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Numerical Simulation of a Subway Station Structure Subjected to Terrorism Bombing

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Abstract: Subway stations are important means of transportation and main targets attacked by terrorists. In order to study the subway station response and damage subjected to blast loading, numerical simulation is carried out to estimate a subway station in beijing. An "explosive-air-structure " dynamic interactive numerical model is built for the blast dynamic analysis of subway station subjected to blast. The patterns of damage about column are compared in different charges of explosive. The damages of concrete and reforcing bar in column are discussed. Although the column near the explosive is destoried under the charge of 30kg TNT, The calculations showns that it's safe for the subway station to subject to blast loading under the charge of 30kg TNT. The local damage of column influence collapse of the station little. The dynamtic response of the structure is given to support the protection on the subway station against terrorism bombing.

Keywords: Blast loading, collapse, subway station, terrorism bombing.

1. INTRODUCTION

Subway are important means of transportation in city. Once an explosion happens inside a subway station, it might make lots of people deaths and injured, with the station structures collapse or damage. Because of the close-in effects of subway station and the reflection by the structure, the blast wave overpressure is larger and blast wave time is longer than the air. So it has been one of possibly attacked targets by terrorists. The terrorism attack of subway stations that happened in Paris(1995), in Moscow(2004), and in London(2005) have made hundreds of people lost lives, considerable damages of subway structures, and interruption of traffic system [1]. Researchers have made extensive efforts on underground structures to resist blast loading, especially in America and Europe. Papres and codes about underground structures to resist blast loading are rare in China [2-3]. It's impossible to solve it in theory when subway stations subjected to blast, also it's hard to conduct a full scale in-site experiment. Numerical techniques are better method to simulate subway stations subjected to blast.

This paper has made numerical simulation for the explosion inside subway stations by means of FEM software LS-DYNA. LS-DYNA is an explicit finite element program for analyzing large deformation and dynamic response of structures. A subway station in Beijing has been analysed which subject to blast loading with the TNT charges of 5kg, 10kg and 30kg. The local damage and collapse of the subway station are discussed. Some of the dynamic responses of the subway station are also presented.

2. NUMERICAL AND MATERICAL CONSTITUTIVE MODELS

2.1. Numerical Model

A subway station in Beijing is a typical two-layer rectangular frame structure. The width of the subway station is 18.40m(X-axis), the height is 15.43m and the length is 54.20m. The depth of soil above the station is 5.0m. The cross section of columns is 0.8m×1.1m. The distance between the columns is 7.0m in Z-axis. The explosive is assumed to be at the bottom of one of coulmns on the platform. The geometric of the subway station is shown in Fig. (**1**).

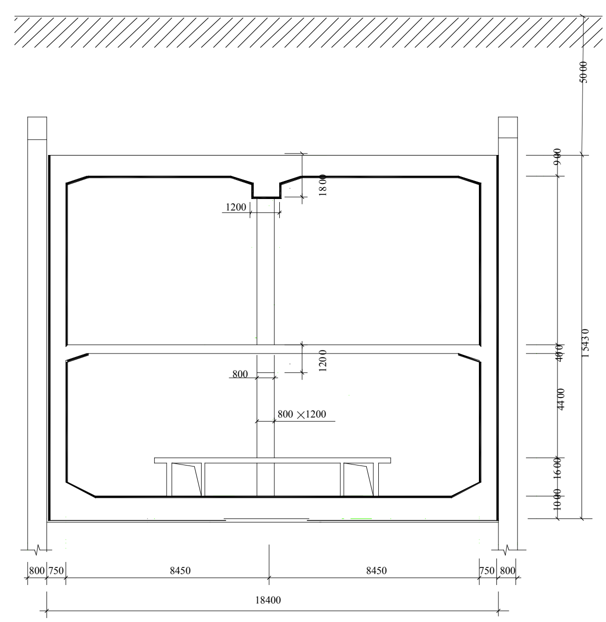

Fig. (1). The section plane of subway station.

Generally, it's difficult to simulate the interaction bettween the blast wave and the structures. The common method is the blast curve can be get by experimental formulas, codes or program(Conwep function, for example), firstly. Then the response of structure can be researched with the previous blast load. In this method, the blast is loaded at the elements of surface of the structure as pressure. When the elements suffered the blast pressure eroded and deleted, the blast can not load at the structure continually. To avoid that, a kind of "explosive - air -structure " dynamic interactive numerical model is built for the blast dynamic analysis of subway station subjected to blast in this paper. In the "explosive-air-structure " model, the explosive and air are modeled by the ALE (Arbitrary-Lagrangian-Eulerian) formulation, which can solve large deformation and fluid flowing problems. The structure can be constructed from Lagrangian solid entities. The interaction between them is calculated by the coupling mechanism for modeling Fluid-Structure Interaction by Ls-Dyna program. The disadvantage of this method is that the element numbers are larger and the compute time is longer.

To reduce element numbers, the soil above subway station isn't modeled. The soil gravity is applicated as pressure loading on the surface of station. Due to the symmetry of the model, half of the station is modeled. The air model volumn is 2.0m×7.0m×10.0m for reducing the element quantity. The calculated length of the station is 21.0m(in Z-axis). As the columns are main bearing members in subway station, the reinforcing bars and concrete in columns are modeled separately to simulate the interaction between them. The cross section of column and numerical model are presented in Figs. (**2** and **3**). The interaction between reinforcing bars and concrete in the other reinforcement concrete members of the subway station is not considered. According to the principle of equivalent stiffness, the stiffness of rebars is converted into the stiffness of concrete.

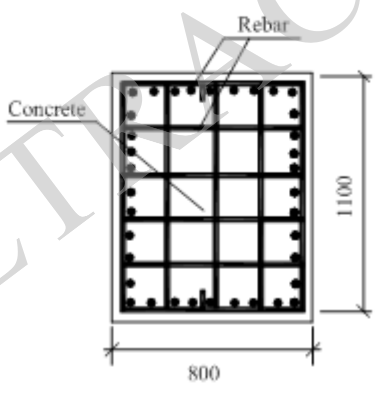

Fig. (2). The cross section of column.

2.2. Material Constitutive Models

In the simulation, the detonation of the TNT explosive is modeled by the Jones-Wilkins-Lee(JWL) equation of state. The JWL equation of state defines the pressure as

$$P = A\left(1-1/R_1\right)e^{-R_1 v} + B\left(1-1/R_2\right)e^{-R_2 v} + \omega E/v \qquad (1)$$

where the parameters A=3.71×10^{11} Pa, B=3.23×10^{9} Pa. R_1=4.15, R_2=0.95, ω=0.38 and E_0=7×10^{9} J/m^3. The density of TNT ρ=1630 kg/m^3, detonation velocity v_D=6930 m/s and Chapman-Jouget pressure P_{CJ}=2.1×10^{10} Pa.

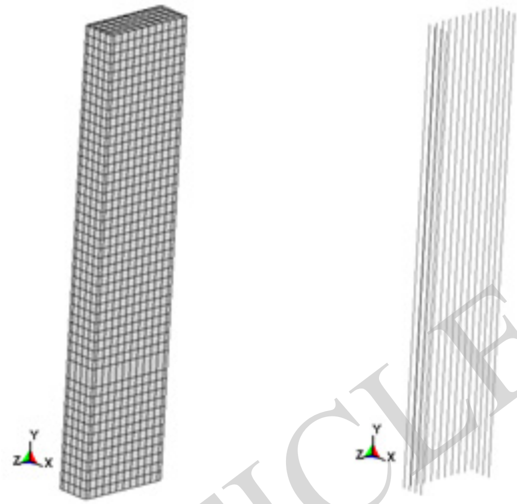

Fig. (3). The numerical model of column.

A linear polynominal equation of station is used to simulate the air behavior. According to the Gama law equation of state, the EOS of air is:

$$P = (\gamma - 1)\frac{\rho}{\rho_0}E \qquad (2)$$

Where γ is 1.4 for ideal gas, ρ is density of air, E is initial energy per unit reference specific volume. ρ_0 is 1.29 kg/m^3, which is initial density of air.

The response of concrete under shock loading is a complex nonlinear and rate-depenent process. Concrete material is modeled by Karagozian & Case (K$C) Concrete Model in this paper. The K$C Concrete Model is material type 72 in Ls-dyna. It's a three-invariant model, uses three shear failure surfaces, includes damage and strain-rate effects. It's based on the Pseudo-Tensor Model, which is proposed by Malvar [4, 5]. Xu and Lu have shown that this model can provide reliable prediction in the numerical simulation [6]. The main parameters of the concrete constitutive model are listed in Table **1**, where ρ_c is the concrete density, E_c is elastic modulus, v is Poisson ratio, f_c is compressive strength of concrete, f_t is tensile strength of concrete, ε_f is failure strain of concrete.

Table 1. Parameters for concrete model.

ρ_c/(kg·m^{-3})	E_c/MPa	v	f_c/MPa	f_t/MPa	ε_f
2400	3.3×10^4	0.18	28	2.6	0.01

The strain-rate effect of concrete is calculated by the Europe CEB Design Code. The scale coefficient is defined as [7]

$$\frac{\sigma_{yd}}{\sigma_{ys}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{1.026\alpha} \qquad \dot{\varepsilon} \le 30 s^{-1} \qquad (3)$$

$$\frac{\sigma_{yd}}{\sigma_{ys}} = \gamma \dot{\varepsilon}^{1/3} \qquad \dot{\varepsilon} > 30s^{-1} \tag{4}$$

$$\frac{\sigma_{td}}{\sigma_{ts}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{1.026\alpha} \qquad \dot{\varepsilon} \le 30s^{-1} \tag{5}$$

$$\frac{\sigma_{td}}{\sigma_{ts}} = \xi \dot{\varepsilon}^{1/3} \qquad \dot{\varepsilon} > 30s^{-1} \tag{6}$$

Where σ_{td}, σ_{yd} is the dynamic compressive and tensile strength of concrete, σ_{ts}, σ_{ys} is the static compressive and tensile strength of concrete, $\dot{\varepsilon}$ is the strain-rate of concrete.

$$\log\gamma = 6\alpha - 0.5, \quad \alpha = 1/\left(5 + 0.9\sigma_{ys}\right),$$
$$\log\xi = 7\delta - 0.5, \quad \delta = 1/\left(10 + 0.6\sigma_{ts}\right) \tag{7}$$

The piecewise linear plasticity model is implemented for reinforcing steel in the simulation. The model is suited to model isotropic and kinematic hardening plasticity with the option of including rate effects. The strain rate is accounted for using the Cowper and Symonds model which scales the yield stress with the factor.

$$1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/P} \tag{8}$$

where $\dot{\varepsilon}$ is the strain rate. The parameters C and P are $40s^{-1}$ and 5. Tab.2 lists the parameters of the reinforcement, where ρ_s is the reinforcing steel density, E_s is initial elastic modulus, v is Poisson ratio, σ_y is yield strength of reinforcement, E_P is the hardening modulus, ε_f is failure strain of reinforcing steel.

Table 2. Parameters for reinforcing steel model.

ρ_s/(kg·m^{-3})	E_s/MPa	γ	σ_y	E_P/MPa	ε_f
7800	2×10^5	0.3	300	200	0.12

2.3. Load and Displacement Boundary

The soil above the subway station is simplified as pressure, loading on the surface of the station. The pressure is ρgh=2000×9.8×5.0=0.98 MPa, where ρ is the density of soil, g is the acceleration of gravity, h is depth of the soil. The live load on the middle plate is 4.0 kPa, which is from the code foe design of metro(GB 50517-2003). The symmetry boundary condition is applied to the nodes at the YZ plane. The bottom and side of the station are fixed boundary. Non-reflected boundary conditions is considered in all the others. The explicit solutions is used to solve the subway station subjected to blast load. Before subjected to blast load, the deformation of station structure is constant under gravity load. The initialize stresses and deformation due to gravity may affect the response of the structure. To simulate exactly, structural implicit-to-explicit sequential solutions are used to solve the problem. The implicit method is used to calculate the deformation of structure, firstly. Then, initializing the structure to the prescribed geometry according to the displacement due to gravity, the explicit method is used to simulate structure subjected to blast.

3. NUMERICAL RESULTS AND DISCUSSIONS

3.1. Damage of Column and Station

Fig. (**4-7**) show different damage patterns of column in the charge of 5kg, 10kg and 30kg TNT.

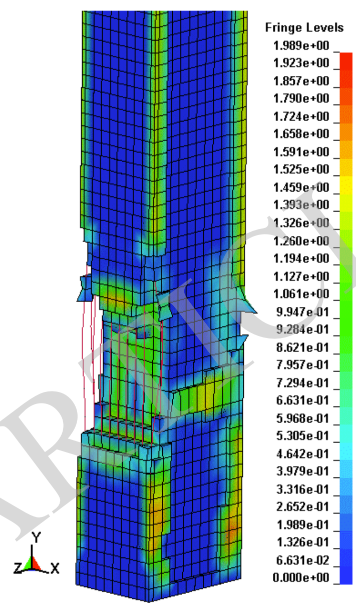

Fig. (4). Damage of column in 5kg TNT case.

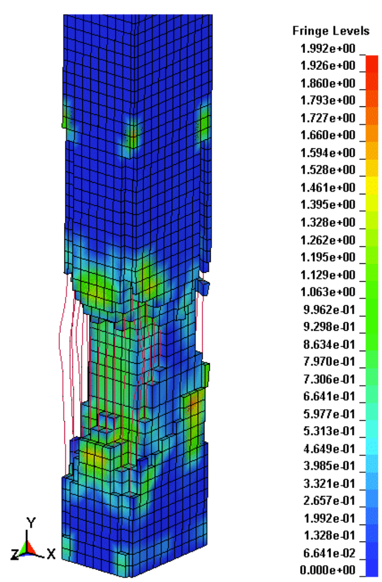

Fig. (5). Damage of column in 10kg TNT case.

Fig. (**4**) shows that a small number of concrete elements eroded, when the mass of explosive is 5kg. The eroded elements are almost at the side of RC column towards the explosive. The protective cover of concrete is gone within a short period. Fig. (**5**) shows the quantity of eroded elements is larger, when the mass of explosive is 10kg. The concrete elements at the other side of the RC column against the explosive also eroded. The reinforcing bars began to bend. Under the explosive load of 30kg TNT, the concrete elements near the explosive almost gone. The reinforcing bars are the mode of bending buckling. The distribution and the diameter of reinforcing bars are so dense and thick that they didn't fail. The reinforcing cage looks like "lantern", under the gravity load of the structure itself and the soil.

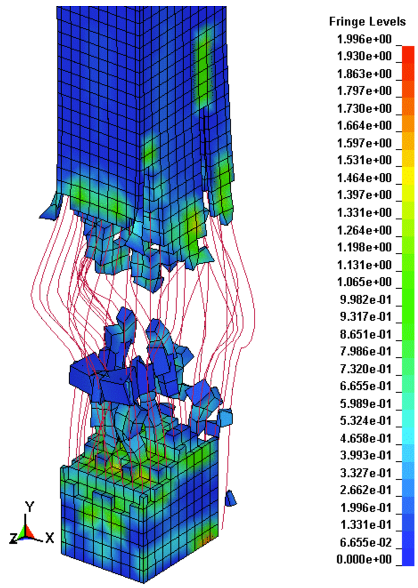

Fig. (6). Damage of column in 30kg TNT case.

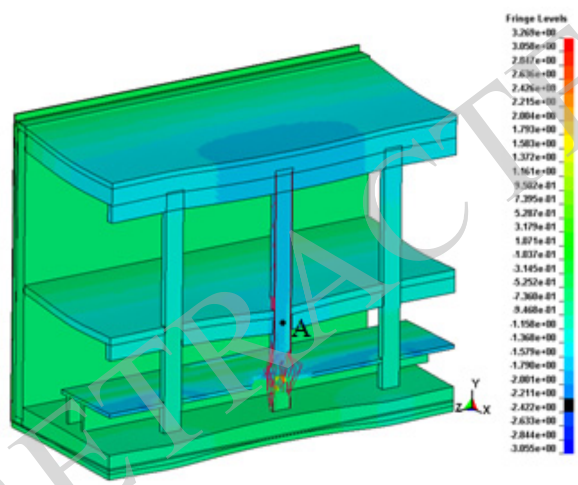

Fig. (7). Deformation of station in 30kg TNT case.

3.2. Response of Structure

The deformation of the station structure is presented in Fig. (**7**). With large damage of the concrete near the explosive, the compression capacity of the column has gone. The middle plate went down where the plate connects to the column. As stiffness of the subway station is large, the structure didn't collapse as the local damage of column. The calculation shows that the subway station is safe subjectd to blast loading unedr the explosive of 30kg TNT. The simulation is useful for the subway station against terrorism attack.

The dynamic response of the point A(shown in Fig. **8**) at structure subjected to blast are shown in Fig. (**8-9**). Fig. (**8**) is time-history response of Y-displacement under different charges of explosive. The peak values of Y-displacement are 1.52cm, 1.59cm and 1.79cm, when the charges are 5kg, 10kg and 30kg respectively. Fig. (**9**) is time-history response of Z-velocity under different charges of explosive. The peak values of Z-velocity are 0.05m/s, 0.13m/s and 0.16m/s, respectively.

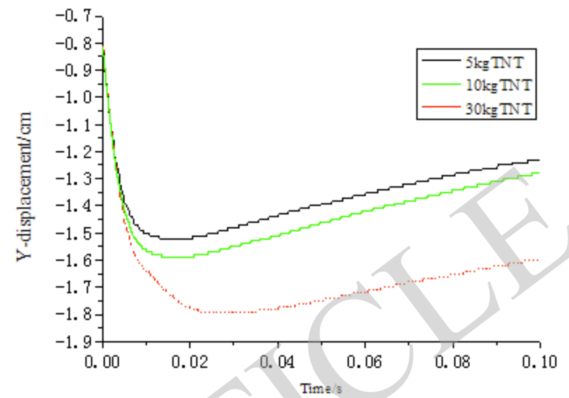

Fig. (8). Y-displacement time-history of point A.

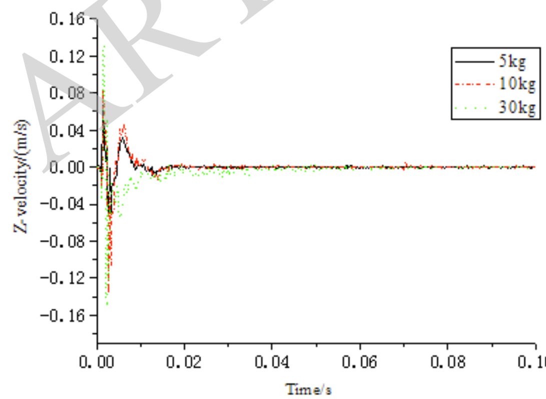

Fig. (9). Z-velocity time-history of point A.

CONCLUSION

When the dynamite explodes in the subway station, the blast wave reflects and superposes inside close-in space. The overpressure peak and continuance time of blast wave would increase more than which explodes in the air. The response of station subjected to blast loading is a complex nonlinear problem. The "explosive - air -structure " model can simulate subway station subjected to blast loading well. The concrete of column where explosive assigned almost eroded, under the blast loading of 30kg TNT. The compression capacity of coulumn has gone. Although the column has been destoried, the station didn't collapse. The effect of the local damage to the station is not so much. The structure of station is safe sbjected to the blast loading of 30kg TNT. The simulation can give supports to reforcement on the subway station against terrorism attack.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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