Engineering Structures 173 (2018) 166–179

Contents lists available at ScienceDirect

Engineering Structures

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

Experimental and numerical studies of ultra-high performance concrete targets against high-velocity projectile impacts

Jian Liu[a], Chengqing Wu[a,*], Yu Su[a], Jun Li[a], Ruizhe Shao[b], Gang Chen[c], Zhongxian Liu[b]

[a] Centre for Built Infrastructure Research, School of Civil and Environmental Engineering, University of Technology Sydney, Ultimo, NSW 2007, Australia
[b] Tianjin Key Laboratory of Civil Structure Protection and Reinforcement, Tianjin Chengjian University, Tianjin 300384, China
[c] Institute of Systems Engineering, China Academy of Engineering Physics, China

ARTICLE INFO

Keywords:
Ultra-high performance concrete (UHPC)
Projectile penetration
Depth of penetration (DOP)
Crater diameter

ABSTRACT

Ultra-high performance concrete (UHPC) which is known for high strength, high toughness, excellent ductility and good energy absorption capacity can be adopted as an ideal material in the impact resistant design of structures. In the present study, impact responses of UHPC targets with 3 vol-% ultra-high molecular weight polyethylene (UHMWPE) fibres and UHPC targets with 3 vol-% steel fibres are experimentally investigated subjected to high-velocity projectile penetration, and plain concrete targets under the same loading scenarios are also tested as control specimens for comparative purpose. In addition, numerical studies are conducted to simulate the projectile penetration process into UHPC targets with the assistance of a computer program LS-DYNA. The numerical results in terms of the depth of penetration (DOP) and crater diameter as well as projectile abrasions and damages are compared with the experimental results. Moreover, DOPs of these two types of UHPC targets obtained from tests are compared with the previously proposed empirical model.

1. Introduction

Protection of structures against intentional and accidental extreme loadings has become a serious public concern in recent decades. Although high strength concrete (HSC) and high performance concrete (HPC) are generally used in military and civil constructions to resist blast and impact loadings, they still lack sufficient strength under a high loading rate. Therefore, there is a growing demand for new construction materials with an outstanding performance to withstand such extreme loading conditions, and it is practical to consolidate buildings or structures through applying the new construction materials.

Ultra-high performance concrete (UHPC) is a promising construction material that contains fibres, a low water-binder ratio and a high micro-silica content with the elimination of coarse aggregates [1]. Compared with conventional concretes, UHPC is known for its outstanding strength, toughness, durability, ductility, serviceability and safety [2–6], and such characteristics enable its great potential to be an ideal construction material in impact and blast resistant designs of structures.

A few number of high-velocity impact tests have been conducted to explore the dynamic behavior of UHPC targets subjected to the high-velocity projectile penetration. Feng et al. [7] studied the dynamic response of a double-layered target of UHPC and armour steel subjected to an armour-piercing projectile impact at 820 m/s, and it was found that the fibres in the UHPC target can effectively refine the crack propagation in the localized ballistic tunnel area due to the fibre bridging effect. Máca et al. [8] explored impact responses of 150 MPa UHPC slabs with various volume fractions of steel fibres subjected to the steel-jacketed projectile penetration at 700 m/s. The test results demonstrated UHPC had much greater impact resistance than the traditional fibre reinforced concrete, but any further increase of the fibre volume fraction beyond 1% had no obvious effect on the depth of penetration (DOP), and the crater diameter tended to remain a constant when the fibre volume fraction was between 2% and 3%. With the purpose of improving the hardness of UHPC and further increasing its impact resistance against the projectile penetration especially for DOP, coarse aggregates were added into the matrix of UHPC, though the tensile strength of concrete might be reduced to some extent accordingly. Wu et al. [9] investigated the impact resistance of 35–142 MPa ultra-high performance cement based composites (UHPCC) with the additions of basalt aggregates and steel fibres through conducting the high-velocity impact tests with the broad striking velocities from 510 to 1320 m/s. In this study, influences of fibre content, basalt aggregate, target strength and impact velocity on the impact response of UHPCC targets were investigated. Besides, Wu et al. [10] further investigated the impact response of 110–130 MPa UHPCC targets with the addition of

---

* Corresponding author.
E-mail address: chengqing.wu@uts.edu.au (C. Wu).

https://doi.org/10.1016/j.engstruct.2018.06.098
Received 22 November 2017; Received in revised form 22 February 2018; Accepted 26 June 2018
0141-0296/

corundum aggregates and steel fibres against the projectile penetration from 510 to 850 m/s. It was found that the aggregate size and content also had an effect on the impact responses of UHPCC targets such as DOP, area and volume of the impact crater.

In recent years, a newly designed UHPC material with nano-material and fibre additions was developed [11–13]. It has been found that the mechanical properties of the newly designed UHPC material are significantly improved, which demonstrates its potential utilization in the protective engineering against impact and blast loadings. Although a number of tests [14–21] have been carried out to investigate the seismic and blast behaviors of the newly designed UHPC material and the test results showed its much better capacity to resist seismic and blast loadings than traditional concretes, limited studies were concentrated on its impact resistance against the high-velocity projectile penetration. In the present study, thick cylindrical UHPC targets with 3 vol-% steel fibres and UHPC targets with 3 vol-% ultra-high molecular weight polyethylene (UHMWPE) fibres are examined by conducting the high-velocity impact tests at striking velocities of ~550 m/s, ~675 m/s and ~800 m/s. Plain concrete targets under the same loading scenarios are also tested as control specimens for comparative purpose. The impact responses of UHPC targets such as DOP, crater diameter and volume loss as well as projectile abrasions and damages are investigated. The experimental results of DOP for UHPC targets are compared with those of the previously proposed empirical model. In addition, numerical investigations are also performed on UHPC targets to simulate the penetration process with the assistance of a computer program LS-DYNA.

2. Preparation of UHPC targets

2.1. Materials

The mix proportions of UHPC materials in the current study are listed in Table 1. In comparison with the conventional concrete, UHPC contains more constituents and finer particles like natural sand. It is noted that coarse aggregates were replaced with the silica fume that was used as the reactive powder material involved in the hydration of cement. Silica fume had a high pozzolanic effect that accelerated the hydration process and promoted the concrete strength. The addition of silica fume can also fill the voids to produce low porosity concrete matrix. In the current UHPC material design, straight steel fibres and UHMWPE fibres were used at a volume dosage (V_f) of 3%. Material properties of these two fibres [17] are given in Table 2. For comparative purpose, plain concrete with the same material compositions but without the addition of fibres was adopted.

2.2. Manufacturing procedure

The UHPC specimens were produced by mixing the silica fume, sand and other powder materials in a laboratory concrete mixer. They were primarily dry mixed for 5 min before 70% water was added and mixed for another 3 min to fluidise the mix. Superplasticizer was added before the other 30% water was finally added to the mixture, and then the mixing process was continued for 5 minutes before fibres were manually added and dispersed with the aim to avoid clumping and to ensure the uniform distribution and random orientation of fibres. The specimens were cured in cylindrical steel tanks which were placed in a humid room at a temperature of 20 ± 5 °C for 24 hours.

Table 2
Material properties of fibres.

Type	Density (kg/m^3)	Length (mm)	Diameter (mm)	Strength (MPa)	Young's modulus (GPa)	Elongation
UHMWPE	970	10	0.012	3000	100	0.04–0.06
Steel	7800	10	0.12	4295	200	0.15

3. Material static tests

Prior to high-velocity impact tests, static uniaxial compression and four-point bending tests were carried out to investigate the mechanical properties of plain concrete and UHPC involving UHPC with 3 vol-% UHMWPE fibres (UHPC-PF) and UHPC with 3 vol-% steel fibres (UHPC-SF). The test procedure confirmed to Chinese Standard GB/T 50081-2002.

Uniaxial compression tests were conducted on 100 mm × 100 mm × 100 mm cubic samples of plain concrete, UHPC-PF and UHPC-SF. The typical compressive failure modes and crack patterns of cubic samples are shown in Fig. 1, where the plain concrete sample displayed a brittle failure with two long longitudinal cracks while the UHPC samples was in a ductile failure mode and the bridging effect from fibres can be observed. Fig. 2 shows the average compressive stress-strain curves of cubic samples. Compared with the plain concrete, UHPCs with fibre materials had a more ductile behavior as they can sequentially bear loading up to strains much greater than the peak strain, and the addition of steel fibres had a positive effect on the enhancement of both compressive strength and ductility than UHMWPE fibres. The compressive strengths of plain concrete, UHPC-PF and UHPC-SF were 75 MPa, 120 MPa and 140 MPa, respectively.

Four-point bending tests were conducted on 100 mm × 100 mm × 400 mm beam samples of plain concrete, UHPC-PF and UHPC-SF. The typical flexural failures for each beam sample are shown in Fig. 3, where the failure modes of UHPC beam samples significantly differed from the plain concrete. The initial crack of the plain concrete was formed from the bottom against the tensile loading, and then the sample was split into two parts when the crack propagation was towards the top. However, the flexural performance of UHPC samples was obviously improved. The crack width and the space between major cracks were restrained and both parts still remained attached due to the bridging effect of fibres. After conducting all the four-point bending tests, the average force and displacement curves for each type of beam samples are shown in Fig. 4. The flexural strength of the beam sample was calculated as: $f_t = FL/bd^2$, where F is the lateral force; L is the length of clear span; b is the width of the beam cross section, d is the thickness of the beam cross section. In this case, observed in Fig. 4, the lateral forces for plain concrete, UHPC-PF and UHPC-SF materials were 10 kN, 51 kN and 95 kN, respectively. After substituting the F values of each material, L value of 0.3 m, b value of 0.1 m and d value of 0.1 m, the plain concrete had a low flexural strength of 3.0 MPa while UHPC-PF and UHPC-SF had an improved flexural strength that reached 15.3 MPa and 28.5 MPa, respectively.

4. High-velocity impact tests

4.1. UHPC targets

In the present high-velocity impact tests, nine cylindrical concrete

Table 1
Mix proportions of UHPC (unit: kg).

Cement	Silica fume	Fine sand	Medium sand	Coarse sand	Superplasticizer	Water	V_f
889	356	550	329	220	29	210	3%