International Journal of Impact Engineering 97 (2016) 1–9

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Residual velocities of projectiles after normally perforating the thin ultra-high performance steel fiber reinforced concrete slabs

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ARTICLE INFO

Article history:
Received 11 March 2016
Received in revised form 2 June 2016
Accepted 13 June 2016
Available online 16 June 2016

Keywords:
Projectile
Perforation
Thin slab
Residual velocity
UHP-SFRC

ABSTRACT

It is very necessary to predict the residual velocity of a projectile after perforating a concrete barrier for the protective structures. In this paper, projectile perforation test on the thin 128.4 MPa ultra-high performance steel fiber reinforced concrete (UHP-SFRC) slabs was conducted, in which the diameter of projectile was 25.3 mm and the thicknesses of slabs ranged from 40 mm to 100 mm. All the slabs were perforated normally and the projectile residual velocities were captured by high-speed camera. To assess the projectile residual velocity, a semi-analytical projectile perforation model for thin concrete slab ($H/d \le 5$) was established, which completes our previous work [Peng et al., 2015] for thick slab ($H/d > 5$) within a unified framework. The proposed model was validated by the present and existing available perforation test data on thin concrete slab. Furthermore, the unified model was employed to evaluate the impact resistance of spaced segmented concrete slabs and good agreements were achieved.

1. Introduction

For a given projectile which has perforated a concrete barrier with finite thickness, how to assess its residual potential penetration capacity to the inner structures? This would be a typical issue for the protection of nuclear power plant containment or spaced floor slabs in a high-rise building against the impact of projectile. Residual velocity of the projectile is obviously the most important factor to assess its impact effects on the subsequent target, the research of which has drawn much attention previously.

As for the experimental studies, Hanchak et al. [1] conducted perforation experiments with 25.4 mm diameter projectiles (301–1058 m/s) into 178 mm thick concrete slabs (48 MPa and 140 MPa) and measured residual velocities with X-ray photographs. Cargile et al. [2] captured and discussed the residual velocities of projectiles with 50.8 mm in diameter perforating concrete slabs with three thicknesses (254, 215.9 and 127 mm) at a striking velocity of approximately 312.9 m/s. Besides, four shots of projectiles perforation test with striking velocities of 379–470 m/s on 254 mm thick slabs were performed. Unosson and Nilsson [3] published four experimental residual velocities from high-speed camera, in which the projectile diameter and concrete thickness were 75 mm and 400 mm, respectively. Li et al. [4] acquired the residual velocities of the projectiles by designing a foil screen target behind the concrete slab, in which the projectiles with 64 mm in diameter were used to strike five concrete slabs with the thicknesses of 300–700 mm at a nominal impact velocity of 400 m/s. Wu et al. [5] performed twenty-five shots of projectiles (25.3 mm in diameter) perforation test on five configurations of monolithic and segmented concrete panels (100–300 mm thick), and the residual velocities of projectiles after perforating every slab were recorded. Parameters of the above experiments are listed in Table 1, where m, d and V_0 are the projectile's mass, diameter and striking velocity, respectively. The symbols f_c and H denote the unconfined compressive strength and the thickness of concrete slab.

While for the analytical works, based on the two-stage (cratering + shear plugging) or three-stage (cratering + tunneling + shear plugging) projectile perforation models, Chen et al. [6,7] proposed the formula to predict the projectile residual velocity and it was validated by the test data from Ref. [1] By considering the kinetic energy carried by the rear ejected fragments of the concrete slabs, Wu et al. [8] presented a modified expression for the residual velocity of projectile. Furthermore, Grisaro and Dancygier [9] proposed a modified energy method to assess the residual velocity of projectile perforating the concrete slab, in which part of the projectile's striking energy is empirically assumed to dissipate through fracture of the ejecting crater into fragments as well as the additional cracking of the panel. More recently, in Ref. [10], we have proposed a semi-analytical model to calculate the residual veloc-

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http://dx.doi.org/10.1016/j.ijimpeng.2016.06.006
0734-743X/

Table 1
Parameters of perforation tests on concrete slabs with residual velocity measured.

No.	Nose shape	m (kg)	d (cm)	V_0 (m/s)	f_c (MPa)	H (cm)	Number of shots	H/d	Ref.
1	Ogive	0.43	2.53	536–737	41	10, 15, 20, 30	44	4, 6–12	Wu et al. [5]
2	Ogive	5.08	6.4	~ 407.8	34.3	30, 40, 50, 60, 70	5	4.7, 6–11	Li et al. [4]
3	Ogive	6.3	7.5	~ 620	153	40	4	5.3	Unosson and Nilsson [3]
4	Ogive	2.34	5.08	306–470	36.5, 40	12.7, 21.59, 25.4	12	2.5, 4.2, 5	Cargile et al. [2]
5	Ogive	0.5	2.54	301–1058	48, 140	17.8	12	7	Hanchak et al. [1]

ity of projectile when perforated the thick concrete slab and the prediction results showed high degree of accuracy with the above mentioned experimental results [1,2,4,5].

However, most of the existing experimental studies were carried out on the relatively thick concrete slabs with the ratio of slab thickness (H) and projectile diameter (d) larger than 5 as listed in Table 1; only few shots were conducted on the relatively thin concrete panel. Moreover, although Chen et al. [7] and Wu et al. [8] have developed projectile perforation models for the thin concrete panel, the validity of which are not clear since the test data of projectile residual velocity after perforating the thin slab is scarce. Additionally, our previously proposed model in Ref. [10] is only applicable for relatively thick concrete target. Therefore, the projectile perforation tests with residual velocity measurement on thin concrete panels as well as the validated analytical model are both scarce and required; the present paper aims to fill these gaps.

In this paper, firstly, two groups of projectile perforation tests on thin ultra-high performance steel fiber reinforced concrete (UHP-SFRC) slabs were conducted, in which the 25.3 mm diameter projectiles were propelled to perforate the UHP-SFRC slabs with thicknesses of 40–100 mm. UHP-SFRC is a relatively new cement based composite with prominent anti-strike properties [11–13]; our previous studies were concentrated on the impact resistance of which against small caliber bullet [12] as well as the penetration depth of flat nosed projectile [13], thus the present test is a supplement to validate its protective performance in the aspect of projectile perforation. Secondly, an experimental-based projectile perforation model for thin concrete slab ($H/d \leq 5$) is further established, which completes our previous work for thick slab ($H/d > 5$) [10] and the two models are successive and consistent. Finally, based on the available experimental data, predicted results from the present and existing formulae are compared and discussed.

2. Perforation test

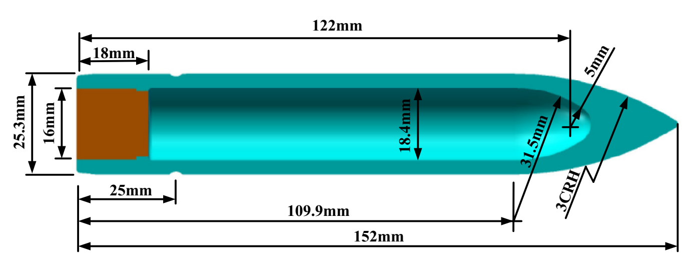
2.1. Projectile

As shown in Fig. 1(a), ogive-nosed projectiles with a diameter of 25.3 mm and a mass of 331 g were used. The projectiles were machined from DT300 (SiMnCrNiMoV) steel rods with the yield strength of 1500 MPa. The dimensions of the projectile is illustrated in Fig. 1(b), where the cartridge thickness is 3.45 mm and the caliber-radius-head (CRH) of the ogival nose is 3 (CRH denotes the ratio of the ogival nose radius and the shank diameter). The projectiles were filled by polymer inert material with the density of 1.5 ± 0.05 g/cm^3 to substitute the filled charge and adjust the centroid of the projectile. A 25.3 mm caliber smooth-bore powder gun, as shown in Fig. 2, was utilized to launch the projectiles to reach the striking velocities between 250 and 478 m/s by adjusting the charge weight. The projectiles in the present impact test are treated as rigid bodies since negligible deformations occur during perforations.

2.2. UHP-SFRC slabs

The mix proportions of UHP-SFRC in the present impact test is listed in Table 2, which is identical with the material used in our previous work and the detailed properties of the mixing gradients as well as the preparation procedure can be referred from Ref. [13]. The components are normalized to the cement weight and the wet density of UHP-SFRC is 2530 kg/m^3. The straight brass-coated steel fiber was chosen since it provides a good trade-off between workability and mechanical properties of concrete, and the volumetric ratio of the mixing fiber were designed as 2%. The equivalent diameter, length and tensile strength of the steel fibers were 0.175 mm, 13 mm and 3000 MPa, respectively. The size of the basalt aggregate was controlled strictly less than 10 mm.

(a)



(b)

Fig. 1. Projectile: (a) photograph and (b) dimensions.

Fig. 2. Powder gun.