International Journal of Impact Engineering 94 (2016) 50–59

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

# Response of steel-tube-confined concrete targets to projectile impact

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ARTICLE INFO

*Article history:*
Received 4 August 2015
Received in revised form 19 January 2016
Accepted 29 March 2016
Available online 1 April 2016

*Keywords:*
Penetration
Armor piercing projectile (APP)
Confined concrete
Depth of penetration (DOP)
Penetration resistance

ABSTRACT

Concrete is widely used in protective structures. Strength and toughness are two key factors for its anti-impact performance. Imposing constraint on concrete is an effective way to improve the anti-impact performance of concrete protective structures. In this paper, penetration tests of steel-tube-confined concrete (STCC) targets impacted by 12.7 mm armor piercing projectile (APP) at velocity around 820 m/s were conducted and different diameters and wall thicknesses of confining steel tube were considered. The typical damage modes of the tested STCC targets were obtained and influences of impact location, diameter and thickness of confining steel tube on the anti-penetration performance of STCC targets were also analyzed. The results show that the anti-penetration performance of STCC targets is obviously superior to that of semi-infinite concrete targets in restraint of the damage area and reduction of depth of penetration (DOP).



## 1. Introduction

Concrete has been extensively used in both military and civil protective structures, such as bulletproof walls and structures in nuclear power facilities. Those structures may suffer the impact of explosive shock waves, high speed fragments and bullets during their life cycle. A lot of research on penetration of concrete has been conducted, such as penetration tests, theoretical models and numerical simulation etc [1–5]; therefore, many accurate and profound understandings of the complex response process and mechanism of penetration were obtained.

Normal concrete is a kind of brittle material with much lower tensile strength than compressive strength, and it is apt to crack, even be fractured, under impact of projectile. Many ways were tried to improve the strength and toughness of concrete so as to make its anti-impact performance much better, and a lot of researches were conducted to explore the impact response, such as high strength concrete [6,7], high performance concrete [8,9], ultra high performance concrete [10–12] and hybrid fiber reinforced concrete [13,14]. The effects of reinforcement arrangement [8,15–17], fiber properties and volume fraction [6,8,10,12–14,18] and aggregate size [7,18,19] on the anti-impact performance of concrete were studied, and some conclusions were obtained: 1) increase of strength of concrete is an effective way to improve penetration resistance; however, the brittleness of concrete increases accordingly and it is an uneconomical way [6,7]; 2) reinforcement of concrete, to a certain extent, can improve penetration resistance and reduce the damaged zone, but it may only be effective under the condition that the reinforcement mesh is densely arranged [9,15,16]; 3) adding fiber can effectively improve the toughness of concrete, arrest the propagation of cracks, reduce the damaged zone and thus improve the multi-hit performance, but it is almost useless for reducing the depth of first-impact [7,14].

Imposing constraint on concrete is another effective way to improve the anti-penetration performance of concrete structures because the response behavior of concrete, to a certain extent, will be restricted with the constraint. In recent years, several kinds of confined concrete targets have been conducted. Vossoughi et al. [20] carried out penetration tests on both confined targets (packing front and rear Polypropylene or Zylon fabric) and unconfined targets of normal concrete under the impact of rigid conical projectiles, and the results show that the imposed constraint can increase the energy consumption of targets and reduce the local damage zone significantly. Abdel-Kader and Fouda [15] carried out penetration tests on normal concrete targets and confined concrete targets with steel plates at front, rear or both sides, and the results illustrate that the anti-penetration performance of targets with both front and rear steel plates are superior to other forms of targets. Choon et al. [21] developed a bio-inspired cellular cement composites system for large scale military applications, which utilize adjacent cells as a mutual confining mechanism to improve ballistic performance. The penetration tests show that the proximal spall damage is reduced up to 26%~33% compared with specimens of similar size and weight but without cellular construction; however, depth of penetration (DOP) increases up to 10%~12%. The reason for the increase of DOP is mainly because that the restraint stiffness of single cell without

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http://dx.doi.org/10.1016/j.ijimpeng.2016.03.012
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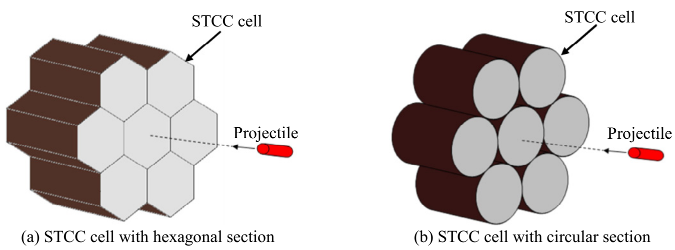



(a) STCC cell with hexagonal section (b) STCC cell with circular section

**Fig. 1.** STCC cellular systems.

**Table 1**
Dimensions and material performance of specimens.

| Target groups | Steel tube | | | | | Target thickness (mm) |
|---|---|---|---|---|---|---|
| | External diameter (mm) | Wall thickness (mm) | Yield strength (MPa) | Tensile strength (MPa) | Elongation (%) | |
| P | 140 | 3.5 | 254 | 412 | 21 | 300 |
| D | 89 | 3.5 | 247 | 416 | 25 | 300 |
| D/W | 114 | 3.5 | 254 | 412 | 21 | 300 |
| W | 114 | 4.5 | 305 | 478 | 32 | 300 |
| | | 2.5 | 247 | 416 | 25 | 300 |
| S | 405 | 6 | ≧ 235 | 372~461 | ≧ 26 | 270 |

confining tube is inadequate. Zhen et al. [22] carried out penetration tests of steel-tube-confined concrete (STCC) targets penetrated by 12.7 mm Armor Piercing Projectile (APP) with impact velocity 830 m/s~840 m/s. The penetration tests show that STCC targets work better in anti-penetration performance than that of semi-infinite targets; moreover multi-impact performance of STCC targets is excellent. However, only one type of STCC target with 140 mm in diameter, 3.5 mm in wall thickness of steel tube was investigated and penetration tests of STCC target with different tube diameters and wall thicknesses are needed for their application in bullet-proof walls, critical roads, or runway pavements mentioned in Choon et al. [21].

STCC is a typical kind of lateral constraint style and can improve the performance of concrete. When a projectile axially penetrates an STCC target, concrete in the STCC target is in three-dimensional compression stress state, so the toughness will be improved, and compressive stress wave reflected from the interface between steel tube and concrete can avoid tensile failure occurring on the lateral side of targets. Additionally, steel tube will exert radial pressure on the concrete and thus restrict the radial displacement of concrete. Thereby, STCC targets have better penetration resistance than normal concrete targets analytically. However, in the existing penetration tests of concrete targets cast in steel tube, diameter ratio of target to projectile ($D_t/D_p$) usually ranged from 20 to 30 and the steel tube was mainly used as mould board for pouring and was used to eliminate the influence of free boundary [23–27]. Generally, the confinement effect of the steel tube on the penetration resistance in these tests can be neglected, and they could be called as semi-infinite targets.

For practical application, STCC cells with hexagonal and circular across sections can be arranged to form cellular system, as shown in Fig. 1. The STCC cellular system not only have the superior anti-penetration performance, but also have excellent multi-impact performance than the cellular system in Choon et al. [21]. Targets with hexagonal across section are convenient to be assembled for a cellular structure while steel tube of circular across section has the best confinement to concrete and already has an extensive use in many building structures, so the latter style is chosen as the initial investigation for mechanism analysis.

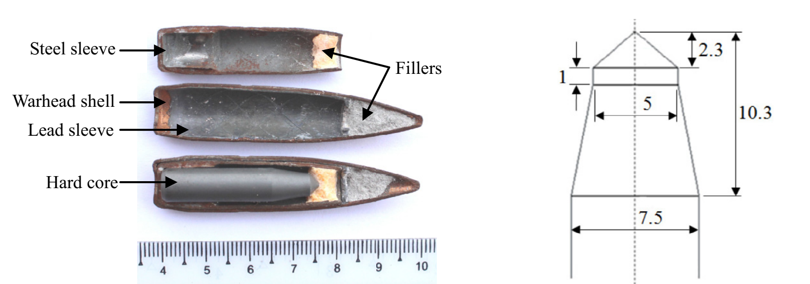
Set against the above background, penetration tests of single STCC targets with different tube diameters and wall thicknesses against 12.7 mm APP were conducted with impact velocity around 820 m/s in this paper. The failure modes, DOP and crater size were obtained, the influence of impact location, confining steel tube diameter and wall thickness on the anti-penetration performance of STCC target was analyzed. Modifications of Forrestal's empirical–analytical formula [28] were made to analyses penetration resistance of STCC targets and the empirical relationship between penetration resistance coefficient and lateral restraint stiffness of steel tube was obtained by curve fitting.

## 2. Penetration tests

### 2.1. Projectile and targets

As shown in Fig. 2, 12.7 mm APP is composed of hard core, steel sleeve, lead sleeve, warhead shell (copper) and fillers in the front spaces between the steel sleeve and the warhead shell. The hard core is a high-strength alloy cylinder with double conical nose, 7.5 mm in diameter and 19.7 g in mass. Steel tubes were low-carbon steel and their mechanical properties are listed in Table 1.

Five groups of targets were designed, as shown in Table 1. One of the four groups of STCC targets with thickness of 300 mm was marked with P, D, D/W and W, respectively. The diameter ratio of target to projectile ($D_t/D_p$) for the four groups ranged from 7 to 11, and they were regarded as finite-diameter and thick target. The tested parameters of the four groups were diameters (89 mm, 114 mm and 140 mm) and wall thicknesses of steel tube (2.5 mm, 3.5 mm and 4.5 mm). The other group was marked as S, and its diameter ratio of target to projectile ($D_t/D_p$) was 32, which was meant to simulate the semi-infinite target. In Table 1, group P was designed to investigate the effects of impact point; groups D, D/W and P with the same wall thickness of steel tube 3.5 mm, were designed to investigate the effects of diameter of steel tube, and groups




(a) Profiles of projectile structure (b) Dimensions of hard core nose shape

**Fig. 2.** Inner structure of 12.7 mm APP (units: mm).