Modeling the fracture behavior of Ultra - High Performance Fiber Reinforced Concrete slabs under contact Blast Loading

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Abstract. This paper presents a fracture behavior modeling of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) slabs under contact blast loading using the finite element method. The UHPFRC is supposed to be brittle material and follow the Johnson–Holmquist-II (JH-2) model. The steel rebar is modeled using the elasto-plastic model. The Emulsion Explosive has been used and modeled by the SPH method. UHPFRC slabs with the dimensions 1000mm of length, 800mm of width and 120mm of thickness is considered. The steel fibers with a volume fraction of 2% is used. The UHPFRC material is fabricated in laboratory using the material available in Vietnam. The concrete crater and spall damage of UHPFRC slab under contact blast loading are considered. The numerical results are compared with experiment. These results allow to evaluate the resistance against blast load of UHPFRC fabricated in lab.

1. Introduction

Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is a new development of construction technology in general and concrete technology in particular. This concrete has a high compressive strength (≥ 120 MPa) and high fracture toughness. The tensile strength when bending can be up to 40 MPa, with high impact resistance, high load repellency and high waterproofing; durability and long-term stability. With these advantages of UHPFRC compared to ordinary concrete (Normal Concrete - NC), this concrete is suitable to apply of special work that against explosions.

When an explosion occurs near the constructions, it destroys the materials and the structure, that may lead to a potential collapse [1]. To reduce the consequence on the works caused by blast load, it is necessary to understand the behavior of the concrete under this load. Therefore, it is necessary to have studies (experiment, theoretical, numerical) on this concrete. Studies on the mechanical behavior of concrete under the effect of explosive loads have been carried out over the past few decades. Some studies formulated the load structure and an explosion damage to produce the same load that causes the same damage, as a basis for the first study of the theory of destructive explosions proposed theoretical methods of concrete destruction under the effect of an explosive load, but these methods are based on some simple assumptions that affect the accuracy of calculation [2]–[6]. With the simulation analysis, the material parameters can be identify by the calibration process. The numerical study based on the finite element method (FEM) and smoothed particle hydrodynamics (SPH) were developed and widely adopted to model the response of concrete under blast load [7]–[10].

Various failure modes of damage can be obtained on the concrete during the blast loading, like flexural damage, shear damage, concrete crater and spall damage. In these mode, the flexural damage
is a desired failure mechanism that allows the maximum energy absorption. However, with during short loading duration in blast test, the flexural failure appears when the shear strength exceeds the bending strength. The first failure modes will be diagonal or direct shear failure if the columns shear capacity is not sufficient enough [11]. The experimental study of UHPFRC concrete panels with various thickness and reinforcement detailing under blast loading is studied in [12]. The experimental results of these test are used to validate a finite-element code.

In this paper, the preparation of specimens is first presented. The UHPFRC material is fabricated in laboratory using the material available in Vietnam. Then, the experimental blast testing is detailed. The tests are realized on two UHPFRC slabs. UHPFRC slabs usually have the same dimension: 1000mm of length, 800mm of width and 120mm of thickness. The emulsion explosive is used. In the next section, the numerical models use to model the damage of UHPFRC, to model the blast load are detailed. The numerical results obtained by the finite element method then compared with the experimental results. The conclusions and discussion are presented in the last section. The concrete crater and spall damage under contact blast loading are considered and compared between numerical and experiment.

2. Fabrication of Specimens

2.1. Material

Material used to produce specimen included: Homogeneous silica aggregates with a particle size of 300μm; Portland cement PC40 (according to Vietnamese standard) with particle size of 11.4μm; Fly ash (FA) and Silica fume (SF) used to replace cement with a density of 2400 kg/m³ and 2200 kg/m³, respectively. The SiO₂ content of SF was 92.3%, the mean particle size of SF and FA were 0.15μm and 5.83μm, respectively, and the corresponding pozzolanic reactivity index were 113.5% and 104.3%; Polycarboxylate superplasticizer (PS) with a dry content of 35%.

A UHPFRC sample using steel fibers with a content of 2% (by volume) (UHPFRC-F2) to determine the blast-resistant capacities of concrete structures. The concrete proportions of use in study are based on the gradation following in Table 1:

| Sample      | Sand  | Cement | FA  | SF  | PS  | Water | Fiber |
|-------------|-------|--------|-----|-----|-----|-------|-------|
| UHPFRC-F2   | 1108  | 831    | 166 | 111 | 36.9| 164   | 157   |

2.2. Fabrication of Samples

The test was realized on the slab specimen, with the dimension: 1000mm of length, 800mm of width and 120mm of thickness (Figure 1.a). Two layers of mesh reinforcements were placed in the UHPFRC slab specimens. The longitudinal reinforcement rebar and stirrup rebar using 8 bars D12 and 6 bars D8 with 110 mm and 190 mm spacing, respectively (Figure 1.b). The mixing and placing processes of UHPFRC mixtures are show in Figure 2.
Figure 1. (a) Arrangement of reinforcement and (b) Installation of formwork

Figure 2. (a) Mixing and (b) Placing of UHPFRC mixtures

2.3. Mechanical properties

The compressive strength of UHPFRC were performed on 100×200mm cylindrical specimens according to ASTM C39M. Flexural strength of concrete was determined according to ASTM C1609M, Prismatic samples of UHPFRC with a size 100×100×400mm. The elastic modulus of concrete was determined according to ASTM C469M. The cylinder samples of UHPFRC with a size 100×200mm. The mechanical properties of the both concrete used in the study are shown in Table 2:

| Sample       | Compressive strength | Flexural strength | Elastic Modulus |
|--------------|----------------------|-------------------|-----------------|
|              | MPa                  | MPa               | MPa             |
| UHPFRC-F2    | 120                  | 15                | 48              |

3. Numerical Modeling

3.1. Material

The UHPFRC is supposed to be brittle material and follow the Johnson–Holmquist-II (JH-2) model [13]. JH-2 model consists of 3 components affecting the fracture behavior of concrete: strength, damage and pressure.
Strength in JH-2 model [14]

Strength is expressed in terms of the normalized von Mises equivalent stress as function (Figure 3):

$$\sigma^* = \sigma_i^* - D\left(\sigma_i^* - \sigma_f^*\right)$$

where $\sigma_i^*$ is normalized intact stress, $\sigma_f^*$ is normalized fracture stress, D is the damage ($0 \leq D \leq 1$).

The normalized equivalent stresses $(\sigma^*, \sigma_i^*, \sigma_f^*)$ have general form $\sigma^* = \frac{\sigma}{\sigma_{HEL}}$

where $\sigma$ is the actual equivalent stress and $\sigma_{HEL}$ is the equivalent stress at the Hugoniot Elastic Limit (HEL).

The normalized intact and fracture stresses can be defined by function of the pressure and strain rate as

$$\sigma_i^* = A \left( P^* + T^* \right)^M \left(1 + C \ln \dot{\varepsilon}^* \right) \leq \sigma_i^{\max},$$

$$\sigma_f^* = B \left( P^* \right)^M \left(1 + C \ln \dot{\varepsilon}^* \right) \leq \sigma_f^{\max},$$

where

- $A$, $B$, $C$, $M$, $N$ are the material parameters;
- $\sigma_i^{\max}$, $\sigma_f^{\max}$ are the optimal limits for the strengths;
- $P^*$ is normalized pressure: $P^* = \frac{P}{P_{HEL}}$, with P is the actual pressure and $P_{HEL}$ is the pressure at the HEL;
- $T^*$ is normalized maximum tensile hydrostatic pressure: $T^* = \frac{T}{P_{HEL}}$, with T is maximum tensile hydrostatic pressure the material can withstand;
- $\dot{\varepsilon}^*$ is dimensionless strain rate: $\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}$, with $\dot{\varepsilon}$ is the actual strain rate and $\dot{\varepsilon}_0$ is the reference strain rate.

Damage is the cumulative fracture damage, flowing as equation:
\[ D = \frac{\sum \Delta \varepsilon_p}{\varepsilon_p} \]

where \( \Delta \varepsilon_p \) is the plastic strain during a cycle of integration; \( \varepsilon_p = f(P) \) is the plastic strain to fracture under a constant pressure \( P \), specific \( \varepsilon_p^f = D \left( P^2 + T^* \right)^{0.5} \). \( \varepsilon_p^f, \varepsilon_p^\text{max} \leq \varepsilon_p^\text{f} \leq \varepsilon_p^\text{m, max} \), with \( D_1, D_2 \) are constants; \( P^*, T^* \) are as defined previously. However, the material will not have any plastic strain at \( P^* = -T^* \), but \( \varepsilon_p^f \) increases as \( P^* \) increases.

Pressure-density relationship before fracture begins (\( D = 0 \)) is defined as:

\[
P = \begin{cases} 
K_1\mu + K_2\mu^2 + K_3\mu^3 & (\mu \geq 0 \text{— compression}) \\
K_4\mu & (\mu < 0 \text{— tension}) \end{cases}
\]

where \( K_1, K_2, K_3 \) are constants \( (K_1 \text{ is bulk modulus}) \); \( \mu = \rho / \rho_0 - 1 \) for currently density \( \rho \) and initial density \( \rho_0 \).

After damage begins accumulate \( (D > 0) \), pressure is added. Function of pressure becomes

\[
P = K_1\mu + K_2\mu^2 + K_3\mu^3 + \Delta P
\]

The pressure increment is determined from energy considerations. It varies from \( \Delta P = 0 \) at \( D = 0 \) to \( \Delta P = \Delta P_{\text{max}} \) at \( D = 1 \).

The elastic internal energy of the shear and deviator stresses is expressed as \( U = \frac{\sigma^2}{2G} \).

Where \( \sigma \) is the equivalent plastic flow stress; \( G \) is shear modulus of elasticity. The loss energy to increase \( \Delta U = U_{D(t)} - U_{D(t+\Delta t)} \).

The pressure increment is determined from energy consideration as

\[
\Delta P_{D(t)} = -K_1\mu + \sqrt{(K_1\mu + \Delta P)^2 + 2\beta K_1\Delta U}
\]

Where \( \beta \) is the fraction of the elastic energy loss converted to potential hydrostatic energy \( (0 \leq \beta \leq 1) \). \( \Delta P = 0 \) when \( \beta = 0 \).

The parameters of UHPFRC included in the model are shown in the following tables (Table 3 to Table 5):

### Table 3. Parameters for Strength of UHPFRC

| A   | B   | N  | C      | M | G (GPa) | PHEL (MPa) | \( \dot{\varepsilon}_0 \) |
|-----|-----|----|--------|---|---------|------------|----------------|
| 0.79| 1.6 | 0  | 0.007  | 0.61| 33.2    | 120        | 1.0 |

### Table 4. Parameters for Damage of UHPFRC

| D1 | D2 | \( \varepsilon_p^\text{f, min} \) | \( \varepsilon_p^\text{f, max} \) | \( \sigma_i^\text{max} \) (GPa) | \( \sigma_f^\text{max} \) (GPa) |
|----|----|-----------------|-----------------|-----------------|-----------------|
| 0.04| 1.0 | 0.001           | 1               | 8.1             | 1.1             |

### Table 5. Parameters for Pressure of UHPFRC

| PHEL | T  | K1 | K2 | K3 | HEL | \( \beta \) |
|------|----|----|----|----|-----|-----------|
| GPa  | GPa| GPa| GPa| GPa| GPa | GPa       |
| 0.048| 0.004| 85 | -171| 208| 0.085| 1.0       |

Steel rebar used in this study is deformed steel bar with material properties that comply with Hook’s law. Diameter and properties of rebar are shown in the Table 6:
Table 6. Rebar properties

| Diameter (mm) | Density (Kg/m³) | Elastic modulus (MPa) | Tensile strength (MPa) |
|--------------|-----------------|-----------------------|------------------------|
| 8            | 7800            | 200000                | 600                    |
| 12           | 7800            | 200000                | 600                    |

The emulsion explosive NT13 with the weight are 0.5kg and 1.22kg. This explosive is calculated by JWL equation (JWL EoS), which was puted forward by Lee Taver and Jones Wilkins Lee [15]. The equation is define as:

\[
P = C_1 \left(1 - \frac{\omega}{r_1 v}\right) e^{-r_1 v} + C_2 \left(1 - \frac{\omega}{r_2 v}\right) e^{-r_2 v} + \frac{\omega}{v}
\]

where P is pressure in explosion; \(v = 1/\rho\) with \(\rho\) is density; \(C_1, C_2, r_1, r_2, \omega\) are parameters.

Parameters of explosion material are show in Table 7:

Table 7. Parameters of explosion material

| Density (g/cm³) | Velocity of detonation (m/s) | Energy per 1 explosion (KJ/Kg) | Pressure of explosion (GPa) | C₁ | C₂ | r₁ | r₂ | ω |
|----------------|------------------------------|-------------------------------|----------------------------|----|----|----|----|----|
| 1.15           | 4095                         | 2800                          | 21                         | 373.77 | 3.75 | 4.15 | 0.9 | 0.35 |

The mass of emulsion explosive NT13 have to converted to the equivalent of TNT by equation:

\[
W_{\text{TNT}} = \frac{W_{\text{NT}-13} Q_{\text{TNT}}}{Q_{\text{NT}-13}}
\]

where \(W_{\text{TNT}}\) is mass of TNT explosion; \(W_{\text{NT}-13}\) is mass of NT-13 explosion; \(Q_{\text{NT}-13}\) is explosion heat of NT-13; \(Q_{\text{TNT}}\) is explosion heat of TNT.

3.2. Numerical Model

Numerical model was built in Abaqus software. In the model, geometrical demensions, boundary conditions and location of the explosive are similar to reality. Properties of material as stated above, include: concrete, steel and explosive show in Figure 4:

![Figure 4](image)

Figure 4. (a) Mesh model into Finite Elements (b) Model of Reinforced

Conduct simulation for two samples UHPFRC-F2 with other explosive masses is 0.5kg and 1.22kg, respectively, show in Table 8:
### Table 8. Numerical samples

| No. | Slab material            | Dimension       | Explosive charge weight (Kg) | Slab specimen |
|-----|--------------------------|-----------------|------------------------------|---------------|
| 1   | UHPC + 2% steel fiber    | 1000x800x120    | 0.5                          | UHPFRC-M0.5   |
| 2   | UHPC + 2% steel fiber    | 1000x800x120    | 1.22                         | UHPFRC-M1.22  |

#### 3.3. Numerical results

Table 9 presents the comparison of experimental result and numerical result. The experimental results of slab specimen UHPFRC-M0.5 correspond to 0.5kg explosive are shown in Figure 5. For UHPFRC-M0.5 slab, the top surface crater diameter is 10cm (Figure 5(a)), the bottom surface spall diameter is 31cm (Ошибка! Источник ссылки не найден. (b)). No side concrete cracking and no reinforcement fracture was observed. The numerical results are presented in Figure 6. The top surface crater diameter is 15cm (Figure 6(a)) and the bottom surface spall diameter is 16cm (Figure 6(b)) are obtained by the simulation.

![Figure 5](image1.png)

(a) ![Figure 5](image2.png)

(b)

**Figure 5.** The failure of slabs with 0.5kg explosive at top (a) and bottom surface (b) by experiment

![Figure 6](image3.png)

(a) ![Figure 6](image4.png)

(b)

**Figure 6.** The failure of slab with 0.5kg explosive at top (a) and bottom surface (b) by simulation

### Table 9. Compare hole size according to experiment and simulation with UHPFRC-M0.5 slab

| Result  | Hole type | Top surface (cm) | Bottom surface (cm) |
|---------|-----------|------------------|---------------------|
| Experiment | Concave  | 10               | 31                  |
| Simulation | Concave  | 15               | 16                  |
For 1.22kg explosive, the top surface crater diameter and bottom surface spall diameter are 18 cm (Figure 7(a)) and 30 cm (Figure 7(b)), with experiment (Table 10). These values are 20 cm and 27 cm, respectively with numerical modeling (Figure 8(a)) and Figure 8(b)). The failure of cross section is shown in Figure 9. In these tests, the cracks and hole begin to appear on the UHPFRC slab. However, the number of these cracks are limited. During the blast loading, the explosion generates a compressive stress wave propagating in the structure. This stress is the cause to appear the crushing and spalling damage on the top and bottom specimen. The shear and bending behavior is small in test because the time is too short for global structural response to develop. The results on top surface crater diameter and the bottom surface spall diameter and cracks obtained by experiment and numerical are quite similar. It demonstrates that the JH-2 model is able to use in modeling the fracture behavior of UHPFRC material.

![Figure 7](image1.png)

(a) (b)

**Figure 7.** The failure of slabs with 1.22kg explosive at top (a) and bottom surface (b) by experiment

![Figure 8](image2.png)

(a) (b)

**Figure 8.** The failure of slap with 1.22kg explosive at top (a) and bottom surface (b) by simulation

![Figure 9](image3.png)

**Figure 9.** The cross section failure of UHPRC-M1.22
Table 10. Compare hole size according to experiment and simulation with UHPFRC-M1.22 slab

| Result   | Hole type | Top surface (cm) | Bottom surface (cm) |
|----------|-----------|------------------|---------------------|
| Experiment | Hole       | 18               | 30                  |
| Simulation | Hole       | 20               | 27                  |

4. Conclusions

The numerical and experimental studies of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) slabs under contact blast loading were presented in this paper. The UHPFRC material is fabricated in laboratory using the material available in Vietnam. The UHPFRC is supposed to be brittle material and follow the Johnson–Holmquist-II (JH-2) model. The Emulsion Explosive has been used and modeled by the SPH method. These studies allow to evaluate the bearing capacity of this material against the blast loads. The experimental results demonstrate that, the UHPFRC concrete have a good resistance against this load. The steel fibers in UHPFRC plays a role as the bridges that connect the crack. It allows limiting the number and the opening of the crack appear in slabs. The comparison of results on top surface crater diameter and the bottom surface spall diameter obtain between experiments and numerical demonstrates that the JH-2 model is able to use in modeling the fracture behavior of UHPFRC material. The results obtain in this study are the important basis for the future research application of UHPFRC concrete for special projects against the blast load, or the impact, especially in defense projects.

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