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An experimental and numerical study of reinforced ultra-high performance concrete slabs under blast loads

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A B S T R A C T

Ultra-high performance concrete (UHPC) which is characterized by high strength, high ductility and high toughness has been widely applied in modern structure construction. Outstanding mechanical feature of UHPC not only enables strong yet slim structure design but also highlights its potential in protective engineering against extreme loads like impact or explosion. In this research a series of reinforced concrete slabs are tested to determine their response under explosive loading conditions. Concrete materials used in the slab construction are ultra-high strength concrete (UHPC) and normal strength concrete (NSC). In total five slabs are tested including four UHPC slabs with varying reinforcement ratios and one control NSC slab with normal reinforcement. Explosive charges with TNT equivalent weights ranging from 1.0 to 14.0 kg at scaled distances ranging from 0.41 to 3.05 m/kg$^{1/3}$ are used in the current experiments. Test results verified the effectiveness of UHPC slabs against blast loads. Numerical models are established in LS-DYNA to reproduce the field blast tests on UHPC slabs. The numerical results are compared with the field test data, and the feasibility and validity of the numerical predictions of UHPC slab responses are demonstrated.

1. Introduction

Contemporary society has witnessed a booming growth of terrorism threats. To protect civilian and/or military personnel and buildings against accidental loads like blast, it is critical to find effective means to mitigate blast effects on structures. Indirect approaches like using concrete barriers to hold back the cars or other vehicles that may contain the explosives are widely used in populated areas [1], however such perimeter protection barriers cannot prevent access of the bombs carried by backpacks or alikes. For important buildings, it is more practical to strengthen the structure itself through utilizing the new technology or new materials.

With the advancement in material science, new concrete materials with enhanced mechanical properties have been under fast development in recent decades. In order to improve the concrete tensile strength and energy absorbing capacity, researchers have been investigating mixing additions like fibre materials into the concrete matrix. Many types of fibres including high modulus steel, glass, carbon and asbestos fibres with different shapes, low modulus synthetic polymer fibres and natural fibres have been studied [2].

Taking advantages of fibrous materials, and replacing the coarse aggregates with reactive powder material like silica fume, ultra-high performance concrete (UHPC), also known as the reactive powder concrete, is now widely studied and applied in civil constructions. UHPC is characterized by steel fibres, a high silica fume content, minimal aggregates, and a low water cement ratio. It typically has a fibre content between 2% and 6% by volume. UHPC has high compressive strength of up to 200 MPa and tensile strength of about 20–40 MPa, as well as the fracture energy of about 20,000–40,000 J/m^2, which is several orders of magnitude higher than that of normal concrete materials [3]. Besides outstanding mechanical performance, Toledo Filho et al. [4] concluded that UHPC can be also considered as an environmental sustainable material given its specific field of application. Recent application of UHPC materials in practical civil designs [5–7] have demonstrated its superior performance and proved its promising potentials in protective engineering.

Under high loading rate conditions such as explosion and impact, UHPC performs better than conventional normal strength concrete. Ngo et al. [8] presented field test results on the blast resistance of concrete panels made of ultra-high strength concrete

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material. The test data including the blast pressures and panel deflections were analysed to assess the performance of UHPC and normal-strength concrete panels. The results showed that the UHPC panels outperformed the normal strength concrete panels with only minor cracks after blast. Barnett [9] investigated the properties of ultra-high performance fibre reinforced concrete under impact and explosion loading for anti-terrorism applications. It was noted that increasing the fibre dosage produced an increase in the maximum load resistance, although the increase was not linear. It was found that the higher rate of testing gave a higher dynamic increase factor for the lower fibre dosage and had a detrimental effect on the flexural toughness of UHPC with higher fibre dosage.

Dragos et al. [10] derived normalized pressure impulse curves for flexural ultra-high performance concrete slabs, and these curves accompanied by the derived normalization equations, can be used for general UHPC blast design. Wu et al. [11] investigated the blast resistances of slabs constructed with plain ultra-high performance concrete (UHPC) and reinforced ultra-high performance concrete (RUHPC). Normal reinforced concrete (NRC) slabs were tested as control specimens. Tests indicated that the plain UHPC slab had a similar blast resistance to the NRC slab and that the RUHPC slab was superior to both.

With wealth of useful data from the field blast tests, numerical simulation can be carried out and the results can be powerful supplement for the existing tests. Thiagarajan et al. [12] performed a preliminary study on the numerical simulation of high strength steel, high strength and normal strength concrete slabs and compared them with experimental results. Prior to explosive testing on the ultra-high performance fibre reinforced concrete panels, Schleyer et al. [13] carried out numerical simulations to determine a suitable distance from the explosives so that the panels would experience permanent damage but not total structural collapse. Wang et al. [14] conducted numerical analysis on influence of fibre aspect ratio on mechanic properties of SRFC under impact loads and compared the results with the experimental counterparts. Based on commercial hydro code LS-DYNA, Teng et al. [15] developed a numerical model of steel fibre reinforced concrete for high velocity impact, and they found the numerical results correlated well with the experimental data. Mao et al. [16] conducted numerical simulation of ultra-high performance fibre reinforced concrete panel subjected to blast loading, and based on a modified material model which takes into account the strain rate effect, the numerical method reproduced the experimental observations with good accuracy.

2. Scope and aims of current study

Rise of terrorism activities in recent decades highlights the need of protective design for modern structures. Recently developed UHPC material is proved to be an effective alternative to conventional concrete and can be used in construction of important structures or key load carrying members. Until now, there is limited systematic investigation on the performance of UHPC material under both static and blast loading condition. In the current study, in-depth knowledge is obtained through a series of experimental tests. Laboratory uniaxial compression tests are carried out on cylindrical UHPC samples and the stress strain relationship confirms the outstanding mechanical strength as well as material ductility of UHPC. Field blast tests are designed and carried out on UHPC slabs with varying reinforcements. A normal strength concrete slab with conventional reinforcement is tested as control sample. In these blast scenarios, various damage modes including flexural damage, combined shear and flexural damage are observed. Impacts from reinforcement strength (ranging from 300 MPa to 1750 MPa), scaled standoff distance (ranging from 0.41 m/kg$^{1/3}$ to 3.05 m/kg$^{1/3}$) are investigated.

Slabs maximum deflection and residual deflection at midspan are quantified through the measurement of Linear Variable Differential Transformer (LVDT), blast pressure time histories in all the trials are recorded and compared with UFC code. Field observations and the test data are used to compare with the numerical results obtained in LS-DYNA simulation, and the validity and accuracy of the proposed numerical model are briefed.

3. Blast test program

3.1. Test samples

The blast program was designed to investigate the performance of reinforced UHPC slabs under blast loading conditions. Test samples include UHPC slabs with various reinforcing ratios and different types of reinforcing steel. One additional normal strength slab which had pressure transducers attached to the surface was tested to determine the pressure loading distribution. All the slabs were constructed by VSL in their Melbourne Laboratory. The type of UHPC used in construction was Ductal® and was identical for all four UHPC slabs. The concrete mix composition for Ductal® is presented in Table 1 [17]. It is worth noting that for UHPC, a normal steel fibre volume fraction ratio is between 2% and 6%, and this value is higher than high strength concrete discussed in previous study [18]. High strength concrete uses gravel as the coarse aggregates, therefore, the amount of steel fibres can be added is limited. Ultra-high performance concrete (or reactive powder concrete) has no coarse aggregates. Instead, the ultra-fine silica fume is added providing prominent pozzolanic effect and filling effect which can significantly improve material strength. Because there is no coarse aggregate, relatively high percentage of steel fibres can be added in UHPC. In the present study, 2% volume fraction was adopted to balance the steel consumption and material performance. In the tests, both the NSC and UHPC slabs were erected vertically as 2000 ∗ 2000 ∗ 100 mm slabs and were later cut in half to generate two 2000 ∗ 1000 ∗ 100 mm slabs. The cross section and reinforcement of the slabs are shown in Fig. 1. In all slabs, no stirrup rebars were used.

To determine the material properties like Young's modulus, Poisson's ratio, compressive strength and the stress strain relationship of the concrete, cylinder tests were carried out for both the NSC and UHPC conforming to Australian Standard 1012.17-1997. All concrete cylinders had a height of 200 mm and a diameter of 100 mm. Material parameters were obtained by attaching four strain gauges symmetrically about the mid-height of each cylinder, two longitudinally and two transversely. The load was applied at a controlled rate of 15 MPa/min. Strain and the corresponding forces were recorded at constant intervals. In total, 10 NSC cylinders and 7 UHPC cylinders were tested and the results were averaged as shown in Table 2.

Fig. 2 shows the compressive stress strain relationship for the UHPC material which is obtained from the above cylinder tests.

Table 1
Ductal® mix proportions.

Constituent	Amount
Cement	680 kg/m^3
Silica fume	204 kg/m^3
Silica flour	204 kg/m^3
Sand	974 kg/m^3
Steel fibres	156 kg/m^3
Superplasticizer	44 l/m^3
Water	150 l/m^3