Developing an Innovative Approach for Retrofitting the Existing Cylindrical Liquid Tanks

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SUMMARY:
According to the past seismic records, above-ground cylindrical liquid tanks are a part of vulnerable lifelines in the earthquake events. Roof failures due to liquid sloshing are the most frequent damages in cylindrical liquid tanks after shell buckling failure modes. Dynamic investigations of several cylindrical liquid tanks as well as numerous internationally accepted publications have shown the negligible influence of the bottom anchor approach on the liquid wave amplitude. In this regard, high criteria for liquid freeboard in liquid tanks are established as a countermeasure.
In this paper a method called "Cell Division" is developed for improving the liquid sloshing behavior in cylindrical liquid tanks. A computer program was chosen to develop a Finite Element Analysis (FEA) model of an existing above-ground, cylindrical steel shell and roof tank structure with contained fluid under seismic loading. The program was opted for its ability to include shell and structural steel elements, contained fluid elements, fluid-structure interaction, geometrical nonlinearities and contact type elements. Using dynamic analysis of finite element models, the seismic behavior of the tanks is studied and the vulnerability of both original and retrofitted tanks is evaluated, as well. Analysis results show a significant reduction in liquid sloshing amplitude, uplift and settlement of the tank. Other than avoiding expensive retrofitting countermeasures, this method increases the economical benefits of the existing tanks by optimum utilization of the tanks' capacity.

Keywords: Liquid tanks, sloshing, retrofitting, freeboard, Cell Division, Curtain

1. INTRODUCTION

Above ground liquid tanks are high risk and vulnerable elements during earthquake events. They suffer from three most frequent failure modes which are shell buckling, roof failure, and uplift and settlement. Past statistical records show same contribution of aforementioned failure modes in liquid tanks [4, 5]. In this regard, retrofitting measures have always been focused on these failure modes. Considering the economical benefit of the above ground liquid tanks (Tanks' capacity) and countermeasure cost, one could always think of more efficient and cheaper retrofitting alternatives with the least disturbance of the operation and function of liquid tanks specially the existing ones.

Over the years the engineers have been using the standard linear static procedures recommended by American Water Work Association (AWWA) and American Petroleum Institute's (API) publications [1, 2]. In these standards no explicit countermeasure for alleviating liquid sloshing is stated and since this phenomenon is highly dependent on the frequency content of the seismic wave, several documented records show the dominance of this failure mode in liquid tanks. These tanks were originally designed based on recommended practices of published standards.

In this paper by following the older published one with the same name and scenario, an innovative method called "Cell Division" is presented and developed and the improved behavior of the liquid tanks under seismic loadings is shown. The results of modal and non linear dynamic analysis of FEM 3D models of typical cylindrical tanks show noticeable reduction in liquid wave amplitude forces, uplift and settlement of the tanks with avoidance of local high peak liquid up-rise as well as main decrease in shell Von Mises stress as a approved criteria of buckling shell seismic vulnerability factor.

Although no full scale test is utilized for modeling verification but analysis results show very suitable consistency with published literatures [3, 5].

2. RESEARCH METHODOLOGY

In this research an innovative retrofitting measure called "Cell Division" is developed aiming optimizing the tank behavior during the seismic event and taking into consideration the economical merits of the tank's capacity. The measure is based on reducing the convective mass for unique frequency and changing the number of effective mode frequencies. Since the free surface of the liquid reservoir (higher convective mass) has a direct impact on the sloshing amplitude, in this developed retrofitting measure, the free surface is divided into smaller areas using "Dividing Curtains".

Following and investigating the claim, a numerical model was developed by using a finite element program and after verifying the simulator based on valid published documents of full-scaled tests approved by latest pioneer codes, a system directly was applied for retrofitted approach as well as a checking schedule was managed to control results.

2.1. Simulation theory

A typical cylindrical liquid tank with containing liquid is modeled using FEM program. The steel shell of the tank is simulated using four-node-shell element and the element representing the containing liquid is eight-node-fluid with free surface.

Surveying a refinery oil depot tanks, dimensions of the model coincide with exiting 7.5 Million-liter tank [5]. The diameter modeled tank is 26.213 meters. Tank height which consists six courses of steel plates (maximum and minimum plates' thickness is 12.0 and 6.35 millimetres respectively) is 14.63 meters. This fix-cone-roof-tank type has designed to store liquid by density of 744 kilogram per cubic meter.

2.1.1. Shell element

Shell element in the model has both bending and membrane capabilities. Both in-plane and normal loads are permitted. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. Stress stiffening and large deflection capabilities are included. A consistent tangent stiffness matrix option is available for use in large deflection (finite rotation) analyses.

2.1.2. Fluid element

The fluid element is used to model fluids contained within vessels having no net flow rate. The fluid element is particularly well suited for calculating hydrostatic pressures and fluid/solid interactions. Acceleration effects, such as in sloshing problems, as well as temperature effects, may be included. The fluid element is defined by eight nodes having three degrees of freedom at each node: translation in the nodal x, y, and z directions.

In order to find the stiffness matrix ([K]) of the fluid elements, stress-strain equations which relate bulk strains (using fluid bulk modulus) to internal fluid pressure are studied. Also the damping matrix is developed based on stress and strain differentiation relationships. In time-history analysis, the total damping matrix ([C]) is calculated by adding Rayleigh and Viscosity matrixes according to Eqn.2.1.

$$[C] = \alpha[M] + \beta[K] + \sum[cf] \tag{2.1}$$

2.1.3. Gap element

The underplaying supporting soil is modeled using compression-only gap conditions. Therefore the non-linear geometrical behavior of uplift and the impact can be calculated by time-history dynamic analysis.

2.1.4. Curtain
The two perpendicular symmetric areas as curtains have meshed with shell element in such a way that are just supported by tension-only link elements from bottom and roof and also have separated nodes that are coupled with fluid nodes in normal area vectors perfectly. The distance between curtains and shell courses has applied obligatory to avoid interactions.

2.1.5. Meshing model into element
By trial and error in several dynamic analyses, the steel shell elements are optimized aiming at higher accuracy and lesser analysis time. Since the liquid elements are dimension-sensitive and their dimension ratio has a great impact on results' accuracy, the optimized shape is very close to a brick. Thus, using manual meshing, the liquid elements were altered to an optimized shape.

2.1.6. Boundary conditions
The boundary conditions in the contact area of liquid and steel shell are only coupled in normal shell direction. Therefore the adjoining nodes are free to move in all directions except for that of normal shell element.

2.2. Model verification

After designing a simulator the first deed is to define a verification system that should be based on the experimental published documents. Moreover parametric valid equation for pressure was considered for every analysis as well.

2.2.1. Hydrostatic pressure of liquid
Hydrostatic pressure check could be simply a primary verification factor. Fig. 2.1 shows the hydrostatic pressure calculated using 3D model for the first model. As illustrated, the hydrostatic pressure (steady-state analysis) coincides with nominal "ρgh" value calculated manually. In addition, the aforementioned verification was also applied to retrofitted tank model and other testing models mentioned in the next section.

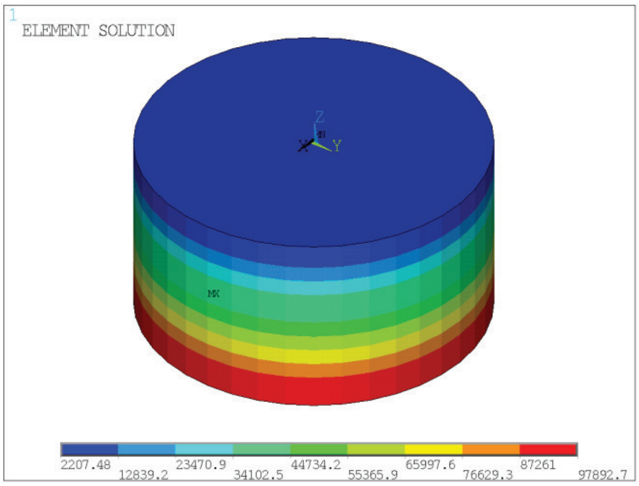

Figure 2.1. Hydrostatic pressure in model (Average value in element center – Unit : Pa)

2.2.2. Natural frequencies
As a reliable factor, natural frequencies (impulsive and convective) of a simulated full tank using the method of simulation are compared with the confirmed values [3]. All mentioned tanks in [3] have been analysed using the research methodology and acceptable results have been obtained consequently. Table 2.1 compares the results between analytic and measured frequencies of the same tank according to the analysis and confirmed published values respectively.

Table 2.1. Comparison of frequencies of modeled tanks with [3]

Numbers are in hertz (Hz)	Tank T of Phase I. [3]			Tank No.1 of Phase II. [3]		
The 1^{st}, 2^{nd} and 3^{rd} computed natural impulsive frequencies of effective modes based on [3]	N/A	N/A	N/A	3.01 *	10.38	15.11
The 1^{st}, 2^{nd} and 3^{rd} measured natural impulsive frequencies of effective modes based on [3] (experimentally)	N/A	N/A	N/A	N/A	9.6	14.3
The 1^{st}, 2^{nd} and 3^{rd} computed natural impulsive frequencies of effective modes based on Analysis	3.32	10.23	14.54	3.42	10.43	14.79
The 1^{st} Obtained natural convective frequency of effective modes from equation based on [3]	0.25	N/A	N/A	N/A	N/A	N/A
The 1^{st}, 2^{nd} and 3^{rd} computed natural convective frequencies of effective modes based on Analysis	0.236	0.342	0.390	0.236	0.343	0.393

* 3.81 for rigid foundation

2.3. Result control system

In this paper, four equal "Cells" (two "Curtains") are studied. The "Curtains" height is more than two third of the standing liquid height as the figures show. In Fig. 2.2, the Isometric perspective view of the tank before and after retrofitting and without roof and liquid is shown.

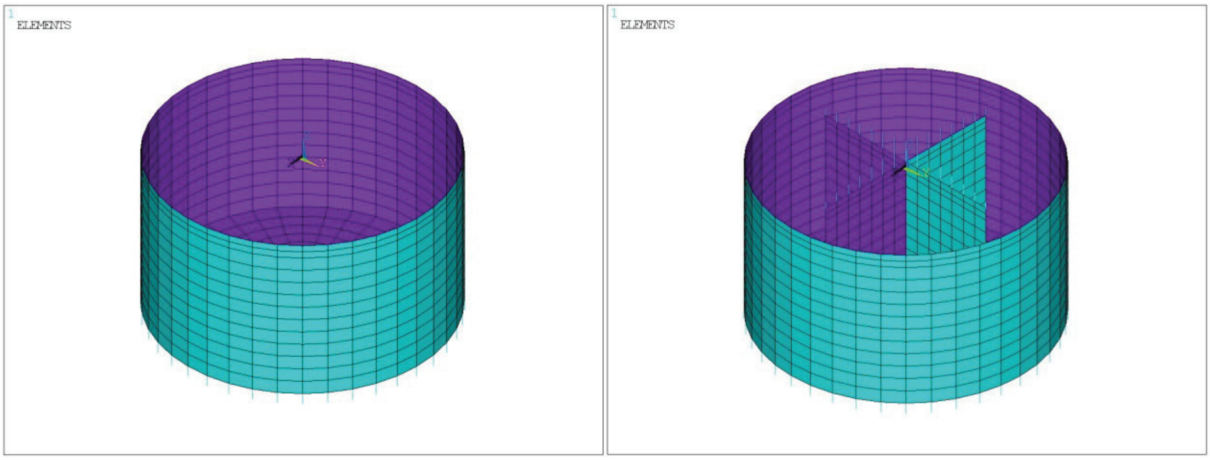

Figure 2.2. Isometric perspective view of the tank before (left) and after (right) retrofitting

After static analysis (first model verification test), nonlinear dynamic analysis of models before and after "Cell-Division" retrofitting is studied. As a prerequisite of time history analysis of the model—to obtain the Rayleigh coefficients and for verification test—a modal analysis for both models is implemented. Since the spectrum analysis is not able to simulate the non-linear conditions of the base nodes, non-linear dynamic analysis (time-history) of both models is undertaken using ground motion acceleration records of three earthquakes in three dimensions (100% in primary direction and 30%, 30% in others) and compatible with tank's site.

Fig. 2.3 shows the reference nodes of the model. The top-left and top-right images depict the selected nodes numbers for liquid free surface before and after retrofitting respectively. The bottom-left, bottom shell nodes numbers are shown, which are the same for before and after retrofitting. Similarly, in the bottom-right image, some of shell nodes numbers (Y=0) are shown.

Analysis results are presented for some of these node definitions.

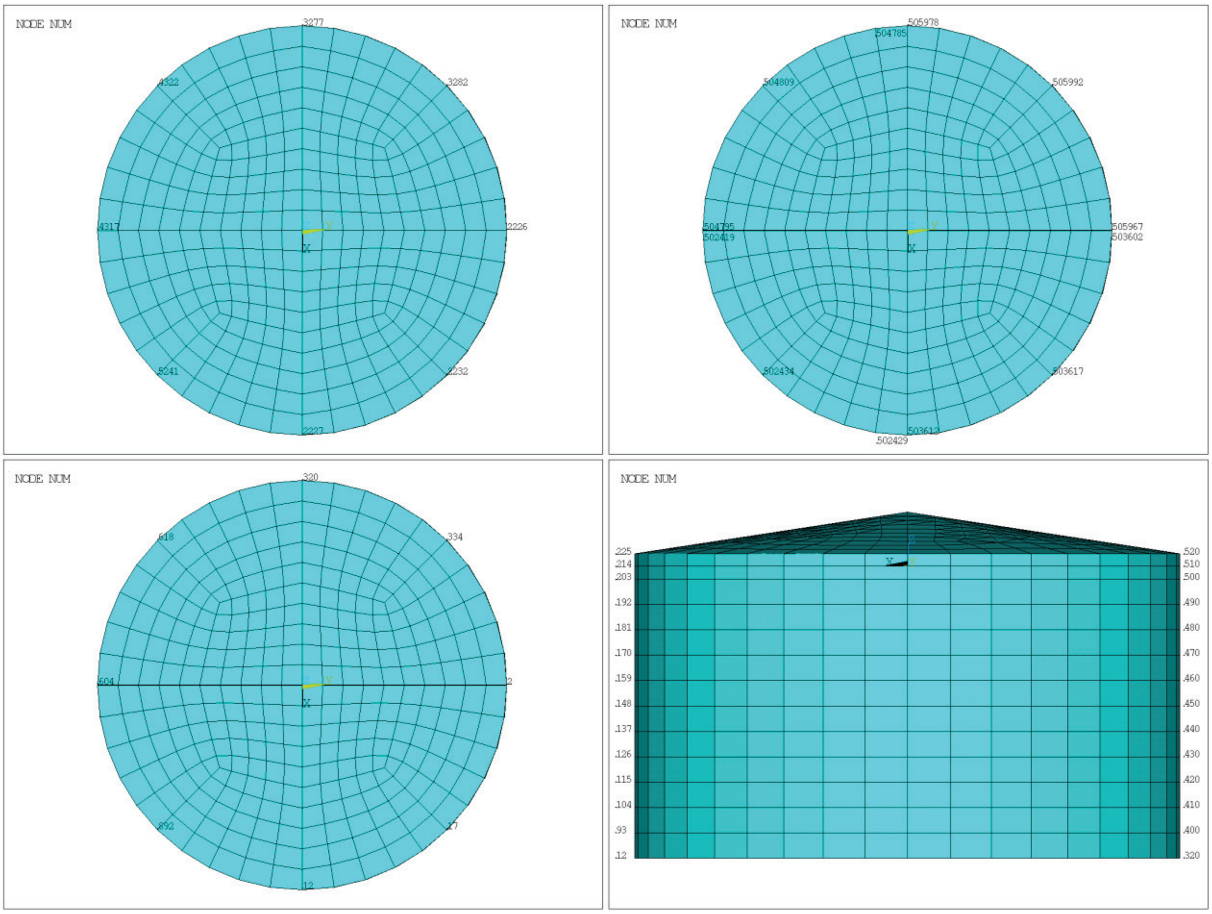

Figure 2.3. Reference nodes numbers in the models

3. ANALYSIS RESULTS

In this section, by illustration of parts of analysis results, tank behavior have been compared before and after retrofitting with each other in order to find the effect of method on vulnerability reduction. All numbers mentioned in figures are represented based on Newton (N), meter (m) and second (s) system.

3.1. Static analysis

Fig. 3.1 depicts Von Mises stress in shell against hydrostatic pressure. As the results show, before (left) and after (right) retrofitting, the maximum amount of stress is 135 MPa.

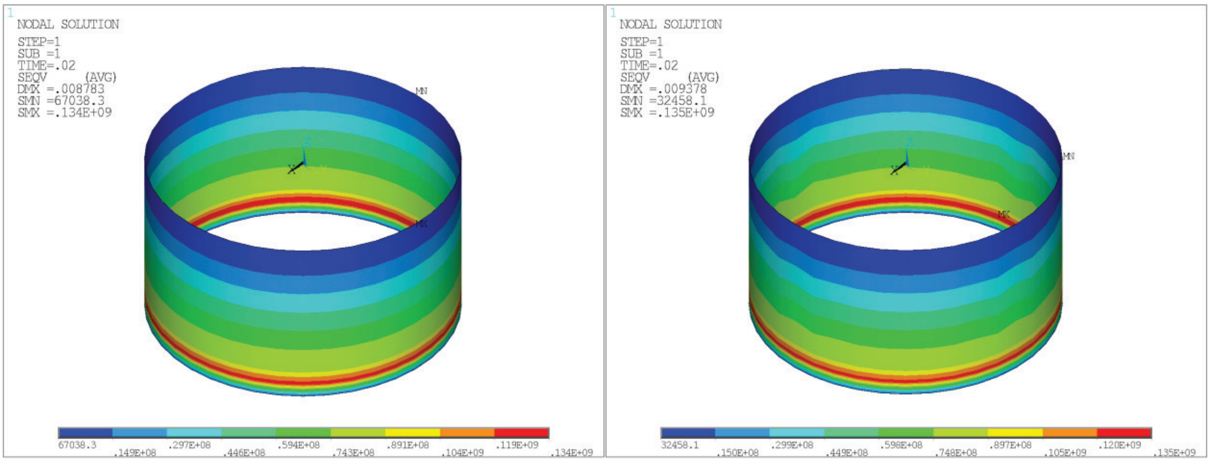

Figure 3.1. Von Mises stress against hydrostatic pressure in shell before (left) and after (right) retrofit

3.2. Modal analysis

Table 3.1 shows the modes with highest effective mass in both before and after retrofitting models. Modal analysis shows that in before retrofitting model, the contribution of only two effective modes is 86.72% while after retrofitting, total effective mass of the four modes is 87.65%. Besides, the effective mass of convective mode is divided into two frequencies with noticeable distance from each other that it will result in lower convective mass and lower sloshing amplitude in the developed "Cell-Division" retrofitting measure when subjected to seismic loadings except for records with wide frequency content. Moreover, the period of impulsive mode reduced whereas it causes less amplitude acceleration for structure in that range of frequency against every earthquake records.

Table 3.1. Modal analysis results

Before retrofitting			After retrofitting		
Frequency (Hz)	Period (s)	Effective mass percentage	Frequency (Hz)	Period (s)	Effective mass percentage
0.1725	5.7956	33.00	0.1596	6.2651	19.38
5.0302	0.1988	53.72	0.2247	4.3679	14.72
			5.1025	0.1960	48.97
			5.1734	0.1933	4.58
Total		86.72	Total		87.65

3.3. Time history analysis (Non-linear Dynamic Analysis)

Non-linear dynamic analysis of both models are undertaken using ground motion acceleration records of three site-compatible earthquakes which were different in frequency content, duration and peak acceleration. As a matter of fact, in all results, retrofitting by curtains had major influences on vulnerability reduction. From this point on, the weakest result—the one that had minimum effect in vulnerability reduction—which is related to the record with wider frequency, is considered.

Fig. 3.2 and 3.3 demonstrates the non-linear dynamic analysis results (sloshing amplitude) in before and after retrofitting models, respectively. Free surface nodes are according to Fig. 2.3 definitions. There is a noticeable consistency in peak vertical deflections during the whole evaluation period (50 seconds) in before retrofitting model (Fig. 3.2.left). This in turn results in higher liquid up-rise zone as can be seen in Fig. 3.2 right, whereas after retrofitting, peak node deflections are not coincident and thus lesser area of peak liquid sloshing amplitude can be observed (Fig. 3.3.right).

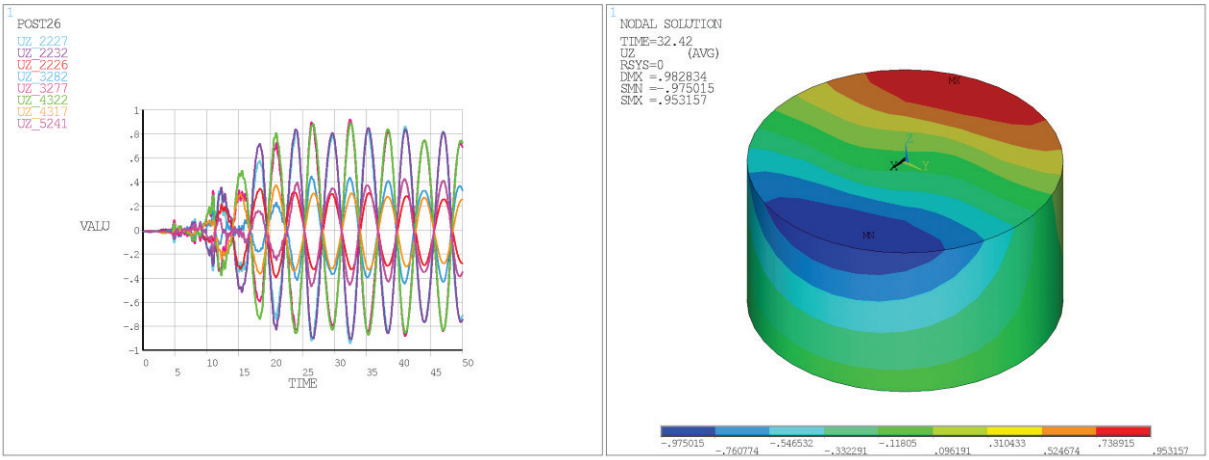

Figure 3.2. Liquid sloshing amplitude before retrofitting

As the recent figures illustrate, Peak vertical deflections are at t=32.42 s and t=35.3 s in normal and retrofitted models, respectively but after 20 second the liquid had the amplitude near the maximum for two times in every cycle of sloshing whereas nodes of liquid had maximum deflection just for two times in all 50 seconds that may cause fatigue in top of the shell and roof or connection.

Obviously, the value and zone area of the peak vertical deflections (sloshing amplitude) are reduced substantially when using "Cell Division" retrofitting. Sloshing amplitude has decreased from an average value of 90 centimeters before retrofitting to 75 centimeters in retrofitted model using the developed "Cell-Division". In addition, since in the retrofitted model, the total contact area of the internal liquid wave is decreased to about one third of the original tank, lower forces are applied to the steel shell. Since the tanks' roofs are constructed in cone or dome forms, the near center peak vertical displacement values in the retrofitted model (Fig. 3.3 right) do not cause any harm during seismic event.

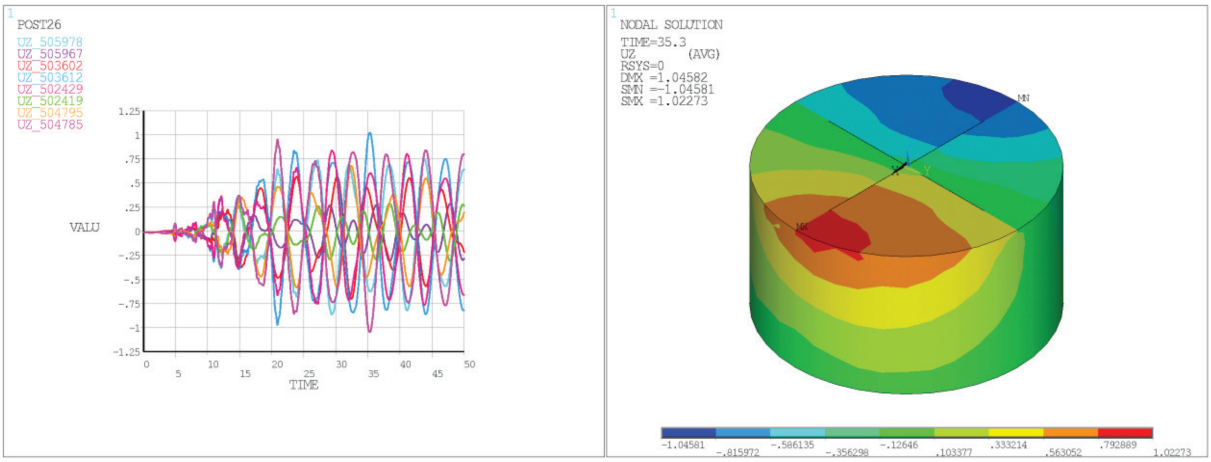

Figure 3.3. Liquid sloshing amplitude before retrofitting

Fig. 3.4 and 3.5 show some sample results of the base vertical displacements obtained from non-linear dynamic analysis. Base nodes are selected according to Fig. 2.3 definitions. These figures can be investigated in two aspects. The developed "Cell-Division" retrofitting measure reduces base vertical displacement in terms of settlement and uplift. In addition the thickness of the deflection curves are reduced which means lower tank's impacts on the course. Base impacts after uplift during seismic events are the main cause of elephant-foot buckling. Lower vertical uplift results in lower shell stress and correspondingly lower risk of elephant-foot buckling.

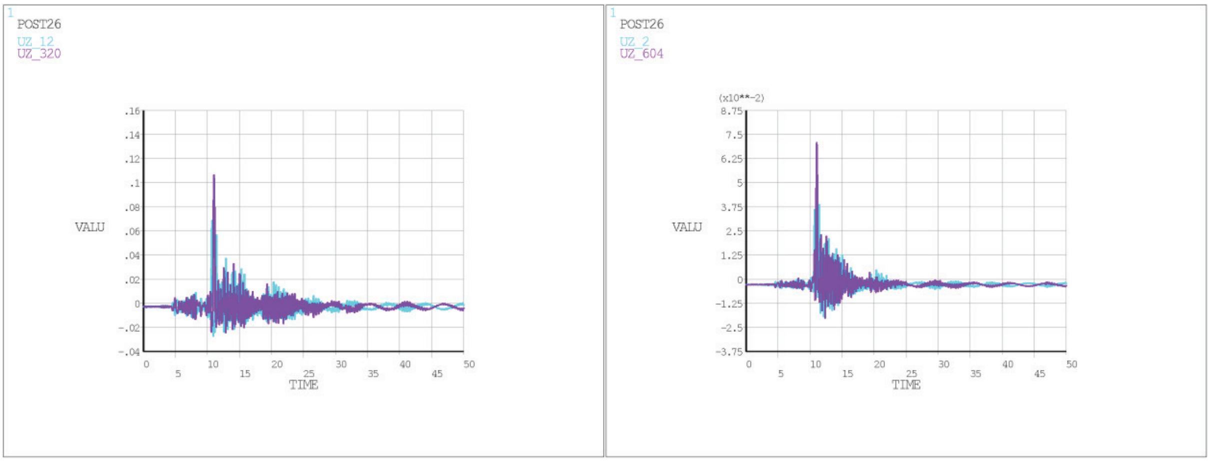

Figure 3.4. Non-linear dynamic (time-history) analysis results – base vertical displacement – Before Retrofitting

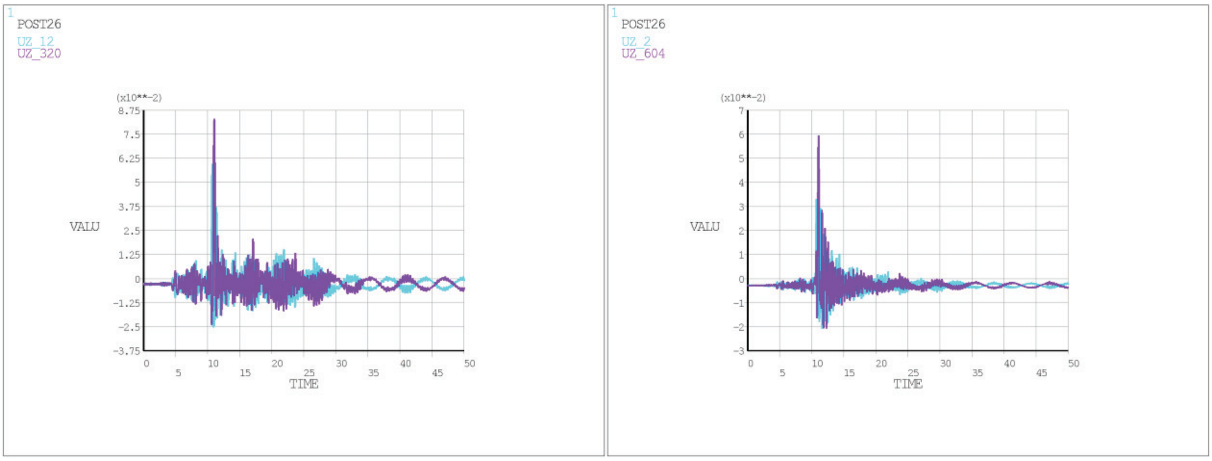

Figure 3.5. Non-linear dynamic (time-history) analysis results – base vertical displacement – After Retrofitting

According to the results, the maximum of settlement occurred at t=10.92 s before retrofitting. Fig. 3.6 shows vertical displacement of shell (left) and Von Mises stress (right) at the critical time before retrofitting. Von Mises stress is 221 MPa based on recent figure.

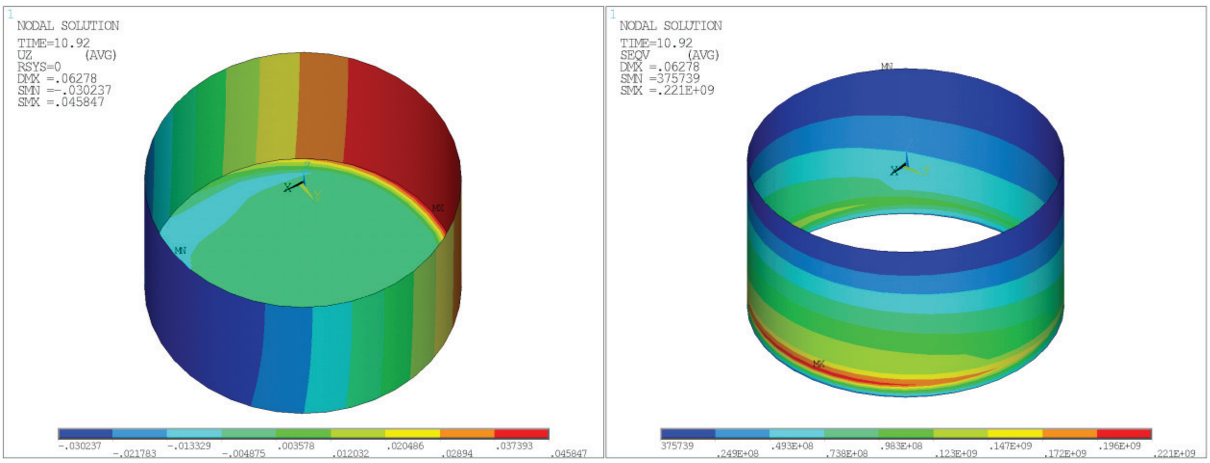

Figure 3.6. Vertical displacement (left) and Von Mises stress in shell before retrofitting

On the other hand, Fig. 3.7 illustrates similar data for tank shell after retrofitting that it was critical at time equal to 10.92. According to the result that Fig. 3.7.right shows, maximum Von Mises stress is 174 MPa. Therefore seismic behavior of tank applied by Cell-Division method, is developed and Von Mises stress as a vulnerability factor had a remarkable reduction.

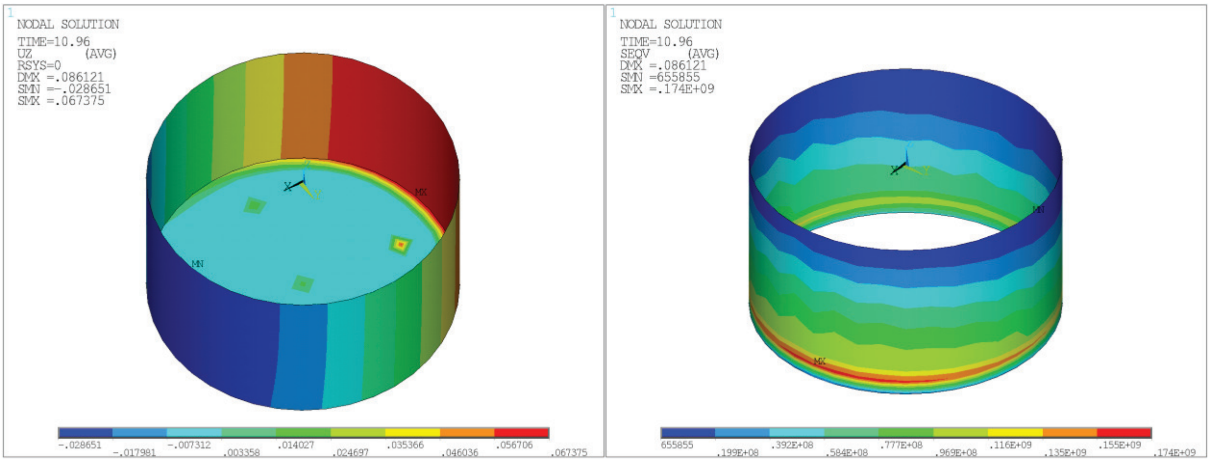

Figure 3.7. Vertical displacement (left) and Von Mises stress in shell after retrofitting

Fig. 3.8 shows vertical deflection of tank shell at t=11.02 s (left) and t=11.06 s (right) for before and after retrofitting respectively whereas the amount of uplift is maximum for each one. As it is shown after using Cell-Division method, the tank had less uplift that causes reduction of damage probability for connections.

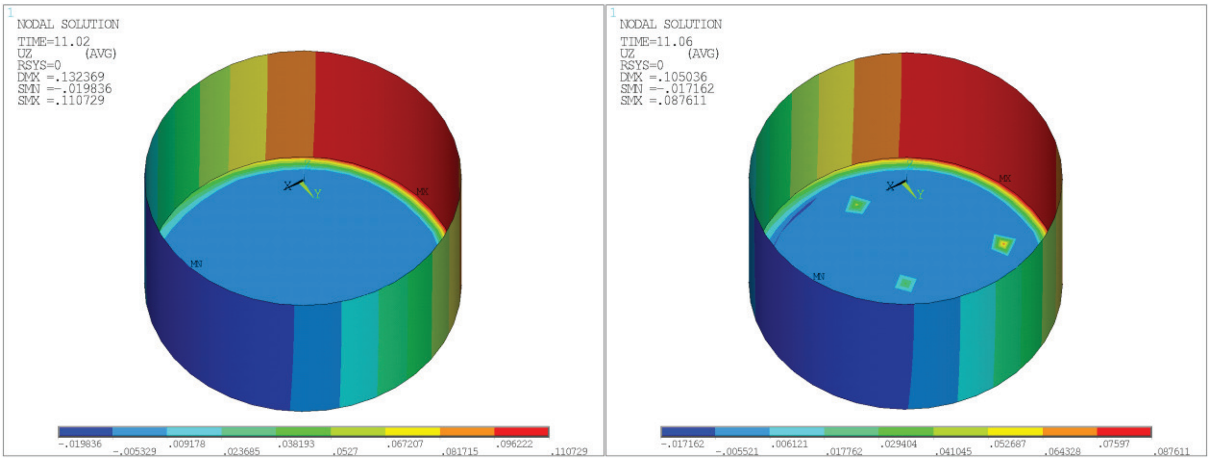

Figure 3.8. Vertical deflection in tank shell before (left) and after (right) retrofitting

4. CONCLUSION

In this paper a developed retrofitting countermeasure called "Cell-Division" is studied. In this method, special "Curtains" are utilized to improve the ground level tanks' behavior during seismic loading. Modal and non-linear dynamic analysis show the enhanced tanks' behavior in terms of liquid sloshing , base displacement (settlement and uplift) and Von Mises stress in shell. On the one hand, "Cell-Division' method divides the effective mass of sloshing modes into two frequencies (reduced liquid wave amplitude) and on the other hand, reduces the area of liquid up-rise zones near the roof and shell connection which in turn result in lower applied loads cause by liquid waves.

Tanks' base vertical displacement (especially uplift), which is the main cause of excessive stresses in some steel shells, are reduced in retrofitted tanks using "Cell-Division" method.

Using this retrofitting method, vulnerability of ground level steel tanks' is substantially reduced. In this method the problem of roof instability due to liquid impacts, is solved and meanwhile the capacity of tanks can also be increased.

In this paper only four "Cells" is studied. Increasing the "Cell" numbers and altering their layout, in special cases, wider and higher curtain could potentially result in better improvement of tanks' behavior during the seismic event.

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