UNIVERSITY OF TECHNOLOGY SYDNEY

BEHAVIOUR OF REINFORCED ULTRA-HIGH PERFORMANCE CONCRETE COMPONENTS SUBJECTED TO LOW-VELOCITY IMPACT LOADING

by Jie Wei

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Doctor Jun Li and Professor Chengqing Wu

University of Technology Sydney
Faculty of Engineering and IT

September 2021

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Jie Wei declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environment Engineering at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Signature: Production Note: Signature removed prior to publication.

Date: 10 September 2021

Abstract

Key load-bearing reinforced concrete (RC) members might be against accidental impact loadings during their service period. The impact resisting-performance of these structural components shall therefore be properly evaluated for accidental dynamic loads. To ensure the structural safety, there is an increasing need to improve the crashworthiness of key structural components which are at risk from dynamic impact loads. Ultra-high performance fibre reinforced concrete (UHPC) with superior mechanical properties and damage tolerance demonstrated good impact and blast resistance. As an emerging material with a specially formulated mixture, a thorough understanding of its mechanical performance against quasi-static and impulsive loadings is deemed necessary. Towards this aim, a series of well-instrumented experimental tests and high-fidelity numerical studies are conducted in this study. UHPC and its application in structural protective design against low-velocity lateral impact loads are systematically studied.

Chapter 1 presents the background, motivation, objective and outline of the current work.

Chapter 2 provides a literature review on current study of impact load induced structural responses of RC and UHPC members.

In Chapter 3, axially loaded UHPC and RC components with mono fibre reinforcement were tested against lateral impact loads. The drop weight test was carried out through a drop hammer collided the component from varying heights. UHPC components exhibited minor flexural damage, whereas RC components failed primarily by shearing. To further interpret the experimental data, associated numerical simulation was proposed. A Continuous Surface Cap Material model (CSCM) that

considered material triaxial strength, strain rate behaviour, compressive and tensile properties was developed for UHPC material. After numerical validation, the residual loading capacity of the UHPC members after impact loads was investigated through plenty of numerical tests. Impact mass-velocity (M-V) diagram and its equations were proposed to quick assess the damage of UHPC members.

After confirming the effectiveness of UHPC components in resisting the lateral impact loads, fibre reinforcement effect in UHPC was studied to achieve better cost-effectiveness. In Chapter 4, material property tests were conducted on UHPC with varying fibre reinforcing schemes. As compared to mono type fibre reinforcement, hybrid fibre reinforcement demonstrated better mechanical strength, especially the flexural strength. With notched three-point bending test results, tensile softening curves of UHPC were obtained, which was then used to quantify the fracture energy of UHPC strengthening with hybrid fibres. Then, the dynamic behaviour of RC members and UHPC members with mono and hybrid fibre reinforcement were experimentally characterized through the drop weight tests.

The high mechanical strength and material ductility of UHPC enables structural design with reduced section size and alternative reinforcement. New structural designs, including hollow-core UHPC columns, steel wire mesh reinforced UHPC columns, are investigated against impact loads in Chapter 5. The impact performances of these UHPC members were experimentally and numerically examined. With the validated numerical model, energy absorption curves, dynamic shear force and bending moment distribution diagrams were derived. Based on current data, the cracking and shear failure mechanisms of UHPC members were studied.

To date, the application of UHPC in construction is hindered by the raw material cost and lack of design guidelines. Towards a more effective use of UHPC in structural protective design, in Chapter 6, structural strengthening with UHPC overlay was investigated based on drop-weight impact testing. Bonded and unbonded UHPC overlay with the RC component was considered. While both designs can improve the shear resisting performance of RC components, the unbonded strengthening design prevented early tensile cracking in the UHPC overlay; hence maximised the impact resistance and energy absorption of the strengthening overlay.

Chapter 7 summaries the overall findings of the study and discuss future research work.

Acknowledgement

This doctoral thesis is the result of three and a half years of dedicated work with my supervisor, Doctor Jun Li, to whom I am incredibly grateful for his unwavering patience and guidance. I sincerely appreciate my co-supervisor, Professor Chengqing Wu, for his advice and contributions that greatly improved this work. I particularly thank Professor Hong Guan and Professor Xiaobo Qu who encouraged me to embark on this PhD journey. I also would like to acknowledge Futian Yang and Jie Li who generously offered their expertise and support. Lastly, my family, thank you for always being there.

List of Publications during the Candidature

Wei, J., Li, J., Wu, C., 2019. An experimental and numerical study of reinforced conventional concrete and ultra-high performance concrete columns under lateral impact loads. *Engineering Structures,* 201, 109822.

Wei, J., Li, J., Wu, C., 2020. Behaviour of hollow-core and steel wire mesh reinforced ultra-high performance concrete columns under lateral impact loading. *International Journal of Impact Engineering,* 146, 103726.

Wei, J., Li, J., Wu, C., Liu, Z., Li, J., 2021. Hybrid fibre reinforced ultra-high performance concrete beams under static and impact loads. *Engineering Structures*, 245, 112921.

Wei, J., Li, J., Wu, C., Liu, Z., Fang, J., 2021. Impact resistance of ultra-high performance concrete strengthened reinforced concrete beams. *International Journal of Impact Engineering,* 158, 104023.

Table of Contents