Experimental study on steel wire mesh reinforced concrete slabs against close-in detonations

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ABSTRACT: High performance and aesthetic appearance of a structural design is the motivation behind high strength concrete development. As a notable representative, high performance steel fibre reinforced concrete is characterized by a much higher compressive and tensile strength compared with conventional concrete, the low water-cement ratio effectively warrants a low porosity microstructure which in turn enhances its durability. In recent years, with threat from terrorism activities, protection of structures against malicious loads such like explosive detonation is attracting more public concern. Due to its excellent mechanical performance and energy absorption capacity, high performance steel fibre reinforced concrete can be used in the construction of key load-carrying components to mitigate the blast induced structural damage. In current study, slabs made of high strength concrete material are field tested under close-in detonations, different reinforcement schemes including steel fibre reinforcement and steel wire mesh reinforcement are used in the slab design. Comparisons are made with normal strength concrete slab. Brief discussion on the different slab design against blast loads are presented.

1 INTRODUCTION

Protection of civilian structures against blast loads is attracting increasingly more public attention over the past several decades. The need of useful and effective guidance for this topic boosts many researches around the world (e.g., US_Department_of_Defense 2005, US_Department_of_Defense 2008, Li and Hao 2014a). Due to the uncertainty of the blast loading scenario and the high cost of increased level of damage protection, structural protection against blast loads lacks an absolute or clear concept. For existing structures, indirect methods such as perimeter protection (traffic control and anti-vehicle barriers) can effectively reduce the threat from Vehicle Borne Improvised Explosive Device (VBIED). However, in the meantime, an adequate evaluation of the structural vulnerability is still necessary and should be carefully carried out. Analysis and design of structures against blast loads had been extensively studied in previous researches (e.g., Li and Hao 2012, Li and Hao 2013).

Over the past several decades, structural retrofitting techniques are under fast development. Various retrofitting materials including fibre reinforced polymer (FRP), aluminum foam and steel etc. have been both analytically and experimental investigated. Morrill et al. (2004) carried out full-scale blast tests to investigate the performance of FRP composites retrofitted concrete columns and walls. Ohkubo et al. (2008) evaluated the effectiveness of fibre sheet reinforcement on the explosive resistant performance of concrete plate. Wu et al. (2007) investigated blast resistance of RC slabs with near surface mounted (NSM) CFRP. Fujikura et al. (2008) studied seismically designed bridge column with steel jacket under blast loads.

On the other hand, thanks to the rigorous progress in material science, steady improvements have been made to the construction material. Through changing the concrete mix with lower water/binder ratio and inclusion of high pozzolanic material such as silica fume, it is now easy to achieve concrete with high compressive strength. However, with the increase of compressive strength, concrete tends to become more brittle, and this nature would cause structural brittle failure which is less energy absorbing under dynamic loads. Efforts have been devoted to improving concrete tensile performance. In previous experimental study, a small amount of micro steel fibre addition has been proved to be effective providing micro confinement and bridging the cracks so as to increase the concrete tensile capacity e.g., (Li et al. 2015a, Li et al. 2015b, and Li et al. 2015c). Beside fibrous material mixing, different reinforcement schemes were also widely investigated, for example, steel wire mesh has been used to embed in concrete members for strengthening and rehabilitating purpose. Comparing with conventional reinforcement, steel wire mesh can be easily adapted into different structural shapes and maximise the workability of concrete. Static experimental study reveals that mortar reinforced with steel meshes can satisfy the ultimate strength requirement. Under dynamic loading condition, concrete with steel wire mesh reinforcement developed localized membrane effect and showed good scabbing resistance. The concrete scabbing and spallation is primarily induced by stress wave propagation, as indicated in previous study by Li and Hao (2014b), close-spaced reinforcement can effectively mitigated blast wave leading to less material damage. According to recent test results by Ibrahim (2011), reinforcement from steel wire mesh can alter the possible failure mode from punching to flexure which significantly increases the energy absorption capacity.

In this piece of research, recent field blast tests results on reinforced concrete slabs are compiled and discussed. Conventional reinforced concrete slab (control sample), steel fibre reinforced concrete slab, and hybrid steel fibre-steel wire mesh reinforced concrete slab are studied under close-in free air detonations.

2 MATERIAL AND SLAB DESIGN

In the present study, high performance steel fibre reinforced concrete is used in the slab construction. 2.5 Vol-% steel fibres are mixed into the concrete matrix to provide enhanced crack confinement and also material ductility. Fibre material in the present study has a length of 3 mm and diameter of 0.12 mm, and fibre tensile strength is 4200 MPa.

Figure 1a shows the compressive stress strain curves for the concrete used in the slab design. These curves are averaged from a series of uniaxial compression tests on 100 mm cubic samples. Two curves representing the concrete with and without fibre reinforcement are shown in this plot. An improved compressive strength of 83 MPa is achieved with fibre addition (versus 57 MPa obtained from sample without fibre addition) and the material ductility is also significantly enhanced. It is also noted from the flexural tensile tests that (see Figure 1b), flexural tensile strength of the concrete composite with fibre addition reached 14 MPa which is much higher than conventional non-fibre reinforced concrete of which the flexural strength is around 2.5 MPa.

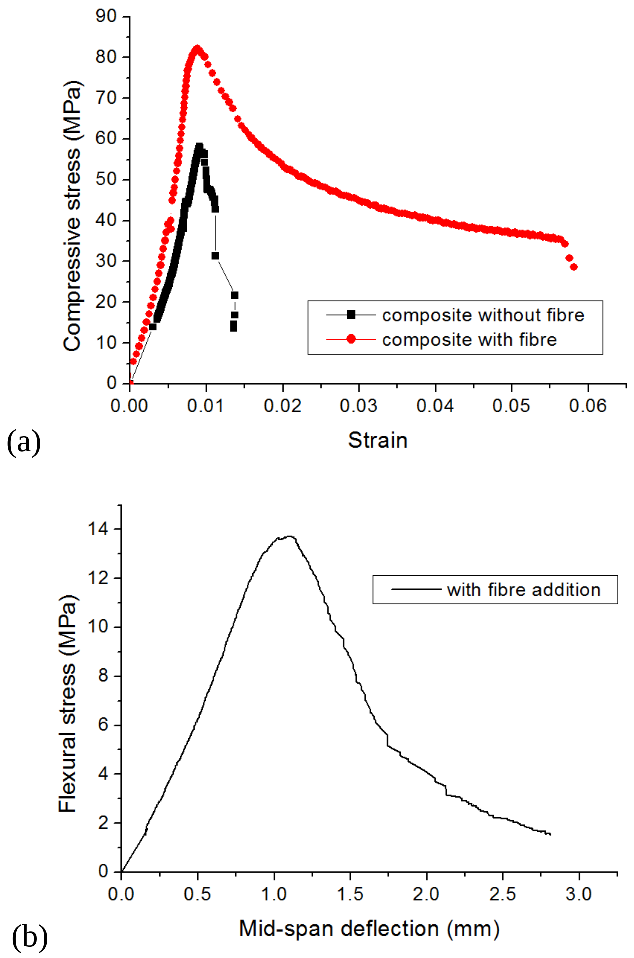

Figure 1. Static performance of concrete composite with fibre addition

The slab dimension is depicted in Figure 2, the dimensions of the slabs are: 2000 mm long, 800 mm wide and 120 mm thick. The diameters of the longitudinal reinforcing rebar and stirrup rebar are 12 mm and 10 mm, respectively. The yielding strengths for the longitudinal rebar at the compressive and tensile surfaces are 270 MPa and 960 MPa, respectively. The stirrup reinforcement has a yielding strength of 270 MPa.

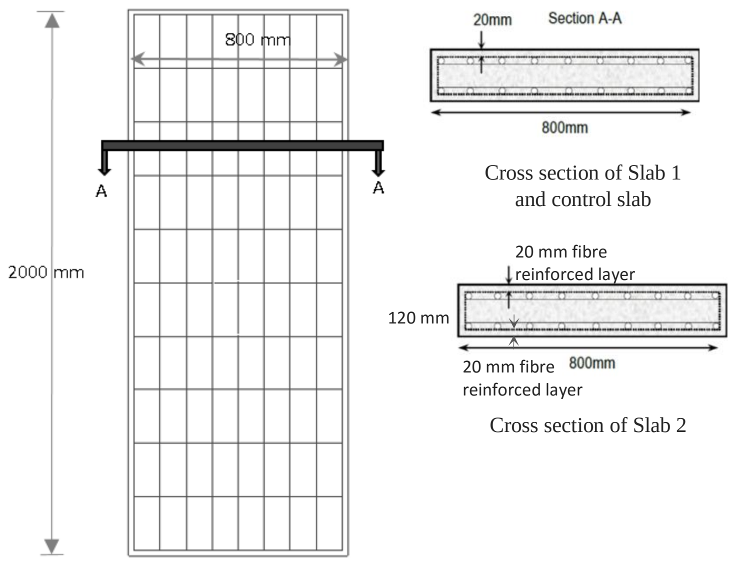

Figure 2. Slab dimension and reinforcement

As shown in Table 1, in the current test matrix, three slabs are tested. Besides control sample made of normal strength concrete (*fc* = 40 MPa) with conventional reinforcement, high performance steel fibre reinforced concrete slab (Slab 1) and hybrid steel fibre-steel wire mesh reinforced concrete slab (Slab 2) are considered. The difference between Slab 1 and 2 are the slab core layer reinforcement. In Slab 1, 2.5 Vol-% steel fibre reinforcement is used in all the layers of the slab, and in Slab 2, steel fibre reinforcement is used in the cover layer only while 4 Vol-% steel wire mesh is used in the core layer (see Figure 2).

Table 1. Field blast test matrix

Slab No.	Type	Explosive weight	Standoff distance
Control sample	Normal strength concrete	8 kg	1.5 m
Slab 1	High performance steel fibre reinforced concrete	12 kg	1.5 m
Slab 2	Steel wire mesh reinforced concrete	12 kg	1.5 m

As shown in Figure 3, the steel wire meshes used in Slab 2 have a diameter of 1 mm and space of 6.35 mm, the wire mesh is made of 304 stainless steel with a tensile strength of 500 MPa. The ultimate strain is 0.15. During the construction of the steel wire mesh reinforced self-compacting concrete slabs, the liquid mortar is poured into a wooden frame with designed steel wire mesh. Due to the high flowability of the mortar, no vibration and compaction plus levelling of the surface is required.

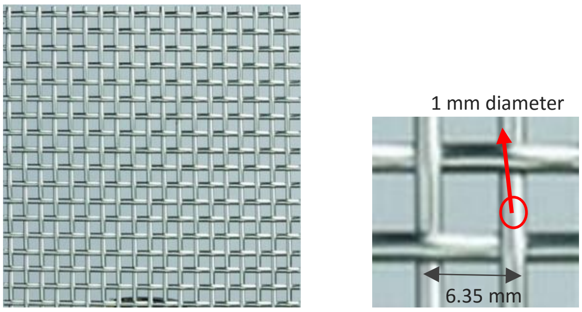

Figure 3. Dimension of steel wire mesh

3 TEST SETUP AND RESULTS

Testing apparatus and TNT explosive used in the close-in explosion are shown in Figure 4. For control slab, an 8 kg TNT explosive was adopted in the test scheme while a 12 kg TNT explosive was designed for the high performance steel fibre reinforced concrete slab and steel wire mesh reinforced concrete slab. The standoff distances in all the cases were set as 1.5 m.

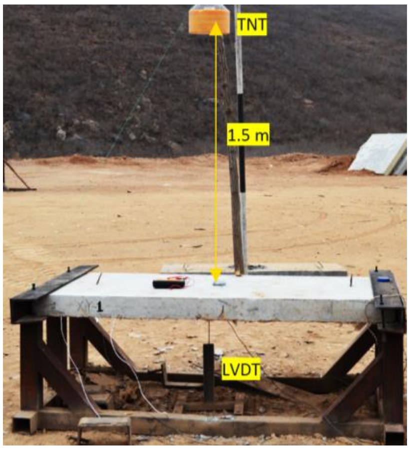

Figure 4. Test setup

Figure 5 shows the control slab after test, the slab failed completely with a permanent deflection of 190 mm which was manually measured after the test. Although some shear cracks can be observed, the failure of the control slab was predominantly flexure with extensive concrete crush in the slab mid-span.

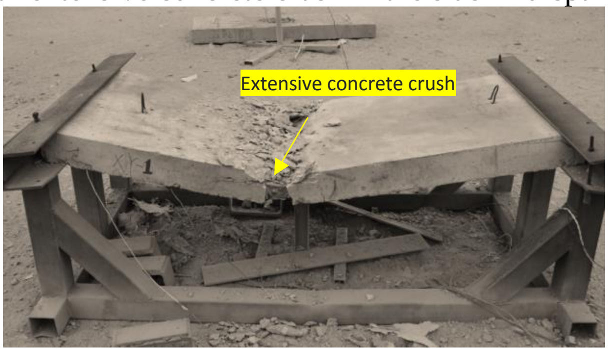

Figure 5: Control slab after 8 kg TNT detonation from 1.5 m standoff distance

Figure 6 shows the Slab 1 after 12 kg TNT detonation, a permanent deflection of 70 mm was measured at slab mid-span. Compared with control sample, similar flexure behaviour and damage mode were observed, however, the slab deflection was much smaller than control panel. When flexure deflection occurred, steel fibres effectively bridged over the cracks and retarded crack propagation. A certain amount of blast energy was consumed by fibres extension and pull-out from the concrete matrix.

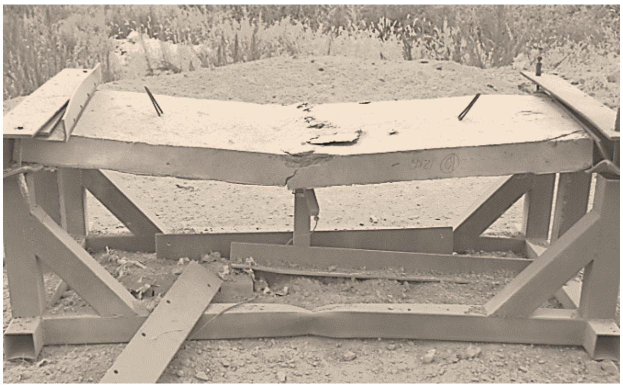

Figure 6. Slab 1 after 12 kg TNT detonation from 1.5 m standoff distance

Figure 7 shows the Slab 2 after test, the slab showed almost no deflection after the test. Hairline cracks were observed from the side of the slab, it is noted that these cracks were widely distributed along the slab major bending plane which indicated an elastic slab deformation after blast loads. This wide crack distribution is different from the control slab and Slab 1 in which the cracks concentrated in the mid-span. It is believed that the steel wire meshes reinforced the slab in both the major and minor bending planes, and they significantly enhanced structural bending and shearing strength. The cracks in the covering area were further confined by the steel fibre material. Upon slab interaction with the blast load, a uniform deformation occurred on the slab and large amount of the blast energy was consumed by the elastic deformation of steel wire meshes.

Figure 7. Slab 2 after 12 kg TNT detonation from 1.5 m standoff distance

4 CONCLUSION

An increasing trend was seen in the protective engineering that high strength concrete had been used against blast and impact loads. Fibrous material addition has been proved to be a solution to the brittleness of high strength concrete, it can enhance concrete material ductility and tensile strength. In the present study, high performance steel fibre reinforced concrete slab is tested under close-in detonation, comparison is made against conventional concrete slab. In addition, a relatively new reinforcing scheme i.e. steel wire mesh reinforcement is employed in the slab design. Under the same blast load, it is noted steel wire mesh reinforced slab showed the best blast resistance while slab with pure steel fibre reinforcement showed flexure deflection and damage. Control slab made of normal strength concrete failed under smaller blast loads.

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