Evaluation and Retrofit of CH-TRU Trailers Using Finite Element Analysis

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ABSTRACT

After years of use in transporting Contact-Handled TransUranic (CH-TRU) waste to the Waste Isolation Pilot Plant (WIPP), TRUPACT-II transport trailers began developing cracks in cross-member welds near the trailer's suspension. Designed in the late 1980s, the transport trailers are 42-ft long, with 10-ft spread-axles designed for a maximum gross weight of 62,000-lbs when transporting up to three TRUPACT-II, Type B, containers.

Portemus Engineering was originally contracted to analyze the trailers for compliance with the design requirements of ANSI N14.30[1]. The resulting analyses showed that the suspension cross-members were highly stressed, and corresponded with the actual locations where cracking was observed to occur. Portemus Engineering was then contracted to design a retrofit to prevent future cracking.

The trailer's main beams were modeled implicitly using shell elements to enable accurate analysis of the variable cross-section. The cross-members were modeled explicitly using beam elements to enable simple extraction of forces and moments for subsequent weld evaluations. The three TRUPACT-II packages were modeled as lumped masses, rigidly connected to the trailer frame at four tie-down locations per package. Linear springs were used to simulate the tractor's suspension at the kingpin interface and the trailer's suspension at both axles.

Initially, four different bounding load cases were developed to simulate road conditions encountered during normal operation (e.g., spalled roadways, railroad crossings, traversing high curbs, etc.). All loads were statically applied, including the required amplification and cyclic fatigue factors from ANSI N14.30. A fifth bounding load case was later identified as the primary cause of cross-member weld cracking: extreme angle backing or pulling the trailer (i.e., lateral application of the tractor's forces). Retrofit modifications consisted of a C3×5 channel welded across the front and rear suspension brackets and two diagonal tie-rods between the spread-axle cross-members. The resulting configuration was analyzed and the results showed a significant stress reduction in the suspension cross-members and corresponding welds.

Modification and subsequent road testing of the semi-trailers is currently in progress.

LOAD CASES

After extensive review of trailer response data, the data provided in Table 1, Peak Shock Accelerations of Bed of Truck, of Draft American National Standard N14.23[2] was concluded to provide somewhat conservative, yet reasonable inertia loads in the three axes (i.e., vertical, longitudinal, and lateral). Within ANSI N14.23, Table 1 specifies, for an "air suspended" trailer, 2.0*g* vertically up (reacting downward), 1.5*g* vertically down (reacting upward), 1.8*g* longitudinally, and 1.1*g* laterally. Since these are values for accelerations of the semi-trailer, the use of a dynamic amplification factor, as required in Paragraph 5.1.3.2 of ANSI N14.30, is already included.

These values were contrasted with the data detailed in Sandia Report SAND91-0079[3]. In this report, the authors report acceleration values at various locations on the semi-trailer and payload for seven road conditions: 1) smooth asphalt primary, 2) railroad grade crossing, 3) rough asphalt primary, 4) bridge approach, 5) rough concrete primary, 6) rough asphalt secondary, and 7) spalled asphalt secondary. In addition, two payloads were considered: 1) a CNS 14-170 cask (concentrated center load), and 2) a CNS 3-55 cask (distributed load). For evaluation purposes, the CNS 3-55 cask was used for comparison since three TRUPACT-II packages on a semi-trailer are effectively a distributed load. As such, the most severe loading condition was the shock due to a railroad grade crossing (Event 2). For Event 2, the reported maximum vertical acceleration is 0.8*g* at accelerometer location 4 (trailer middle, vertical), the reported maximum longitudinal acceleration is 0.5*g* at accelerometer location 3 (package top, longitudinal) and 3.0*g* at accelerometer location 6 (trailer rear, longitudinal), and the reported maximum lateral acceleration is 0.14*g* at accelerometer location 1 (package top, transverse). Since the trailer response is effectively coupled to the massive payload, the accelerometer reading on or adjacent to the package was utilized (i.e., 0.8*g* vertical, 0.5*g* longitudinal, and 0.14*g* lateral).

Conservatively assuming a dynamic amplification factor of 2.0 for a step input, the resulting inertia loads are 1.6*g* vertically, 1.0*g* longitudinally, and 0.28*g* laterally). Hence, the accelerations of 2.0*g* vertically, 1.8*g* longitudinally, and 1.1*g* laterally from Table 1 of ANSI N14.23 are conservative. Consistent with the requirements of Paragraph 5.1.3.2 of ANSI N14.30, each of the accelerations from Table 1 of ANSI N14.23 are multiplied by a 1.2 factor to account for cyclic fatigue. As such, the resulting inertia loads are then 2.4*g* vertically, 2.16*g* longitudinally, and 1.32*g* laterally. Note that the 1.32g lateral force can never be achieved because overturning (rollover) of the semi-trailer occurs at approximately 0.48*g*. Within the finite element analysis, the 0.48*g* lateral force is determined to reduce the load on one side of the semi-trailer to nearly zero.

Thus, five load cases were selected to provide a comprehensive evaluation of the TRUPACT-II semi-trailer when loaded with a maximum live load of three 17,500 pound, TRUPACT-II packages:

1. A 2.5*g* vertical static inertia load per the requirement of Paragraph 5.1.3 of ANSI N14.30,
2. Combined 2.4*g* vertical and 2.16*g* longitudinal static inertia loads to simulate travel over unimproved roadways, bridge approaches, and railroad crossings,
3. Combined 2.4*g* vertical and 0.48*g* lateral static inertia loads to simulate near-rollover conditions (i.e., high-speed, tight-radius turns) over unimproved roadways,
4. A 1.0*g* vertical static inertia load with vertical displacement of a single axle on one side of the semi-trailer to simulate traversing a high curb; separate load cases are considered for both the front and rear axle, and
5. A 1.0*g* vertical static inertia load with a side load applied to the kingpin and friction loads applied to the corresponding semi-trailer's wheel locations to simulate a tight trailer backing maneuver (i.e., the tractor normal to the semi-trailer's longitudinal axis).

FINITE ELEMENT ANALYSIS MODEL

The ANSYS® finite element model was comprised of nearly 8,000 nodes and elements, with the global Cartesian coordinate system's X-direction representing the semi-trailer's longitudinal axis, the Y-direction the lateral axis, and the Z-direction the vertical axis. Figure 1 illustrates the finite element model, illustrating the main beams and structural cross-members.

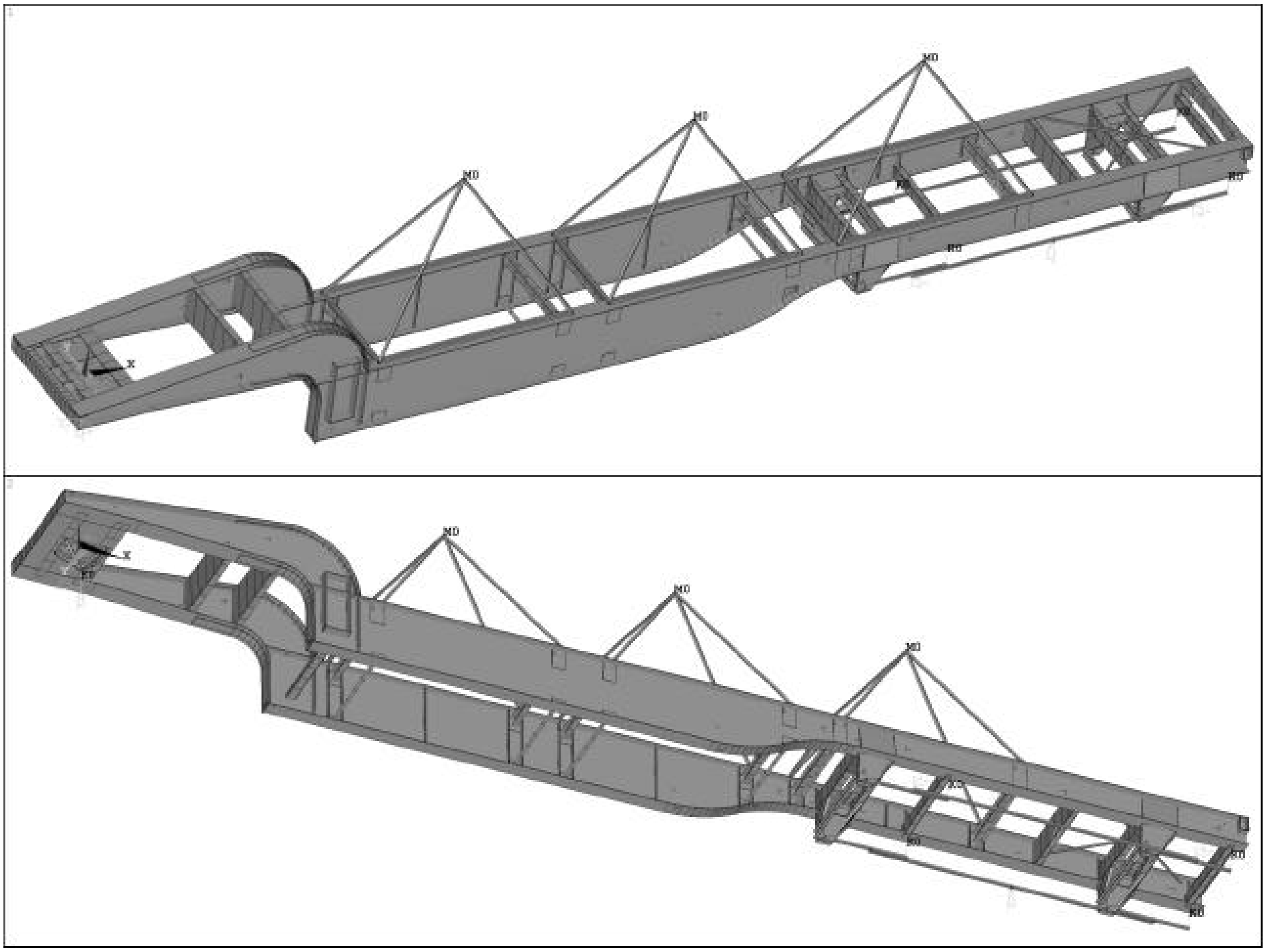

Figure 1, Finite Element Model of the TRUPACT-II Semi-Trailer

Due to their non-uniform configuration, and the plurality of localized stiffeners and gussets used in the trailer's design, the main rails are modeled using SHELL63 shell elements. SHELL63 elements have both bending and membrane capabilities. In the regions of localized web doublers, element thicknesses are changed to reflect the collective thickness.

SHELL63 elements are also used to model the cross-plate reinforcements used in the kingpin region, landing gear box structure in the gooseneck region, all the web and crossbeam gussets, and suspension structure plates and gussets in the suspension region. The suspension structure plate thickness reflects the suspension system's relatively heavy structure in that region.

With the exception of the tie-down crosspipes and rear diagonal tierods, all cross headers are modeled using BEAM24 elements. BEAM24 is a uniaxial element of arbitrary cross section (either open or closed) with tension-compression, bending, and torsional capabilities. BEAM24 elements are utilized for three reasons: 1) designation of an arbitrary cross section allows accurate modeling of all beam configurations used in the semi-trailer design, 2) the six degrees of freedom are fully compatible with the SHELL63 elements requiring no additional constraints to assure the proper transfer of forces, and 3) the BEAM24 forces are easily extracted to determine combined stresses both in the beam structure and the weld connection groups.

Befitting of their nature, PIPE16 elements are used for the tie-down crosspipes. Because they, too, exhibit the full six degrees of freedom at each node and their forces are easily extractable, their use is almost identical to the BEAM24 elements used for all headers.

Finally, BEAM4 elements are used to represent the simple circular cross-section of the rear diagonal tierods. As with BEAM24 and PIPE16 elements, BEAM4 elements exhibit the full six degrees of freedom at each node and their forces are easily extractable. BEAM4 elements are also used to represent the rigid model structures such as the load transfer frames at the kingpin and TRUPACT-II package locations, and the pivot beams and walking beams in the suspension. To enhance their rigidity, these elements are given an elastic modulus that is three orders of magnitude higher than normal.

At the kingpin location, the BEAM4 load transfer frame simulates the tractor's fifth-wheel structure in transferring loads directly into the front and rear kingpin headers. Similarly, BEAM4 load transfer frames are located at each of the three TRUPACT-II package locations to elevate the package's mass 60 inches above the main rails. Use of these rigid frames for transferring package loads directly into each main rail's web properly simulates the extremely rigid nature of each TRUPACT-II package and the relatively rigid tie-down system. Each package, once secured, effectively "locks up" that section of the main rails resulting in maximum stresses occurring between package positions where the semi-trailer's frame is free to twist.

Finally, BEAM4 elements are used for the suspension simulation. A "walking beam" configuration is used to simulate the true nature of the air ride suspension system, as idealized in Figure 1. Each air spring receives air to properly balance forces in the two axles; otherwise, the rear axle would never carry a load in the finite element model. This effect was observed in an earlier model that used only linear springs at each suspension location…the rear axle springs always went into tension. By observation, the walking beam must rotate to balance forces at each end; because of this geometry, the forces in each air bag spring must be equal.

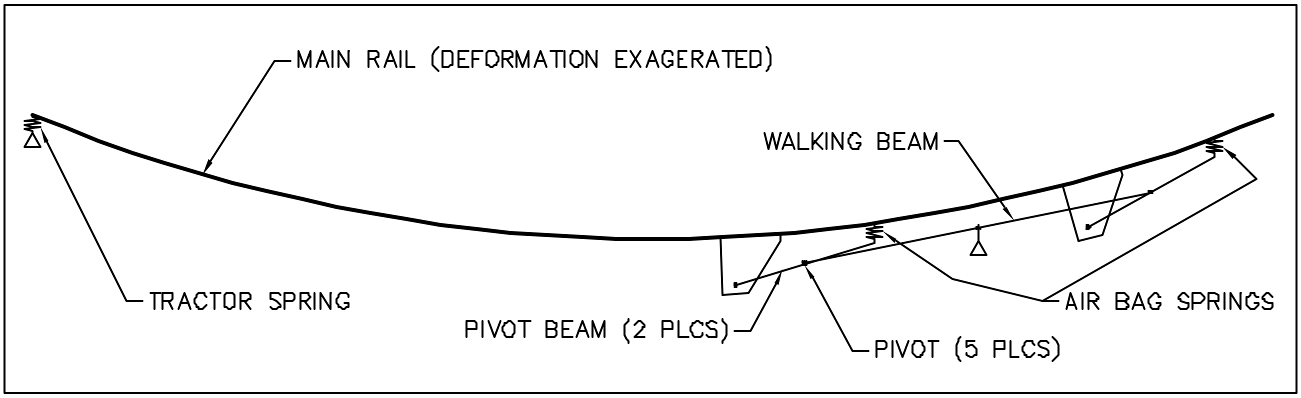

Figure 2, Walking Beam Representation of the Air Ride Suspension

Frictionless COMBIN7 revolute joints are used at each of the five pivot locations used at the suspension regions on each side of the semi-trailer, and COMBIN14 spring-damper elements are used to represent the tractor and semi-trailer suspension springs, and rubber axle stop pads.

Full constraint is applied between the various cross headers and their respective gussets thereby simulating the existing connectivity.

Load Cases 1, 2, and 3 use longitudinal (X-axis), lateral (Y-axis), and vertical (Z-axis) displacement constraints at each of the three reaction points: the ground point on the tractor spring and two walking beam center pivots points. Out-of-plane stability is achieved by longitudinal (X-axis) and lateral (Y-axis) displacement constraints at the kingpin location, and a lateral (Y-axis) displacement constraint at each semi-trailer axle location on the left side. Load Case 3 modifies the lateral constraints at these axle locations to be CONTAC52 gap elements at the front pivot points on each suspension pivot beam.

Load Cases 4A and 4B use essentially the same restraint conditions with the exception that the nearside (left) walking beam is removed (decoupling the front and rear axles) so that each axle can be independently displaced 10 inches vertically upward.

Load Case 5 has lateral constraints applied to the kingpin and rear, near-side suspension pivot beam node to react lateral loads (to simulate wheel friction) applied to the front, near- and far-side suspension pivot beam nodes, as illustrated in the free-body diagram in Figure 3.

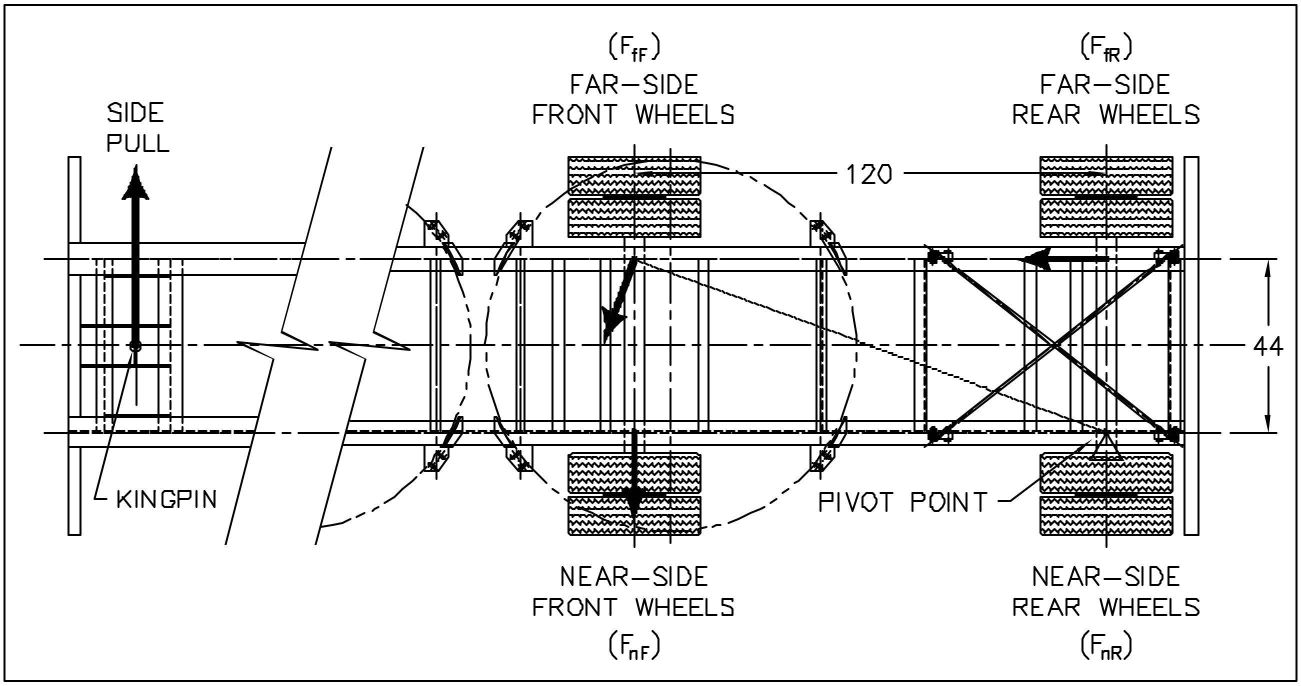

Figure 3, Free Body Diagram of Load Case 5, Side Pull at Kingpin

For a 1*g* static load, the vertical load at the kingpin is 22,200 pounds and the vertical load at each set of dual wheels is 9,025 pounds, resulting in a total vertical load of 58,300 pounds (5,800 pounds for the empty semi-trailer frame plus three TRUPACT-II packages, each weighing 17,500 pounds). Conservatively assuming a friction coefficient of 1.0 and frictionless rotation about the near-side rear wheels (F_{nR}), the lateral friction load at each of the remaining three wheel locations, near-side front (F_{nF}), far-side front (F_{fF}), and far-side rear (F_{fR}) is 9,025 pounds. Further, assuming all loads normal to the side pull (i.e., in the semi-trailer's longitudinal axis) are frictionless wheel rotation, the force vectors are as follows:

$$_{nF} = 9{,}025 \text{ lb}; \;\; F_{fF} = (9{,}025)\left(\frac{120}{\sqrt{(44)^2 + (120)^2}}\right) = 8{,}473 \text{ lb}; \;\; F_{nR} = F_{fR} = 0 \text{ lb}$$

Only four material property parameters are utilized: 1) the elastic modulus is set to 29 × 10^6 psi for structural steel, 2) Poisson's ratio is 0.3, 3) the friction coefficient for the CONTAC52 gap elements is set to zero, and 4) the density of the carbon steel is adjusted to result in an overall structure mass of 5,800 pounds, per the design drawings. A second set of material properties is defined for the rigid beams where the elastic modulus utilized in the first material property set is increased by three orders of magnitude to result in rigid beams relative to the semi-trailer structure.

DETERMINATION OF STRESS INTENSITIES

Per the subparagraphs within Paragraph 5.1.3, *Structural Members*, of ANSI N14.30-1992, the cumulative application of loads, including the application of dynamic and cyclic fatigue factors, shall not result in stresses that exceed the yield strength of the materials of construction.

The maximum stress intensity in the main rails is determined by linearizing stresses across the beam height and, where significant, across the beam flanges. To eliminate peak stresses in the main rails, the reported stress result is the maximum membrane plus bending stress intensity. The maximum stress intensity occurred in the main rail bottom flange in the height transition region for every load case.

Beam stresses are determined using the beam area, A, torsional modulus, S_x, and bending moduli, S_y and S_z. The biaxial stress components for the beams are:

F_x axial stress.................... $\sigma_X = \dfrac{F_X}{A}$

M_x torsional shear stress......... $\tau_X = \dfrac{M_X}{S_X}$

M_y bending stress .... $\sigma_Y = \dfrac{M_Y}{S_Y}$

F_y direct shear stress .... $\tau_Y = \dfrac{F_Y}{A}$

M_z bending stress............. $\sigma_Z = \dfrac{M_Z}{S_Z}$

F_z direct shear stress .... $\tau_Z = \dfrac{F_Z}{A}$

Using Mohr's circle, the stress intensity is twice the maximum shear stress:

$$SI = 2\sqrt{\left(\frac{|\sigma_X| + |\sigma_Y| + |\sigma_Z|}{2}\right)^2 + \left(|\tau_X| + \sqrt{\tau_Y^2 + \tau_Z^2}\right)^2}$$

Weld stresses are determined using the weld area, A_W, torsional modulus, S_x, and bending moduli, S_y and S_z. Stress intensity is determined using the same equations for the beams given above. The major difference between calculated stresses in the beams and in the welds is the application of a torsional constant versus the polar moment of inertia. For open sections that exhibit low torsional rigidity (e.g., I-beams, channels, etc.), the torsional constant is applicable. For closed sections that exhibit high torsional rigidity (e.g., pipes, tubes, etc.), the polar moment of inertia is applicable. Because welds cannot warp, the polar moment of inertia is used. Thus, for cases where the torsional moment (M_X) is relatively large on an open section, beam stresses will usually govern.

RETROFIT OF THE SUSPENSION REGIONS

Significant effort was undertaken to correctly identify and understand the load paths through the suspension regions for the five load cases, including visually inspecting a large number of different semi-trailer air ride suspensions and noting the configurations where cracks occurred. The proposed modifications are consistent with semi-trailers that exhibited no cracking.

The worst-case condition for deformations and stresses occurs for Load Case 3, where the maximum lateral load to the semi-trailer's frame is reacted by the kingpin and rear suspension. The presence of the three TRUPACT-II packages locally stiffens the semi-trailer's frame resulting in a flow of forces to the more flexible region directly aft of the rearmost package. Consequently, the suspension cross headers carry the load from one main rail to the other resulting in overstressed conditions in some of the front suspension cross beams and many of the rear suspension cross beams.

The following two design changes are applied to create a better distribution of forces for the various load conditions resulting in suspension region stress intensities below stress allowables:

- Addition of a C3 × 5 standard channel between the suspension structures at both the front and rear suspensions, parallel to each axle (see Figure 4). Use of the two standard channels provides additional rigidity and load paths within the suspension regions thereby lowering stresses in the adjacent suspension cross headers, adding ~40 pounds to the empty semi-trailer weight. The suspension structures on newly fabricated trailers include a stabilizing channel.

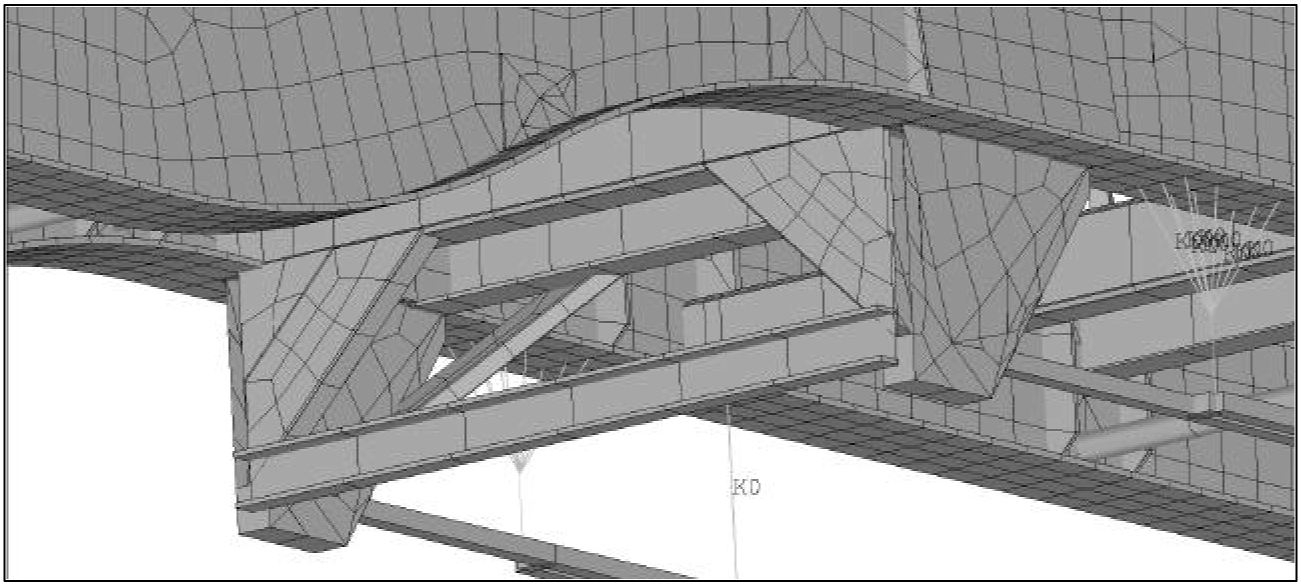

Figure 4, C3 × 5 Suspension Bottom Cross Header Configuration (Front)

- Addition of two 3/4 inch diameter tierods diagonally between the main rails, crossing directly over the rear suspension cross headers; the 78 inch long tierods are threaded at each end and attached to the main rail webs through a tierod block using 3/4-10UNC, Grade 5, hex nuts tightened to 100 lb-ft torque (see Figure 5). The tierod blocks are attached to the main rail webs via two 7/8-9UNC, Grade 5, hex head bolts tightened to 150 lb-ft torque. The two tierods are vertically centered in the gap between the top of the suspension cross headers and the bottom of the main rail upper flanges, with one tierod vertically offset 1½inches relative to the other. The tierods penetrate the main rail webs ~20½inches on either side of the suspension cross headers, resulting in a center-to-center spacing of 56 inches. Use of the tierods stiffens the rear region of the trailer thereby enabling a more even distribution of loads through the various crossbeams, and adds ~75 pounds to the empty semi-trailer weight.

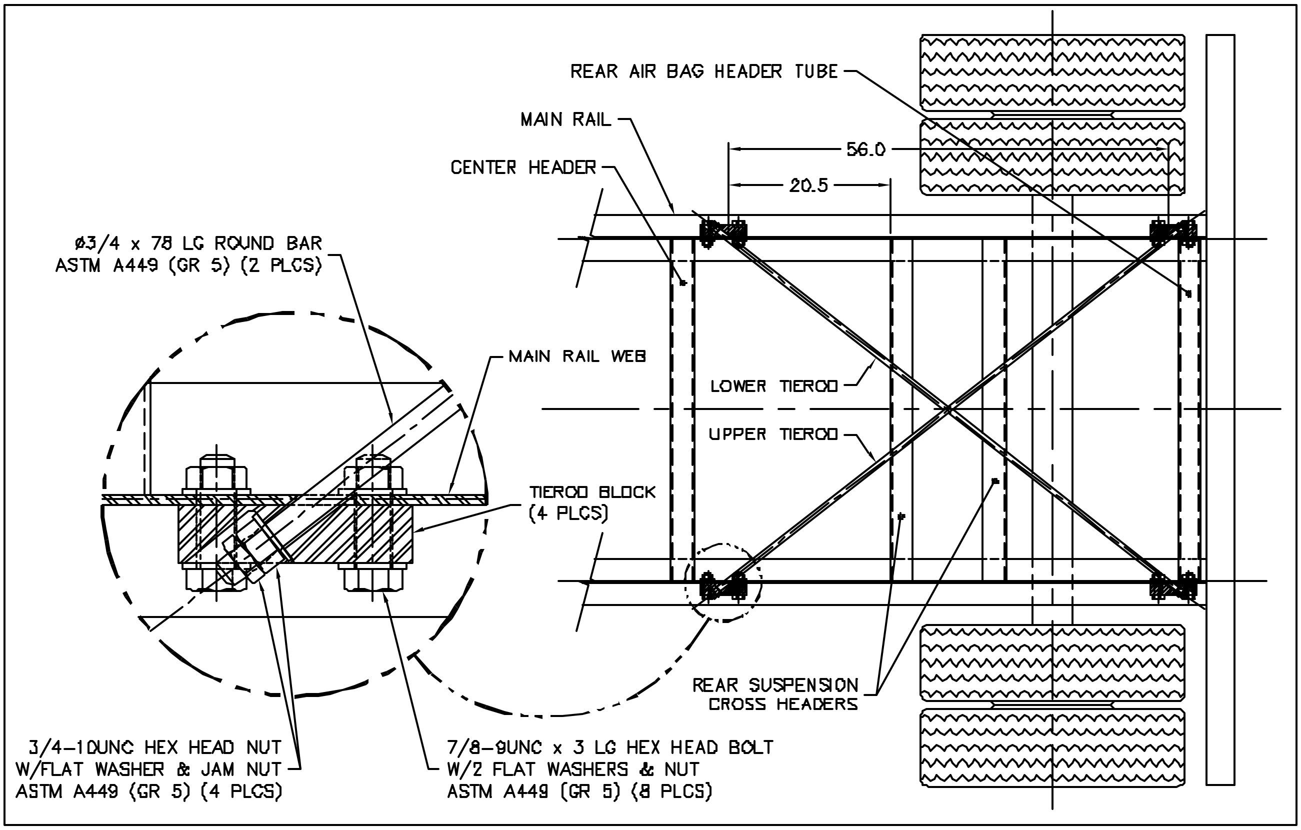

Figure 5, Rear Diagonal Crosstie Configuration

SUMMARY

Developed as an ultra-lightweight design, the TRUPACT-II semi-trailer maximizes payload for each shipment thereby lowering the overall CH-TRU waste transport costs. Compared to a standard semi-trailer that uses a bed/box structure to significantly increase structural stiffness, the relative flexibility of the TRUPACT-II semi-trailer results in unacceptable ANSI N14.30 defined stress levels when various load cases are applied. Although finite element analysis of the revised design demonstrates acceptable stress levels, only retrofitting and subsequent road testing of TRUPACT-II semi-trailers will determine the ultimate effectiveness of the recommended design changes.

REFERENCES

[1] ANSI N14.30-1992, *American National Standard for Nuclear Materials – Semi-Trailers Employed in the Highway Transport of Weight-Concentrated Radioactive Loads – Design, Fabrication, and Maintenance*, American National Standards Institute, New York, 1993.

[2] ANSI N14.23, *Draft American National Standard Design Basis for Resistance to Shock and Vibration of Radioactive Material Packages Greater than One Ton in Truck Transport*, American National Standards Institute, New York, May 1980.

[3] K. W. Gwinn, R. E. Glass, K. R. Edwards, *Over-the-Road Tests of Nuclear Materials Package Response to Normal Environments*, SAND91-0079 (UC-722), Sandia National Laboratories, Albuquerque, NM, December 1991.