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Post-blast capacity of ultra-high performance concrete columns

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ABSTRACT

Over the past several decades, iconic and public buildings have become targets of terrorist bomb attacks, but most of these buildings were built without consideration of blast loading scenarios. Key load-carrying elements such as concrete columns are probably the most critical structural components for structural protection against bomb threats. Failures of columns may trigger catastrophic progressive collapse if there is insufficient structural redundancy. In a recent study, novel ultra-high performance concrete (UHPC) material formulated based on reactive powder concrete (RPC) was developed. Field blast tests on columns made of this material were performed. Test results showed that UHPC columns had excellent blast resistant capability, only small mid-height deflection and minor concrete damage was observed after the blasting tests. In the present study, to quantify blast-induced damage and assess residual loading capacity of UHPC columns, static axial loading tests on post-blast UHPC columns were carried out. Undamaged control samples were tested to provide benchmarks. Damage index and residual loading capacity of UHPC columns after various blast loadings were obtained. It was found that column cast with micro steel fibre reinforced UHPC preserved more than 70% of its loading capacity after 35 kg TNT detonation at 1.5 m standoff distance, while high strength concrete column only maintained 40% loading capacity after 8 kg TNT detonation at 1.5 m standoff distance.

1. Introduction

Accidental and intentional events involving blast effects on structures are attracting increasingly more public concerns nowadays. A Large number of casualties and countless property loss could be induced by unexpected blast loads. While immediate structural damage and casualties are normally caused by blast overpressure released in an explosion, progressive failures of structures and their components result in the majority of casualties and damages [1]. Despite widely spreading concerns about this issue, most structures including iconic and public buildings were and are still being constructed without considering these extreme loading scenarios.

In a structural system, failure of one or several key load-carrying columns may trigger large-scale disproportionate structural progressive collapse. A progressive collapse can be initiated for many reasons, including design and construction errors and load events that are outside the normal structural design basis that is seldom considered by the structural engineers [2]. Documentation of such disastrous failure has a long history tracked back in the 1900s on stonemasonry structures. In modern construction, although steel-frame or steel-reinforced concrete structures are adopted to provide enhanced ductility and redundancy, structural progressive collapses might still occur. Extensive study on structural progressive collapse has been carried out in recent decades. Sasani [3] analytically studied the response of a six-story reinforced concrete infilled-frame structure after removal of two adjacent columns, and identified the major mechanism in load redistributions after the loss of columns. Woodson et al. [4] verified the importance of in-fill walls in affecting the load applied on the structural column, and concluded that collapse would have occurred if slab edge beams failed to carry dead weight when load-carrying columns incurred severe damage. With high-fidelity physics-based computer program, the vulnerability of structures to progressive collapse was numerically studied [5,6]. In all these studies, failure of columns was identified as the most critical cause for triggering a structural collapse.

Due to easy accessibility, perimeter columns in modern structures may be targeted by terrorists using improvised explosive devices such as VBIED (vehicle-borne improvised explosive device) and suitcase bombs. To prevent initiation of progressive collapse, it is necessary to investigate failure mechanism of an individual column in a frame structural system and provide adequate protec-

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tions. Under blast loading environments, concrete structural members may fail in brittle modes like shear punching and concrete spall [7,8] rather than desired flexural mode. According to UFC 3-340-2 [9], if the structural response is ductile, which means the plastic/permanent deflection absorbs blast energy, concrete structural members are capable of attaining 6 degrees support rotation. This damage criterion, however, is not suitable for describing brittle damage modes of columns. Hao [10] discussed possible failure modes and applicable damage criteria of structures subjected to dynamic loads of various loading rates. A concrete beam or column could suffer localized crushing/spalling damage, direct shear, diagonal shear, ductile flexural damage, or combined damage of these damage modes depending on the explosion standoff or loading rates. Hao, et al. [11] recently conducted a review of the current practices in blast resistant analysis and design of concrete structures. The methods that lead to more reliable predictions of concrete structures to blast loads are discussed. For concrete columns, in particular Shi et al. [12] adopted residual loading capacity of reinforced concrete columns after blast loading as the damage criterion to generate Pressure-Impulse (P-I) curves. Based on parametric studies, analytical formulae to predict pressure–impulse diagrams for RC columns were proposed. Later in the study carried out by Bao and Li [13], residual strength of reinforced concrete columns after small standoff blast loads was investigated, and the formulae which were capable of estimating column residual strength were provided. The validity range of these formulae was later refined through the experimental results obtained by Li et al. [14]. In their experimental setup, the columns were loaded with three horizontal actuators to simulate the actual blast loads. Wu et al. [15] carried out experimental and numerical studies on the residual axial compression capacity of reinforced concrete columns after localized blast effects. The relationship between residual axial capacity and structural and loading parameters such as material strength, column detailing and blast conditions was investigated through numerical parametric studies. Roller et al. [16] observed that there was just little knowledge about the behaviour of elements with one-dimensional load capacity like columns under blast loading conditions. To provide in-depth knowledge, they started a test program involving both standard reinforced concrete columns and retrofitted concrete columns under blast loads first and then static loads. Remaining load-carrying capacities of blast-damaged columns were obtained through uniaxial compressive tests.

Unpredictable terrorist activity and its disastrous consequences highlight the necessity of protection of reinforced concrete structures against blast effects. Besides perimeter protection through regulating the accessibility of vehicles, direct protection on the structures is attracting interests from property owners and researchers. For existing structures, a convenient and effective method to enhance their performance under dynamic loads is outer layer retrofitting. Crawford et al. [17] carried out full-scale blast tests on RC columns that are typically used in four-storey office buildings. Under short standoff distance explosions, columns failed because of their shear and flexural capacities were exceeded at the both ends. An additional experiment was conducted to determine the increase in blast-loading capacity of the RC column when reinforced with a layer of carbon fibre-reinforced polymer (CFRP). It was apparent from the results obtained that the retrofitted column remained elastic and sustained no permanent deformations. Mosalam and Mosallam [18] developed computational model for RC slabs with and without CFRP retrofitting, and they proposed that the improved slab behaviour with CFRP composite system is best when retrofitting is applied to both sides of the slab. The effectiveness of FRP retrofitting on columns against blast loads was extensively studied [19–21].

Efforts were also devoted to the improvement of concrete at the material level. In recent decades, new concrete materials like steel fibre reinforced concrete (SFRC), reactive powder concrete (RPC) are used increasingly in new structural constructions. These materials overcome the inherent disadvantages of normal strength concrete and provide better mechanical strength, material ductility and energy absorption capability. As a notable representative of novel constructional material, ultra-high performance concrete (UHPC) which is formulated based on RPC with steel fibre reinforcement is under fast development. However, until now, research work on UHPC material is focused on material performance [22,23] and some static structural behaviours [24,25], and only a few structural tests under dynamic loads were reported. In previous studies, blast testing was conducted on UHPC slabs [26] and control slabs made with normal strength concrete. It was concluded that combination of high strength concrete with steel fibre can significantly increase blast resistance of structural components. Li et al. carried out experimental and numerical studies on UHPC slabs against free air explosions [27], and it was found that while normal strength concrete slabs displayed brittle damage such as shear and concrete spall, UHPC slabs underwent only minor flexural damage. Under contact detonations, a UHPC slab also demonstrated high spall and crater resistance when compared with a slab made of normal strength concrete [28].

Until now, no systematic study on UHPC columns against blast loads and their corresponding post-blast behaviours are found in the open literature. Some preliminary experimental results on UHPC columns under and after blast loads were recently reported [29,30], and the capability of UHPC columns to resist the blast loads ranging from 1 kg to 17.5 kg TNT explosion was demonstrated. It was noted that under 17.5 kg TNT detonation at 1.5 m standoff distance, only hairline cracks were observed on UHPC column and almost no global deflection occurred. To observe responses of UHPC columns in more advanced stages, more field blast tests on UHPC columns were carried out. In this paper, field blast test results on 10 UHPC columns and 5 high strength reinforced concrete (HSRC) columns are compiled and compared, and laboratory residual load-carrying capacity tests on these columns are presented and discussed.

2. Field blast tests

2.1. UHPC material preparation

In the current research, UHPC was mixed to prepare column specimens. The complete mix proportion of UHPC is shown in Table 1. In UHPC composition, coarse aggregates are replaced with silica fume to improve its properties, in particular its compressive strength, bond strength, and abrasion resistance. These improvements stem from very fine powder addition to the cement mix and also the pozzolanic reactions between the silica fume and free calcium hydroxide in the paste. 2.5% weight dosage of nano particles nano-$CaCO_3$ were mixed in the concrete matrix to provide nanoscale filling effect and also facilitate hydration process. Two types of steel fibre material, i.e. Twisted Fibre (TF) and Micro Fibre (MF) were mixed at a volume dosage of 2.5% to provide additional tensile and crack resistance. TF has 0.3 mm diameter and 30 mm length, and its tensile strength is 1500 MPa. MF has a 0.12 mm diameter and 6 mm length, and its tensile strength is 4295 MPa.

Compressive stress-strain relationships from cylinder tests and force-displacement curves from flexural tests of UHPC with different fibre reinforcements are shown in Fig. 1. Stress strain relationships for the two UHPCs are obtained from uniaxial compression test. The addition of MF and TF reinforcement gives a compressive