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Dynamic response of single-layer reticulated shell with explosion-protection wall under blast loading

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ABSTRACT

To investigate the structural dynamic response of long span reticulated shell under external blast loading considering explosion-protection wall, explicit finite element (FE) programme LS-DYNA is used to set up the analytical model of explosion-protection wall corresponding to an experiment to grasp the propagation law of blast shock waves around the wall. The results of simulation and experiment are compared and the results verify the creditability and applicability of numerical simulation by using ALE (Arbitrary-Lagrange-Euler) algorithm. A Kiewitt8 single-layer reticulated shell of refinement with span of 40 m is established to simulate the responses of structure considering explosion-protection wall, which contains reticulated shell member, purlin hanger, purlin, rivet and roof boarding. According to simulation results from the maximum nodal displacement, average plastic strain and yielding degree of cross section of reticulated shell member, the dynamic response laws are proposed based on varying parameters, including height, position, length, material of the explosion-protection wall, rise-span ratio of reticulated shell and TNT explosive weights. Meanwhile, the influence rules of explosion-protection wall and structure on diffraction and reflection action of blast shock wave are obtained. In addition, the adverse height of the explosion-protection wall for reticulated shell with span of 40 m under external blast loading is proposed. Four damage types of reticulated shell with the explosion-protection wall subject to external blast loading are defined by summarizing all the structural response of FE numerical models, which could provide reference for reasonable explosion-proof design for reticulated shell structure.

1. Introduction

As a simple and useful explosion-protection measure, explosion-protection wall could protect important buildings from surfing terrorist explosion attacks by insulating the target compounds and explosion source. Setting up the wall flexibly could reduce the damaging effects of buildings according to blast levels and importance of structure [1].

Blast shock wave flow around the wall leads to diffraction behind the wall when blast happens beside the explosion-protection wall, and the propagation law has been studied by many scholars [2–4]. Langdon and Schleyer [5] simulated explosion through applying pressure impulsive loading to stainless steel plate and obtained the plate response and influence of connection on plate performance. Zhou and Hao [6] proposed estimation formula of peak pressure behind the rigid wall based on numerical simulation. Some researchers studied diffraction flow of air shock wave and law of overpressure-time behind the explosion-protection wall. They got pressure-time in the front and back of wall using pressure sensor and studied influence of the wall on blast shock wave [7–10].

The above research concentrated on the diffraction mechanism of blast shock wave and overpressure around the explosion-protection wall while giving less attention to the material and size of wall. Taking shock wave diffraction action and effect of reflecting action between the explosion-protection wall and building into account simultaneously is less more. Furthermore, existing publications have focused mostly on the performance of steel, concrete, fiber reinforced members and structural connections [11–15]. Studies on the whole structure under blast loading are less relatively, which focus on pressure field distribution, structural response, damage, failure mechanism, explosion-proof design and explosion venting [16–20]. As for long span spatial structure, some scholars have established the finite element model of long span spatial structure under internal blast loading and external blast loading, and studied the response and failure mode of structure [21–24]. However, it is found that no research on the dynamic response of long span spatial structure considering the explosion-protection wall under blast loading has been carried out.

In this paper, the propagation characteristics of blast shock waves around the explosion-protection wall based on FE software LS-DYNA

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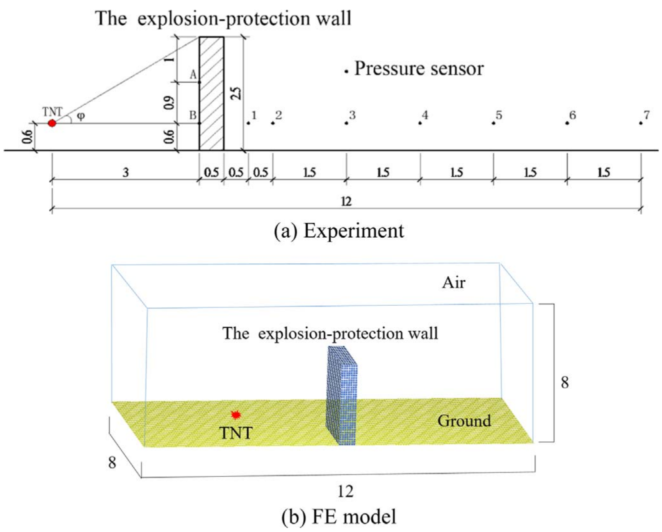

Fig. 1. Experiment and FE model (unit: m).

[25] is firstly simulated and verified by comparing with experiment results from literature. A kiewitt8 single-layer reticulated shell of refinement with a span of 40 m is established to simulate the dynamic responses of structure considering the explosion-protection wall subjected to external blast loading. The parameters analysis including varied height, position, length, material of the explosion-protection wall, span ratio of reticulated shell and TNT explosive weights are performed to obtain the blast response rules, damage types, and the effect of explosion-protection wall on structure.

2. Experimental verification

Numerical simulation corresponding to the explosion experiment in Ref. [10] is conducted to determine the accuracy of ALE (Arbitrary-Lagrange-Euler) algorithm in process of analyzing the blast shock wave propagation around the explosion-protection wall.

2.1. Experiment introduction and FE model

The experiment model include air, explosive and the explosion-protection wall, as shown in Fig. 1(a). The TNT explosive is placed on the medial axis of the explosion-protection wall which keep distance of 3 m away from the wall and 0.6 m away from ground. Weights of TNT explosive are 4 kg and 2 kg. The height of measuring points of A and B before the wall are 1.5 m and 0.6 m respectively. Seven measuring points are placed behind the wall which have the same height with the TNT explosive.

Numerical simulation corresponding to the above explosion experiment is carried out using ANSYS/LS-DYNA. The FE model including the TNT explosive, air, ground and the explosion-protection wall. The wall is 0.5 m × 3 m× 2.5 m and simulated using the material model of MAT_Concrete_Damage_Rel3 in LS-DYNA [26]. The main material parameters of concrete are given in Table 1. Fixed constraint is adopted in the bottom of explosion-protection wall. The position and equivalent weight of the TNT explosive are consistent with the experiment. 1/2 FE model is built and symmetrical boundary condition is set in the symmetrical plane, as shown in Fig. 1(b). The air dimension is 12 m × 8 m × 8 m that encapsulates the TNT explosive, wall and required measuring points. SOLID164 is adopted to simulated the air, the TNT explosive and the wall by using ALE algorithm. Mesh size of the air and explosive is 0.075 m. The ground is reflection boundary condition and other is none-reflected boundary condition.

Table 1
Material parameters of the concrete.

Density/kg m^{-3}	Poisson ratio	Maximum shear failure surface parameter A0
2500	0.2	-3.5×10^7

The TNT explosive is simulated using the material model of MAT-High-Explosive-Burn in LS-DYNA and the governing equation for the detonation products is defined using the Jones-Wilkins-Lee(JWL) equation of state given as formula (1) [26]:

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

The main material parameters of the TNT explosive are given in Table 2.

The air is assumed to be an inviscid ideal gas using Mat-Null material model with Eos_Liner_Polynomial equation of state [26], which is given by formula (2):

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \quad (2)$$

The main material parameters of air are given in Table 3.

2.2. Numerical simulation results and error analysis

Pressure distribution of blast shock wave in the propagation process at different time in the case of 4 kg TNT explosive is shown in Fig. 2. This represent the whole process of reflection action when shock wave contacts the wall and diffraction action after shock wave flow around the wall.

As shown in Fig. 2, blast shock wave is reflected when it contacts ground and the pressure around ground is large (t = 0.8 ms), the reflected shock wave combines with shock wave that propagates forward originally and propagate together. The pressure in the front of explosion-protection wall increases (t = 3.2 ms) when the shock wave acting on the wall while pressure in other position is small and form overpressure difference, causing air flows from high pressure region to low pressure region (t = 4.4 ms). The air ahead the wall flow to wall margin in the role of rarefaction wave and pressure of side and top of the explosion-protection wall heightens gradually (t = 6.0 ms). Meanwhile, the air form clockwise cyclone under the influence of margin incident wave (t = 8.0 ms), and then together with adjacent incident wave form into circulation. The circulation moves downward after flowing around the top of wall and comes into being Mach reflection at the place certain distance behind the wall (t = 23.2 ms).

Figs. 3 and 4 show reflection and diffraction overpressure-time curve of measuring points under the condition of 4 kg and 2 kg TNT explosive, respectively. The location of measuring points is shown in Fig. 1(a). The results of simulation are consistent with the experiment. The measuring points A and B precede the wall reach peak overpressure at about 3 ms while points 1 and 4 behind the wall reach peak overpressure at about 20 ms and then decay gradually. The peak overpressure behind the wall is an order of magnitude smaller than that in the front of wall. The results comparison of experiment and FE simulation are shown in Table 4, the maximum error of peak overpressure is 21.94%. Therefore, using ALE algorithm to simulate the propagation of blast shock wave in the effect of the explosion-protection wall is feasible.

3. Finite element model of single-layer reticulated shell

Material model of the air and the TNT explosive are same with Section 2.1, Piecewise Linear Plasticity material and Cowper-Symonds model are adopted to capture the strain rate effect. The main material parameters of steel and parameters in Cowper-Symonds model are given in Table 5.

A kiewitt8 single-layer reticulated shell of refinement with a span of