Construction and Building Materials 135 (2017) 447–458

Contents lists available at ScienceDirect

Construction and Building Materials

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

Numerical study of ultra-high performance concrete under non-deformable projectile penetration

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HIGHLIGHTS

- Mat_72R3 is used to characterize UHPC under static and impact loadings.
- The DOP is investigated under various compressive strengths of UHPC, striking velocities and CRHs of projectile.
- The crater damage is investigated under various compressive strengths of UHPC, striking velocities and CRHs of projectile.
- An empirical formula is proposed to determine the DOP for UHPC.

ARTICLE INFO

Article history:
Received 15 August 2016
Received in revised form 14 December 2016
Accepted 31 December 2016

Keywords:
UHPC
Projectile
LS-DYNA
DOP
Cratering damage

ABSTRACT

This paper presents a numerical study in evaluating impact response of ultra-high performance concrete (UHPC) cylinder targets under ogive-nosed projectile penetration with broad striking velocities from 300 m/s to 1000 m/s. Steel ogive-nosed projectiles with an average mass of 360 g are launched to penetrate UHPC cylinder targets with 750 mm diameter and 1000 mm length. The *Karagozian & Case* (K&C) cementitious material model, namely, MAT_Concrete_Damage_Rel3 (Mat_72R3), is implemented into finite element package LS-DYNA for UHPC. In order to accurately predict depth of penetration (DOP) and cratering damage of UHPC cylinder targets, uniaxial compressive and four-point bending testing results are used to validate 3D finite element material model. With the validated numerical model incorporating dynamic increase factors (DIF) of UHPC, parametric studies are conducted to investigate effects of UHPC compressive strength, projectile striking velocity and projectile caliber-radius-head (CRH) ratio on both DOP and cratering damage of UHPC targets. Moreover, an empirical formula to predict DOP is derived according to the simulated data.

1. Introduction

In recent years, terrorist attacks are becoming more and more frequent throughout the world. Not only does the terrorism lead to structural damage, but it seriously threatens resident's regular life. Therefore, investigations on resistance of construction materials against impact loading caused by projectiles have attracted much attention by researchers and engineers. Ultra-high performance concrete (UHPC) is a promising construction material that contains a large volume of fibers, low water-binder ratio, high micro-silica content and elimination of coarse aggregate [1]. It has excellent material qualities, such as ultra-high strength, good ductility, excellent durability, outstanding abrasion resistance, self-consolidating workability and low drying shrinkages [2–5].

While attracting great interests from both weapon designers and structural engineers over the past few decades, impact response of UHPC under high velocity projectile penetration remains to be one of the greatest challenges in modern concrete technology. Experimental investigations on UHPC under high-velocities projectile impact have been conducted throughout the world [6–10]. However, their achievements have been hindered by rather high cost of facilities for experiments under high-velocities projectile impact and by a time-consuming nature of their experimental procedures.

Attempts have been made to build and optimize the material model and appropriate algorithms for accurately numerical simulations of conventional concrete targets, with the assistance of explicit finite element software LS-DYNA or AUTODYN to document the potential relationship between variables of impact response, reducing even replacing complicated experiments. Teng et al. [11] simulated process of high-velocity (2474 m/s) projectile

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http://dx.doi.org/10.1016/j.conbuildmat.2016.12.216
0950-0618/

penetrating into normal strength concrete (NSC) with compressive strength of 28–33 MPa by using the elastic-plastic hydrodynamics material model, and it was found that the numerical results show a good agreement with experimental results in terms of the residual velocity of projectile and the scabbing diameter of concrete targets. Nyström and Gylltoft [12] applied a numerical approach to describe the penetration into NSC target (40 MPa) by an ogive-nosed projectile (485 m/s). In this work, modified Riedel, Hiermayer and Thoma (RHT) material model was employed in simulating impact response of NSC targets, and the numerical results show a good correlation with experimental data with respect to the depth of penetration (DOP), crater diameter and scabbing diameter. Wang et al. [13] numerically studied the impact response of high strength concrete (HSC) with the compressive strength ranging from 60 to 140 MPa subjected to high-velocity (400–600 m/s) projectile penetration, and the numerical results are very consistent with experimental results, especially for DOP. Tai [6] employed the Johnson-Holmquist Concrete (JHC) model to elucidate impact response of reactive powder concrete (RPC) with compressive strength of 162–193 MPa under low-velocity (35–104 m/s) projectile penetration, indicating that numerical results correlate well with experimental data.

There exist a large number of numerical studies to simulate projectile penetration into the conventional concrete. However, very limited numerical research had been conducted to investigate the impact response of UHPC subjected to high-velocity projectile penetration. Existing numerical studies on conventional concrete will provide effective research strategies and methodologies for the present study on UHPC. Furthermore, valid and accurate prediction of impact response of UHPC by numerical simulation will also provide an alternative for engineers in designing defence structural members to resist high velocity projectile perforation.

In the present numerical study, a calibrated and validated material model, that is, *MAT_CONCRETE_DAMAGE_REL3, along with an equation of state *EOS_TABULATED_COMPACTION and erosion criteria *MAT_ADD_EROSION, is applied to simulate the steel ogive-nosed projectile penetration into UHPC cylinder targets. This validated material model is then coded into explicit finite element package LS-DYNA to simulate impact response of UHPC targets subjected to high-velocity projectile penetration from 300 m/s to 1000 m/s. The effects of UHPC compressive strength, projectile striking velocities and projectile caliber-radius-head (CRH) ratio on DOP and cratering damage of UHPC targets are investigated. Moreover, the empirical formulae to predict DOP and cratering damage subjected to projectile penetration are derived according to the simulated data.

2. Finite element model validation

In this paper, uniaxial compression and four-point bending tests were conducted to validate the accuracy of the material model used in the numerical simulation of projectile penetration into UHPC targets. In the numerical simulations of uniaxial compression and four-point bending tests, LS-DYNA Implicit Solver is used for the quasi-static analysis.

2.1. Mix design of UHPC samples

All UHPC samples were produced by mixing silica fume, fine sand and powder materials in a laboratory concrete mixer. They were primarily dry mixed for 5 min, before the addition of 70% water and mixing for 3 min. Superplasticizer was then added before the remaining 30% water was finally mixed. The mixing process was undertaken for another 5 min before the addition of steel fibers. The steel fibers were manually dispersed with the aim to avoid clumping and to guarantee the uniform distribution and random orientation of steel fibers. The steel fiber materials were employed at a volumetric dosage of 2.5%, and the mix proportions of UHPC are listed in Table 1.

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

Constituent	Amount
52.5 Cement	750
Silica Fume	225
Silica Flour	190
Sand	1030
Superplasticizer	16
Water	190
Steel Fibers	191
Nanoparticles	63

2.2. Uniaxial compression test

Uniaxial compression test, shown in Fig. 1, was conducted at Structural Laboratory, with the aims to obtain the material properties like Young's modulus, Poisson's ratio, compressive strength and the stress-strain relationship curve, shown in Fig. 2, according to Chinese Standard GB/T 50081-2002 test method. In the test, a number of 100 mm × 100 mm × 100 mm UHPC cubes were mix designed, and then they were cured at the room temperature (20 ± 2 °C) for 28 days. All specimens were loaded via the hydraulically controlled constant load rate of 0.2 mm/min until failure. The data was recorded employing two axial and lateral strain gauges on each specimen, and four axial LVDTs were placed at each corner of the loading dial. The average value for each material property was listed in Table 2.

In order to ensure the sufficient accuracy of the material model used in the numerical simulation of UHPC targets against projectile penetration, a numerical simulation of uniaxial compression test is primarily conducted to compare the average material sample results. The comparison between the testing and simulated results of compressive stress-strain curves is illustrated in Fig. 2, which shows a good correlation between two curves. Therefore, the material model accurately characterizes UHPC's material behaviour under compression.

2.3. Four-point bending test

Four-point bending test was carried out on a number of beam specimens by using an electromechanical servo hydraulic pressure testing machine with capacity of 3000 kN according to Chinese Standard GB/T 50081-2002 test method as shown in Fig. 3. The dimensions of beam specimen were 100 mm × 100 mm × 400 mm. The space between two load points was 1/3 of the clear span which generated a region of no shear, and two supports were symmetrically applied to the place at 50 mm from two edges of the specimen. LVDTs were placed at mid-span and two supports to measure the deflection of the specimen, and strain gauges were located at mid-span along the depth of the specimen to produce an experimental curvature profile.

A numerical simulation of the four-point bending test is carried out to validate the material model used in the numerical simulation of projectile penetration into UHPC targets. The comparison between the test results and numerical simulation of typical force-displacement curve at mid-span is shown in Fig. 4, which indicates a fair agreement between two curves. Therefore, the material model will accurately characterize UHPC's material behaviour under flexural tension.