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Behaviour of ultra high performance fibre reinforced concrete columns subjected to blast loading

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ABSTRACT

Ultra high performance fibre reinforced concrete (UHPFRC) is a cement-based composite material mixing with reactive powder and steel fibres. It is characterized by its high strength, high ductility and high toughness and such characteristics enable its great potential in protective engineering against extreme loads such as impact or explosion. In the present study, a series of field tests were conducted to investigate the behaviour of UHPFRC columns subjected to blast loading. In total four 0.2 m × 0.2 m × 2.5 m UHPFRC columns were tested under different designed explosions but all at a standoff distance of 1.5 m. Blast tests were also performed on four high strength reinforced concrete (HSRC) columns with the same size and reinforcement as UHPFRC columns to evaluate their behaviour under the same loading conditions. The data collected from each specimen included reflected overpressures, column deflections at centre and near the supports. Three major damage modes, including flexural, shear and concrete spalling failure modes, were observed. The post blast crack patterns, permanent deflections and different levels of damage observations showed that UHPFRC columns performed superior in blast loading resistance as compared with HSRC columns.

1. Introduction

The analysis and design of civilian and military buildings and structures to withstand shock and blast loading has been a subject of extensive studies in the last decade due to the increase of terrorist attacks around the world. There are two main approaches to protect structures against man-made explosive hazards. One approach is to reduce damage by protecting the structures with external claddings (e.g., aluminium foam); the other is to strengthen the structures to better withstand explosion-induced loads such as by applying ultra-high performance fibre reinforced concrete (UHPFRC) [1]. Based on standoff distance and charge weight of detonations, blast loads can be categorised into contact, close-in and far field detonation. Contact detonation is a case that explosive is in contact with a structure, therefore, contact blast load is a high-intensity and non-uniform. For close-in detonation, it is a spherical shock wave generated by the explosion striking a structure with a non-uniform and impulse-dominated load. Far field detonation is the explosive located at a large distance from the structure, where a planar wave with a uniform load is applied to the structures. The main aim of the present research is to investigate the capabilities and dynamic response of ultra-high performance fibre reinforced concrete columns against close-in blasts.

UHPFRC members are investigated in the current study because of their outstanding safety, serviceability, durability and ductility [2–5]. Ultra-high performance concrete is known as a reactive powder concrete that can provide compressive strength up to 200 MPa and flexural tensile strength up to 40 MPa while exhibiting strain-hardening behaviour under uni-axial tension [6,7]. There are two important considerations in selecting UHPFRC columns to resist blast loading, i.e., their capability of preventing catastrophic failure like progressive collapse and reducing fragmentation due to projectiles [8]. Basically, the most significant characteristics of UHPFRC are its high compressive/tensile strength and outstanding ductility stemming from inclusion of steel fibre, which lead to a

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dramatic increase of the energy absorption capacity of UHPFRC members and prevent them from suffering catastrophic failure under blast loads. Also, the recent development in nano-material science has been included to further improve the strength and energy absorption capacity of UHPFRC members so that their sizes can be reduced significantly in comparison with use of conventional concrete counterparts, leading to a remarkable reduction of material used in structural members with a much lower carbon footprint and sustained more active load on members before and after blast events [8]. Furthermore, as mentioned by Brandt [9], steel fibres create a homogeneous matrix in the mix and bridge the gaps of the micro-crack so as to control local crack opening and propagation as well. Thus in addition to increasing integrity of a structure, it is envisaged that application of UHPFRC will contribute to reducing spalling and scabbing.

In recent years there have been considerable numerical and experimental work conducted to understand UHPFRC material under both static and dynamic loading condition [10–18]. However, because of the high technical requirements, high costs of manufacturing UHPFRC and the security restrictions required for full scale blast tests, experimental studies on UHPFRC members against blasts are very limited. The results of 72 fibrous-reinforced concrete slabs against explosive loading tests were presented by Williamson [19] and it was reported that there is only slight difference in response of high-strength and medium-strength concrete, when used in conjunction with fibres under explosive loading. The experimental data revealed that the failure mode was primarily flexure for a slab in a vertical position with bearing only on two sides, also, the concrete mixed with steel or nylon fibres could be significantly reinforced to withstand the stresses, and effectively reduce the amount and velocity of fragments. Some experimental investigations have been conducted to examine the blast resistant capability of concrete panels/beams/slabs made of UHPFRC materials [7,20–22]. Compared with structures made of normal concrete, these tests not only verified that UHPFRC members could perform extremely well, surviving with minor cracks under the applied blast loads, but also proved that UHPFRC structure could minimize the risk of injury or damage caused by concrete debris as they did not break into fragments.

The study [23] on UHPFRC structures subjected to high strain rates has revealed some important differences on behaviours of UHPFRC subjected to relatively low strain rate dynamic loads. In the latter study, for determining the plates subjected to quasi-static loading, three- and four-point bending tests were applied and drop weight tests were performed in order to apply dynamic three-point-bending loading to UHPFRC plates [23]. Wu et al. [24] conducted a series of blast tests on evaluating the effectiveness of slabs using different materials as blast enhancement reinforcement, and some slabs retrofitted with fibre reinforced polymer plates, others constructed with ultra-high performance concrete. It was reported that the reinforced ultra-high performance fibre concrete slabs which suffered least damage was superior to all slabs made of other concrete materials, confirming that ultra-high performance fibre concrete (UHPC) is a more effective material for use in structures susceptible to terrorist attack or accidental impacts. These studies have generally indicated the benefits of UHPC in improving damage tolerance, enhancing control of cracking and spalling, and the ability to minimize the flying debris from damaged slabs and beams. However, most of the information and results provided by the studies have been used for evaluating the application of UHPC on slabs/beams and there is little published literature pertaining to resistance and behaviour of UHPC columns under blast loading.

Several researchers have studied the blast vulnerability of RC columns with/without FRP-retrofitted composites using blast experiments, numerical prediction and drop-weight tests; and different failure modes have been observed [25–28]. For analysing columns under blasts, a general classification of different failure modes needs to be established according to orientations of major cracks. Three failure modes are generally characterized. In general, flexural response governs failure mechanism when plastic hinges form in centre and supports of columns. If the static shear-bending capacity ratio is less than unity or under high-velocity impact or blast loading, some columns may collapse in a shear failure mode due to development and widening of severe diagonal cracks and rupture of longitudinal rebars [29–32]. Furthermore, as the current research is dealing with a close-in blast loading condition, the extremely high intensity and short duration of blasts give rise to localized failure modes such as direct shear failure mode, spalling and scabbing which are under less consideration in the previous literatures.

The objective of this study is to experimentally investigate whether UHPFRC columns can effectively improve their resistance to blast loads at relatively close standoff distance. In total, 8 column specimens, including 4 specimens built with UHPFRC, and 4 specimens built with HSRC were tested under blast loads ranging from 1 kg to 35 kg equivalent TNT at a distance of 1.5 m. The experiment program including constructing specimens, test set-up and procedure is described. Particular interests of assessing the nature of damage and dynamic response, overpressure, duration time, displacement and failure modes are well-documented and analysed. The concluding remarks are presented in the final section.

2. Outline of experiment

2.1. Material characteristics

In the current UHPFRC material composition, constant water to binder ratio 0.16 is adopted. Aggregates (river sand) at the same weight dosages (40% by weight) was used, a constant content of silica fume, silica flour was used to provide high pozzolanic effect that accelerated the hydration process and enhanced the material compressive strength. To further improve the performance of matrix, nanoscale $CaCO_3$ particles which acted as an effective filling material and also provided high pozzolanic reactivity had been used. The nanoparticle Nano-$CaCO_3$ has mean particle sizes about 40 nm and the specific surface area (in BET methods) more than 30 m^2/g.

Micro steel fibre (MF) was added into the mixtures and MF has 0.1 mm diameter and 6 mm length which can sustain tensile strength more than 4000 MPa. The steel fibres at a dosage 2.5% by volume were used. This dosage was decided on the basis of a series of preliminary tests. Table 1 shows mix proportions of UHPFRC/HSRC. Please note that HSRC has the same proportions of mix design as UHPFRC except fibre material addition.

Static test results based on uniaxial compression and four-points bending tests indicated that the specified UHPFRC compressive strength and flexural tensile strength at 28 days was 148 MPa and 32 MPa, respectively.

2.2. Specimen geometry

The test specimens consist of four UHPFRC columns (that is, U1A, U1B, U2A and U2B) with span length 2.5 m, having square cross section of 0.2 m. The geometry of UHPFRC column, layout of longitudinal reinforcements and spacing of transverse reinforcement are shown in Fig. 1. The reinforcing bar has diameter of 16 mm with cross-section area of 201.1 mm^2 and the centre-to-centre spacing of 57 mm. The thickness of the concrete cover is 35 mm; the yield stress and ultimate strength of high strength reinforcing bars are 1450 MPa and 1600 MPa, respectively.