Penetration Response of Ultra-High Performance Concrete (UHPC) under Projectile Impact

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ABSTRACT

In recent decades, terrorism activities are becoming increasingly more frequent throughout the world. Terrorist attacks that target military and civil buildings will not only cause structural damages, but also lead to massive casualties and property loss. Therefore, the development of new construction materials with excellent performance to resist extreme loadings has been attracting much attention from researchers and engineers.

Evolving from reactive powder concrete (RPC), novel ultra-high performance concrete (UHPC) materials with nano-material and fibre addition have been developed by many universities and government agencies in these years. With the purpose of enriching the knowledge of UHPC materials subjected to high-velocity projectile penetration, this thesis presents a number of experimental and numerical research findings on UHPC materials in journals.

Prior to real high-velocity projectile impact tests, numerical approaches in simulating the impact response of UHPC targets under projectile penetration are presented. The numerical models of UHPC targets are validated against the uniaxial compressive and four-point bending testing results. With the validated numerical models incorporating dynamic increase factors (DIF), parametric studies on the effects of target compressive strength, projectile striking velocity and projectile Calibre Radius Head (CRH) ratio on depth of penetration (DOP) and crater diameter of UHPC targets are discussed. Based on the simulation data on DOP, an empirical model to predict DOP of UHPC targets is proposed.

High-velocity projectile impact tests are then conducted on UHPC targets reinforced with 3 Vol-% ultra-high molecular weight polyethylene (UHMWPE) fibres and UHPC targets with 3 Vol-% steel fibres. Under the same loading scenarios, plain concrete targets without the addition of fibres are also tested as control specimens for comparative purpose. Dynamic behaviours of concrete targets involving DOP, crater diameter, volume loss as well as abrasions and damages of projectiles after impact are observed and compared with the numerical results. Also, DOPs of UHPC targets are compared with the previously proposed empirical model and the fair agreement is achieved in terms of UHPC targets with steel fibres.

Although UHPC reinforced with steel fibres has been a promising material with excellent impact resistance which can be directly used in the structural components in civil and military constructions, the high cost of steel fibres may limit the use of UHPC in military and civil constructions, so an extended investigation of steel wire meshes with relatively low cost to replace steel fibres in UHPC is necessary. In this thesis, the impact responses of 44-layer steel wire meshes reinforced RPC targets such as DOP, crater diameter, volume loss as well as abrasions and damages of projectiles after impact are investigated under the same loading environment as UHPC targets.

In order to comprehensively understand the effects of steel wire meshes on the impact response of reinforced RPC targets, parametric studies are conducted after validating numerical models, in which the variables include configuration of whole steel wire meshes, number of layers, space between two layers, space between two steel wires per layer as well as the diameter and tensile strength of steel wires. Based on the results of parametric studies, an empirical model derived from the simulation data is proposed to predict DOP of reinforced RPC targets.

Simultaneously, optimal structural designs with effective reinforcement configurations are under extensive investigation to enhance the impact performance of UHPC targets. A numerical approach is used to investigate the impact response of uniformly distributed ceramic balls as a shielding structure on UHPC targets under high-velocity projectile penetration. Parametric studies are conducted on thin UHPC slabs to explore the influence of impact location, diameter, spatial arrangement and material properties of ceramic balls on impact response. Perforation and ballistic limits of ceramic balls protected thin UHPC slabs are obtained. Besides, DOPs of thick UHPC slabs protected with 6-layer ceramic balls with a diameter of 20 mm in a hex-pack arrangement are compared with existing UHPC targets.

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LIST OF PUBLICATIONS

1) Liu, J., Wu, C., Li, J., Su, Y., Shao, R., Liu, Z. and Chen, G., 2017. Experimental and numerical study of reactive powder concrete reinforced with steel wire mesh against projectile penetration. *International Journal of Impact Engineering* **(Impact Factor: 2.938)**, 109, pp.131-149.
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3) Liu, J., Wu, C. and Chen, X., 2017. Numerical study of ultra-high performance concrete under non-deformable projectile penetration. *Construction and Building Materials* **(Impact Factor: 3.169)**, 135, pp.447-458.
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5) Liu, J., Wu, C., Li, J., Fang, J. and Su, Y., 2018. A novel structure of ceramic balls reinforced ultra high performance concrete targets under projectile impacts.
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CHAPTER 1: INTRODUCTION

1.1 Background information

Terrorism activities in recent decades have drawn more considerations and concerns throughout the world. Not only do the terrorism activities lead to structural damages, but it seriously endangers residents' life, so investigations on the resistance of structures against blast and impact loadings have attracted much attention from researchers and engineers.

Although some conventional concretes such as 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 capacity under such a high loading rate. More importantly, it is a challenge to ensure that the conventional materials and structures maintain their structural integrity without any collapse and perforation under terrorist attacks involving explosive blasts, projectiles or missiles. 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.

Previous experimental studies [1, 2] have demonstrated that penetration and perforation resistances of concrete structures are strongly affected by the strength and toughness of concrete, and the depth of penetration (DOP) of the projectile decreases with the greater toughness of concrete. Toughness measures the amount of energy expended to propagate the crack in concrete under impact loading and markedly affects the impact resistance. Despite HSC is characterized by excellent load carrying capacity, its brittleness increases with the increase of compressive strength which limits the practical use.

Ultra-high performance concrete (UHPC), evolving from reactive powder concrete (RPC), 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 [3]. Compared with conventional concretes, UHPC is known for its outstanding strength, toughness, durability, ductility, serviceability and safety [4-8], and such characteristics enable its great potential to be an ideal construction material in impact and blast resistant designs of structures.

A small number of high-velocity impact tests have been conducted to explore the dynamic behaviours of UHPC targets subjected to high-velocity projectile impacts. Feng et al. [9] 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 UHPC targets can effectively refine the crack propagation in the localized ballistic tunnel area due to the fibre bridging effect. Máca et al. [10] explored impact responses of 150 MPa UHPC thin slabs with various volume fractions of steel fibres subjected to the steel-jacketed projectile penetration at 700 m/s. The test results demonstrated that 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 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 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. [11] 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 m/s 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. [12] further investigated the impact response of 110–130 MPa UHPCC targets with the addition of corundum aggregates and steel fibres against projectile penetration from 510 m/s to 850 m/s. It was found that the aggregate size and content also had an effect on the impact response 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 [13-15]. 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. A large number of tests [16-21] have been carried out to investigate the blast performance of the newly designed UHPC material and the test results showed its much better capacity to resist blast loadings than conventional concretes, but limited studies were concentrated on its impact resistance against high-velocity projectile penetration.

The addition of fibres in UHPC improves the strength and toughness, which further enhances the impact behaviour, but insignificant improvement of impact resistance occurs when the volumetric fraction of fibres exceeds a certain amount. Additionally, achievements have been hindered by the high cost of fibres, so an investigation of new protective materials with relatively low-cost reinforcement to replace fibres in UHPC is also necessary.

Steel wire mesh with high ductility and strain capacity has a good effect on the energy absorption [22-24], and it has been added in UHPC to replace steel fibres to resist blast loadings [25-27]. According to the previous research [28, 29], a number of tests were conducted to investigate the effect of steel wire mesh on conventional concrete targets under projectile impacts. Dancygier and Yankelevsky [28] investigated the impact response of HSC targets reinforced with a layer of 5 mm diameter steel mesh with spacing of 100 mm and two layers of 0.5 mm diameter steel wire mesh with spacing of 7 mm against the sharp-nosed projectile penetration with striking velocities from 85 m/s and 230 m/s, and the results denoted that steel wire mesh can effectively reduce the localized damage, especially in DOP and crack propagation, but the observations should also consider the amount of reinforcement. Kamal and Eltehewy [29] studied the impact response of NSC blocks reinforced by a different number of layers of woven wire steel mesh (Ferrocement) penetrated by the steel blunt-nose projectile with a mass of 175 g and a striking velocity of about 980 m/s. The main findings demonstrated that DOP and localized damage in the front and rear face of concrete targets showed an overall reduction by using steel wire meshes as a reinforcement compared with the plain concrete target.

Another concern about UHPC to resist projectile impact is that although UHPC has been a promising material in terms of the impact resistance which can be directly used in the structural components in civil and military constructions, optimal structural designs with different reinforcement configurations are under extensive investigation to maximize the impact resistance of UHPC components. The outstanding mechanical properties of ceramic panels such as light weight, great hardness and high compressive strength are widely exploited as the reinforcement or shielding for the metal structures [30-33] or concrete structures [34] to resist projectile impact. However, some disadvantages limit its use in ballistic design when the expensive panel is penetrated or perforated by a projectile even in a small area and the whole panel becomes non-repairable and requires complete replacement, so the design of a new ceramic structure as a protective part on UHPC targets is supposed to be taken into consideration.

Attempts have been made to build and optimize the material model for accurate simulations of steel fibre reinforced concrete targets and even UHPC targets using finite element (FE) method to document the potential relationship between variables of impact response, reducing even replacing complicated experiments. Wang et al. [2] used Concrete Damage Rel3 (Mat_72 Rel3) to simulate localized damages of fiber-reinforced high-strength concretes and strain hardening cement-based composites due to the high-velocity projectile impact tests, where the numerical model predicted DOP well. Prakash et al. [35] used the Riedal Hiermaier Thomas (RHT) concrete model (Mat_272) to successfully predict the local damages of fiber-reinforced high-strength concrete targets induced by the projectile impact, in which good agreement was found to corroborate well with experimental results. Zhang et al. [36] employed Winfrith Concrete (Mat_84) to reproduce the impact phenomenon of UHPC slabs subjected to engine missile hitting and the numerical results showed good agreement with the test results in terms of engine deformation, target damage and residual velocity of missiles. Hu et al. [37] and Lai et al. [38] adapted Johnson Holmquist Concrete (Mat_111) to describe the dynamic behaviours of UHPC targets under projectile impacts involving DOP and crater damages.

FE method has been widely used to simulate the impact behaviours of concrete targets under high-velocity projectile impact, but it is not capable of handling large distortions of elements under such extreme loading conditions, which could cause computational overflow and inaccurate predictions. With the aims to avoid the computational overflow caused by element distortions, “erosion algorithm” is always used to delete elements that surfer large distortions, but the deletion of elements breaches the mass and momentum conservations. Also, the debris information after impact is impossible to be captured. In order to overcome these disadvantages brought by FE methods, various mesh-free methods such as smoothed particle hydrodynamics (SPH) [39, 40], element free Galerkin (EFG) [41], etc. has been proposed and developed in recent decades [42-44]. As the most widely used mesh-free method, SPH method has been successfully used in failure and fragmentation of brittle materials under projectile impact loadings. Sovják et al. [45] successfully used the SPH method to predict the local damages of UHPC targets induced by the projectile impact, in which good agreement was found in the shape of the shear crack pattern of UHPC targets. Lai et al. [46] also used the same method to simulate the fracture process and damage development of anti-penetration layer protected UHPC targets under high-velocity projectile impact. Although SPH method is effective in numerical simulations of projectile penetration, there are some shortcomings to limit its use in dynamic problems, such as tensile instability, higher computational cost than traditional FE methods and boundary condition problems. Therefore, hybrid FE and SPH methods are often considered to make full use of the good properties of both methods.

1.2 Research goals

This research was conducted to experimentally and numerically investigate the impact response of the novel UHPC and UHPC-based structures subjected to high-velocity projectile impacts. The specific topics as reported in the thesis comprise:

1) Experimental and numerical investigations of dynamic behaviours of UHPC targets under high-velocity projectile impacts;
2) Exploring the influence of the properties of target and projectile on the impact response of UHPC targets, and building an empirical model to predict DOP of UHPC targets under projectile impacts based on the parametric studies;
3) Experimental and numerical investigations of dynamic behaviours of steel wire mesh reinforced RPC targets under high-velocity projectile impacts;
4) Exploring the influence of the properties of steel wire meshes on the impact response of reinforced RPC targets, and building an empirical model to predict DOP of reinforced RPC targets under projectile impacts based on the parametric studies;
5) Numerically designing and testing a novel structure of ceramic balls protecting on thin and thick UHPC targets against rigid projectile impacts.

1.3 Outlines

This thesis consists of seven chapters. The six chapters following this introductory chapter are organized as below:

Chapter 2 conducts the numerical simulation of the high-velocity projectile impact tests on UHPC targets with steel fibres. Parametric studies are carried out to explore how the variables of UHPC target and projectile affect the impact response of UHPC targets. Moreover, an empirical formula to predict DOP of UHPC targets is derived based on the simulation data;

Chapter 3 experimentally and numerically investigates the impact response of UHPC targets with different types of fibres as well as projectile abrasions and damages subjected to high-velocity projectile penetration, and then the results are compared with the empirical formula as proposed in Chapter 2;

Chapter 4 focuses on the impact response of reactive powder concrete (RPC) targets reinforced with 44-layer steel wire meshes under projectile impacts by experimental and numerical methods. With the validated numerical models, parametric studies are then conducted to investigate the influence of the properties of steel wire mesh on the reinforced RPC targets when subjected to projectile penetration;

Chapter 5 conducts a further numerical study on the influence of steel wire mesh on the impact performance and an empirical equation derived from the simulation data is proposed to predict DOP of reinforced RPC targets. Besides, the energy evolution of the projectile and steel wire meshes during projectile penetration is discussed;

Chapter 6 numerically tests the dynamic behaviours of ceramic balls protected thin and thick UHPC targets against rigid projectile impacts. Parametric studies are then carried out on thin UHPC slabs to investigate the influence of the properties of ceramic balls. Furthermore, DOPs of ceramic balls protected UHPC targets are obtained at three striking velocities and the results are compared to the existing advanced UHPC targets from the previous studies;

Chapter 7 summarizes the major findings of this research, together with some suggestions for future study.

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CHAPTER 2: NUMERICAL STUDY OF ULTRA-HIGH PERFORMANCE CONCRETE UNDER NON-DEFORMABLE PROJECTILE PENETRATION

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Abstract

This paper presents a numerical study in evaluating impact response of cylindrical ultra-high performance concrete (UHPC) targets under projectile impact with broad striking velocities from 300 m/s to 1000 m/s. Steel ogive-nosed projectiles with a mass of 360 g are launched to penetrate UHPC targets with 750 mm diameter and 1000 mm length. The Karagozian & Case (K&C) cementitious concrete model, namely, *MAT_CONCRETE_DAMAGE_REL3 (Mat_72R3), is implemented into finite element package LS-DYNA to build UHPC targets. In order to accurately predict the depth of penetration (DOP) and cratering damage of UHPC 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 Calibre 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.

Keywords: Ultra-high performance concrete (UHPC); Projectile; LS-DYNA; Depth of penetration (DOP); Cratering damage

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CHAPTER 3: EXPERIMENTAL AND NUMERICAL STUDIES OF ULTRA-HIGH PERFORMANCE CONCRETE TARGETS AGAINST HIGH-VELOCITY PROJECTILE IMPACTS

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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.

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

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CHAPTER 4: EXPERIMENTAL AND NUMERICAL STUDY OF REACTIVE POWDER CONCRETE REINFORCED WITH STEEL WIRE MESH AGAINST PROJECTILE PENETRATION

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Abstract

This paper presents experimental and numerical studies on impact resistance of reactive powder concrete (RPC) targets reinforced with 44-layer steel wire meshes. Steel ogive-nosed projectiles with an average mass of 330 g and striking velocities ranging from 550 m/s to 800 m/s were launched against cylindrical RPC targets with 750 mm diameter and 700 mm thickness. The impact responses observed in the tests, including depth of penetration (DOP), crater diameter and volume loss, were investigated and discussed, which indicates an effective impact resistance in terms of DOP and crater diameter in comparison with the previous studies on ultra-high performance based cement composites (UHPCC) target with additions of fibres and basalt aggregates. Numerical studies based on the validated material and element model are also conducted to simulate the impact response of reinforced RPC targets against high-velocity projectile penetration in explicit hydro-code LS-DYNA. The localized damage, especially DOP, is well predicted by using the numerical models. Moreover, further investigation based on the verified numerical models is discussed in the present paper to explore the influence of mechanical and physical properties of steel wire mesh reinforcement on the resistance of projectile penetration.

Keywords: Reactive powder concrete (RPC); Steel wire mesh; Projectile penetration; DOP; crater diameter

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Liu, J., Wu, C., Li, J., Su, Y., Shao, R., Liu, Z. and Chen, G., 2017. Experimental and numerical study of reactive powder concrete reinforced with steel wire mesh against projectile penetration. *International Journal of Impact Engineering*, 109, pp.131-149.

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CHAPTER 5: NUMERICAL INVESTIGATION OF REACTIVE POWDER CONCRETE REINFORCED WITH STEEL WIRE MESH AGAINST HIGH-VELOCITY PROJECTILE PENETRATION

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Abstract

This paper numerically investigates the effects of steel wire mesh reinforcement on reactive powder concrete (RPC) targets subjected to high-velocity projectile penetration. A numerical model based on a computer program called LS-DYNA was validated with experimental data concerning the depth of penetration (DOP) and crater diameter of reinforced RPC targets. With the validated numerical model, a series of parametric studies are conducted to investigate how the variables of steel wire mesh reinforcement such as the configuration of steel wire meshes, number of layers, space between layers, space between steel wires per layer, as well as the diameter and tensile strength of steel wires affect DOP and crater diameter of reinforced RPC targets. Moreover, the energy evolution of the projectile and steel wire meshes during projectile penetration is discussed. Based on the results of parametric studies, an empirical equation derived from the simulation data is proposed to predict DOP of reinforced RPC targets.

Keywords: Reactive powder concrete (RPC); Steel wire mesh; Projectile penetration; Depth of penetration (DOP); Crater diameter; Internal energy

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Liu, J., Wu, C., Li, J., Su, Y. and Chen, X., 2018. Numerical investigation of reactive powder concrete reinforced with steel wire mesh against high-velocity projectile penetration. *Construction and Building Materials*, 166, pp.855-872.

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CHAPTER 6: CERAMIC BALLS PROTECTED ULTRA HIGH PERFORMANCE CONCRETE STRUCTURE AGAINST PROJECTILE IMPACT - A NUMERICAL STUDY

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Abstract

Ceramic materials have excellent mechanical properties such as light weight, great hardness and high compressive strength. In this paper, a numerical study is conducted to investigate the response of ceramic balls protected ultra-high performance concrete (UHPC) targets against the high-velocity rigid projectile impact using the coupled smoothed particle hydrodynamics-finite element (SPH-FE) method in LS-DYNA. Based on the validated numerical models, parametric studies are performed to explore the effect of diameter, spatial arrangement and material type of ceramic balls as well as the impact position on the dynamic performance of UHPC targets, and then perforation and ballistic limits of ceramic balls protected UHPC targets are obtained. Compared with other UHPC slabs at the striking velocities from 500 m/s to 850 m/s, UHPC slabs protected with 6-layer hex-pack arranged ceramic balls with the diameter of 20 mm is most effective in terms of reducing the depth of penetration (DOP). In addition, the utilization of ceramic balls is economical in protective structures since the damaged ceramic balls can be replaced and undamaged ceramic balls are reusable.

Keywords: Ceramic balls; UHPC; SPH-FE method; Projectile impact

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Liu, J., Wu, C., Li, J., Fang, J., Su, Y. and Shao, R., 2019. Ceramic balls protected ultra-high performance concrete structure against projectile impact–A numerical study. *International Journal of Impact Engineering*, 125, pp.143-162.

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CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Major findings

This thesis mainly presented two approaches including experiment and numerical simulation to investigate dynamic behaviours of novel UHPC and UHPC-based structures under high-velocity projectile impacts. Based on the simulation data from parametric studies, empirical equations were proposed to predict the depth of penetration (DOP) of concrete targets. The major findings of this research are concluded in this section.

7.1.1 UHPC

Dynamic behaviours of UHPC targets with 3 Vol-% ultra-high molecular weight polyethylene (UHMWPE) fibres and UHPC targets with 3 Vol-% steel fibres were evaluated subjected to high-velocity projectile penetration from ~550 m/s to ~800 m/s and compared with numerical simulations. Prior to tests, parametric studies were conducted to explore the variables that influence the dynamic behaviours of UHPC targets reinforced with steel fibres with validated numerical models. Based on the simulation data, an empirical model was proposed to predict DOP of UHPC targets. Some conclusions can be drawn as follows:

1) UHPC reinforced with UHMWPE fibres performs much better than the plain concrete without fibres regarding DOP, crater diameter and volume loss because fibres can provide the greater strength, toughness and bridging, and UHPC reinforced with steel fibres is superior to both;
2) In the non-deformable (rigid) projectile penetration regime, DOP and crater diameter of UHPC targets enlarge with the increase of the projectile striking velocity and the decrease of the concrete compressive strength. The sharper head of projectiles can lead to the increase of DOP values but the decrease of crater diameters of UHPC targets;
3) The calibrated concrete model can reasonably reproduce DOP of UHPC targets under high-velocity projectile penetration, but the concrete model overestimates the crater diameter. However, the variation tendency of crater diameters versus the

projectile striking velocity observed from numerical simulations shows good agreement with experimental results;

4) The proposed empirical model to predict DOP shows the fair agreement with the test data of UHPC-SF targets, while this model is too conservative for UHPC targets with UHMWPE fibres especially when the striking velocity of projectiles exceeds 675 m/s.

7.1.2 Steel wire mesh reinforced RPC

Dynamic behaviours of RPC targets with 44-layer steel wire mesh were evaluated subjected to high-velocity projectile penetration from ~550 m/s to ~800 m/s and compared with numerical simulations. With the validated numerical models, parametric studies were conducted to explore the variables of steel wire mesh that influence the dynamic behaviours of reinforced RPC targets. Based on the simulation data, an empirical model was conducted to predict DOP of reinforced RPC targets. Some conclusions can be drawn as follows:

1) The spiral distribution of steel wire mesh reinforcement effectively reflects and refracts the stress wave produced by projectile impact because of the dense grids, which can contribute to an outstanding impact performance under projectile penetration;
2) The impact performance of reinforced RPC targets improves with the increase of steel volumetric fraction, including increasing number of steel wire mesh layers, enlarging steel wire diameter and densifying mesh grid size. The impact performance of reinforced RPC targets is only slightly influenced by the tensile strength of steel wires and the space between layers when the projectile completely perforates the protective part of steel wire meshes;
3) The calibrated numerical models can reasonably reproduce the impact responses of steel wire mesh reinforced RPC targets regarding DOP, crater damage, as well as abrasion and damage of projectiles;
4) The empirical model is proposed to predict DOP of steel wire mesh reinforced RPC targets and it shows good agreement with experimental data.

7.1.3 Ceramic balls protected UHPC

Dynamic behaviours of ceramic balls protected thin and thick UHPC slabs were investigated against rigid projectile impacts at velocities between 500 m/s and 800 m/s through using the SPH-FE method in LS-DYNA. Parametric studies were then conducted on thin UHPC slabs to investigate the influence from impact location, diameter, spatial arrangement and material properties of ceramic balls. After that, perforation and ballistic limits of ceramic balls protected thin UHPC slabs were obtained. DOP of ceramic balls protected thick UHPC targets was explored and compared with the existing advanced UHPC targets from the previous studies. Some conclusions can be obtained herein:

1) After projectile penetration, only a small number of ceramic balls close to the impact region are damaged and the ceramic balls far away from the impact region do not suffer such severe brittle damages. These observations prove reusable of undamaged ceramic balls in protective structures;
2) The hex-pack arranged ceramic balls protected UHCP slabs have the better impact performance to reduce the residual velocity of projectiles than the checkerboard arranged ceramic balls protected UHPC slabs, but the former tends to change the ballistic trajectory more possibly than the latter;
3) When the diameter of ceramic balls is not much greater than the projectile diameter, the residual velocity of projectiles after impact is only slightly affected by the various impact positions and the extent of the effect will be reduced with the decrease of ceramic balls;
4) Ceramic balls with the smaller diameter are more effective in the impact resistance because of the higher compaction, because they can consume the more kinetic energy of projectiles. However, the ballistic trajectory of ceramic balls with the larger diameter is easier to be altered;
5) At the impact velocity within 800 m/s, 6-layer D20 ceramic balls in the hex-pack arrangement protected on the thick UHPC slabs have the smaller value of DOP compared with the existing advanced UHPC targets.

7.2 Recommendations for future work

On the basis of current research outcomes, further improvement could be made in the future study as follows:

1) In the current research, the high-velocity projectile impact tests were conducted at the striking velocity within 1000 m/s, in which the impact response of concrete targets is highly related to the mechanical properties. When the striking velocity of the projectile is ultra-high that is over 1000 m/s, the equation of state of concrete targets may play a major role in the dynamic behaviours. Therefore, experimental and numerical tests are suggested to be undertaken to investigate the impact response of UHPC and other UHPC-based structures under the projectile impact over 1000 m/s;
2) Although Mat_72_Rel3 can well reproduce DOP of UHPC targets under high-velocity projectile penetration, it overestimates the crater damages. This indicates that the numerical model for UHPC needs to be refined. Significant efforts should be placed on such fundamental work to address this issue;
3) Portland Cement-based UHPC materials in the present research have excellent impact resistance against projectile penetration, while high cement dosage of UHPC is a critical concern that not only raises the cost, but also reduces the sustainability and limits the practical engineering applications. To solve these environmental problems, developing new concrete materials that are cost-efficient but more environmentally friendly and sustainable for partial or full replacement of cement from the concrete mixture will overcome this detrimental environmental impact;
4) Numerical investigations indicated that ceramic balls are effective in maximizing the impact resistance of UHPC components as a protective part, and they are also economical in protective structures since the damaged ceramic balls can be replaced and undamaged ceramic balls are reusable. However, real projectile impact tests are still in need to justify the assumptions.