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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 localised 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 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 responses 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 studies 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

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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, localised damage of concrete crushing and spalling can result in complete loss of structural loading capacity that 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 that compromised the calculation accuracy. Later in 1980s, a series of concrete spall tests from different sources were summarised 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 that 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 that 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 utilising 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 Fig. 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.

Fig. 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 Fig. 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