Agenda Item: 650-1121

Title: Using Finite FEA as an Alternate Tool to Verify Anchorage Requirements due to Higher Seismic Loads in Atmospheric Storage Tanks

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Purpose: Propose an alternate method to verify the anchorage requirements of storage tanks. An FEA is utilized to verify the resistance to the seismic overturning moment and uplift provided by the head of the stored product. The verification is performed using a static non-linear model of the full storage tank, where a seismic moment and uplift force acting on the tank shell are balanced by the dead weight of the tank shell and the annular portion of the floor that lifts the column of stored product.

Source: Presentation at the 2023 API Storage Tank Conference, Denver Colorado.

Impact: Eliminate the need and large expense to mechanically anchor storage tanks in areas with high seismic loads and coincident high vertical accelerations.

Rationale: Provide an option to design the annular ring to bottom shell ring by non-linear finite element analysis.

Background: Historically API seismic loads were based on ground motion based on a 10% probability of exceedance in 50 years or a 475-year event. In the last 15 to 20 years, the design criteria in ASCE 7[1] lowered this probability in less seismically active areas to 2% (2500-year event) and introduced very significant vertical acceleration loads. Both changes greatly increase seismic overturning moment and the need to mechanically anchor replacement storage tanks in which they were not originally designed. Also, the flexibility of attached piping needed to be assessed and modified. Unfortunately, the existing tank foundation most likely will not be sufficient to resist the vertical anchor forces or internal bending moments.

API Standard 650[2], paragraph E.6.2.1.1 defines this force resisting seismic uplift in the annular region, $\boldsymbol{w_a}$. The resistance to tank overturning is dependent on a radial width of

[1] "Minimum Design Loads and Associated Criteria for Buildings and Other Structures" ASCE/SEI 7-16, American Society of Civil Engineers.
[2] "Welded Tanks for Oil Storage", API Standard 650, 13th Edition, Errata 1, January 2021.

stored product lifted by the overturning moment. Wozniak & Mitchell[3] published a procedure in which the floor under the bottom shell ring was conservatively analyzed as a cantilever strip with two plastic hinges, one at the edge of the shell to floor and the other at a point on the deflected floor between the tank shell and the point where the floor initially lifts off the foundation surface. The practice at that time of publication was to limit this radial dimension to 3.5% of the tank diameter[4]. Wozniak & Mitchell state their assumptions were conservative as they did not account for two-dimensional membrane stress and plastic strain in the annular ring. The Wozniak and Mitchell paper did not consider nonlinear finite element analysis when limiting counterbalance as it was not available at the time of publication.

Recently API revisited the basis of design for the pressure limits of previous versions of specification 12F[5] when the document was transferred from the Production Committee. The bottom to shell region was analyzed by nonlinear finite element analysis and specific upgrades as well as an increase in design pressure to the 13th edition were incorporated.

Example of an External Floating Roof Tank in Southern California

A nonlinear finite element analysis was performed on an existing tank. The design information on this tank was as follows:

- Diameter – 100 feet
- Shell Height – 48 feet
- Liquid Level – 46 feet
- Vertical Acceleration, %g – A_V = 0.448
- Liquid Specific Gravity – 0.865
- Effective Specific Gravity, G_e= 0.71
- Annular Ring Material – A537 (Yield / Ultimate Tensile Strength) 50 / 70 ksi - 0.5 inch thick
- Shell & Bottom Material – A36 (Yield / Ultimate Tensile Strength) 36 / 58 ksi - 0.25 inch thick
- Bottom Shell Ring Thickness – 0.596 inch
- Ringwall Moment, M_{rw} – 67,856 kip-ft
- Seismic Uplift – 8640 lb/ft
- Shell and participating roof weight at base of shell, w_t = 1174.5 lb/ft
- No internal pressure, w_{int} = 0

[3] "Basis of Seismic Design Provisions for Welded Steel Oil Storage Tanks", R. S. Wozniak & W. W. Mitchell, American Petroleum Institute, Subcommittee on Pressure Vessels & Tanks and Manufacturers Subcommittee on Tanks & Vessels, 1978 (See Appendix)

[4] "Lateral Seismic Loads on Flat Bottomed Tanks", R. S. Wozniak, The Water Tower, November 1971.

[5] "Specification for Shop-Welded Tanks for Storage of Production Liquids", API Specification 12F, 13th Edition, January 2019

- Force Resisting uplift, w_a (lb/ft)

  An ABAQUS finite element model was generated using 8 node axisymmetric elements. An elastic modulus of 25000 psi was applied to the foundation. The seismic moment was converted into a couple at the top of the shell. This uplift was resisted by the weight of the shell under a triangular head load and a portion of the liquid head acting on the tank bottom that lifted off the tank foundation. The center of the tank floor was fixed in all planes of translation and rotation. The tank bottom was restrained from settlement.

  The results show in Figure 1 that the width of participating resistance to seismic uplift is approximately 5.5% of the tank diameter, 45% greater than the current API limitation.

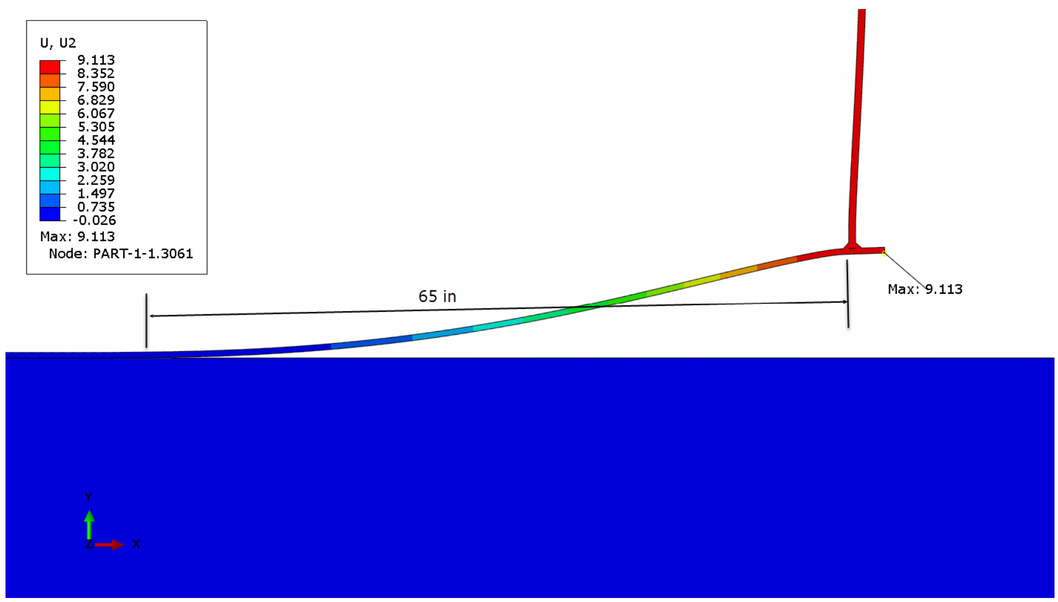


Figure 1. Shell uplift and the radial participating length of seismic resistance.

Observations and Conclusions

After reviewing the deflection of the tank floor in Figure 1, the basic assumption of two plastic hinges in Wozniak & Mitchell[2] in confirmed in the model. The reduction of tank head by using a lower effective specific gravity, G_e greatly increased the active length of the lifted annular ring (65 inches) and the vertical shell deflection (9 inches). Although this deflection may seem high, it has been noted that tank column guides were raised to one foot to prevent columns from jumping out of their guides during an earthquake.

An anchorage ratio is calculated in API 650[1] (eq. E.6.2.1.1.1-1) to determine if the tank requires anchorage. The uplift resistance, $\boldsymbol{w_a}$ is determined by calculating the effective weight of a column of liquid of 65” wide by 46 feet tall times the effective specific gravity, G_e. This calculated value is three times the current limit in the current version of API-650[1].

$M_{rw} := 67856\text{kip}\cdot\text{ft} \qquad D := 100\text{ft}$

$w_t := 1174.5 \frac{\text{lbf}}{\text{ft}} \qquad A_v := .448$

$w_a := 9548.8 \frac{\text{lbf}}{\text{ft}}$

$$J := \frac{M_{rw}}{D^2 \cdot \left[w_t \cdot (1 - 0.4A_v) + w_a\right]}$$

$J = 0.645$ << 1.54 Tank is stable - No anchorage needed

As a result of this example, the tank is stable. No anchorage or ringwall modification would be required. Should one consider reducing the liquid height by the sloshing wave height calculated in equation E.7.2-1, the anchorage load might increase 20%. But in this example, the tank would still be stable.

It must be noted the increased size of the annular ring would add to the cost of modifying an existing tank, but this cost would be pale in comparison to adding a reinforced spread footer to an existing ringwall or moving the tank and installing a reinforced concrete foundation. Furthermore, the interconnecting piping would require modification to ensure sufficient flexibility to withstand the 9 inches of vertical shell deflection shown in Figure 1. The higher bottom deflection is caused by the significantly larger annular ring. If the annular ring thickness were increased, the plastic strain, and Von Mises stress within the junction of the shell to tank bottom should be carefully investigated.

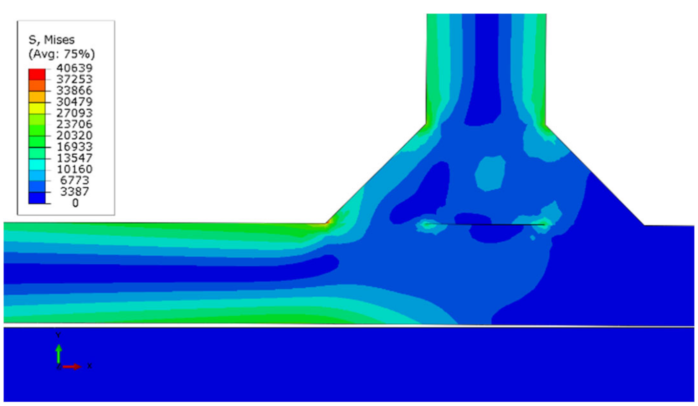


Figure 2. Von Mises Stress Prior to Edge Lift Off

The von Mises Stress of the floor to shell junction is low and shown in Figure 2. The high stresses at the fillet weld can be ignored as it is a geometric anomaly.

The example was shown as a proof of concept to document the increase in counterbalance. A full ASME Section VIII, Div. 2, Part 5 analysis is not shown and is proposed below.

Proposal: The subgroup discussed in detail wording of the scope of Annex E. While the scope mentions the Annex provides minimum requirements, the use of FEA to determine an alternate method to determine the resistance to uplift is intended to be applied within the existing rules and not an alternate within the scope of Annex E.

The subgroup discussed whether this is applicable to API-653, all but one reference to seismic analysis in API-653 refers the original code of construction for the tank. The only reference to the current applicable seismic standard is in section 8.8 is for Reconstructed tanks. That is required for a dismantled tank that is relocated to a new site and reassembled.

The subgroup raised the concern that specific direction needs be given for the nonlinear finite element analysis methodology employed for this detailed analysis. The subgroup noted that while API 650 addresses new construction, it does not reference API 579 / FFS-1 as it is intended to provide guidance for NB-23, API 510, API RP 570, API 653, and other post construction codes.

Changes: Append to paragraph in red font.

SECTION 2 – NORMATIVE REFERENCES

ASME Boiler and Pressure Vessel Code (BPVC) Section VIII Division 2, Part D - Design by Analysis Requirements
API Standard 620, *Design and Construction of Large, Welded, Low-Pressure Storage Tanks*

E.6.2.1 Anchorage

Resistance to the design overturning (ringwall) moment at the base of the shell may be provided by:

— The weight of the tank shell, weight of roof reaction on shell W_{rs}, and by the weight of a portion of the tank contents adjacent to the shell for self-anchored tanks. Tanks are permitted to be designed without anchorage when they meet the requirements for self-anchored tanks listed in E.6.2.1.1 or alternately as determined by non-linear finite element analysis employing all load case combinations in ASME Section VIII, Div. 2, Part D.

PRESENTED AT THE SESSION ON
ADVANCES IN STORAGE TANK DESIGN
API, REFINING
43RD MIDYEAR MEETING
SHERATON CENTRE
TORONTO, ONTARIO, CANADA
TUESDAY, MAY 9, 1978

Appendix

BASIS OF SEISMIC DESIGN PROVISIONS FOR WELDED STEEL OIL STORAGE TANKS

SPONSORED BY
S/C ON PRESSURE VESSELS AND TANKS
MANUFACTURERS S/C ON TANKS AND VESSELS

R.S. Wozniak
Chicago Bridge & Iron Company
Oak Brook, Illinois

and

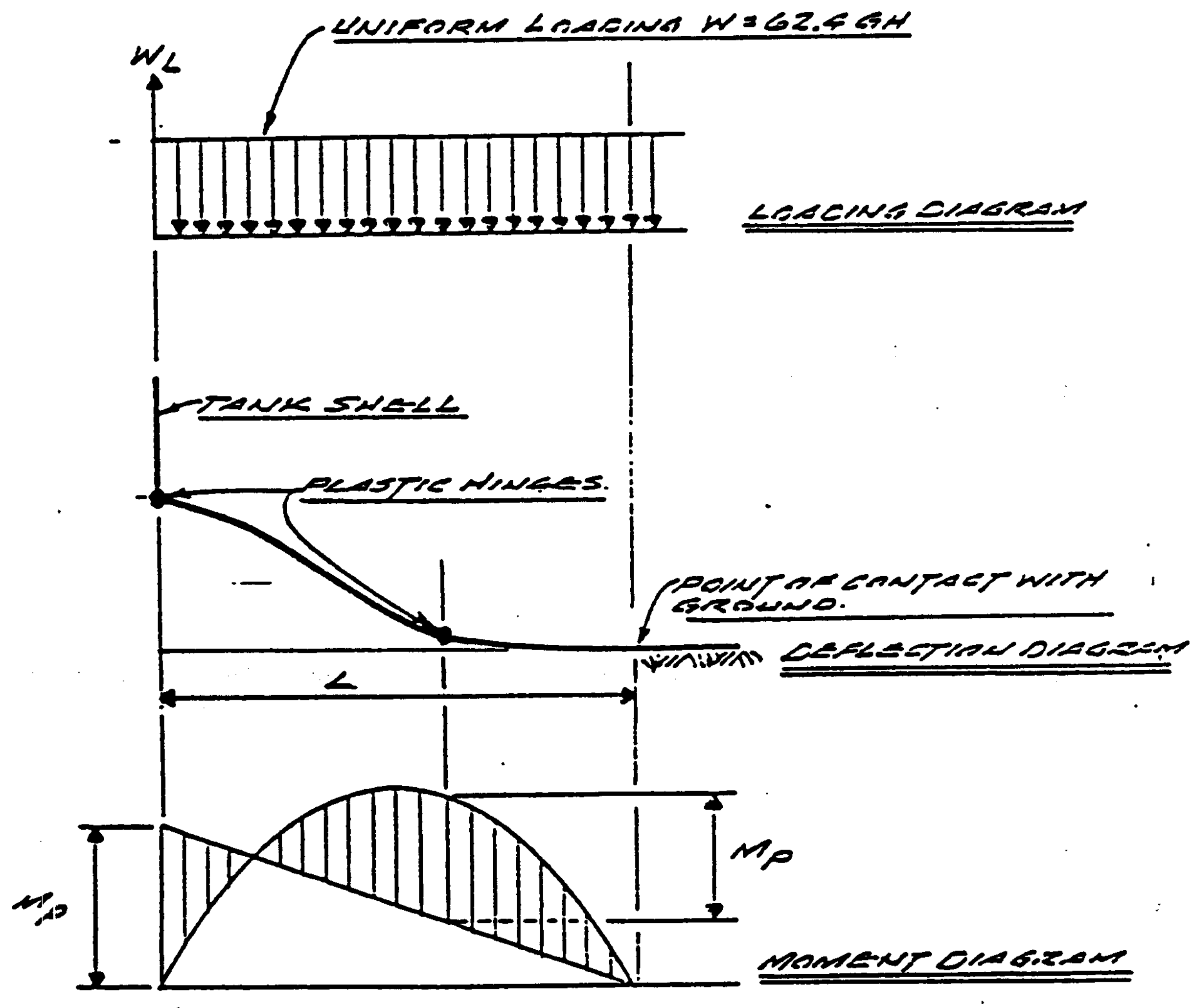
W.W. Mitchell
Standard Oil Company of California
San Francisco, California

CBT—5359

fuel for power generating facilities which are essential for emergency postearthquake operations.

RESISTANCE TO OVERTURNING

The factors which may contribute to resistance of the overturning moment are noted in paragraph P.4. The weight of the contents which may be utilized to resist overturning is based on the calculated reaction at the tank shell of an elemental strip of the bottom plate perpendicular to the shell which can be lifted off the ground. The calculation is based on small deflection theory and assumes the development of two plastic hinges, one at the junction to the shell and the other at some distance inward from the shell. The assumed loading, deflection and moment diagram are shown below:



The equilibrium solution leads to the following relationships:

$$w_L = 2\sqrt{w M_p} \tag{11}$$

and

$$L = 1.707 \frac{w_L}{w} \tag{12}$$

Substituting $M_p = \frac{F_{by} t_b^2}{4}$ and $w = 62.4GH$,

$$w_L = 7.90 t_b \sqrt{F_{by} GH} \tag{13}$$

and

$$L = 0.0274 \frac{w_L}{GH} \tag{14}$$

Practice has been to limit the uplift length, L, to 6 to 7 percent of the tank radius [9]. The limitation of w_L to 1.25 GHD limits L to about 6.8% of the radius. Recent shaking table model tests of tanks [10] show significant changes in the response characteristics which are not accounted for by current design procedures when greater amounts of uplift occur.

The above procedure to establish the maximum resistance of the liquid contents to overturning of the tank is conservative since it does not take into account membrane stresses which will develop in the bottom upon uplift. Further studies need to be undertaken to better determine the uplift resistance and to account for the changes in response when large amounts of uplift occur.

SHELL COMPRESSION

Methods for determining the maximum longitudinal compression force, b, at the bottom of the tank shell are