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Effect of the model updating on the earthquake behavior of steel storage tanks

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ABSTRACT

In this paper, effect of the finite element model updating on the earthquake behavior of steel storage tanks considering fluid–structure interaction is investigated. For this purpose, a cylindrical steel storage tank filled some liquid fuel oil located in Trabzon, Turkey is selected as an example. Initial finite element model of the storage tank is developed by ANSYS software and dynamic characteristics (natural frequencies, and mode shapes) are determined analytically. Ambient vibration tests are conducted on the storage tank under natural excitations to obtain dynamic characteristics (natural frequencies, mode shapes and damping ratios), experimentally. Peak Picking technique in the frequency domain is used to extract experimental dynamic characteristics. When the analytically and experimentally identified dynamic characteristics are compared to each other, some differences are found between both results. To minimize these differences, initial finite element model of the storage tank is updated according to experimental results using some uncertainties modeling parameters such as elasticity modulus. To investigate the effect of finite element model updating on the earthquake behavior of the storage tank, earthquake analyses are performed before and after model updating. In the earthquake analyses, YPT330 component of 1999 Kocaeli earthquake is selected and applied to the models in the horizontal directions. It is seen from the analyses that the displacements and the stresses after model updating are more effective than the displacements and the stresses before model updating.

1. Introduction

Cylindrical steel tanks are widely used as engineering structures to store water, fuel or the other liquids. Due to the simplicity of design and cost efficiency, very thin perimeter walls are used in construction of the storage tanks. Earthquake behavior of liquid storage tanks is highly complex due to liquid–structure interaction leading to a tedious design procedure [1]. In the liquid–structure interaction systems, liquid considerably affect response of the structure under earthquake loads. These systems have been investigated by many researchers [2–10] to understand the hydrodynamic pressures in the liquid as a result of both the rigid body and the vibration motions of the structures, and the effects of the liquid on the dynamic properties of the structure as well as on its response to earthquake ground motions [11–14].

Satisfactory performance of the storage tanks during strong ground motions is crucial for modern facilities. Earthquake damage to the steel storage tanks can take several forms. Common modes of failure are wall buckling, sloshing damage to roof, inlet/outlet pipe breaks and implosion due to rapid loss of contents. Large axial compressive stresses due to beam like bending of the tank wall can cause "elephant-foot" buckling of the wall. Sloshing liquid can damage the roof and the top of tank wall. Initial analytical studies deal with the hydrodynamic effects of liquids in rigid tanks resting on rigid foundations. It is shown that a part of the liquid moves in long-period sloshing motion, while the rest moves rigidly with the tank wall [15,16]. One reason for not designing the storage tanks to better withstand these environmental loadings is that the dynamic behavior of the storage tanks is not adequately known. The dynamic behavior of the storage tanks is related to their dynamic characteristics such as natural frequencies, mode shapes and damping ratios. This unknown dynamic behavior is a combination of many factors including assumptions in the design criteria and construction, uncertainties in geometrical and material properties or some modeling uncertainties related to a lack of information on the as-built structure such as boundary conditions. So, the current behaviors of the storage tanks have to be determined look like the other engineering structures, especially against dynamic loads such as liquid pressure and earthquakes. But it is difficult to determine the behavior of these structures by analytical studies because of mentioned reasons. For these purposes, ambient vibration testing is commonly used to determine dynamic behavior of storage tanks.

In the modal testing, various methods including time and frequency domain are available to extract modal information from the dynamic response of a structure and corresponding input excitation. The process of establishing the dynamic characteristics of

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Fig. 1. A view of the liquid fuel storage tank.

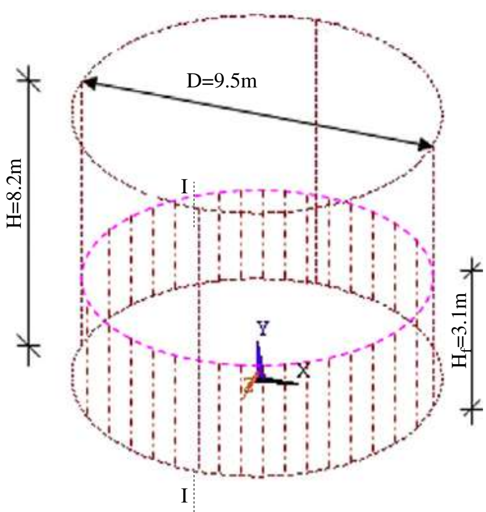


Fig. 2. Geometrical properties of the tank.

a system from an experimental model is known as system identification [17]. In the modal testing, there are basically two different methods experimentally identify the dynamic characteristics of a structure: Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA). In Experimental Modal Analysis, the structure is excited by known input forces (such as impulse hammer and electrodynamics shakers) and responses of the structure are measured. In Operational Modal Analysis, the structure is excited under real operating conditions by unknown input force (ambient vibrations such as traffic, wind, and earthquake loads) and responses of the structure are measured. Some heavy forced excitations become very expensive and may cause the damage to the structure. But, ambient excitations such as traffic, wave, wind, earthquake and their combinations are environmental or natural excitations. Therefore, the system identification techniques through ambient vibration measurements become very attractive. In this case, only response data of ambient vibrations are measurable while loading conditions are unknown [18].

The finite element model of a structure is constructed on the basis of highly idealized engineering blueprints and designs that may or may not truly represent all the physical aspects of an actual structure. When ambient vibration tests are performed to validate the analytical model, natural frequencies and mode shapes, do not coincide commonly with the expected results from the analytical model. These discrepancies originate from the uncertainties in simplifying assumptions of structural geometry, materials, as well as inaccurate boundary conditions. The problem of how to modify the analytical model from the dynamic measurements is known as the finite element model updating in structural dynamics [19,20]. The main purpose of the model updating procedure is to minimize the differences between the analytically and experimentally identified dynamic characteristics by changing uncertainty parameters such as material properties, boundary conditions. In addition, material properties and boundary conditions of a structure can be shifted with time, if the structure loses rigidity by external loads in its life. So, determination of the dynamic behavior of the storage tanks after model updating is very important.

In this paper, finite element analysis, ambient vibration testing, finite element model updating and earthquake behavior of a partly full steel storage tank are studied. Firstly a comprehensive literature reviews given above. Then a numerical example is presented. Lastly the results of the study are discussed.

2. Numerical example

2.1. Description of the cylindrical steel storage tank

A cylindrical steel liquid fuel storage tank located in Trabzon, Turkey is selected as a numerical example. The storage tank constructed in 1974 is used to store liquid fuel oil. A view of the storage

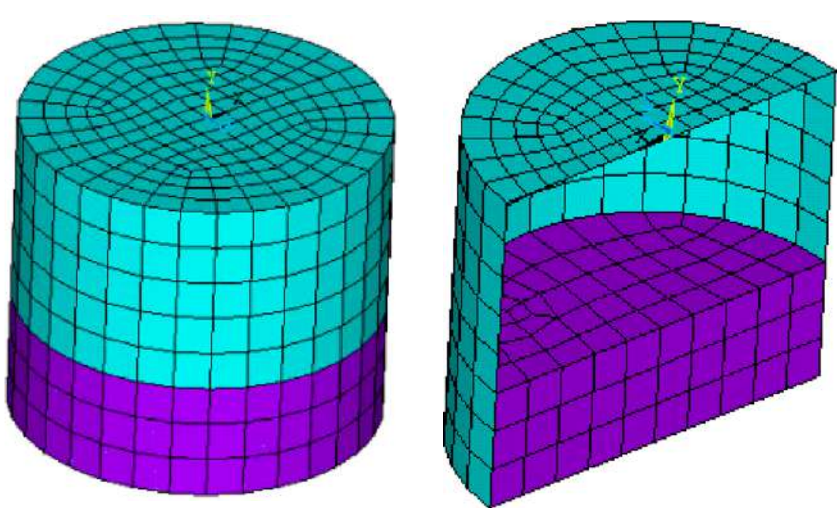
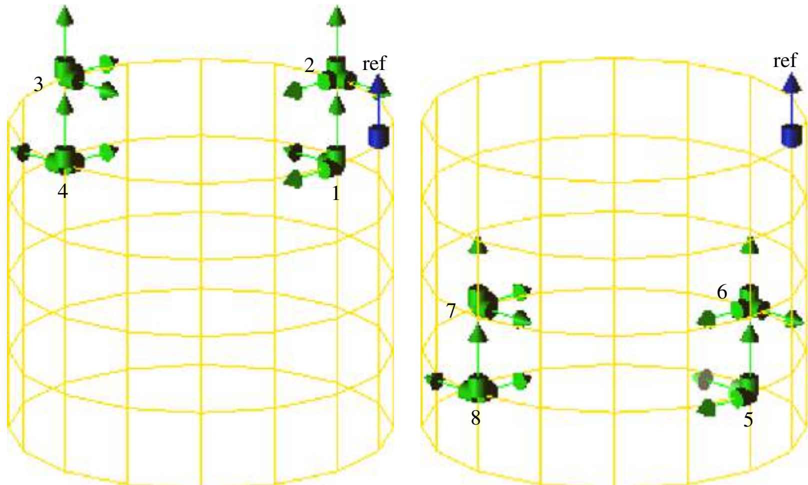


Fig. 3. 3D finite element model of the storage tank–liquid fuel oil system.



(a) First step. (b) Second step.

Fig. 4. Accelerometer locations on the storage tank.

(a) Data acquisition system. (b) Tri-axial accelerometer.

Fig. 5. Equipments of the experimental measurements.

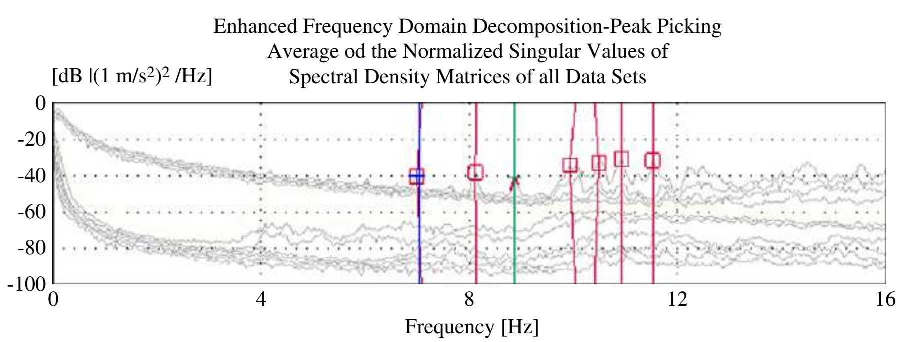


Fig. 6. Singular values of spectral density matrices obtained from PP technique.

tank is given in Fig. 1. As it is seen from Fig. 1, the tank has cylindrical shape and has been constituted with sheet irons. Sheet irons are welded each other. The thickness of the sheet irons variable from the base to top as 8 mm at the base and 5 mm at the top. The top cover thickness of the storage tank is measured as 5 mm. The geometrical properties of the liquid fuel storage tank are given in Fig. 2. The height of the fuel oil is 3.1 m during the experimental measurements (Fig. 2). The tank has approximately 550 m^3 fuel oil capacities. At the top of the tank, 1 m height scarecrows made from iron are taken place (Fig. 1). The storage tank is fully anchored at the base.

2.2. Finite element modeling

ANSYS [21] finite element program, which includes shell and fluid elements and fluid–structure interaction, is used to obtain the analytical dynamic characteristics. The average thickness of the side sheet and cover of the tank are taken into account as 6.5 and 5 mm, respectively. The storage tank is partly full when ambient vibration tests are conducted. So, the 3D finite element model of the storage tank is developed considering partly full fuel oil. Before deciding 3D finite element mesh model of the storage tank, some mesh studies are done for empty storage tank model. Mesh model is accepted according to changes in the natural frequencies. In the finite element model of the storage tank–liquid fuel oil system, 448 Shell63 and 192 Fluid80 elements are used to represent the storage tank and the fuel oil, respectively (Fig. 3). Each element has four nodes and each node has six degrees of freedom: Translations and rotations in the nodal x, y, and z directions. The behavior of the liquid fuel oil is represented by Lagrangian approach [5]. In this approach, fuel oil is assumed to be linearly elastic, inviscid and irrotational. The formulation of the fluid system based on

Lagrangian approach is given in the literature [5,22]. The determination of the interface condition is required to obtain the coupled equations of the storage tank–liquid fuel oil system. Because the fuel oil is assumed to be inviscid, only the displacement in the normal direction is continuous at the interface of the system. Lengths of coupling elements as 0.001 m are used to supply fluid–structure interaction between liquid fuel oil and storage tank interface. The main objective of the couplings is to hold equal the displacements between two reciprocal nodes in normal direction to the interface.

Determination of material properties and boundary conditions is very important for engineering structures such as storage tanks. In this study, the elasticity modulus, Poisson ratio and mass per unit volume are specified as 2.1E5 MPa, 0.3, and 7850 kg/m^3, respectively for initial material properties of sheet iron. In addition, all of the degrees of freedoms at the base of the storage tank are fixed for initial boundary conditions. The term "initial" is used to suggest that the finite element model could be inaccurate due to various modeling and parametric uncertainties and that the model is the basis for the model updating. On the other hand, material properties of the fuel oil are determined by chemical analyses materialized on sample fuel oil. So, these material properties are assumed as current material properties. In the analytical analysis, the elasticity (bulk) modulus and mass per unit volume of the fuel oil are selected as 2.35E3 MPa and 940 kg/m^3, respectively.

2.3. Ambient vibration tests

Ambient vibration tests are conducted on the steel storage tank–liquid fuel oil system when it has fuel oil with 3.1 m height. Brüel&Kjaer 3560 type data acquisition system with 17 channels, a uni-axial accelerometer as a reference, 4 tri-axial accelerometers, PULSE [23] and OMA [24] softwares are used as equipments in the experimental measurements. One end of the signal cables are connected to data acquisition system and the other are connected to accelerometers. The ambient vibration tests are conducted under environmental loads such as wind effects and human movement. In the test setup, frequency range is chosen as 0–25 Hz based on the expected frequencies of the modes obtained from the initial finite element analysis of the storage tank. In the test, since the intended number of the measurements is larger than the number of the available channels and accelerometers, measurements are performed in two steps. In the first step, tri-axial accelerometers are placed at locations points 1, 2, 3 and 4, and in the second step, tri-axial accelerometers are placed at locations points 5, 6, 7 and 8 seen in Fig. 4. The signals in the two steps are incorporated using a reference uni-axial accelerometer located between 1 and 2 accelerometer. Signals acquired from the accelerometers are combined with 17 channel data acquisition system and they are sent to PULSE [23] software for the further processing (Fig. 5). After the processing of the signals, dynamic characteristics are extracted using Operational Modal Analysis (OMA) software [24].

In (OMA), Peak Picking (PP) technique is used to extract the natural frequencies, mode shapes and damping ratios of the storage tank. PP technique is a kind of frequency domain and the simplest known way to extract the dynamic characteristics of a structure. Frequency domain algorithms have been the most popular, mainly due to their simplicity and processing speed. So, PP technique is often used in civil engineering practice for ambient vibration measurements. Moreover, some refinements are existed of PP technique. For instance, the coherence function between two channels tends to go to one at the resonance frequencies because of the strong structural response leading to high signal-to-noise ratio at these frequencies. Consequently, inspecting the coherence function can assist in selecting the eigen frequencies [25]. In this study, singular values of spectral density matrices obtained from vibration signals using PP technique is shown in Fig. 6.

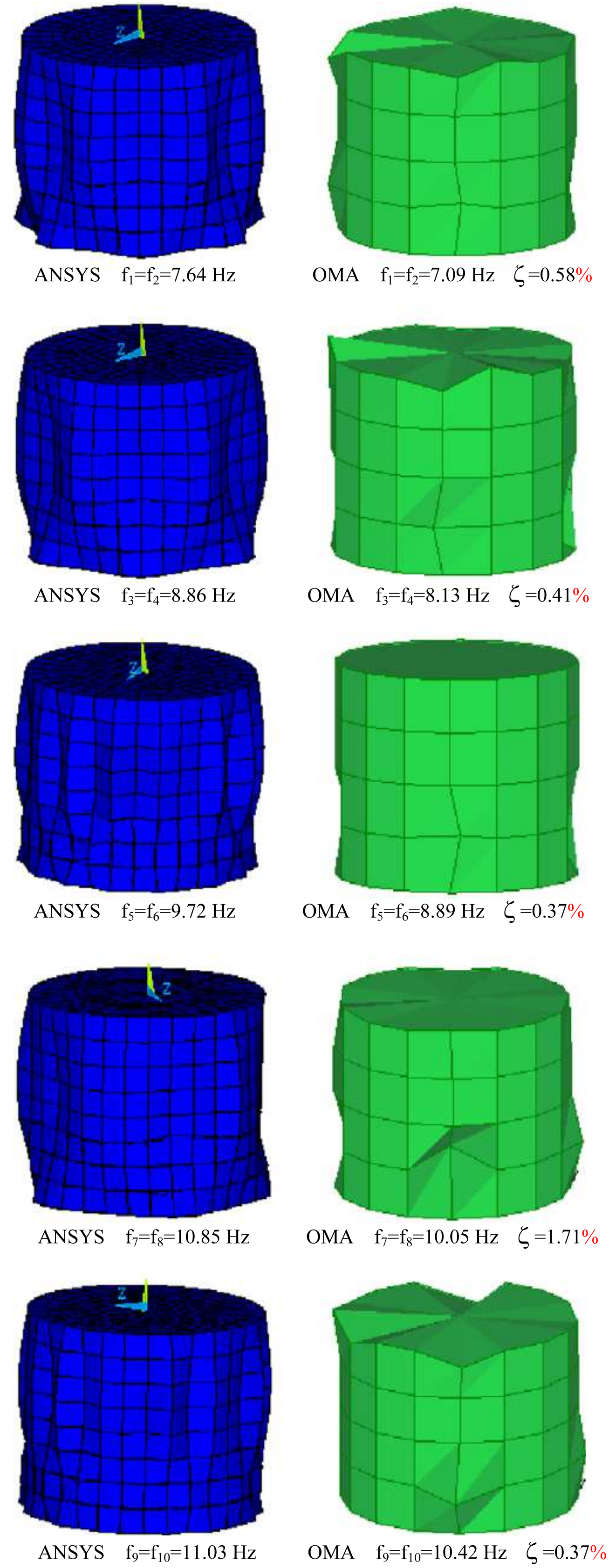


Fig. 7. The first ten modes obtained from the analytical and operational modal analyses.

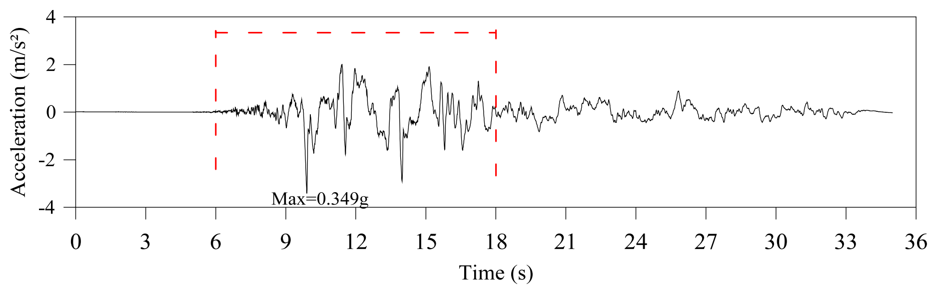


Fig. 8. The time-history of ground motion acceleration of Kocaeli earthquake (1999).

Table 1
Analytical and experimental frequencies before/after model updating.

Frequency number	Analytical frequencies (Hz)		Experimental frequencies (Hz)
	Before finite element model updating	After finite element model updating	PP method
1–2	7.64	7.09	7.09
3–4	8.86	8.12	8.13
5–6	9.72	8.92	8.89
7–8	10.85	10.04	10.05
9–10	11.03	10.40	10.42

2.4. Comparison of the analytical and experimental dynamic characteristics

The first ten mode shapes and corresponding natural frequencies obtained from the analytical and Operational Modal Analyses are shown in Fig. 7. It can be seen from Fig. 7, the first ten modes are bending modes and related to side sheet of the storage tank on horizontal directions. Because of the symmetry, the coupled modes shapes are obtained from the analyses. In addition, damping ratios (ζ) of the storage tank obtained from OMA are given in Fig. 7.

It is seen from Fig. 7 that there is a good agreement between mode shapes, but there are some differences between analytical and experimental natural frequencies. So, finite element model of the storage tank–liquid fuel oil system must be updated according to experimental results to minimize these differences as much as possible.

2.5. Finite element model updating

The finite element model of the storage tank–liquid fuel oil system is updated by changing the initial material properties of the steel tank. Material properties of the fuel oil are not changed because of the fact that the values are obtained from chemical tests. Approximately 300 kg mass (researchers', test equipment and scarecrows' weight) is added to couple nodes between side sheets and cover of the tank. Updated elasticity modulus of the steel iron is estimated as 1.80E5 MPa. Natural frequencies obtained from before and after finite element model updating and OMA are given in Table 1. It is seen from Table 1, analytical and experimental natural frequencies are almost closed to each other after finite element model updating of the storage tank. The mode shapes obtained before and after finite element model updating are similar each other. So, it is can be said that updated finite element model of the storage tank–liquid fuel oil system reflects the current dynamic behavior. Therefore, updated 3D finite element model can be used for the following and next studies.

2.6. Earthquake behavior

In this part of the study, earthquake behavior of the liquid fuel storage tank is investigated before and after finite element model updating. The aim of the investigation of earthquake behavior is to compare both situation and to highlight the importance of the ambient vibration testing and finite element model updating.

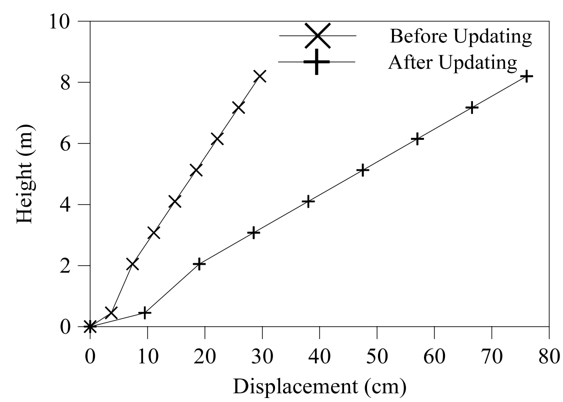


Fig. 9. Maximum horizontal displacements on I-I section before and after model updating.

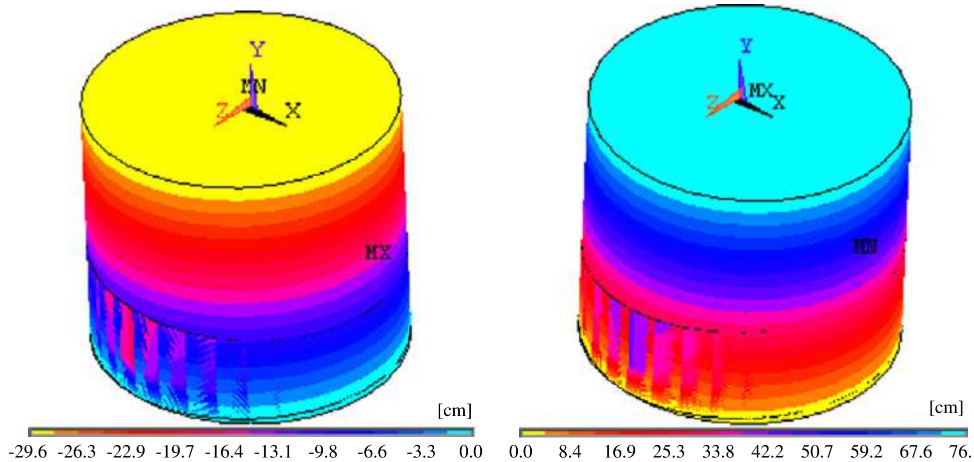
Table 2
Material properties of the updated storage tank–liquid fuel oil system

	ANSYS element type	Material properties		
		Elasticity modulus (MPa)	Poisson ratio	Mass density (kg/m^3)
Storage tank	Shell63	1.80E5	0.30	7850
Fuel oil	Fluid80	2.35E3	–	940

Linear transient analyses of the storage tank are performed using YPT330 component of 1999 Kocaeli earthquake (Fig. 8) [27]. Element matrices are computed using the Gauss numerical integration technique [26]. The Newmark method is used in the solution of the equation of motion. Because of needed too much memory for the analyses, 12 s between 6 and 18 s of the ground motion, which is the most effective duration, is taken into account in calculations. 5% damping ratio is used in the analysis before model updating. In the analysis after finite element model updating, updated material properties (Table 2) and averagely 0.7% damping ratio are used which are obtained from experimental measurements (Fig. 7).

The variation of maximum horizontal displacements on I-I section (Fig. 2) of the storage tank before and after model updating is given in Fig. 9. Also, maximum horizontal displacements contours are given in Fig. 10. These represent the distribution of the peak values reached by the maximum displacement at each point within the section. It is seen that displacements increase along to height of the storage tank, maximum displacement occurs at the top of the storage tank, and also the maximum displacement is obtained after finite element model updating.

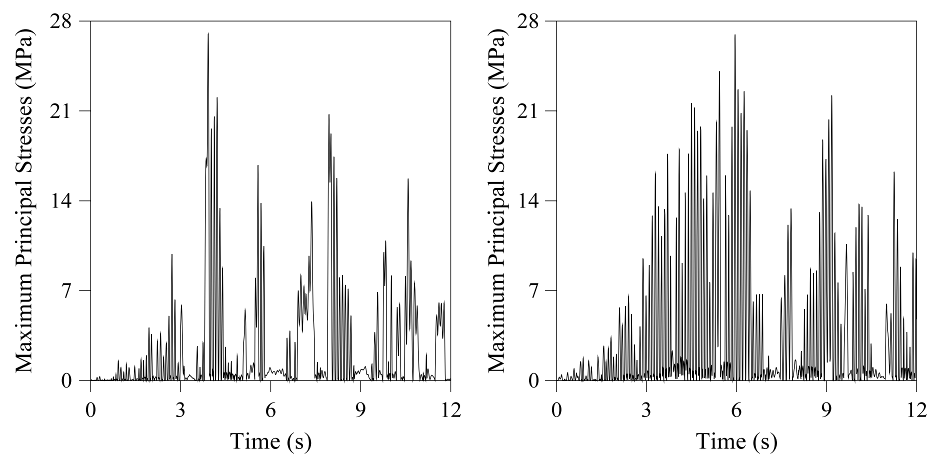
The time histories of the maximum and minimum principal stresses of the storage tank before and after model updating are



(a) Before model updating.

(b) After model updating.

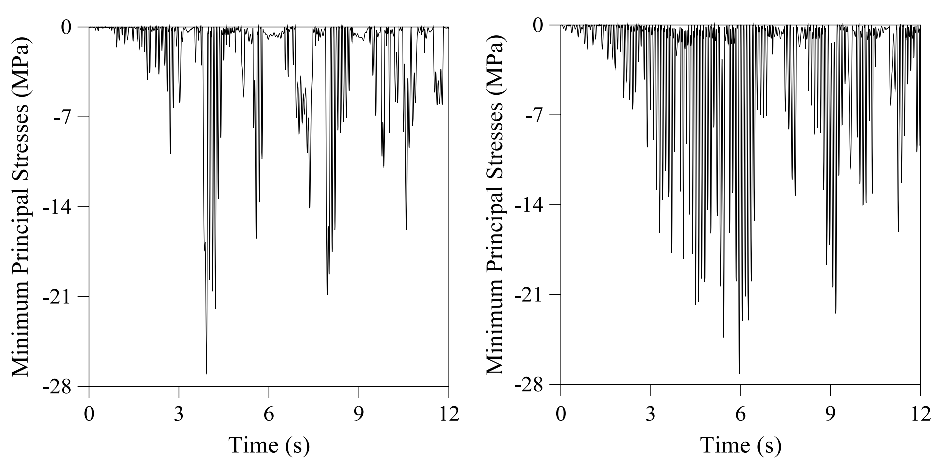
Fig. 10. Maximum displacement contours of the storage tank.



(a) Before model updating.

(b) After model updating.

Fig. 11. Maximum principal stresses of the storage tank.



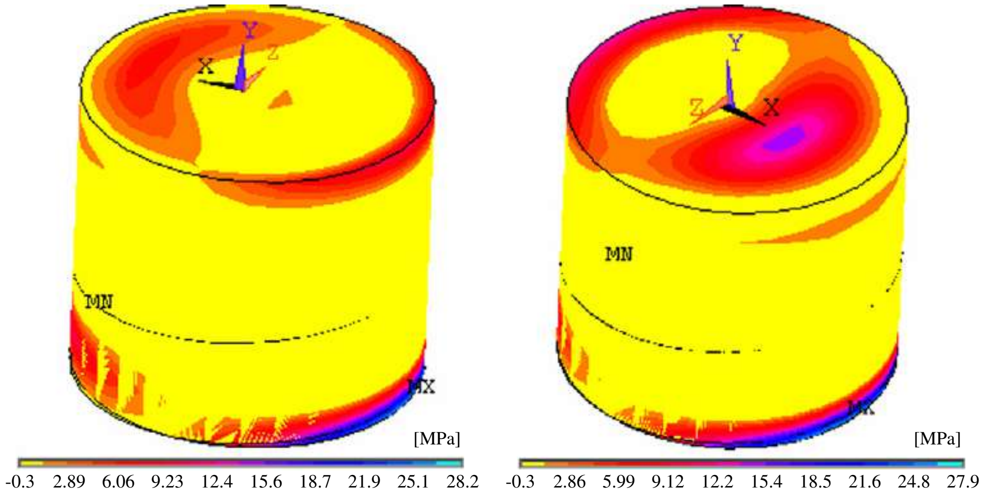
(a) Before model updating.

(b) After model updating.

Fig. 12. Minimum principal stresses of the storage tank.

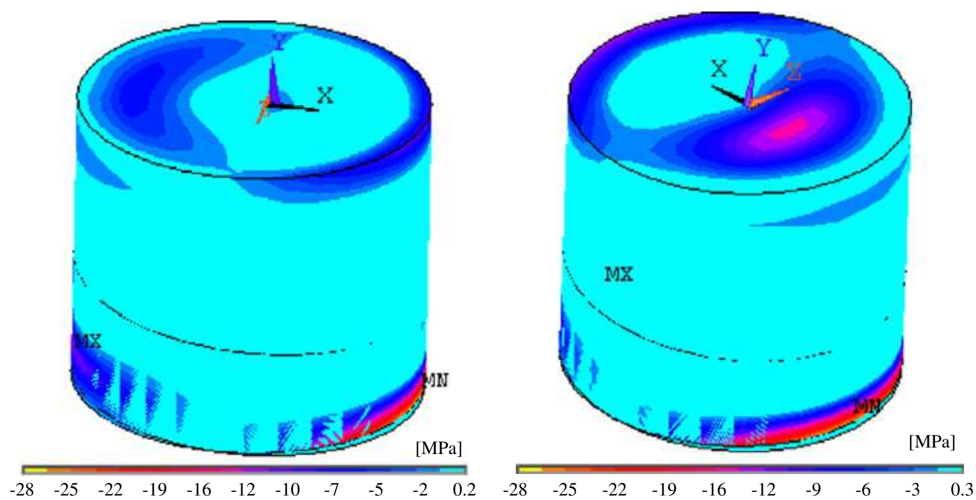
given in Figs. 11 and 12. The maximum and minimum values of the principal stresses are near for both situations. However, time histories of the principal stresses after finite element model updating are more effective during the earthquake.

Maximum and minimum principal stress contours of the storage tank before and after model updating are given in Figs. 13 and 14, respectively. These stress contours represent the distribution of the peak values reached by the maximum principal stress at each point within the section. It is clearly seen from Figs. 13 and 14 that the maximum and minimum principal stresses are occurred at nearly 0.5 m above from base of the tank.



(a) Before model updating. (b) After model updating.

Fig. 13. Maximum principal stress contours of the storage tank.



(a) Before model updating. (b) After model updating.

Fig. 14. Minimum principal stress contours of the storage tank.

3. Conclusions

In this paper, analytical and experimental studies are performed on a cylindrical steel liquid fuel storage tank. The studies include the finite element modeling, ambient vibration testing, finite element model updating and earthquake analyses of the storage tank. In these studies, analytical dynamic characteristics are obtained from modal analysis. Experimental dynamic characteristics are attained from the ambient vibration tests, Earthquake analyses of the storage tank before and after finite element model updating are performed, and the results for both situations are compared to each other. In conclusion, the following observations and suggestion can be made from this study:

- From the initial finite element model of the liquid fuel storage tank, a total of 10 natural frequencies are attained analytically, which range between 7-12 Hz. The mode shapes are bending modes and related to side sheet of the tank on horizontal directions. The liquid fuel oil affected upon the mode shapes. Coupled modes are obtained due to symmetry of the system.
- When the analytical and experimental results are compared to each other, it could be seen that there is good agreement between mode shapes, but some differences in the natural frequencies. Also, the analytical frequencies are bigger than those of the experimental.
- To minimize differences between analytical and experimental dynamic characteristics, the finite element model of the tank is updated by changing of material properties. Initial elasticity modulus is reduced 14%, and also additional mass is considered.
- After finite element model updating, maximum differences between analytical and experimental natural frequencies are reduced from 15% to 1%. In addition to these, there is good agreement between the mode shapes obtained from the updated finite element model and experimental results.
- When earthquake analyses' results are compared displacements after finite element model updating are nearly treble bigger than the other. The peak values of the principal stresses are nearly similar. However time histories of the principal stresses after finite element model updating are more effective than the other.
- Material properties and damping ratios, which are used transient analyses of the updated model of the storage tank, are realized to be very effective on the earthquake behavior of the storage tank.
- Finally, OMA is very important for determination current dynamic behavior of fluid–structure interaction systems such as

liquid fuel storage tanks. Also, finite element model updating procedure is very necessary to develop a finite element model which reflects the current behavior.

Acknowledgements

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References

[1] Shrimali MK, Jangid RS. Earthquake response of isolated elevated liquid storage steel tanks. Journal of Constructional Steel Research 2003;59:1267–88.
[2] Housner GW. The dynamic behavior of water tanks. Bulletin of the Seismological Society of America 1963;53(2):381–7.
[3] Westergaard HM. Water pressures on dams during earthquakes. Transactions ASCE 1933;98:418–33.
[4] Zienkiewicz OC, Bettes P. Fluid–structure dynamic interaction and wave forces; an introduction to numerical treatment. International Journal of Numerical Methods in Engineering 1978;13:1–16.
[5] Wilson EL, Khalvati M. Finite elements for the dynamic analysis of fluid–solid systems. International Journal of Numerical Methods in Engineering 1983;19:657–68.
[6] Virella JC, Godoy LA, Suarez LE. Influence of the roof on the natural periods of steel tanks. Engineering Structures 2003;25:877–87.
[7] Virella JC, Suarez LE, Godoy LA. Impulsive modes of vibration of cylindrical tank–liquid systems under horizontal motion: Effect of pre-stress states. Journal of Vibration and Control 2005;11(9):1195–220.
[8] Virella JC, Godoy LA, Suarez LE. Fundamental modes of tank–liquid systems under horizontal motions. Engineering Structures 2006;28(10):1450–61.
[9] Virella JC, Godoy LA, Suarez LE. Dynamic buckling of anchored steel tanks subjected to horizontal earthquake excitation. Journal of Constructional Steel Research 2006;62(6):521–31.
[10] Virella JC, Prato CA, Godoy LA. Linear and nonlinear 2-D finite element analysis of sloshing modes and pressures in rectangular tanks subject to horizontal harmonic motions. Journal of Sound and Vibration 2008;312:442–60.
[11] Mariana RK. Free vibrations of cylindrical storage tanks: Finite-element analysis and experiments. Journal of Engineering Mechanics ASCE 2007;133(6):728–33.
[12] Dooms D, Degrande G, Roeck G, Reynders E. Finite element modelling of a silo based on experimental modal analysis. Engineering Structures 2006;28:532–42.
[13] Jhung MJ, Jo JC, Jeong SJ. Impact analysis of a water storage tank. Nuclear Engineering and Technology 2006;38(7):681–8.
[14] Hamdan FH. Seismic behavior of cylindrical steel liquid storage tanks. Journal of Constructional Steel Research 2000;53:307–33.
[15] Malhotra PK, Wenk T, Wieland M. Simple procedure for seismic analysis of liquid-storage tanks. Structural Engineering International 2000;3:197–201.
[16] Jacobsen LS. Impulsive hydrodynamics of fluid inside a cylindrical tank and of fluid surrounding a cylindrical pier. Bulletin of the Seismological Society of America 1949;39(3):189–203.
[17] Ljung L. System identification: Theory for the user. Englewood Cliffs (NJ): Prentice-Hall; 1987.
[18] Roeck GD, Peeters B, Ren WX. Benchmark study on system identification through ambient vibration measurements. In: Proceedings of the 18th international modal analysis conference. 2000. p. 1106–12.
[19] Modak SV, Kundra TK, Nakra BC. Comparative study of model updating methods using experimental data. Computers and Structures 2002;80(5–6):437–47.
[20] Bayraktar A, Altunışık AC, Sevim B, Türker T. Modal testing and finite element model calibration of an arch type steel footbridge. Steel and Composite Structures 2007;7(6):487–502.
[21] ANSYS. Swanson analysis system, US. 2008.
[22] Calayır Y. Dynamic analysis of concrete gravity dams using the eulerian and lagrangian approaches. Ph.D. thesis. Trabzon (Turkey): Karadeniz Technical University; 1994 [in Turkish].
[23] PULSE, Analyzers and solutions. Release 11.2, Bruel and Kjaer, Sound and Vibration Measurement A/S, Denmark; 2006.
[24] OMA. Operational modal analysis. Release 4.0, Structural vibration solution A/S, Denmark. 2006.
[25] Brincker R, Zhang L, Andersen P. Modal identification from ambient responses using frequency domain decomposition. In: Proceedings of the 18th international modal analysis conference. 2000. p. 625–30.
[26] Bathe KJ. Finite element procedures in engineering analysis. Englewood Cliffs (NJ): Prentice-Hall; 1996.
[27] Url-1. http://peer.berkeley.edu/smcat/data/ath/DUZCE/YPT330.AT2, 12.01.2008.