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DAMAGE MODES AND FAILURE MECHANISM OF 160,000 m^3 LNG OUTER CONCRETE TANK UNDER IMPACT LOADING

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In order to investigate the damage models and failure mechanism of the outer concrete tank of the liquefied natural gas (LNG) storage tank under impact loading, the finite element (FE) model of the outer concrete tank of 160,000 m^3 LNG storage tank for an actual LNG project and a cylindrical impactor are established based on ANSYS/LS-DYNA FE analysis software platform. Through the result comparison of the numerical simulation and an impact perforation test of reinforced concrete slabs subjected to projectile with high speed, the accuracy of the numerical simulation method and material model proposed from this paper are verified. The dynamic response of the concrete dome for LNG outer concrete tank structures under impact loading is studied. Based on response rules and failure phenomena of the dome for LNG outer concrete storage tank subject to impact loading, three damage modes are defined, and the failure mechanism for each mode is revealed from the view point of energy.

Keywords: LNG storage tank, Concrete dome, Cylindrical impactor, Dynamic response, Response characteristic, Failure phenomena.

1 INTRODUCTION

In recent years, the demand for clean energy has been increasing year by year. Liquefied Natural Gas (LNG) has gradually become the most important energy in this century due to its green, economical, safe and reliable advantages. LNG storage tank structure also gets more application. In view of the importance and particularity of the structure of LNG storage tank, the impact failure of tank structure and its secondary explosion and fire disaster can lead to great loss of life and property. Therefore, it is of great significance to put forward reasonable evaluation of impact resistance and defensive design theory to ensure the safety of LNG tank in major disasters.

At present, the anti-impact performance of large-scale reinforced concrete structures such as nuclear containments and dams are relatively rich in research results, while the impact resistance of large-scale LNG outer concrete tank is less. Iqbal (2012) and Mohammed (2005) studied the dynamic responses of nuclear containment structure and the World Trade Center under impact of aircraft. Fan (2010) and Wang (2008) got the failure process and damage modes for single-layer reticulated domes under impact loads. Zhang (2011) and Su (2012) analyzed the degree of damage and dynamic response of LNG outer concrete tank under impact and blast loading. Furthermore, British Standard BS7777-1 (1993) states that the tank should have the ability to withstand flying objects, and mentions that it may be considered reasonable to use the impact from a valve weighing 50 kg travelling at 45 m/s. However, the damage modes and failure mechanism of LNG outer concrete tank under impact load are still in the black.

The FE model of the outer concrete tank of 160,000 m^3 LNG storage tank for an actual LNG project is established based on ANSYS/LS-DYNA FE analysis software platform. Based on dynamic response of the dome for LNG outer concrete storage tank subject to impact loading, three damage modes are defined, and the failure mechanism for each mode is proposed based on energy concept.

2 EXPERIMENTAL VERIFICATION

Numerical simulation corresponding to the experiment accomplished by Dong (2005) about impact perforation of reinforced concrete slabs subjected to projectile with high speed is conducted to determine the accuracy of the FE simulation method and the concrete constitutive models. The macroscopic damage image of reinforced concrete slabs under impact effect and the residual velocity of the projectile are gained from the tests.

Numerical simulation corresponding to the above experiment is carried out using ANSYS/LS-DYNA. SOLID164 is adopted to simulate the concrete slabs and projectile, reinforcements are modelled using the link element LINK160 sharing the common nodes of the solid element. Three hypotheses for the FE model are as follows: (1) the impactor is a rigid body; (2) only the change of kinetic energy and strain energy is taken into account under the impact, excluding the loss of heat energy; (3) the friction is neglected. The FE model is shown in Figure 1.

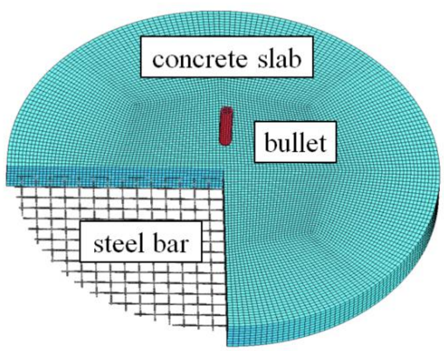

Figure 1. FE Model of the test.

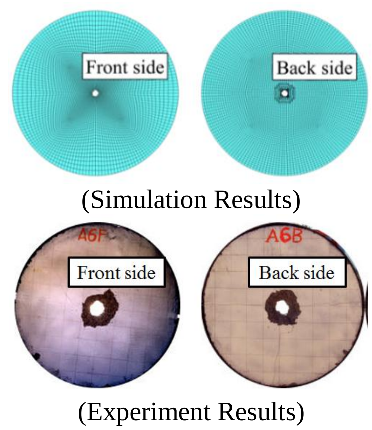

Figure 2. Impact perforation.

The reinforcements are modeled using the material model *MAT-PLASTIC-KINEMATIC. *MAT_CSCM and *MAT_JOHNSON_HOLMOGUIST_CONCRETE are used to model the concrete in order to find the most accurate concrete constitutive models. The continuous surface cap model (CSCM) material model is developed by the US Department of Transportation (FHA 2007) for roadside safety applications, and HJC material model is a rate-dependent damage constitutive model for concrete. In order to select the most optimal material model for concrete subjected to large strains, high strain rates and high pressures, the residual velocities of the projectile shown in Table 1 are obtained through numerical simulation. As we can see from the Table 1, the results of numerical simulation are similar to the experimental results. Because the simulation results of CSCM material model are more accurate than HJC model, CSCM model is used for further simulation.

Figure 2 shows the experimental results and the simulation results of the damage of the concrete slab after penetration. When the bullet reaches the thin plate, the concrete units near the hit point are failed instantly. At the same time, target plate produces spherical stress wave in the same direction of the bullet. The stress wave is reflected when it contacts the back of the target plate, the concrete is subjected to tensile failure when the reflected stress wave acting on the wall. Then the bullet continues penetrating the target plate until the plate is destroyed. The diameter of the funnel-shaped hole generated by the breakdown is larger than the diameter of the bullet.

Table 1. The comparison of simulation results and experiment results.

Cases	Velocity (m/s)	Residual Velocity （m/s）			Error		Cases	Velocity （m/s）	Residual Velocity （m/s）			Error	
		Test ①	CSCM ②	HJC ③	②/①	③/①			Test ①	CSCM ②	HJC ③	②/①	③/①
A1	218	166	160	148	0.964	0.892	C1	193	131	131	96	1.000	0.732
A2	250	199	197	191	0.990	0.960	C2	268	195	195	191	1.000	0.979
A3	376	280	277	323	0.989	1.154	C3	361	300	290	283	0.967	0.943
A4	620	529	540	553	1.021	1.045	C4	608	528	512	519	0.958	0.982
B1	501	301	332	326	1.103	1.083	C5	812	701	704	735	1.004	1.049
B2	753	554	551	566	0.995	1.022	C6	1246	1111	1170	1220	1.053	1.098

3 FE MODEL INTRODUCTION OF LNG STORAGE TANK

Full containment LNG storage tank consists of prestressed concrete outer tank and 9% nickel steel inner tank. The outer tank is composed of concrete cylindrical shell, spherical dome, bottom plate and pile foundation. The outer diameter of the concrete outer tank is 82 m, the height is 38.55 m, and the wall thickness is 0.8 m. The section of wall-supporting column is 4.22×1.4 m^2, the section of ring beam is 1.05×1.56 m^2, the curvature radius of spherical dome is 82 m, and the vector height is 10.975 m. The thickness of the center shell of dome is 0. 6m, the edge of the shell is 0.8 m. Concrete strength grade is C50 (the characteristic value of concrete cube compressive strength is 50 MPa). The section of the LNG project is shown in Figure 3.

The FE model of the outer concrete tank of the 160,000 m^3 LNG storage tank is established based on ANSYS/LS-DYNA FE analysis software platform. SOLID164 is adopted to simulate the outer concrete tank and impactor. The impactor is 4 m in length, 1m in diameter and the front of impactor is hemispherical. The contact type of ESTS is defined to describe the contact between the impactor and the tank. CSCM material model is used to represent the concrete, and an additional *MAT ADD EROSION command is used for the concrete models. When the effective plastic strain reaches 0.1, the solid elements are removed (or eroded) from the rest of the FE model mesh. The FE model of LNG tank outer tank is shown in Figure 4. In order to improve the calculation efficiency and save time, the region with relatively large dynamic response is defined as the impact zone of dome, and the elements of impact zone are refined. The contact option of *CONTACT TIED_NODES_TO_SURFACE is applied between the impact zone and the rest of the dome to established a link between them.

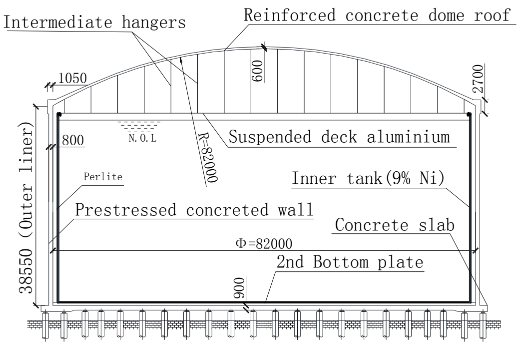

Figure 3. Profile map of LNG tank.

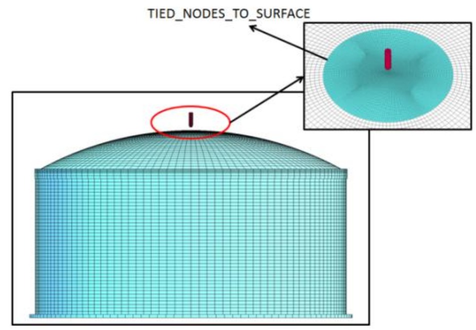

Figure 4. FE Model of LNG outer tank.

4 DAMAGE MODES OF THE LNG CONCRETE DOME

In this paper, a rigid cylindrical impactor with different masses and velocities is used to strike the center of dome vertically. In order to avoid causing some influence due to the volume and shape change of impactor, the mass of the impactor is changed by varying the density of the impactor. The range of impactor's energy is enlarged until the dynamic responses of LNG outer concrete tank do not change obviously in the numerical analysis. The parameters of the mass and velocity in this paper are shown in Table 2.

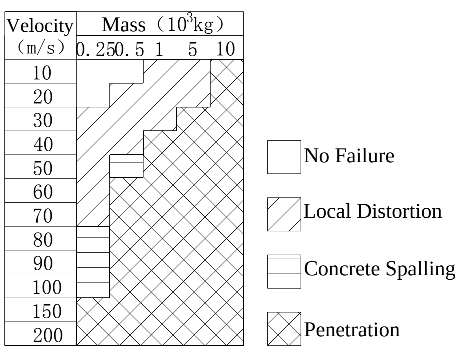

Figure 5. Distribution of failure modes.

Table 2. Parameters of the impactor.

Mass (10^3 kg)	0.25、0.5、1、5、10
Velocity (m/s)	10、20、30、40、50、60、70、80、90、100、150、200

Based on the above FE parametric analysis, the impact response modes of the concrete dome of LNG storage tank under impact load are obtained and summarized, which includes no damage, local distortion, concrete spalling and penetration. With less initial energy, the impactor causes no damage or less damage to dome, and the displacements of the dome are mainly local depression around the impact central point. There are no eroded elements, and the tank is still in a safe state, in this case, the local distortion is main features. With increasing of initial energy of the impactor, the concrete inside the dome is spalled and the distortion zone is expanded. The concrete outer tank can still protect the internal steel tank from damage. This failure mode is called concrete spalling. When the initial impact energy continues to increase, following the concrete spalling failure, the center of the dome is broken down, all the elements near the impingement point are eroded, and the damaged outer tank no longer provides protect actions to steel inner tank. This failure mode is called penetration. According to the failure characteristics of three failure modes, the distributions of three failure modes shown in Figure 5 are obtained.

5 FAILURE MECHANISM OF THE LNG CONCRETE DOME

In this paper, the failure mechanism for each mode can be revealed from the view point of energy. It is the initial energy of impactor that affects mainly the emergence of three different failure modes. Based on the variation of energy, the whole impact process can be divided into three steps: (1) energy transfers from impactor to impact zone of dome; (2) energy transfers from impact zone to the entire dome; (3) the residual energy is consumed by lag vibration of the dome. The specific failure mechanisms of three failure modes are presented in the following sections.

5.1 Failure Mechanism of Local Distortion Model

Taking the working conditions (m = 1×10^3 kg, v = 25 m/s) as an example, the entire failure process is divided into three steps as described below and as shown in Figure 6.

Step 1: The first stage is from the time when impactor begins to contact with dome to the time when maximum displacement appears on the direct contact area. During this period, the impactor transfers energy to dome and its velocity decreases rapidly. At the same time the impact area of dome obtains a lot of kinetic energy, but dynamic responses of the outer impact zone are not obvious for the short impact duration.

Step 2: The second stage is from the end of first stage to the end of impact force. Characteristics of this step are that the energy is transferred from impact zone to outer of impact zone, which means that dynamic responses of the outer impact zone increase obviously. Large displacement zone is limited to the area that directly contact with the impactor and the scope of the energy transfer is relatively small due to the small initial energy input.

Step 3: The last stage is after the end of impact force. The rebound of dome deformation can be found but the dome does not return to its original dimensions. The left impact energy is consumed by lag vibration of the dome until the dome finally reaches equilibrium state.

5.2 Failure Mechanism of Concrete Spalling and Penetration Model

Taking the working conditions (m = 1×10^3 kg, v = 100 m/s) as an example, the failure mechanism of the concrete spalling and penetration model is analyzed. As we can see from the diagram of impact load shown in Figure 7, the impact force decreases rapidly after the peak load. It has extremely short duration and high magnitude because of the great speed of impactor. The first stage is from the time when impactor begins to contact with dome to the end of impact force.

During this stage, the impactor transfers a large amount of energy to dome so that the dome is penetrated. Additionally, the damaged concrete takes away m of transferred energy, only little energy transfers to the outer impact zone of dome, and the dynamic responses of outer impact zone are relatively small. Unlike penetration model, when concrete spalling mode appears, the concrete inside dome spalls first. Here is why this could happen: When the object impact on dome, the spherical stress wave produced by dome spreads from outside to inside of the dome. The stress wave is reflected when it contacts the inner surface of dome, the concrete elements with the failure criterion of 0.1 for tensile strain are subjected to tensile failure because of reflected extension wave. The second stage is from the time when impact force begins to fluctuate at a low level to the moment when the deletions of concrete elements complete. The residual energy is transferred to outer of impact zone, and the stress spreads out from impact zone to outer of impact zone annularly. The stress and deformation of the dome increase as well during continuous contacting of the impactor and dome. Different from the local distortion model, during the stage of energy transfer, impact force is not zero because impactor maintains contact with the dome to damage the concrete rather than rebounds from the dome immediately.

When the impactor is no longer in contact with dome, the deformation of structure stabilizes gradually. In the process of continuous consumption of energy, the kinetic energy of dome decreases and strain energy tends to be stable. The whole impact process comes to an end.

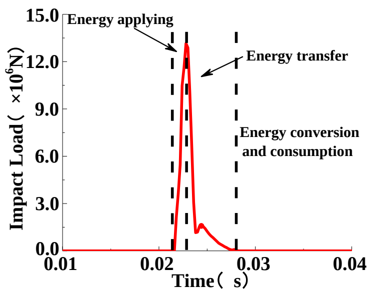

Figure 6. Failure process of local distortion.

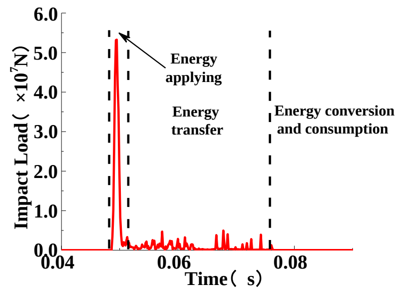

Figure 7. Failure process of penetration.

6 CONCLUSION

The FE model of the outer concrete tank of the 160,000 m^3 LNG storage tank is established based on ANSYS/LS-DYNA FE analysis software platform. Three damage modes and failure mechanisms for the dome of LNG outer concrete storage tank were obtained by analyzing the dynamic response of the dome subject to impact loading. In conclusion:

- The failure modes of local distortion, concrete spalling and penetration are obtained by analyzing the dynamic response and damage degree of LNG external concrete dome under the impact loading.
- The failure mechanism of impact is explained from the energy point of view, and the whole impact process can be divided into three stages: energy applying, energy transfer, energy conversion and consumption.
- However, the characteristics of the impact load and the variation rule of energy at each stage are different, especially for energy transfer stage.

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