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# Numerical simulation of blast responses of ultra-high performance fibre reinforced concrete panels with strain-rate effect

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## HIGHLIGHTS

- Material model calibration procedures are presented for simulation of UHPFRC.
- Selection of DIF equation is discussed for the consideration of strain-rate effect.
- The developed 3D FE model is accurate for modelling UHPFRC under blast loads.
- UHPFRC shows better blast resistance than high strength reinforced concrete.
- The effect of reinforcement ratio varies under different blast scenarios.

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## ABSTRACT

Ultra-high performance fibre reinforced concrete (UHPFRC) is a promising construction material for protective structures due to its superior material characteristics. In this study, a finite element model is developed for the simulation of structural responses of UHPFRC panels subjected to blast loads. Based on the available experimental data, the procedures for the material model calibration are presented. The effect of strain rate on the dynamic material properties is reviewed, and the formula of dynamic increase factor is selected and proposed based on the steel fibre dosage and matrix strength. The developed finite element model is validated by comparing the numerical predictions with the test results from literature. In addition, a parametric study is carried out to investigate the effects of steel reinforcement ratios and the blast scenarios on the resistance of UHPFRC panels, and the advantages of using UHPFRC in protective structures are demonstrated by the comparison against high strength reinforced concrete panels.

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## 1. Introduction

With the increasing risk of terrorist attacks and the accidental industrial explosions, the blast and impact resistance has become crucial in the design of engineering structures, in particular for strategically important infrastructures such as government and defence buildings. Ultra-high performance fibre reinforced concrete (UHPFRC) has gained worldwide interests in recent years due to their superior characteristics over conventional reinforced concrete, including their high strength, high ductility, improved strain capacity, high toughness, excellent energy absorption capacity, good durability and good fatigue resistance [1–3], which have made UHPFRC a promising construction material for the structures subjected to extreme loads, such as impact and blast. Moreover, compared to normal reinforced concrete, UHPFRC is expected to reduce spalling damage which could generate flying fragments at very high speed under blast loads, causing tremendous casualties and property loss. Therefore, it is of great significance to investigate the responses of UHPFRC structural components to blast loads before employing them as a substitute in the protective structures.

Impact and blast resistance of UHPFRC is affected by various factors, such as loading rates, fibre properties (shape and strength), fibre volume fractions and cementitious matrix strength. At present, a number of experimental tests have been reported on the blast and impact responses of UHPFRC structural components. Mao et al. [4] conducted experimental tests on UHPFRC panels with various fibre volume fractions and ratios of steel reinforcement under blast loads generated by 100 kg TNT. It was found that, under far-field blast loading, both steel fibres and steel reinforcing bars had equivalent effects on providing resistance to the blast loads, whereas the steel reinforcing bars showed greater blast resistance improvement under near-field blast loading. Later,

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UHPFRC slabs under close-in explosions were tested by Mao et al. [5]. No spalling was found on the rear face of the slab, and the cracks on the front face were observed only at critical charge size. Contact explosion tests were carried out by Li et al. [6] on both normal reinforced concrete and unreinforced UHPFRC panels. It was found that, with the presence of steel fibres, concrete cracking and spalling could be effectively prevented, and the concrete punching failure could be reduced by the improved strength, ductility and energy absorption capacity compared to normal reinforced concrete. Later, Li et al. [7] investigated the influences of different slab depths and longitudinal reinforcement spacing by conducting contact explosion tests on UHPFRC slabs. They also predicted the spall resistance using the existing empirical methods, whereas those methods were found to significantly underestimate the performance of UHPFRC slabs. Nicolaides et al. [8] conducted a series of firing shots on UHPFRC thin panels to investigate their impact resistance. It was observed that the UHPFRC thin panels could be used as an outstanding protective overlay of existing structures due to their advanced abilities to prevent the penetration of strong projectiles, minimise the damage to the retrofitted reinforced concrete structures, and control the back face spalling and fragmentation. In addition, Xu et al. [9] tested UHPFRC columns under various blast loading scenarios, and an improved blast resistance was observed compared to the high strength reinforced concrete columns.

Although recent studies have made progress in the investigation of structural behaviour of UHPFRC components subjected to blast and impact, a reliable design guideline for the application of UHPFRC in the protective structures is lacking due to the insufficient data available. As blast and impact tests are normally costly, and require a large amount of time and efforts, numerical simulation of dynamic structural responses has become a desirable alternative. UHPFRC panels under both free air explosion and contact explosion were modelled by Li et al. [6,10] using LS-DYNA. The Elastic-Plastic Hydrodynamics Model was employed for modelling of UHPFRC in compression, and a tensile cut-off value was applied for the tensile stress failure. As UHPFRC is characterised by its improved tensile strength and tensile ductility, the use of single cut-off value might lead to inaccuracy in the numerical modelling. Also, in their model, the value of dynamic increase factor (DIF) for UHPFRC was assumed to be 1.0, which indicated that the strain-rate effect on the material properties was not considered in the numerical simulation. As the strength enhancements of UHPFRC under higher loading rates were found to be significant [2,3,11,12], the appropriateness of this assumption is debatable. The same numerical model was employed by Li et al. [13] to simulate the UHPFRC columns under blast loads. The Concrete Damage Model in LS-DYNA was employed by Mao et al. [4] for simulating UHPFRC panels under blast loads, in which the parameter controlling the tension softening behaviour was modified to fit the designed stress-strain relationship for UHPFRC under tension. However, the origin of the designed curve used in their study was not mentioned, and the hardening and softening behaviours shown in the designed curve were not very well captured by their modified model. In addition, the stress-strain relationship of UHPFRC in compression and the modulus of elasticity were retained the same as normal concrete in their model. To take into account the strain-rate effect, the CEB-FIP model code 1990 [14] for normal concrete and the model proposed by Ngo et al. [15] for ultra-high strength concrete were utilised for UHPFRC under tension and compression respectively, whereas the strain-rate effect on the steel reinforcing bars was not considered. The predicted maximum and residual deflections showed relatively large discrepancies compared to the test data, especially for the cases when the ratios of steel reinforcing bars were low. Later, Mao et al. [5] applied the same model for simulating UHPFRC panels with different fibre types and fibre volume fractions, however, the failure modes predicted by the numerical model showed more serious damage, and the deflections were not accurately estimated for the panels with higher fibre volumes. This model was again employed by Mao and Barnett [16] for modelling of UHPFRC beam under drop weight impact, whereas detailed model validation was not presented in this study. In addition, Johnson Holmquist Concrete Model was employed by Rong et al. [17] for modelling of UHPFRC cylinders under impact loads. However, the predicted damage patterns did not match very well with the test results.

In the previous numerical studies, the effect of strain rate on the material properties of UHPFRC has been either neglected or assumed to be the same as normal concrete, which might lead to inaccuracy in the numerical simulation. Also, the selection and application of an appropriate material model which can capture the behaviour of UHPFRC is essential to achieve reliable predictions. Therefore, a further study on the numerical simulation of UHPFRC structural members under impact and blast loads is required. In this paper, a 3D finite element (FE) model is developed for the modelling of structural responses of UHPFRC panels under blast loads. The Concrete Damage Model is employed in the current study. To better describe the behaviour of UHPFRC, the material model is calibrated based on the available experimental data. In particular, new sets of scaling parameters are proposed to conduct the interpolation between shear failure surfaces, and the equation of state is adjusted based on the modulus of elasticity from material test. In order to take into account the effect of strain rate in the numerical simulation, the rate sensitivity of UHPFRC under both compression and tension is carefully reviewed and applied with the considerations of fibre volume fraction and matrix strength. In addition, a formula is proposed to estimate the dynamic increase factor for the compressive strength of UHPFRC. The commercial software package LS-DYNA is employed for the nonlinear FE analysis, and the developed numerical model is validated against the existing experimental results from literature. A parametric study is then carried out using the proposed FE model to investigate the effect of steel reinforcements on the blast resistance of UHPFRC panels. Also, the advantages of using UHPFRC in protective structures are demonstrated by comparing the structural performance with high strength reinforced concrete panels.

## 2. Material model for UHPFRC

To simulate the responses of UHPFRC structural members under blast loads, an appropriate material model which can capture the characteristics of UHPFRC is essential. As the material model specifically developed for UHPFRC is currently not available, the Concrete Damage Model (MAT72 R3) is employed in this study for modelling of UHPFRC under dynamic loading. This model has been successfully used by the author in simulating the dynamic responses of normal reinforced concrete structures and the static behaviours of structural components strengthened by high performance fibre reinforced cementitious composites [18,19]. Detailed descriptions and advantages of this model have been discussed in [20–22]. MAT72 R3 was originally developed for normal concrete. In order to describe the material behaviour of UHPFRC, this model has to be calibrated based on the experimental data. In this section, the commercial UHPFRC – Ductal tested by Li et al. [10] is employed as an calibration example.

### 2.1. Three failure surfaces

MAT72 R3 is a three-invariant model, where three shear failure surfaces are used with the consideration of damage and strain rate effects [23]. The three independent strength surfaces include initial

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