CONCRETE SPALL DAMAGE OF UHPC SLABS UNDER CONTACT DETONATION- AN EXPERIMENTAL INVESTIGATION

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ABSTRACT

Concrete spallation is a typical brittle damage mode under close-in or contact explosions. Upon concrete spallation, a large number of fragments displace from the concrete surface with high speed and these fragments endanger the personnel and equipment shielded by the concrete member. It is therefore important to have a better understanding on the concrete spall phenomena. In the present study, contact explosion tests are carried out on concrete slabs. Four slabs including two made of normal strength concrete (NRC) and two ultra-high performance concrete (UHPC) slabs are tested. Different size of contact explosives are used in the tests. Test observations are compared with the predictions made by available empirical methods.

KEYWORDS

Concrete spallation, UHPC, NRC, Blast loads.

INTRODUCTION

Under blast loading environment, structures and their components can fail in multiple ways. For structural load-carrying members like columns and slabs, if damage is unavoidable, flexural damage is always the desired damage mode as such damage is most ductile and can absorb the largest amount of energy. However, in most blasting scenarios, brittle damage modes like shear damage or combined flexural and shear damage are commonly observed (Li and Hao 2013).

It is commonly acknowledged that the damage associated with blasts is dependent on the scaled distance. When an explosion is in the close proximity to or in contact with a concrete structure, on the surface facing the detonation, the concrete experiences compression and may fail under high compressive force and generate cratering. When the compressive shock wave propagates within the concrete and interacts with the free surface, it will be reflected and converts to a tensile wave. Under this condition, due to the low tensile resistance of concrete, crack will form if the net stress exceeds concrete dynamic tensile strength. Furthermore, if the trapped impulse is large enough to overcome the resistant forces such as the bond, shear around the periphery of the cracked portion, and the mechanical interlocking, the cracked off parts will displace from the backside of the structure at various velocities. Although spall damage is highly localized damage, loss of mass can influence structural loading capacity, and the out-bursting fragments can be dangerous to the personnel and valuable instruments shielded inside. Until now, although some work has been found in the literature, including both theoretical and numerical studies (Li and Hao 2014, Li and Hao 2014), more knowledge is required to understand the spall phenomenon and also propose effective means resisting such damage.

For structural protection purpose, besides concrete retrofitting technology (Wu et al. 2009, Ohkubo et al. 2008, Beppu et al. 2010), development of new concrete material with high blast and impact proof capacity has been gaining increasingly more momentum. Ultra-high performance concrete (UHPC) is a relatively new construction material with higher strength, ductility and toughness. The outstanding mechanical properties of UHPC stems not only from addition of high pozzolanic particles like silica fume but also from the reinforcement of small steel fibers in the concrete matrix. In a recent study, a novel UHPC material with nano-material addition was developed (Su et al. 2015, Su et al. 2015). The mixture of nano scale particle provides nano-size filling effect and better pozzolanic effect, both of which are beneficial to the concrete mechanical performance. Experimental study conducted on columns confirmed the superior blast resistance of this new material under free air explosions (Li et al. 2015).

To gain more information about this novel UHPC material, especially its performance under contact explosions, contact explosion tests were carried out on four slabs. In the four slabs, two slabs were constructed with conventional concrete and the other two slabs were made of ultra-high performance concrete with nano material addition. The spall areas and crater areas are quantitatively analyzed and compared. Feasibility of utilizing existing theoretical and empirical methods predicting concrete spallation under blast loads is discussed. Furthermore the fragments from each single test were collected for a sieve analysis, and the results are used for predicting fragments size distribution.

FIELD TESTS

Sample Preparation

In total four slabs including two normal strength concrete (NRC) slabs and two micro steel fiber reinforced ultra-high performance concrete (UHPC) slabs were tested in the program. As shown in Figure 1, the dimension of slabs was: 2000 mm long, 800 mm wide and 120 mm thick. Longitudinal reinforcement rebar number in the compressive and tensile surface was both 9. The diameters of the longitudinal reinforcing rebar and stirrup rebar were 12 mm and 8 mm, respectively. Both of these two reinforcements were designed with 360 MPa yielding strength.

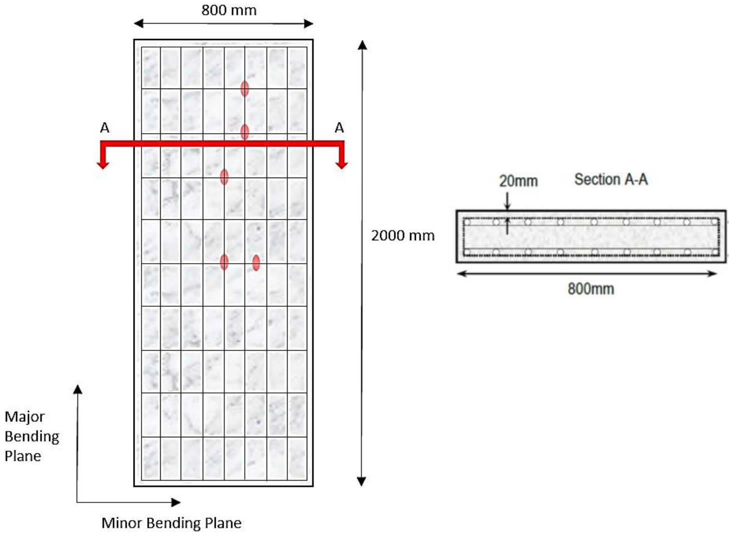

Figure 1 Slabs configuration

NRC slabs were constructed by concrete with unconfined compressive strength of 40 MPa. Ultra-high performance concrete with uniaxial compressive strength 145 MPa and tensile strength 22 MPa was used to build the UHPC slabs. For UHPC material, micro steel fibers with a length of 15 mm and diameter of 0.12 mm were mixed at a volume dosage of 2.5%, the tensile strength of the micro steel fiber was 4295 MPa.

During the sample preparation, strain gauges were attached to the reinforcement bars at different locations in each slab as indicated by red dots in Figure 1. These strain gauges were used to record the strain time history and the data obtained can be further used to derive the strain rate experienced by the slabs in each blast scenario.

Blast Scenarios

TNT explosives with different charge weights, i.e. 0.1 kg and 1 kg were used in the contact tests. These explosives were placed end-on the slabs. Based on preliminary investigations, it was determined that these two charge weights can induce different levels of spall damage in NRC slabs. For comparative purpose, the same explosive weights were used for UHPC slabs.

(a) 0.1 kg cylindrical TNT explosive (b) 1.0 kg cylindrical TNT explosive

Figure 2 Cylindrical TNT explosives

Blast Test Set Up and Results

In the tests, the slabs were placed on the steel support and bolt fixed at both ends of the longer span as shown in Figure 3. Explosives were placed end-on the slab center.

Figure 3 Test set-up

Figure 4 shows the NRC slab under 0.1 kg TNT contact explosion. Clear concrete crater and spall was noticed on the top and bottom side of the slab. The diameters of the concrete crater and spall were 20 cm and 33 cm, respectively. Neither perforation nor flexural damage was found at the slab mid-span.

Figure 4 NRC slab under 0.1 kg TNT contact explosion

Figure 5 shows the NRC slab under 1 kg TNT contact explosion. Severe blast load induced perforation failure in the slab. Fracture happened on the central stirrup reinforcement. It is also noted that significant concrete cracking occurred along the two unsupported directions near the slab boundary. As no obvious slab deformation was observed, these damages were believed also caused owing to stress wave propagation and reflection. Stress wave caused cracks along the two free ends because of the short propagation distance between the explosive and the free boundary, which generated large tensile stresses owing to wave reflection and hence scabbing failure of concrete.

Figure 5 NRC slab under 1 kg TNT contact explosion

Figure 6 depicts UHPC slab with 0.1 kg TNT contact detonation. It is noted no spall damage was observed on the bottom surface of the slab, and a small concrete crater with a diameter of 9 cm and a depth of 2.7 cm was found on the top surface. Comparing with NRC slab subjected to the same blast load, it is clear that UHPC material has much higher blast resistance capacity.

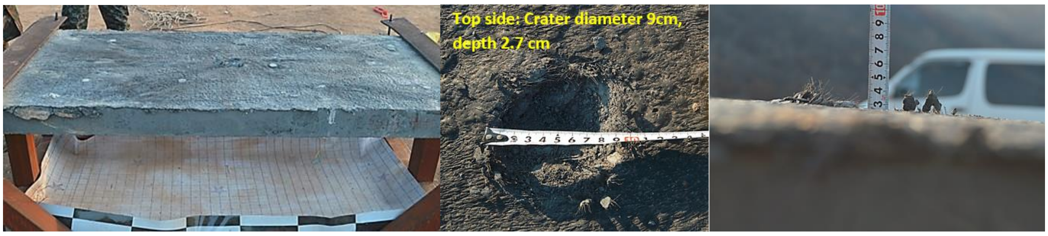

Figure 6 UHPC slab under 0.1 kg TNT contact explosion

The response of UHPC slab under 1 kg TNT contact explosion is shown in Figure 7. The slab was observed with spall and concrete crushing failure. Compared with NRC slab under the same blast load, the top surface crater diameter and the bottom surface spall diameter were reduced from 46 cm and 82 cm to 23 cm and 45 cm, respectively. Moreover, no side concrete scabbing damage as in NRC slab was observed, and no reinforcement fracture was observed either. These comparisons clearly demonstrate the better blast loading resistant capacity of UHPC than normal concrete.

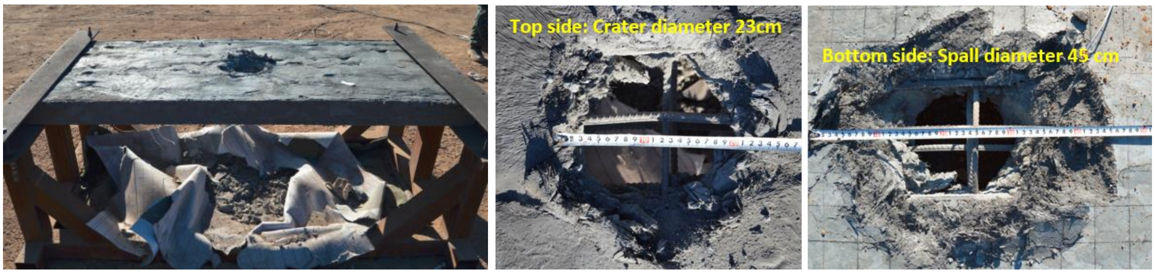

Figure 7 UHPC slab under 1 kg TNT contact explosion

DATA ANALYSIS

Comparison with Empirical Methods

McVay (1988) in his work compiled hundreds of contact or close-in blast test data and proposed empirical formulae to predict the local damage of concrete slabs subjected to bare explosive charges. As shown in Figure 8, *T* is the slab thickness, *R* is the standoff distance, and for contact explosion, *R* is taken as one-half of the outer diameter of the cylindrical explosive charge, *W* is the charge weight, *T*/*W*^1/3 and *R*/*W*^1/3 are scaled slab thickness and scaled standoff distance, respectively. After substituting these parameters into Figure 8, it is noted that the empirical evaluation can give good prediction of spall damage of the two tested NRC slabs under contact explosion. For UHPC slab under 0.1 kg TNT contact explosion, empirical predictions derived by McVay underestimate its spall resistance capacity and give wrong prediction. For UHPC slab under 1 kg TNT contact explosion, the observed spall damages, however, are substantially smaller, and these are not reflected from the empirical predictions. To more accurately quantify the damage severity, more studies, either blast testing or numerical simulations using verified numerical models, are deemed necessary.

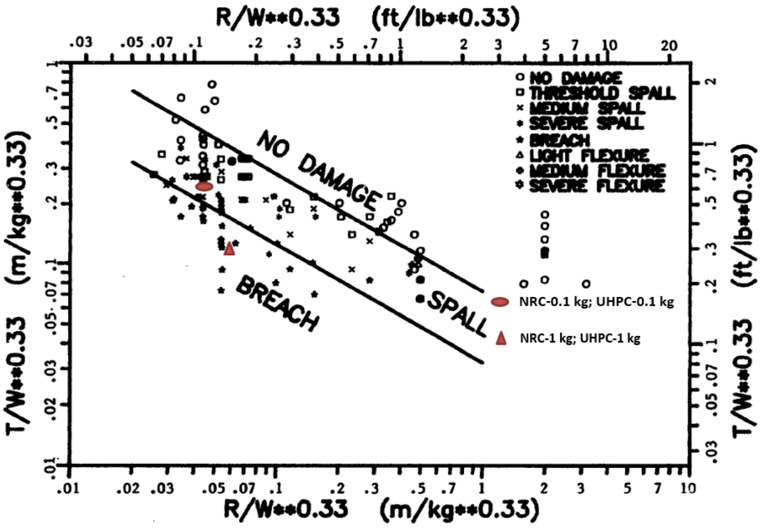

Figure 8 Prediction with empirical formulae

Fragments Size Distribution Analysis

In the current study, complete samples of fragments from both NRC slabs and UHPC slabs were collected and sieved. Six sieves with size range from 0.6 mm to 15 mm were used. The weights of fragments passing through each sieve had been measured. Typical sizes of the fragments passing through each sieve are shown in Figure 9.

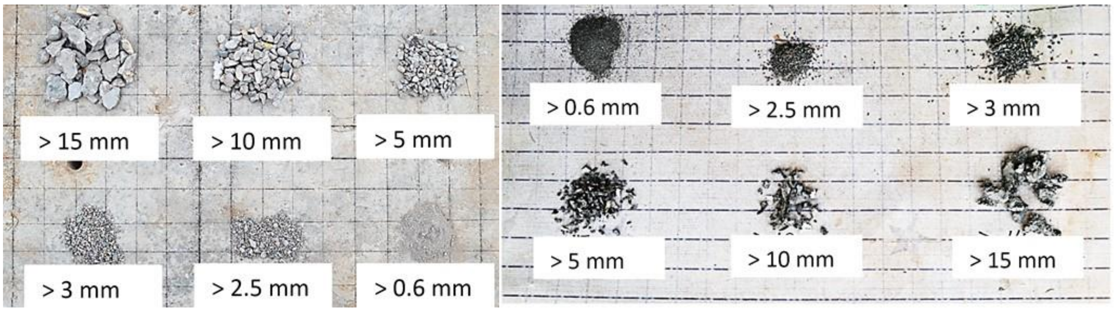

Figure 9 Typical fragments in the sieve analysis. Left) NRC; Right) UHPC.

A typical comparison between UHPC slab and NRC slab is made and shown in Figure 10. Both the slabs were subjected to 1 kg TNT contact explosion. As depicted in the figure, under the same blast loading condition, NRC slab generates more fragments than UHPC slab and the fragments weights passing through every sieve level are all higher than UHPC slab.

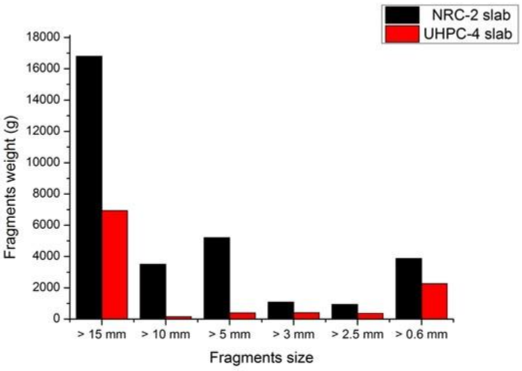

Figure 10 Samples of fragments with different sizes

To describe the fragments distribution of NRC slab, Weibull distribution is adopted, as depicted in Figure 11, Weibull distribution with modulus of 1.63 and 0.67 can well represent the size distribution of fragments from NRC slab under 0.1 kg TNT and NRC slab under 1 kg TNT. Residual sum of squares (R^2 values) are 0.976 and 0.95 for NRC-1 and NRC-2 slabs, respectively.

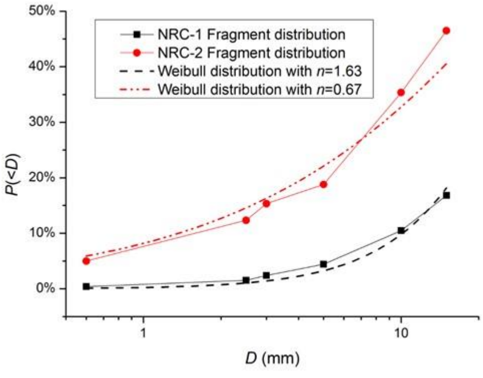

Figure 11 Weibull distribution for fragments from NRC specimens

Weibull distribution was also adopted to describe the fragment size distribution of UHPC slab, however, it was found the fitting contains large deviations, and it was deemed inaccurate to used Weibull distribution for describing the fragments from UHPC. After several trials, Log-normal distribution was used. As depicted in Figure 12, size distribution of fragments from UHPC slabs fits well the Log-normal distribution. Location parameters and scale parameters are plotted for each fitting. Residual sum of squares (R^2 values) is 0.89 for UHPC slab under 1 kg TNT contact explosion.

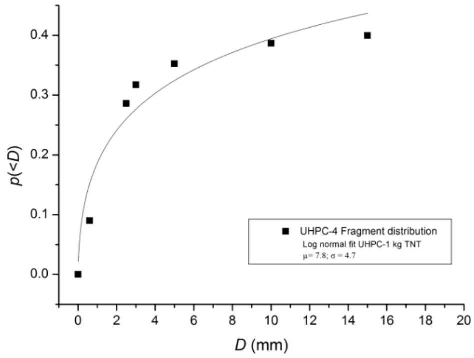

Figure 18 Log-normal distribution for fragments from UHPC specimen

CONCLUSIONS

In the present study, concrete slabs made with normal strength concrete material and ultra-high performance concrete material are tested under contact explosions. Spallation and cratering are observed and investigated quantitatively. UHPC slabs displayed significantly improved blast resistant capacity than NRC slabs. Empirical methods developed based on large number of tests are adopted to evaluate the performance of slabs in the current study and it is noted these empirical methods can give good predictions on concrete spallation of NRC slabs but can significantly underestimate the spall resistance of UHPC slabs. Size distributions of fragments are also investigated and it is noted that Weibull distribution can be used to represent the fragment sizes from NRC slabs while fragments from UHPC slabs can be fitted to Log-normal distributions.

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