Numerical study of UHMWPE fiber reinforced concrete slabs exposed to blast loading

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Abstract. This research aims to study the effect of UHMWPE fiber content on the blast resistance of concrete slabs. A 3D fluid-solid coupling model was established by numerical simulation method to simulate UHMWPE fiber reinforced concrete slab under close-in detonation. It turns out that the simulation results show the damage behavior of reinforced concrete slabs greatly. UHMWPE fibers can effectively reduce the local damage of the slab and improve the overall blast resistance. When the UHMWPE fiber content is less than 0.5%, the performance of blast resistance increases with the content. When the fiber content exceeds 0.5%, the effect of blast resistance caused by fibers is limited.

1. Introduction

The development of weapon technology such as precision strikes and highly efficient damage poses a major challenge to the blast resistance of protective building structures. In addition, the increase of terrorist attacks and accidental explosions in manufacture and daily life brings serious threats to the safety of buildings. Therefore, the resistance to explosion problems of building structures has become a heated topic in this field [1].

Technologies that improve the blast resistance of reinforced concrete structures are useful in practice. An important research direction is to use high-performance fiber concrete instead of usual plain concrete. There have been many studies on the blast resistance of fiber reinforced concrete so far. Yu and Shi [2] conducted a contact explosion test on polypropylene fiber reinforced concrete slabs, indicating that polypropylene fibers increased the tensile strength, compressive strength, shear strength, impact toughness and ductility of concrete materials, which prevented the spallation on specimens due to explosion. Luccioni et al. [3] added high carbon steel fibers with different contents to the concrete and then carried out the contrast blast tests of four-sided simply-supported fiber reinforced concrete slabs. The contact blast tests showed that the plain concrete slabs could hardly withstand any blast loading, while 0.5% fiber content was sufficient enough to prevent flexure failure. The close-in blast tests revealed that the exact scaled distance when flexural cracks generating decreased with the increase of the fiber content, and the influence of fiber content change on overall damage was more obvious than local damage. Zahra et al. [1] performed blast tests of reinforced concrete slabs incorporating long carbon fibers. The statistical results of surface damage area indicated that the fiber reinforced concrete reduced the damage degree by 75-89% compared with ordinary concrete.

Recently, in order to improve the impact resistance of concrete, Zhang [4, 5] used a new kind of high-strength UHMWPE bulletproof fiber concrete to study the mechanical properties of UHMWPE fiber concrete, and found that UHMWPE fibers can greatly improve the toughness and tensile strength of concrete. Compressive strength, peak strain and elastic modulus all represented excellent strain rate...
enhancement effect under dynamic loading conditions. Related penetration study [6] also shows that UHMWPE fiber reinforced concrete has good crack resistance and energy absorption ability, which significantly reduce the number of cracks, the size of the crater and the depth of penetration of the target and indicate its good impact resistance. However, research on blast resistance of this fiber reinforced concrete is rarely reported, so carrying out relevant research is of great practical significance.

The numerical simulation method is used to study the blast resistance of UHMWPE fiber reinforced concrete slabs in this paper. A 3D fluid-solid coupling model is established including air, reinforcement and fiber concrete. Based on the research of UHMWPE fiber concrete RHT material model parameters, the effects of the UHMWPE fiber and its content on the blast resistance of reinforced concrete slab under different scaled distances are discussed comparing with blast test result of normal reinforced concrete slab. The results can provide a reference for the application of UHMWPE fiber reinforced concrete in blast-resistant structure.

2. Numerical simulations

2.1 Research objects

A reinforced concrete slab tested in research [7] was selected as the research object in this study. The slab measures 1100×1000mm with a thickness of 40mm, and the diameter of steel reinforcement is 6mm. The single-layer reinforcing mesh was arranged at the middle thickness of the slab with a distance of 75mm from one and another bar in both directions. The one-way slab is fixed along two opposite sides, so the span is 1000mm.

The reinforcement has a yield strength of 395MPa and Young's modulus of 200GPa. The compressive strength of concrete is 40MPa. Three fiber volume contents of 0.3%, 0.5% and 0.7% are considered in this paper.

TNT explosive was used in test and the weight is 0.46kg. The detonation point is set above the slab. Two different scaled distances (0.52 and 0.65(m/kg^{1/3}) respectively) were taken into consideration.

2.2 Numerical model

Figure 1. 1/4 numerical model.

1/4 finite element model was established as shown in Figure 1 because of symmetry. The reinforced concrete slab and air were discretized with a Lagrange mesh and Euler mesh respectively. Reinforcement, concrete and air were all modeled by solid elements. The element sizes of both reinforcement and concrete were 3mm, while the air mesh was partially encrypted. The element numbers of the concrete, reinforcement and air were 424825, 10532 and 15625 respectively. Symmetrical conditions were set for the symmetry boundaries. Both upper and back supports were created along the supporting areas of the slab to constrain its lateral displacement, and their materials were defined as rigid bodies. The boundary condition of the air was set as an outflow boundary.
2.3 Material model

2.3.1 Air and explosive. Air is described using an ideal gas expression of state (EOS). In this form of EOS, the material parameters are: specific heat ratio constant, $\gamma = 1.4$; reference density, $\rho = 1.29$ (g/cm$^3$); initial internal energy, $E = 2.068 \times 10^5$ (J/m$^3$) [8].

Explosive is modeled using the JWL EOS. The material parameters are shown in Table 1.

Table 1. Explosive material parameters [8].

| A (GPa) | B (GPa) | E (MJ/m$^3$) | $\rho$ (kg/m$^3$) | $R_1$ | $R_2$ | $\omega$ | V |
|---------|---------|-------------|------------------|------|------|--------|----|
| 3.737e2 | 3.747   | 6.00e3      | 1.63e3           | 4.15 | 0.95 | 0.35   | 1.00 |

Where, $V$ is the relative detonation product volume; $E$ is the specific internal energy; $\rho$ is reference density; $A$, $B$, $R_1$, $R_2$ and $\omega$ are material constants.

2.3.2 Reinforcement steel. The reinforcement steel is represented using the JC material model. The material parameters are shown in Table 2.

Table 2. Reinforcement material parameters [8].

| A (MPa) | B (MPa) | n  | C  |
|---------|---------|----|----|
| 300     | 384     | 0.26| 0.014 |

Where, A is yield strength; B and n are strain hardening constants; C is strain rate constant. Failure strain is set to 0.1.

2.3.3 Concrete. The RHT model is applied to simulate concrete [9]. The experimental studies on static and dynamic mechanical properties of UHMWPE fiber concrete with 0%, 0.3%, 0.5%, 0.7% and 1.0% content in research [4] show that UHMWPE fibers represent a certain enhancement effect on concrete compressive strength. Their rates of increase are around 10%, and the change is not obvious with the variation of fiber content. Different fiber contents have a great influence on the tensile strength of concrete, which increases by 43%~63% with the increase of the content. Also, the fibers reduce the deformation modulus of concrete. The triaxial effect of UHMWPE fiber concrete and the dynamic strain rate effect of tensile and compressive strength were obtained in research [5, 10]. Meanwhile, the suitable parameters of UHMWPE fiber concrete RHT material were studied in research [11]. Thus, the modified parameters of the UHMWPE fiber concrete RHT model (Table 3) were used based on above studies. In the table, $f_t$ and $f_c$ are tensile and compressive strength; $E$ is deformation modulus; $A$, $B$, $Q0$ and $BQ$ are all material failure surface parameters; $\alpha$ and $\delta$ are tensile and compressive strain rate effect exponent, respectively.

Table 3. RHT material model parameters of UHMWPE fiber concrete [11].

| $V_f$ (%) | 0     | 0.3   | 0.5   | 0.7   |
|----------|-------|-------|-------|-------|
| $f_t$ (MPa) | 4.00  | 5.72  | 6.17  | 6.53  |
| $f_c$ (MPa) | 40.0  | 44.0  | 44.0  | 44.0  |
| E (GPa)   | 20.0  | 18.8  | 17.0  | 16.4  |
| A         | 2.103 | 1.557 | 1.625 | 1.864 |
| N         | 0.8776| 0.6934| 0.7670| 0.8811|
| Q0        | 0.6804| 0.6245| 0.6842| 0.7224|
| BQ        | 0.9181| 1.4200| 1.0454| 0.2652|
| $\alpha$ | 0.0208| 0.0168| 0.0222| 0.0179|
| $\delta$ | 0.0883| 0.0829| 0.0771| 0.0752|

3. Analytical results

3.1 Comparisons with test results.
In research [7], the blast test of reinforced concrete discussed in this paper was carried out with a scaled distance of 0.52(m/kg\(^{1/3}\)), and the damage results of the upper and back surfaces were obtained after test, as shown in Figure 2. The measuring spall radius is 120mm and the central deflection is 35.2mm in test. The numerical results of upper and back surfaces after detonation were shown in Figure 3(a), Figure 4(a), Figure 5(a).

Comparisons between numerical and test results for reinforced concrete slab are presented in Figure 2, Figure 3(a), Figure 4(a) and Figure 5(a). Numerical results suit well with the damage characters of RC slab after detonation. A certain range of destroy caused by compression occurs on upper surface, also several connected annular cracks and extended radial cracks generate around central area. A tensile spallation mainly happens on the back surface. Many discontinuous annular cracks and radial cracks through boundaries generate from central damage area. The numerical simulation presents the radius of the damage area as 138mm, which is consistent with test result. The central displacement of the bottom is 33.0mm, which is slightly smaller than the test value by 6.25%. This is because the actual compressive strength of concrete used in the test slab is less than the design strength (40MPa). In addition, the steel support device was loosened during the test.

The results show that the numerical model can simulate the mechanical behavior of reinforced concrete slabs well under close-in detonation.

![Figure 2. Experimental results of reinforced concrete with 0% fiber content.](image)

3.2 Influence of fiber and content

Figure 3, Figure 4 and Figure 5 show the damage results of the upper and back surfaces and central cross sections of slabs with different UHMWPE fiber contents at a scaled distance of 0.52(m/kg\(^{1/3}\)) respectively. The corresponding results of spall radius on back surface and central deflection at bottom are shown in Table 4.

As for damage phenomena, the addition of fibers reduces the number of cracks on the upper and back surface, and with the increase of fiber content, the resistance to crack appears to be more obvious and damage range and level at back surface decreases clearly. As for damage area, the number of annular cracks on upper surface reduces evidently and cracks near the support sides seem more concentrated, indicating that the fiber reduces the local damage. As fiber content increases, the failure mode of the slab tends to gradually change from local punching failure to overall flexure failure. As for central deflection, fiber can improve the overall mechanical behavior of reinforced concrete slab under pressure to a certain extent. Although the fiber content increases, central deflection at bottom does not change dramatically. The blast resistance of slab of 0.5% fiber content is relatively superior, revealing that the best effective fiber content may exists around 0.5%.

![Table 4. Numerical results.](table)

| V_f (%) | 0    | 0.3  | 0.5  | 0.7  |
|---------|------|------|------|------|
| Central deflection (mm) | 33.0 | 32.7 | 31.6 | 32.2 |
| Spall radius (mm) | 138  | 105  | 42   | 36   |
3.3 Influence of scaled distance

Keeping the same explosive charge unchanged, after a blast condition of another scaled distance of 0.65 (m/kg)^{1/3} was simulated, the numerical results of fiber reinforced concrete slabs changing with the variation of fiber content are shown in Figure 6.

For two different scaled distances, the variable laws of central deflection and spall radius appear to follow similar tendency. Blast resistance is improved with the raise of fiber content approximately. When the fiber content is lower than 0.5%, the decline rate of central deflection increases with fiber content while spall radius decreases at the same time. However, when it exceeds 0.5%, the decline rate of central deflection drops slightly, and the change of spall radius is not significant. It can be found that a critical fiber content may exist close to 0.5% to obtain the best blast resistance.

Figure 6. Analytical results.
After Comparing the failure phenomena under conditions of two different scaled distances, it turns out that the failure mode of the slab gradually changes from local punching failure to overall flexure failure with the increase of fiber content, demonstrating that UHMWPE fibers improve the integrity of the slab. When the scaled distance is larger, the central deflection and the spall area reduce correspondingly, but the effect on decrease of displacement response is more obvious. Local punching failure take place in reinforced concrete slabs under both two scaled distance conditions. But for slabs of 0.3%, 0.5% and 0.7% fiber content, local punching failure occurs at the smaller scaled distance while overall flexure failure happens at the larger scaled distance.

4. Conclusions
A fluid-solid coupling model, including air, reinforcement and concrete, is created to simulate the blast test. Numerical results are basically consistent with the damage phenomena and overall response of reinforced concrete slabs under blast loading.

UHMWPE fibers significantly reduce the local damage level of the reinforced concrete slab, and improve the blast resistance. The explosion resistance capacity increases with fiber content, but the promoting effect is limited when the fiber content exceeds 0.5%.

The addition of fiber can cause the transformation of the failure mode of the slab, which is dominated by overall flexure failure at a large scaled distance and local punching failure at a small scaled distance. The improving effect of blast resistance of fibers to the slab is more significant at a larger scaled distance.

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