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Numerical Simulation of Fluid-Structure Interaction of LNG Prestressed Storage Tank under Seismic Influence

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Abstract: Aim of this paper is to estimate the integrity of liquefied natural gas (LNG) prestressed storage tank under seismic influence. The coupled Eulerian-Lagrangian (CEL) analysis technique is used to simulate the fluid-structure interaction between LNG and the cylinder of LNG prestressed storage tank. The 3-D model of LNG has been dispersed by Eulerian mesh that is different from traditional analysis method which is called the added mass method. Meanwhile, both of the 3-D models of prestressed rebar and concrete structure are dispersed by Lagrangian mesh. Following conclusions are obtained: 1) Natural frequency of the whole model has been obtained by using the Block Lanczos algorithm in Abaqus; 2) Seismic waves of El Centro and Taft have been selected for time history analysis, and curves of displacement, stress and acceleration have been plotted under two seismic waves respectively. By comparing time points when the maximum displacement, stress and acceleration occurred to splash phenomena of LNG liquid surface, numerical results can fit splash phenomena of LNG very well. 3)When El Centro wave is imported, the maximum values of displacement and tension stress of concrete structure are 7.729mm and 2.16MPa respectively, and the maximum values of displacement and tension stress of concrete structure are 9.4mm and 0.24MPa respectively when Taft wave is applied. The values of maximum tension stress are less than the axial tensile strength of the standard value of concrete, which indicate that the structure of LNG prestressed storage tank is safe, and numerical results can provide a reference to monitor the liability of this kind of structures.

Keywords: Fluid-Structure Interaction, CEL Analysis, LNG Tank, Finite Element Method, ABAQUS

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1 Introduction

With the continuous growth of energy consumption, the level of demand of the natural gas which is clean energy is increasing sharply in the world wide energy market. Meanwhile, considering the boiling point of natural gas is about $-160°C$ under the normal atmospheric pressure, the natural gas is always made into liquefied natural gas (LNG) by using cooling technology under low pressure Li (2006), and the volume of LNG is 1/600 of gas. The LNG is convenient and flexible for transportation and using, with these advantages the LNG is engaged more and more the attention of each country and LNG prestressed storage tank has been widely used.

For the storage tank full of LNG, it's significant and arduous to deal with hydrodynamic interaction between LNG and cylinder structure which is called fluid-structure interaction. When seismic loads are applied respectively, cylinder structure is not only affected by inertia force caused by itself and hydrostatic pressure, but also impacted by hydrodynamic pressure due to the phenomenon of liquid sloshing Veletsos and Yang (1976).

In 1933, the added mass method which is the theory of computing hydrodynamic pressure on the interface of fluid structure interaction has been established by H.M. Westergaard. However, cylinder must be considered as rigid body with this method, and then hydrodynamic pressure has been transformed into the added mass and applied on the storage structure. Obviously, the real situation cannot be simulated by using this method Westergaard (1933).

In 1940s, an improved research of rigid storage tank has been done by Hoskin et al, and then in 1957, based on the former researches, a simple model has been presented by Housner. In this model, rigid storage tank has been simplified into mass elastic system which is called virtual mass method. Though this model is very simple and recognized by engineering, seismic shear stress and moment which are calculated by using this model are lower than reality, so it cannot be fully used in the calculation of LNG prestressed storage tank analysis Hoskin and Jacobsen (1934); Housner (1957, 1963).

In 1969, the first study about coupled vibration between storage tank and LNG by using the finite element method has been done by N.W. Edwards. Later, coupled seismic behavior of LNG and storage tank has been simulated by W.A. Nash and Haroun by using finite element method as well as N.W. Edwards, sander shell theory has been used for cylinder and potential theory has been applied to fluid, and it's assumed that there is no sloshing in free surface of LNG Edwards (1969).

With developing of simplified analysis model of storage tank, in 1974, Veletsos-Yang model has been established by Veletsos and Yang, acronym is V-Y model.

Solid fluid system has been simplified into a single degree of freedom system which vibrates with a prior assumption of modal, and LNG also has been converted into the added mass and applied on the cylinder Veletsos and Yang (1976).

After Veletsos, in 1983, Haroun-Housner model has been presented. LNG has been regarded as non-individual body; velocity potential theory and boundary integral method have been used to transform mass of LNG into the added mass. Convection component, flexible pulsation component and rigid pulsation component have been considered in this model Haroun and Housner (1981); Haroun (1983). However, the added mass method has been used in all above researches, considering computational expense and computer performance requirements; no 3-D model has been created for LNG in former studies.

In recent years, with rapid development of the commercial calculation software, it has become possible to simulate the fluid-structure interaction behavior by using finite element method with 3-D element model. The earliest analysis technology for simulating fluid-structure interaction is Arbitrary Lagrangian-Eulerian method (ALE), and then the coupled Eulerian-Lagrangian analysis technology (CEL) has been presented, with this method, both elements of Lagrangian and Eulerian are considered. Moreover, interference is accepted in two types of elements with this technology which can make the simulation of fluid-structure interaction to approach the reality Abaqus (6.10). However lots of elements must be meshed in this method and it's very difficult to complete by ordinary computer which is the reason of current researches who used simplified method to simulate fluid-structure interaction.

Recently, with the emergence of large-scale computing server, the capability of computing has increased sharply; it's viable to complete the simulation of fluid-structure interaction by using CEL analysis technology with 3-D element model which is the numerical basis and valuable reference for engineering.

2 Finite element models

In this paper, large liquefied natural gas prestressed full containment tank has been studied Zhang et al (2010), which can store LNG in $-165°C$ and under 230mbarg pressure. The cylinder structure is prestressed concrete type in order to prevent the LNG divulging, and the volume of LNG tank is 50,000m^3, the thickness, inside diameter and height of cylinders shell are given as 0.65m, 54.8m and 29.3m respectively. The dome and ring beam are built on the top of LNG tank, and the diameter, sagitta and thickness of dome are 54.8m, 7.342m and 0.4m respectively. The maximum storage height of LNG tank is 23.67m, see Fig. 1.

Both of 3-D models of LNG prestressed tank and prestressed rebar are created by the parameter above and some details are simplified, different from the added mass

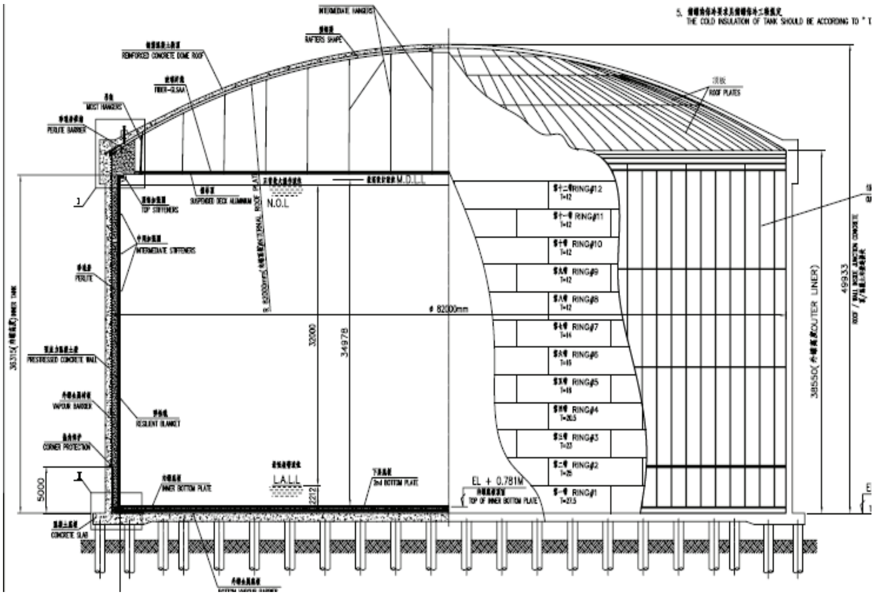

Figure 1: The design of LNG pretressed tank

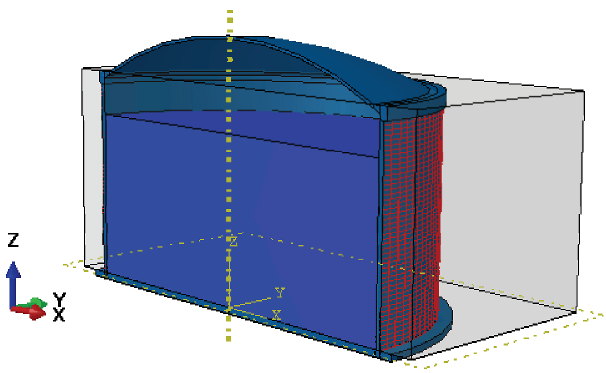

Figure 2: The whole model of LNG pretressed tank

method, 3-D model of LNG is created by Eulerian part. In this part, the initial location of LNG should be discretized by Eulerian volume fraction (EVF) Abaqus (6.10), as is shown in Fig. 2.

The strength of concrete of the LNG tank structure is C40, the ordinary rebar is HRB400, and the type of unbonded rebar is No.270 steel strand which belong to the criterion ASTMA416. The vertical rebar is set one per 3° along the circle direction, totally 120 lines, and the circle prestressed rebar is set one per 0.6m along the radial direction, totally 47 lines Shu et al (2007). The maximum storage height of LNG tank is 23.67m which is the initial height of LNG, and the scale of Eulerian mesh should be large enough to include all the possible behavior of LNG. Detail properties of concrete, rebar and LNG materials and boundary conditions are shown in next sections.

3 Property

Material properties for Eulerian analysis are defined in the same way as for Lagrangian analysis. Liquids and gases can be modeled using equation of state materials (EOS), Hyperelastic and anisotropic materials are not supported because of inaccuracies introduced to deformation gradient and orientation data during material transport. Brittle cracking is not supported because the failure mode is anisotropic.

In this paper, LNG material has been modeled by using EOS, and density ρ, viscosity coefficient η and sound velocity in liquids C_0 of LNG should be given, all the other coefficients are default, which is shown in the Tab. 1.

Table 1: Material properties of LNG(EOS)

ρ(kg/m^3)	η(Ns/m^2)	C_0(m/s)	Us-Up s	Grüneisen Γ_0
480	0.00113	1500	0	0

Detail material properties of concrete, prestressed rebar and ordinary rebar are shown in the Tab. 2.

4 Loads and boundary conditions

Loads include the dead load, live load, prestress, gas pressure, hydrostatic pressure and seismic loads Shu et al (2007). The acceleration of gravity for the whole model can apply the dead load, and the value of the live load is $P = 1.2KN/m^2$ which is applied on the top of dome, the value of gas pressure is $P_g = 230mb\arg$ which is distributed on the whole internal face of cylinder shell. Meanwhile, both of pressures of hydrostatic and hydrodynamic are performed by 3-D model of LNG in Eulerian mesh.

Seismic waves of El Centro type and Taft type are chosen to simulate the behavior of earthquake, the unit of acceleration is cm/s^2, and unit of time is s, as shown in Fig. 3.

Table 2: Material properties of LNG prestressed tank

Concrete C40		**Unbonded prestressed rebar**		**Rebar HRB400**
Elasticity modulusE_c ($\times 10^4$ N/mm^2)	3.25	Elasticity modulusE_c ($\times 10^5$ N/mm^2)	1.95	2.0
Poisson's ratio	0.2	Poisson's ratio	0.3	0.3
Density ρ(N/mm^3)	2500	Density ρ(N/mm^3)	7800	7800
Coefficient of linear expansion	1×10^{-5}	1.2×10^{-5}	Circle rebar ratio	1%
Coefficient of heat conductivity	1.74	52.8	Vertical rebar ratio	1%
Axial tensile strength of the standard value f_{tk}(N/mm^2)	2.39	Strength of the standard value f_{tk}(N/mm^2)	1860	400
Axial tensile strength of the design value f_t(N/mm^2)	1.71	Tension control stress σ_{con}(N/mm^2)	$0.75 f_{ptk}$	—
Axial compressive strength of the standard value f_{ck}(N/mm^2)	26.8	Nominal diameter (mm)	15.2	28
Axial compressive strength of the design value f_c(N/mm^2)	19.1	Nominal section area (mm^2)	139	615.8

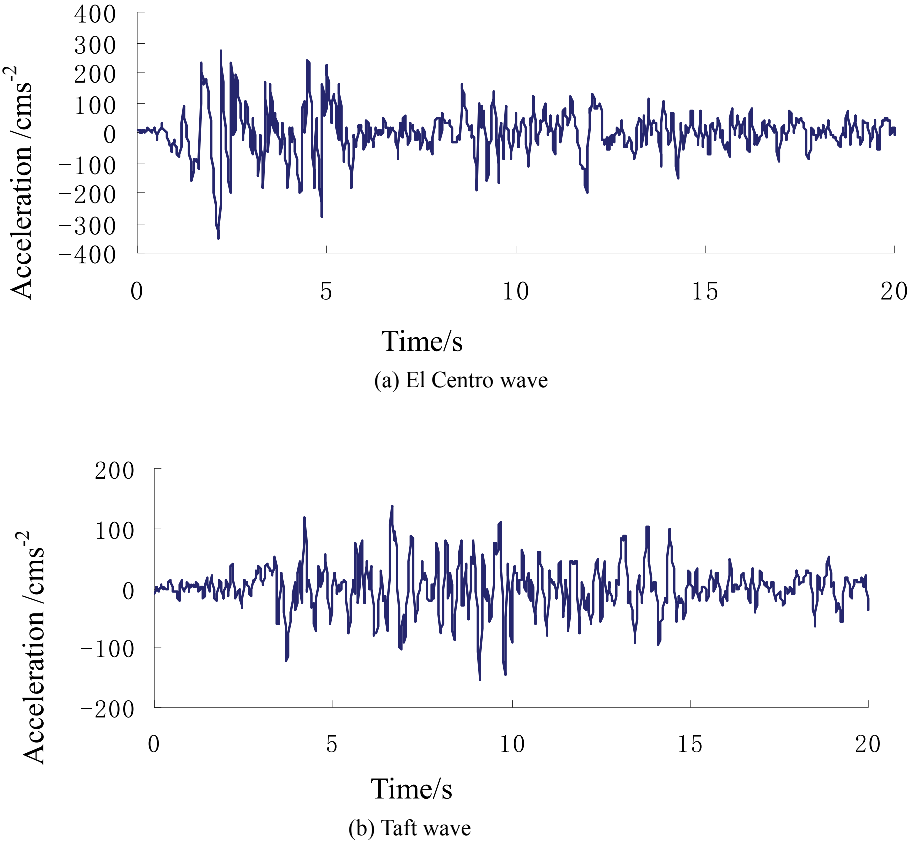

Figure 3: Seismic waves

The calculation of prestress is extremely significant, because LNG prestressed tank must be store enough residual stress to protect the concrete under a little tensile stress. The hooptension of cylinder shell which is caused by the dead load, live load, gas pressure and hydrostatic pressure is bear by the high strength prestressed steel strand. Because of the high performance of compression, the concrete tank will under the compression condition with the enough prestress, which can avoid the concrete of tank cracking. Considering to the Tab. 2, Tension control stress of prestressed rebar σ_{con} as in Eq. 1:

$$\sigma_{con} = 0.75 f_{tpk} = 0.75 \times 1860 = 1395 N/mm^2 = 1.395 \times 10^9 N/m^2 \quad (1)$$

Remove about 20% of the prestress loss, and the valid prestress σ_{pe} as in:

$$\sigma_{pe} = (1-0.2)\sigma_{con} = 1.395\times10^{9}\times0.8 = 1.116\times10^{9}N/m^{2} \quad (2)$$

In abaqus, there are several methods for the prestress such as the falling temperature method, initial prestress method, MPC method, single rebar method and rebar layer method Shu et al (2007). In this paper, the prestress is applied for rebar by falling temperature method which is commonly used. This method need initial temperature field and the final temperature field which can create valid prestress, the temperature difference between the initial and final is as in (3):

$$\sigma_{pe} = \lambda\cdot\Delta T\cdot E \quad (3)$$

Where, λ is the coefficient of linear expansion, E is the elasticity modulus.

Then substitute Eq.2 into Eq.3, and then ΔT is given by:

$$\sigma_{pe} = \lambda\cdot\Delta T\cdot E = 1.2\times10^{-5}\times1.95\times10^{11}\Delta T = 2.34\times10^{6}\Delta T = 1.116\times10^{9} \quad (4)$$

$$\Delta T = 476.9^{\circ}C \quad (5)$$

Consequently the valid prestress is created when the initial temperature is $0^{\circ}C$ and the final temperature is$-476.9^{\circ}C$, and the rebar is embedded in the cylinder shell by "*embedded" technology in Abaqus which can make rebar working together with concrete Zhuang et al (2009).

Considering there is no reaction force of the foundation, the boundary condition of bottom of the model is ENCASTRE; however, if seismic load is activated, degree of freedom should be removed in the direction of seismic load.

All the surfaces of Eulerian section are constrained with zero velocity conditions except the symmetric surface which can avoid material "flowing" in or out. The symmetric boundary condition is applied on the front surface of half model, which is shown in Fig. 4:

5 Mesh

In this model, rebar model is discretized by truss element and element type is T3D2, total of 5593 elements. The three dimensional 8-nodes element is used to discretized concrete model instead of shell element in order to simulate the reality stress behavior and minimum the calculation simultaneously. The element type of concrete is C3D8R, total of 12232 elements. Eulerian element is expanded by C3D8R element, which is used to discretized model of LNG, element type is EC3D8R, because the accuracy of simulation of liquid behavior depends to the

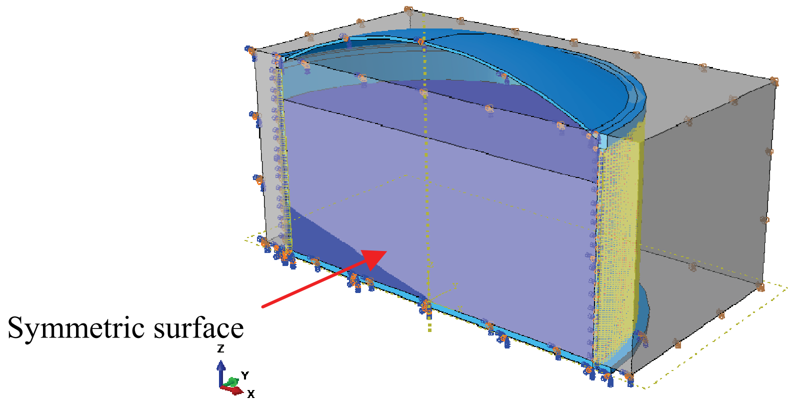

Figure 4: Loads and boundary conditions of LNG pretressed tank model

quality of Eulerian element, so the Eulerian element must be fine enough, LNG model is discretized into 65340 elements. There are total 83165 elements in whole model, as shown in Fig. 5:

6 Numerical results

Before dynamic analysis of LNG prestressed tank, natural frequency and natural period of vibration should be obtained. Basic characteristic equations can be determined by Eq.6:

$$[K]\{\Phi_i\} = \omega_i^2[M]\{\Phi_i\} \tag{6}$$

Where

$[K]$ is stiffness matrix; $[M]$ is mass matrix;

$\{\Phi_i\}$ is formation vector of the ith modal ;

ω_i is natural frequency of the ith modal ;

It's critical to how to obtain natural frequency and characteristic vector for calculating, in implicit dynamic analysis of Abaqus, there are two methods for calculating natural frequency and characteristic vector which are Subspace iteration method and the Block Lanczos algorithm. In this paper, natural frequency of the whole

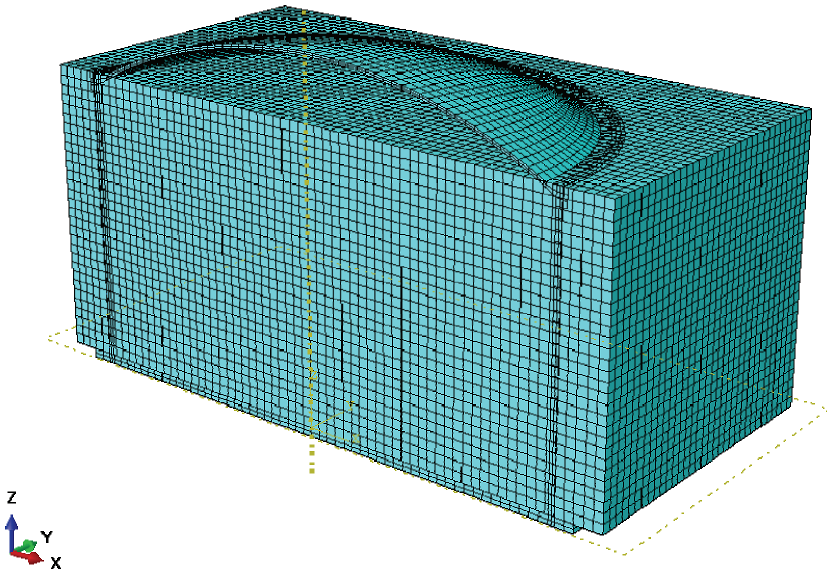

Figure 5: The mesh of LNG pretressed tank model

model has been obtained by using the Block Lanczos algorithm, and results are listed in Tab. 3.

Results show that natural frequency of LNG prestressed storage tank is 4.9787Hz and natural period of vibration is 0.2008s.

Waves of El Centro and Taft have been applied for the foundation of LNG prestressed storage tank respectively, when El Centro type is applied, the sloshing of liquid surface is shown in Fig. 6:

The sloshing of liquid surface has been simulated by using CEL analysis technology. Splash phenomena of LNG liquid surface indicate that fluid-structure interaction between LNG and storage tank is drastic.

Symmetry plane is defined as a datum plane, the highest height points of cylinder structure with angles 0, 45 and 90 degrees respectively from datum plane are defined as reference points, and the time history curves of displacement at reference points are plotted in Fig. 7, units of displacement and time are m and s respectively. The maximum displacement at the highest height point of cylinder is 7.729mm and the time is 3.19s when is 0.05s later than the time of peak of El Centro wave, at that moment, the drastic splash phenomenon of LNG liquid surface is occurring simultaneously.

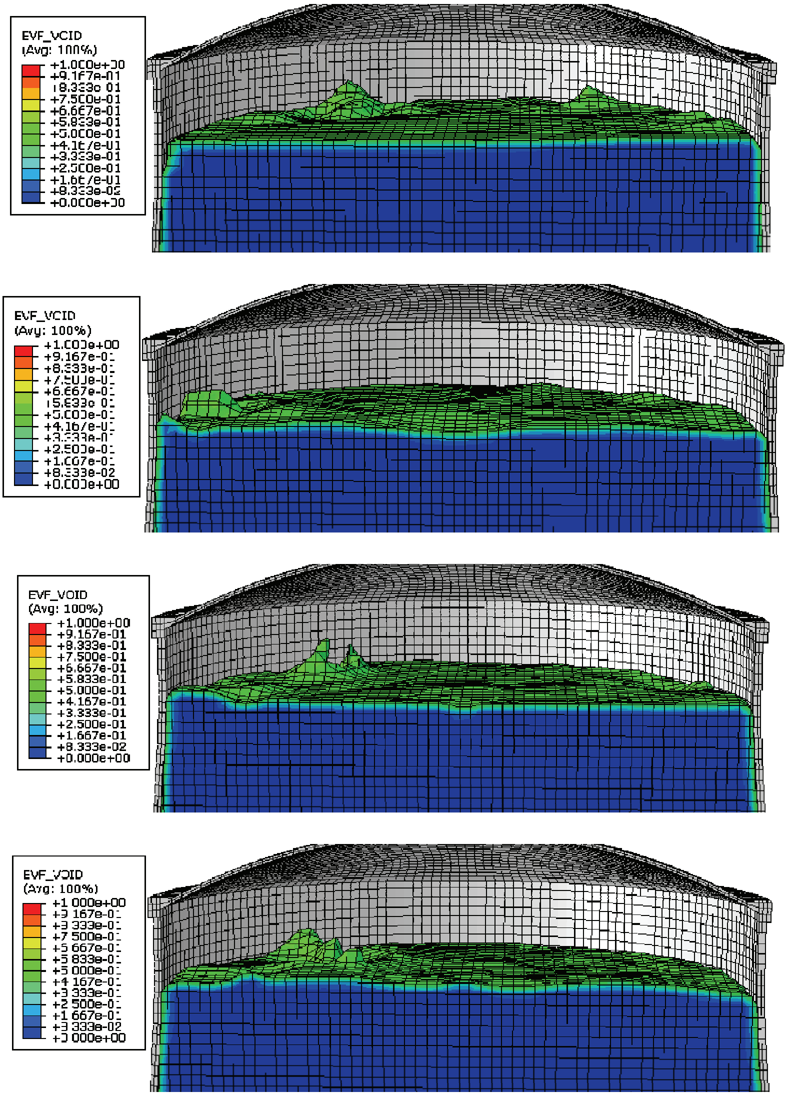

Figure 6: The sloshing of liquid surface under El Centro wave

Table 3: The 1st-10th natural frequency of LNG prestressed tank

Modal order	1	2	3	4	5	6	7	8	9	10
Frequency(Hz)	4.9787	4.9713	5.0225	5.0245	5.1839	5.1876	5.3968	5.3969	5.5694	5.5743
Period (s)	0.2008	0.2011	0.1991	0.1990	0.1929	0.1927	0.1852	0.1852	0.1795	0.1793

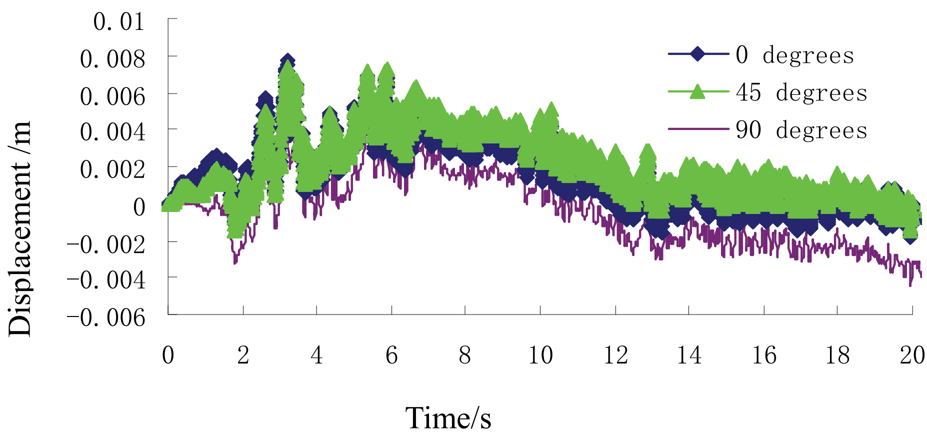

Figure 7: The time history curves of displacement at reference points under El Centro wave

The time history curve of stress and acceleration at the reference point are plotted in Fig. 8-Fig. 9, units of stress, acceleration and time are Pa, cm/s^2 and s respectively.

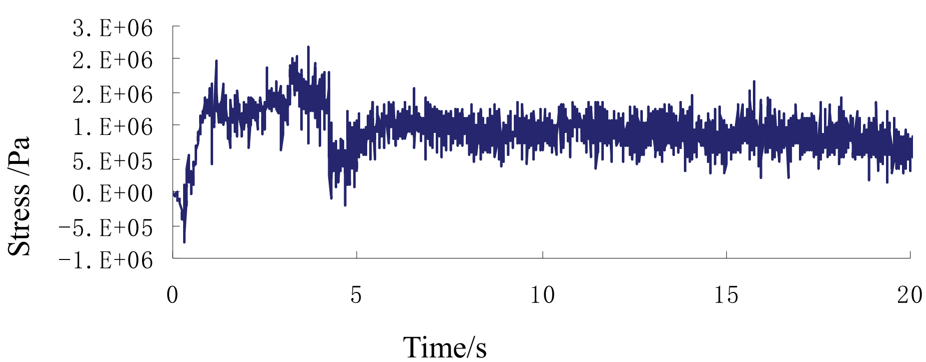

Figure 8: The time history curve of stress at reference point

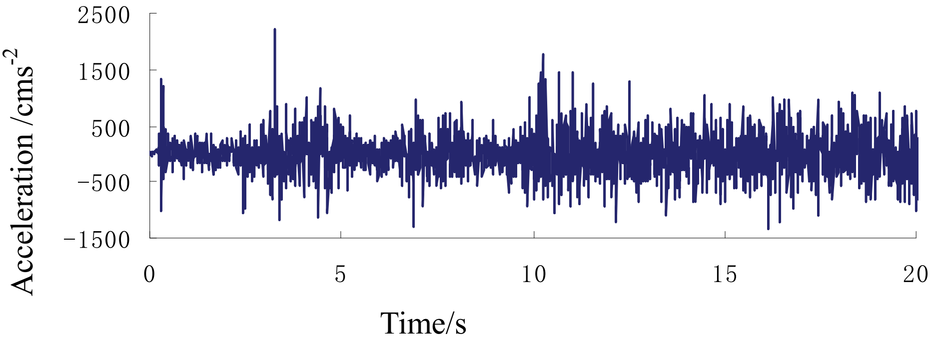

Figure 9: The time history curve of acceleration at reference point

At the time of 3.69s, the maximum value of tension stress occurred. The value is 2.16MPa which is less than the axial tensile strength of the standard value of concrete, results show that the structure of LNG prestressed storage tank is safe.

The maximum value of acceleration is 2228.3cm/s^2 which occurred at the time of 3.26s when approached to the time points of the maximum displacement and stress, numerical results can fit splash phenomena of LNG liquid surface very well.

When Taft type is applied, the sloshing of liquid surface is shown in Fig. 10.

Splash phenomena of LNG liquid surface occurred too when Taft seismic load was applied. The time history curves of displacement at reference points are plotted in Fig. 11, units of displacement and time are m and s respectively.

The maximum displacement at the highest height point of cylinder is 9.4mm and the time is 10.12s when is 4.05s later than the time of peak of Taft wave, but at the time of 11s, the drastic splash phenomenon of LNG liquid surface is also occurring simultaneously.

The time history curve of stress and acceleration at the reference point are plotted in Fig. 12-Fig. 13, units of stress, acceleration and time are Pa, cm/s^2 and s respectively.

At the time of 14.93s, the maximum value of tension stress occurred. The value is 0.24MPa which is less than the axial tensile strength of the standard value of concrete, results show that the structure of LNG prestressed storage tank is safe.

The maximum value of acceleration is 1135.21cm/s^2 which occurred at the time of 18.3s when is approached to the time points of the maximum displacement and stress.

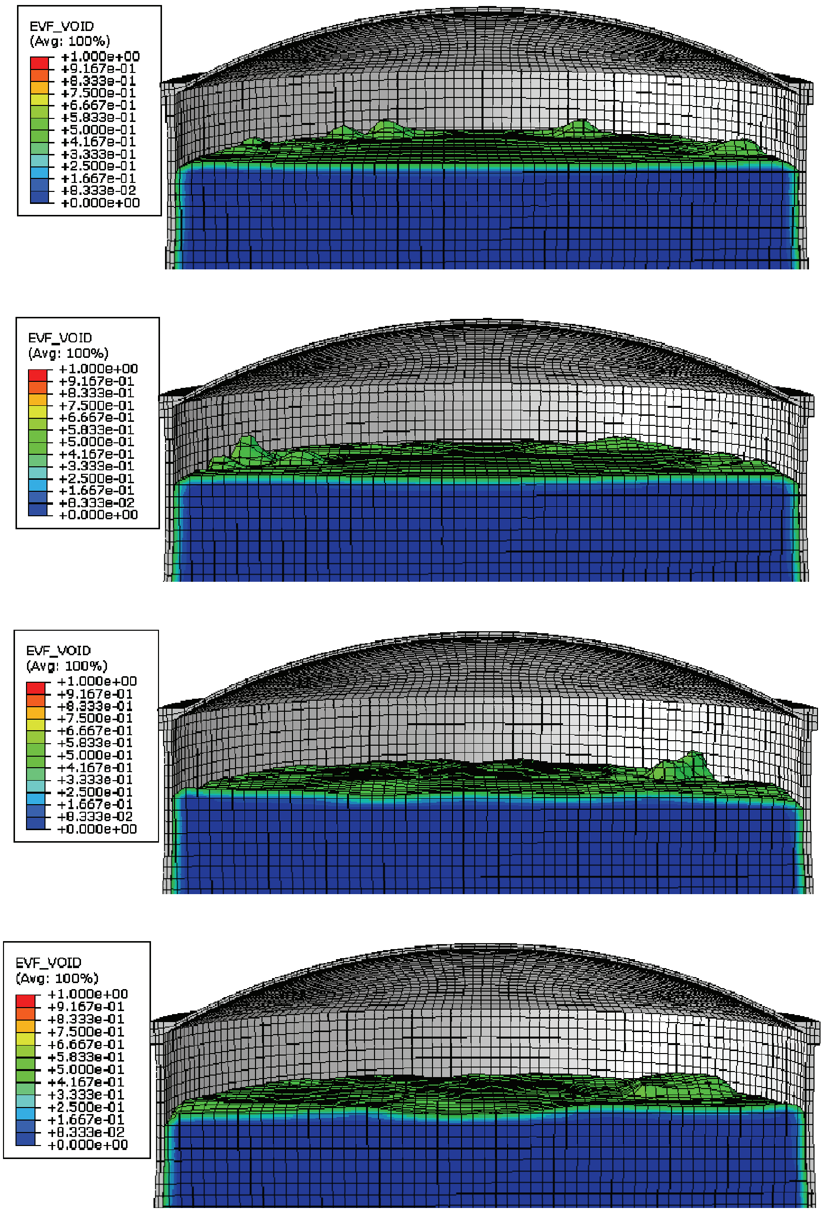

Figure 10: The sloshing of liquid surface under Taft wave

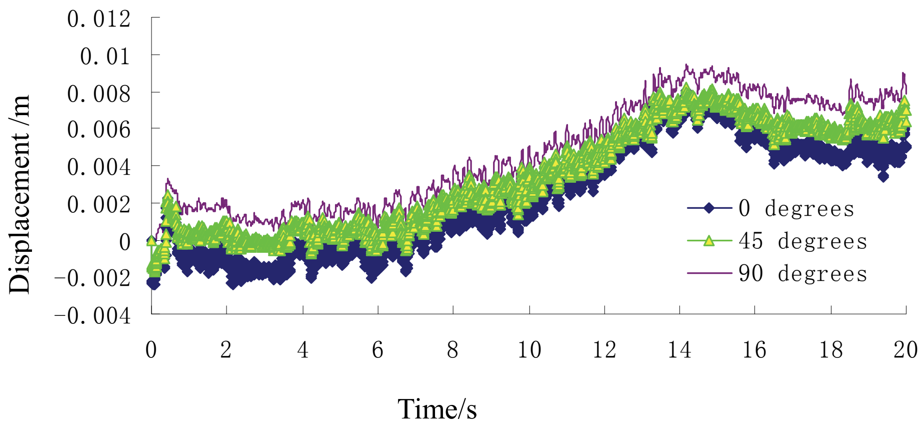

Figure 11: The time history curves of displacement at reference points under Taft wave

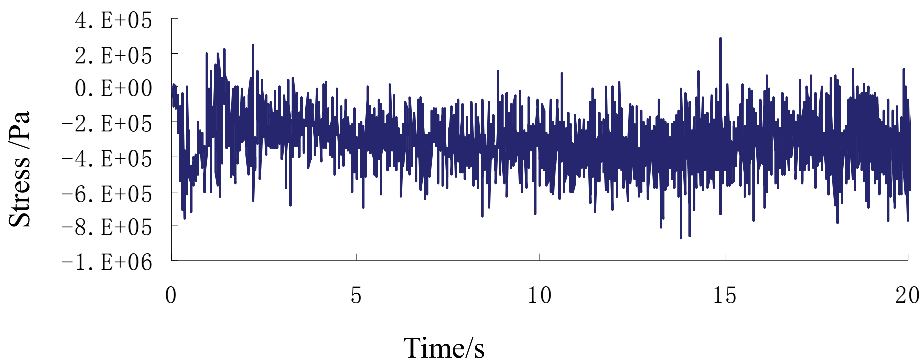

Figure 12: The time history curve of stress at reference point

7 Conclusions

Natural frequency of the whole model has been obtained by using the Block Lanczos algorithm, results show that natural frequency of LNG prestressed storage tank is 4.9787Hz and natural period of vibration is 0.2008s.

The sloshing of liquid surface has been simulated by using CEL analysis technology. Splash phenomena of LNG liquid surface indicate that fluid-structure interaction between LNG and storage tank is drastic which show that numerical simulation

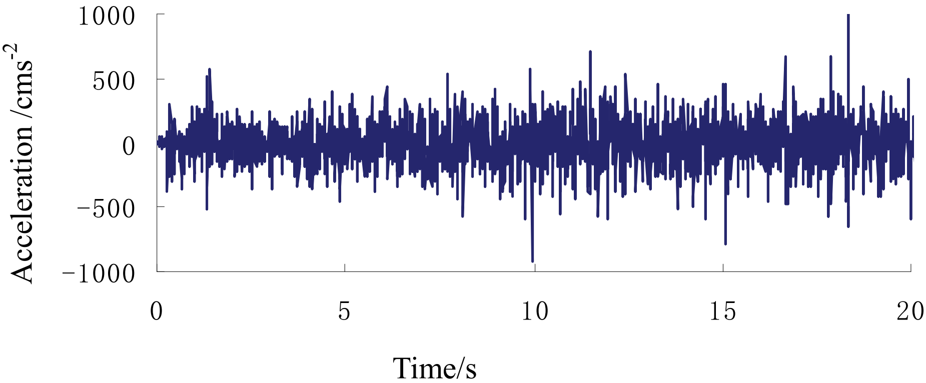

Figure 13: The time history curve of acceleration at reference point

of fluid-structure interaction of LNG prestressed storage tank under seismic influence by using CEL analysis technology is available and reasonable.

Curves of displacement, stress and acceleration at reference points have been plotted under seismic loads. Numerical results can fit splash phenomena of LNG liquid surface very well. When El Centro seismic wave is applied, values of maximum displacement is 7.729mm within concrete structure, and that of tensile stress is 2.16MPa. The value of maximum displacement under action of Taft wave is 9.4mm, and that of tensile stress is 0.24MPa. The values of maximum tension stress are less than the axial tensile strength of the standard value of concrete, which indicate that the structure of LNG prestressed storage tank is safe, and numerical results can provide a reference to monitor the liability of this kind of structures.

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