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Numerical investigation of reactive powder concrete reinforced with steel wire mesh against high-velocity projectile penetration

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HIGHLIGHTS

- Numerical models of reactive powder concrete, projectile and steel wire mesh have been validated.
- Parametric studies on how steel wire mesh affects impact response of reactive powder concrete have been conducted.
- An empirical equation to predict the depth of projectile penetration has been proposed and preliminarily validated.

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ABSTRACT

This paper numerically investigates the effects of steel wire mesh reinforcement on reactive powder concrete (RPC) targets subjected to high-velocity projectile penetration. A numerical model based on a computer program called LS-DYNA was validated with experimental data concerning the depth of penetration (DOP) and crater diameter of reinforced RPC targets. With the validated numerical model, a series of parametric studies are conducted to investigate how the variables of steel wire mesh reinforcement such as the configuration of steel wire meshes, number of layers, space between layers, space between steel wires per layer, as well as the diameter and tensile strength of steel wires affect DOP and crater diameter of reinforced RPC targets. Moreover, the energy evolution of projectile and steel wire meshes during the projectile penetration is discussed. Based on the results of parametric studies, an empirical equation derived from the simulation data is proposed to predict DOP of reinforced RPC targets.

1. Introduction

Reactive powder concrete (RPC) is characterized by a very low water to cement ratio and high micro-silica fumes to replace coarse aggregates [1], which is equipped with a very high compressive strength and excellent durability. However, RPC is a brittle construction material with a very low tensile strength and energy absorption capacity, so the incorporation of fibres made of carbon, steel, polymer, *etc.* into RPC, which is so-called ultra-high performance fibre-reinforced concrete (UHPFRC), is of great significance to overcome the brittleness, to enhance the compressive and tensile strengths, and to improve the energy absorption capacity [2–5].

Experimental investigations on the impact response of UHPFRC subjected to the high-velocity projectile penetration have been conducted throughout the world [6–9], and the results indicate that UHPFRC has a better dynamic behaviour subjected to the high-velocity projectile penetration because of the higher strength and the addition of fibres in comparison with the conventional concretes, especially in the depth of penetration (DOP), cratering damage and crack propagation. However, the impact resistance of UHPFRC will not have a significant enhancement when the fibre volumetric content exceeds 2% [7,8,10–12]. Also, some achievements have been hindered by the high cost of fibres. Thus it is necessary to investigate new kinds of protective materials with relatively low-cost reinforcing in RPC targets to resist the high-velocity projectile penetration.

Steel reinforcement and steel wire meshes with an excellent ductility and strain capacity have a good energy absorption capacity subjected to the impact loadings [13–15]. Dancygier and Yankelevsky [16] experimentally studied the impact responses of two kinds of high strength concrete (HSC) targets with an average compressive strength of 95–110 MPa penetrated by the sharp-nosed projectile penetration with striking velocities ranging from

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85 m/s to 230 m/s. The HSC targets include the HSC reinforced with 5 mm diameter steel wire mesh with a spacing of 100 mm and two layers of 0.5 mm diameter steel wire meshes with a spacing of 7 mm. The main findings demonstrated that steel wire meshes is effective in constraining DOP and crack propagation, but the reinforcement volumetric content is supposed to be taken into account. Kamal and Eltehewy [17] investigated the dynamic behaviours of normal strength concrete (NSC) blocks reinforced with various number of layers of woven steel wire mesh subjected to the steel blunt-nose projectile at the striking velocity of around 980 m/s, and the experimental results illustrated that DOP and localized damage on the front and rear faces of concrete targets tend to decrease by using steel wire meshes as a reinforcement in comparison with the plain concrete targets. It was also concluded that the increasing of reinforcement ratio only slightly influences DOP and localized damage.

A large number of numerical studies have also been carried out to simulate the projectile penetration process into concrete targets with steel reinforcement. Teng et al. [18] proposed a simple but effective method to analyse the normal and oblique impact on the reinforced concrete, by considering the reinforced concrete as a homogeneous material, which can simplify the finite element meshes and significantly save the computational cost of analysis. Huang et al. [19], Tham [20], as well as Tai and Tang [21], numerically studied the normal perforation of steel-bar-reinforced concrete targets, which demonstrated the good consistence with the experimental results reported by Hanchak et al. [22].

As introduced above, although some experimental and numerical studies have been carried out to examine the effect of steel reinforcement reinforcing in the conventional concrete target on resisting the high-velocity projectile penetration, the related research on the dynamic performance of RPC targets reinforced with steel wire meshes was limited. According to the previous work by Liu et al. [23], the impact responses of RPC targets reinforced with spiral 44-layer steel wire meshes were experimentally and numerically studied, and preliminary parameter studies by numerical simulations were also conducted on the basis of the verified numerical models, but how the steel wire meshes affect the dynamic behaviour of reinforced RPC targets still needs the further comprehensive investigation. In the present study, the variables of steel wire meshes include the configuration of whole steel wire meshes, number of layers, space between two layers, space between two steel wires per layer as well as the diameter and tensile strength of steel wires. Numerical investigations are performed on RPC targets reinforced with steel wire meshes considering the impact responses at the striking velocities from 539 to 1000 m/s, with the assistance of a computer program LS-DYNA.

2. Numerical modelling

In the current study, RPC target and steel projectile are created using eight node hexahedron solid elements with one-point integration, and the Flanagan–Belytschko stiffness hourglass control (Type 5) with the coefficient of 0.1 is adopted in all simulation cases. Hughes-Liu beam elements with cross section integration are adopted to simulate the steel wire meshes. After conducting the mesh convergence test, the element size of 2.8 mm was reasonably adopted for the RPC material in the numerical study to avoid excessive calculation time while maintaining the simulation accuracy. In order to ensure the accuracy and mesh size dependency through adopting the function of constrained Lagrange in solid, the beam element size of 3 mm that is almost equal to RPC element size is selected.

2.1. Material model for concrete

In the present study, Mat_Concrete_Damage_Rel3 along with Mat_Add_Erosion and EOS_Tabulated_Compaction is calibrated and validated to build RPC targets. Mat_Concrete_Damage_Rel3 is a plasticity-based model that applies three independent strength surfaces and this model has been successfully used in simulating the dynamic behaviour of steel reinforced concrete under blast loadings [24,25]. The major advantage of this concrete model is that most of material parameters as well as the equation of state can be automatically generated based on simple input parameters, i.e., the unconfined compressive strength, density and Poisson's ratio. All the key inputs for RPC targets reported are listed in Table 1.

Since the mechanical properties of concrete under high loading rate conditions are significantly different from those under quasi-static conditions, a large number of experiments have been carried out to determine the dynamic increase factor (DIF) values in compression for the plain RPC [26–29]. In the current study, the DIF values for RPC in tension are predicted according to the previous study by Su et al. [30] owing to the lack of experimental data. The detailed DIF values for RPC both in compression and tension can be seen in Ref. [23].

2.2. Material model for steel wire mesh

Mat_Plastic_Kinematic is adopted to simulate the localized damage of steel wire meshes under impact loadings. Isotropic and kinematic hardening plasticity including the strain rate effect are taken into account in this model [21,31]. In order to explore the effect of the tensile strength of steel wire meshes on RPC against the projectile penetration, four types of steel wire meshes with various tensile strengths are used in the present study and the mechanical properties obtained from the previous studies [32–35] are given in Table 2. The strain rate effects on the steel are defined through the Cowper-Symonds model [36,37] to describe its dynamic behaviour. The typical Cowper-Symonds model represents the change of dynamic flow stress with respect to the strain rate, which is derived as:

$$\frac{\sigma_d}{\sigma_y} = 1 + (\varepsilon/C)^{1/P} \tag{1}$$

where σ_d denotes the dynamic yield strength; σ_y denotes the static yield strength; ε represents the strain rate; C and P are the Cowper-Symonds coefficients.

Steel wire meshes are fully constrained in RPC targets and the coupling between steel wire meshes and RPC is realized through the function of constrained Lagrange in solid.

2.3. Material model for steel projectile

Mat_Johnson_Cook together with EOS_Gruneisen is used to build the DT300 alloy steel casing of projectile with the yield strength of 1500 MPa. The flow stress of Johnson-Cook material model is expressed as:

$$\sigma = (A + B\varepsilon^n)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right) \tag{2}$$

where ε is the plastic strain; $\dot{\varepsilon}$ is the strain rate (s^{-1}); $\dot{\varepsilon}_0$ is the reference strain rate (s^{-1}); T is the temperature of material (°C); T_m is the melting temperature (°C) and T_r is the room temperature (°C); A is the yield strength (MPa) at the strain rate of 1 s^{-1}; B is the hardening modulus (MPa) and n is the hardening coefficient; C is the strain rate sensitivity coefficient; m is the thermal softening coefficient.

The inputs of the material model for the casing of projectile are derived through fitting the experimental work [38,39] as given in Table 3. The eroding surface to surface contact is adopted to define the contact between the projectile and RPC target, and the eroding node to surface contact is defined the contact between the projectile and steel wire meshes.

2.4. Numerical models setup

To examine the dynamic performance of steel wire mesh reinforcement, numerical simulations are conducted on RPC targets reinforced with various types of steel wire meshes against the projectile penetration. As shown in Fig. 1, the diameter and thickness of cylindrical RPC targets are 750 mm and 700 mm, respectively. The cylindrical reinforced RPC target can be considered as two parts involving the top part embedded with steel wire mesh reinforcement (protective part) and the bottom part of plain RPC target (protected part). The thicknesses of protective and protected parts are 140 mm and 560 mm, respectively.

Table 1
Key inputs for 100 MPa RPC targets [23].

Model parameter	Value
Density	2400 kg/m^3
Poisson's ratio	0.19
Compressive strength	100 MPa
Tensile strength	6.5 MPa
Loc Width	1.9 mm
b_1	0.82
b_2	3.2
Omega	0.75
Maximum Principle strain	0.16