Experimental investigation of ultra-high performance concrete slabs under contact explosions

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Abstract

Unlike ductile behaviour under static loads, a reinforced concrete structure can respond in a brittle manner with highly localized damage like concrete spalling, cratering and reinforcement rupturing under close-in or contact explosions. High speed fragmentation resulting from concrete spall may cause severe casualties and injuries. It is therefore important to have a better understanding of the concrete spall phenomena and fragments distribution. In the present study, contact explosion tests were carried out on concrete slabs to observe the concrete crater and spall damage. Seven slabs including two control specimens made of normal strength concrete (NRC) and five ultra-high performance concrete (UHPC) slabs are tested. The superior blast resistance capacity of UHPC slabs is verified through comparison against NRC slabs. The influence of longitudinal reinforcement spacing and slab depth on the spall resistance of UHPC slabs is investigated. Predictions through available empirical methods are made and compared

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with the test observations. The accuracy of these empirical methods is discussed. All fragments resulting from the contact blast tests are collected and analysed through sieve analysis. It is found that Weibull distribution can be used to model the fragments size distribution of NRC slabs while Log-normal distribution better models the fragments size distribution of UHPC slabs.

1. Introduction

In modern society, reinforced concrete (RC) is one of the most commonly used construction materials. During the service life of a RC structure, accidental or intentional explosion is a threat with relatively low probability but disastrous consequences. Blast loads with large amplitude and short duration impart tremendous amount of energy to the structure and excite global and local response associated with damages including immediate effects like failure of structural members and consecutive hazards like structural progressive collapse. This threat has drawn renewed interests since the rising of terrorism activities in recent decades.

Under blast loading conditions, 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 a largest amount of blast energy. However, in most blasting scenarios, brittle damage modes like shear damage or combined flexural and shear damage are commonly observed [1-3]. It is assumed that a large loading with short duration is more likely to cause a shear failure mode while a relatively small amplitude load with longer duration will result in flexural failure; this phenomenon is well understood, and some researches have been carried out to define the structural and blast loading conditions for causing the respective damage modes [4, 5]. For high rise buildings in modern city, failure of one or several key load-carrying members may trigger the disproportionate progressive collapse with catastrophic casualties and property loss [6, 7]. The failure mechanism behind the progressive collapse phenomena has been under an ongoing discussion [8, 9].

When an explosion is in 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 in the structure 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, cracks 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 some velocity [10].

Unlike other damage modes like flexural or shear damage, concrete spall damage is usually not considered in conventional protective designs of concrete structures. However, in some extreme cases, localized damage of concrete crushing and spalling can result in complete loss of structural loading capacity which may promote the progressive collapse. Moreover the high-speed debris accompanying the concrete spall could cause unexpected casualties and property loss.

Researches on concrete spallation under blast environment have been carried out in the past several decades. Back in the 1970s, Kot et al. [11, 12] proposed theoretical prediction methods for spall damage of concrete wall, however these methods were limited to light and moderate bomb threats and were based on several simplified assumptions which compromised the calculation accuracy. Later in 1980s, a series of concrete spall tests from different sources were summarized by McVay [13], and parameters affecting concrete spall were investigated and these parameters included scaled standoff distance, explosive charge weight, wall thickness, concrete strength, concrete additives and reinforcement spacing. Based on the test results, an empirical approach for determining if and where a stress wave would cause the concrete to crack in tension was derived. In this method, the changes in the stress caused by stress waves travelling at different velocities, wave attenuation, and dispersion were neglected. The only change in the stress wave propagation that was taken into consideration was wave divergence. Recently, Wang et al. [14] carried out close-in explosion tests on square reinforced concrete slabs and spall damage at different severity was observed, and the experimental results were used to verify their numerical model. Based on a large database of empirical slab/wall tests, AFRL-MN-EG-TR-1998-7032 *Concrete Hard Target Spall and Breach Model* [15] details the development of a spall/breaching algorithm for RC slabs and walls.

Different from a slab or wall in which only the reflection of the blast induced stress wave from the back surface needs be considered, a stress wave in a column generated from a close-in detonation can be reflected from both the back and side faces which makes it a 3D shock propagation problem. In NCHRP Report 645 [16], test results from eleven concrete columns were compiled and used to evaluate the performance of several design parameters and to determine the capacity and failure limit states of concrete highway bridge columns. Wu et al. [17] carried out contact explosion test on steel-concrete composite column and developed numerical model reproducing the spall damage. Based on extensive parametric studies, they [18] investigated the relationship between residual axial capacity and structural and loading parameters such as material strength, column detail and blast conditions. In a recent study, Li and Hao [10] developed three-dimensional numerical models to predict the concrete column spalling under blast loads. Intensive numerical simulations were carried out to investigate the influences of the column dimensions and reinforcement mesh on concrete spall damage.

Recent decades have witnessed an increasing demand of structural protection under explosive loads, and tremendous efforts have been dedicated to the development of new concrete material or concrete retrofitting technology. Riisgaard et al. [19] introduced an efficient method for implementing high fractions of polymer shock reinforcement into a compact reinforced composite, and a significant improved blast resistance was observed. Wu et al. [20] conducted air blast tests on two RC specimens in a blast chamber, it was observed that RC specimen retrofitted with 6 near surface mounted (NSM) carbon fibre reinforced polymer (CFRP) plates on both the top and bottom faces outperformed the conventional reinforced RC specimen. Ohtsu et al. [21] experimentally and analytically investigated the dynamic failure of fibre-reinforced concrete (FRC) slabs, and it was observed that the averaged diameters and the volumes of the spall failure remarkably decreased with the increase in the flexural toughness of FRC concrete. Ohkubo et al. [22] conducted contact-explosion tests on concrete plates reinforced by carbon or aramid fibre sheet, and it was noted that local spall damage had been significantly reduced with fibre sheet reinforcement, and fibre sheets also had prevented concrete plates from fragmentation. Recently Foglar and Kovar [23] plotted their experimental results on these spall and breach prediction curves, and they concluded that the observed spall damages in RC specimens agree with the spall and breach prediction curves according to UFC 3-340-02 [24]. However, they also noted the spall and breach prediction curves according to UFC 3-340-02 are not suitable for predicting the spall damage in fibre reinforced concrete. Moreover, the spall damage severity is not clearly defined in UFC guideline. Therefore it can only predict the occurrence of spall damage in the wall slab under a blast load, but cannot quantify the damage levels.

Ultra-high performance concrete (UHPC) is a relatively new construction material with higher strength, deformation capacity 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 fibres in the concrete matrix. Previous experimental study conducted by Wu et al. [25] confirmed the superior blast resistance of UHPC.

In the present study, to further investigate the concrete spall damage, especially the spall phenomena of ultra-high performance concrete, contact explosion tests were carried out on seven slabs. In the seven slabs, two slabs were constructed with conventional concrete and the other five slabs were made of ultra-high performance concrete with different slab depths and longitudinal reinforcement spacing. The spall areas and crater areas are quantitatively analysed 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.

2. Contact-explosion tests on concrete plates

2.1 Explosive charges

TNT explosives with a Heat of Detonation density of 4521 kJ/kg and a material density of 1.65 g/cm^3 were used in the tests. Two cylindrical charges with a mass of 0.1 kg and 1.0 kg were placed on the top centre of the slabs. Detonator was used to electrically activate the explosive. As shown in Figure 1a, the electrical detonator was bonded together with the TNT through adhesive bandage. The explosive in the detonator is Hexogen (RDX) with TNT equivalence of 1.58. One detonator contains 0.4-0.6 g RDX with NEQ (net explosive quantity) less than 1 g TNT per detonator. Comparing with the explosive charge weights used in the current tests (100 g and 1000 g TNT), the effects from the detonator is deemed not prominent and can be neglected.

Figure 1 illustrates the dimensions of the TNT explosives used in the tests.

2.2 Sample preparation

In total seven slabs including two normal strength concrete (NRC) slabs and five micro steel fibre reinforced ultra-high performance concrete (UHPC) slabs were tested. As shown in Figure 2, the dimension of slabs is: 2000 mm long, 800 mm wide and 100-150 mm thick. Slabs of different depths were designed to explore the depth influence on the spall damage. One of the five UHPC slabs was reinforced by less longitudinal reinforcement bars in which the rebar number in the compressive and tensile surface decreased from 9 each to 5. This modification was made to investigate the influence of longitudinal reinforcement spacing on slab response. The diameters of the longitudinal reinforcing rebar and stirrup rebar are 12 mm and 8 mm, respectively. Both of these two reinforcements have 360 MPa yielding strength.

Two control NRC slabs were constructed by concrete with unconfined compressive strength of 40 MPa. In UHPC material, micro steel fibres 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 fibre is 4295 MPa. Ultra-high performance fibre reinforced concrete with uniaxial compressive strength 145 MPa and tensile strength 22 MPa was used to build the UHPC slabs. Material composition of the current UHPC material is given in Table 1. Typical stress-strain relationship obtained from uniaxial compression test and force-displacement relationship obtained from four points bending test are shown in Figure 3.

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 2. The positions where the strain gauges located were carefully grinded using electrical grinder, and later mopped using liquid acetone. These procedures were carried out to guarantee the contact between the strain gauge and reinforcing bar. 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.

2.3 Experimental setup

As depicted in Figure 4, the slab was firstly placed on the steel rig using a crane, then both ends of the slab were bolt fixed with the angle steel cleats. In the previous study carried out by Beppu et al. [26] and Ohkubo et al. [22], a simply supported boundary was adopted to study the contact explosion resistance of concrete slab reinforced with FRP laminates. It is deemed that contact explosion induces highly localized response and damage which is independent of the boundary condition.

2.4 Test program

In total seven shots were carried out in the current study. In test events 1 and 2, two identical NRC slabs reinforced by 9 Ø 12 mm longitudinal rebars and 11 Ø 8 @ 200 mm stirrup rebars (as shown in Figure 2) were subjected to contact explosions of cylindrical explosives of 0.1 kg and 1 kg, respectively to obtain different level of damages. In blast events 3 and 4, two UHPC slabs with the same reinforcements as the two reference NRC slabs were also subjected to the same blast scenarios in order to compare the blast resistances of NRC slabs with those of UHPC slabs. The influence of the slab depth was investigated in blast events 4-6, in which three UHPC slabs with different thickness but the same reinforcements were subjected to 1 kg TNT contact explosion. To investigate the reinforcement mesh confinement effect on spalling damage, UHPC-7 slab in blast event 7 was made the same as UHPC-4 but with less number of the longitudinal reinforcements in both the compressive and tensile face, i.e., the number of longitudinal reinforcement bars is reduced to 5 from 9. The slab was also tested with 1.0 kg contact explosion. Comparison was made between UHPC-7 and UHPC-4 to investigate the influence of reinforcement mesh confinement effect on concrete crushing and spalling damages.

The test program is summarized in Table 2.

2.4 Results and discussion

NRC-1 is a NRC slab with conventional steel reinforcement. 0.1 kg TNT was placed at the centre of slab surface as shown in Figure 5. After explosion, clear spall damage and concrete crater were observed on the bottom and top surface 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.

In blast event 2, normal strength concrete slab NRC-2 was subjected to 1 kg TNT placing also at the centre of slab surface. As can be noticed from Figure 6, 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 cracking of concrete.

UHPC-3 was an UHPC slab with the same steel reinforcement as the two NPC slabs. 0.1 kg TNT was placed at the centre of slab surface and detonated. As shown in Figure 7, after explosion, 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-1 slab which has the same steel reinforcement and subjected to the same blast load, it is clear that UHPC material has much higher blast resistance capacity.

UHPC-4 was tested with a 1 kg TNT detonated at its central surface. The slab was observed with spall and concrete crushing failure. Compared with NRC-2 slab under the same blast load, it was noted that UHPC-4 slab has better blast resistance capacity. 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 cracking as in NRC-2 was observed, and no reinforcement fracture was observed either. These comparisons clearly demonstrate the better blast loading resistance capacity of UHPC than normal concrete.

UHPC-5 was an UHPC slab with a depth of 100 mm. The reinforcements in the slab were kept the same as in the previous slabs. As shown in Figure 9, subjected to 1 kg contact explosion, the slab suffered perforation failure. The stirrup and longitudinal reinforcements at mid span were also fractured. Slight side concrete cracking which was similar to NRC-2 slab under 1 kg TNT was also noticed. Comparing with UHPC-4, the crater diameter and spall diameter both increased, indicating slab depth played a positive role in resisting the contact explosion induced damage, as expected.

UHPC-6 was an UHPC slab with an increased depth of 150 mm subjected to 1 kg TNT contact explosion. Similar to the previous two trials, perforation failure was again observed. However the damage severity was reduced. Comparing with UHPC-5, the top surface crater diameter and bottom surface spall diameter dropped from 27 cm and 47 cm to 22 cm and 41 cm, respectively. Only one longitudinal rebar at the bottom side was fractured. No side concrete cracking was observed in this thicker slab.

As mentioned above, the UHPC-7 slab was made with less number of reinforcements. It was also subjected to the same 1 kg TNT explosion. After the test, severe perforation failure was observed. Comparing with UHPC-4, the top surface crater diameter and bottom surface spall diameter increased from 23 cm and 45 cm to 25 cm and 48 cm, respectively. Longitudinal reinforcement at mid span experienced fracture failure which was not observed in UHPC-4. Generally speaking, the reinforcement mesh contributed to the resistance against the contact blast loads. However, in this particular case, the crater and spalling damage dimensions only slightly increased even the number of reinforcement bars were almost reduced to half as compared to UHPC-4, indicating the reinforcement confinement effect is not prominent. This observation nonetheless is based on only two types of reinforcement meshes. It is believed that if denser reinforcement mesh was used, its confinement effect on concrete would have been more prominent. More studies are deemed necessary to confirm and possibly quantify the reinforcement confinement effects on concrete materials subjected to blast loadings.

As observed from the above tests results, the failure modes of slabs under contact explosion can be classified into three categories, i.e. “crater only”, “crater and spall”, and “perforation”. Table 3 summarizes the test results.

Figure 12 shows the recorded strain time histories on refinrcement bars. Locations of the five strain gauges are depicted in Figure 2. It should be noted that no meaningful strain data was successfully recorded in UHPC-3 and UHPC-5 owing to malfunction of the sensor and/or equipment during these two tests. The strain time histories were recorded by resistance strain gauges provided by Jin-Li Sensor Company from China. The effective length of the gauge is 5 mm. The strain gauges were placed along the longitudinal direction of the rebars. Testing circuit was quarter-bridge strain gauge circuit with 2 V powering voltage and 100 amplification coefficient. The data was collected by high speed data collecting system TST5205 provided by Chengdu-Test company. The sampling rate was set at 1 million Hertz in all the recordings.

Under contact explosion, the intense blast load is highly localized with extremely short duration. During the blast loading phase, the global structural response (shear and bending) is small because the time is too short for global structural response to develop. During the loading phase, explosion generates a stress wave propagating in the structure, which may cause concrete crushing and spalling damage, as observed in the tests presented in this paper. After the action of blast loads, the structure continues to deform because significant explosion energy has been imparted into the structure and the global structural response modes and damage will be induced.

The measured strains as shown in Figure 12 are associated with stress wave propagation in the initial stage and followed by global structural responses with lower frequency contents. Stress wave propagation results in rapid strain oscillations owing to wave reflection and refraction. The measured strain associated to stress wave propagation also decays quickly with respect to their distance to explosion. Taking NRC-1 as an example, the measured strain at gauge 1, which is buried directly underneath explosion, is larger than those at gauge 2 and 3. Moreover, the wave arrival time at gauge 1 is slightly earlier than that of gauge 2 and 3, which were placed further away from the explosion. These observations confirm the measured strains are associated with stress wave propagation.

The strain rates in all the tested slabs are derived from the recorded strain time histories. In NRC-1, the explosive weight was 0.1 kg and the maximum strain rate reached 22000 s-1. When the explosive weight increased to 1.0 kg in NRC-2 slab, the maximum strain rate increased to 68000 s-1. For the UHPC slabs under 1 kg TNT contact explosion, strain rates around 50000 s-1 were noticed. The strain rate data reported in the present paper is ultra-high and not seen or reported in previous studies. These ultra-high strain rate values were caused by shock wave propagation in the specimen. As shown in Figure 12, in the global structure response stage, the strain rate is substantially lower.

3. Failure predictions using existing methods

3.1 Theoretical prediction methods

Theoretical predictions on concrete spall damage is not straightforward because there are many unknown parameters and uncertainties such as the influence of charge geometry on blast loads, stress wave propagation and attenuation rate in concrete, wave dispersion effects, dynamic compressive strength and tensile strength under high and varying strain rates. As a result, the existing theoretical methods have to be used with some assumptions and simplifications [11, 12]. It was reported [27] that the theoretical methods do not necessarily give accurate predictions to concrete damage under close-in blast loads.

3.2 Empirical prediction methods

It is commonly acknowledged that empirical methods which are primarily based on large number of test trials are expensive to develop. Their application scopes are limited to situations similar to the data upon which the empirical methods were based.

In the widely used design guideline UFC 3-340-02 [24], prediction of concrete spall under blast loading condition is discussed and spall test results have been compiled and plotted. Threshold spall and breach curves are plotted as approximate upper bounds to the spall and breach data points, and these curves may be used in practical analysis and design to approximately predict the concrete spall damage. However, it is noticed the configurations in all these tests are different from the current study and thus the empirical damage curves are not applicable for predicting the slab response in the present study.

After reviewing test data from 334 field blast tests, McVay [13] compiled the test data and proposed empirical formulae to predict the local damage of concrete slabs subjected to bare explosive charges. As shown in Figure 13, *T* is the slab thickness, *R* is the standoff distance in unit of meter, and for contact explosion, *R* is taken as one-half of the outer diameter of the cylindrical explosive charge, *W* is the charge weight, $T/W^{\wedge 1/3}$ and $R/W^{\wedge 1/3}$ are scaled slab thickness and scaled standoff distance, respectively. In McVay's method, the unit used is *kg* and *m*. Table 4 summarizes the corresponding parameters obtained from the current study. After substituting these parameters into Figure 13, 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 3 which has the same scaled slab thickness and scaled standoff distance as NRC-1, empirical predictions derived by McVay underestimate its spall resistance capacity and give inaccurate prediction. For UHPC slabs 4 and 7, they have the same scaled slab thickness and scaled standoff distance as NRC-2, the observed spall damages, however, are substantially smaller, and these are not reflected from the empirical predictions. For UHPC 5 and 6 with different slab depths as compared with NRC-2, empirical methods give good predictions to the slabs perforation. As indicated in Figure 13, although these testing data were obtained from NRC slabs, they give good predictions of UHPC spall and breach damage. This is because the boundary lines in the graph only give a very broad range of these damages, but not detailed damage severities. As indicated in Table 3, although both the NRC and UHPC slabs could both experience spall and perforation damage, the damaged area of UHPC slab is always smaller than that of NRC slab because of the higher UHPC strength than NRC. To more accurately quantify the damage severity, more studies, either blast testing or numerical simulations using verified numerical models, are deemed necessary.

Based on McVay's formulae and their own tests results, Morishita et al. [28] proposed new formulae to predict the contact explosion induced concrete slab damage as given below:

Limit of crater: $T/W^{1/3} > 3.6$ (1)

Limit of crater and spall: $2.0 \leq T/W^{1/3} \leq 3.6$ (2)

Limit of perforation: $T/W^{1/3} \leq 2.0$ (3)

The values of $T/W^{1/3}$ based on Morishita's method are given in Table 4 as well, the unit used in Morishita's formulae given above is $cm/g^{1/3}$. Applying the above formulae to the present study, it is again noticed that although the NRC slabs damage modes are well predicted, the performance of UHPC slabs like UHPC-3 are underestimated.

These comparisons demonstrate that the existing empirical methods, which were derived based on testing data on NRC slabs, can underestimate the performance of UHPC slab subjected to contact explosions. It should also be noted that these empirical predictions do not consider the influences of reinforcements, which certainly affect the spall damage of RC slabs. In future study, numerical tool will be adopted to investigate the UHPC slabs under contact explosions. The current test results will be used to calibrate the numerical model, and the verified numerical model will be used to conduct extensive contact explosion simulations.

4. Fragments distribution

Safety concern is always related with accidental explosions. The injuries under blast loading environment can be divided into five mechanistic types [29], in which secondary injuries induced by fragments under blast environment are of particular concerns.

As well discussed in the previous studies, contact explosion on brittle material like concrete can generate large number of fragments displacing from the material surface at high velocities and these fragments are responsible for the human casualties and economic loss in those blast scenarios. It is thus important to investigate the fragment velocity, launching distance and size distribution for concrete material. Unfortunately, the current test data only allow examining the fragment size distributions. Until now, although some work has been carried out identifying the fragments distribution of normal strength concrete material, no discussion or effort had been made to understand the size distribution of fragments from UHPC material under blast loading.

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 as shown in Figure 14.

Fragment samples of NRC and UHPC passing through each sieve are shown in Figure 15. It is observed that fragments from NRC slabs have relatively more regular shapes while the shapes of fragments from UHPC slab are more irregular due to the existence of the micro fibre reinforcement.

A typical comparison between UHPC-4 slab and NRC-2 slab is made and shown in Figure 16. 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.

Under impact or blast loading condition, size distribution of fragments from brittle materials like rock and concrete is usually described by Weibull distribution which was suggested by Grady and Kipp [30]. Weibull distribution is suitable for handling characteristics of the cumulative distribution of fragment fractions. The cumulative density function is described by

$$P(<D) = 1\text{-exp}\ [-(D/D^*)^n] \tag{4}$$

where $P(<D)$ is the cumulative weight percentage of all fragments with diameters smaller than D. The parameter D^* is defined as the scale parameter or characteristic diameter which is referred to as the maximum mean diameter of the fragment, and n is a shape parameter which is referred to as the Weibull modulus.

Figure 17 shows the standard size distribution of fragments from all the tested slabs except UHPC-3 and UHPC-5. Blast load only generated a small crater in UHPC-3 and no perforation. Therefore only very few fragments underneath the slab were collected as shown in Figure 7. As shown in Figure 9, blast flame caused damage of the rug placed underneath the slab for fragments collection. This made the collection of fragments from UHPC-5 difficult. Therefore fragments from UHPC-3 and UHPC-5 are not included in the analyses here. It is obvious in Figure 17 that the fragment size distributions from UHPC slabs differ from those from the two NRC slabs, indicating Weibull distribution is not a representative distribution type of the fragment sizes generated from UHPC slabs due to contact explosions.

Data from limited experimental observations suggested that the distribution parameter i.e. n in Weibull distribution varies significantly. Direct impact experiments conducted by Costin and Grady [31] showed n with a range between 2 and 3. O’keefe et al. [32] summarized fragment size distributions from nuclear and chemical explosions, and a value of n between 0.4-0.55 was noticed.

For the fragments generated from the contact explosion tests in the current study, as depicted in Figure 18, Weibull distribution with modulus of 1.63 and 0.67 can well represent the size distribution of fragments from NRC-1 slab and NRC-2 slab. Residual sum of squares (R^2 values) are 0.976 and 0.95 for NRC-1 and NRC-2 slabs, respectively.

After careful examination, it is found that Log-normal distribution can well represent the size distributions of fragments from UHPC slabs.

The cumulative distribution function is

$$P(<\mathrm{D}) = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\ln x - \mu}{\sigma\sqrt{2}}\right)\right] = \frac{1}{2}\mathrm{erfc}\left(-\frac{\ln x - \mu}{\sigma\sqrt{2}}\right) = \phi(\frac{\ln x - \mu}{\sigma}) \tag{5}$$

where erf is an error function and erfc is the complementary error function, Φ is the cumulative distribution function of the standard normal distribution. μ is the location parameter and σ is the scale parameter.

As depicted in Figure 19, 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) are 0.89, 0.94 and 0.93 for UHPC-4, UHPC-6 and UHPC-7 slabs, respectively.

Conclusions

Concrete spall and crush are important damage modes under blast loading condition, and these phenomena become prominent when the explosives are detonated in close proximity to or in contact with concrete structures. Concrete spall and crater cause severe loading capacity loss and fragments generated with spallation can eject from concrete surface with high velocity which will bring further threat to personnel and instruments shielded by the concrete structures. 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 resistance 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 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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