ARTICLE IN PRESS

Construction and Building Materials xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Response of small scale ultra high performance fibre reinforced concrete slabs to blast loading

L. Mao [a,*], S.J. Barnett [a], A. Tyas [b], J. Warren [b], G.K. Schleyer [c], S.S. Zaini [c]

[a] School of Civil Engineering and Surveying, University of Portsmouth, Winston Churchill Avenue, Portsmouth PO1 2UP, UK
[b] Department of Civil and Structural Engineering, The University of Sheffield, Western Bank, Sheffield S10 2TN, UK
[c] Department of Engineering, University of Liverpool, Brownlow Hill, Liverpool L69 3GH, UK

HIGHLIGHTS

- The paper provides a systematic study of the performance of UHPFRC slabs under close-in explosions.
- Field tests show behaviour UHPFRC slabs under close-in explosion and corresponding crack pattern.
- Performance of UHPFRC slabs under explosion can be simulated with good quality using numerical model.

ARTICLE INFO

Article history:
Received 18 November 2014
Received in revised form 5 May 2015
Accepted 6 May 2015
Available online xxxx

Keywords:
UHPFRC
Close-in explosion
Blast load
Steel fibre
Finite element modelling

ABSTRACT

This paper provides a systematic study of the performance of ultra high performance fibre reinforced concrete (UHPFRC) slabs under close-in explosions. In the study, the UHPFRC slabs were manufactured with varying amounts and types of steel fibres. In field tests, various PE4 charge sizes were employed to generate blast load until a sudden increase in maximum deflection was observed. Peak 1/4 span deflections and development of slab cracks were recorded. With the results, the effect of steel fibres on performance of UHPFRC slabs can be better clarified. Static tests were also used to study the effect of fibres on the behaviour of UHPFRC specimens, results indicate that fibre distribution and orientation can clearly affect UHPFRC slab behaviour. Finally, finite element modelling was employed to simulate the performance of UHPFRC slabs under blast loading and these modelling results were compared to test data. Based on the comparison results, potential further enhancement of numerical models is discussed.

1. Introduction

Whilst numerous studies have been conducted on the performance of fibre-reinforced concrete (FRC) under intense transient loading from impact [1–10], relatively few studies have been presented in peer reviewed literature into the performance of FRC structures to blast loading, especially for UHPFRC (ultra high performance fibre reinforced concrete) structures. The reason is that due to financial and logistical restrictions, it is difficult to perform large numbers of blast tests. There is also little research devoted to investigating the performance of UHPFRC structures with numerical studies.

Agardh [11] reported experimental and numerical studies of the response of 1.2 m square by 0.06 m thick FRC panels to shock tube pressure loading. The panels were constructed from nominal 90 MPa concrete, reinforced with 55 kg/m^3 Dramix 30/0.50 fibres. The panels were subjected to shock loading of up to 1.37 MPa peak pressure with duration up to 70 ms. The panels were fully clamped around the periphery and, from the presented images, appeared to exhibit classic near-circular hogging yield lines around the support with X-shape sagging yield lines through the mid-span. Maximum displacements at centre span of 23 mm were recorded in surviving panels, indicating maximum rotations of ~2°.

Lok and Xiao [12] presented a study of one- and two-way spanning FRC slabs to blast loading from ground burst detonations of 8–40 kg bare TNT explosive charges at 5 m distance from the target slab. The slabs had a clear span of 760 mm and were 50 mm thick. They were constructed using conventional strength concrete (compressive strength around 50 MPa) and relatively light fibre densities (0.5–1.5% by volume). Blast loading varied from ~550 to 2750 kPa, with positive durations of ~0.8–1.6 ms and estimated specific reflected impulses of ~200–1800 kPa ms. Measured permanent residual central deflections of up to 45 mm in surviving simply supported two-way spanning panels and 31 mm in surviving fixed support two-way spanning panels were recorded,

* Corresponding author. Tel.: +44 79 8574 9226.
E-mail address: lei.mao@port.ac.uk (L. Mao).

http://dx.doi.org/10.1016/j.conbuildmat.2015.05.085
0950-0618/© 2015 The Authors. Published by Elsevier Ltd.

indicating peak rotations of ~2.5–3.5°. The work concluded that, in general, the optimum fibre density was 1%, with panels deflecting further when the fibre dosage was increased beyond this.

More recently, Wu et al. [13] carried out a series of tests on conventional bar reinforced, fibre reinforced and combine bar/fibre reinforced concrete panels using ultra-high performance concrete (static compressive strength ~150 MPa and tensile strength ~30 MPa). Their panels were 1-way spanning, 1.8 m span × 1.0 m wide and 0.1 m thick. Blast loading was from detonation of 1 to 20 kg TNT equivalent charges at stand-offs of up to 3 m. Peak pressures and specific impulses were in the range 0.3–6.0 MPa and 133–715 kPa ms respectively. Only one test was reported on a panel reinforced with only steel fibres (i.e. no additional bar reinforcement), this panel survived a detonation of 3.4 kg TNT equivalent at 0.75 m stand-off, with a peak central deflection of 13.2 mm, indicating a peak rotation of ~1°.

Barnett et al. [14] and Schleyer et al. [15] investigated the performance of ultra high performance fibre reinforced concrete (UHPFRC) panels under blast loading. These UHPFRC materials have high compressive strength of up to 200 MPa and tensile strength of about 20–40 MPa. In addition, the fracture energy of UHPFRC can be about 20,000–40,000 J/m^2. In the field tests, the UHPFRC panels with dimension of 3.5 m × 1.3 m × 0.1 m contained various steel reinforcement bar and steel fibre volumes, blast loading was generated with 100 kg TNT equivalent explosive charge placed at different stand-off distances (7 m, 9 m, and 12 m). The recorded peak pressures were in the range of 498–2488 kPa, and duration of 1.9–5.0 ms. A UHPFRC panel with combine bar/fibre reinforcement could survive under blast loading with peak pressure of 2488 kPa, and its maximum deflection was 210 mm, whilst UHPFRC panels with only fibre reinforcement broke into two parts under blast loading with peak blast pressure of 498 kPa. Mao et al. [16] employed the numerical modelling method to predict the behaviour of these panels under blast loading. In the study, the concrete material model in LS-DYNA was modified to better express the behaviour of UHPFRC material, such as strain softening behaviour and strain rate effect. With the modified concrete model, the deflection time history of UHPFRC panel under various blast loadings could be well predicted, whilst the failure mode of panels could also be obtained with reasonable accuracy.

However, based on previous work, it appears that no systematic assessment of the response of UHPFRC panels subjected to blast loading has been reported in the available literature. This absence provided the impetus for the work reported in this article, which formed part of a project to investigate the blast and impact resistance of UHPFRC [17–19].

In this paper, the performance of UHPFRC slabs under blast loading is investigated systematically. The blast tests performed to UHPFRC slabs are described and the effect of fibres is studied using UHPFRC slabs with varying types and amounts of steel fibre reinforcement. Static tests were performed to further understand the steel fibre effect and material properties obtained from static tests were also used in numerical studies. Numerical modelling was employed to study the performance of UHPFRC slabs under blast loading, using the finite element modelling package LS-DYNA. Results from these models are compared to the experimental test data. Even with simplifications in the model, crack pattern and deflection of UHPFRC slab can be captured with reasonable accuracy.

2. Description of UHPFRC slabs

The UHPFRC specimens used for this work were square slabs measuring 660 × 660 × 25 mm thick and were manufactured at the University of Liverpool. The slabs were manufactured with varying amounts and types of steel fibre reinforcement. Table 1 lists the mix proportions of the UHPFRC used for manufacturing the slabs. Two types of fibres were used in varying amounts in these mixtures. The first type was 13 mm long, 0.2 mm diameter, straight, high tensile steel fibres. The second type was 25 mm long, 0.4 mm diameter, stainless steel fibres with hooked ends. Three mixtures which differed only in their fibre type and quantity were investigated. The mixture which contained 2% by volume of 13 mm long fibres was chosen as the industry norm for this type of material, whilst the other two mixtures had a 50:50 combination of both fibre types. These mixtures had total fibre contents of 4% and 6% by volume and were chosen based on material performance in static tests to maximise the flexural strength and toughness of the material.

The slabs were manufactured with 16 cast-in holes around the edge to allow for mounting the slabs for testing, as shown in Fig. 1. It can be seen that the slab is tested as a two-way span condition, which is selected for two reasons. Firstly, whilst no definitive standard test arrangement exists, two way spanning is commonly preferred where possible, as it eliminates the possibility of blast pressure venting past the free edge of the panel. Secondly, in the pulse pressure tests (Fig. 7) two-way spanning conditions were used (again, to provide a seal on all for edges) and it was considered sensible to match these conditions in the small scale blast tests. They were cast horizontally and compacted using a vibrating table. Slabs were produced in batches of three panels. Cube specimens were also manufactured from each batch in order to measure compressive strength of the concrete and check consistency of the results between batches. After 24 h, all specimens were removed from the moulds and transferred to a hot water curing tank set at 90 °C where they remained until they were 7 days old. Following this hot curing treatment, there was very little further change in the compressive strength of the concrete.

3. Blast test arrangement and experimental results

A series of 19 blast tests was conducted at the University of Sheffield blast and impact laboratory, Harpur Hill, Buxton, UK between January and July 2009. All tests were conducted with the slabs held in a two-way spanning test frame designed to provide edge constraints that fully restrained the slab in both translation and rotation. The slabs were sandwiched between two 50 mm thick grade 43 steel plates, each 800 mm square on plan, with a 500 mm square central space. The plates were clamped together using 16 grade 8.8 M20 bolts, which passed through the bottom plate and into a stiff base frame. The slabs were therefore effectively fully clamped, with a clear span of 500 mm.

Due to the possibility of slab failure, it was impractical to use dynamic displacement recording equipment in the tests. Instead, peak deflection measurements were recorded by the use of a

Table 1
UHPFRC mix proportions.

Properties	Fibre volume		
	2%	4% Hybrid	6% Hybrid
Cement (kg/m^3)	657	657	657
GGBS (kg/m^3)	418	418	418
Microsilica (kg/m^3)	119	119	119
Silica sand (kg/m^3)	1051	1051	1051
SPA (kg/m^3)	40	40	40
Added water (kg/m^3)	185	185	185
13 mm long fibres (kg/m^3)	157	157	235
25 mm long fibres (kg/m^3)	–	157	235

Please cite this article in press as: Mao L et al. Response of small scale ultra high performance fibre reinforced concrete slabs to blast loading. Constr Build Mater (2015), http://dx.doi.org/10.1016/j.conbuildmat.2015.05.085