Structure-Fluid Interaction Analysis of an Existing Water Tank

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Abstract

An analytical study was completed investigating the cause and consequences of significant vibrations resulting from the operation of a hot water storage tank. Deformations and strain readings of the tank wall were measured during the operation and used to calibrate and validate results from the analytical model.

The steel storage tank is supported on a concrete foundation. The diameter of the tank is 18 meters and the height is 28 meters. The shell wall thickness varies in steps as plate segments reduce in thickness from 16.2mm at the bottom to 6.7 mm near tank mid height and above. A 64 inch diameter pipe at the top of the tank supplies the inflow water. Three 42 inch and two 36 inch diameter discharge nozzles are located near the bottom of the tank.

The tank wall has been observed to be "breathing" at low water levels. These vibrations reduce as the tank water level increases.

In order to evaluate the deformations and stress level of the tank, optical measurement of the deformations and strain gauge readings for inflow rates of 4500, 6000 and 8500 m^3/hr were performed. The results were then used within a calculation to check for fatigue failure.

To study the dynamic behavior of the hot water tank, a set of FE (Finite Element)-CFD (Computational Fluid Dynamics) models were prepared at flow rates of 4500 to 12500 m^3/hr. Standard shell elements were used to model the tank shell and both content and inflow water were modeled using the SPH (Smooth Particles Hydraulics) elements available in LS-DYNA®. Interaction between the structure and fluid was defined using contact scenarios.

These models were calibrated using the results of strain gauge readings and optical measurements. The size of the elements, geometry and physical properties were decided after numerous test analyses results were adjusted for consideration of certain variables. The final model represented the most critical arrangement considered.

Results of the analyses were within an acceptable range of the readings from the strain gauges. Scale factors were used to calibrate the FE results for better compliance. Field measurements and results from the analysis demonstrate stress levels and displacement increase with higher inflow rates.

Introduction

Fluid dynamics has interested scientist and engineers for many years. As early as the 1930's, research into dynamic fluid pressure due to earthquakes was investigated [1]. Fluid Dynamics has been considered an important topic in design of the dams and tanks. G. W. Housner (1954) carried out an analytical study and formulated the liquid dynamic loads and natural frequencies of various tanks and contents. API 650 code which is widely used for seismic analysis and design of liquid containment tanks is based on Housners' research. In recent years there has been numerous analytical, experimental and numerical studies that validate the simple concept presented by him [3, 4].

In the simplified method, the bottom and walls of the tank is considered to be rigid bodies. The fluid dynamics problem becomes more complicated when response of the structure is added to the fluid system. Unlike conventional structural systems where mass and stiffness of the system is constant, where there is fluid involvement, the effective mass and stiffness of the system can not be easily predicted. In addition, mode shapes imposed by the liquid should be considered in the analysis. For open surface tanks these modes include the bulging (tank wall oscillations moving the liquid) and sloshing (free surface waves that have amplitudes larger than the wall displacement).

In this study, fluid structure interaction has been investigated with emphasis on the structural component. There is a major difference in the numerical models that are used for structures verses those used for fluids. Lagrangian models that are based on force-displacement-stiffness equations are considered for the FE (Finite Element) structural models. Eulerian models based on the pressure-volume-energy equation of state are used for CFD (Computational Fluid Dynamics) analysis. LS-DYNA provides very effective tools to combine these two models for the study of the interaction.

Problem Description

The investigated hot water storage tank (Figure 1) has been designed and manufactured according to API 650 where only static hydro static pressure is considered in the design of the tank and no dynamic loads, either operation or seismic has been accounted for. The diameter of the tank is 18m and the height is 28m and the shell thickness varies between 16.2mm near the bottom to 6.7 mm in the upper half. The shell material conforms to CSA G40.21 260W. The tank is supported on a concrete pile cap. A 64 inch pipe at top of the tank supplies the inflow water and three 42 inch and two 36 inch diameter discharge nozzles are located near the bottom of the tank. The inflow water drops on the free surface of the tank from an elevation of 32m above the tank base and the free falling distance could be as high as 20 m for the minimum water level in the tank. The maximum inflow rate at the current operational stage is 8800 m^3/hr and that will increase to 12500 m^3/hr in the future.

The tank has been observed to be "breathing" and the attached piping and cladding becomes noisy especially at low water levels. These vibrations reduce as the tank water level increases. The maximum deformations occur at two locations; around the inlet pipe and at mid height of tank when water levels are 45-60% of the tank height. Observations suggested that these vibrations were caused by the dropping water mass on the free surface of the water, releasing considerable amounts of kinetic energy on the water surface and causing turbulence. The energy led to the vibration of the thin shell of the tank wall.

Figure 1: Hot water tank

Failure of the tank under excessive stresses or fatigue could cause some catastrophic results and interrupt the production. The owner requested a prompt investigation of the causes of these vibrations and a possible retrofit of the tank. A reliable study that could predict the fatigue life of the tank under normal operational conditions would indicate how early the retrofit should be planned.

Field observations and measurements

In order to perform a direct measurement of the stresses in the various sections of the tank, use of strain gauges was suggested. These gauges could collect strain data for several operating conditions of the tank and show how the stresses are distributed. Strain gauges should be installed at the points with maximum strain, however given the size of the tank, these maximum vibration points could not be located from observation of the tank. The challenge was to find a technique to measure the dynamic motion of the large tank shell at a sufficient number of points and to determine the fundamental mode shape of the tank vibration and location and magnitude of the radial displacements.

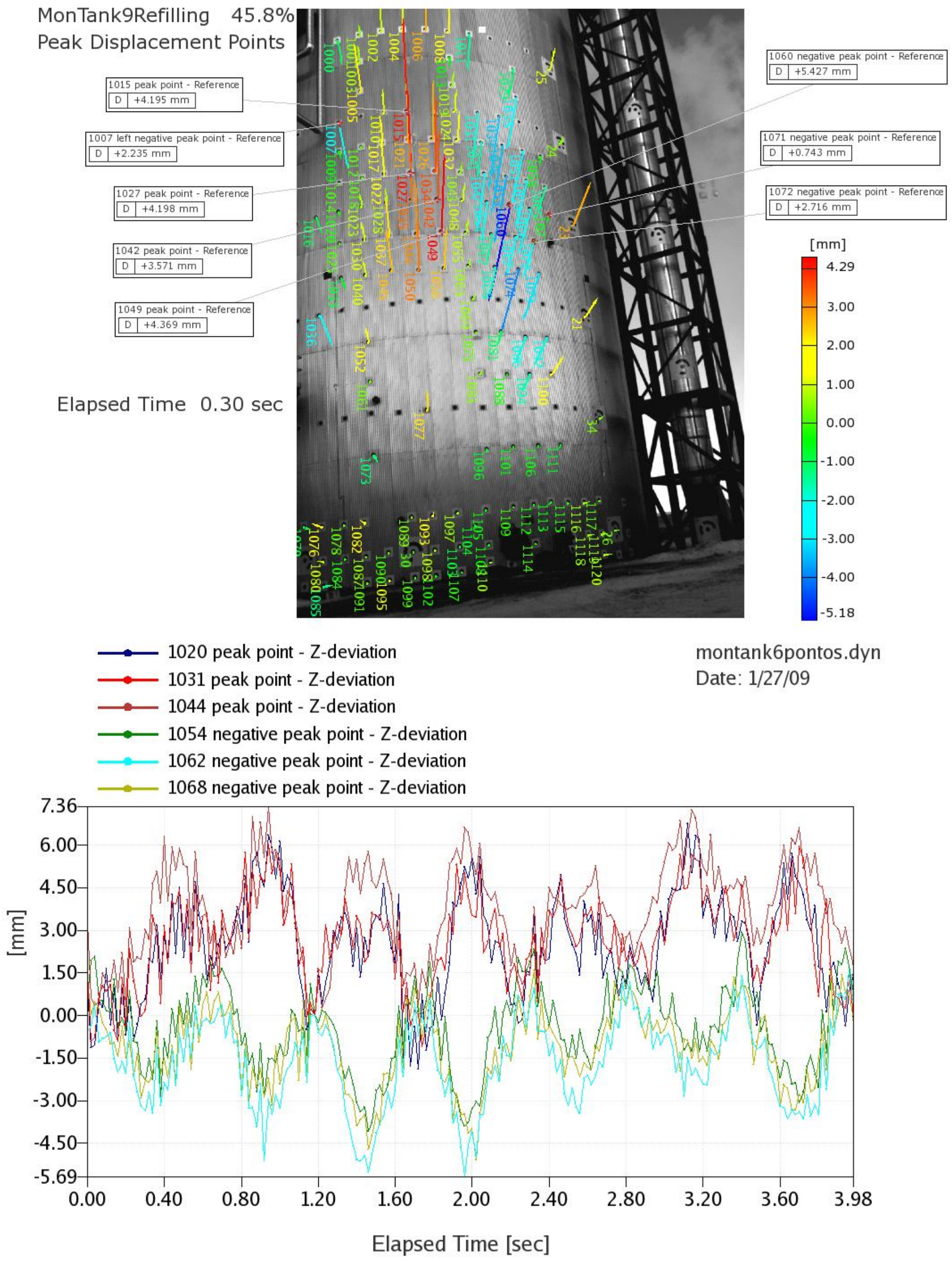

Figure 2: Optical measurement of the tank vibrations

A non-contact, optical dynamic measurement technique was used to capture the vibration of the tank. In this measurement, targets were attached to the tank and using stereo cameras installed at a distance of 10m from the tank and focused on these targets, high speed digital pictures were produced. Post processing of these images provided the precise measurement of the tank shell movement with a resolution of +/- 1 mm. These measurements were conducted for various tank levels and inflow rates. A sample measurement of the displacements imposed on the picture of the tank is shown in Figure 2.

Maximum displacements were observed around the inlet pipe and total of 64 strain gauges were installed on these points and also around the nozzles. Strains were collected simultaneously on these gauges at a rate of 1000 to 2048 readings per second at a resolution of 0.5µE (5e-7 mm/mm). Each snippet of 10 seconds was recorded at discrete tank levels from approximately 45 to 80% full during both draining and filling. Recordings were made at three flow rates of 4500, 6000 and 8500 m^3/hr. Strain ranges for selected gauges are plotted against the inflow rate in Figure 3. This graph shows a nonlinear increase in the strains with the rate of inflow water.

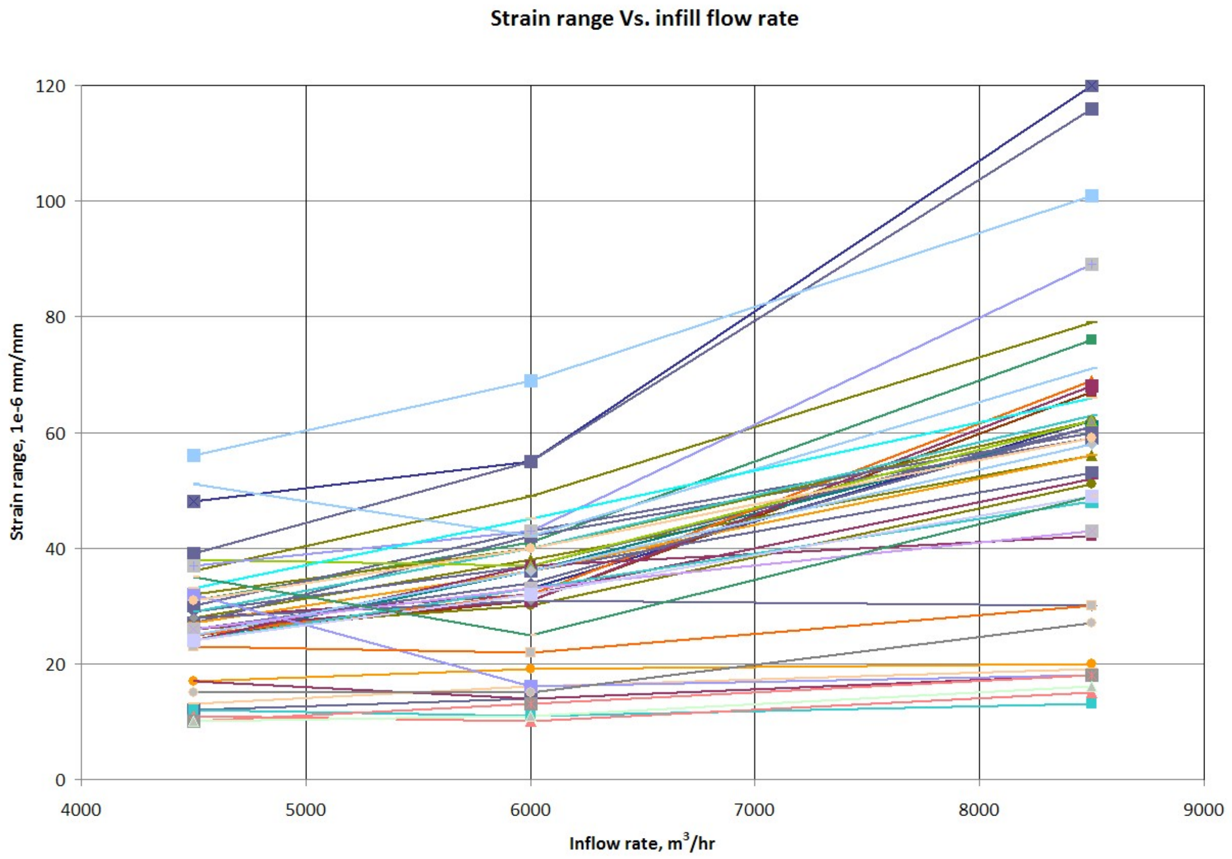

Figure 3: Strain range for various infill water flow rates

FE-CFD models

Strain gauge measurements of the tank provided a reliable basis for evaluating the tank performance under induced vibrations. Due to the operation restrictions at the duration of the recordings, only a maximum inflow rate of 8500 m^3/hr was provided. Although the stress range of the tank under this inflow rate appeared to be marginally below the limit and the tank could be operated for unlimited cycles, no measure existed for the performance of the tank under higher inflow rates.

To study the dynamic behavior of the hot water tank, using the LS-DYNA software a set of FE (Finite Element)-CFD (Computational Fluid Dynamics) models were prepared at flow rates of 4500 to 12500 m^3/hr. In order to validate the numerical process, models for 4500, 6000 and 8500 m^3/hr were calibrated using the available strain gauge readings. Standard shell elements were used to model the tank shell and both content and inflow water were modeled using the SPH (Smooth Particles Hydraulics) elements available in LS-DYNA. Interaction between the structure and fluid was defined using contact scenarios.

The FE model for the tank is shown in Figure 4. The tank base and the nozzles were considered as restrained nodes. The thickness of the shell was defined based on the tank drawings.

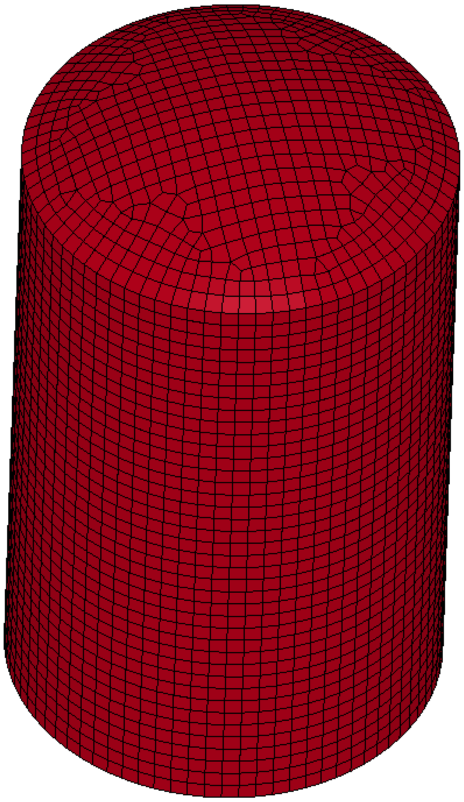

Figure 4, FE model for the tank

Viscosity of the water was corrected to 3e-4 N.s/m^2 at 98 ºC. Density of water was considered as 1000 kg/m^3 for single phase (Water) and 200 kg/m^3 for the two-phase state (Water-Air). It should be noted that only the density of the two-phase state is reduced and other properties were considered the same as single-phase state. The water level in the tank was modeled at 50% of the capacity. A section of the tank with the SPH elements as content is shown in Figure 5.

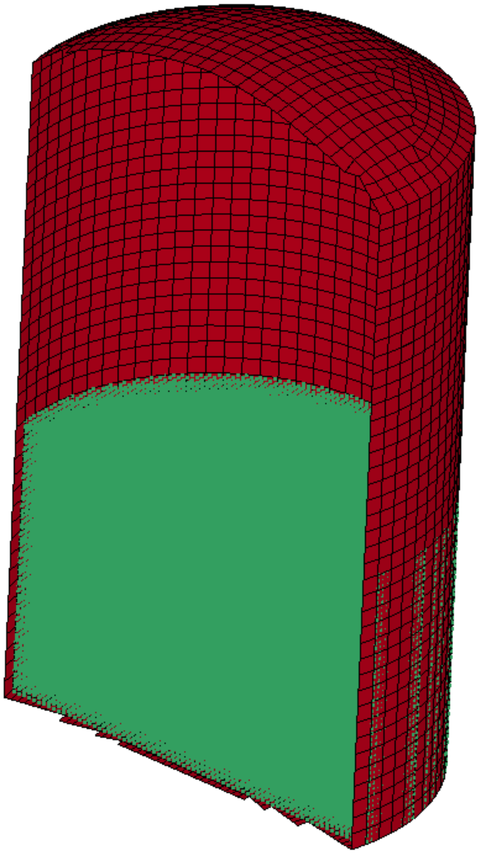

Figure 5, Cross section of the tank

The water was modeled using 0.25x0.25x0.25m particles. This element size was determined after performing a sensitivity analysis and also based on the hardware limitations. Considering the size of the tank, this element size produced results that were reasonably satisfactory and no further refinement was necessary.

Equations of state (relationship between pressure, energy and volume of the liquid or gas) were defined for the liquid. A linear polynomial equation of state as per LS-DYNA's definition with $C_0 = 0$ and $C_1 = 2.3e9$ was considered for the liquid.

Interaction between the structure and the fluid was defined using the contact option. "Automatic Nodes to Surface" option with the structural shell defined as master and the fluid particles as slaves.

For the inflow water, identical particle sizes and properties were used. Various geometries were assumed for the inflow water and the case with maximum deflections was chosen for the final models. Initially, a cylindrical continuous column of water impacting the free surface of water was assumed. In order to consider the possibility of fragmentation of the dropping water, an alternate model was prepared that considered disc shaped masses of water at certain spacings. The time interval between discs impacting the free surface was selected as 0.45 second. This was equal to the period for the dominant mode of the tank and was obtained from the preliminary analyses. It was expected that this harmonic loading would cause resonance in the tank causing vibrations close to the first mode shape of the tank. Finally, in order to avoid some numerical instability, discs were replaced with round volumes.

The third alternative produced the most critical results and was used for all final models. The size of falling balls was calculated for various flow rates. Figure 6 shows the above three options.

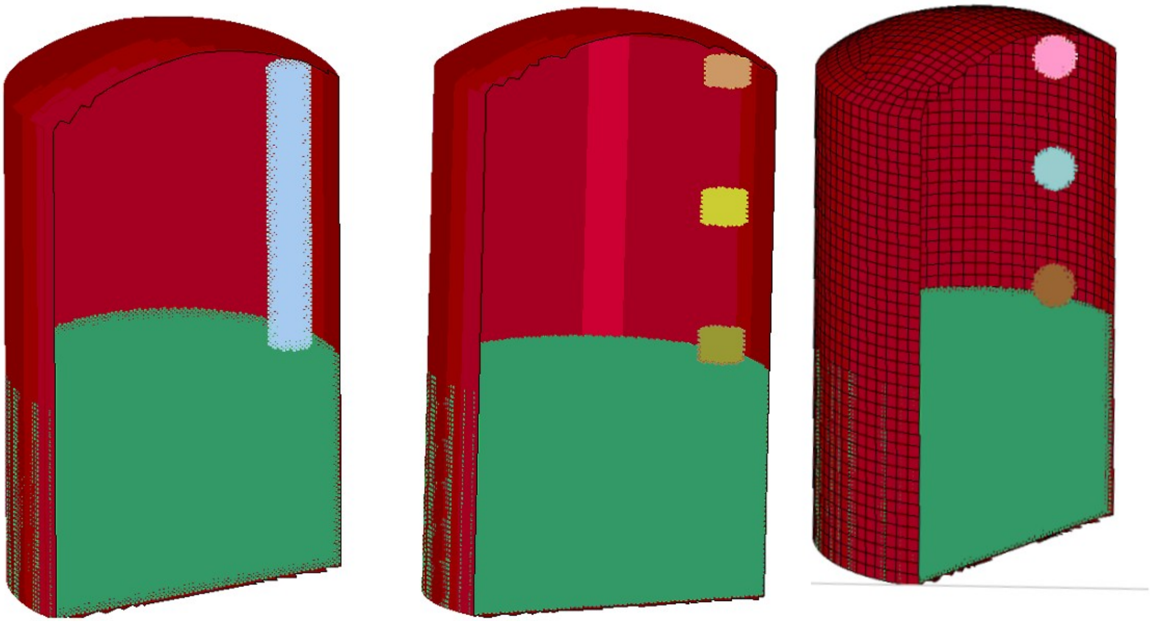

Figure 6, Continuous, Fragmented (Disc) and Fragmented (Round) inflow water

Results

Lateral displacement of the tank after impact is shown in Figure 7. Maximum displacement occurred immediately after the first impact and was followed by harmonic vibrations. However after a few cycles, vibrations attenuated quickly. This was expected as water in the vicinity of vibrating elements provides high damping. Figure 8 shows the maximum displacement in the tank for various flow rates. Maximum displacements increased for higher inflow rates. However the trend seems to be nonlinear as was observed from the strain gauge recordings. Figure 9 shows the stress distribution in the shell. Maximum stress was produced near the inflow pipe close to the water surface.

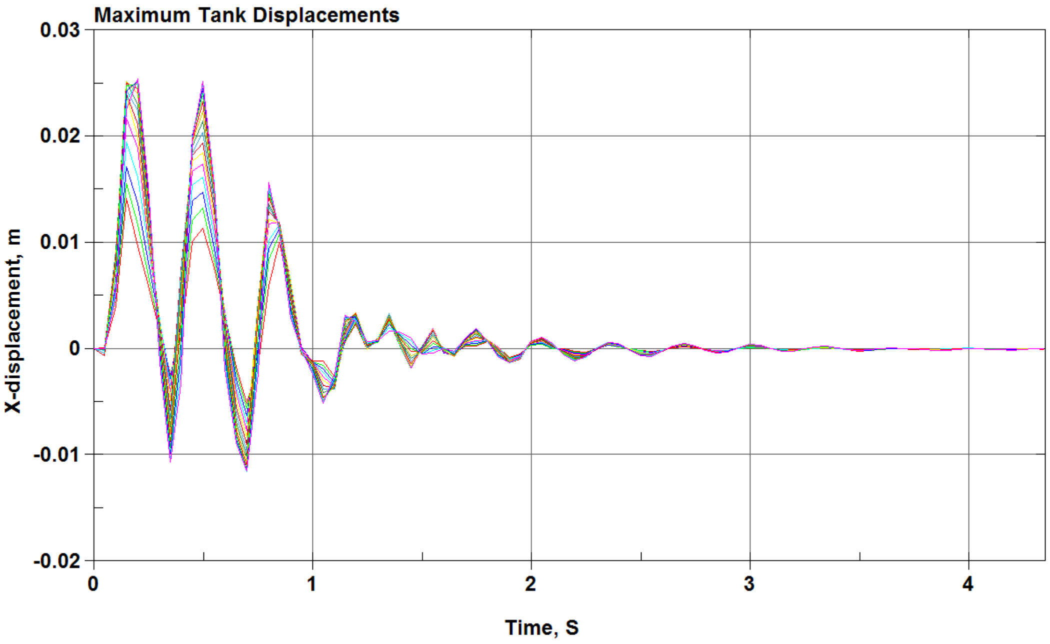

Figure 7, Maximum displacement of the tank for 12500 m^3/hr flow rate

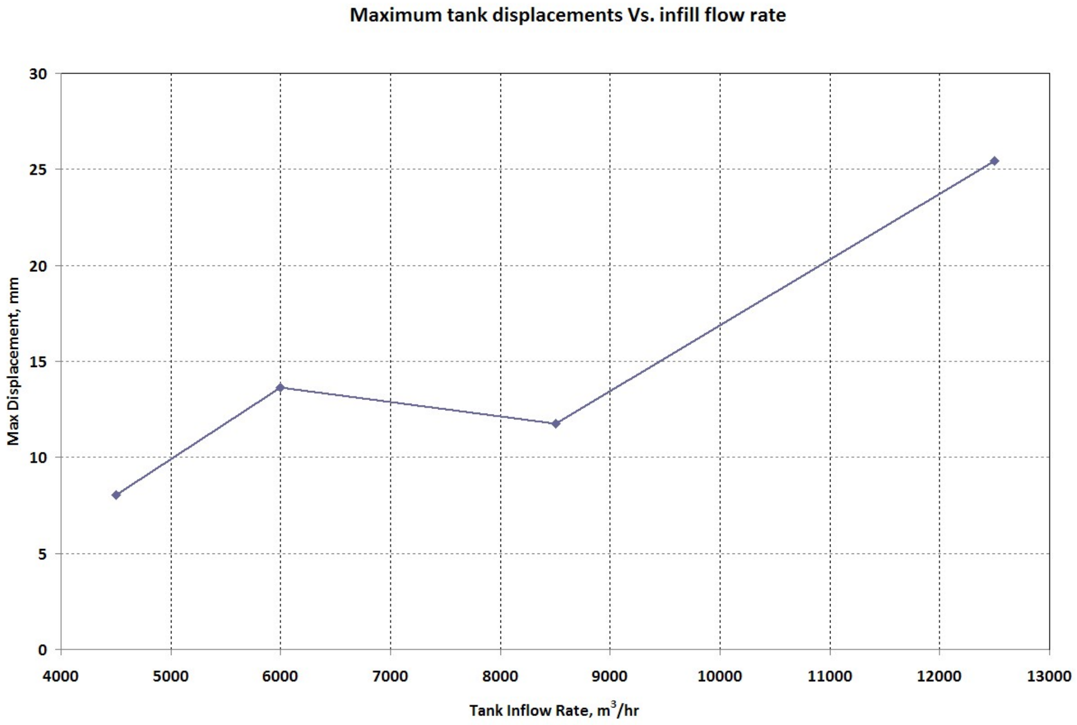

Figure 8, Maximum displacement of the tank for various flow rates

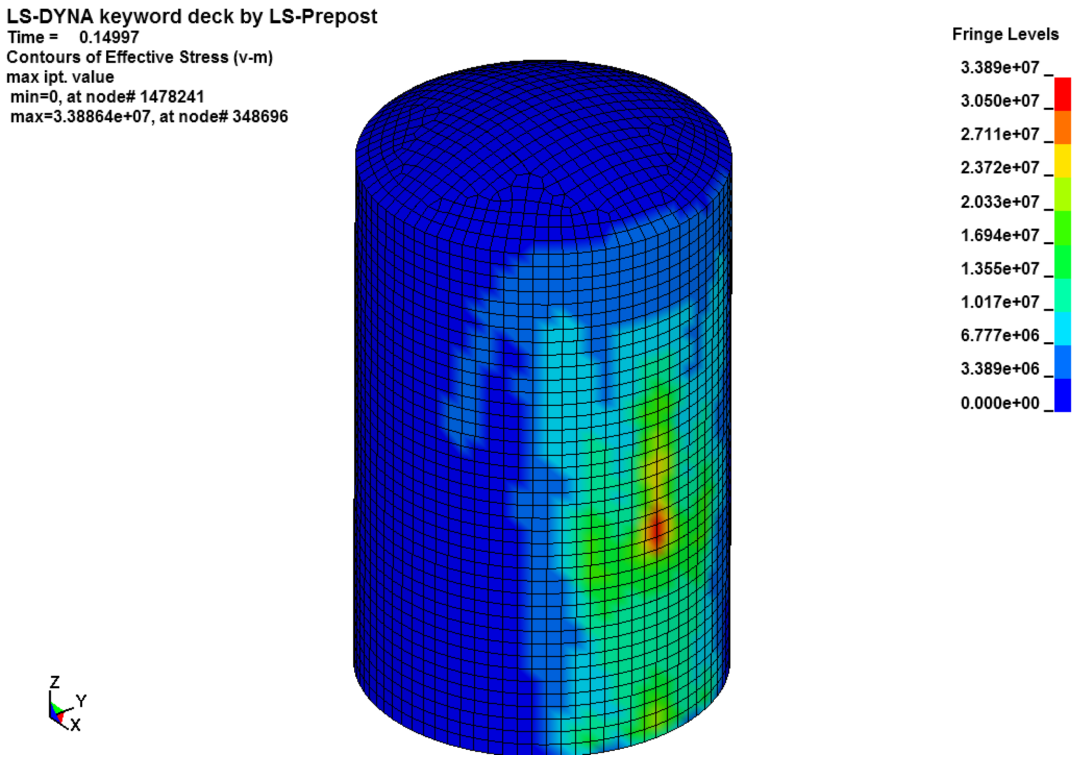

Figure 9, Maximum stresses in the tank for 12500m^3/hr flow rates

Calibration of the results

Stress values measured using the strain gauges were utilized to validate the results of the dynamic analyses. A total of 67 gauges were installed at the critical locations of the tank including the padded areas around the nozzles, several locations at the base of the tank where the shell is welded to the bottom plate and also two areas at mid height of the tank close to the inflow pipe where the maximum displacement was observed.

The strain gauge measurements were observed only for 4500, 6000 and 8500 m^3/hr rates and no data was available for the response of the tank under maximum flow rates of 12500 m^3/hr. The finite element analyses was carried out for the range of 4500 to 12500 m^3/hr and after calibration with the results of the strain measurements, were used for fatigue analysis of the tank. During the analysis, element size, geometry, impact parameters and node restraints were modified so that the results would be reasonably close to the measurements. Hence FE results were scaled up or down to match the measured stress patterns.

Figure 10 compares the strain gauge readings and FE results at the base of the tank. The results of the FE model before calibration were higher than the gauge readings that could be attributed to the stress concentration at the joint between the wall and bottom plates. The average ratio between the gauge readings and FE model at three flow rates were used to scale the results of the FE model. The outcome is also shown in the same figure.

Figures 11 and 12 show the comparison of the results from the FE model for the gauge readings at the body of the tank and at the nozzles. The calibrated results are also presented in the same graphs. In all cases, a sudden increase was observed for the stress range quantities at maximum flow rate. Using linear extrapolation between the results of the gauges, could under estimate the stress level at the maximum flow rate.

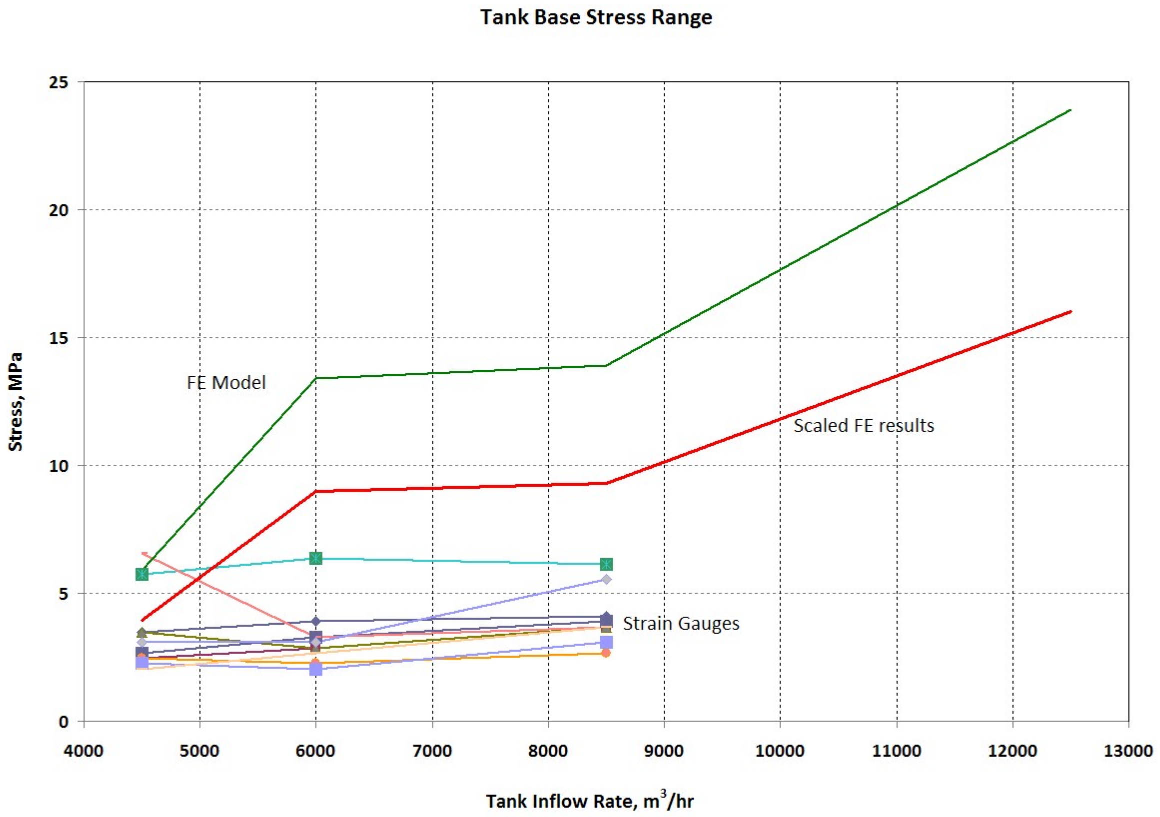

Figure 10, Maximum stress range values at the base of the tank

Summary and conclusions

In order to estimate the performance of the tank at its future operational level, a series of FE analyses were performed. The size of the elements, geometry, physical properties and sensitivity of the results to certain variables were decided after numerous test analyses and final models represented the most critical arrangements.

Results of the analyses were within an acceptable range of the readings from strain gauges. However scale factors were used to calibrate the FE results for better compliance.

Stress levels and displacement showed an increase for higher flow rates. The increase rate was larger for higher flow rates. Thus extrapolation of the gauge results would underestimate the stress at 12500 m^3/hr flow rates.

Calibrated flow rates could be used for the fatigue analysis at the future operational flow rate of the tank.

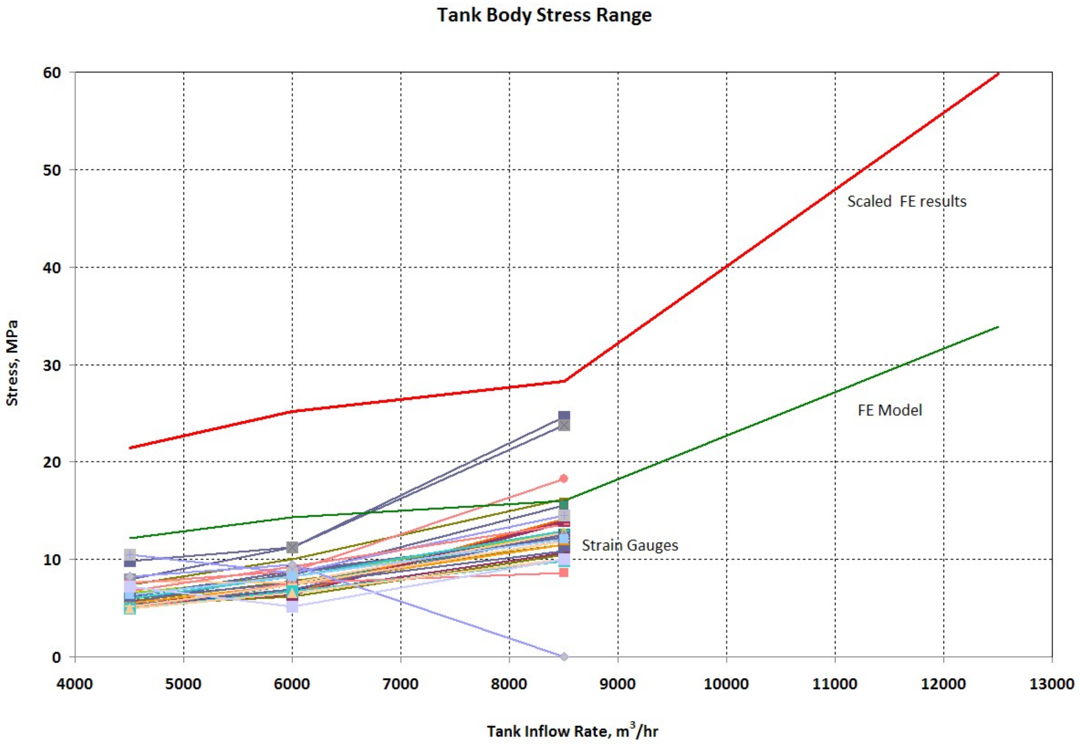

Figure 11, maximum stress range values at the body of the tank

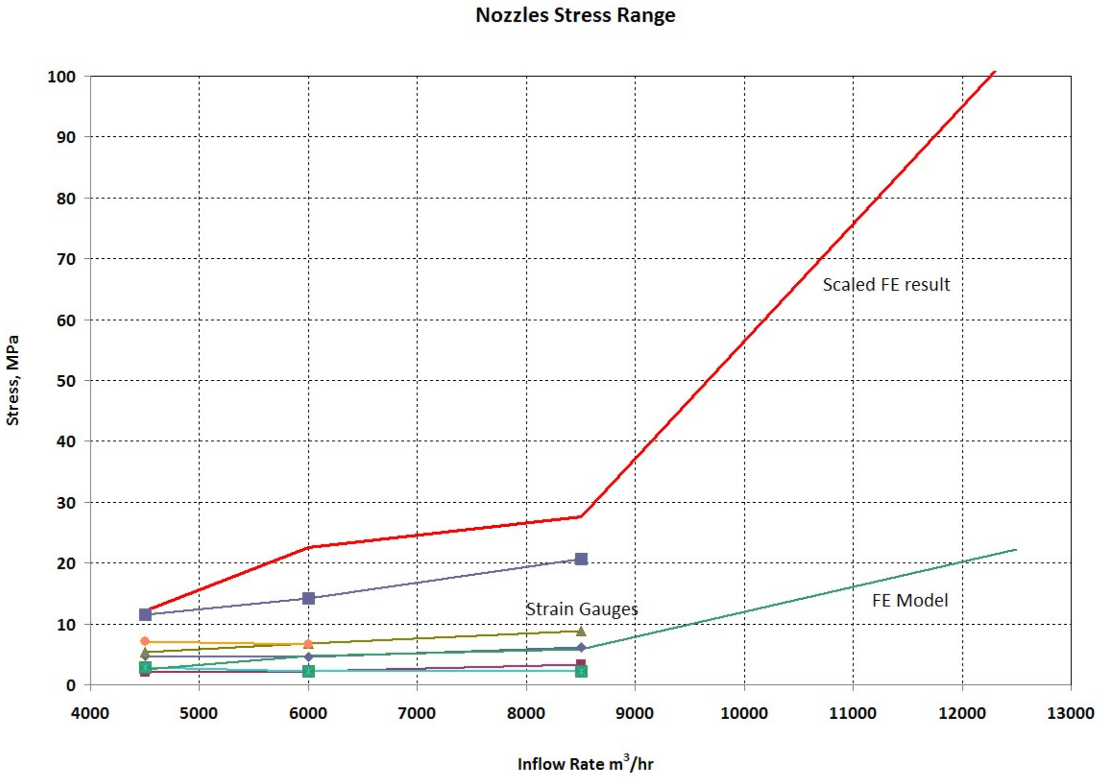

Figure 12, maximum stress range values at the nozzle locations

References

1. H. M. Westergaard, Water Pressure on Dams during Earthquakes, Trans. Amer. Soc. Civ. Eng. Vol. 98, 1933
2. G. W. Housner, Earthquake pressure on Fluid Containers, Eight Technical Report under Office of Naval Research 1954.
3. Sami A. Killic, Zuhal Ozdemir, Simulation of Sloshing Effects in Cylindrical Containers under Seismic Loading, 6.LS-DYNA Anwenderforum, Frankenthal 2007.
4. M. Amabili et al., Vibration of Partially Filled Cylindrical Tanks with Ring-Stiffeners and Flexible Bottom, Journal of Sound and Vibration 1998, 213(2), 259-299.
5. API Standard 650, Welded Steel Tank for Oil Storage, Eleventh Edition, June 2007.