POST-BLAST RESIDUAL LOADING CAPACITY OF ULTRA-HIGH PERFORMANCE CONCRETE COLUMNS

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Abstract:

Concrete columns are key load-carrying components in modern structures, and their performance is directly related to serviceability of the entire building. Due to their easy accessibility and inherent, vulnerability which mainly comes from low tensile strength of construction materials, concrete columns are under potential threat of rising terrorism attacks. Sufficient residual strength is sought after blasts to avoid catastrophic progressive collapse. In this paper, a series of residual load carrying capacity tests on post-blast ultra-high performance concrete (UHPC) columns are presented. These columns are made of a newly developed UHPC material which boasts of ultra-high compressive and tensile strength as well as excellent material ductility. Test results are compared with undamaged columns built with the same material. It is generally concluded that these UHPC columns retain a high level of load carrying strength after blast loads and the results highlight a potential of utilizing such materials in protective design.

Keywords:

UHPC column, blast test, residual loading capacity

1. Introduction

In a framed structural system, progressive collapse can be initiated by loss of key load-carrying columns (Ellingwood 2006). Extensive study including experimental trials (Sasani 2008, Woodson and Baylot 1999) and high fidelity numerical analysis (Kwasniewski 2010, Shi et al. 2010, Li and Hao 2013, Li and Hao 2014) were carried out to understand vulnerability of structures to progressive collapse. In all these studies, failure of columns was identified as the most important factor for triggering structural failure.

To prevent initiation of progressive collapse, it is necessary to investigate failure mechanisms of individual columns in a framed structure system and provide adequate protections. Residual loading capacity of reinforced concrete columns after blast loads was adopted as the damage criterion to generate Pressure-Impulse (P-I) curves (Shi et al. 2008). Based on parametric studies, analytical formulae to predict the pressure–impulse diagrams for RC columns were proposed. Later in a relevant study (Bao and Li 2010), residual strength of reinforced concrete columns after short standoff blast conditions was investigated, and the formulae which were capable of estimating column residual strength were provided. Experimental and numerical studies on the residual axial compression capacity of reinforced concrete columns after localized blast effects were carried out (Wu et al. 2011). The relationship between residual axial capacity and structural and loading parameters such as material strength, column detail and blast conditions was investigated through numerical parametric studies. Despite some research work can be found in open literature, it was observed that there was little knowledge about the behavior of elements with one-dimensional load capacity like columns under blast loading conditions (Roller et al. 2013). To provide in-depth knowledge, a test program was started 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.

In recent decades, new concrete materials like steel fiber reinforced concrete (SFRC) and reactive powder concrete (RPC) are used increasingly in new structural constructions (RPC is the generic name for a class of cementious composite materials developed by the technical division of Bouygues in the early 1990s). These materials overcome the inherent defects of normal strength concrete and provide better mechanical strength, material ductility and energy absorption capability. After a combination of SFRC and RPC, ultra-high performance concrete (UHPC) is formulated. Until now, research working on UHPC material is focused on material performance, and only a few structural tests under dynamic loads were reported, for example, the work conducted in Australia by Cavill et al. 2006. Recently, experimental and numerical studies on UHPC slabs against blast loads were carried out (Li et al. 2015), and it was found while normal strength concrete slabs displayed brittle damage such as shear and concrete spall, UHPC slabs underwent only minor flexural damage.

Until now, there is no systematic study on UHPC columns against blast loads and corresponding post-blast behaviours are not found in the open literature. In a recent study, a series of UHPC columns were field tested under various blast scenarios (Li et al. 2015). The blast-damaged columns were then taken back to laboratory and subjected to static tests to determine the residual load-carrying capacities. In this paper, field blast tests and laboratory residual load-carrying capacity tests are presented and discussed.

2. Field blast test results

In the current study, two fiber materials, namely Micro Steel Fiber (MF) and Twisted Steel Fiber (TF) are considered in UHPC design. The fibers were mixed at a volume dosage of 2.5%. 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. Mechanical properties of UHPC with different fiber reinforcement are shown in Figure 1. Stress-strain relationships for the two UHPCs were obtained from uniaxial compression tests. Addition of MF and TF reinforcement gave a compressive strength of 148 MPa (21.5 ksi) and 130 MPa (18.9 ksi), respectively. Flexural force-deflection relationships were obtained from four-points bending tests on beam samples. The samples in four point bending tests had a length of 400 mm (15.1 in.) and cross-section of 100 mm (3.8 in.) × 100 mm (3.8 in.), and clear loading span was 300 mm (11.3 in.). According to the test sample configuration, the flexural tensile strengths for UHPC with MF and TF reinforcement could be derived as 32 MPa (4.6 ksi) and 25 MPa (3.6 ksi).

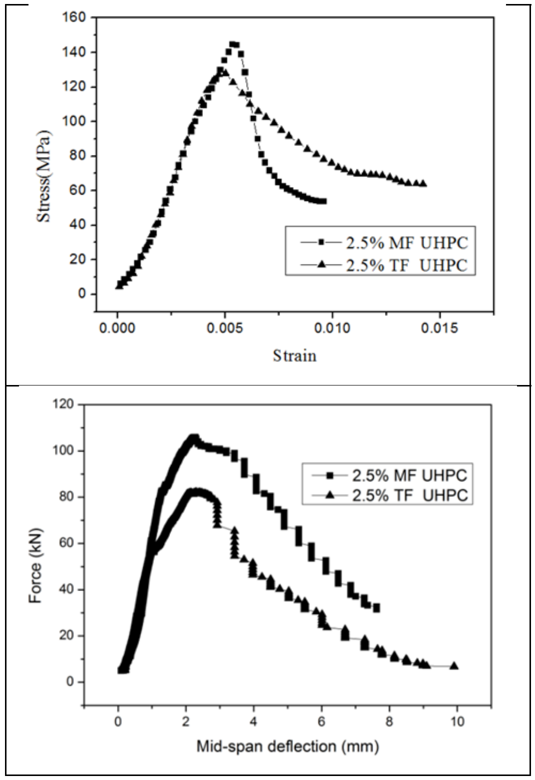


Figure 1. Compressive stress-strain and flexural bending force-displacement curves of UHPC

Test matrix is shown in Table 1. In total five columns including 3 UHPC columns and 2 normal strength concrete (NSC) columns are considered. TNT equivalence of the explosives are given as the charge weight. An axial load was applied to all columns as noted in Table 1 during the blast testing. The blast effects are usually given as a function of the dimensional distance parameter (scaled distance) $Z = R/W^{1/3}$, in which R is the standoff distance from the detonation and W is the charge weight (US DOD 2008).

Due to damage of NSC columns after blast load testing, they were not considered in the residual loading tests.

Table 1. Blast tests matrix

Column	Dimension (m)	Fiber material	Compressive/ tensile strength (MPa)	Axial load (kN)	Charge weight (kg)	Standoff distance (m)	Scaled distance ($m/kg^{1/3}$)	Residual test
UHPC-1	0.2 × 0.2 × 2.5	Micro fiber	148/32	1000	35	1.5	0.46	Yes
UHPC-2	0.2 × 0.2 × 2.5	Micro fiber	148/32	1000	17.5	1.5	0.58	Yes
UHPC-4	0.2 × 0.2 × 2.5	Twisted fiber	130/25	1000	35	1.5	0.46	Yes

NSC 1	0.2 × 0.2 × 2.5	nil	60/2.5	1000	8	1.5	0.75	No
NSC 2	0.2 × 0.2 × 2.5	nil	60/2.5	500	17.5	1.5	0.58	No

* Metric conversions 1m = 3.28 ft, 1 kN = 225 lbf, 1 kg = 2.2 lb.

Field test set up is shown in Figure 2. The explosive hangs over the column at mid-span using a bamboo tripod for stabilization. LVDT was installed on the bottom side of the column to record the mid-span column deflection. Pressure sensor was installed at column mid-span facing the detonation to record the blast overpressure time history. In the present test setup, column was placed in the horizontal direction for easy application of axial load. Such setup also protects the instruments underneath from blast wave diffraction.

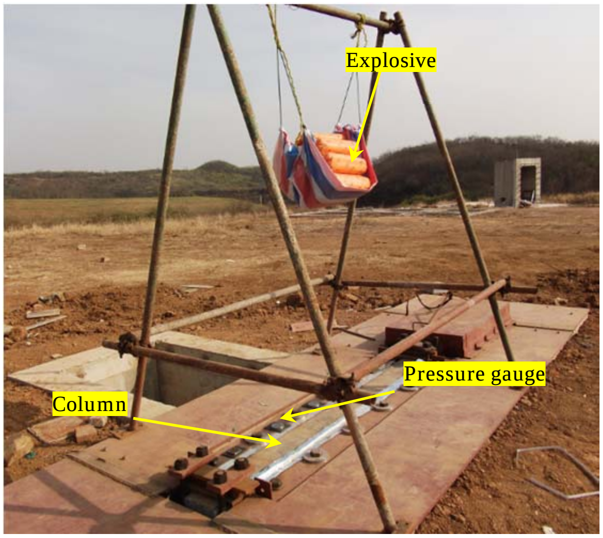
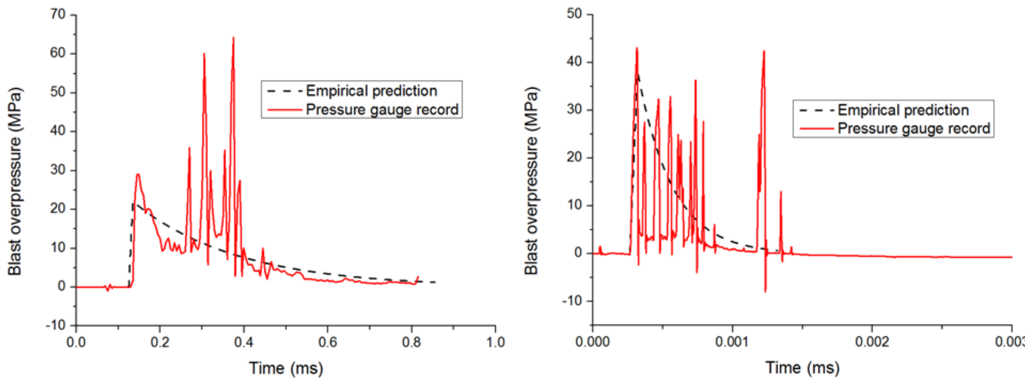


Figure 2. Field test setup

Blast overpressure time history curves were detected and recorded from a pressure gauge located at the center of the column. Empirical prediction on the peak blast overpressure was based on UFC 3-340-2 (US DoD 2008) and pressure decay history was predicted by a formula proposed by Ethridge in his 1965 work (Baker 1973). Although several models are available to predict blast overpressure decay, formula proposed by Ethridge is adopted in the present study because it was noted that this model can fit pressure gauge results more accurately (Chock 1999).

Based on the comparison between experimental and empirical blast pressure time histories as shown Figure 3, it is generally concluded that the empirical method can give reasonable overpressure decay prediction although it underestimates the peak blast overpressure for all the blast scenarios. However, the deviation between the experimental and empirical predictions is relatively small in an acceptable range for blast tests.

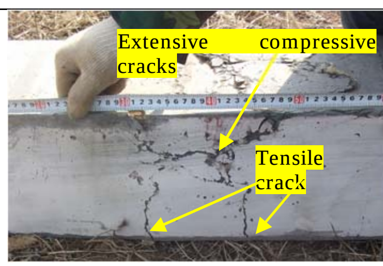
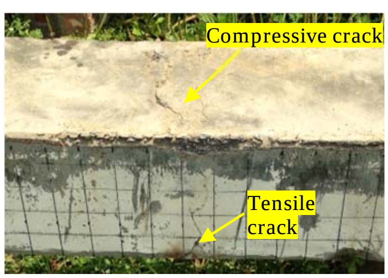


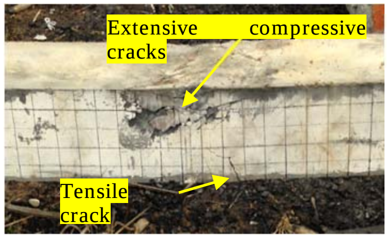
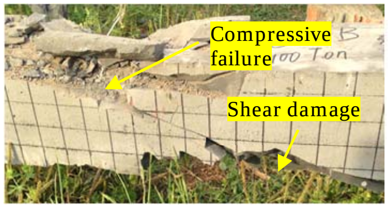
17.5 kg TNT equivalence **35 kg TNT equivalence**

Figure 3. Blast pressure time-histories

Test results are summarized in Table 2. It is easily noted, under the most severe blast loading environment, i.e. 35 kg (77 lb) TNT equivalence detonated at 1.5 m (4.92 ft) standoff distance, UHPC columns UHPC-1 and UHPC-4 only underwent minor flexural damage at mid-span. One or two tensile cracks and compressive concrete crushing can be found on the column. With decreased charge weight, UHPC-2 column only showed hairline tensile and compressive cracks. After exposed to the same blast loads as UHPC-2 column, NSC-2 column failed completely, and clear buckling happened under the action of axial load. Although with a decreased charge weight, NSC-1 column failed in a brittle manner, clear shear cracks and concrete peeling off can be noticed at column distal surface.

Table 2 Field blast test results

Column No.	Damge mode	Residual deflection / Maximum deflection
UHPC-1		23 mm / 68 mm
UHPC-2		4 mm / 41 mm

UHPC-4		24 mm / 70 mm
NSC-1		7.5 mm / 35 mm
NSC-2		100 mm / faulty value

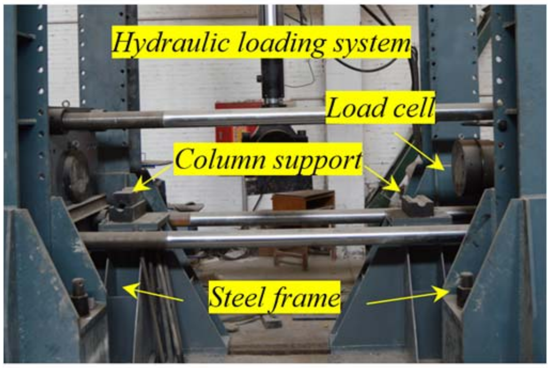
* Metric conversions 1mm = 0.00328 ft.

3. Residual loading tests

Resilience of UHPC columns were investigated in two-phase experimental tests. The first phase was the field blast tests as discussed in the above section, and in the second phase, the residual load-carrying capacities of these damaged columns were studied to observe their post-blast serviceability.

Figure 4a shows the apparatus for static load testing of UHPC columns. This hydraulic testing system is capable of providing a maximum axial load of 10,000 kN (1000 ton). In testing, column was placed on top of the supports, and an axial load was applied gradually on column ends with a loading scheme shown in Figure 4b. The testing procedures were made to conform to safety regulations and also guaranteed the hydraulic load cell was in a firm contact with the column ends.

(a)



(b)

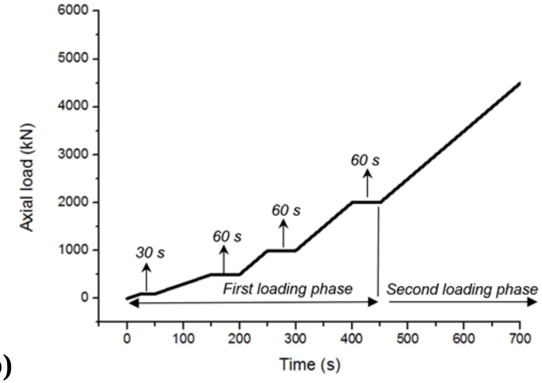


Figure 4. Axial load-carrying capacity testing system and load sequence

Two undamaged (non-blast tested) UHPC columns with MF and TF fiber reinforcement were also tested to provide the benchmark load carrying capacity. Failure of an undamaged UHPC column is shown in Figure 5, and under axial loading condition, the column lost load-carrying capacity owing to the concrete fracture at the column support. No flexural damage at the column mid-span was observed. With damage and cracking only distributed over the column surface and where the provision of fibers prevented cover spalling, superior damage tolerance was observed in UHPC column. In this test on the undamaged UHPC columns, upon column failure, axial loads for column with MF and TF reinforcement were 5900 kN and 5010 kN, respectively.

Figure 5. End concrete crushing of undamaged (non-blast tested) UHPC column

Residual test results on UHPC columns are summarized in Table 3. Damage index D is defined as the percentage of loading capacity loss over the undamaged column loading capacity. After experiencing the same blast loading conditions, but due to a higher material strength and ductility, UHPC-1 column with MF fiber reinforcement performs better than UHPC-4. UHPC-2 preserved most of its loading capacity after a 17.5 kg (38.5 lb) TNT explosion at 1.5 m (4.92 ft) standoff distance.

Table 3. Residual load-carrying tests results

Column	Fiber material	Charge weight (kg)	Standoff distance (m)	Scaled distance (m/kg^1/3)	Residual Strength (kN)	Damage D (%)
UHPC-1	Micro fiber	35	1.5	0.46	4540	23%
UHPC-2	Micro fiber	17.5	1.5	0.58	5660	5%
UHPC-4	Twisted fiber	35	1.5	0.46	3068	39%

* Metric conversions 1m = 3.28 ft, 1 kN = 225 lbf, 1 kg = 2.2 lb.

The damage mode of each UHPC column is shown in Figure 6. UHPC-2 only suffered slight blast damage, and its performance under residual loading condition was dominated by the steel reinforcement buckling. The less confinement to reinforcement bars at the mid-span due to concrete damage and plastic deformation of the reinforcements by blast load reduced the capacity of the section at the mid-span. As a result, failure occurred at the mid-span due to concrete crushing and reinforcement buckling when the axial load was applied.

UHPC-1 and UHPC-4 experienced minor flexural damage during the field blast tests, increasing axial loads will increase the mid-span deflection until yielding of all the longitudinal reinforcement.

UHPC-1 **UHPC-2**

UHPC-4

Figure 6. UHPC columns after residual loading test

4. Conclusion

In the present study, resilience of ultra-high performance (UHPC) columns is experimentally evaluated in a two-phase study. In the first-phase, field blast tests were carried out, and UHPC columns demonstrated high blast resistant capability. This performance stems not only from the ultra-high mechanical properties but also from to the bridging effects from steel fiber material. UHPC columns outperformed comparative column samples made of conventional concrete. In the second phase study, the blast tested columns were taken back to the laboratory and subjected to axial static loading tests to determine the column residual loading capacity. Test results reveal that the UHPC columns retain more than half of their loading capacity after blast loads. Column with micro fibers had low damage compared to columns with twisted fibers after the same blast loading event.

5. References

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6. ACKNOWLEDGMENTS

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