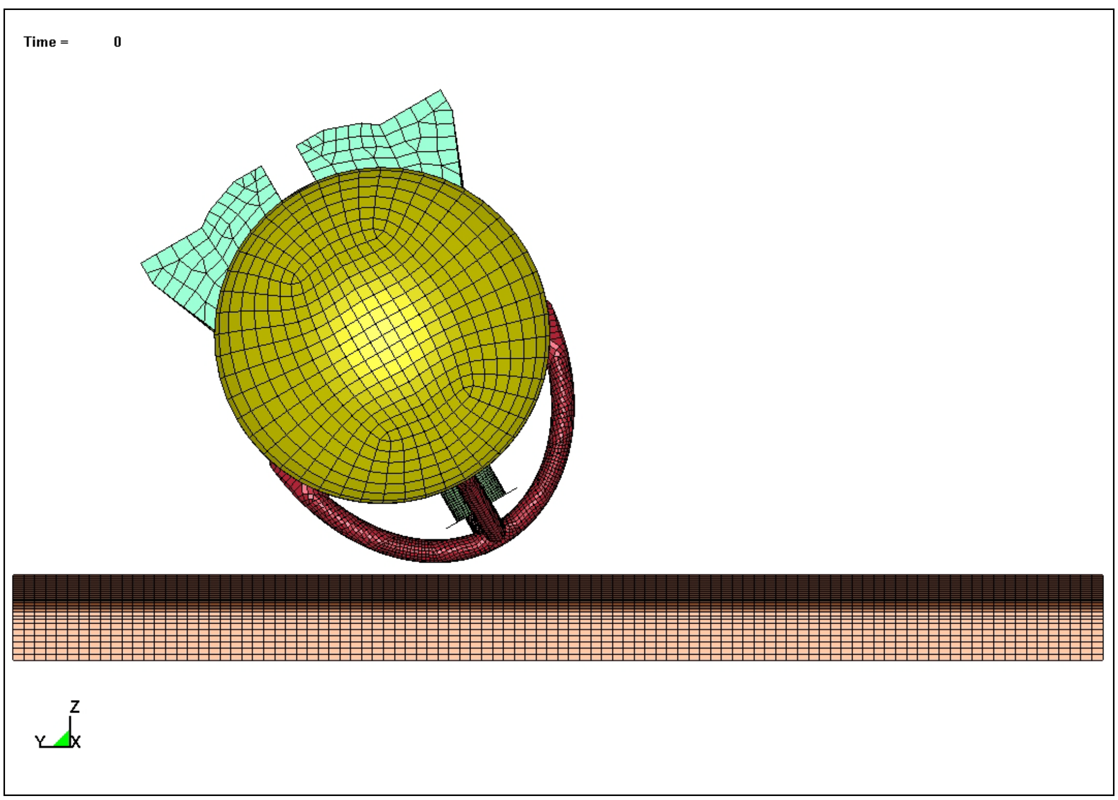

Figure 9. Concept 3 Model with Concrete Barrier (End View)

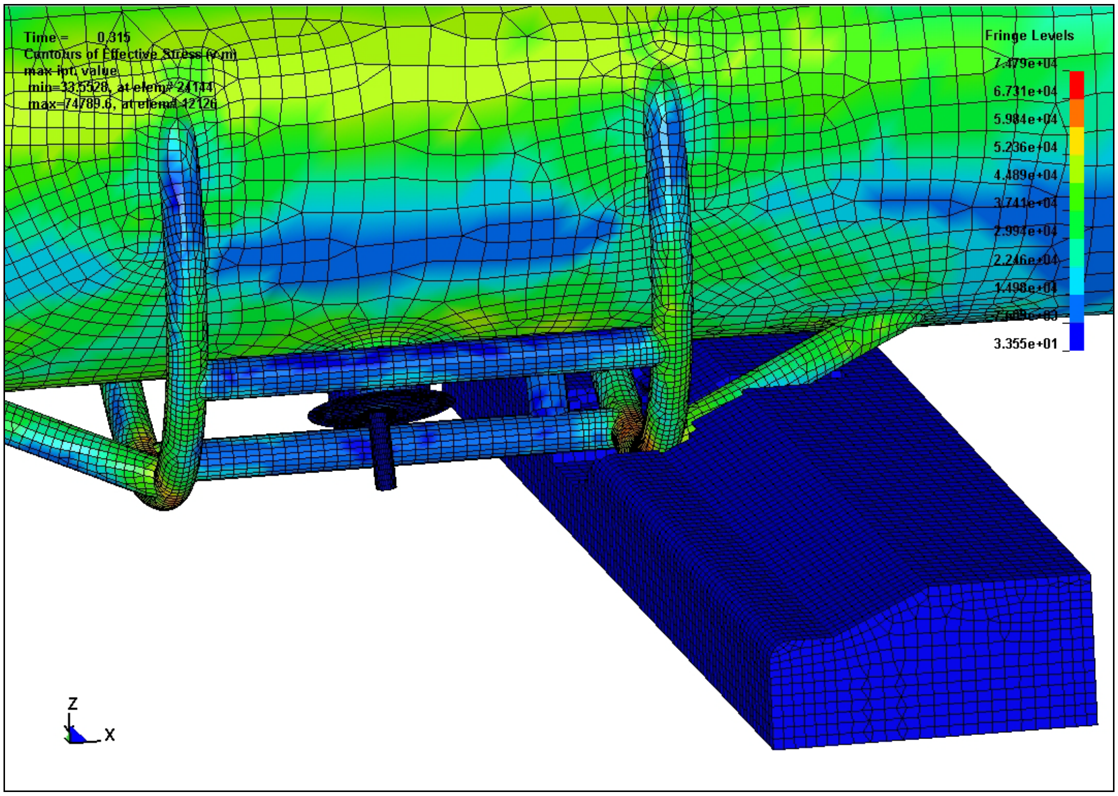

Figure 10. Rollbar Assembly Penetrating Concrete Barrier

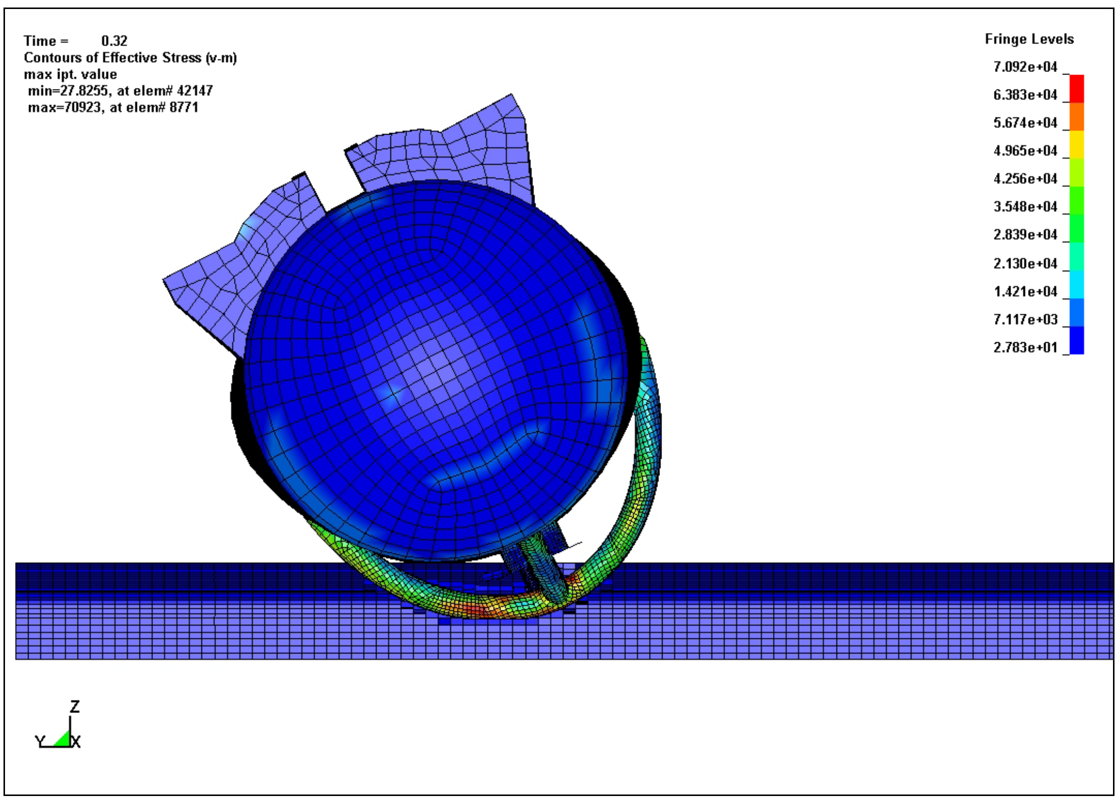

Figure 11. Rollbar Assembly Penetrating Concrete Barrier (End View)

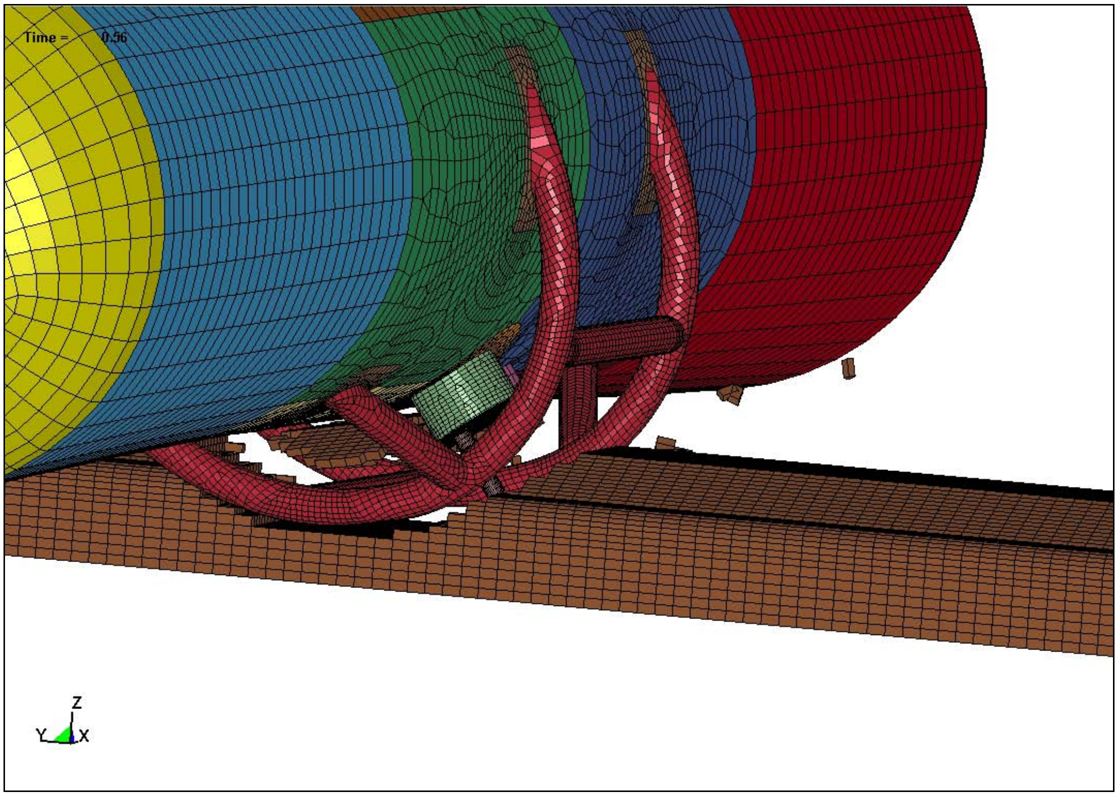

Figure 12. Rollbar Assembly Protecting Fittings (Shaded View)

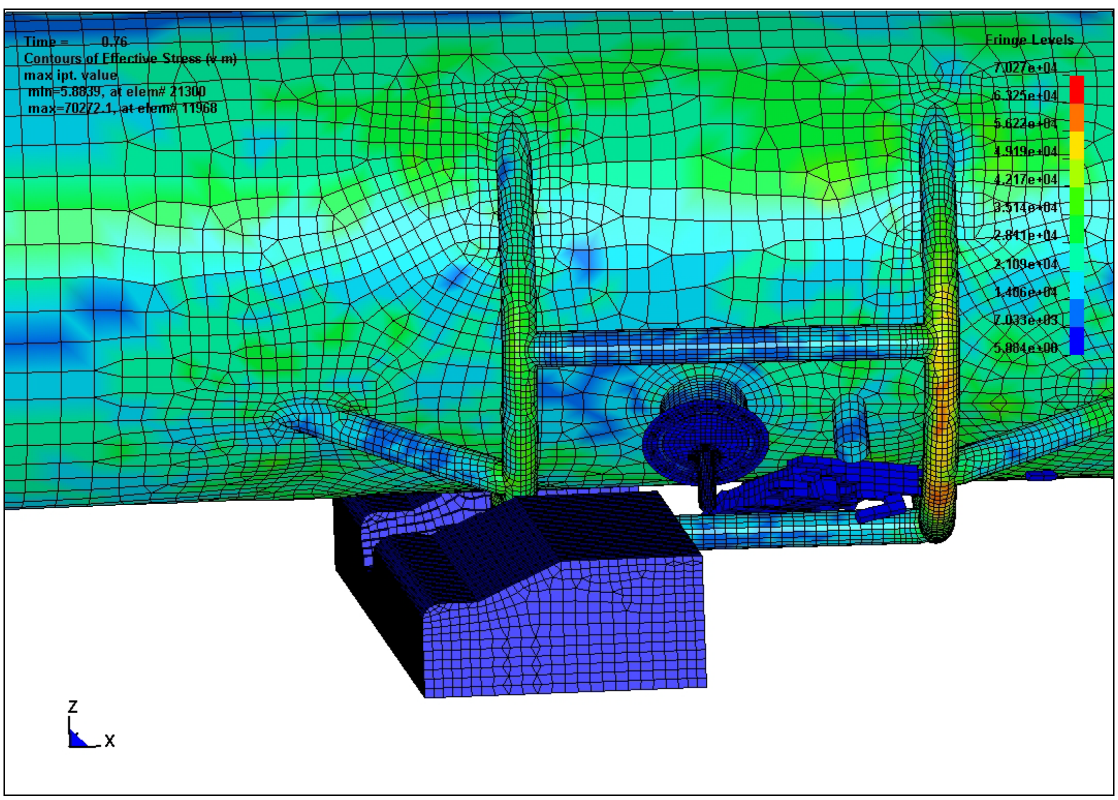

Figure 13. Rollbar Assembly Protecting Fittings

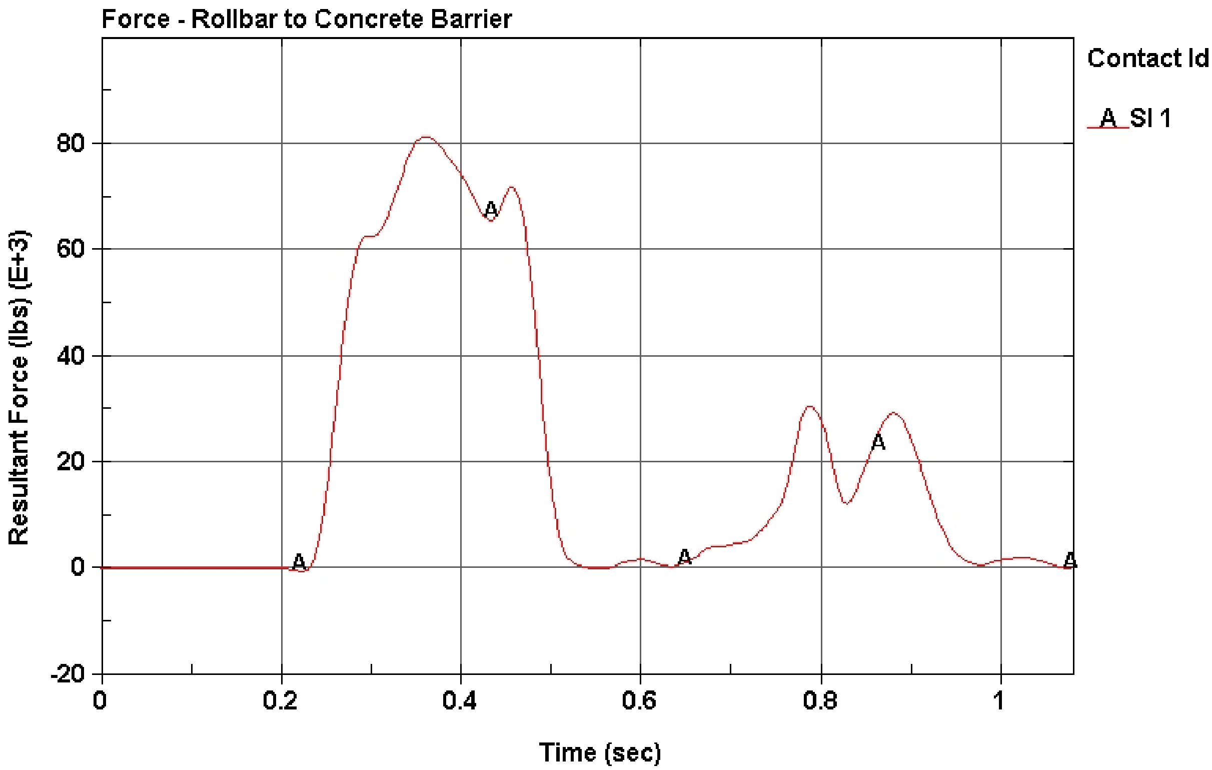

Figure 14. Force between Rollbar Assembly and Concrete Barrier

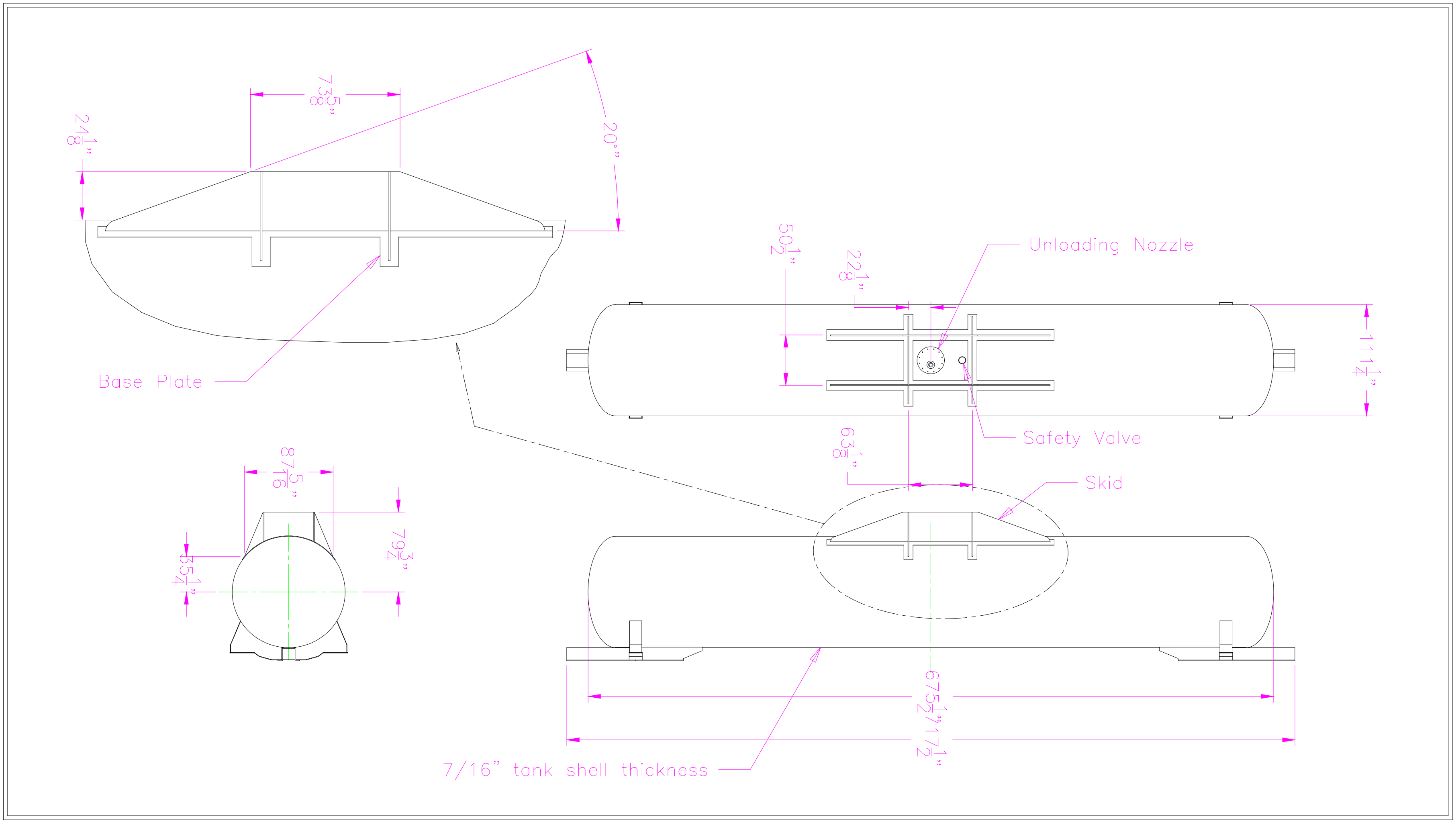

Figure 15. Schematic of Specimen Tank Car with Top Skid (Concept 4)

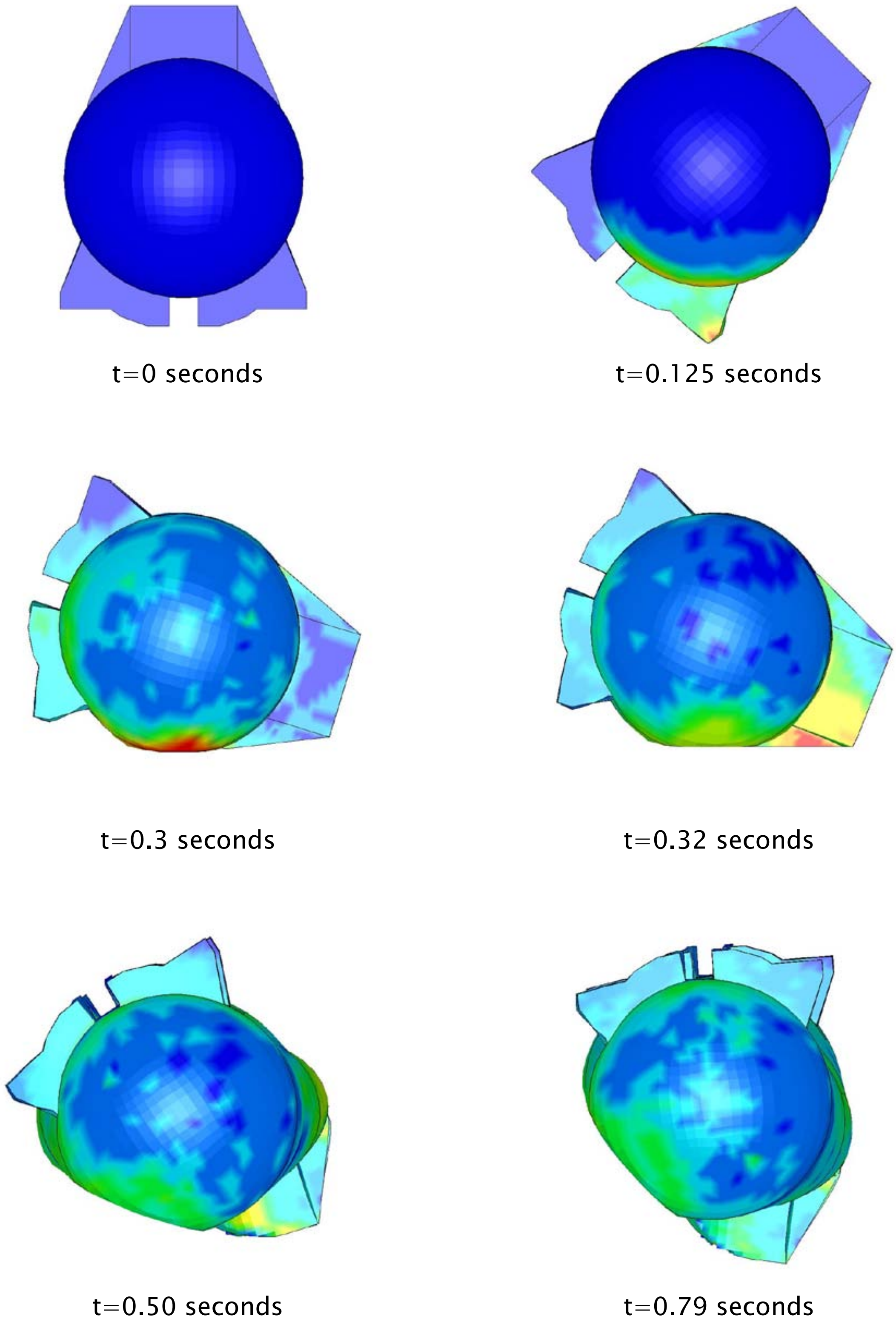

Figure 16. Simulation Sequence (Concept 4/Scenario 1)

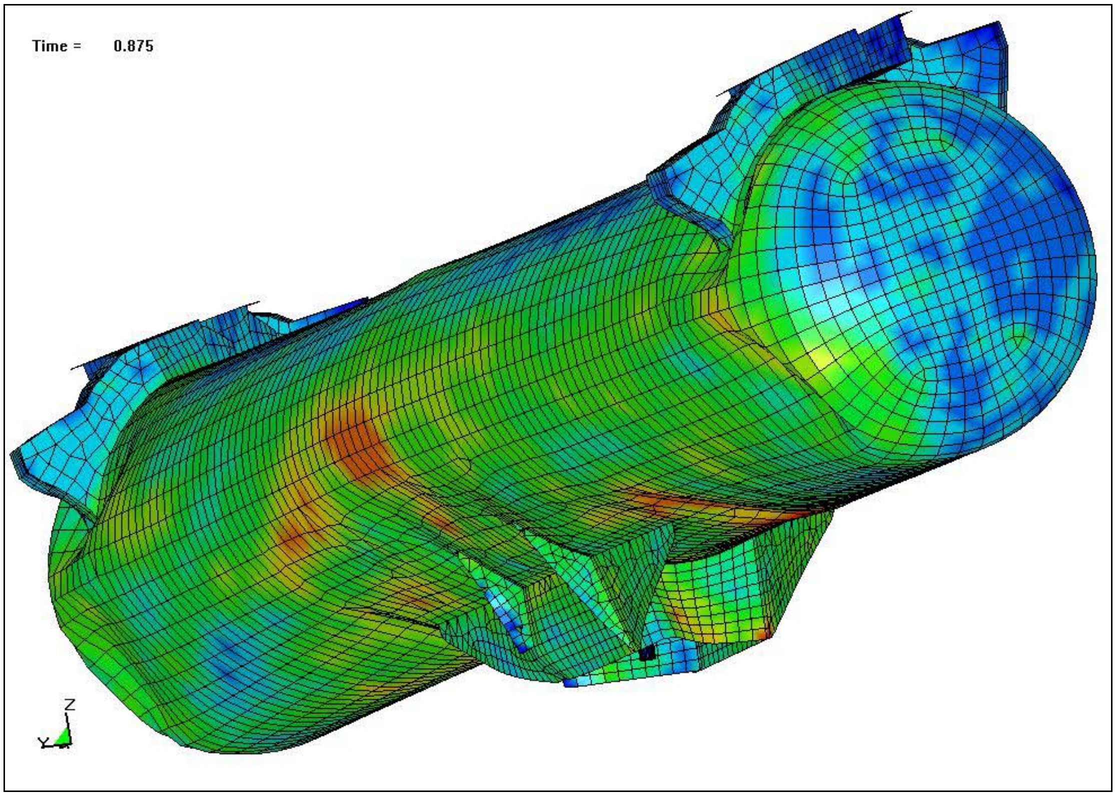

Figure 17. Concept 4 Successfully Protects Fittings (View 1)

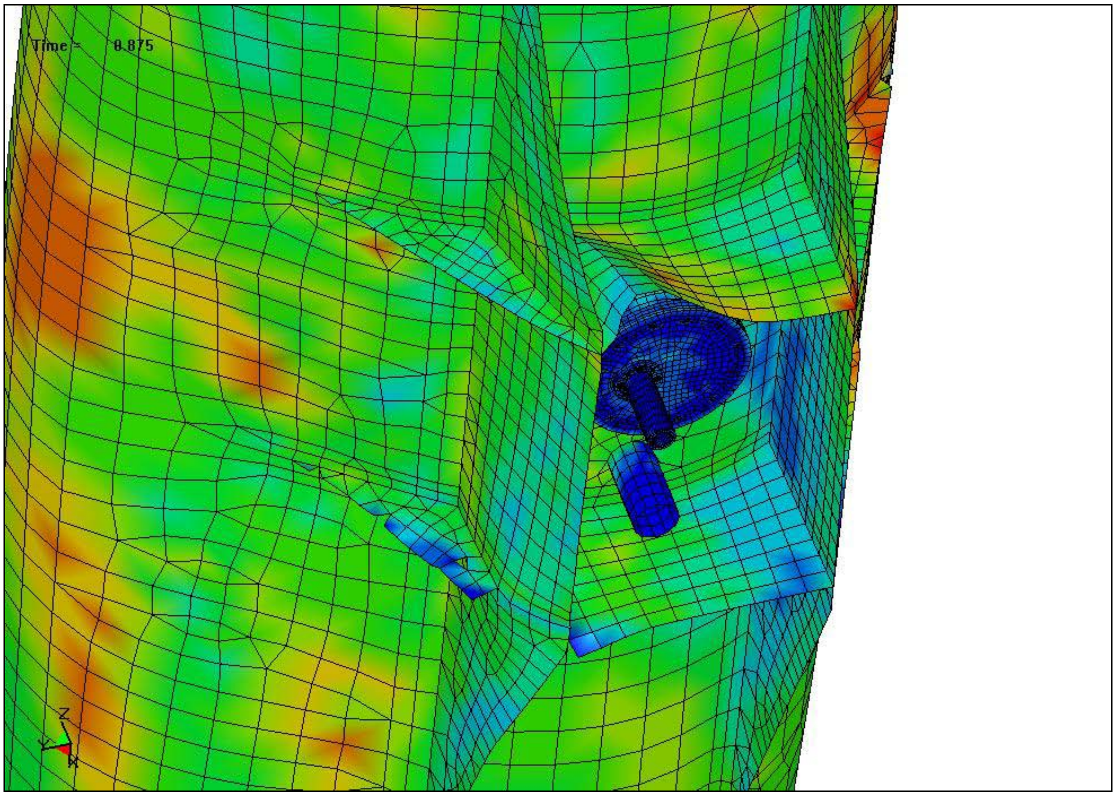

Figure 18. Concept 4 Successfully Protects Fittings (View 2)

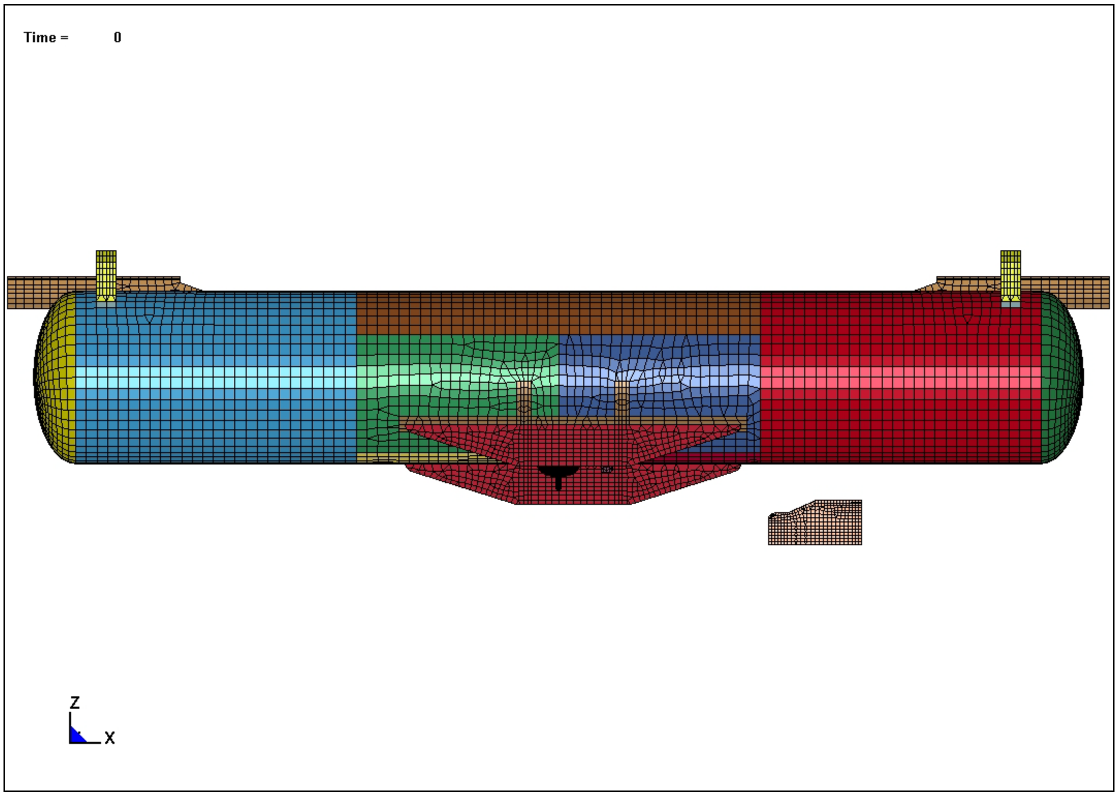

Figure 19. Concept 4 Model with Concrete Barrier (Side View)

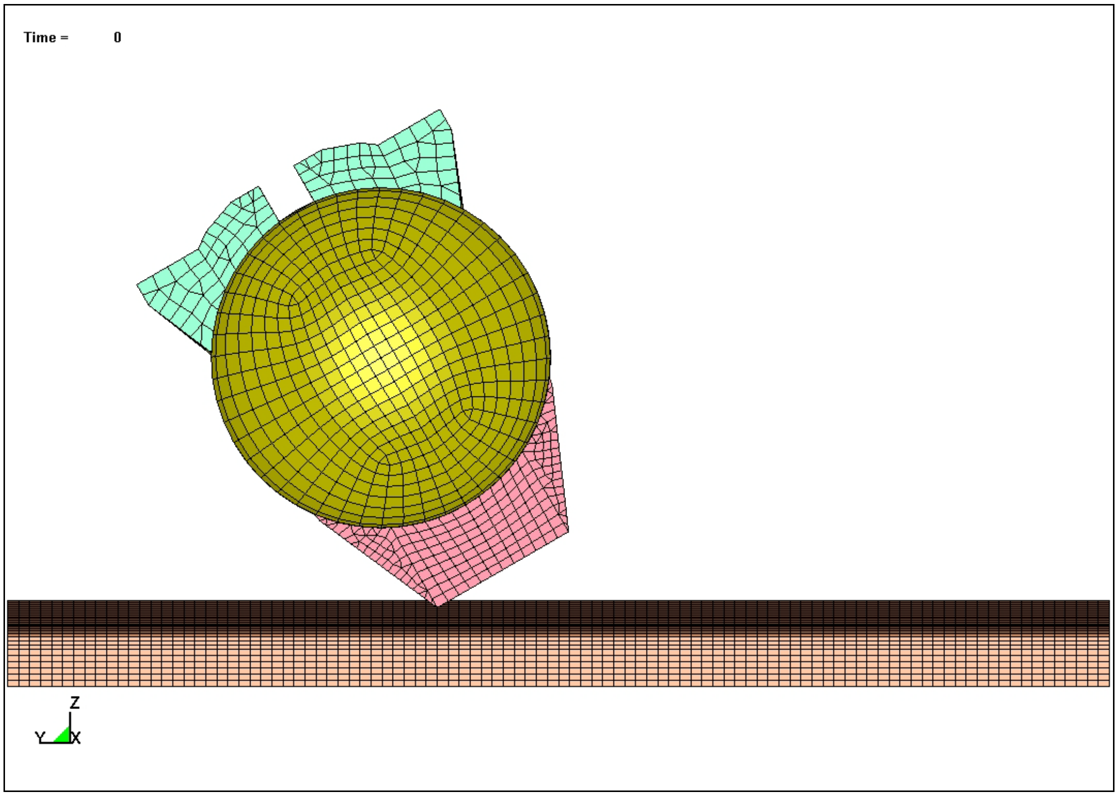

Figure 20. Concept 4 Model with Concrete Barrier (End View)

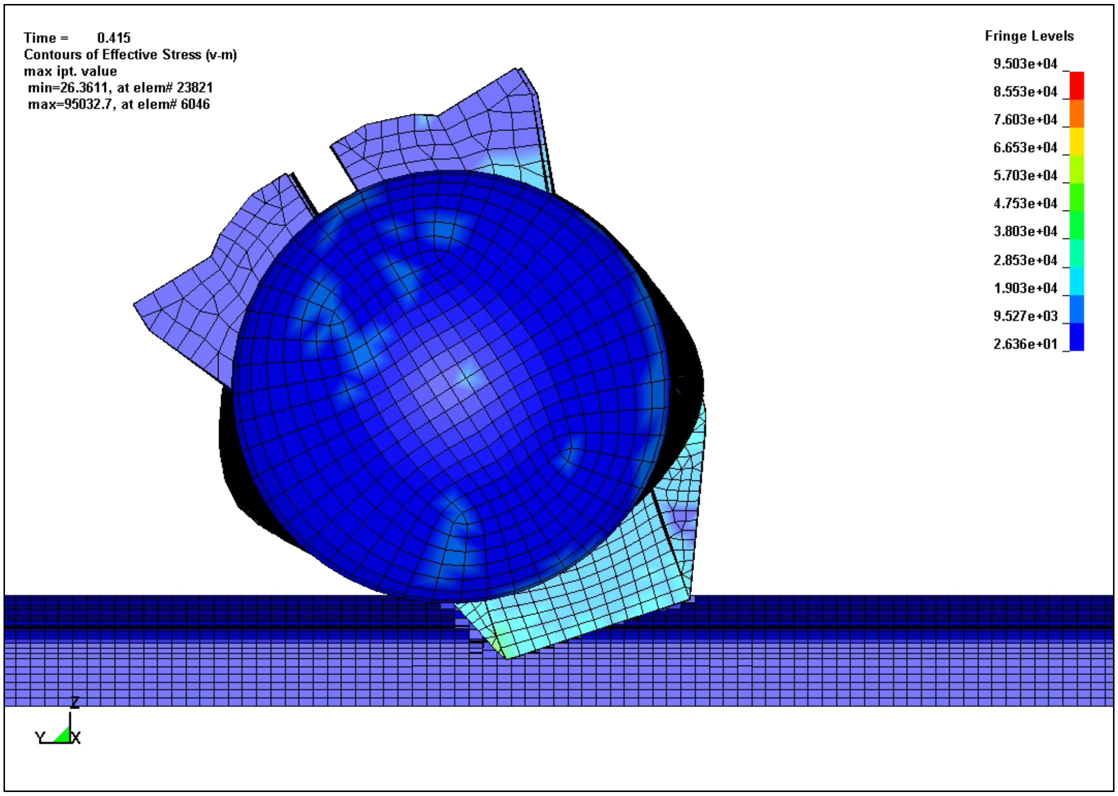

Figure 21. Skid Impact (Side View)

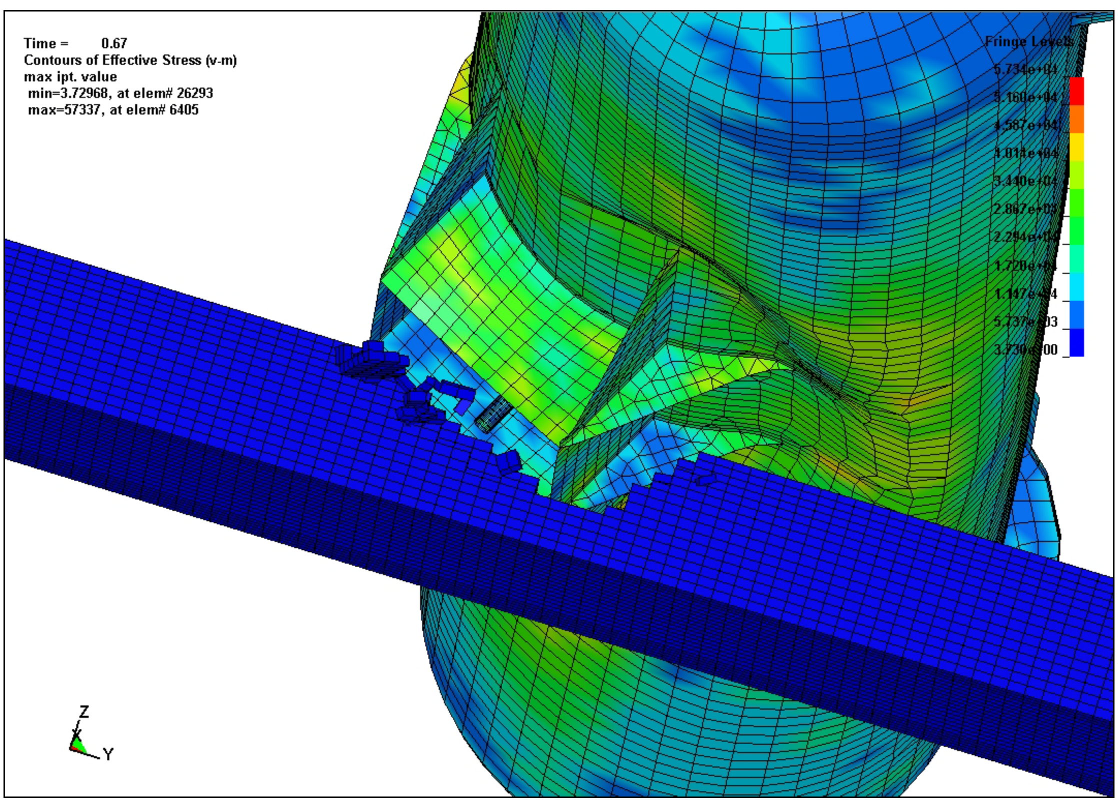

Figure 22. Skid Penetrating Concrete

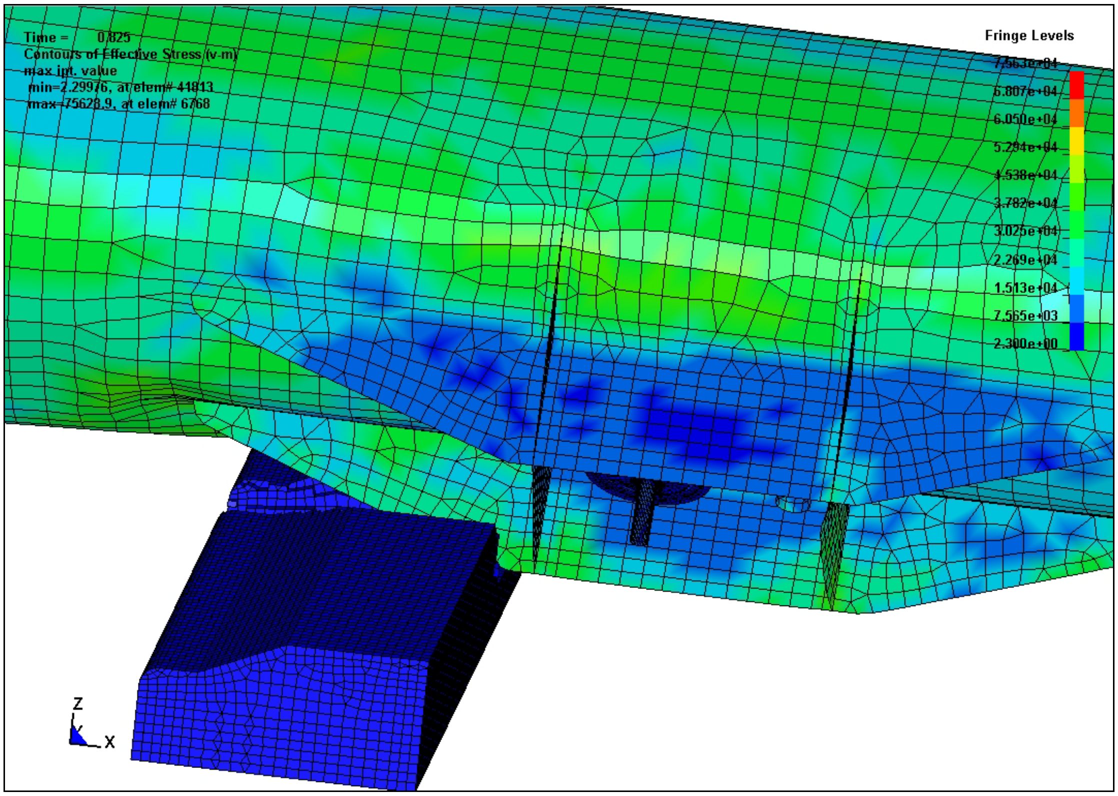

Figure 23. Skid and Fittings Survive Impact (View 1)

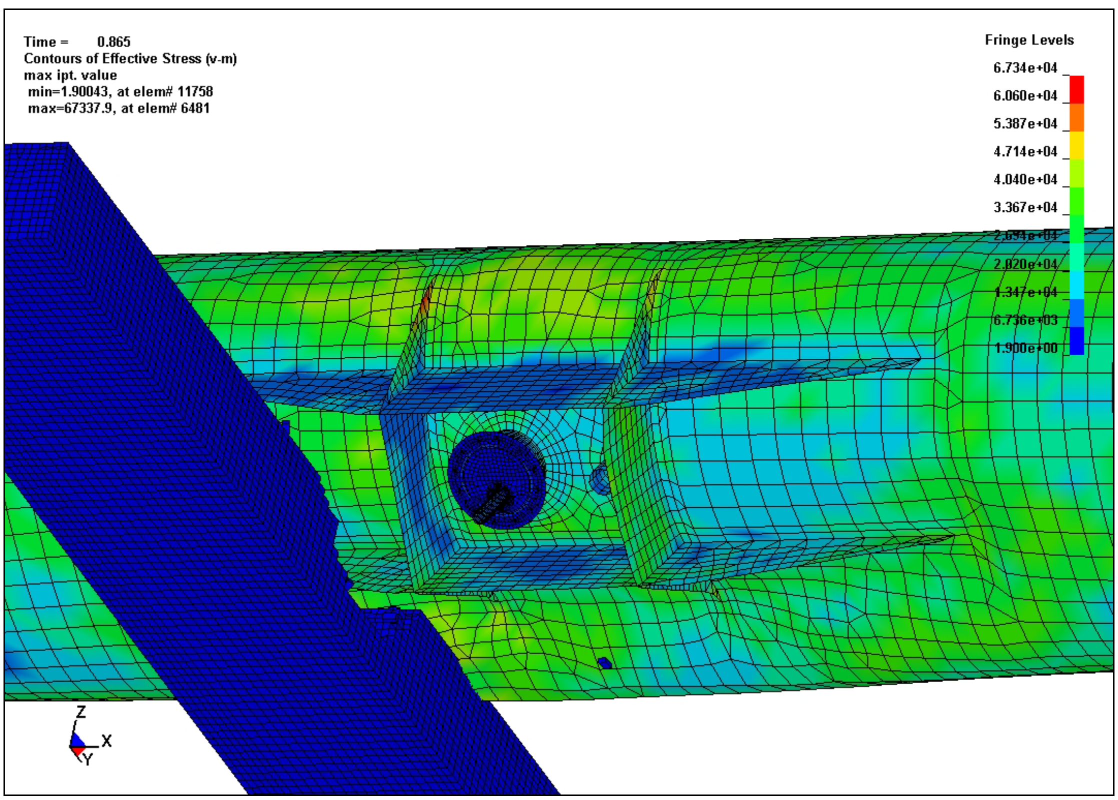

Figure 24. Skid and Fittings Survive impact (View 2)

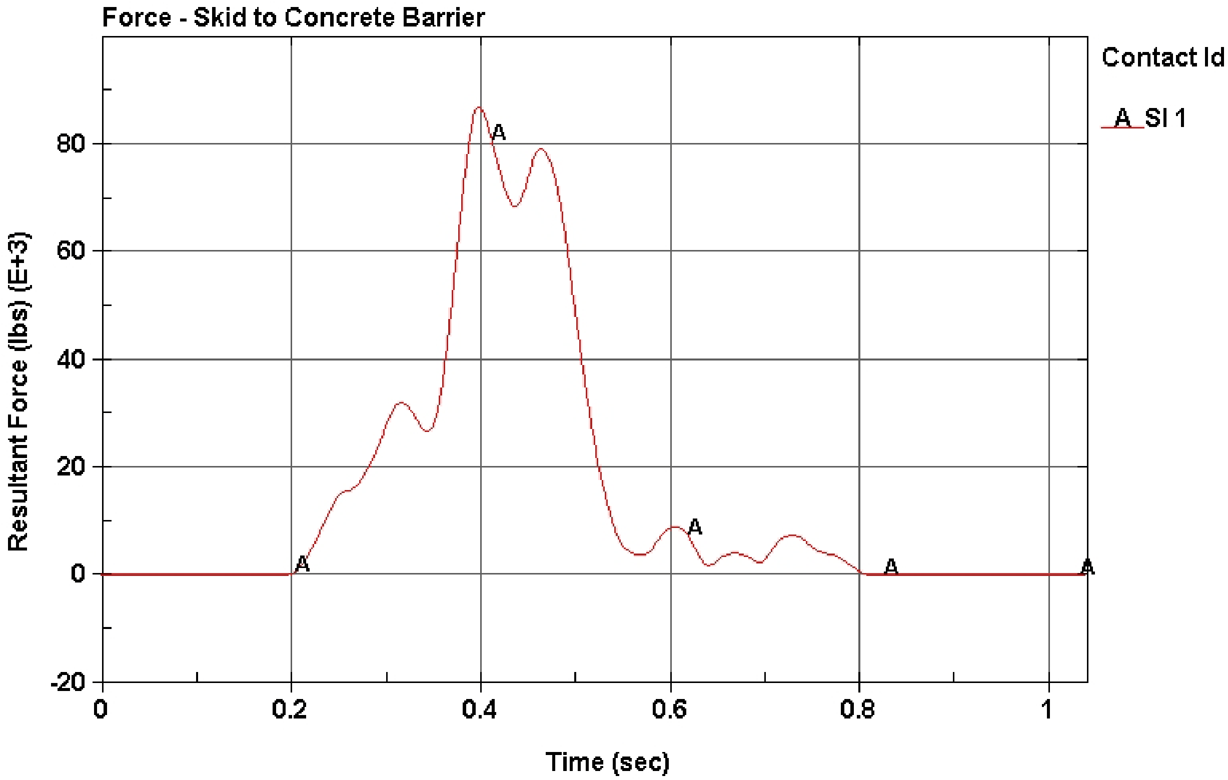

Figure 25. Force between Skid and Concrete Barrier

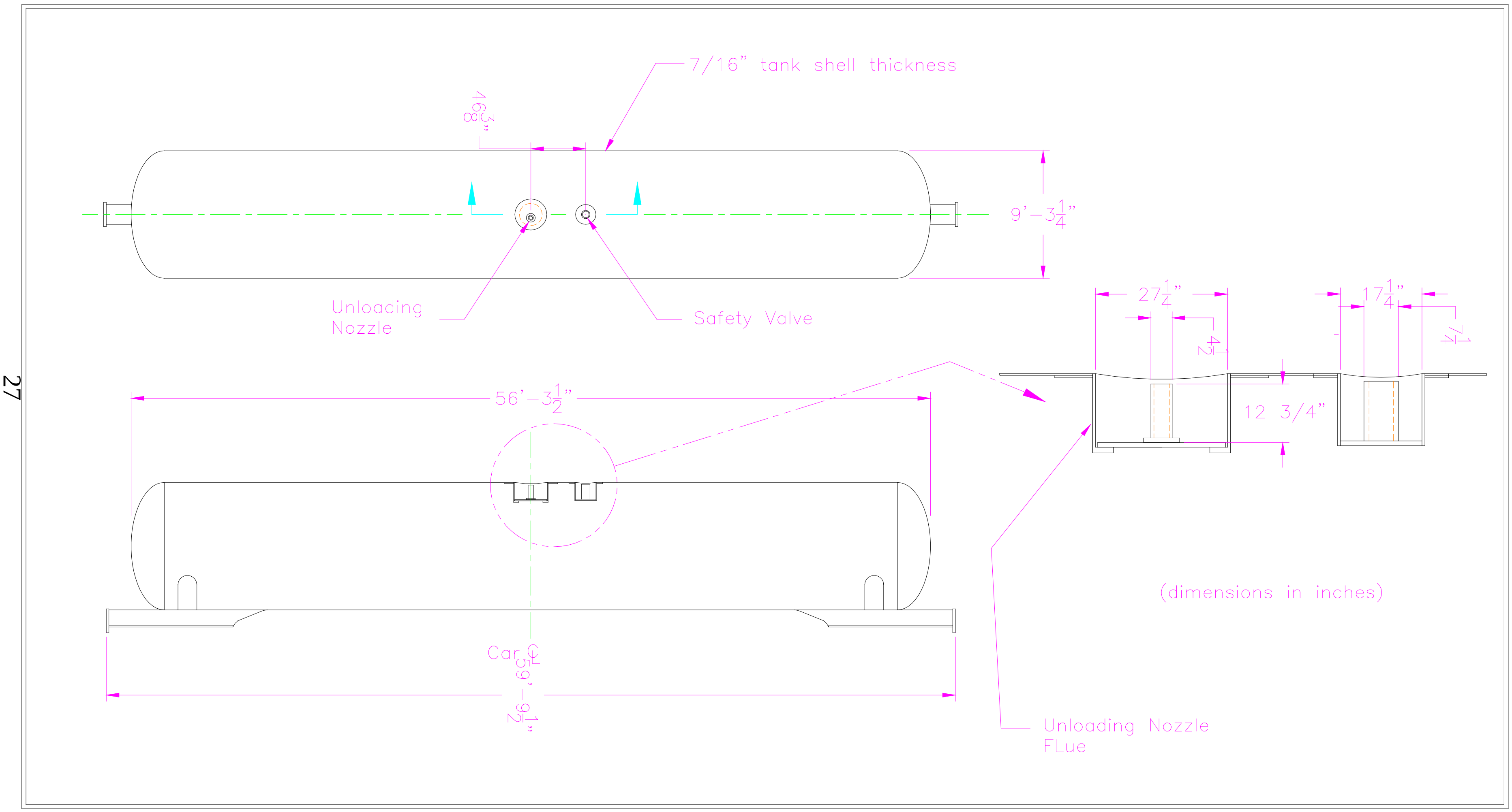

Figure 26. Schematic of Subject Tank Car with Recessed Fittings (Concept 5)

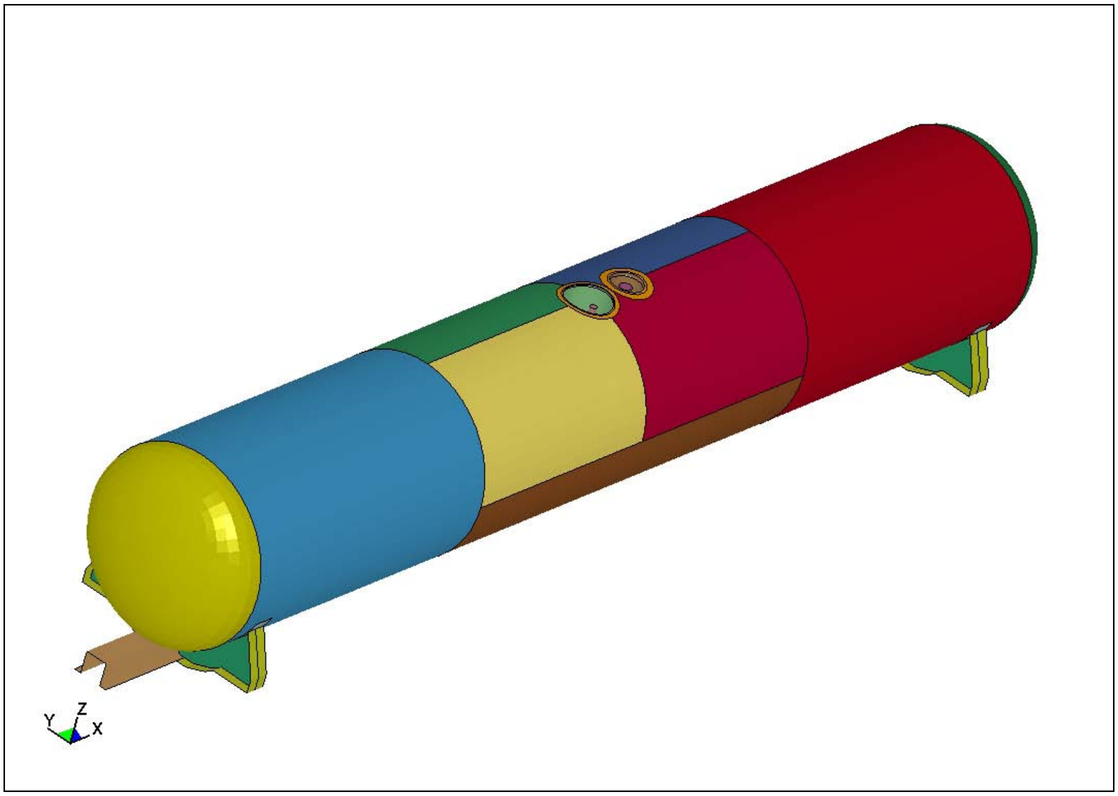

Figure 27. Recessed Fittings Model

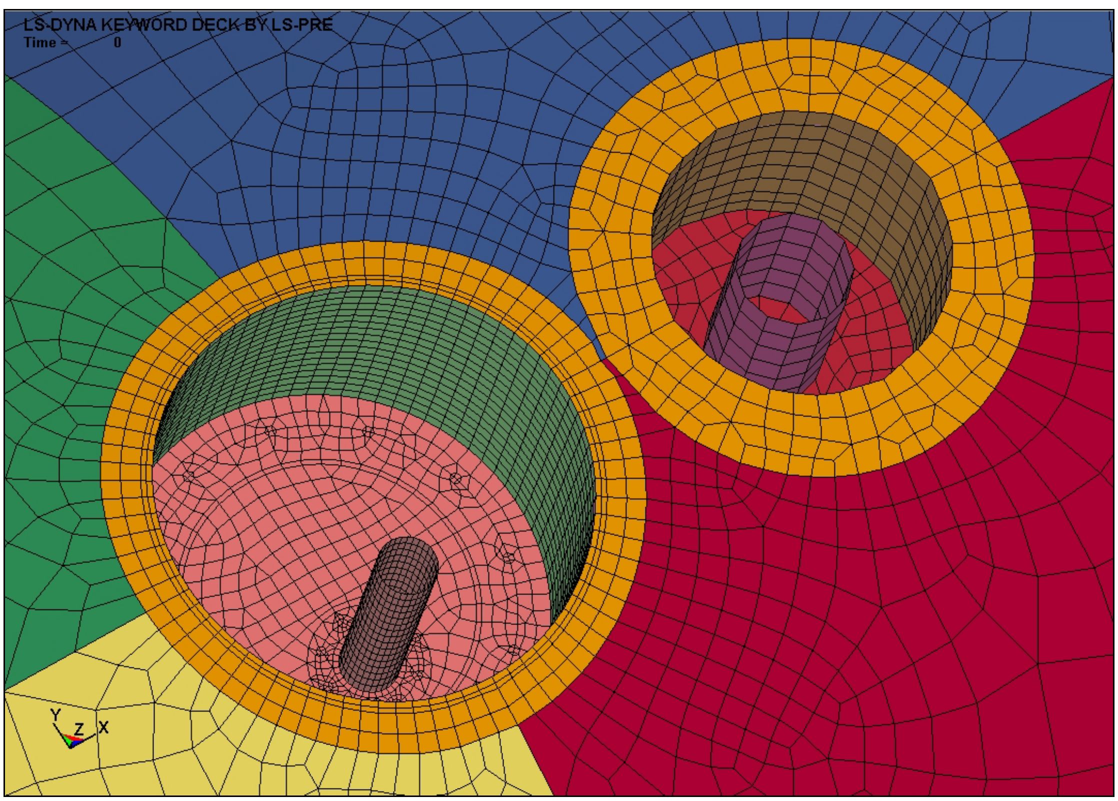

Figure 28. Recessed Fittings Detail

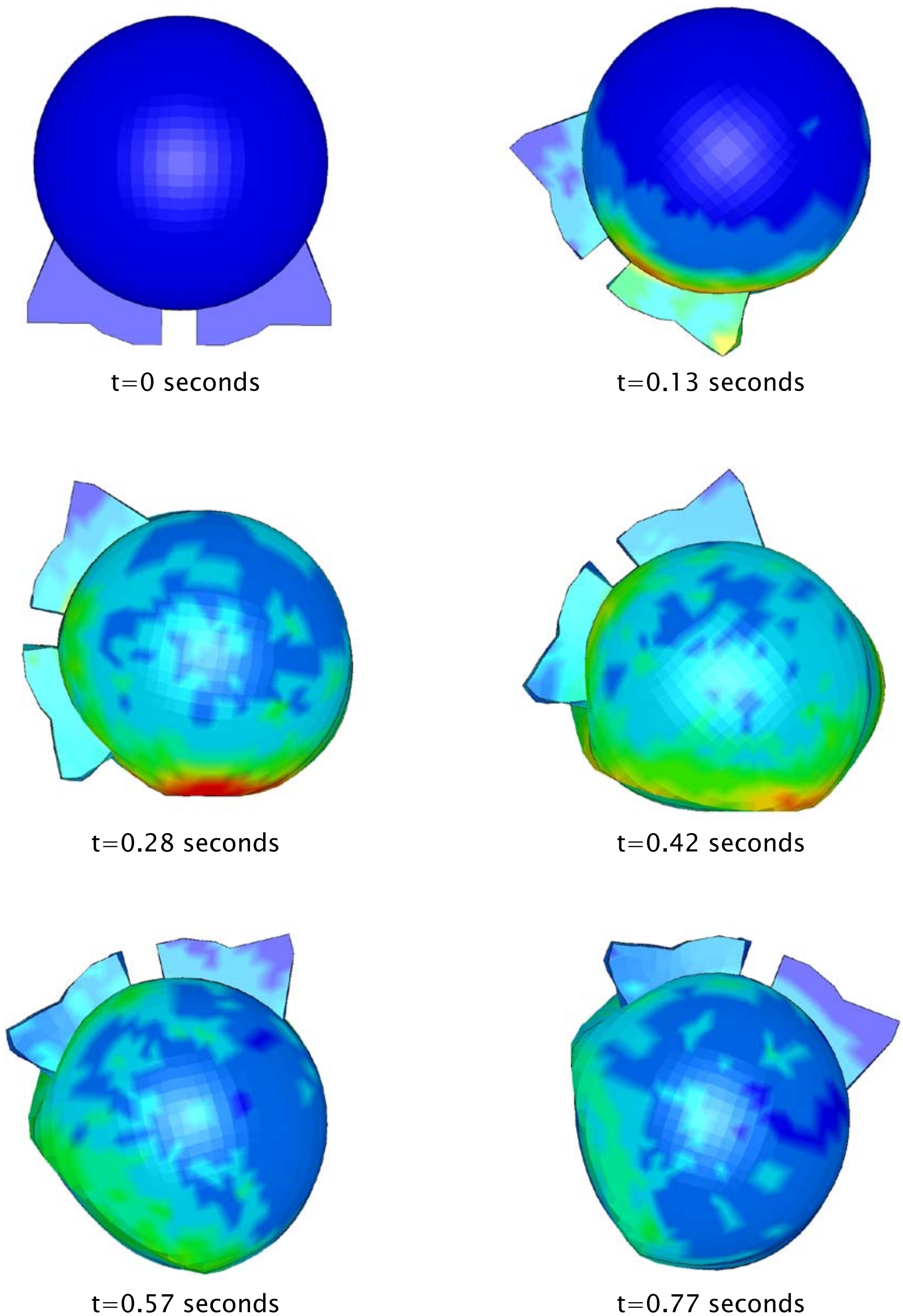

Figure 29. Simulation Sequence (Concept 5/Scenario 1)

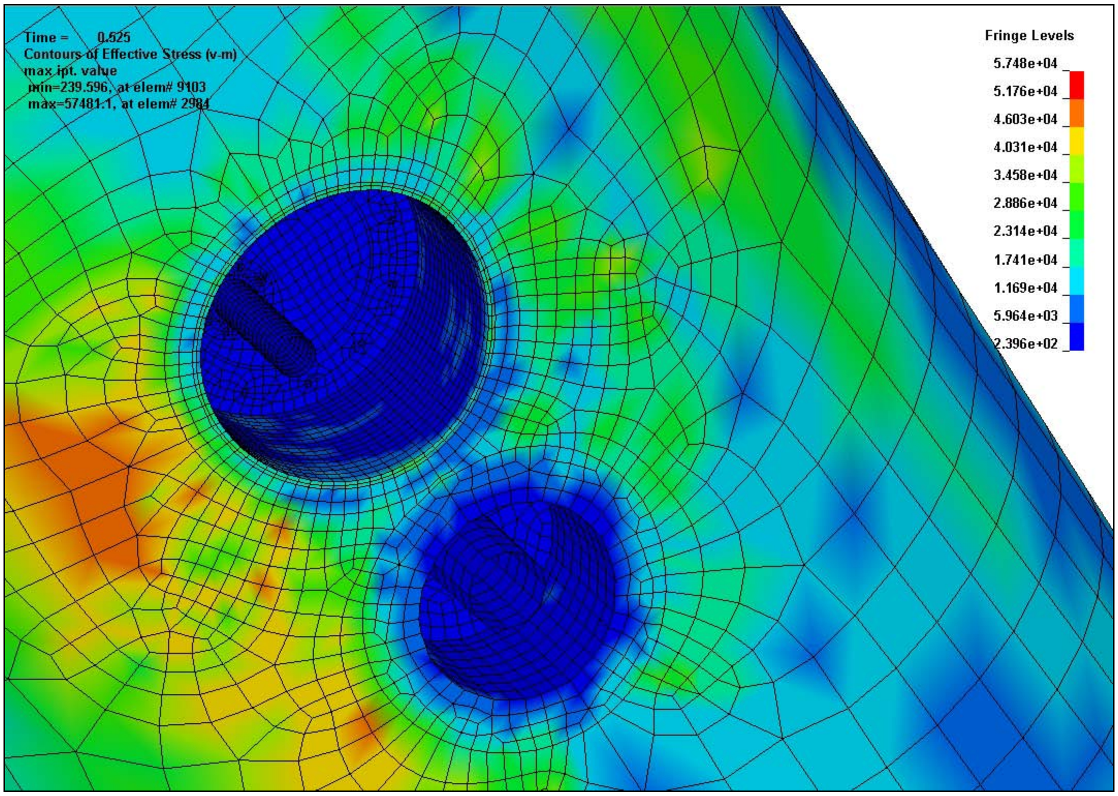

Figure 30. Survival of Concept 5 Fittings (Shown at t=0.53 sec)

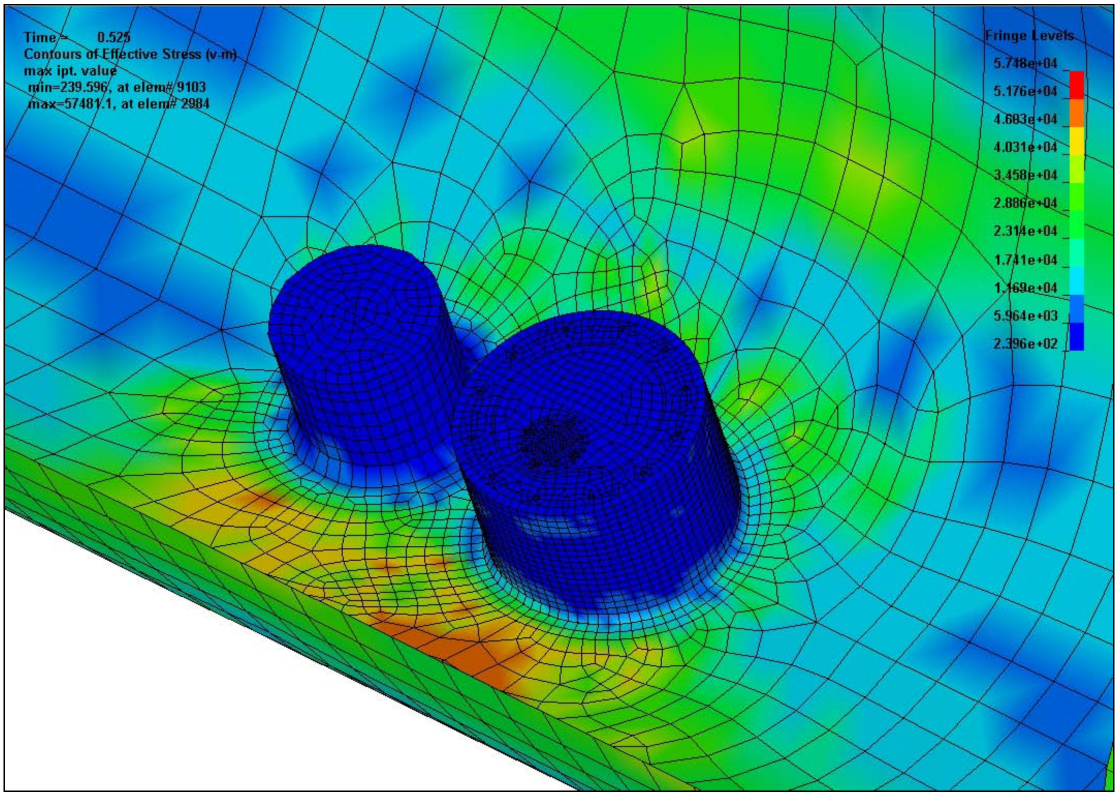

Figure 31. Concept 5 Fittings Shown from Inside Tank (Shown at t=0.53 sec)

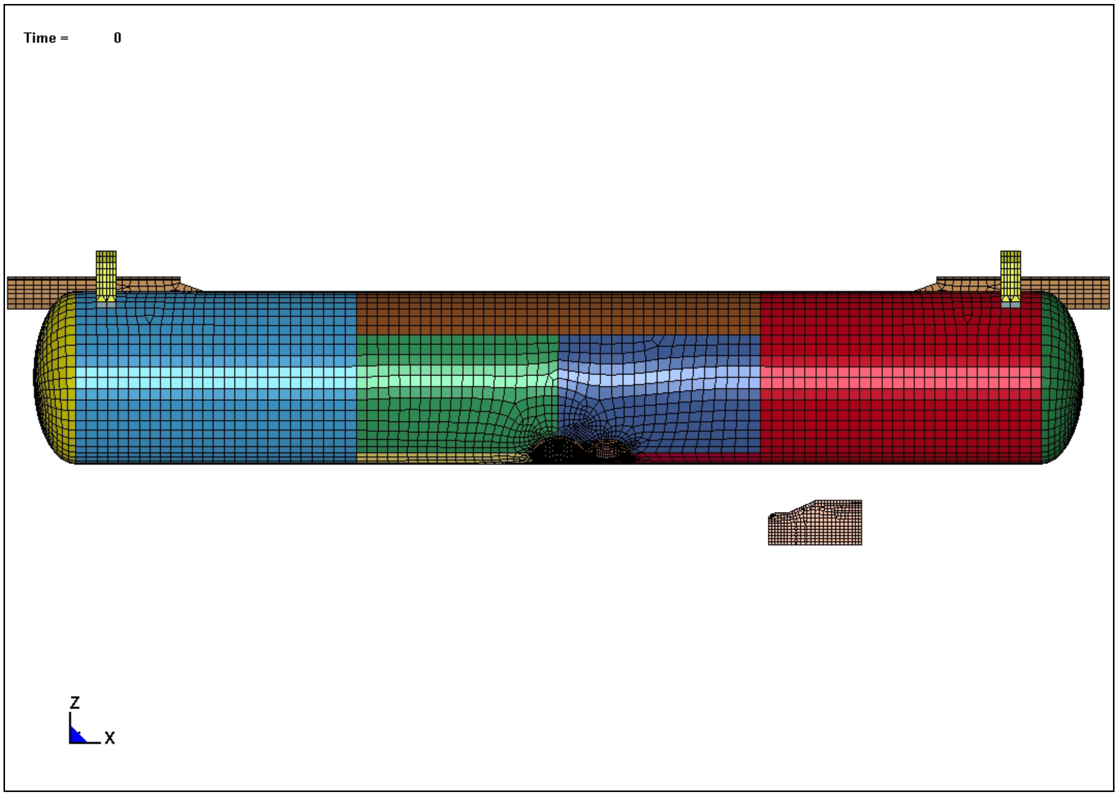

Figure 32. Recessed Fittings Model (Concept 5/Scenario 3)

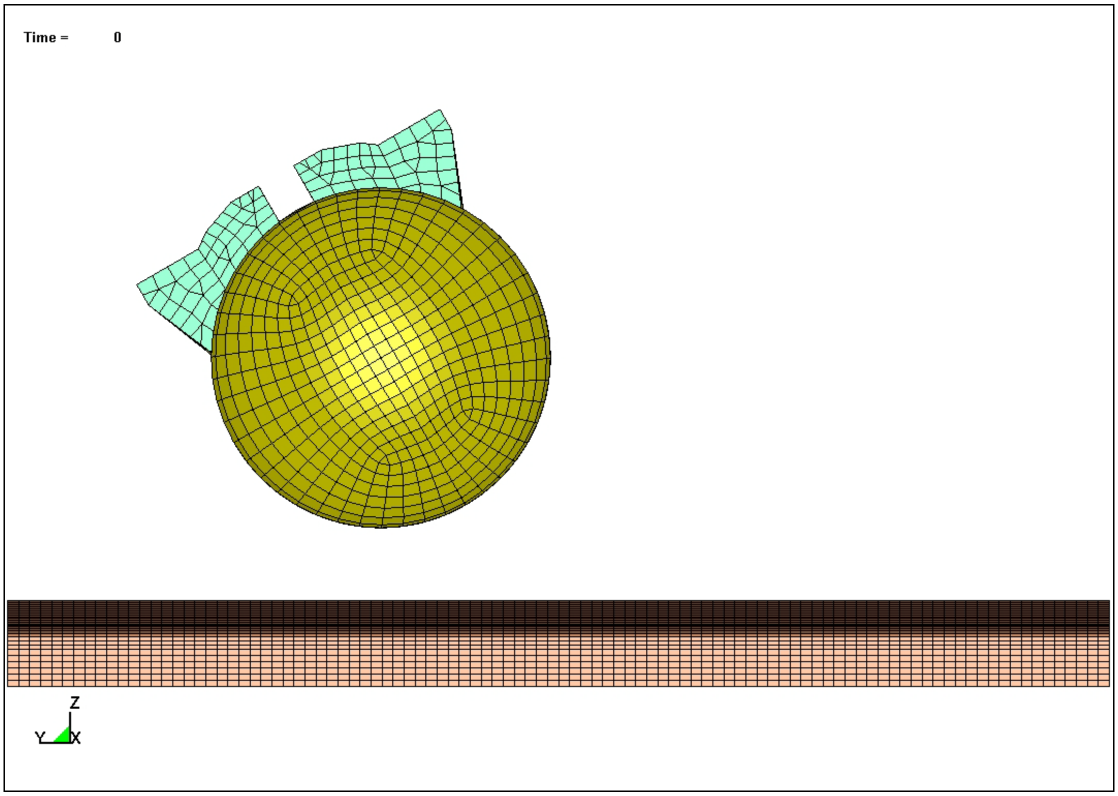

Figure 33. End View of Recessed Fittings Model (Concept 5/Scenario 3)

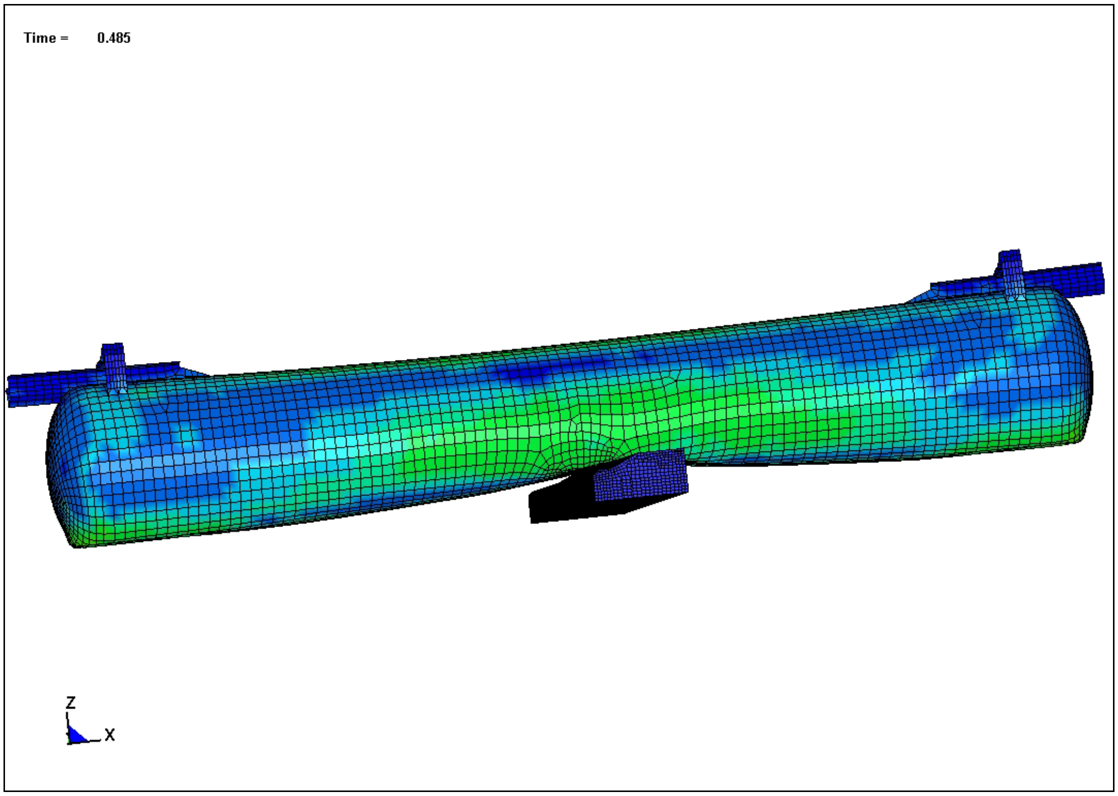

Figure 34. Tank Impacting Concrete Barrier (Concept 5/Scenario 3)

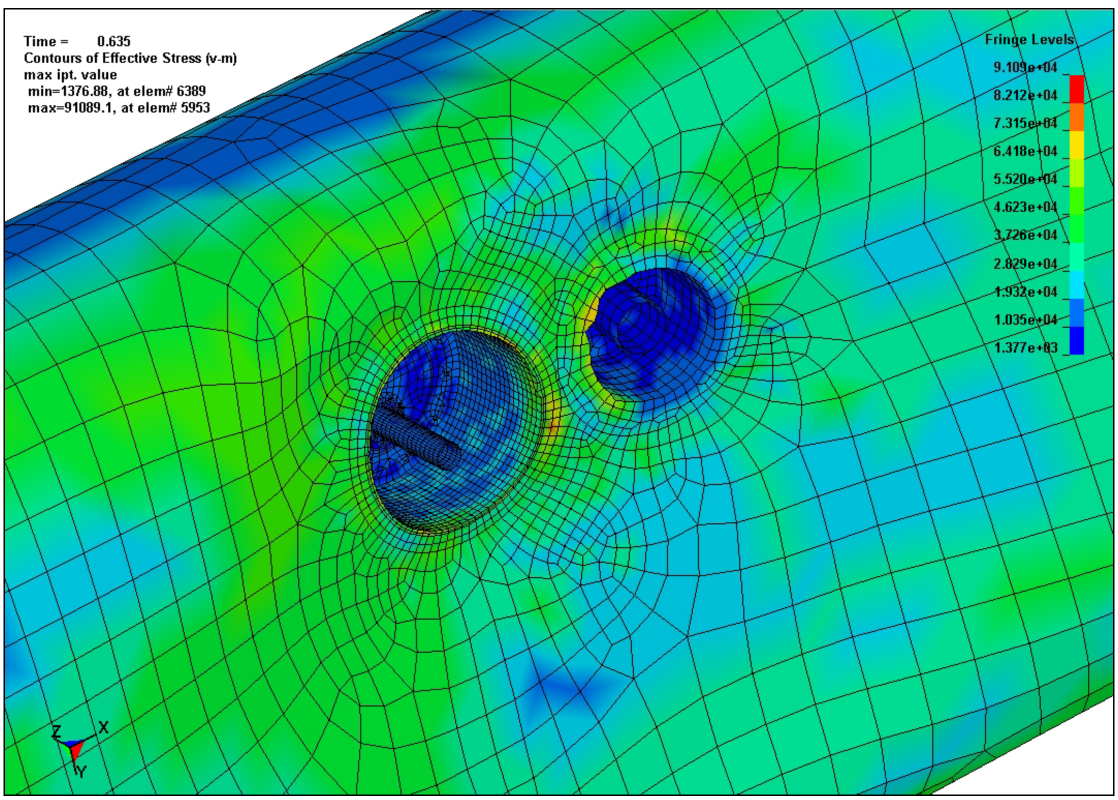

Figure 35. Survival of Fittings (Concept 5/Scenario 3)

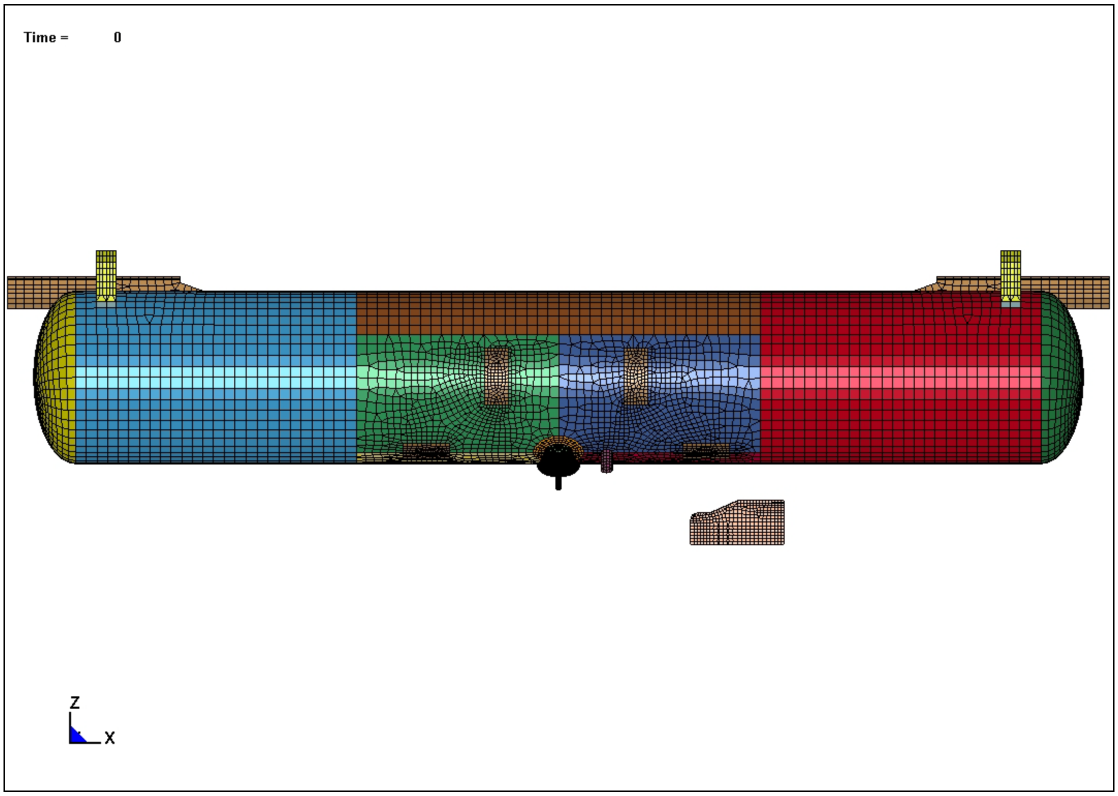

Figure 36. Base Case Model (Side View)

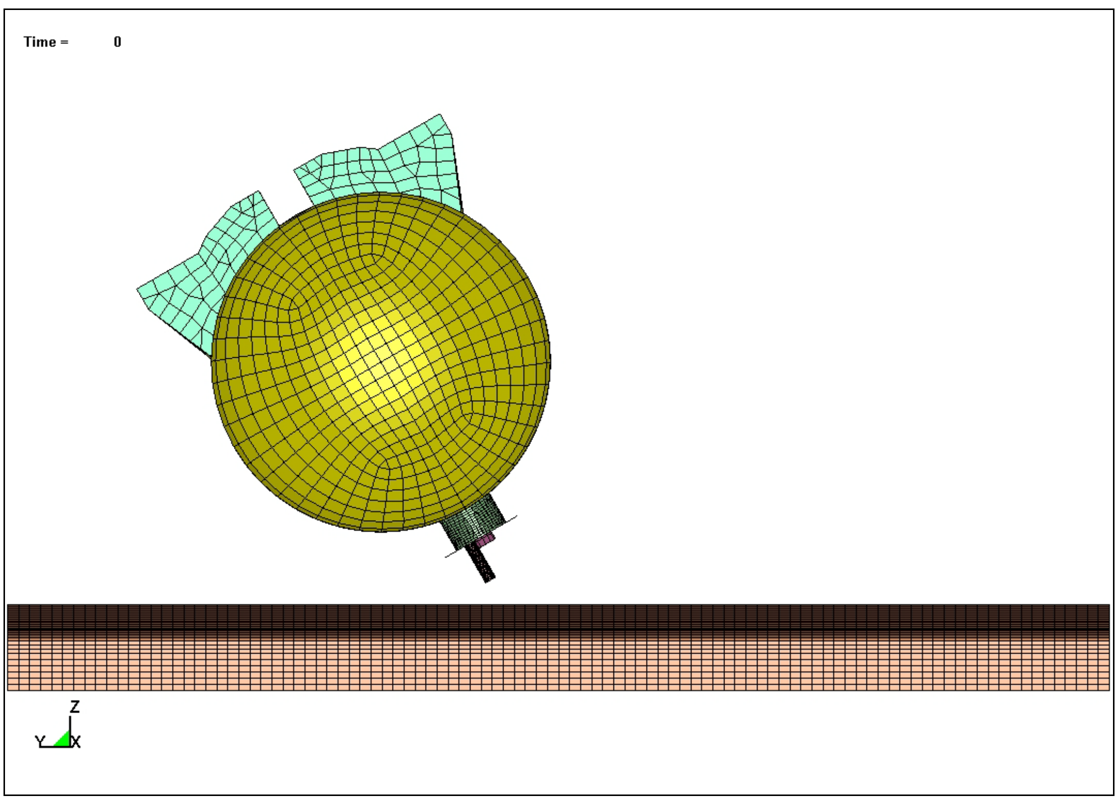

Figure 37. Base Case Model (End View)

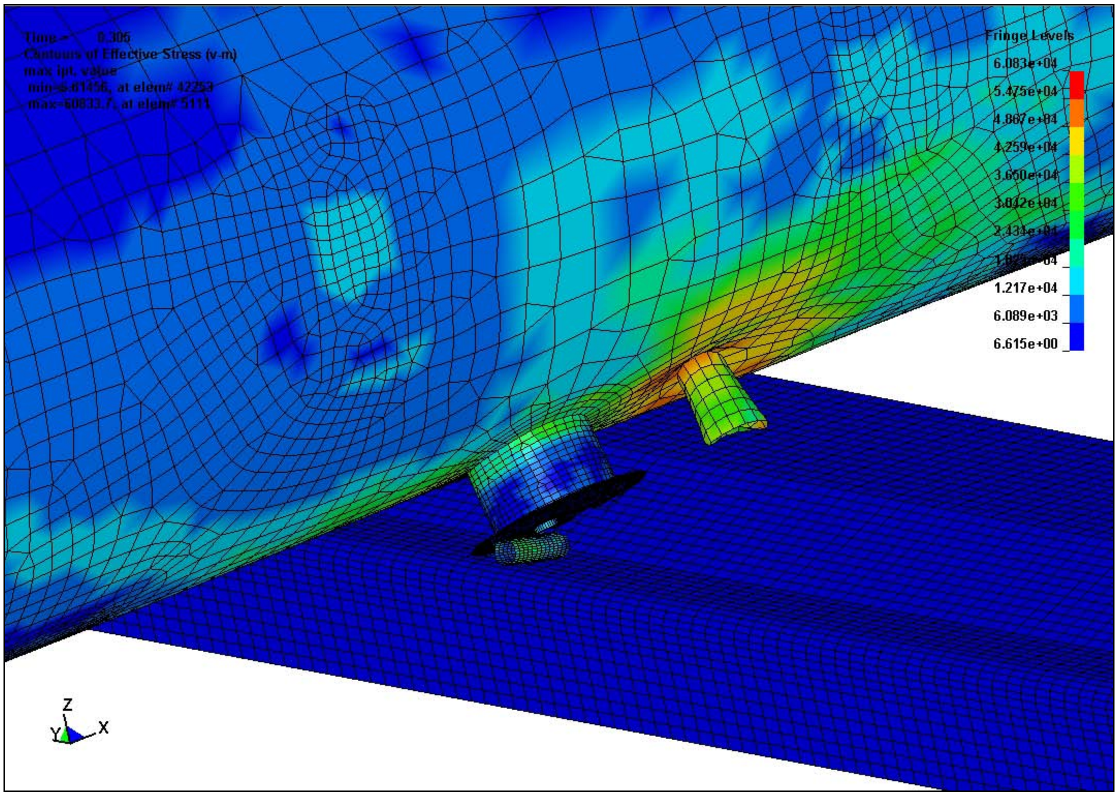

Figure 38. Impact of Fittings on Concrete (Base Case)

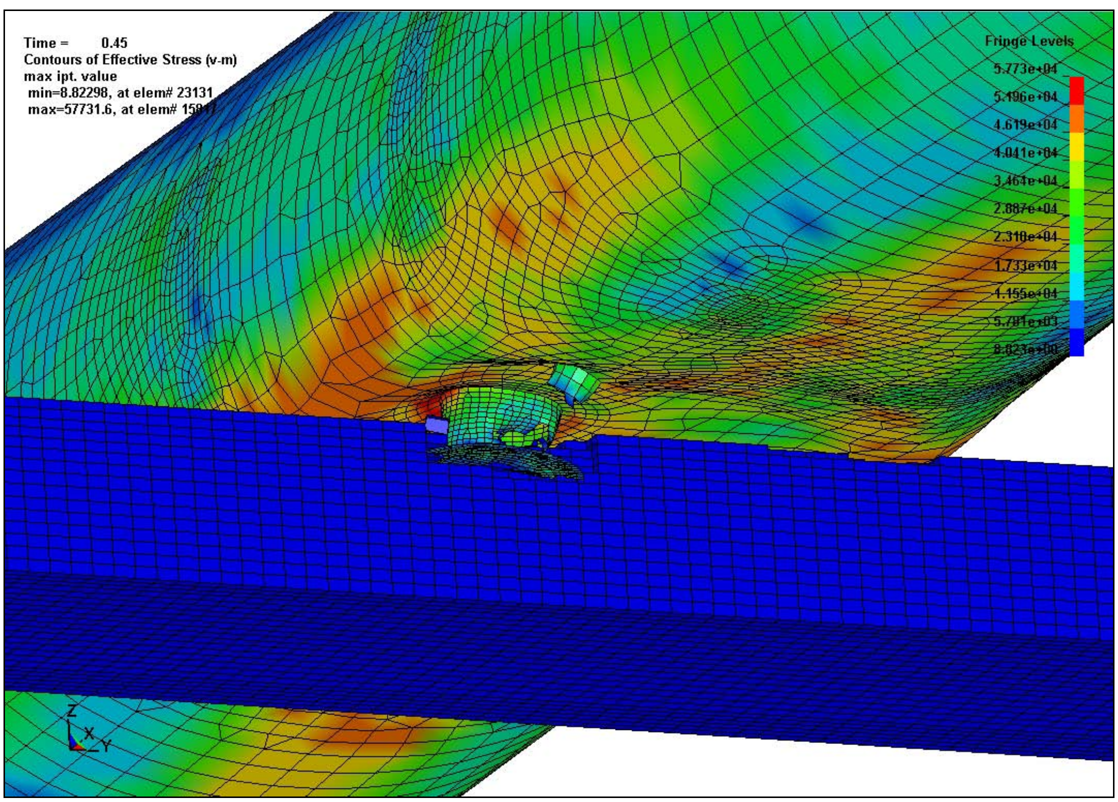

Figure 39. Failure of Fittings on Concrete (Base Case)

5. Summary of Protective Concepts

Three new concepts for protecting the top fittings were investigated.

Concept 3 adds a rollbar assembly to the top of the tank surrounding the fittings arrangements. This structure is designed to allow the car to roll with little resistance (as described in section 4.1). The results of this method show that it will prevent fittings damage in the scenario modeled. This method is suitable for retrofit on existing cars. Concept 3 adds 3,950 lbs about 12 percent less weight than Concept 4.

Concept 4 incorporates a fabricated deflective top skid attached to the tank top surrounding the top fittings arrangement. The TC-128 steel version of this skid succeeds in protecting the fittings from failure albeit with some material failure and large deflection on the skid itself.
A T-1 steel version protects the fittings with no material failure of the skid. This concept adds about 4,500 lbs as modeled to the car weight.

Finally, Concept 5, recesses the fittings into the tank. This concept proves to be a very effective method of protecting the fittings from damage. This method adds only a few relatively small structural parts to the original tank design and adds very little weight to the car. This concept offers the greatest protection because the fittings have little chance of impacting any object during a car rollover. For Scenario 3 (directly impacting a concrete barrier), the specific design in this study produced high stresses in the tank shell in the area between the two cutouts for the recessions. This area should be reinforced if this type of geometry is used. Alternatively, one large recession could be used, which incorporates the unloading appurtenances and the safety valve. For Scenario 3, peak stresses (around 100 ksi) near the inner diameter of the tank shell reinforcing discs require the use of a high strength steel such as T-1 used in this study.

6. Static Evaluation of Protective Structure

The results of this study may assist in the general design of top fittings protective structure, those different than presented here, by providing static loads to failure of the concepts explored in this study. Because the concepts studied in this report succeed in protecting the fittings in the scenarios presented, it was desired to obtain a benchmark of their strength in a way that can be used as a guide for the design of other structures.

Concept 3 (rollbar assembly) was selected for static stress analysis. This analysis was performed using the finite element analysis tool ANSYS® to determine static loadings which resulted in failure of the structure. Nonlinear material properties were used to represent yielding and ultimate failure. Separate analyses were performed for the lateral, longitudinal, and vertical load cases. For each case, increasing load steps in 50 kip increments were applied until failure of the protective structures. In all cases, the tank carbody was constrained using two rings of nodes around the tank circumference, each located 15 ft from the car center as shown in Figure 40. These locations (⅓ points) were selected to approximate the effect of the tank body being unsupported just prior to impact. AAR Manual of Standards and Recommended Practices, M-1002, Appendix E10 was used as a guide for the application of load distribution.

The horizontal loads for the lateral case were applied along the centerlines of both elliptical tubes. This load was uniformly distributed for a height of 22 in. The lower point of the load distribution was 16 in below the top of the tank shell at the car longitudinal centerline (see Figure 40).

The horizontal loads for the longitudinal case were applied along the center of the leading longitudinal tube and along a portion of the leading transverse tube. The load was uniformly distributed for a length of 16 in along the longitudinal tube starting at 8 in above the tank top centerline and for 47 in along the leading transverse tube centered about the longitudinal centerline (Figure 41).

The loads for the vertical case were uniformly distributed and applied to nodes on the lateral tubes for a distance of 12 in each side of center as shown in Figure 42.

A reference case using the bonnet sleeve type protection similar to the phase 1 study was evaluated for comparison. The sleeve was specified with ASTM A 516 Gr. 70 steel. Lateral and longitudinal cases were analyzed. The vertical case was not analyzed since the force vectors would have been parallel with the shell mesh of the bonnet sleeve; a condition not solvable in ANSYS®. Loads for the lateral and longitudinal cases are shown in Figures 43 and 44, respectively.

Table 1 below shows the results of the static analysis and also includes a column showing the maximum load seen in the LS-DYNA3D simulations for each case.

In all the rollbar cases, the maximum filtered loads seen in the dynamic simulations are less than the ultimate loads determined from the static analysis. This is expected because the protective structures (Concept 3 and Concept 4) did not experience failure in the dynamic simulations. The resulting loads at ultimate failure for the protective structure, shown in Table 1, are very close to the loads at which the tank shell steel sheets experience ultimate failure as a result of this same loading on the protective structure (reference columns 4 and 5 of table 1). This was observed in the FEA post-processor. This indicates that the rollbar protective structure as designed in this study has appropriate stiffness and strength relative to the tank shell.

The results of the reference case show much lower strength for the bonnet-tank shell system than that obtained for the rollbar-tank shell system. For example, the tank shell in the bonnet longitudinal case fails at 335 ksi versus 1440 ksi in the rollbar longitudinal case. This is a result of the more concentrated stress resulting from the force applied to the compact bonnet-type protection.

During the lateral reference case, the tank shell continued to deflect as the load was applied to the bonnet sleeve. No failure in the bonnet was reached as a result.

Table 1. Static FEA Results

CONCEPT	***LOAD CASE***	***LOAD AT YIELD (KIPS)***	***LOAD AT FAILURE (KIPS)***	***LOAD AT TANK SHELL FAILURE (KIPS)***	***MAX LOAD SEEN IN DYNA SIMULATIONS (KIPS)***
Rollbar	Lateral	640	1240	1280	600
	Longitudinal	1200	1440	1440	270
	Vertical	950	2460	2600	286
Reference Case	Lateral	82	No Fail	174	Not available
	Longitudinal	91	303	335	Not available

The data in Table 1 shows that the ultimate load-based strength for the rollbar structure studied in this report is about 2 to 8 times higher, depending on the case, than the maximum force seen on the protective structure alone in the dynamics simulations. Therefore, when designing alternative, but similar protective structures for top fittings for scenarios studied in this report, the static load magnitudes reported in Table 1 (column 4) could provide preliminary minimum design loads. Protective structures designed with a minimum static load-based strength corresponding to the levels shown in Table 1 would likely protect the top fittings in rollover derailment scenarios at least as severe as those presented in this report, and possibly in even more severe rollovers if the strength of the tank shell itself is increased.

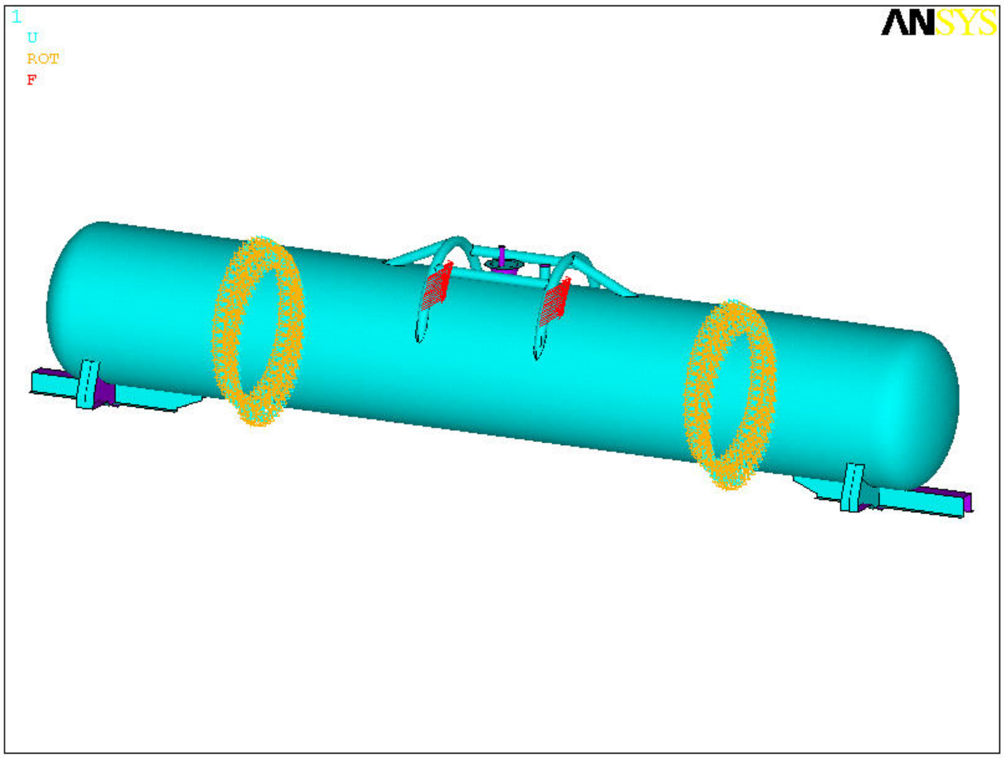

Figure 40. Constraints and Lateral Case Force Vectors

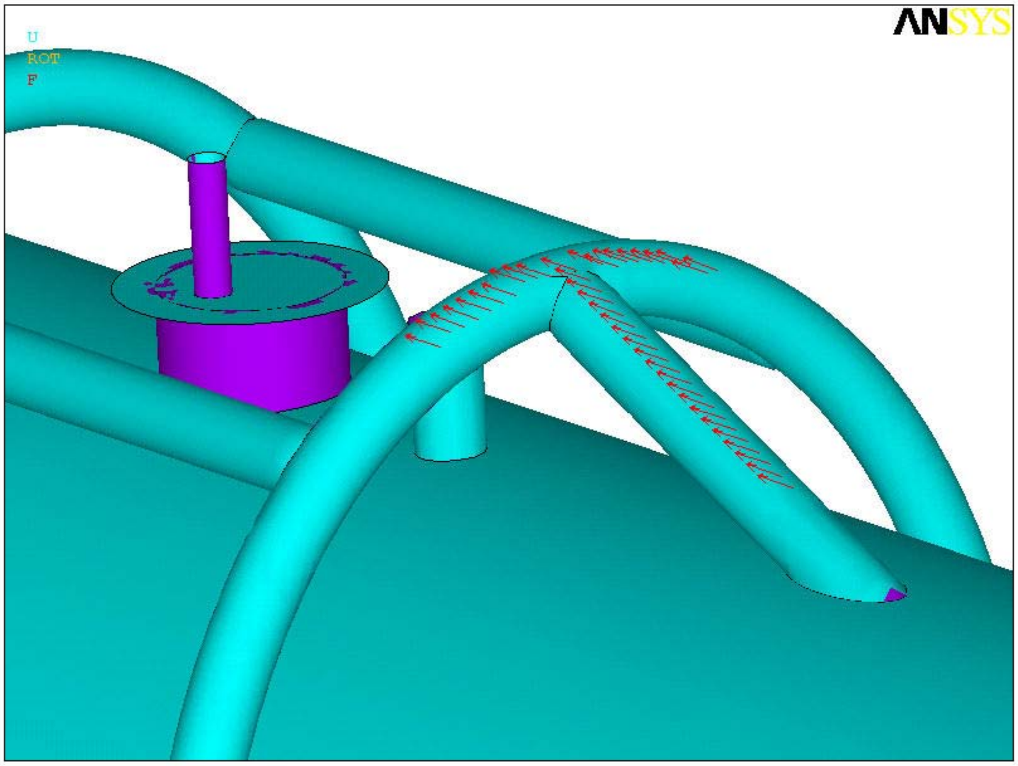

Figure 41. Longitudinal Case Force Vectors

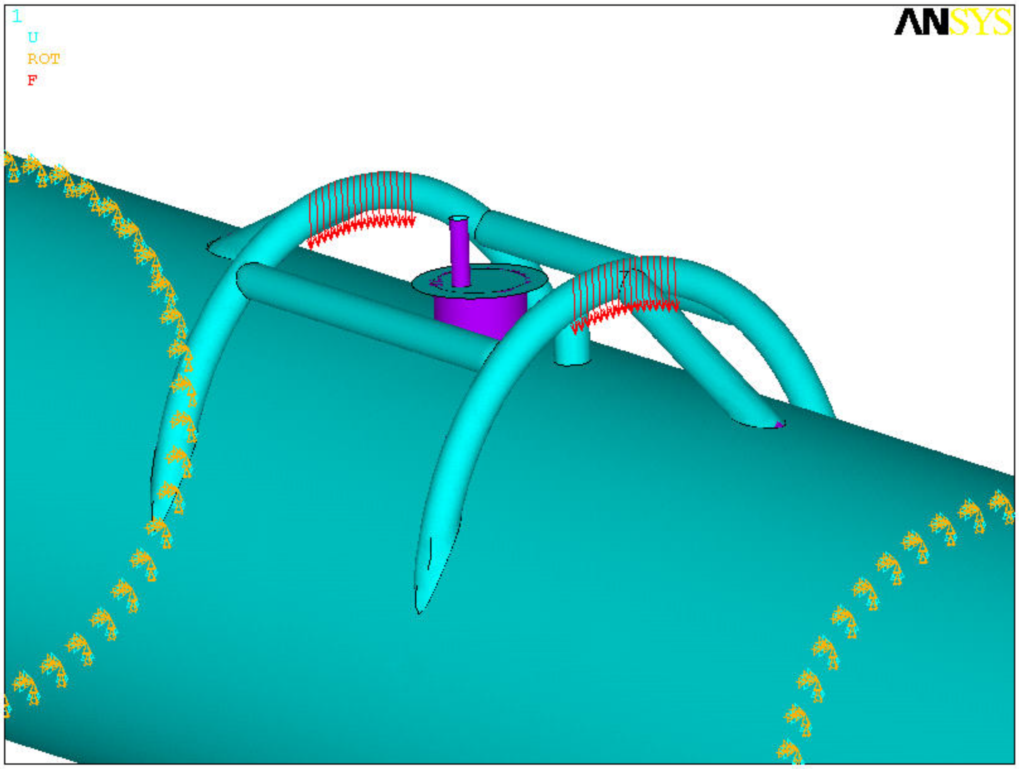

Figure 42. Vertical Case Force Vectors

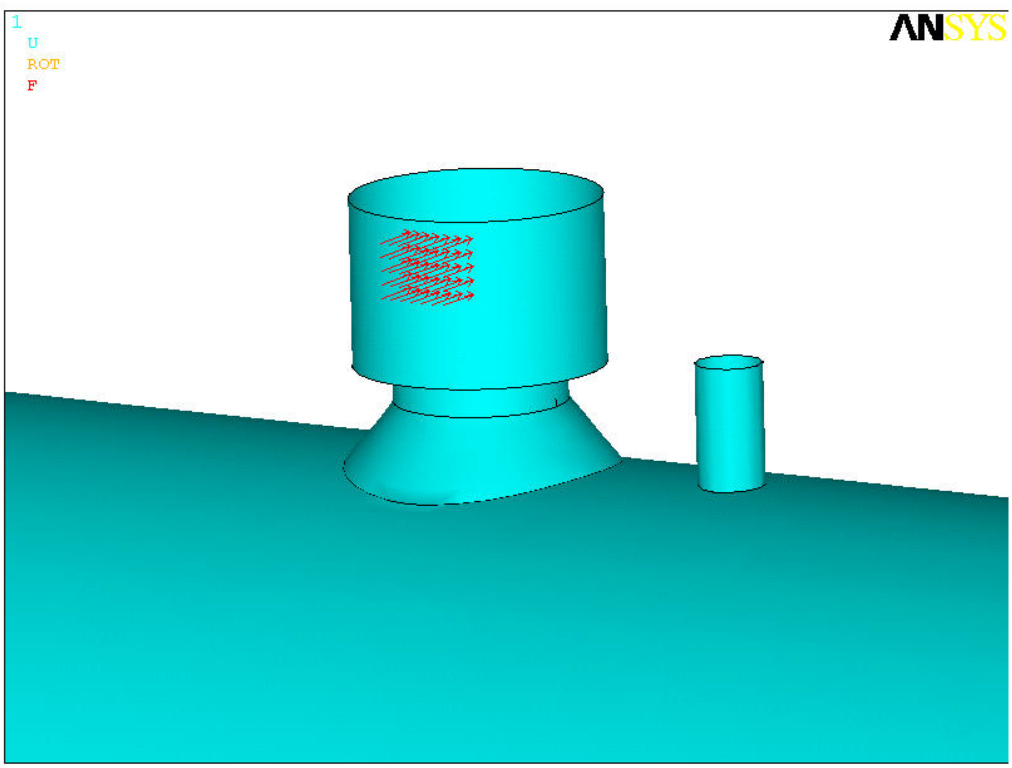

Figure 43. Reference Case Lateral Force Vectors

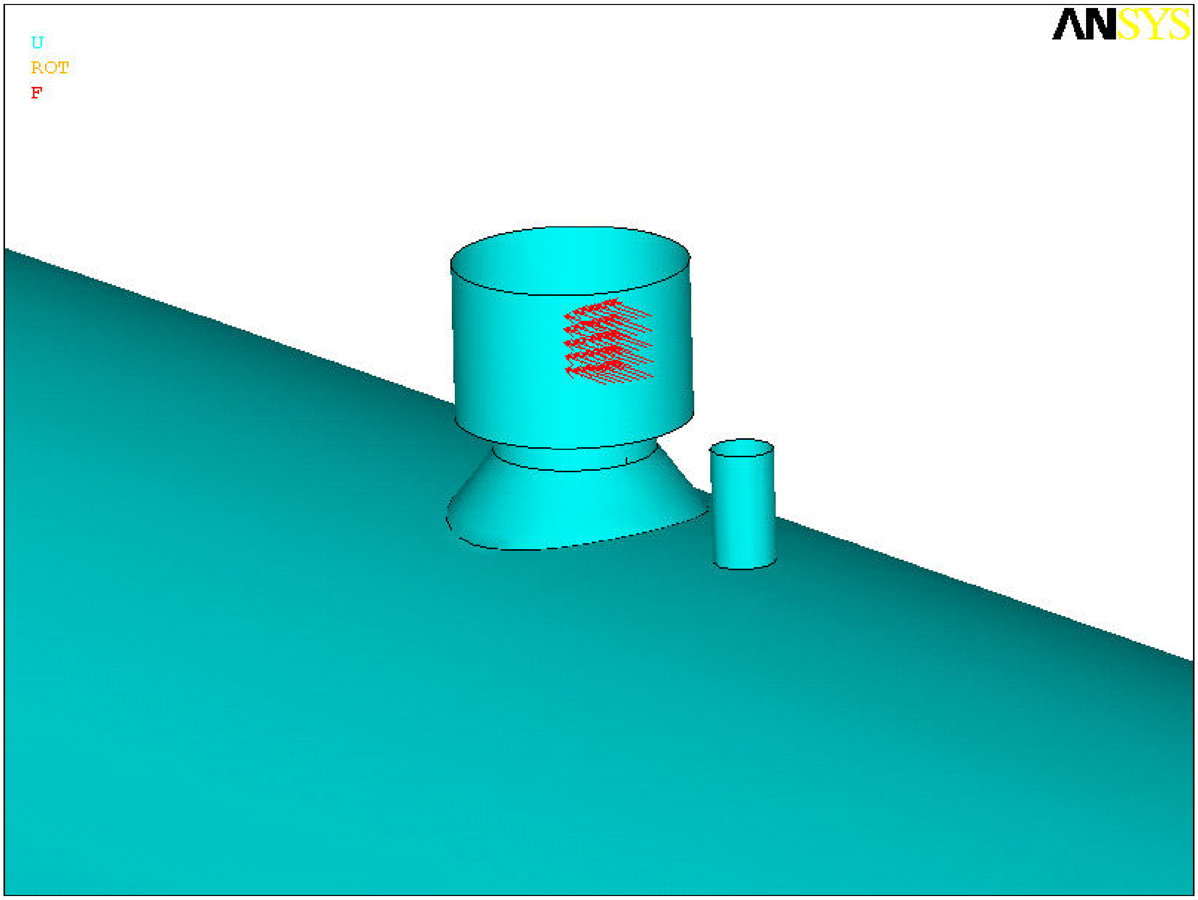

Figure 44. Reference Case Longitudinal Force Vectors

7. Conclusion

In Phase 2 of this study, three new concepts for protecting tank car top fittings were developed with the goal to better protect the fittings in severe rollover scenarios than was possible with the Phase 1 concepts. These new concepts were analyzed for their effectiveness in both the severe dynamic rollover scenario of the Phase 1 study (Scenario 1) and an additional scenario involving longitudinal velocity of the car and impact with a concrete barrier (Scenario 3).

The results of this analysis show:

1. The rollbar assembly (Concept 3) succeeds in protecting the top fittings in Scenario 1 and Scenario 3.

2. The skid assembly (Concept 4) succeeds in protecting the top fittings in Scenario 1 and Scenario 3.

3. The recessed fittings (Concept 5) succeed in protecting the top fittings in Scenario 1 and Scenario 3.

4. The unprotected fittings (base case) are destroyed in Scenario 3 with a significant lading release resulting.

8. Recommendations

The following presents recommendations based from this study:

1. This report recommends, for further investigation, modeling the systems of protection in the more probable case of a rollover into softer impact surfaces such as common soil types.

2. This report also recommends that the Federal Railroad Administration consider the study of optimizing the designs presented in this report for weight reduction, economy, and usability with existing loading and unloading facilities and for manned operation of the fittings in service.

3. This report also recommends, for further investigation, performing full-scale static strength and full-scale dynamic impact testing of the protective concepts studied in this report for validation.

Appendix A
FRA and AAR Document Summary

AAR M-1002 Appendix E9

This document describes requirements for protection of bottom discontinuities on stub sill equipped pressure tank cars. It includes structural requirements for the protective skid, the skid to tank interface, and material requirements. It also includes design requirements for break-off points in the discontinuities that extend beyond the protective skid and other requirements.

AAR M-1002 APPENDIX E10

This document describes the requirements for protection of bottom and top discontinuities on stub sill equipped non-pressure tank cars. It includes structural requirements for the protective skid, the skid to tank interface, and material requirements. It also includes design requirements for break-off points in the discontinuities that extend beyond the protective skid and other requirements. Requirements in this specification are somewhat less restricting regarding bottom protection than that of Appendix E9. This specification covers top protection of fittings including design loads (2W vertical and 1W horizontal in any direction). The protection can be either a pressure car type protective housing or a skid type structure. In either case the device must withstand the design loads without exceeding the allowable stresses. No factor of safety is specified.

49 CFR 179.100-12

This document outlines the required materials and dimensions of the manway nozzle, cover, and protective housing for pressure tank cars. The protective housing must be cast, forged, or fabricated out of approved material and be bolted to the manway cover with not less than twenty ¾-in studs. The shearing value of the bolts attaching the protective housing to manway cover must not exceed 70 percent of the shearing value of bolts attaching manway cover to manway nozzle. The protective housing must have steel sidewalls not less than ¾ in thickness.

49 CFR 178.337-10

This specification is for highway motor vehicle tank trailers and describes DOT requirements for collision damage protection. For protective devices of fittings, this specification states that the device and its attachment to the tank must withstand static loading in any direction equal to twice the loaded weight of the tank and attachments. A factor of safety of 4 based on the tensile strength of the material must be used. Other requirements are included.

49 CFR 178.337-12

This section specifies that discharge control valves (for highway motor vehicle tank trailers) must be designed with a shear section or breakage groove that would prevent leakage through the valve in the event of a crash or rollover.

Appendix B
Material Data

Table B1. Part Materials by Concept

<table>
<tr><th>ITEM</th><th>BASE CASE</th><th>CONCEPT 3 (Rollbar)</th><th>CONCEPT 4 (Skid)</th><th>CONCEPT 5 (Recessed)</th></tr>
<tr><td>Tank Shell</td><td colspan="4">TC-128 Steel</td></tr>
<tr><td>Tank Shell Reinforcing Discs (at Fittings)</td><td colspan="3">TC-128 Steel</td><td>T-1 Steel</td></tr>
<tr><td>Other Fittings</td><td colspan="4">A516 Gr 70</td></tr>
<tr><td>Rollbar</td><td></td><td>4140 Steel</td><td></td><td></td></tr>
<tr><td>Skid</td><td></td><td></td><td>TC-128 Steel</td><td></td></tr>
<tr><td>Recessed Unloading Nozzle Flue</td><td colspan="3">A516 Gr 70</td><td>T-1 Steel</td></tr>
<tr><td>Recessed Sleeve for Safety Valve</td><td></td><td></td><td></td><td>T-1 Steel</td></tr>
<tr><td>Recessed Base Plate for Safety Valve</td><td></td><td></td><td></td><td>A516 Gr 70</td></tr>
</table>

Table B2. Material Properties

MATERIAL	YIELD STRENGTH (psi)	TANGENT MODULUS (psi)	FAILURE STRAIN	ULTIMATE STRENGTH (psi)
A516 Gr 70 steel	38,000	152381.0	0.21	70,000
T-1 steel	100,000	63816.2	0.16	110,000
4140 steel	70,000	116414	0.26	100,000
TC-128 steel	50,000	164602.0	0.19	81,000

Table B4. Material Thickness by Component (in.)

COMPONENT	CONCEPT 3 (Rollbar)	CONCEPT 4 (Skid)	CONCEPT 5 (Recessed)	BASE CASE (longitudinal)
Tank Shell	0.4375 (7/16)			
Tank Disc Reinf.	0.50 (1/2)			
Nozzle Flue	0.625 (5/8)			
Nozzle Flue Flange	1.25			
Flue Cover	1.00			
Safety Valve	0.4375 (7/16)			
Unloading Valve	0.75			
Rollbar	1.00			
Skid		1.00		
Rec. Un. Nozzle Flue				0.625 (5/8)
Rec. Sleeve Safety V.				1.00
Rec. Base Plate Safety V.				1.00

Appendix C.
Discussion of Velocities and Forces

Force on Ground Surface

Scenario 1

Figures C1 through C3 show the total normal force on the ground rigid wall surface for Scenario 1 as a function of time for Concepts 3, 4 and 5. This data has been filtered using a 20 Hz low pass Butterworth filter. Annotated arrows are shown on the plots indicating major events during the simulation.

For the rollbar model (Concept 3), the total force on the ground reaches a maximum of about 1.2 million lbs during the time interval when the tank shell is in contact with the ground. In scenario 1, the tank shell absorbs the majority of the impact force. A maximum force of about 370,000 lbs is seen later in the simulation when the rollbar structure alone is in contact with the ground surface (see Figure C1).

A somewhat similar curve profile is seen for the skid model (Concept 4) with the maximum force reaching about 2.3 million pounds. Different geometry, a heaver total tank body weight (with the skid structure), along with different dynamics from the altered center of gravity produce the increased force. The abrupt protruding planer surfaces of the skid slam into the ground surface at a higher velocity (compare Figures C11 and C13) than the elliptical profile of the rollbar with its smooth tangential transition.

The ground force for the recessed model shown in Figure C3 shows a maximum normal force of about 840,000 lbs. This lower force seems reasonable since this model lacks the stiff protective structure protruding out of the tank envelope near the impact area existing on Concepts 3 and 4. The force is partially absorbed by the flexibility in the tank shell.

Scenario 3

Figures C4 through C6 show the total normal force on the ground rigid wall surface for scenario 3 as a function of time for Concepts 3, 4 and 5. This data has been filtered using a 20 Hz lowpass Butterworth filter.

Figure C4 shows a maximum normal force on the ground rigid surface of about 1.1 million lbs for Concept 3, which occurs immediately after impact of the rollbar with the concrete barrier. Concept 4 produces a maximum force of about 790,000 lbs (Figure C5) and Concept 5 shows a maximum force of 900,000 lbs, both at impact with the concrete.

Force between Protective Structure and Tank Shell

A section plane card was included in the LS-DYNA3D input deck for the purpose of extracting forces at a plane cutting through the protective structure. This plane, relative to the initial position of the tank carbody, is horizontal and cut just above the tank shell top surface (at tank longitudinal centerline). A local coordinate system that moved with the tank carbody during the simulation was used for this force data output. Figures C7 through C10 show the force output data. This data closely indicates the forces occurring between the protective structure and the tank shell. Force plots on each graph are reported separately for the lateral, vertical and, if appropriate, longitudinal directions. Vertical forces are negative since the tank car is in a top down orientation during impact.

Scenario 1

Figures C7 and C8 cover the rollbar (Concept 3) and the skid (Concept 4) respectively in scenario 1. The longitudinal force is not shown in these plots since it is negligible.

Both the plots for the Rollbar and the skid show similar form and order of magnitude. The significant initial rotational velocity produces a larger lateral force than the vertical force obtained form gravity and the initial vertical velocity.

Scenario 3

Figures C9 and C10 cover the Rollbar (Concept 3) and the skid (Concept 4) respectively in Scenario 3.

Both the plots for the rollbar and the skid show similar form and order of magnitude. In this case the vertical force reaches a value greater than that of the lateral force since the initial rotational velocity is lower for scenario 3 than for scenario 1. The longitudinal force reaches the lowest maximum of the three reported forces. This is the case since the x-direction (longitudinal) velocity of the tank body produces an impact with the ground surface (and concrete) at a much shallower angle than the impact in the lateral and vertical directions. The tank body impacts the ground surface at an orientation (in the lateral-vertical plane) of about 153° from vertical. This results in a maximum lateral force higher than the maximum longitudinal force as reported in the local coordinate system used. Had the tank body impacted in a 180-degree (perfectly top down) orientation, the longitudinal force would be greater than the lateral since a small rotational velocity was used.

Velocity Data

Figures C11 through C18 are velocity plots of select points on the models for referencing impact velocities.

Scenario 1

Figure C11 shows that the rollbar (Concept 3), impacts the ground with a z-direction (normal to ground surface) velocity of 88 in/sec at time t=0.275 s. This impact was near the tangency point of the rollbar attachment to the tank shell.

Figure C12 shows the velocity at the unloading valve extremity (Concept 3) for comparison to other simulations.

Figure C13 displays the velocity over time of a top outer point on the skid model (Concept 4). This point impacts the ground at t= 0.32 s with a velocity normal to the ground of 211 in/s.

Figure C14 shows the velocity of the unloading valve extremity. This curve is almost identical to that of the Concept 3 model verifying the kinematic consistency of the simulations.

Scenario 3

A maximum z direction velocity of 114 in/sec is shown in the plot of Figure C15 for the rollbar (Concept 4). This point was on the lateral bar near the impact location and is the velocity at impact.

Figure C16 shows the x direction (longitudinal) velocity of the rollbar over time. The initial 18 mph (317 in/sec) is seen decaying after impact.

For the skid model, Figure C17 shows the z direction velocity for a point on the skid at the intersection of the lateral and longitudinal plates. A velocity of 97 in/sec occurs at impact with the ground surface.

Figure C18 is x-velocity data for Concept 4 and shows the initial velocity of 18 mph (317 in/s), confirming consistency between simulations.

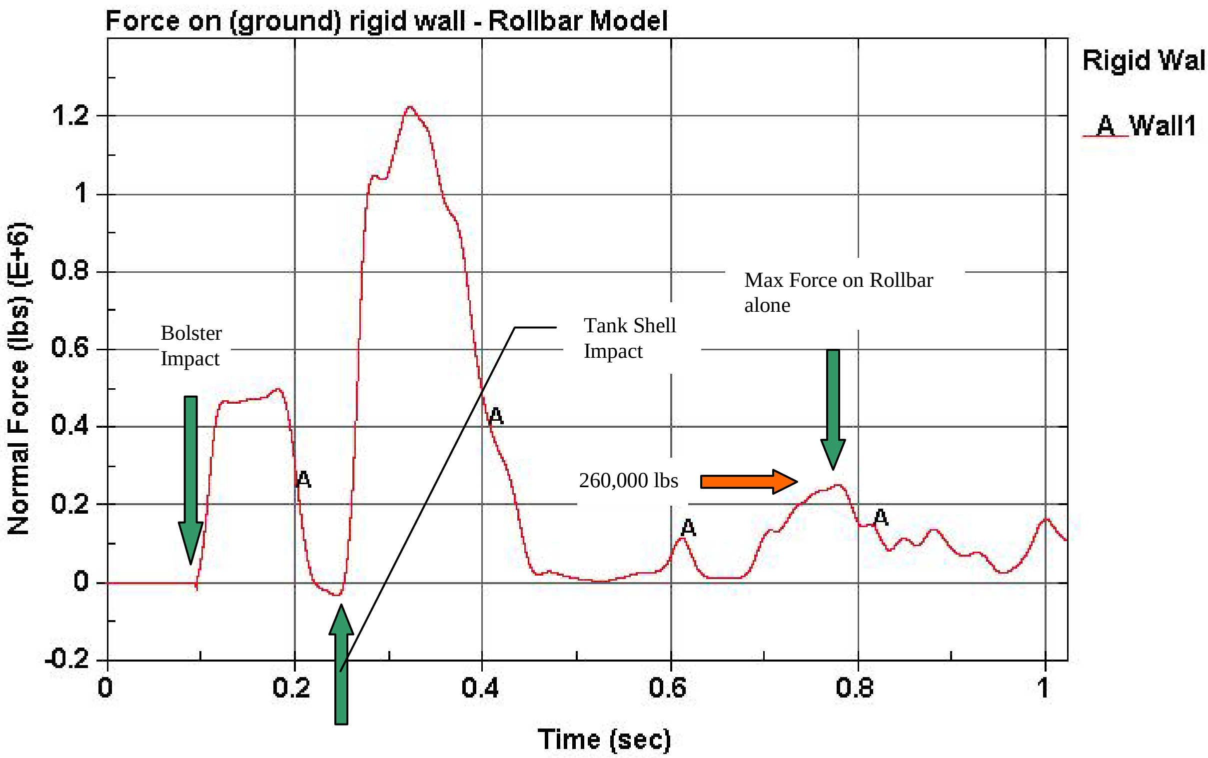

Figure C1. Ground Force – Rollbar Model (Scenario 1)

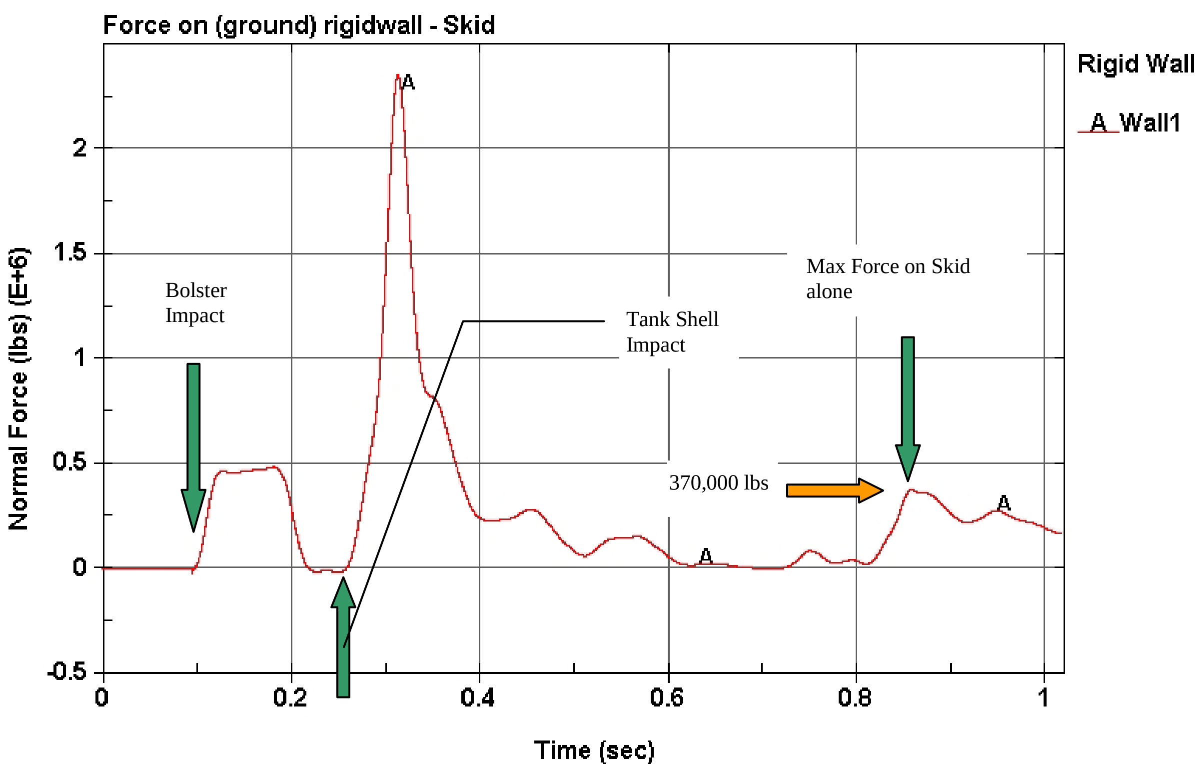

Figure C2. Ground Force—Top Skid Model (Scenario 1)

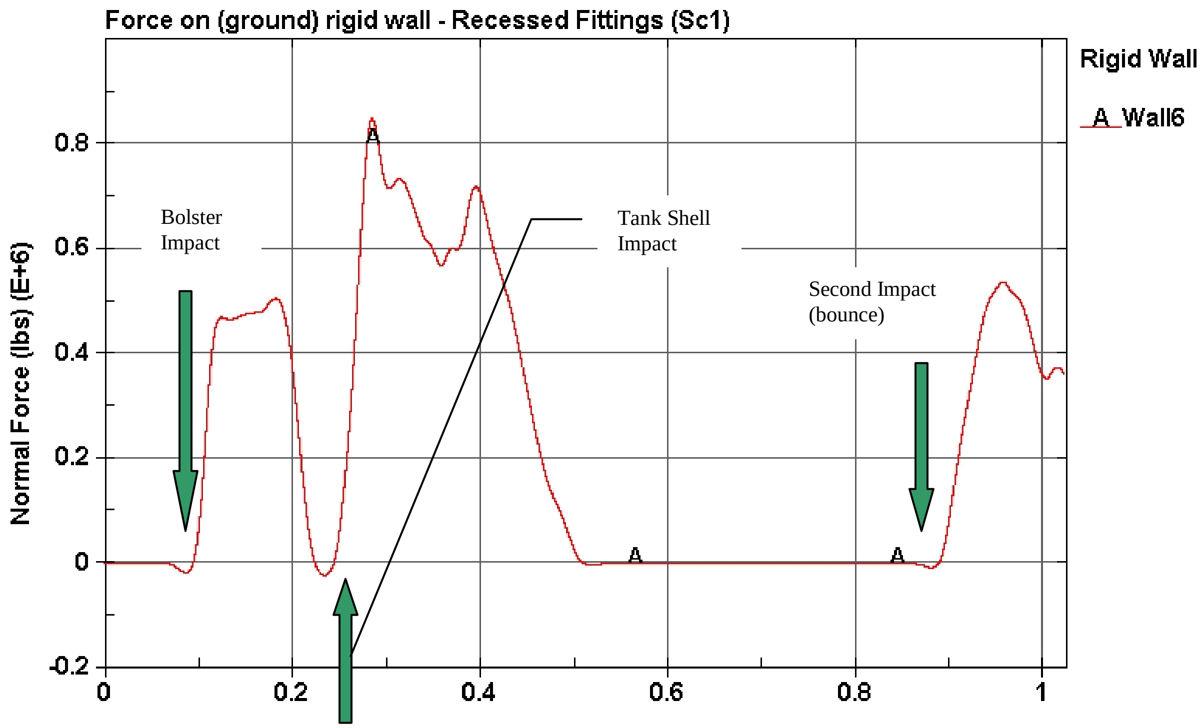

Figure C3. Ground Force—Recessed Fittings Model (Scenario 1)

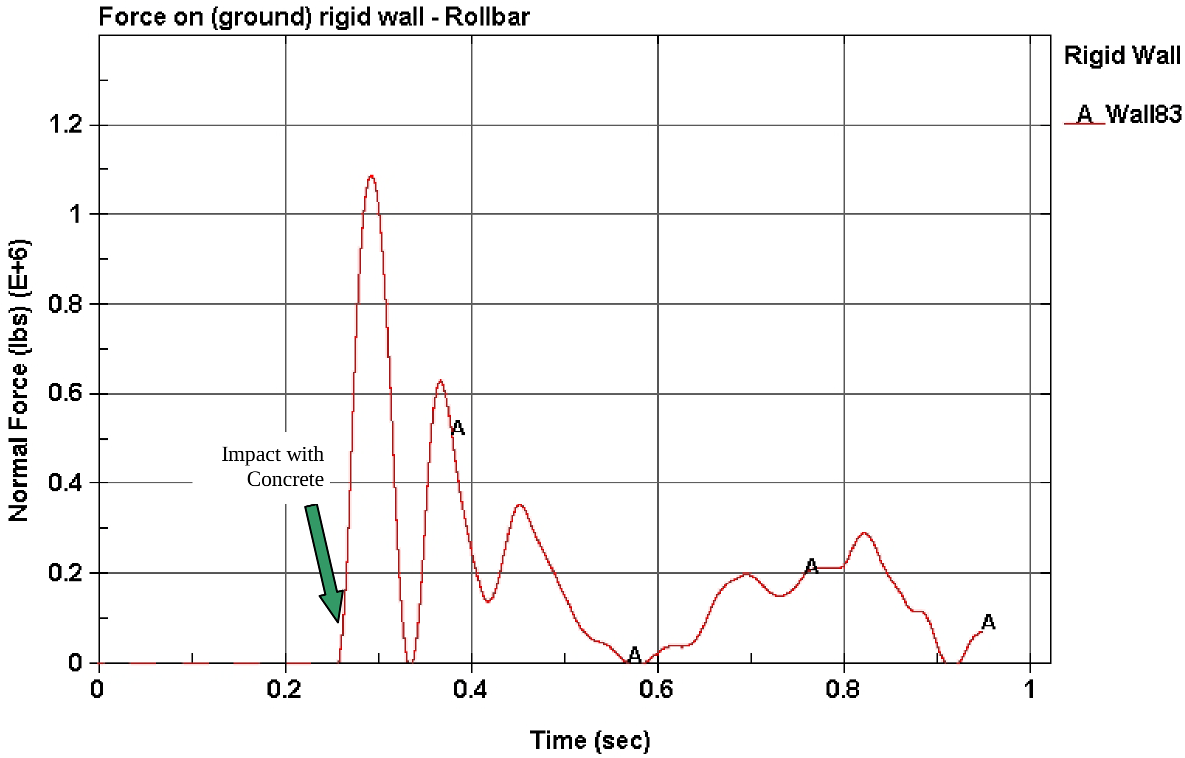

Figure C4. Ground Force—Rollbar Model (Scenario 3)

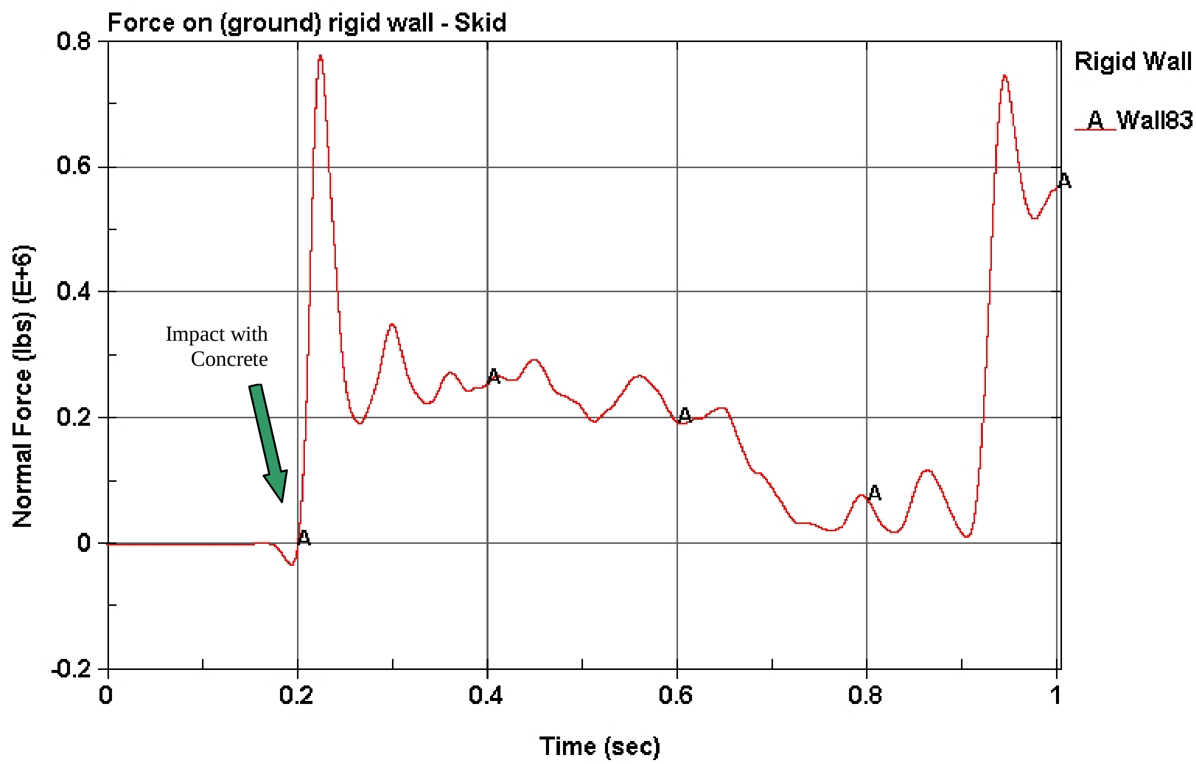

Figure C5. Ground Force—Skid Model (Scenario 3)

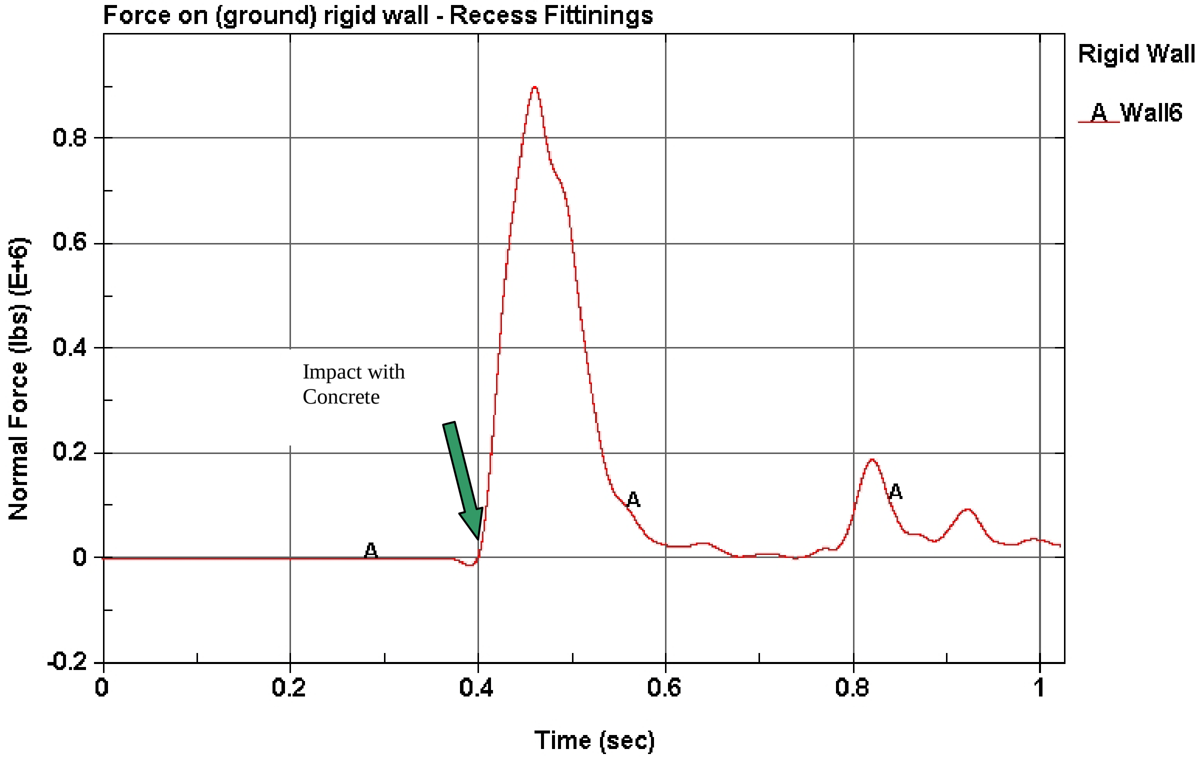

Figure C6. Ground Force—Recessed Fittings Model (Scenario 3)

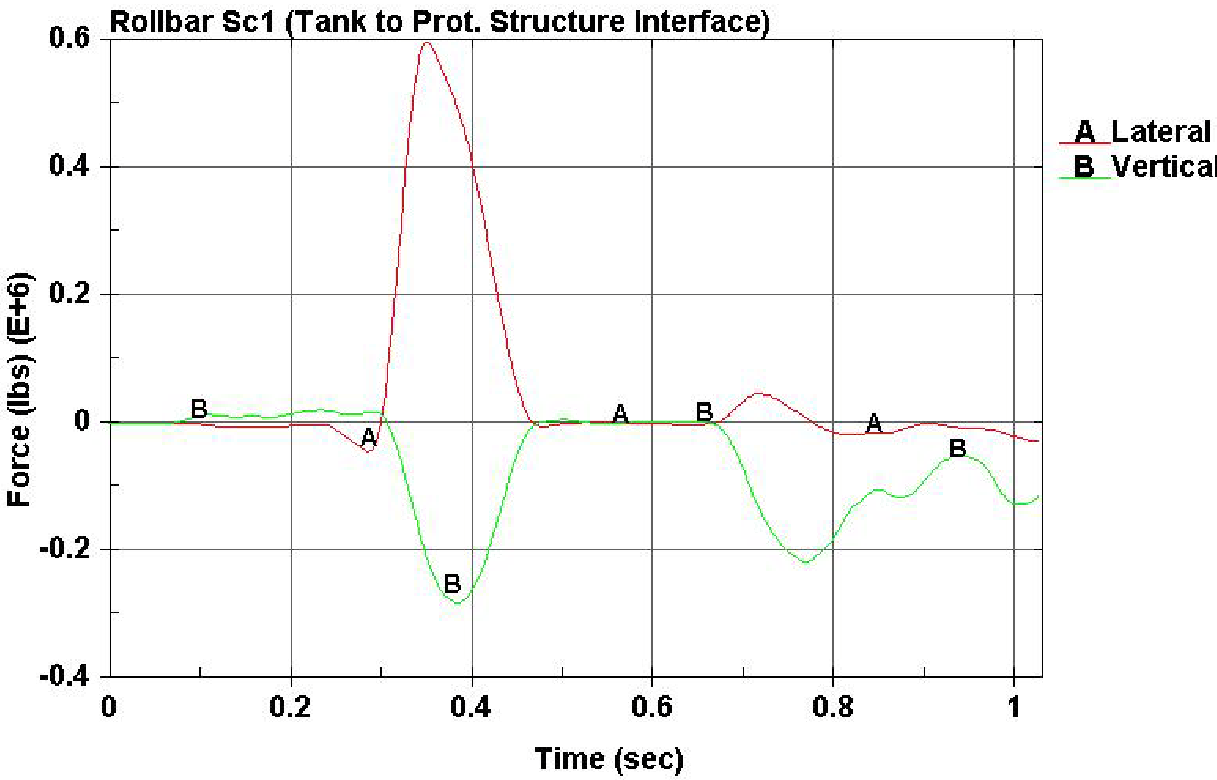

Figure C7. Section Plane Forces near base of Rollbar (Scenario 1)

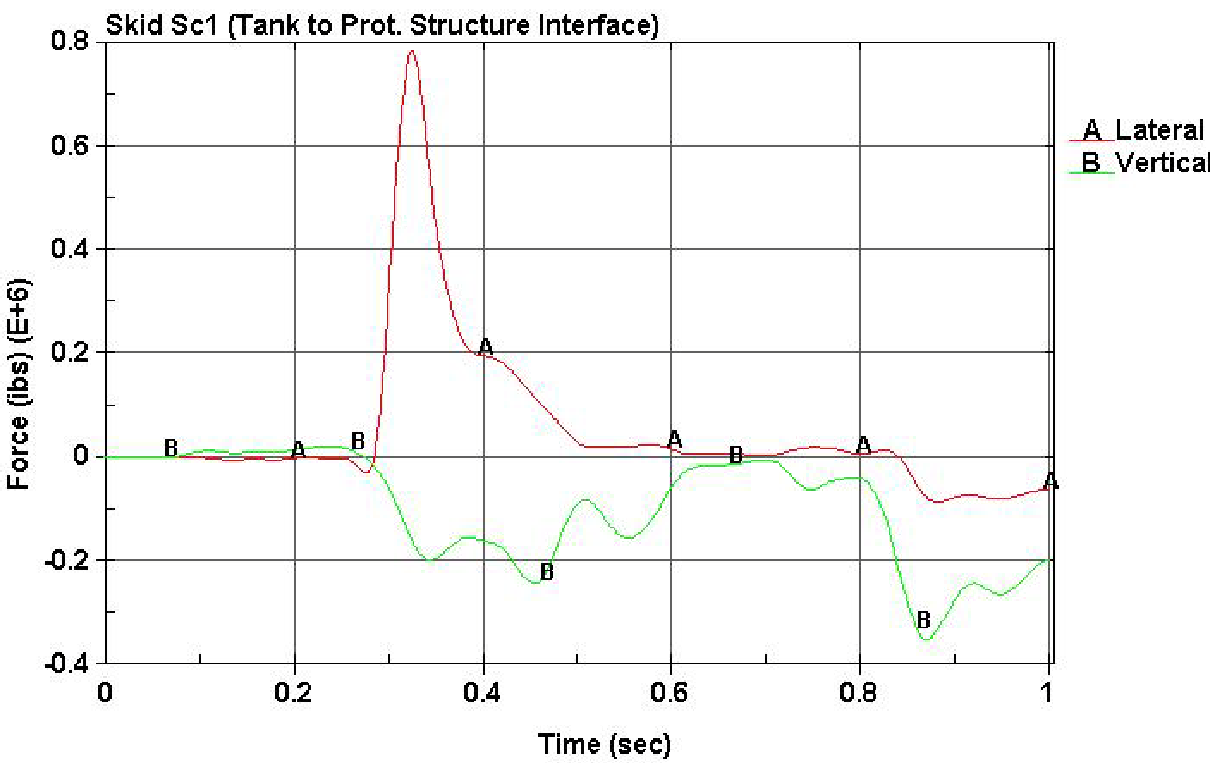

Figure C8. Section Plane Forces near base of Skid (Scenario 1)

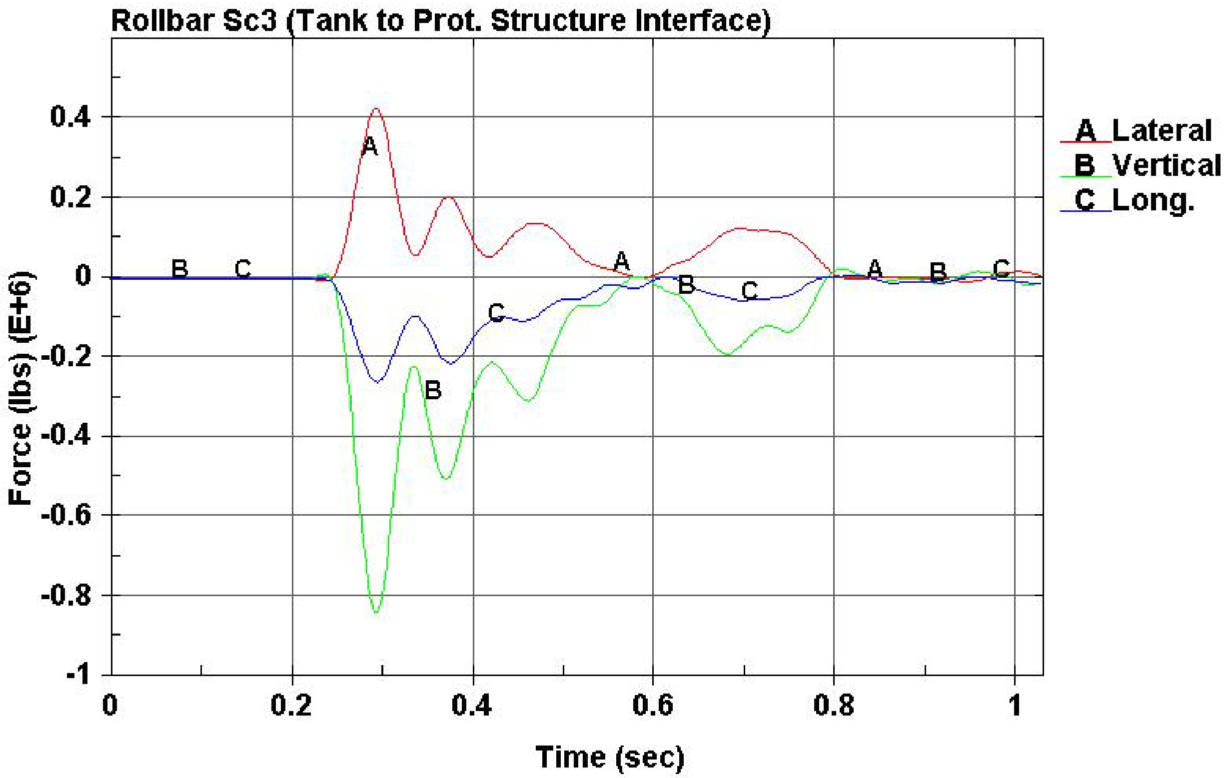

Figure C9. Section Plane Forces near base of Rollbar (Scenario 3)

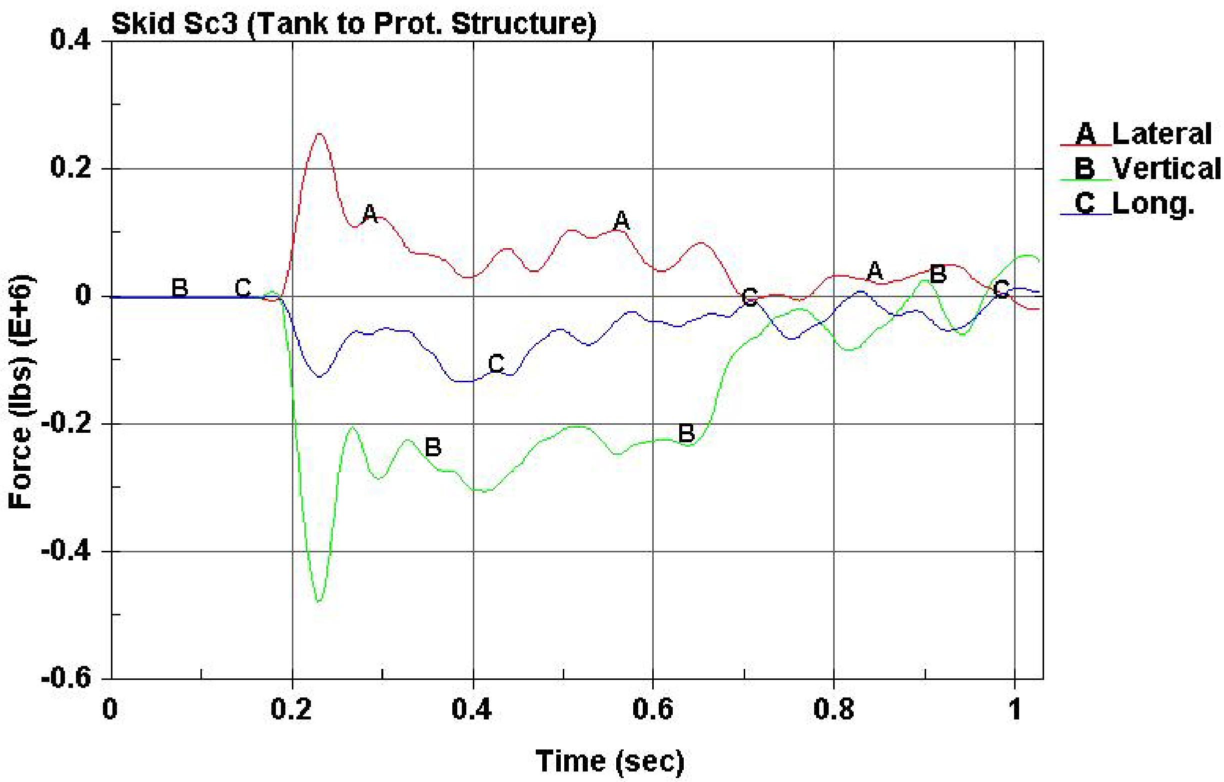

Figure C10. Section Plane Forces near base of Skid (Scenario 3)

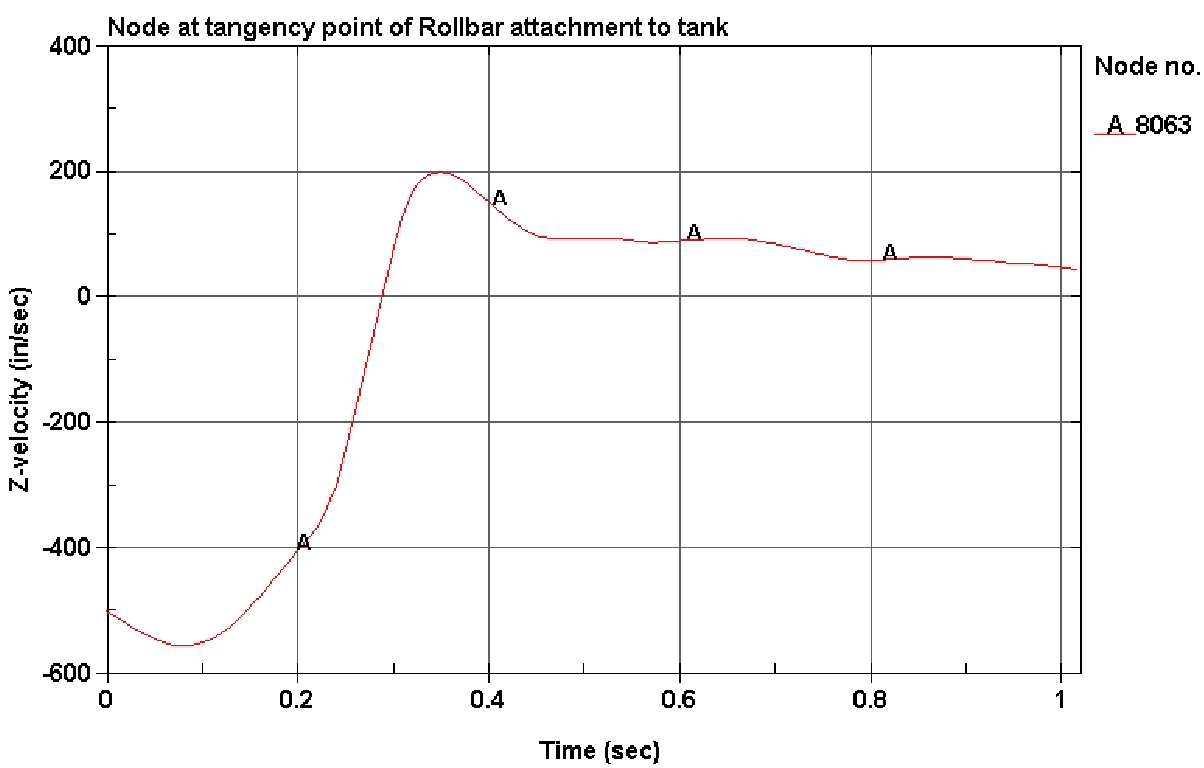

Figure C11. Velocity—tangency attachment point of Rollbar to tank (Scenario 1)

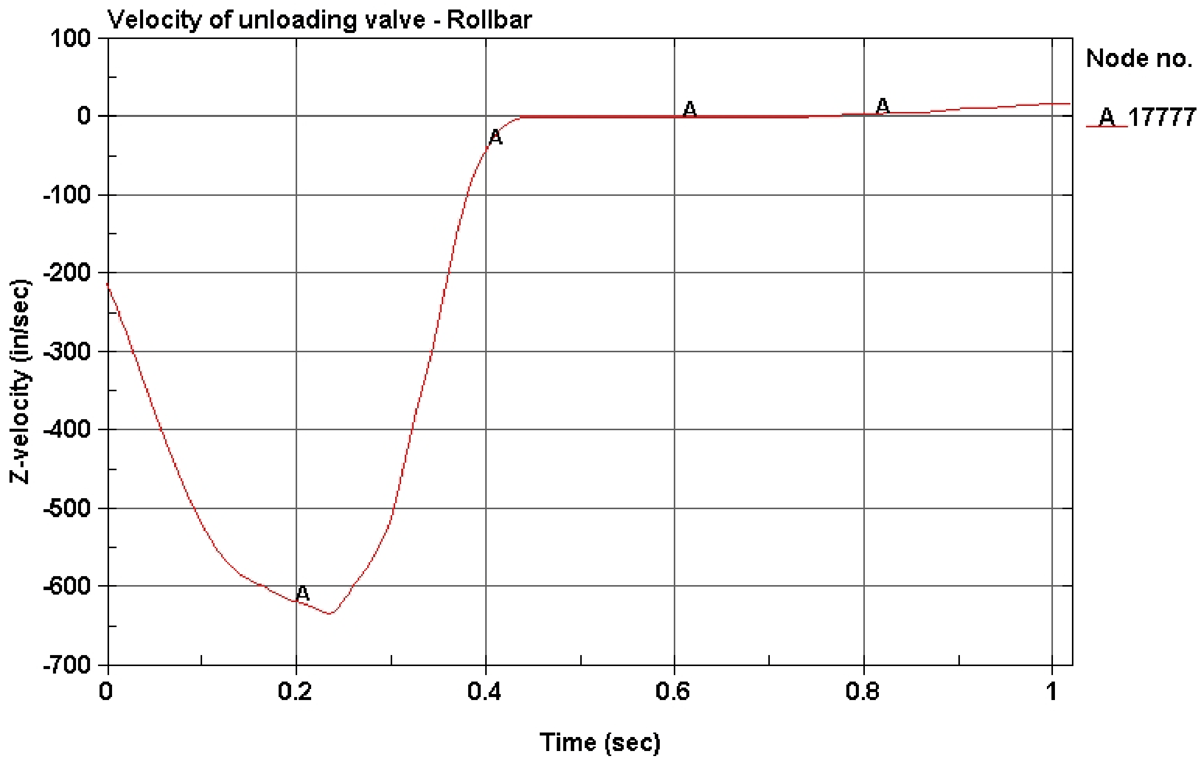

Figure C12. Velocity of Unloading Valve – Rollbar Model (Scenario 1)

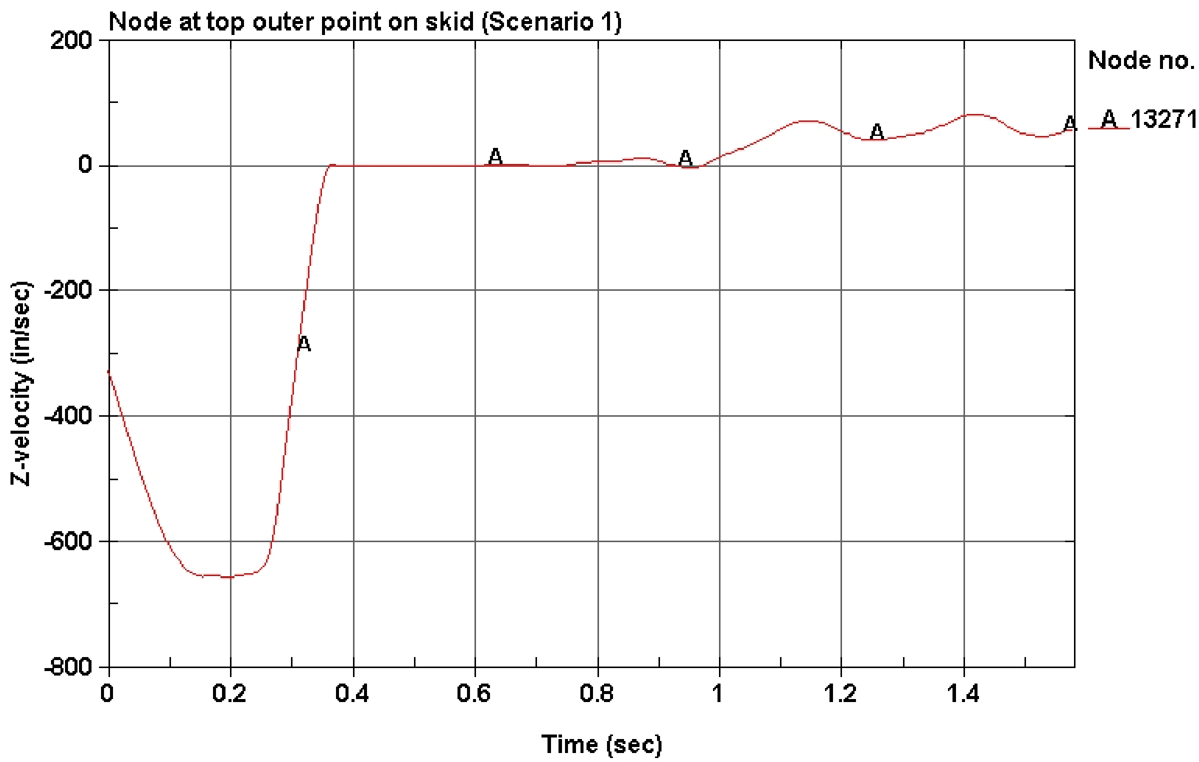

Figure C13. Velocity of Skid at side impact point (Scenario 1)

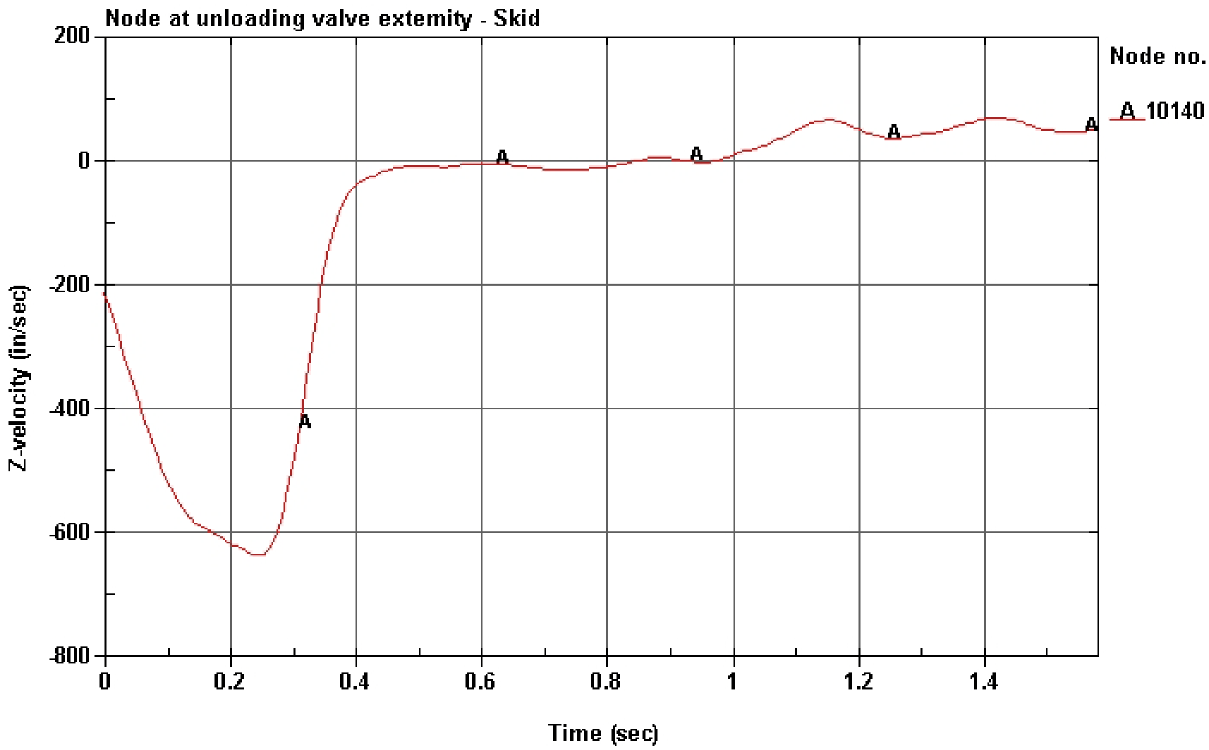

Figure C14. Velocity of Unloading Valve – Skid Model (Scenario 1)

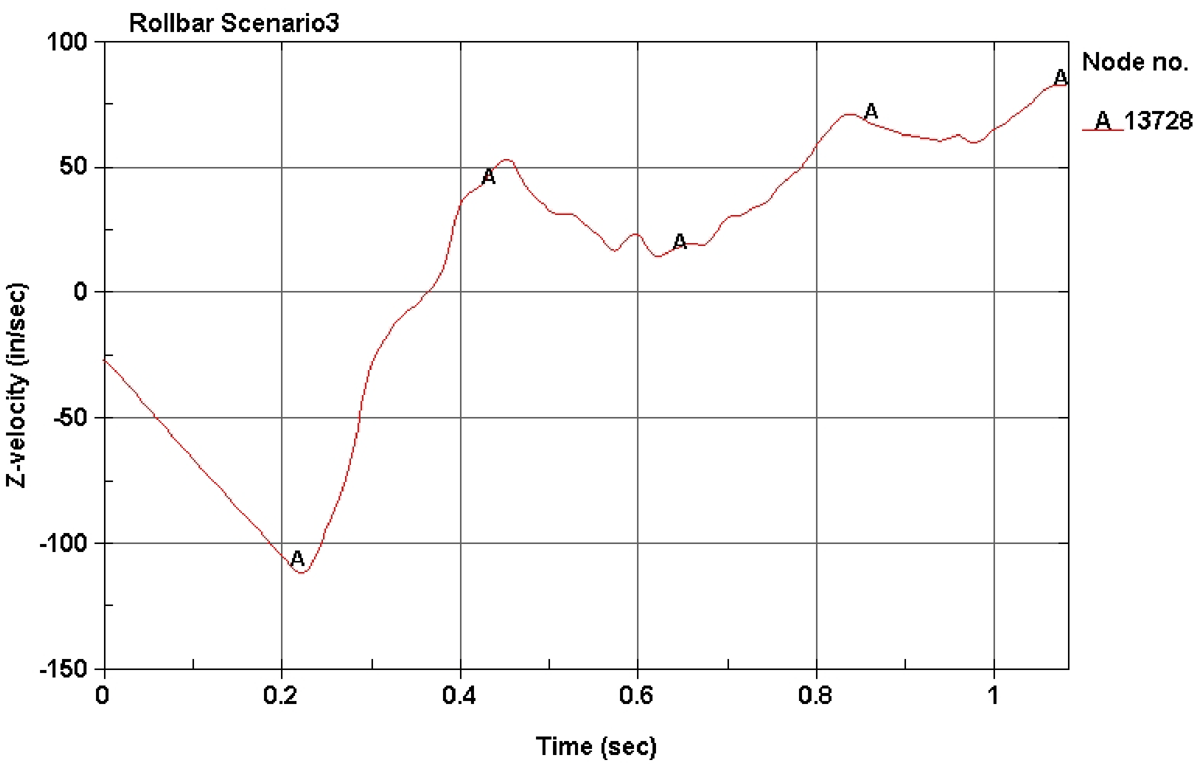

Figure C15. Velocity (z-dir) of Rollbar at point on lateral bar near impact (Scenario 3)

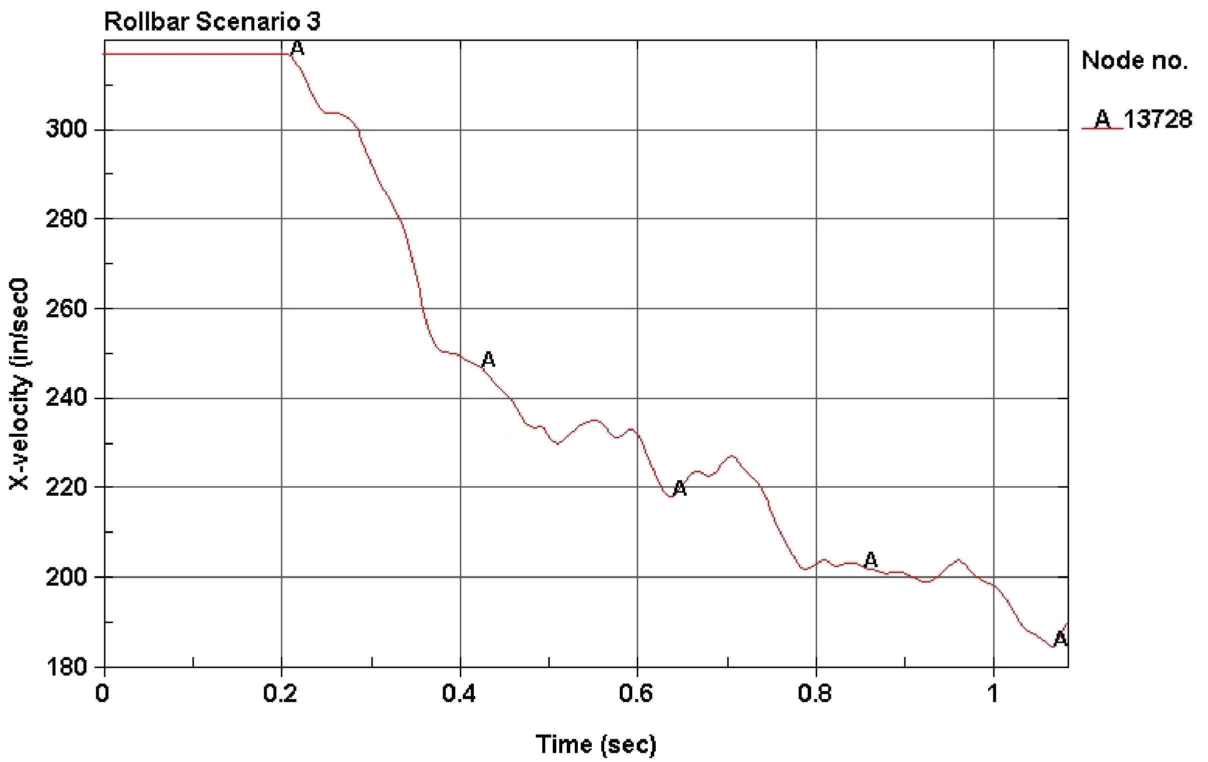

Figure C16. Velocity (x-dir) of Rollbar at point on lateral bar near impact (Scenario 3)

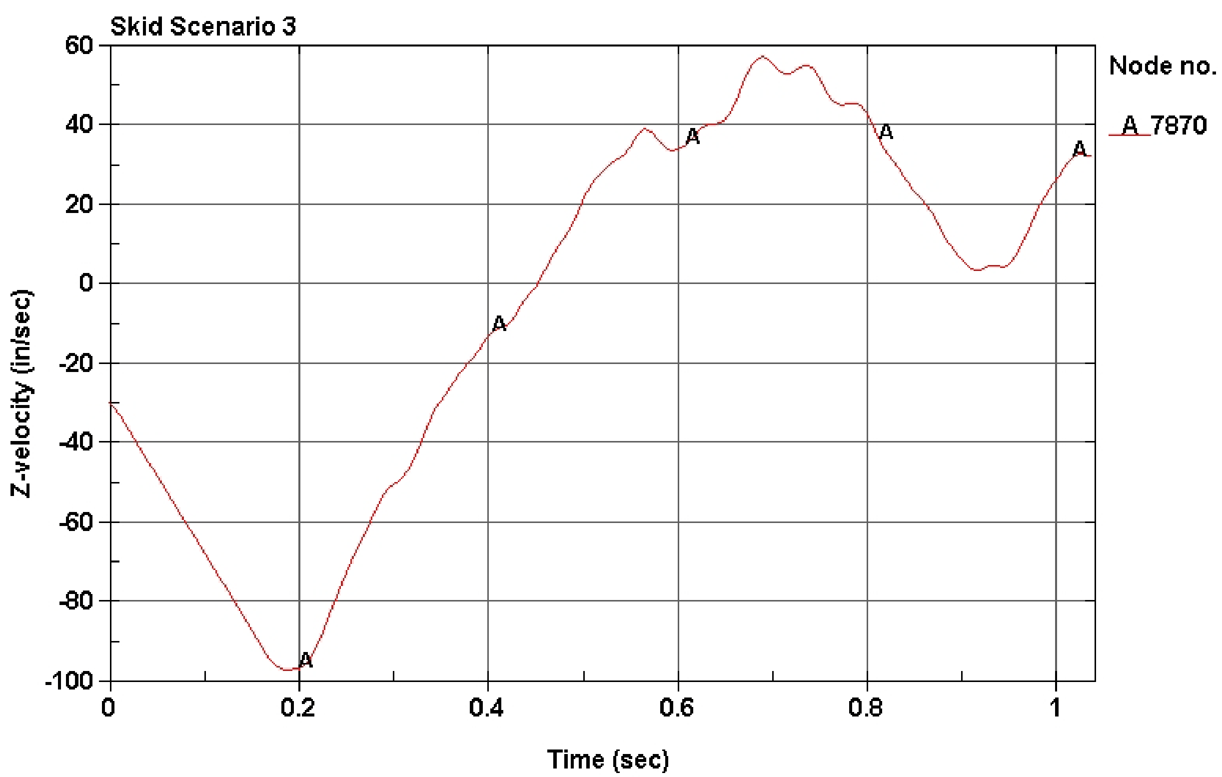

Figure C17. Velocity (z-dir) of point on Skid at intersection of lateral and longitudinal plates (Scenario 3)

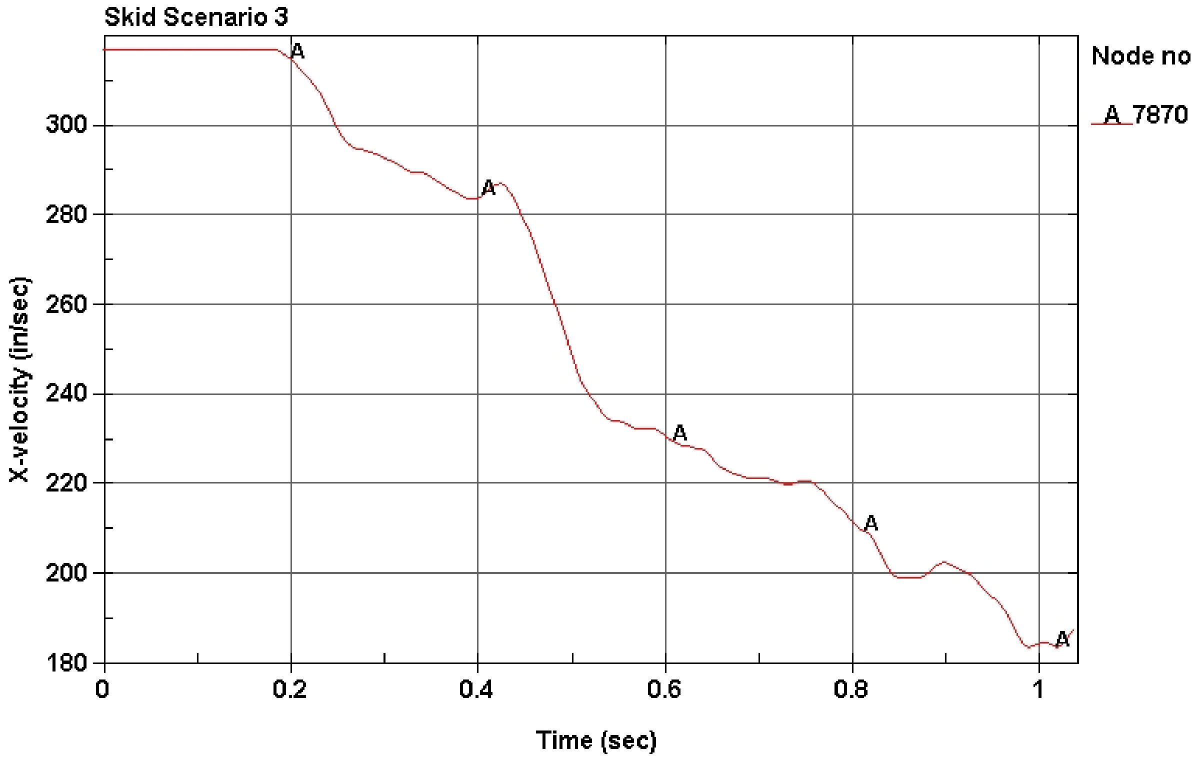

Figure C18. Velocity (x-dir) of point on Skid at intersection of lateral and longitudinal plates (Scenario 3)