Research on Contact Explosion Response of Reinforced Concrete Slab

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Abstract. In order to compare the contact explosion response of reinforced concrete in the air to that under the water, a FEM model based on multi-material fluid-structure coupling method is constructed to simulate the responses and failure process of two-way reinforced concrete slabs under contact explosion. The model is verified by fellow tests, then used to calculate dynamic responses and damage conditions of two-way reinforced concrete slabs subjected to underwater contact explosion and air contact explosion. It is found that the local destruction area of the slab subjected to underwater contact explosion roughly turned into a circle, while it turned into a rhombus for air contact explosion. Nonetheless, the damage of the reinforced concrete slab subjected to underwater explosion is more serious.

1. Introduction

With the extensive use of precision-guided weapons, civil and military structures are more vulnerable to explosions near or in contact with Reinforced Concrete (RC) slabs, which is known as contact explosion. Contact explosion event involves detonation, high-pressure gas expansion and the shock wave propagation. Under blast loading conditions, various failure modes including flexural damage, shear damage and concrete spall damage can be observed on RC structures. Finite Element Method (FEM) or smoothed particle hydrodynamics (SPH) is required to solve highly nonlinear contact explosion models, which is impossible to calculate through analytical method.

Many researches have been done on the contact explosion of RC slabs via numerical and experimental methods. Zhang [1] conducted a test to investigate the spalling and the damage modes of RC slabs. Numerical simulation utilizing LS-DYNA was verified by tests results. Lu [2] experimentally investigated the failure mechanism, the development and the crack distribution of explosively loaded reinforced RC slabs. Both High-strength RC slabs and regular RC slabs are tested as a comparison. Li [3] conducted a numerical analysis on spall damage to blast load. A calibrated numerical model was used in the concrete spall simulation. Hou [4] numerically simulated the anti-contact explosion failure patterns of high strength reinforced concrete slab, in which the steel and the concrete materials are simulated as kinematic hardening model and HJC model respectively. It was found that the anti-contact explosion ability of the concrete slab improves as the reinforcement spacing narrows given that the reinforcement ratio is remain unchanged. Li [5] experimentally and numerically investigated the performance of slabs made of the Ultra-High-Performance-Concrete. Coupled FEM
and SPH were used in the simulation process to deal with the situation of large deformation and explosion induced fragments.

In this paper, LS-DYNA is applied to simulate the contact explosion performance of two-way RC slabs. Multi-material fluid-structure coupling method is applied. The numerical method is verified by tests from another paper. The main purpose of this paper is to compare the performance of slabs subjected to contact explosion under the water.

2. FEM Modelling

2.1. Constitutive Model
The built-in damage model MAT_CONCRETE_DAMAGE_REL3 [6] (also known as K&C model) in LS-DYNA is intended for analyzing RC structural responses to blast and impact loadings [7]. The dynamic damage constitutive model is widely used in the field of explosion and penetration, since they take the stiffening effect, the tensile and compressive damage, the volume deformation damage and the strain-rate effect into consideration. It has been applied in analyzing many RC structures subjected to quasi-static, blast, and impact loads [8-10]. Therefore, the damage model is applied in this paper to analyze the nonlinear dynamic response of the concrete two-way slab under the contact explosion.

Parameters required to input for the material model include the Poison’s ratio of the concrete, the density, the unconfined uniaxial compressive strength and the strain-rate & strengthening factor relation curve.

The largest strain rate of the concrete subjected to the explosion can reach a level of $10^{-2}$~$10^{-5}$ s$^{-1}$ [11]. The concrete has a higher dynamic than static strength [12], including the tensile and compressive strength. In general, the strain rate effect is quantitatively calculated based on the Dynamic Increase Factor (DIF), which is defined as a ratio of the dynamic strength of the material to its static strength.

Given in the CEB-FIP model code 1990 [12], the Compressive Dynamic Increase Factor (DIF$_c$) is calculated as:

$$
\text{DIF}_c = \begin{cases} 
(\varepsilon_c / \varepsilon_{c0})^{0.026}\alpha & \varepsilon_c \leq 30/\text{s} \\
\gamma(\varepsilon_c / \varepsilon_{c0})^{0.3} & \varepsilon_c > 30/\text{s}
\end{cases}
$$  

(1)

where $\varepsilon_c$ and $\varepsilon_{c0}$ are the compressive strain rate and the static compressive strain rate respectively. In this paper $\varepsilon_{c0} = 3.0 \times 10^{-5}$/s. Coefficients $\alpha$ and $\gamma$ can be acquired from the unconfined compressive strength $f'_{c}$:

$$
\alpha = \frac{1}{(5 + 9 f'_{c}/10)} 
$$  

(2)

$$
\gamma = 10^{0.156\alpha - 2} 
$$  

(3)

The Tensile Dynamic Increase Factor (DIF$_t$) is calculated as follow referring to the formulation suggested by Crawford and Malvar [13]:

$$
\text{DIF}_t = \begin{cases} 
(\varepsilon_t / \varepsilon_{t0})^{0.6} & \varepsilon_t \leq 1.0/\text{s} \\
\beta(\varepsilon_t / \varepsilon_{t0})^{0.3} & \varepsilon_t > 1.0/\text{s}
\end{cases}
$$  

(4)

where $\varepsilon_t$ and $\varepsilon_{t0}$ are the tensile strain rate and the static tensile strain rate respectively, $\varepsilon_{t0} = 10^{6}$/s. Similarly coefficients $\alpha$ and $\gamma$ can be acquired from the unconfined compressive strength $f'_{c}$:

$$
\delta = \frac{1}{(1 + 8 f'_{c}/10)} 
$$  

(5)

$$
\beta = 10^{0.8\delta - 2} 
$$  

(6)
A conclusion can be drawn from many tests and papers that the yield strength and the ultimate strength of the steel increase with increasing strain rate. In this paper, the built-in Plastic Kinematic Model is applied for the steel bar. The constitutive equation is:

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\nu_1}\right] \left(\sigma_0 + \beta E_p \varepsilon_{\text{eff}}^p\right)$$  \hspace{1cm} (7)

where $\dot{\varepsilon}$ is the strain rate. The two coefficients for the Cowper-Symonds equation are $C=40.0$ and $P=5.0$. $\sigma_0$ is the initial yield stress, $\varepsilon_{\text{eff}}^p$ is the effective plastic strain, and $E_p$ is the plastic hardening modulus which is given by

$$E_p = \frac{E E_t}{E - E_t}$$  \hspace{1cm} (8)

where $E$ is the elastic modulus, $E_t$ is the tangent modulus.

2.2. Bond Slip and Element Failure
Rebars are simulated as two-nodes beams in this paper. They are connected with the concrete through the coupling and constraint equation of the nodes [14-16]. The bond slip between the rebar and the concrete is ignored. The built-in erosion algorithm is applied to simulate the crack, the fragment and the spalling of the concrete. The critical strain of failure is 0.001 [17] under the maximum strain theory.

2.3. Equation of State
TNT explosive is used here. The pressure $p_T$ of the TNT is given as [18]:

$$p_T = A \left(1 - \frac{\omega}{R_V} \right) e^{R_V} + B \left(1 - \frac{\omega}{R_V} \right) e^{R_V} + \frac{\omega E_0}{V}$$  \hspace{1cm} (9)

where $E_0$ is the initial energy density, $V$ is the relative volume. The coefficients [19] for the TNT explosive are: $A=371$ GPa, $B=3.23$ GPa, $R_1=4.15$, $R_2=0.95$, $\omega=0.3$. The density of the TNT is $\rho_T=1630$ kg/m$^3$, the explosive velocity is $D=6930$m/s, the explosive pressure is $P_{CJ}=21$ GPa.

The air is assumed to be an ideal gas, so its pressure $p$ is simplified as follow [20]:

$$p = C_4 (1 + \mu) E$$  \hspace{1cm} (10)

where $\mu=\rho/\rho_0-1$, $\rho$ and $\rho_0$ are the actual and the reference density respectively. $C_4=\gamma-1$, $\gamma=1.4$, $\rho_0=1.29$ kg/m$^3$, the initial internal energy is $\bar{E}=2.5\times10^5$ J/m$^3$.

The equation of state for the water [21] pressure $p$ is:

$$p = \rho_0 c^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2}\right) \frac{\mu - \frac{\alpha}{2} \mu^2}{1 - (S_1 - 1) \mu} \right] + (\gamma_0 + \alpha \mu) \bar{E}$$  \hspace{1cm} (11)

where the initial water density $\rho_0=1000$ kg/m$^3$, the sound-speed $c=1484$ m/s, the specific internal energy $\bar{E}=0$ J·kg$^{-1}$, the Gruneisen Coefficient $\gamma_0=0.11$, the calibrate coefficient of the volume $\alpha=3$, $S_1=1.979$.

3. Verification of the FEM Model
A numerical analysis is conducted on the contact explosion of the RC two-way slab through the fluid-structure coupling method. The numerical method will be verified by the test in reference [22] as follow.
3.1. Test Setup
Contact explosion tests are conducted on two simply supported two-way rectangular RC slabs labeled CS01-1 and CS08-1. The dimension for both of the slabs is 2.0×2.0×0.4 m. Rebars for CS01-1 is 8 mm diameter with a space of 140 mm, while it is 20 mm for CS08-1 with a space of 110 mm. The TNT dosage for CS01-1 and CS08-1 are 0.8 kg and 6.0 kg respectively. The concrete cover is 25 mm for both slabs. The reinforcement grade is Chinese HRB400, and the concrete grade is Chinese C40. TNT explosive is concentrated at the center of the slabs, as can be seen in figure 1.

![Figure 1. Test setup.](image)

3.2. Test Results
The depth and the diameter of the crater caused by the explosion are shown in table 1. Experimental results are compared with present numerical results and that in reference [4]. As can be seen from table 1, the crater depth for CS01-1 acquired by present method is larger than the experimental data, with a relative error of 14.3%. The crater diameter is shorter than the experimental data, with a relative error of 15.5%. To sum up, the results by present method is better than that in reference [4].

| Slab number | TNT dosage (kg) | Crater depth (cm) Test | Present method | Reference [4] | Crater diameter (cm) Test | Present method | Reference [4] |
|-------------|----------------|------------------------|----------------|----------------|--------------------------|----------------|----------------|
| CS01-1      | 0.8            | 10.5                   | 12.0           | 11.5           | 46.0                     | 40.0           | 38.0           |
| CS08-1      | 6.0            | /                      | /              | /              | 98.0                     | 80.0           | 84             |

The damage of the RC slab acquired by the three methods are comparatively shown in table 2 and table 3. Both the front and the back of the slab are presented.

Table 2. Damage and failure of slab CS01-1 under the contact explosion.

| Method       | Front view | Back view |
|--------------|------------|-----------|
| Test         | ![Image]   | ![Image]  |
| Present method | ![Image]    | ![Image]  |
| Reference [4] | ![Image]    | ![Image]  |
Tab

le 3. Damage and failure of slab CS08-1 under the contact explosion.

| Method          | Front view  | Back view  |
|-----------------|-------------|------------|
| Test            | ![Front View](image1) | ![Back View](image2) |
| Present method  | ![Front View](image3) | ![Back View](image4) |
| Reference [4]   | ![Front View](image5) | ![Back View](image6) |

From table 2, it is observed that under the explosion of 0.8 kg TNT, a local damage (the crater) occurred at the front surface of slab CS01-1. There is no obvious damage at the back surface. From table 3, it is observed that under the explosion of 6 kg TNT, a larger crater occurred at the front surface of slab CS08-1. The spalling at the back surface exaggerates the damage of the slab, which is perforated through by the explosion and left with a hole at the center.

Results showed that present method is precise enough to simulate the damage mode of RC slab under contact explosion, which is attributed to the combined use of the K&C damage model and the fluid-structure coupling method. In comparison, there is a big divergence between the damage mode in reference [4] and that in the test, especially at the back surface of the slab. An absence of tensile damage for the concrete constitutive model is the main reason for that divergence.

4. Comparative Analysis of Contact Explosion

The fluid-structure coupling method is now applied to analyze the response of two-way rectangular RC slabs subjecting to the contact explosion both in the air and under the water. The slabs are clamped on its edges. The dimension of the slabs is 3000×3000 mm, with 100–200 mm thickness. The cover thickness is 15 mm. Concrete grade is C30. Rebars are HRB400 grade, arranged on both directions of the slab with 10 mm diameter and a spacing of 100 mm.

For water, Mie-Gruneisen equation of state [21] is introduced, its form determined by the state of water. The pressure of water in compressive state is given by

\[ p = \rho_0 C_0^2 \mu \left(1 - \gamma_0/2\mu - (a/2)\mu^2\right) \left[1 - (S_1 - 1)\mu - S_2 \mu^2/2 - S_3 \mu^3/3\right] + (\gamma_0 + a\mu)z \] (12)

while the pressure of water in expansion state is given by

\[ p = \rho_0 C_0^2 \mu (\gamma_0' + a\mu)z \] (13)

where \( \mu \) represents the condense ratio, \( \mu = \eta - 1 \). Water is in compressed state when \( \mu > 0 \), and in expansion state when \( \mu < 0 \). \( C_0 \) represents the sound-speed; \( \gamma_0 \) represents Gruneisen coefficient; and \( a \) is volume correction factor; \( S_1, S_2, S_3 \) are experimental fitting coefficients.

1.0 kg and 3.0 kg TNT are employed in the analysis. The damage results of the two-way RC slabs are presented in table 4. It is seen in the table that the radius of the damaged area for the RC slab under the water is 3 times as large as that in the air.
Table 4. Damage comparison of slabs in the two fluid type.

| Slab thickness (mm) | Fluid type | Local damage mode and the radius of the damaged area on exploding surface (m) |
|--------------------|------------|------------------------------------------------------------------------|
|                    |            | W=1.0 kg                                                               |
|                    |            | W=3.0 kg                                                               |
| 100                | water      | Punching shear failure 0.57                                            |
|                    | air        | Punching shear failure 0.18                                            |
| 150                | water      | Punching shear failure 0.57                                            |
|                    | air        | Perforation 0.17                                                      |
| 200                | water      | Perforation 0.32                                                      |
|                    | air        | Crater 0.14                                                           |

Presented in tables 5-6 are the comparative damage plot of RC slabs. As seen in table 5, 100 mm thick slab is damaged more severe under the water than that in the air for the 1.0 kg TNT explosive. The damage is described as local punching shear failure. As the slab thickness is enlarged to 150 mm, the damage mode for the slab in the air is changed to perforation. The damage mode for the 200mm slab under the water is perforation while it is crater in the air. It can be concluded that the damage degree is lower as the slab thickness improves.

Table 5. Comparison of damage and failure of slabs (W=1.0 kg).

Table 6. Comparison of damage and failure of slabs (W=3.0 kg).
In the condition of 3.0 kg TNT explosive, the damage mode for all the slabs are local punching shear failure, as can be seen in table 6. More cracks are seen on the slab under 3.0 kg TNT explosion, including the areas near the edges.

From the damage plots, it is observed that the under water damage area of the slab is generally in circle shape, while it is rhombus shape for that in the air. It is also noted that the damage and the crack of the slab is much more severe for under water explosion than in air explosion, mainly caused by the fluid-structure coupling effect. The water-structure coupling effect is much larger than the air-structure coupling effect in the condition of present event.

5. Conclusion
Numerical model based on multi-material fluid-structure method is constructed to simulated underwater contact explosion responses of two-way RC slabs. The effectiveness of the model is verified by tests. The local damage condition of slabs subjected to air and underwater contact explosion are compared. Several conclusions can be draw from the analysis:

(1) The combined use of fluid-coupling method and the K&C concrete damage constitutive model is key to precisely simulate the performance of the RC slab under contact explosion.
(2) The local damage mode for the RC slab is progressed in the way: crater-perforation- punching shear failure, as the thickness becomes smaller or the TNT explosive weight becomes larger. There will be cracks around the damaged area and at the edges if the explosive wave is large enough.
(3) The damage area is in circle shape for under water contact explosion, while it is more like a rhombus for explosion in the air. This phenomenon is mainly due to a different fluid-structure coupling effect in those two fluid media.

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