JSEE Vol. 23, No. 1, 2021 DOI: 10.48303/jsee.2022.252304

Research Paper

A Method for Seismic Protection of Liquid Storage Tanks By Disconnecting the Tank Wall from the Base and Using Energy Absorbing Circumferential Connection

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Received: 30/01/2019
Revised: 27/02/2022
Accepted: 23/05/2022

ABSTRACT

Ground-supported cylindrical tanks are used to store a variety of liquids, e.g. water for drinking and fire-fighting, crude oil and liquefied natural gas. Tanks are critical components of modern industrial facilities and life-line systems, and must be designed to withstand safely the earthquakes to which they are subjected. The failure of such systems may lead to environmental hazard, loss of valuable contents, and disruption of fire-lighting elements following destructive earthquakes. Water storage tanks, in particular, are important to the continued operation of water distribution systems in the event of earthquakes. Recent earthquakes have shown liquid storage tanks to be vulnerable to damage. Elasto-plastic shell buckling called "Elephant's Foot" Buckling (EFB) has been the critical aspect in the earthquake resistant design or retrofit of steel cylindrical tanks. In this paper, an innovative method based on using seismic energy absorbing connection at the base of tank wall is introduced to protect the liquid storage tank against seismic loads. In this method, the tank wall is fully disconnected from the base plate and the special connection is provided at the bottom of the tank. The connection is supported by a ring of rigid foundation and the base plate is supported directly on the ground. The seismic performance of the method is numerically examined for one broad and one slender steel tank. It is shown that this method can prevent the EFB of the tank wall by using the plastic deformation of the connection. Numerical results confirm the efficient performance of the proposed system to reducing seismic vulnerability of shell tanks.

Keywords:
Liquid storage tank; Shell buckling; FEM; Seismic design

1. Introduction

Liquid storage tanks are important elements of lifeline and industrial facilities. The evolution of codes and standards for the seismic design of these structures has relied greatly on observations of tank damages during past earthquakes, yet the time lag between acquiring the information and implementing the findings in practice has remained relatively long. Even though current codes and standards reflect a mature state of knowledge for tank design, recent earthquakes as well as advanced state-of-the-art analyses continued to point out to a few overlooked issues.

Failure modes of ground-based tanks included, among others, shell buckling that is typically characterized by diamond-shaped buckles or "Elephant's Foot" bulges (EFB). EFB that is the plastic deformation of the lower part of a side walls is one of the typical types of damage on a cylindrical liquid storage tank caused by an earthquake (Figure 1). EFB drew wide attention when it occurred on an oil tank under the Alaska Earthquake (1964) and on a water tank at Olive View Hospital under the San Fernando Earthquake (1971). EFB had high probability of inducing cracking at a tank corner, resulting in serious liquid leakage.

Figure 1. EFB phenomenon observed in past earthquakes [1].

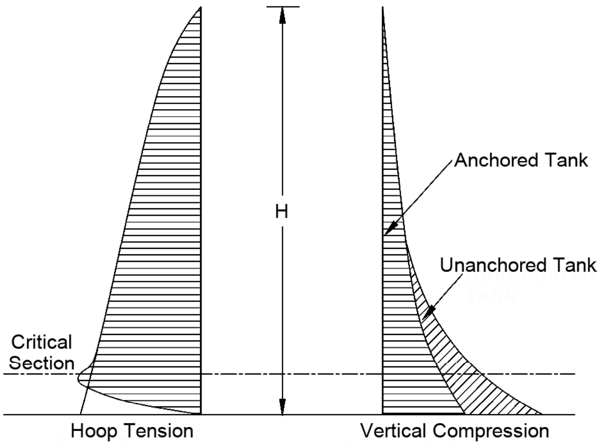

Figure 2. Stress distribution along the height of liquid storage tanks.

EFB at the side wall of a tank can be regarded as large deflection accompanying plastic deformation induced by circumferential tensile stress produced by internal pressure such as liquid pressure and vertical compressive force due to the overturning moment under an earthquake.

It occurs near the tank base predominantly due to the axial stress in the tank wall, though it is significantly affected by the circumferential membrane stress caused by hydrostatic and hydrodynamic pressures.

The axial compressive stress developed at the base of tanks under seismic excitations must be less than an allowable buckling stress to preclude the occurrence of shell buckling. The allowable stress in current codes and standards is basically specified for a uni-directional stress state whereas the actual stress state at the shell bottom is bi-axial. Figure (2) shows the schematic distributions of axial and hoop stress along the tank height for anchored and unanchored tanks.

Response of ground supported liquid-storage steel tanks to strong ground shaking differs from that of building structures. Due to the fact that EFB had high probability of inducing cracking at a tank corner, resulting in serious liquid leakage, the current design guidelines against seismic loads usually do not take into account the energy absorbing capacity of tank walls. Therefore, in order to seismically protect the liquid storage tanks, the plastic deformation of the tank wall should be retarded.

Some methods are proposed by previous researchers to postpone the buckling of tank wall by mitigating the buckling stress of seismic loads. For example, seismic isolation, as an approach for reducing the earthquake consequences on liquid storage tanks, has been introduced in recent years in some practical projects alongside a number of researches. Conducted experimental investigations on base isolated tanks have shown that reduction in hydrodynamic pressures and increase in sloshing height are the consequences of using isolation techniques [2-3]. Also, several theoretical studies on seismic isolation of tanks have revealed similar results with regard to the aforementioned response characteristics while their aims were different [4-9]. In the isolation approach, damping characteristics of the system has an important role in reducing the displacements that are reluctant effects. Some investigations have been conducted in recent years in which viscous or friction devices have been used, representing the most common approach [2, 6]. Based on the investigations conducted in this regard, the advantage of seismic isolation of liquid storage tanks is to reduce hydro-dynamic pressures that result in lower overturning moment and base shear while reducing the probability of shell buckling and uplift.

Although, using the isolation technique reduce the seismic stress in the tank wall, but due to larger displacements in seismically isolated tanks, connections and pipes with more flexibility are required. Also, the implementation cost of this method is respectively very high for liquid storage tank. Moreover, using this approach may lead to greater sloshing height compared to fixed base tanks.

In the present study, the innovated method based on employing new tension connection on the bottom part of the tank is introduced and numerically examined in the following section.

2. Introducing the Innovated Method

The innovated method of protecting grounds supported liquid storage metal tanks is being proposed here, includes providing an energy-dissipating seismic connection designed to absorb seismic energy and postpone EFB of shell. In this method, the wall of the tank is disconnected from the base plate and the relation between base plate and tank wall is indirectly reconnected by new tension plate supported on the extended base plate, as shown in Figure (3). In this figure, the vertical section through a liquid storage metal tank equipped by a preferred embodiment of the invention is presented. Also, an enlarged side elevation view of a preferred plate of the invention is shown in Figure (3).

The method includes, from the broad standpoint, fixing the liquid storage tank is fixed around its full periphery by energy dissipating connection, which is completely adhered between the tank and a base plate and absorb seismic energy by yielding during seismic loads. This connection can form in other configurations (as shown in Figure 4), which typically consists of a vertical plate circumferentially surrounded the tank wall and the supported heel. It should be noted that the tank wall should be fully disconnected from the base plate. Also, the ring rigid foundation should be provided under the tank wall. This proposed connection could also be supposed as a practical and inexpensive anchoring device.

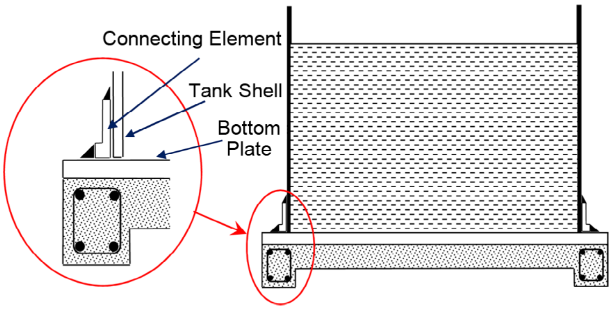

Figure 3. Liquid-storage tank equipped with the proposed circumferential energy dissipating connection.

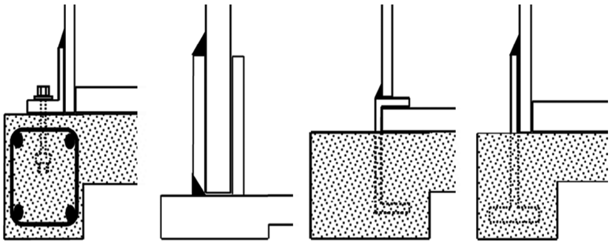

Figure 4. Other possible configurations for the proposed connection.

During strong ground shaking, the axial tensional and compressive stresses in the tank shell, and consequently the wall of the tank uplifts on one side and pushes down the base plate on the opposite side due to the hydrodynamic overturning moments (Figure 5).

By properly designing of the connection plate thickness, the vertical movement of the tank wall on tension side of tank wall causes yielding of the plate. Hence, the compression buckling forces experienced by the tank wall on the other side is reduced. The vertical sectional view of the tank showing the operation of the invention and the

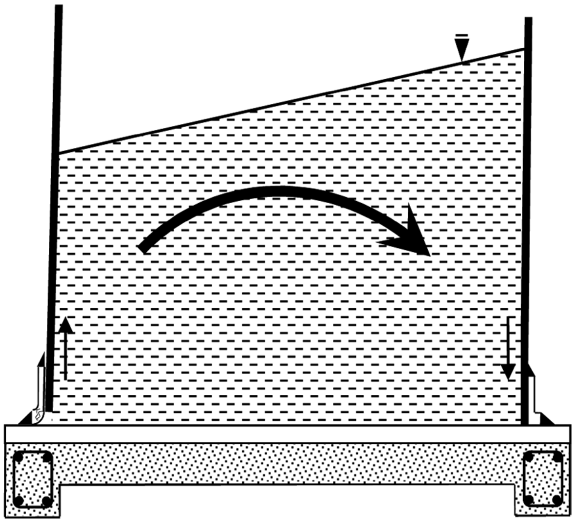

Figure 5. Reaction of an equipped liquid storage tank to seismic ground shaking.

reaction of a liquid storage lank to severe seismic ground shaking is shown in Figure (5). For weak ground shaking, the yielding of the plate does not occurred; hence, the system behaves as a rigidly anchored system. In contrast, for strong ground shaking, the loss of seismic energy takes place by plastic displacement, which occurs in connected plate. The seismic performance of the introduced method is numerically examined and shown in next section using Finite Element Method (FEM).

3. Numerical Assessment of the Method Performance

A quasi-static large displacement finite element analysis was performed on two steel tanks - one broad and one slender - to investigate the seismic capability of the innovated.

3.1. Nonlinear Buckling Analysis Approach

A nonlinear buckling analysis is a static analysis with large deflection active, extended to a point where the structure reaches its limit load or maximum load. In order to perform a three-dimensional nonlinear EFB at the side wall of a tank, the material nonlinearity is also considered besides of geometrical nonlinearity. The basic approach in a nonlinear buckling analysis is to constantly increment the applied loads until the solution begins to diverge.

A full Newton-Raphson solution approach is used due to better convergence characteristics for the very large displacements obtained. The analysis is extended into the post-buckled range by activating the arc-length method. The arc-length method is suitable for nonlinear static equilibrium solutions of unstable problems. Application of the arc-length method involves the tracing of a complex path in the load-displacement response into the post buckling regimes. The arc-length method uses the explicit spherical iterations to maintain the orthogonality between the arc-length radius and orthogonal directions [10].

3.2. Finite Element Model and Boundary Conditions

The Finite Element (FE) method is utilized to model the tank shell, as well as the connected plate. ANSYS (ANSYS Inc. 2005), a finite element code, is used to model the structure in the three-dimensional space and perform static nonlinear EFB analysis. Taking advantage of the symmetry of a cylindrical tank, one can model only half of the structure considering a vertical plane of symmetry that crosses through the axis of symmetry of the cylinder and exerting equivalent seismic loads with direction parallel to the plane of symmetry. Appropriate boundary conditions $(u_Y = \theta_X = \theta_Z = 0)$ are applied at the nodes lying in the plane of symmetry (Figure 6).

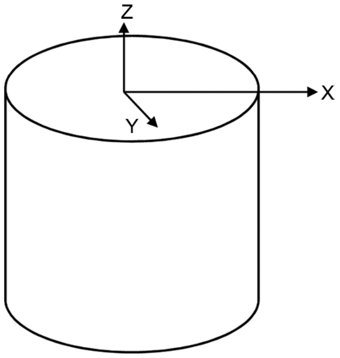

Figure 6. Global Cartesian coordinate system.

The tank wall is thin compared to the radius of the tank. Four-node, 24 DOF quadrilaterals elastic-plastic shell elements (SHELL181) that have both membrane and bending capabilities are used to model the tank wall.

To confirm that the numerical model used has sufficient mesh density to correctly capture the buckling behavior, simply supported cylindrical shells were subjected to increasing axial loads. A mesh with 96 elements along the circumference was selected as this captured 99% of the classical buckling formula.

In order to provide stability to the shell wall near the top of the tank, the effects of tank roof is modeled by coupling the highest nodes of the tank shell in both horizontal directions. For each tank, two numerical models - with and without proposed connection - are analyzed and their results are compared. The base plates and the shell rigid foundation are ignored in numerical models. For the simple tank (without the base connection), the nodes at the bottom of the tank wall are fixed in all three displacement degrees of freedom. However, in the case of equipped tanks (with the base connection), the shell tank could uplift from the ground. Therefore, the bottoms of the shell elements were modeled with link elements, which are effective only for compression. In this case, the nodes at the bottom of the connection plates are fixed in all three displacement degrees of freedom. Moreover, the nodes at the top of plate connection are coupled by the shell nodes in the same level. The modulus of elasticity for tank wall is considered as E = 2E +08 KPa, its Poisson's ratio and yield stress are considered $v = 0.3$ and $F_y = 2400\ \mathrm{Kg/cm^2}$, respectively.

3.3. Static Equivalent Loads

As shown in Figure (2), a hydrodynamic pressure distribution was assumed on the tank wall as:

$$p = p_0\left(1-\frac{x^2}{H^2}\right)Cos\,\theta \qquad (1)$$

where x is the elevation of a point on the shell measured from the base. H is the liquid depth, θ is the angle measured from the axis of excitation and p_0 is the pressure amplitude at the tank base at $\theta = 0$. It is seen from analysis of rigid tanks [11] that the hydrodynamic pressures exerted on the wall of the tank are indeed similar to those obtained from the above equation.

If Q is the base shear, then:

$$Q = \int_0^H\int_0^{2\pi} p\cos\theta\, R\, d\theta\, dx = \frac{2\pi}{3}Hp_0R \qquad (2)$$

And similarly, if M denotes the overturning moment about the center of the base, then:

$$M = \int_0^H\int_0^{2\pi} p\, x\cos\theta\, R\, d\theta\, dx = \frac{\pi}{4}H^2p_0R \qquad (3)$$

3.4. Selected Tanks Dimensions for Numerical Analysis

As mentioned before, two steel tanks - one broad and one slender - are considered to investigate the seismic performance of introduced connection. Broad tank (H / R = 0.6) is a 29500 m^3 capacity steel tank with a radius of 25 m. The filled liquid is water with height of 15 m and the tank shell height is 18 m. Its equivalent uniform shell thickness of 0.03 m is used. Slender tank (H / R = 1.7) is a 5340 m^3 capacity steel tank has a radius of 10 m; it is filled with water to a height of 17 m. Its shell thickness is 0.0225 m and the tank shell height is 20 m.

First, equivalent static load, in terms of surface pressure, is exerted on each shell tank (without modeling the connection) until the EFB occurs. Then, the tanks are equipped with proposed connection and the same analysis is performed. Finally, the analysis results in both situations are compared.

4. Nonlinear Static Analysis Results

4.1. Results of FE Analysis for Tanks without Proposed Connection

In order to investigate a behavior of tank after EFB, nonlinear static analysis was conducted. In these analyses, the dynamic fluid pressure was used as a static load. Circumferentially expanded load introduced in previous section is increased step by step until EFB occurs. After yielding, analysis is continued to investigate the development of EFB.

The stresses obtained from the FEA analysis clearly point towards elastic-plastic buckling in both cases (broad and slender tank). It should be noted that the maximum coexistent pressure was used in the elastic-plastic buckling computation, which in this case is the sum of the static pressure and the pseudo-dynamic pressure. Elastic buckling usually occurs only at low values of membrane circumferential stress coupled with high compression stress in the shell wall. This combination is rare. Even the elastic-plastic buckling stress values are not conservative for slender tanks.

For the broad tank, relationship between lateral force and displacement at top of the side wall of 90 deg meridian is presented in Figure (7). Side wall near the base of 0 deg meridians was yield when horizontal displacement at the top of the side wall of 90 deg meridian was 6.5 mm, as shown in Figure (7). After shell yielding, exerted lateral force rise to its maximum value at the displacement of 12 mm and grew down slowly. Finally, analysis is unstable at the displacement of 30 mm. A yielding area extends up to 26 deg in the circumferential direction at the displacement of 6.5 mm and over 75 deg at 12 mm as shown in Figures (8) to (10). It shows that the tank is stable and does not collapse easily after EFB.

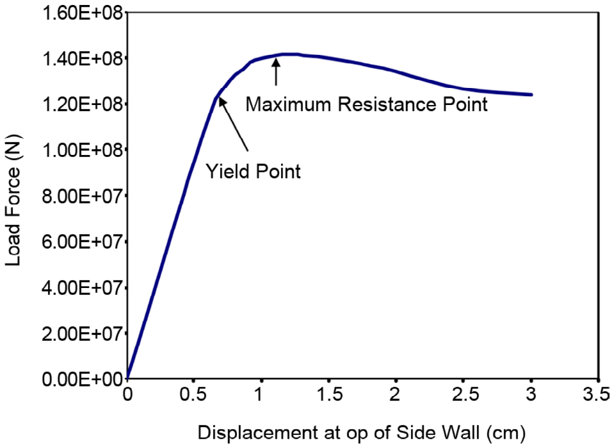

Figure 7. Relationship between lateral force and displacement at top of the side wall of 90 deg meridian (broad tank without the proposed connection).

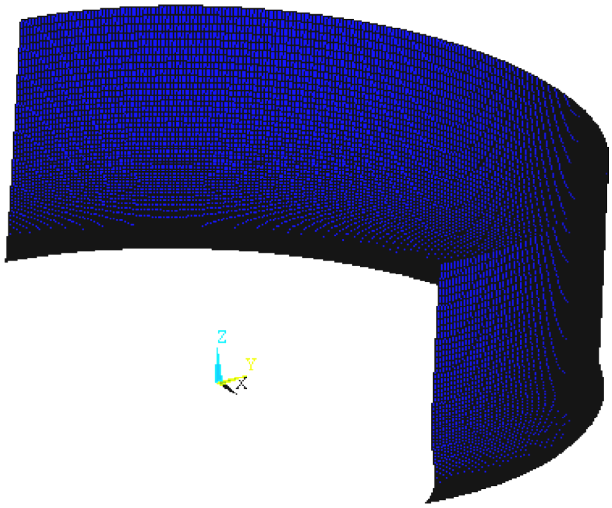

Figure 8. Deformed shape of EFB (broad tank without the proposed connection).

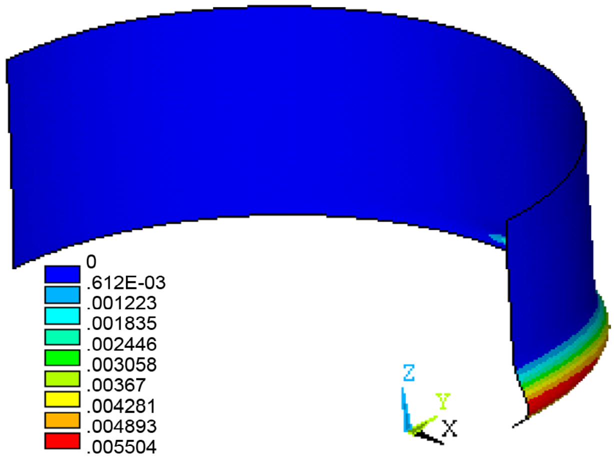

Figure 9. Contour of plastic strain at side wall (broad tank without the proposed connection).

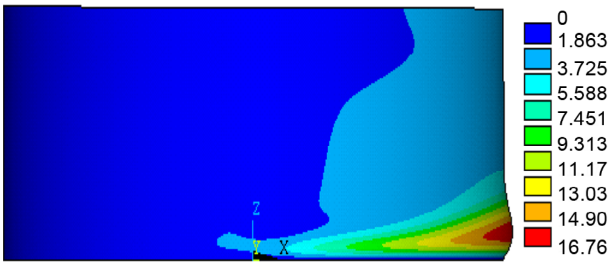

Figure 10. Contour of X direction displacement of tank wall (cm) - (broad tank without the proposed connection).

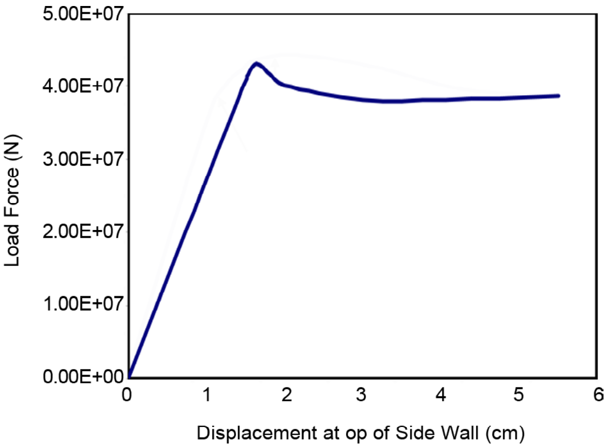

Figure 11. Relationship between lateral force and displacement at top of the side wall of 90 deg meridian (slender tank without the proposed connection).

For slender tank, the same results are obtained from static analysis, as shown in Figure (11). As can be seen in this graph, for slender tank, there is more clear point where actual failure occurs and the resistance force is reduced with deeper slope respect to broad tank. Also, the post buckling resistance force is slightly increased respect to the broad tank. The EFB extended over a range of 70 deg, with the bulge rising about 50 mm at a level of 70 cm from slender tank bottom as shown in Figures (12) to (14).

4.2. Results of FE Analysis for Tanks Equipped with Proposed Connection:

The plots of Figures (15) and (16) relating horizontal load to horizontal displacement compare the results of FEM analysis for broad and slender tanks respectively. In these figures, the results of FEM for related equipped tanks are also presented. As can be seen, the EFB buckling of tank wall is retarded by using the proposed tension connection. In other words, the plate of the connection yields before the time that the stress in tank wall reaches to the critical buckling stress. The area under the

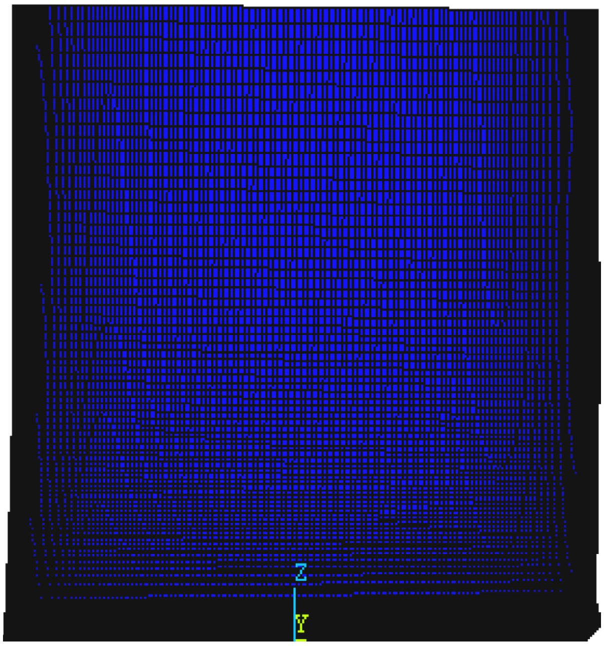

Figure 12. Deformed shape of EFB (slender tank without the proposed connection).

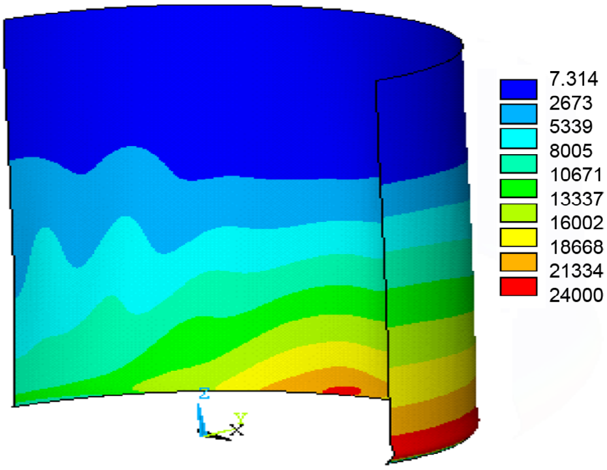

Figure 13. Contour of Von-misses at side wall (slender tank without the proposed connection).

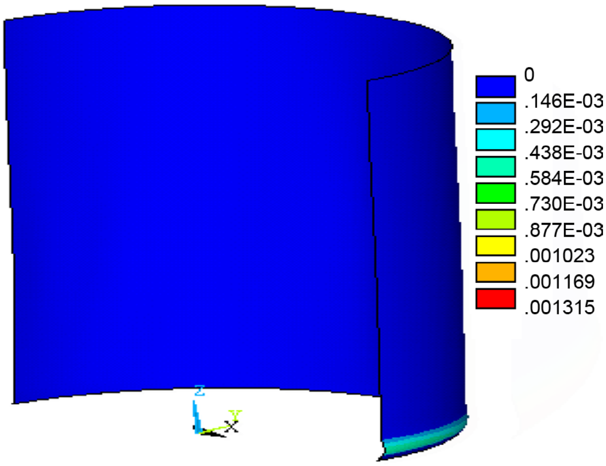

Figure 14. Contour of plastic strain at side wall (slender tank without the proposed connection).

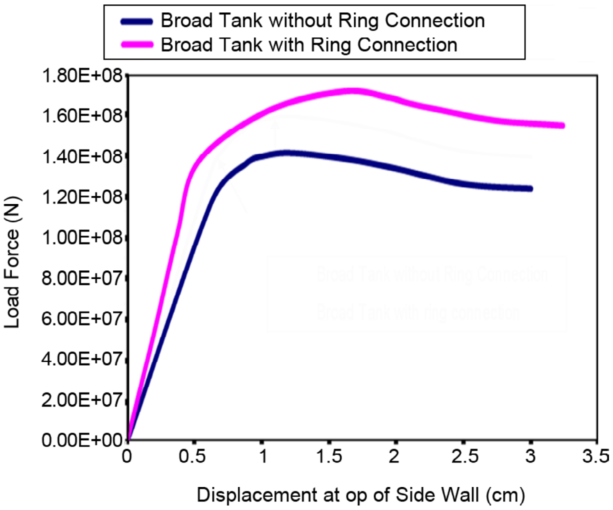

Figure 15. Relationship between lateral force and displacement at top of the side wall of 90 deg meridian (broad tank without the proposed connection).

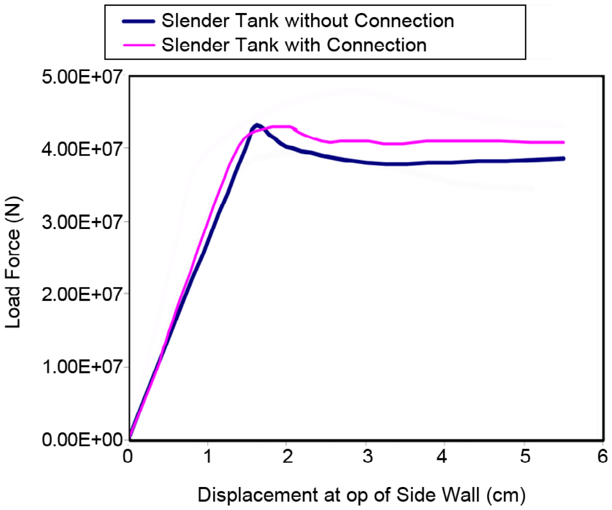

Figure 16. Relationship between lateral force and displacement at top of the side wall of 90 deg meridian (slender tank without connection).

force-displacement curves are also increased in the case of equipped tanks, which are the indication of enhancing the energy absorption capacity when the tension connection is used.

Greater load force leads to more extending of connected plate plastic deformation (Figure 17). Increasing of external static load continues until the tank wall stress reaches to the critical buckling stress. In this point, EFB occurs and the maximum load is obtained Figure 18). Therefore, EFB is the final mechanism of failure for all cases.

This maximum load is slightly higher than the tank without connection. Therefore, it can be seen that although the main purpose of using connection is the increasing of energy absorbing capacity, the

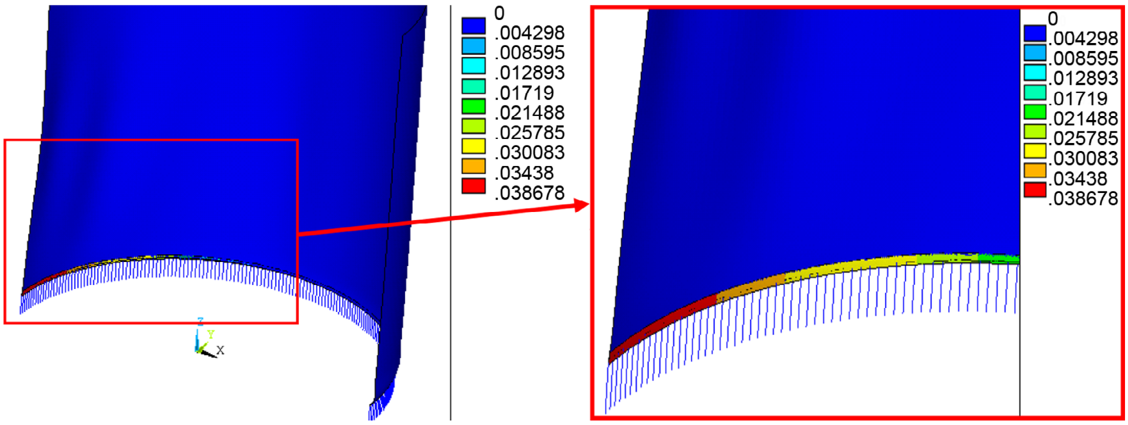

Figure 17. Plastic strain contour in proposed tension connection (slender tank with the proposed connection).

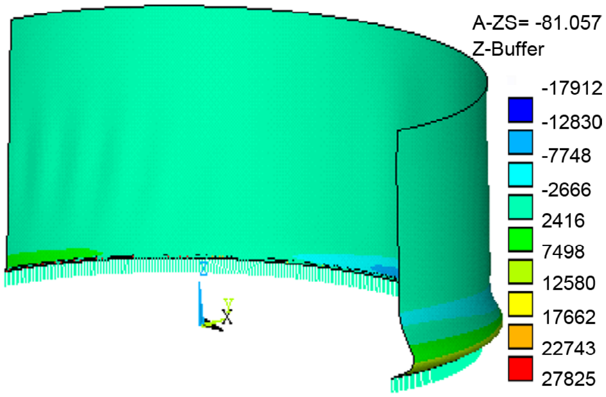

Figure 18. Contour of Von-misses at side wall (broad tank with the proposed connection).

connection could also be efficient to postpone the EFB and rise the critical buckling stress.

5. Conclusion

Seismic protection method for cylindrical, ground-supported, liquid-storage, steel tanks has been proposed by disconnecting the wall of the tank from the base plate and reconnecting it using a special tension connection. This innovated connection provides a method of improving the seismic performance of storage tanks by dissipating energy that otherwise would be imparted to the same by potentially damaging ground motion. The pushover analysis approach using Finite Element Model (FEM) is used to numerically examine the dynamic performance of proposed method. The nonlinear FE method could satisfactorily model EFB phenomenon. Also, the FE results show that after EFB, the considered tanks can be stable and do not fall down easily. The buckling point for slender tank is clearer than those of broad tank.

It is also seen that the proposed method not only postpones the Elephant Foot Buckling (EFB), but could increase the energy absorption capacity of the tank system before and after buckling.

References

1. Bakalis, K., Vamvatsikos, D., and Fragiadakis, M. (2015) Seismic fragility assessment of steel liquid storage tanks. *Proceedings of the ASME 2015 Pressure Vessels and Piping Conference*. **8**: Seismic Engineering. Boston, Massachusetts, USA. July 19-23. V008T08A023. ASME. https://doi.org/10.1115/PVP2015-45370.

2. Castellano, M.G., Infanti, S., Dumoulin, C., Ducoup, L., Martelli, A., and Dusi, A. (2000) Shaking table tests on a liquefied natural gas storage tank mockup seismically protected with elastomeric isolators and steel hysteretic torsional dampers. *Proceedings of the 12th World Conference on Earthquake Engineering*, [Paper 2082].

3. Kim, N.S. and Lee, D.G. (1995) Pseudodynamic test for evaluation of seismic performance of base-isolated liquid storage tanks. *Engineering Structures*, **17**(3), 198-208.

4. Malhotra, P.K. (1997) New method for seismic isolation of liquid-storage tanks. *Earthquake Engineering and Structural Dynamics*, **26**, 839-47.

5. Shrimali, M.K. and Jangid, R.S. (2002) Seismic response of liquid storage tanks isolated by sliding bearings. *Engineering Structures*, **24**, 909-21.

6. Wang, Y.P., Teng, M.C., and Chung, K.W. (2001) Seismic isolation of rigid cylindrical tanks using friction pendulum bearings. *Earthquake Engineering and Structural Dynamics*, **30**(7), 1083-99.

7. Jadhav, M.B. and Jangid, R.S. (2006) Response of base isolated liquid storage tanks to near-fault motions. *Structural Engineering and Mechanics*, **23**(6), 615-34.

8. Shrimali, M.K. and Jangid, R.S. (2004) Seismic analysis of base-isolated liquid storage tanks. *Journal of Sound and Vibration*, **275**(1-2), 59-75.

9. Almazan, J.L., Cerda, F.A., De la Llera, J.C., and Lopez-Garcia, D. (2007) Linear isolation of stainless steel legged thin-walled tanks. *Engineering Structures*, **29**, 1596-611.

10. Forde, W.R.B. and Stiemer, S.F. (1987) Improved arc length orthogonality methods for nonlinear finite element analysis. *Computers & Structures*, **27**(5), 625-630.

11. Veletsos, A.S., Tang, Y., and Tang, H.T. (1992) Dynamic response of flexibly supported liquid-storage tanks. *Journal of Structural Engineering*, **118**, 264-283.