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SEISMIC FRAGILITY EVALUATION OF METAL FLAT-BOTTOM STORAGE TANKS WITH SHORT ANCHOR BOLT CHAIRS

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ABSTRACT

Seismic fragilities of anchored metal flat-bottom storage tanks are usually governed by tank overturning. Tank overturning capacity is typically influenced more by the hold-down strength of the anchors rather than the buckling strength of the tank shell. For tanks with short anchor bolt chairs, the anchor bolt hold-down strength may be limited by the ability of the tank shell near the bolt chairs to accommodate the local demands resulting from the eccentricity between the anchor bolts and the tank shell. The smaller the height of the bolt chairs, the lower the capacity of the tank shell to accommodate this eccentricity.

This paper presents a case study for an anchored tank with relatively short bolt chairs. An initial seismic fragility was developed for the tank following the standard approaches outlined in EPRI (1994), EPRI (1991a) and EPRI (1991b). The short bolt chairs controlled the hold-down strength of the anchors. The resulting overturning capacity computed was low, and the tank was a dominant risk contributor in initial seismic risk quantification runs for the plant seismic probabilistic risk assessment. Consequently, a static nonlinear analysis of the tank shell at and around an anchor bolt chair was performed to compute a more realistic anchor bolt hold-down strength and the associated maximum permissible uplift at the heel of the overturning tank. Material nonlinearity in the tank shell, bolt chair, and anchor bolt was included. Effects of fluid pressures were captured in the analysis.

The analysis results showed that the anchor force corresponding to the tank shell failure was nearly two times the force computed following the guidance in EPRI (1991a). Furthermore, the analysis justified the consideration of this failure mode as ductile, as opposed to the traditional guidance in EPRI (1994) to consider it as non-ductile. As such, a significantly higher permissible uplift was demonstrated by the nonlinear analysis. The substantial increases in the anchor bolt hold-down strength and the maximum permissible tank uplift significantly improved the tank seismic fragility. The improvement essentially eliminated any contribution to seismic risk from the tank.

INTRODUCTION

The tank at the focus of this study was included on the seismic equipment list for a nuclear power plant seismic probabilistic risk assessment (SPRA). The tank is a metal flat-bottom storage tank anchored to a reinforced concrete mat foundation, storing water at atmospheric pressure. Seismic fragility evaluation of the tank initially followed the approaches outlined in EPRI (1994), EPRI (1991a) and EPRI (1991b). Because of the short anchor bolt chairs, the hold-down strength of the tank anchors was governed by yielding of the tank shell near the bolt chairs due to the localized out-of-plane loading from the eccentric anchor force. The associated anchor bolt hold-down strength was computed in accordance with EPRI (1991a) using the following equation:

$$P_u = f_y t_s^2 \left[\frac{1.43ah^2+(4ah)^{\frac{1}{3}}}{1.32Z} + \frac{0.031}{\sqrt{Rt_s}}\right]; \; Z = \frac{1.0}{\frac{0.177at_b}{\sqrt{Rt_S}}\left(\frac{t_b}{t_S}\right)^2+1.0} \qquad (1)$$

Where P_u is the anchor bolt hold-down strength, R is the tank shell radius, and f_y is the tank shell steel yield strength; other parameters in Equation 1 are defined in Figure 1. The resulting anchor bolt hold-down strength was significantly lower than its tensile strength. Furthermore, EPRI (1994) associates this localized failure of the tank shell with limited ductility. Therefore, EPRI (1994) recommends limiting the maximum permissible tank uplift (at the heel of the overturning tank) to the uplift at which the force in the anchor bolts reaches the hold-down strength. The low anchor bolt hold-down strength along with the small maximum permissible uplift resulted in a low seismic overturning capacity for the tank. Preliminary risk quantifications using this initial tank fragility identified the tank as a dominant risk contributor. This necessitated a refined and more realistic evaluation of the tank seismic fragility. Consequently, a static nonlinear analysis of the tank shell at and around an anchor bolt chair was performed to compute a more realistic anchor bolt hold-down strength and the associated maximum permissible uplift at the heel of the overturning tank. This paper focuses on the details of this nonlinear analysis.

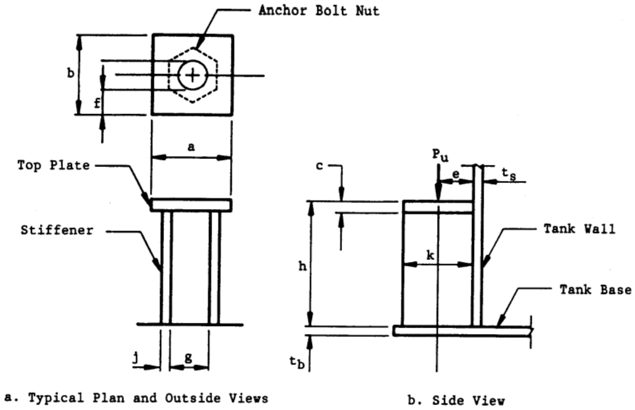

Figure 1. Tank Bolt Chair Parameters, EPRI (1991a)

TANK DESCRIPTION

Figure 2 illustrates the construction of the flat-bottom vertical cylindrical steel tank under investigation. The tank has a diameter of 36 ft, with an approximately 50 ft tall shell whose thickness varies from 0.5 in. at the base to 5/16 in. at the top. It is covered by a 0.25 in. thick spherical domed roof and has a 5/16 in. thick bottom plate. The tank stores water at atmospheric pressure. Under normal operation, the water height in the tank is 48 ft. The tank is anchored to a reinforced concrete mat foundation using forty 2.5 in. diameter ASTM A36 anchor bolts. Anchor bolt chairs are provided to transfer the stresses in the tank shell to the foundation through the anchor bolts. The bolt chair height is 9 in., and the eccentricity between the tank shell and the anchor bolts is 3.25 in. The tank shell, bottom plate, and the anchor bolt chairs are all formed from ASTM A283 Grade C steel plates.

The anchor bolt hold-down strength computed using Equation 1 was 50 kip. The associated maximum permissible uplift was estimated as 0.3 in. Using these values, the overturning capacity of the tank was estimated to be 36,000 kip-ft following the approach in EPRI (1994).

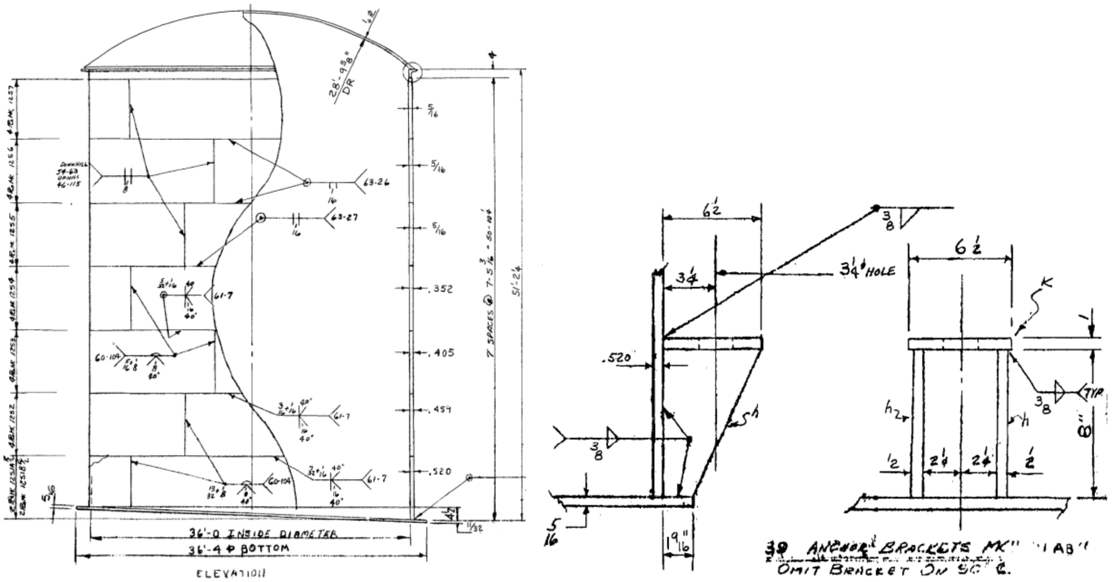

Figure 2. Tank and Bolt Chair Details

NONLINEAR ANALYSIS

A static nonlinear pushover analysis was performed using the computer program Abaqus (Dassault (2012)) to determine the median anchor bolt hold-down strength and associated maximum permissible tank uplift. A finite element model was developed for a wedge of tank shell and bottom plate, one anchor bolt, and one anchor bolt chair. Material nonlinearity of the various steel components was incorporated. At each step of the pushover analysis, the limit state corresponding to the plastic strain demand exceeding the strain failure criteria was checked for the various structural elements. The anchor bolt force and the tank uplift at the first step this limit state was achieved are the required anchor bolt hold-own strength and the associated maximum permissible tank uplift.

Pushover Finite Element Model

Figure 3 shows the Abaqus model developed for the pushover analysis. The model represents a 9 deg wedge model of the tank shell, bottom plate, one anchor bolt, and one anchor bolt chair. The chosen 9 deg extent of the wedge equals the angular spacing of tank anchor bolts. Shell elements were used for all model components except the anchor bolt, which was modeled using beam elements. The model origin was located at the center of tank bottom plate. The X axis is oriented toward the anchor bolt. The Z axis is oriented upward, and the Y axis is along the tangential direction at the center of anchor bolt following the right-hand rule.

Axisymmetric boundary conditions were applied to the vertical tank shell boundaries by restraining tangential translation, and rotations about the radial and vertical axes. All translations and rotations are restrained at the inner boundary of the bottom plate. Springs were applied to the bottom plate nodes to simulate contact between the bottom plate and base mat. These springs were assigned very large stiffness and strength values in compression, and very small stiffness and strength values in tension. The anchor beam elements representing the embedded portion of the bolt were restrained against all horizontal translations, with the end node additionally restrained vertically to simulate restraint by the anchor plate embedded in the mat foundation.

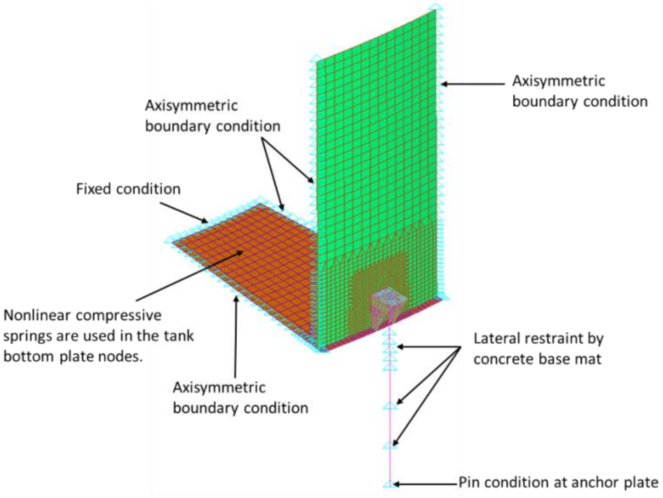

Figure 3. Abaqus Model

Nodes at the top boundary of the tank shell were constrained to have the same vertical displacement to facilitate application of uplift loading for the pushover analysis by a prescribed displacement at a single node at the center of the boundary. Furthermore, the chair top plate was connected to the tank shell using equal displacement constraints in all directions to avoid moment transfer to reflect the as-built configuration, wherein the top plate is connected to the tank shell by a fillet weld on only the top face of the chair top plate (Figure 2).

Figure 4 shows the material behavior implemented in the model for tank material (shell, bottom plate, anchor bolt chairs) and the anchor bolt. The shown stress-strain curves reflect median properties as determined from available literature. Abaqus requires that material stress-strain relationships be defined in terms of true stress (σ_{true}) and true strain (ε_{true}), instead of engineering stress (σ_{eng}) and engineering strain (ε_{eng}). These parameters are related as:

$$\sigma_{true} = \sigma_{eng}(1+\varepsilon_{eng});\;\; \varepsilon_{true} = \ln(1+\varepsilon_{eng}) \tag{2}$$

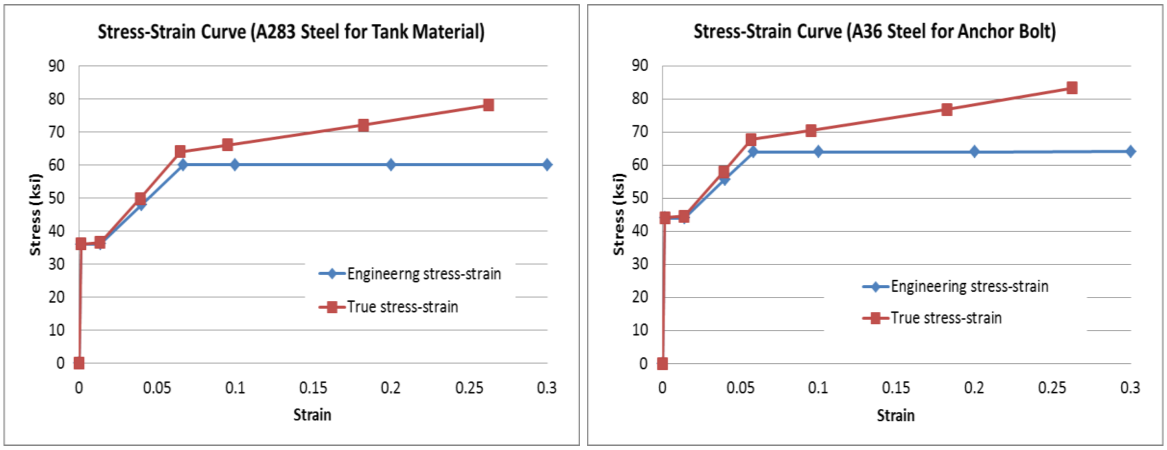

Figure 4. Stress-Strain Curves for Tank and Anchor Bolt Materials

Failure Criteria

Failure of a structural element represented in the model was deemed to have occurred if the computed equivalent plastic strain during the pushover analysis exceeded the median strain capacity. Equivalent plastic strain (PEEQ) is a scalar measure of the inelastic strain tensor at a given location, analogous to Von Mises stress being a scalar measure of the stress tensor at a particular location. Following Manjoine (1982) and Flanders (1995), the median true strain capacity (ε_{truem}) is computed as:

$$\varepsilon_{truem} = \ln(1 + \varepsilon_{engm}) \tag{3}$$

$$\varepsilon_{engm} = \varepsilon_u F_T F_{AB} \tag{4}$$

$$F_T = \min\left(\frac{1}{TF}, 2^{1-TF}\right) \tag{5}$$

$$TF = \frac{\sigma_1+\sigma_2+\sigma_3}{\sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]}} \tag{6}$$

Where ε_{eng} is the median engineering strain capacity, ε_u is uniaxial stain capacity (Figure 4), F_T is the median triaxiality factor, F_{AB} is strain capacity reduction factor for as-built configuration, TF is the Davis triaxiality factor; and σ_1, σ_2, σ_3 are the first, second and third principal stresses, respectively. The triaxiality factors (F_T and TF) adjust the uniaxial strain capacity to account for the triaxial state of stresses. The reduction factor F_{AB} is a value between 0.8 and 1 that accounts for the reduction in strain capacity due to differences between the as-built configuration and the idealized configuration evaluated for design. A value of 0.8 was judged appropriate for this study.

Nonlinear Pushover Analysis

The nonlinear pushover analysis was performed in two successive load steps: (1) force-controlled application of fluid pressures on the interior surfaces of tank shell and bottom plate, and (2) displacement-controlled uplifting of the tank shell. The fluid pressure loading in the first load step was representative of the minimum net hydrostatic and hydrodynamic pressure value at tank overturning failure. Sensitivity studies indicated that the effect of fluid pressure on the analysis results was not significant and further refinement was unnecessary. The second load step was applied using a prescribed displacement at the top boundary of the tank shell. Gravity loads were estimated to be insignificant and consequently not included in the analysis.

Analysis Results

Figure 5 shows the growth of anchor force with increasing tank uplift. The tank uplift was measured at the intersection between the tank shell and the chair top plate. Also shown in the same figure is a curve of the uplifting force versus tank uplift. Comparison of the two curves in Figure 5 indicates that most of the applied tank uplift was resisted by the anchor bolt, with a small amount resisted by fluid pressures applied on the bottom plate during the first load step. Figure 5 indicates significant ductility for the behavior being analyzed.

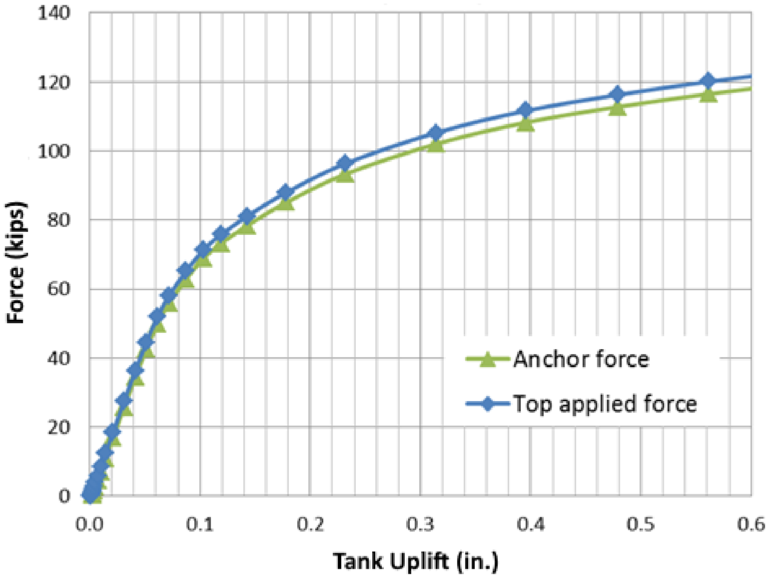

Figure 5. Pushover Curves

Figure 6 shows the Von Mises stress and PEEQ contour plots at 0.48 in. of tank uplift. The figure indicates large stress concentrations and plastic strains around the tank shell to chair top plate connection, with the largest plastic strains occurring in the tank shell. Analysis results were reviewed to confirm that the weld connecting the chair top plate to the tank shell was adequate to accommodate the large computed stresses. Figure 6 also indicates that the anchor bolt was subjected to flexure under tank uplift. An examination of the analysis results showed that as the tank uplifted, the top plate moved outward radially, while the bottom of the bolt chair did not due to restraint from the bottom plate. This resulted in rotation of the bolt chair, causing the anchor bolt to bend.

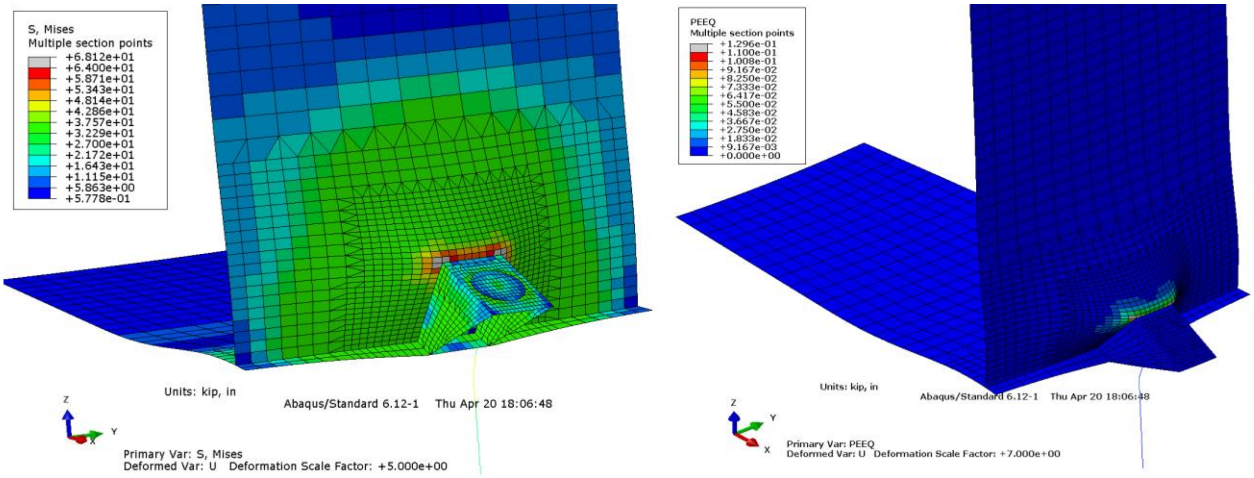

Figure 6. Von Mises Stress Contour Plot (Left) and PEEQ Contour Plot (Right)

Figure 7 shows the PEEQ versus tank uplift curves for the tank shell and the anchor bolt. The PEEQ values shown in the figure for the tank shell were computed as the average PEEQ across the integration points for the two most strained tank shell elements. Locations of these elements are shown in the same figure. The PEEQ values shown in Figure 7 for the anchor bolt correspond to the PEEQ values at the surface of the most strained anchor bolt element, which is identified in the same figure. The uniaxial strain capacity is same for both the tank shell and the anchor bolt (Figure 4). As such, Figure 7 indicates that tank shell strength governs the anchor bolt hold-down strength. Shear stresses in the anchor bolt were reviewed, and confirmed to be low.

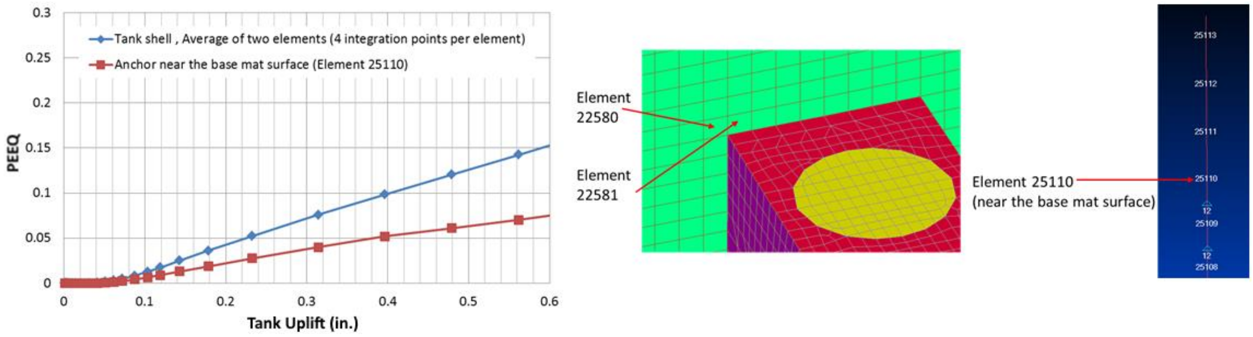

Figure 7. PEEQ versus Tank Uplift

Figure 8 compares the true strain capacity to PEEQ values for the tank shell computed at various stages of the pushover analysis. Like the PEEQ values, the true strain capacity at each stage was computed as the average value across the integration points for the critical tank shell elements identified in Figure 7. At 0.46 in. of tank uplift, the true strain capacity and the PEEQ curves intersect. The corresponding anchor bolt force is about 110 kip. Thus, the required median anchor bolt hold-down strength and the associated maximum permissible tank uplift are 110 kip and 0.46 in., respectively. This represents an improvement of more than a factor of two on the bolt hold-down strength, and more than a factor of 1.5 on the maximum permissible tank uplift.

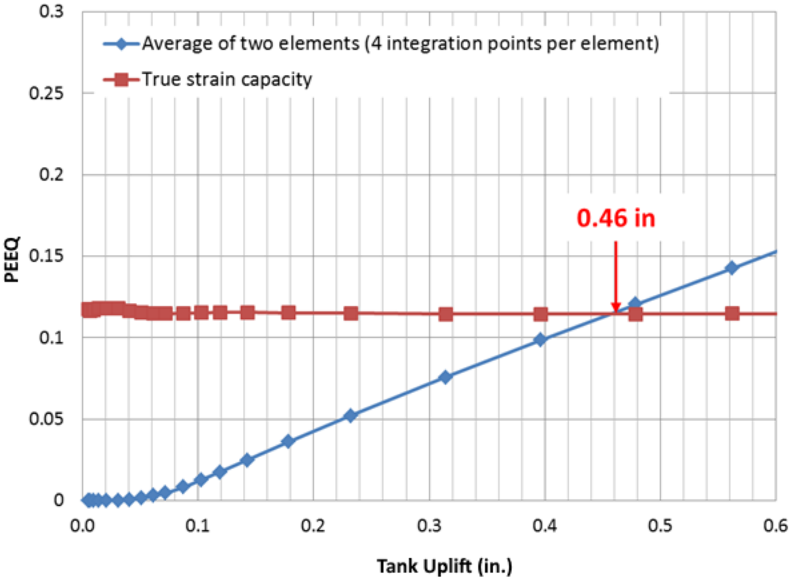

Figure 8. PEEQ versus True Stain Capacity for Tank Shell

Additional Discussion

Some sensitivity studies were performed to obtain insight into parameters that might be important to the analysis. The main observations and conclusions from these studies are summarized below:

- An analysis to consider large deformation effect was performed. The large deformations increased the anchor force at a given tank uplift. However, the plastic strains at the tank shell also increased. The overall effect on the analysis was thus determined to be insignificant. The large deformation analysis also confirmed that there is no buckling in the tank bottom plate.

- A model to allow the bolt to slide freely in the chair top plate bolt hole until it contacts the bolt hole edge was investigated. The force-uplift behavior is not significantly different after contact with the bolt hole edge.

- A model to allow the bolt to rotate independently of the chair top plate was investigated. Analysis results were essentially unaffected.

Based on insights gained from the pushover analysis and the sensitivity studies, it was noted that if the bolt rotation allowed the nut to lift off the top chair plate, the top chair plate would deflect and the nut would bear on its edge near the tank shell. This would reduce the eccentricity between the tank shell and the reaction on the top plate, thus reducing the out-of-plane flexural demands on the tank shell. The analysis results showed the ratio of anchor moment at the top to the anchor axial force to be much less than the nut radius. The results of the pushover analysis are consequently considered to be slightly conservative.

IMPROVED TANK OVERTURNING CAPACITY

The median tank overturning capacity was recomputed using the improved estimates of the anchor bolt hold-down strength and the maximum permissible tank uplift. A higher bolt hold-down strength increases the tank overturning capacity. A higher maximum permissible tank uplift increases the fluid hold-down forces, increasing the resistance against tank overturning. Due to substantial increases in these two parameters, the median seismic capacity for tank overturning improved by 70%. Because of the significantly improved seismic fragility, the tank's risk contribution to plant risk was essentially eliminated.

CONCLUSIONS

The nonlinear analysis performed for the tank under study computed a significantly higher anchor bolt hold-down strength than previously estimated from Equation 1. Analysis results also showed the behavior to be ductile, unlike the guidance in EPRI (1994), resulting in a significantly higher maximum permissible tank uplift than previously computed. Equation 1 and the guidance in EPRI (1994) concerning the non-ductile nature of the failure mode are thus shown to be conservative. The resulting improvement in the seismic fragility essentially eliminated any contribution to seismic risk from the tank.

SPRAs are intended to identify significant and realistic seismic vulnerabilities. The tank discussed herein was identified as a potentially significant seismic vulnerability in the initial stages of the SPRA. The detailed nonlinear analysis that was subsequently performed demonstrated that the tank presented no significant implications to the plant risk. This enhanced the quality of the SPRA for the plant. If not for the detailed nonlinear analysis, the tank would have potentially masked other, more realistic and significant contributors to the plant risk.

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