Study on the blast resistance of concrete beams reinforced with ultra-high-molecular-weight polyethylene (UHMWPE) fibers

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Abstract. Experiments and numerical simulations were performed to investigate the blast resistance of concrete beams reinforced with ultra-high-molecular-weight polyethylene (UHMWPE) fibers under close-in blast loads. The blast tests were carried out on fiber-reinforced concrete beams with a volume content of 0.7% at three scaled distances (i.e., 0.36, 0.40, and 0.47 m/kg\(1/3\)) and the damage results were compared with the characteristics of normal reinforced concrete beams. The results show that the UHMWPE fibers can decrease the damage degree of the beams, hinder the generation and development of cracks, and prevent spalling on the back surface, indicating that the blast resistance of UHMWPE-fiber-reinforced concrete beams is better than that of normal reinforced concrete beams with the same strength grade. Due to the addition of fibers, the improvement in the damage resistance to blast loads at the bottom surface of the beam is better than that at the top surface. A 3D blast-test model was established and calculated using the LS-DYNA software. A numerical study of the extended scaled distances was carried out to determine the change law of the damage features based on it. When the scaled distance is greater than 0.41 kg/m\(1/3\), the damage mode of the beam begins to change from the mode of large damage at the bottom and small damage at the top to the mode involving large damage at the top and small damage at the bottom.

1. Introduction

In recent years, explosions due to terrorist attacks or to accidents in daily production and life have occurred, posing a major threat to the safety of buildings and easily causing personal injuries and economic loss. Therefore, research on the blast resistance of building structures has become a topic of great concern [1].

An important approach to improving the blast resistance of traditional reinforced concrete (RC) structures consists in using high-performance fiber concrete instead of normal concrete. There are many studies on the blast resistance of steel-fiber-reinforced-concrete (FRC) beam members. Marek et al. [2] carried out a close-in blast test of simply supported full-scale bridges made of steel-fiber concrete, which showed that increasing the steel-fiber content or improving the compressive strength of the concrete can improve the blast resistance of the bridge. The specimens casted with high-strength steel-fiber concrete presented a lower damage degree under blast loading compared to those casted with normal concrete, normal-strength steel-fiber concrete, or polypropylene-fiber concrete. Algassem et al. [3] performed a comparative test between high-strength concrete and high-strength steel-fiber concrete beams under close-in blast loads. After considering the failure mode, midspan displacement, and overall blast resistance, it was found that incorporating steel fibers into concrete can prevent shear
failures in the beam, improve its bending resistance, and reduce the number of personal injuries caused by broken concrete under blast loads. Lee et al. [4, 5] performed blast tests on steel-fiber-RC beams with three fiber contents and found that the shear strength and energy absorption of the beam were improved and the maximum and residual displacement were reduced. Their results indicate that the influence of steel fibers should be taken into consideration to obtain a better blast resistance when designing reinforcement schemes for the beam.

Different types of fibers can improve the mechanical properties of concrete from different aspects [6, 7]. The improvement of the blast resistance of concrete members does not only depend on improving their strength, but also on enhancing their toughness, especially their tensile toughness, which can improve the vulnerability to tensile damage of the surface of concrete structures. Several studies [8-10] have shown that the static and dynamic tensile strength, the tensile toughness, and the elastic modulus of fiber-RC containing ultra-high-molecular-weight polyethylene (UHMWPE) fibers are significantly improved compared with normal concrete. Related penetration studies [11-13] also indicate that the fiber-RC presents good crack resistance and energy-absorption properties under such high strain rate loads as impact. However, little research on the blast resistance of this kind of fiber concrete under close-in blast loading has been reported. Therefore, it is of great significance to carry out research on the blast resistance of UHMWPE-fiber concrete.

In this paper, close-in blast tests on typical UHMWPE-fiber-RC and normal RC beams under three scaled distances were carried out. The differences in blast resistance between the two kinds of RC beams were compared and analyzed, and the blast-resistance-enhancement mechanism of the UHMWPE fibers was revealed. The finite-element-simulation software LS-DYNA was used for the modeling and calculations, and the variations in the damage features with the scaled distance were studied based on the verification of the test results. This study can provide references for further research and future applications.

2. Experimental research

2.1. Design and production of the test specimens

The materials and content of the test concretes are shown in Table 1, and the concretes are designed according to the strength grade of C70. V0 represents normal concrete, where the volume content of UHMWPE fibers is 0, whereas V7 represents fiber concrete in which the volume content of UHMWPE fibers is 0.7%. A single UHMWPE fiber [10] is made of 400 filaments twisted together, and the basic physical and mechanical properties are shown in Table 2.

| Material                        | V0 | V7  |
|--------------------------------|----|-----|
| Water                          | 185| 185 |
| Portland cement                | 547| 547 |
| Coarse aggregate a             | 936| 936 |
| Fine aggregate                 | 615| 615 |
| Silicon powder                 | 57.5| 57.5|
| Water reducing additive b      | 12 | 12  |
| UHMWPE fiber                   | 0  | 6.79|

Note: a 5–10 mm aggregate size range
b early strength and high-efficiency naphthalene water reducer with a water reduction rate of 26.5%

The beam was designed according to the requirements of structures to resist the effects of accidental explosions [14] (UFC3-340-02). All beams were constructed using the same dimensions and reinforcement. The section geometry and reinforcement details are shown in Fig. 1. The measured uniaxial compressive strength of the concrete is 68.0 MPa after curing, and the yield strength of the steel reinforcement is 458 MPa.
Table 2 Physical and mechanical properties of the UHMWPE fibers

| Property                  | Value       |
|---------------------------|-------------|
| Diameter μm               | 60          |
| Length mm                 | 30          |
| Density g/m³              | 0.97        |
| Tensile strength MPa      | 3000        |
| Modulus of elasticity GPa | 100         |
| Ultimate elongation %     | 2.8         |

2.2. Blast-test setup and procedure

The blast-test device is shown in Fig. 2. Both ends of the beam are fixed by bolted steel cover plates to simulate the fixed support conditions, and the span is 1200 mm. Cubic TNT explosive was used in the tests; it was suspended by a rope directly above the beam midspan and adjusted to the appropriate height according to different cases. The explosive was detonated at the center of the block through a detonator. The blast-test conditions are shown in Table 3. The control group contains normal RC beams (V0-1, V0-2, and V0-3), whereas test group contains FRC beams (V7-1, V7-2, and V7-3). The scaled distances were achieved by changing the standoff distance and charge weight. These three scaled distances (i.e., 0.36, 0.40, and 0.47 m/kg^{1/3}) were chosen according to previous simulation trails, which present clearly distinct damage phenomena within the close-in blast range.

Table 3 Test cases

| Case | Beam IDs | Charge weight | Standoff distance | Scaled distance |
|------|----------|---------------|-------------------|-----------------|
| 1    | V0-1, V7-1 | 0.60 kg       | 0.30 m            | 0.36 m/kg^{1/3} |
| 2    | V0-2, V7-2 | 0.60 kg       | 0.40 m            | 0.47 m/kg^{1/3} |
| 3    | V0-3, V7-3 | 1.00 kg       | 0.40 m            | 0.40 m/kg^{1/3} |
3. Test results

3.1. Damage phenomenon

Figs. 3–5 show the damage phenomena of the two types of RC beams for three scaled distances. The damage results can be found as follows:

Fibers can significantly reduce the degree of damage of concrete members under close-in detonation. As shown in Fig. 3, for a small scaled distance (i.e., 0.36 m/kg$^{1/3}$), both FRC and RC beams present obvious local damage. The concrete at the top surface of the midspan is crushed and cracking happens at the bottom area of the beam, together with spalling. However, the compression fracture on the top surface of the FRC beam is obviously smaller than that of the normal RC beam. The length and depth of the bottom spallation area are also smaller than those of the normal RC beam. Partial concrete does not fall off at the bottom due to insufficient development of the cracks. The concrete on the side surfaces of the RC beam almost presents a connected damage phenomenon between the top and the bottom, whereas the concrete on the sides of the FRC beam exfoliate less and presents an unconnected damage scenario.

Fibers effectively prevent the generation and development of cracks in the concrete under blast loading. As shown in Fig. 4, when the scaled distance is 0.47 m/kg$^{1/3}$, a number of transverse cracks caused by flexure and tensile cracks due to the tensile-reflection wave at the bottom surface can be observed on the side faces of the midspan of the RC beam. The cracks on the bottom surface correspond to the lateral cracks and there are many transverse cracks whereas the FRC beam barely has cracks. The UHMWPE fibers have the effect of bridging and bonding the microcracks, which diminishes the extension of such cracks in the material. Thus, failures and strength decreases in the local concrete can be mitigated. The fibers also make the mechanical properties of concrete mixtures more uniform and reduce the stress-concentration effects caused by defects in such mixtures. Thus, fibers can have a significant effect on crack resistance.

The incorporation of fibers changes the scaled distance on which the beam depends from the local-punching failure mode to the overall-bending failure mode. As shown in Fig. 5, for the same scaled distance (i.e., 0.40 m/kg$^{1/3}$), the RC beam shows a large degree of concrete exfoliation on both the side and bottom surfaces, which corresponds to the local-punching failure phenomenon. On the other hand, in the case of the FRC beam, only spallation and flexural cracks in the midspan were generated and no concrete exfoliation occurred. That means that the response of the FRC beam was close to the overall-bending failure mode, indicating that the critical scaled distance that makes local-punching failure happen was reduced upon addition of the fibers. The fibers improve the concrete strength and toughness as well as the overall load-carrying capacity. Although many cracks were intensively generated in the midspan in the case of the FRC beam, the fibers presented a superior energy-absorption ability, which prevented the concrete on the bottom surface from ejecting. This is quite important for the safety of personnel in building structures.

(a) V0-1. (b) V7-1

Fig. 3 Comparison of damages ($Z = 0.36$ m/kg$^{1/3}$). The top, side, and bottom surfaces are shown.
Fig. 4 Comparison of damages on the side surface ($Z = 0.47 \text{ m/kg}^{1/3}$) $V_0-2$ (up) and $V_7-2$ (below).

(a) top surface                   (b) side surface               (c) bottom surface

Fig. 5 Comparison of damages ($Z = 0.40 \text{ m/kg}^{1/3}$) $V_7-3$ (up) and $V_0-3$ (below) in each picture.

Fig. 6 shows the concrete fragments of two RC beams collected after the explosion of test case 1. It can be seen that the fragments of normal concrete are small and numerous whereas in the case of the fiber concrete, the number of fragments is very small and they exhibit a large size. This reveals that the fibers have a strong bonding effect on the cracked debris, thereby reducing the danger of injuries and fatalities caused by flying fragments.

Fig. 6 Fragments (fiber concrete on the left and normal concrete on the right).

Fig. 7 Mass-loss rate

3.2. Damage phenomenon

Based on the mass measurements carried out before and after the blast of the beam, the mass losses of the two kinds of beams for the three studied cases are shown in Fig. 7. Obviously, in the case of the large-scale distance, the two beams were not damaged, so the mass losses are small in both cases. When the scaled distance decreases, the mass-loss rate of the FRC beam is much lower than that of the RC beam; for example, the mass loss of the FRC beam is only equivalent to 28% of the RC beam when the scaled distance is 0.36 m/kg$^{1/3}$.

Table 4 gives the damage lengths of the top and bottom surfaces of the beams after the tests. As shown in Fig. 8, the damage length of the top surface was obtained by measuring the compression-
fracture size, which indicates the degree of compressive damage. The damage length of the bottom surface was obtained by measuring the size of the damage area which was formed by the spalling cracks connected to the surface in the midspan. It can be found that for the same scaled distance, the damage lengths on the top and bottom surfaces of the FRC beam are smaller than those of the RC beam. When the scaled distance is 0.36 m/kg$^{1/3}$, the damage lengths on the top and bottom surfaces of the FRC beam are about 81% and 64% of those of the RC beam, respectively. The damage length on the bottom surface is reduced more strongly, indicating that the improvement of the tensile properties caused by the presence of fibers in the concrete is important for structural blast resistance.

| IDs | Top surface (mm) | Bottom surface (mm) |
|-----|-----------------|---------------------|
|     | Experiment | Simulation | Error | Experiment | Simulation | Error |
| V0-1 | 209         | 204          | 2.39% | 390        | 421          | 7.95% |
| V7-1 | 169         | 174          | 2.96% | 251        | 234          | 6.77% |
| V0-2 | 149         | 137          | 8.05% | 236        | 207          | 12.29% |
| V7-2 | 91          | 102          | 12.09% | 0          | 24          | -     |
| V0-3 | 217         | 189          | 12.90% | 393        | 415          | 13.23% |
| V7-3 | 187         | 168          | 10.16% | 139        | 156          | 12.23% |

Fig. 8 Measurement of the damage length.

Fig. 5 and Table 4 show that the damage size of the beam in case 3 (with larger scaled distance) is greater than that in case 1 (with smaller scaled distance). The main reason is that a larger charge weight was used in case 3, which resulted in longer length of the explosive. This also indicates that the coupling effect of the equivalent and scaled distances should be considered under certain conditions.

4. Numerical simulations

4.1. Geometric model

In this paper, the damage characteristics and laws of beams under blast loads were analyzed using the transient dynamic finite-element analysis software LS-DYNA. The 3D finite-element geometric model was established as shown in Fig. 9. Air, explosive, concrete, and supports were modeled using eight-node solid elements while the longitudinal reinforcement and the stirrups were modeled using two-node beam elements. The air field was created with a size of 1400 mm x 200 mm x 700 mm and the explosive was modeled by filling the air elements (INITIAL VOLUME FRACTION GEOMETRY). The size of the concrete, support, and reinforcement elements was 3 mm and that of the air and explosive elements 5 mm. The element number of the concrete was 636480, that of the reinforcement steel was 2820, that of the supports 12792, and that of air 1568000. The number of explosive elements according to 0.6 and 1.0 kg was 3000 and 5000, respectively.

The fluid-solid coupling method was applied for the calculations. The air and the explosive were set as the Euler grids and the concrete Lagrangian grids. The coupling command (CONSTRAINED LAGRANGE IN SOLID) was applied to simulate the fluid-solid coupling effect between air and RC, and the solid–solid coupling effect between concrete and reinforcement steel.

A contact command (CONTACT AUTOMATIC SURFACE TO SURFACE) was applied between supports and both ends of the beam to simulate the constrain boundary conditions. The material of the supports was defined as a rigid body and nodes were fixed on the upper and lower surfaces. A non-
reflecting boundary condition was defined for the surfaces of the air field so that the shock wave in the air would not present a reflection effect while propagating to six boundaries. The explosive was detonated at its geometry center by the command (INITIAL DETONATION).

Fig.9 Finite-element model

4.2. Material model

The air adopted the *MAT NULL material model and the *EOS LINEAR POLYNOMIA equation of state to simulate the pressure propagation. The material parameters were: specific heat ratio constant, \( \gamma = 1.4 \); reference density, \( \rho = 1.29 \text{ (g/m}^3) \); initial internal energy, \( E = 2.068 \times 10^5 \text{ (J/m}^3) \).

The explosive was modeled by the *MAT HIGH EXPLOSIVE BURN material model and the *EOS JWL equation of state to describe the release of chemical energy. The material parameters are shown in Table 5.

Table 5 Explosive material parameters.

| A(GPa) | B(GPa) | E(MJ/m3) | \( \rho \) (kg/m3) | R1 | R2 | \( \omega \) | V |
|-------|-------|----------|------------------|----|----|----------|----|
| 3.737e2 | 3.747 | 6.00e3   | 1.63e3           | 4.15 | 0.95 | 0.35     | 1.00 |

In Table 5, V is the relative detonation product volume; E is the specific internal energy; \( \rho \) is a reference density; and A, B, R₁, R₂, and \( \omega \) are material constants.

The *MAT PLASTIC KINEMATIC model was applied for steel reinforcement, which is suitable to simulate isotropic and kinematic hardening plasticity considering the rate effect. The material parameters were: yield stress, 458 (MPa); Poisson’s ratio, 0.3; density, 7800 (kg/m³); elastic modulus, 210 (GPa).

The fiber concrete in the simulation was described by the Riedel–Hiermaier–Thoma (RHT) model [15, 16]. The RHT model parameters in LS-DYNA could be automatically generated based on the concrete’s uniaxial compressive strength and revised by the user if needed. The material parameters of the RHT model for UHMWPE-fiber concretes with different volume contents of UHMWPE fibers are given in the literature [17], which given the correction method of obtaining suitable parameters for UHMWPE-fiber concrete based on the same concrete strength grade in this paper. The critical concrete parameters for V0 and V7 are shown in Table 6.

Table 6 Concrete parameters.

| Concrete parameters          | V0  | V7  |
|------------------------------|-----|-----|
| Compressive Strength FC      | 70  | 70  |
| Relative tensile strength FT*| 0.10| 0.15|
| Failure surface parameter A  | 2.103| 1.864|
| Failure surface parameter N  | 0.8776| 0.8811|
| Lode angle dependence factor Q0 | 0.6804| 0.7224|
| Lode angle dependence factor B | 0.9181| 0.2652|
| Compressive strain rate dependence exponent BETAC | 0.0208| 0.0179|
| Tensile strain rate dependence exponent BETAT  | 0.0883| 0.0752|
| Residual surface parameter AF | 1.5  | 1.4  |
| Residual surface parameter NF | 0.66 | 0.81 |
4.3. Validation of the simulation results

Table 4 shows a comparison of the damage-length values obtained in the experiments and simulations. Figs. 10 and 11 show a comparison of the local-damage phenomena based on the experimental results and simulations on the two types of beams at a scaled distance of 0.36 m/kg$^{1/3}$. For test case 1, the incident peak pressure at the standoff distance of 0.3 m below the charge is 6.69 MPa, which is similar to the peak pressure of 6.90 MPa obtained from UFC3-340-02 [14]. It can be seen from Table 4 that the simulated values of the damage lengths on the top and bottom surfaces are basically consistent with the experimental values, the maximum error being 13.23%—a very reasonable prediction that certainly meets the accuracy requirement for analysis given the unpredictable nature of the blasts. The results of the simulations, shown in Figs. 10 and 11, reflect the damage characteristics of the local concrete in the beam midspan. Connecting cracks—from the bottom to the top areas—were observed in the normal RC beams (V0-1 and V0-3), whereas no large-area fractures occurred on the side face of the FRC beam, which maintained a relatively good integrity.

5. Analysis of the damage features

Systematic numerical simulations of the FRC beam were carried out for scaled distances between 0.24 and 0.59 kg/m$^{1/3}$ to study the change laws of the blast resistance of UHMWPE-FRC beams as a function of the scaled distance. Keeping the geometry of the explosive model of 0.6 kg unchanged, the scaled distance was changed only by adjusting the standoff distance. The variations in the damage lengths on the top and bottom surfaces of the UHMWPE-FRC beam with the scaled distance are shown in Fig. 12.

Previous studies [18] suggest using a logarithmic function to describe the relationship between the damage range on the concrete's surface and the scaled distance. The damage-length data of the FRC beams was fitted accordingly. At present, there are almost no studies on the relationship between the damage length on the back surface of an RC beam and the scaled distance under close-in blast loading. It can be seen from the data that the damage length of the bottom surface is inversely proportional to the scaled distance with different decrease rates. Thus, this paper proposes a method to use the Boltzmann function expression to fit the relationship between the damage length and the scaled distance. The relationships between the damage lengths on the top and bottom surfaces of FRC concrete beams and the scaled distance can be expressed as follows:

$$L_t = -0.276 \ln Z - 0.105$$

(1)

$$L_b = \frac{0.3957}{1 + e^{(Z - 0.3854)/0.0431}} - 0.0112$$

(2)
where $L_t$ and $L_b$ represent the damage lengths (mm) on the top and bottom surfaces, respectively, and $Z$ represents the scaled distance (m/kg$^{1/3}$). The fitting correlation coefficient for formulas (1) and (2) are 0.9791 and 0.9967, respectively, which are accurate enough to describe the trend.

![Graph](image)

**Fig.12** Changes in damage length with the scaled distance (for the FRC beam).

It can be seen from Fig. 12 that the damage features vary with the scaled distance. The damage length of the top surface of the FRC beam nearly decreases by the logarithmic function relationship (formulas (1)) with the scaled distance increases, and the damage length of the bottom surface approximately decreases in consistent with the Boltzmann function relationship (formulas (2)) while the scaled distance increases. It can be seen that the damage length on the bottom surface of the FRC beam is more sensitive to the influence of the scaled distance. When the scaled distance increases, the damage length of the bottom surface decreases rapidly (until the spallation phenomenon disappears), which indicates that the fiber plays a significant role in the tensile strength. Keeping a certain distance from the explosive to the FRC members is an effective way to resist damage under blast. When the scaled distance is small, the FRC beam exhibits a damage behavior that is characterized by little damage on the top surface and large damage on the bottom surface. When the scaled distance exceeds 0.41 m/kg$^{1/3}$, the damage length of the bottom surface of the FRC beam begins to be smaller than that of the top surface, and the damage resistance of the bottom surface is better than that of the top surface. When the scaled distance is large enough, the damage length of the bottom surface reduces to zero. The damage caused by the spalling phenomenon no longer occurs and the local-damage effect is no longer obvious, indicating that the failure mode of the FRC beam begins to change. These results could provide a reference for reinforcing the existing methods for FRC beam members focused on the front and back surfaces or on the overall safety to resist blast effects at certain possible scaled distances. If the predicted scaled distance of the blast event affecting the FRC beam is less than 0.41 m/kg$^{1/3}$, more emphasis should be put on resisting the damage of the back surface.

6. Conclusion

In this paper, the blast resistance of a UHMWPE-FRC beam under close-in blasts was studied and the differences in blast resistance compared to normal RC beams were discussed. Numerical simulations were also carried out to analyze the relationship between the blast resistance of FRC beams and the scaled distance. The conclusions are as follows:

1. Upon addition of UHMWPE fibers, the damage degree of FRC beams is greatly reduced compared to similar normal RC beams under close-in blast loads; the danger of injuries and fatalities caused by concrete fragments is also greatly reduced. Fibers greatly resist the generation and development of cracks, which increases the safety of RC members.
2) The damage lengths on the top and bottom surfaces of the FRC beam show different decrease trends upon increasing the scaled distance. If the scaled distance exceeds 0.41 m/kg\(^{1/3}\), the damage length on the bottom surface begins to be less than that on the top surface.

3) Compared to normal RC beams, the critical scaled distance value of the FRC beam is smaller when a transition from the local-punching to the overall-bending failure mode happens.

Despite the above results, this study is still a preliminary investigation and only two fiber contents (namely, 0 and 0.7%) have been considered so far. Further studies will be performed on the influences of the UHMWPE-fiber content, the stirrup ratio, the beam dimensions, and other factors on the blast resistance of FRC beams. Also, the empirical formula proposed herein does not consider other factors such as the geometry of the beam section.

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