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Numerical study of dynamic response and failure analysis of spherical storage tanks under external blast loading

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A B S T R A C T

The performance of energy infrastructures under extreme loading conditions, especially for blast and impact conditions, is of great importance despite the low probability for such events to occur. Due to catastrophic consequences of structural failure, it is crucial to improve the resistance of energy infrastructures against the impact of blasts. A TNT equivalent method is used to simulate a petroleum gas vapor cloud explosion when analyzing the dynamic responses of a spherical tank under external blast loads. The pressure distribution on the surface of a 1000 m^3 spherical storage tank is investigated. The dynamic responses of the tank, such as the distribution of effective stress, structural displacement, failure mode and energy distribution under the blast loads are studied and the simulation results reveal that the reflected pressure on the spherical tank decreases gradually from the equator to the poles of the sphere. However, the effects of the shock wave reflection are not so evident on the pillars. The structural damage of the tank subjected to blast loads included partial pillar failure from bending deformation and significant stress concentration, which can be observed in the joint between the pillar and the bottom of the spherical shell. The main reason for the remarkable deformation and structural damage is because of the initial internal energy that the tank obtained from the blast shock wave. The liquid in the tank absorbs the energy of impact loads and reduces the response at the initial stage of damage after the impact of the blast.

1. Introduction

With the expanding scopes of storage of petroleum products, the possibility of accidents caused by petroleum combustible gas explosions also increases. During the past several years, a series of oil tank fires and explosion accidents caused great financial loss and casualties (Persson and Lönnermark, 2004; Abbasi and Abbasi, 2007; Chang and Lin, 2006). Most of the explosions were triggered by the detonation of a vapor cloud, which was initiated by the petroleum products themselves (Lees, 1996; Lieb, 2002). Once a combustible gas explosion occurs in petroleum facilities, chemical plants or storage areas, it may not only cause serious damage to a single oil tank, but also can lead to a chain reaction of explosions and trigger a secondary disaster. Therefore, the investigation on the failure mechanism and dynamic response of oil storage tanks subjected to combustible gas explosions is important and necessary.

Storage tanks can be cylindrical and spherical in shape. Spherical storage tanks primarily consist of the lower support structures and the spherical shell structures, which sit on support structures. Specifically, the shape of the shells can be spherical, elliptical, and teardrop-shaped, among which spherical tanks are the most widely used because for the same volume and thickness, spherical tanks use the minimum amount of steel and cover a minimum area.

During the past five decades, many researchers have investigated the dynamic behaviors (James and Raba, 1991; Sezen et al., 2008; Korkmaz et al., 2011; Moslemi and Kianoush, 2012) and failure modes (Trebuňa et al., 2009; Dogangun et al., 2009; Kim et al., 2009) of liquid-filled tanks, which were mostly cylindrical and rectangular, that had been subjected to earthquakes. The seismic responses of elevated liquid storage tanks are mainly studied because of their importance to the petrochemical industry. The effects of liquid sloshing in spherical containers have been investigated in some studies (McIver, 1989; McIver and McIver,

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1993; Evans and Linton, 1993). Moreover, two recent studies presented the development of a mathematical model for quantifying the influence of the linear sloshing effects on the dynamic responses of horizontal cylindrical and spherical liquid tanks under earthquake excitation (Karamanos et al., 2006; Patkas and Karamanos, 2007). For the particular case of the dynamic behavior of elevated spherical tanks under lateral excitation, only a few works were found. For example, Drosos et al. (2005) numerically investigated the seismic response of a typical spherical liquid storage tank equipped with a nonlinear viscous bracing system.

With regards to the dynamic analysis of storage tanks under blast loads, several studies have been published using computational and experimental methods. Zhou et al. (2009) investigated the dynamic characteristics of an underground vertical tank subjected to an explosion impact. One of the key conclusions of this work was that the tank seismic check method which considered seismic loads did not apply to explosion impact loads. Lu et al. (2011a, 2011b), Lu and Wang (2012) used a combustible gas detonation device to generate a stable detonation shock wave by exploding a methane/air mixture, which was stored in the pipeline beforehand. The device was used for conducting experimental tests to study the dynamic response characteristics and failure mechanisms of large-scale storage tanks under blast impact loads.

So far, studies of dynamic response and failure analysis of spherical storage tanks under external combustible gas explosion shock waves have not been published yet. Since large scale or prototype explosion tests are very expensive, numerical simulations should be conducted in order to investigate attenuation laws and destructive effects of gas explosion shocks which will also assist the future design of experimental tests.

The present study performs numerical simulations to investigate the dynamic responses and failure modes of spherical storage tanks under external combustible gas explosions. Commercial explicit finite element software LS-DYNA (LSTC, 2007) is employed to analyze the blast resistance and energy absorption capacities of the spherical storage tanks. A TNT equivalent method is used to establish equivalent load models for petroleum gas cloud explosions. Considering the effect of material strain rate effects, the dynamic response and failure mechanism of the tanks under gas blast loads are studied to provide scientific references for the rational design of such structures in the future.

2. Finite element model

2.1. Finite element code and ALE method

The numerical simulation is carried out using the commercial software LS-DYNA, which is based on explicit numerical methods and has been widely employed to analyze the problems associated with large deformation, structure response to high velocity impact and blast load and strain rate behavior of materials. There are at least three approaches for such kind of problems: (1) Lagrangian formulation; (2) Eulerian formulation; and (3) arbitrary Lagrangian–Eulerian (ALE) formulation, which makes it possible to follow large flows of various materials without encountering numerical distortion problems often experienced in Lagrangian formulations. The Arbitrary Lagrangian–Eulerian (ALE) element formulation is a standard numerical approach for solving large deformation problems encountered in metal forming subjected to high-speed impact or blast loading. The general concept of the ALE formulation is that an arbitrary referential domain is defined for the description of motion that is different from the material (Lagrangian) and spatial (Eulerian) domains (LSTC, 2007).

3 types of elements are used herein: (1) LINK160 element: a 2-nodes beam element which is only able to carry axial loads; (2) SHELL163 element: a 4-node rectangular shell element which can carry bending moment and membrane force and both in-plane and normal loads are permitted; (3) SOLID164 element: a 8-nodes solid element used for the 3-D modeling of structures.

2.2. Numerical model for spherical tanks and explosion source

A finite element model is created for a 1000 m^3 equator tangent column spherical storage tank which consists of four parts: the spherical shell, pillars, links and connecting plates. The thickness of the shell is 45 mm. The nominal cross-section dimension of the circular pillar tubes (diameter $D \times$ thickness t) is 250 mm $\times$ 10 mm, and the dimension of the link is 48 $\times$ 6 mm. Fig. 1(a) shows the shape and the size of the spherical storage tank model. In this study, a gas containing water assumed in the spherical storage tank (Shebeko et al., 2007) was modeled using water with volume of 80% in order to simply simulate the effect of outside explosion on the tank. The distance between the explosion's center to the face of the tank was assumed to be 25 m.

2.3. Elements and meshing

Considering the actual size of the model, SHELL 163 elements are used to simulate the spherical shell, connecting plate and pillars of the spherical storage tank, and LINK 160 elements are used to represent the links. TNT, liquefied petroleum gas and air are modeled using SOLID 164 elements. Since the ALE fluid-solid coupling method cannot simultaneously consider both the inside and outside of the structure, the meshless Smooth Particle Hydrodynamics (SPH) method is used to simulate the liquid in the tank and the forces transferred from the liquid to the spherical shell can be modeled by examining the contact between them. To do so, mapping mesh is adopted. The size of shell elements and the solid elements representing TNT is 40 mm, and the size of the solid elements representing air is 100 mm.

The fluid-structure interaction is simulated by employing a coupling algorithm. The fluid is treated with an ALE fixed/mobile mesh, while the structure is treated with a Lagrangian deformable mesh. The coupling algorithm computes the coupling forces at the fluid-structure interface. These forces are added to the fluid and the structure nodal forces, which are calculated on the basis of explicit finite element analysis. Predicting the local peak pressure on the structure requires an accurate fluid-structure coupling algorithm. The ALE coupling algorithm presented in this paper uses penalty based formulation similar with the penalty contact in Lagrangian analyses.

2.4. Material models and equation of state

Explosion loading is associated with strain rate effects. The mechanical properties of steel are remarkably affected by the strain rate. Therefore, in this study, a multi-linear kinematic hardening model (MAT_PLASTIC_KINEMATIC model in LS-DYNA), which is able to take into consideration the strain rate is used to represent the responses of the Q235 steel. The initial yielding stress of the steel is 235 MPa, the elastic modulus is 206 GPa, and the Poisson ratio is 0.3. The rate-dependent plasticity model for the yielding stress of steel, proposed by Cowper and Symonds (1957) is given by:

$$\sigma_{dy} = \left[1 + \left(\frac{\dot{\varepsilon}^{pl}}{\gamma}\right)^{m}\right]\sigma_y \tag{1}$$