Materials and Design 116 (2017) 77–91

Contents lists available at ScienceDirect

Materials and Design

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

Experimental and numerical study on steel wire mesh reinforced concrete slab under contact explosion

Jun Li [a,*], Chengqing Wu [a], Hong Hao [b], Yu Su [a]

[a] Centre for Built Infrastructure Research, School of Civil and Environmental Engineering, University of Technology Sydney, NSW 2007, Australia
[b] Department of Civil Engineering, Curtin University, WA 6845, Australia

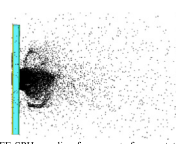
HIGHLIGHTS

- Beam reinforced by steel wire mesh and micro steel fibres shows high flexure capability
- Slab with steel wire mesh reinforcement develops local membrane effect under blast
- FE-SPH algorithm can model the fragmentation process with reasonable accuracy
- The contact detonation generates fragments with velocity exceeding 100 m/s
- The blast shock front velocity detected in the field test exceeds 700 m/s

GRAPHICAL ABSTRACT

Hybrid steel wire mesh and micro fibre reinforced beam under static flexure

High speed camera capture on fragments induced by contact detonation



FE-SPH coupling for concrete fragmentation modelling

ARTICLE INFO

Article history:
Received 27 July 2016
Received in revised form 24 November 2016
Accepted 26 November 2016
Available online 05 December 2016

Keywords:
Steel wire mesh
Composite slab
Contact detonation
SPH algorithm

ABSTRACT

With the rising of terrorism and rapid urbanization around the world, increasingly more structures are exposed to the threats from accidental and hostile explosion loads. To provide adequate structural protection against blast load, novel materials and strengthening techniques are under fast development. In the present study, a composite slab design aiming at high level blast resistance is studied. In the matrix of high strength self-compacting concrete, besides conventional rebars serving as primary reinforcement, steel wire meshes are embedded and served as secondary reinforcements. Moreover, on the concrete cover layer where the tensile cracks locate, steel fibres are added to provide micro crack-bridging effect. Preliminary numerical simulations adopting coupled Finite Element (FE) and Smoothed Particle Hydrodynamics (SPH) are carried out in hydro-code and the results are used as guide for field blast test. Composite slab with optimal design is field tested under 1 kg TNT contact detonation, and the results are compared with slabs made of conventional and ultra-high performance concrete without steel wire meshes. The results demonstrate that slab with steel wire mesh reinforcement develops localized membrane effect when subjected to blast loads and shows better blast resistant capability as compared to the slabs without steel wire meshes.

1. Introduction

Structural response under dynamic loading is a topic of increasing interest in recent decades. Short duration high intensity loads like impact or blast usually cause local response of a structure. The damages

* Corresponding author.
E-mail address: Jun.li-2@uts.edu.au (J. Li).

http://dx.doi.org/10.1016/j.matdes.2016.11.098

observed on post-blast structural components are usually in brittle manner [1]. Given there is not necessarily sufficient structural redundancy, damage of individual components can cause disproportional collapse of the entire structure [2], which is now an important concern for structural engineers and researchers.

To conduct analysis and provide rational protective design of structures against accidental or hostile explosions, it is critical to understand blast loading amplitude and distributions on the structures. Until now, most information about blast loads is semi-empirical and the most extensively used blast load parameters (including blast overpressure and impulse) are plotted versus the scaled blast standoff distance ($R/W^{1/3}$) as presented in manual UFC 3-340-02 [3]. The amplitude and distribution of air blast loads are functions of the type of explosive material, weight and shape of the explosive, distance and location of the explosive relative to the structure, and the interaction of the shock front with the ground and the target structure. The most extensive data about blast load parameters are for bare spherical TNT airbursts and bare hemispherical TNT surface bursts. When explosions occur in close proximity to or in contact with the structure, since the loadings on structures from these explosion scenarios are extremely severe and complex, it is very difficult to conduct an accurate measurement, and the curves in UFC manual therefore start at about $R/W^{1/3} = 0.15\ \text{ft/lb}^{1/3}$ ($0.06\ \text{m/kg}^{1/3}$). Although the empirical approaches provide predictions of blast load from explosion at a scaled distance less than $1.0\ \text{m/kg}^{1/3}$, previous studies demonstrated that significant variations exist on predicted blast load from different empirical formulae and design charts, indicating it is very difficult to reliably predict blast loads from explosions with scaled distance less than $1.0\ \text{m/kg}^{1/3}$ [4], let alone predicting loads from contact explosions.

In case contact explosions occur, structural components usually suffer highly localized damage such as concrete crushing and spalling, and these damages are induced by stress wave propagation rather than global shear and bending deformation. Upon detonation, high intensity compressive stress wave impinges on the concrete surface which easily exceeds the dynamic compressive strength and induces concrete crushing. When the blast induced compressive stress wave propagating inside the structure strikes the free surface of concrete, it will be reflected and turn into tensile stress wave. At a certain depth of the concrete, if the resultant stress is larger than the dynamic concrete tensile strength, concrete spalling initiates. During the propagation of the stress wave, attenuation, dispersion and divergence occur which change the shape and amplitude of the stress wave. In general, concrete spalling is caused by the shock impedance mismatch during the wave propagation, and it is dependent on the material strength, porosity, reinforcement spacing and other imperfections while it is relatively insensitive to the structural global stiffness and support boundary conditions.

Analytical solutions to stress wave induced structural failure is complex. Existing analyses [5–7] are based on simplifications which overlook the influence of wave attenuation and dispersion. Furthermore, these derivations are based on assumption that blast load can be determined and idealized in a specified scenario, however, as mentioned above, blast load is extremely hard, if not impossible, to be reliably predicted in a contact detonation case. McVay [8] proposed an empirical approach for determining if and where a stress wave would cause the concrete to crack in tension. 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.

Experimental study of this topic has widely been conducted in recent decades. Based on a large database of empirical slab/wall tests, AFRL-MN-EG-TR-1998-7032 Concrete Hard Target Spall and Breach Model [9] details the development of a spall/breaching algorithm for RC slabs and walls. In UFC guideline [3], data from spall tests have been compiled and damage curves are given to predict the concrete spall damage. In these tests, a cylindrical charge, cased or bare, is oriented side-on at a standoff distance from a wall slab and oriented end-on in contact with the ground. Foglar and Kovar [10] 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 guideline. However, they also noted the spall and breach prediction curves according to UFC 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. Wang et al. [11] carried out close-in explosion tests on square reinforced concrete slabs and spall damage at different severities was observed. Shi et al. [12] studied the influence from explosive shape on the concrete slab spall damage, and they observed that increase in the height/diameter ratio of the cylindrical TNT charge will significantly increase the spalling damage of the RC slab, although the mass of the TNT charge is unchanged. Ohtsu et al. [13] 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. [14] 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.

Upon occurrence of spall damage, besides structural damage, the secondary fragments generated with the concrete spall are also of significant importance as these fragments with large momentum can cause severe casualties and property loss. Technical paper [15] details procedures for the collection, analysis and interpretation of explosion-produced debris. It reports that a fragment with an impact kinetic energy of 79 J has a 31% probability of being lethal while an impact kinetic energy of 103 J would generate more than 50% probability of fatality. Later study in [16] gives more discussions about lethality criteria for debris generated from accidental explosions. Clearly, characterization of debris would enable improvement of current guidelines on safe standoff distances from building undergoing demolition or terrorism attack. Fragments velocity and mass distribution are therefore of vital importance when analysing fragment hazards of structures. Under blast loading environment, the concrete fracture and fragmentation result from both impulsive loading by stress waves and explosive gas-driven fracture propagation [17]. Brinkman [18] studied the fragmentation and projectile throwing process of brittle concrete-like material and concluded that stress waves generated by the detonation of an explosive charge are responsible for the development of a damage zone in the concrete material and the subsequent fragment size distribution, while the explosion gases are important in the separation of a crack that has already been formed during the passage of the stress wave, and in the subsequent launch of the fragments. Regarding the fragments mass and size distribution, a well-known analytical model of dynamic fragmentation [19] based on energetic criterion has found an extensive use in describing experimental data in a variety of solid materials. Wu et al. [20] carried out a sieve analysis to investigate the fragments size distributions from the concrete specimens under close-in detonations. It was found that the fragment size followed both a Weibull distribution and a Rosin–Rammler–Sperling–Bennet (RRSB) distribution. In a later experimental study, Li et al. [21] studied the distribution of debris from ultra-high performance concrete under contact detonations. Formulae aiming at crude estimation of the launch velocity of debris that is projected into the far field are proposed in [15]. From the perspective of energy and momentum, Xu and Lu [17] derived a simple formula for predicting velocity of debris generated by an internal explosion. Zhou and Hao [22] developed mesoscale model to analyse the damage and fragmentation of concrete slab under contact detonation. The dynamic