THE UNIVERSITY of ADELAIDE

AXIAL COMPRESSIVE BEHAVIOUR OF FRP-CONFINED HIGH-STRENGTH CONCRETE

Thomas J. Vincent

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CONTENTS

ABSTRACT

External confinement of concrete columns with fibre-reinforced polymer (FRP) sheets has been shown to lead to significant improvements on the axial compressive behaviour of these columns. This application of FRP composites is effective as a confinement material for concrete, in both the seismic retrofit of existing reinforced concrete columns and in the construction of concrete-filled FRP tubes (CFFTs) as earthquake-resistant columns in new construction. However, experimental studies on the axial compressive behaviour of FRP-confined concrete columns manufactured with high strength concrete (HSC) remain very limited. This thesis presents the results from a Ph.D. study at the University of Adelaide that was aimed at undertaking a comprehensive review on the axial compressive behaviour of monotonically-loaded circular FRP-confined HSC columns.

The 10 journal articles developed as part of this thesis present the findings from experimental tests on a total of 282 FRP-concrete composite specimens. The effects of amount of confinement, concrete strength, confinement method, specimen size, fibre type, manufacturing method, fibre orientation, specimen end condition, specimen slenderness, concrete shrinkage, strain measurement method, FRP overlap and lateral prestress were investigated. The test specimens were manufactured with aramid FRP (AFRP), carbon FRP (CFRP) or high-modulus CFRP (HMCFRP) and their unconfined concrete strengths ranged from 34.0 to 119.3 MPa. Specimens were manufactured as either FRP-wrapped or concrete-filled FRP tubes (CFFTs), with all specimens cylindrical in shape and the majority 152 mm in diameter and 305 mm in height. The large quantity of the results presented in this thesis allows for a number of significant conclusions to be drawn.

The experimental results presented in this thesis provide a performance comparison between FRP-confined normal-strength concrete (NSC) and the experimentally limited area of FRP-confined HSC. The results from this thesis indicate that, above a certain confinement threshold, FRP-confined HSC columns exhibit highly ductile behaviour. However, for the same normalised confinement pressures, axial performance of FRP-confined concrete reduces as concrete strength increases. The results also indicate that the behaviour of FRP-confined concrete is significantly influenced by the manufacturing method, with specimens manufactured through an automated filament winding technique exhibiting improved compressive behaviour over companion specimens manufactured through a manual wet layup technique. In addition to this, the influence of fibre type was examined with an improvement in compressive behaviour linked to an increase in fibre rupture strain. Further experimental testing on the influence of specimen size, confinement method and end condition found these parameters to have negligible effect for the range of parameters tested in this study. Experimental testing on specimens with inclined fibres revealed specimen performance is optimised when fibres are aligned in the hoop direction and the performance diminishes with decreasing fibre angle with respect to the longitudinal axis.

The influence of height-to-diameter ratio (*H/D*) on axial compressive behaviour revealed specimens with *H/D* of 1 outperform companion specimens with a *H/D* ratio of 2 to 5, with significantly increased strength and strain enhancements. The influence of slenderness on

specimens with a *H/D* ratio between 2 and 5 was found to be significant in regards to axial strain enhancement, with a decrease observed as specimen slenderness increased. Conversely, the influence of slenderness on axial strength enhancement was found to be negligible. The strain results indicate that hoop rupture strains along the height of FRP-confined concrete become more uniform for specimens with higher amounts of confinement. On the other hand, the variation of hoop strains around the perimeter was not observed to be significantly influenced by slenderness, concrete strength or amount of confinement.

An examination on the effect of FRP overlap length revealed no significant influence exists for the amount of overlap length on strain enhancement ratio. On the other hand, an increase in overlap length leads to a slight increase in strength enhancement, with these observations equally applicable to both continuously and discontinuously wrapped specimens. The results also indicate that continuity of the FRP sheet in the overlap region has some influence on the effectiveness of FRP confinement. Furthermore, it was observed that the distribution of FRP overlap regions for discontinuously wrapped specimens can influence the axial compressive behaviour of these specimens in certain overlap configurations. Finally, it is found that the distribution of lateral confining pressure around specimen perimeter becomes less uniform for specimens with higher concrete strengths and those manufactured with overlap regions that are not evenly distributed.

The results from experimental testing of specimens with FRP-to-interface gap revealed that the influence of gap on axial strain enhancement is significant, with an increase observed as the gap increased. Conversely, the influence of interface gap on axial strength enhancement is found to be small with a slight reduction observed with increased gap. The results also indicate that an increase in gap causes an increase in strength loss during the transition region of the stress-strain curve, as a result of the delayed activation of the FRP shell.

The results from experimental study on FRP-confined concrete with lateral prestressing indicates that the influence of prestress on compressive strength is significant, with an increase in ultimate strength observed in all prestressed specimens compared to that of non-prestressed specimens. On the other hand, the influence of prestress on axial strain was found to be dependent on the amount of confinement, with lightly-confined and well-confined prestressed specimens displaying a decrease and increase in ultimate strain, respectively, compared to their non-prestressed counterparts. The results also indicate that prestressing the FRP shell prevents the sudden drop in strength, typically observed in FRP-confined HSC specimens, that initiates at the transition point that connects the first and second branches of the stress-strain curves. Finally, it was observed that prestressing the FRP tube results in a significant increase in the specimen toughness as well as in the hoop strain efficiency of the FRP shell.

In addition to the summarised experimental findings, an analysis of the experimental databases for specimens manufactured with an interface gap and lateral prestress led to the development of a lateral strain-to-axial strain model. A comparison of the proposed model with the experimental results of specimens prepared with an interface gap or prestressed FRP tubes showed good agreement.

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LIST OF PUBLICATIONS

A total of 23 journal and conference papers resulted from the research reported in this thesis. A list of these publications is presented below.

Journal Papers - Published and In Press

1. Ozbakkaloglu, T., Lim, J. C., and Vincent, T. (2013) "FRP-confined concrete in circular sections: Review and assessment of stress-strain models." *Engineering Structures,* 49: pp 1068 – 1088.
2. Vincent, T., and Ozbakkaloglu, T. (2013) "Influence of concrete strength and confinement method on axial compressive behavior of FRP confined high- and ultra high-strength concrete." *Composites Part B,* 50: pp 413 – 428.
3. Ozbakkaloglu, T., and Vincent, T. (2013) "Axial compressive behavior of circular high-strength concrete-filled FRP tubes." *ASCE Journal of Composites for Construction,* 18(2), 04013037.
4. Vincent, T., and Ozbakkaloglu, T. (2013) "Influence of fiber orientation and specimen end condition on axial compressive behavior of FRP-confined concrete." *Construction and Building Materials,* 47: pp 814 – 826.
5. Vincent, T., and Ozbakkaloglu, T. (2014). "Influence of slenderness on stress-strain behavior of concrete-filled FRP tubes: experimental study." *ASCE Journal of Composites for Construction*, 19(1), 04014029.
6. Vincent, T., and Ozbakkaloglu, T. (2015). "Influence of shrinkage on compressive behavior of concrete-filled FRP tubes: An experimental study on interface gap effect." *Construction and Building Materials,*75: pp 144 – 156.
7. Vincent, T., and Ozbakkaloglu, T. (2015). "Influence of overlap configuration on compressive behavior of CFRP-confined normal- and high-strength concrete." *Materials and Structures,* DOI: 10.1617/s11527-015-0574-x.
8. Vincent, T., and Ozbakkaloglu, T. (2015). "Compressive behavior of prestressed high-strength concrete-filled aramid FRP tube columns: Experimental observations." *ASCE Journal of Composites for Construction,* DOI: 10.1061/(ASCE)CC.1943-5614.0000556, 04015003.

Journal Papers - To Be Submitted

1. Vincent, T., and Ozbakkaloglu, T. (2015). "Lateral strain-to-axial strain relationship for concrete-filled FRP tube columns incorporating interface gap and prestressed confinement."

Special Publication - Published

1. Vincent, T., and Ozbakkaloglu, T. (2014). "Axial compressive behaviour of FRP-confined concrete columns: investigation of less-understood influences." *Concrete in Australia – Feature: Fiber Reinforced Polymer,* 40 (2) pp 37 – 45. *(Invited Paper)*

Conference Papers - Published

1. Vincent, T., and Ozbakkaloglu, T. (2009). "Influence of concrete strength and fibre type on the compressive behaviour of FRP-confined high-strength concrete." *9th Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-09),* Sydney, Australia, July 12–15.
2. Vincent, T., and Ozbakkaloglu, T. (2013). "Axial compressive behavior of high- and ultra high-strength concrete-filled AFRP tubes." *3rd International Conference on Structures and Building Materials (ICSBM-3),* Guiyang, China, March 9-10.
3. Vincent, T., and Ozbakkaloglu, T. (2013). "An experimental study on the compressive behavior of CFRP-confined high- and ultra high-strength concrete." *3rd International Conference on Structures and Building Materials (ICSBM-3),* Guiyang, China, March 9-10.
4. Vincent, T., and Ozbakkaloglu, T. (2013). "The effect of confinement method and specimen end condition on behavior of FRP-confined concrete under concentric compression." *3rd International Conference on Civil Engineering, Architecture and Building Materials (CEABM 2013)*, Jinan, China, May 25-26.
5. Vincent, T., and Ozbakkaloglu, T. (2013). "Influence of fiber type on behavior of high-strength concrete-filled FRP tubes under concentric compression." *2nd International Conference of Civil Engineering, Architecture and Sustainable Infrastructure (ICCEASI 2013)*, Zhengzhou, China, July 13-15.
6. Vincent, T., and Ozbakkaloglu, T. (2013). "Influence of fiber orientation on axial compressive behavior of high-strength concrete-filled FRP tubes." *21st Annual International Conference on Composites or Nano Engineering* (*ICCE-21),* Tenerife, Spain, July 21-27.
7. Vincent, T., and Ozbakkaloglu, T. (2013). "Influence of slenderness on behavior of high-strength concrete-filled FRP tubes under axial compression." *3rd International Conference on Civil Engineering and Transportation (ICCET 2013)*, Kunming, China, December 14-15.
8. Vincent, T., and Ozbakkaloglu, T. (2013). "Variation of hoop strains in concrete-filled FRP tubes with concrete strength, amount of confinement and specimen slenderness." *3rd International Conference on Civil Engineering and Transportation (ICCET 2013)*, Kunming, China, December 14-15.
9. Vincent, T., and Ozbakkaloglu, T. (2014). "Axial strains in FRP-confined normal- and high-strength concrete: An examination of strain measurement methods." *4th International Conference on Structures and Building Materials (ICSBM-4),* Guangzhou, China, March 15-16.
10. Vincent, T., and Ozbakkaloglu, T. (2014). "Influence of overlap region configuration on behaviour of concrete-filled FRP tubes." *13th International Symposium on Structural Engineering (ISSE-13),* Hefei, China, October 24-27.
11. Vincent, T., and Ozbakkaloglu, T. (2014). "Influence of FRP-to-concrete gap effect on axial strains of FRP-confined concrete columns." *4th International Conference on Mechanical Engineering Materials and Energy (ICMEME-4)*, Singapore, Singapore, November 14-15.

12. Vincent, T., and Ozbakkaloglu, T. (2014). "An experimental study on the effect of concrete shrinkage on compressive behaviour of high-strength concrete-filled FRP tubes." *23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM-23)*, Byron Bay, Australia, December 9-12.
13. Vincent, T. (2014). "Influence of prestress on axial compressive behaviour of high-strength concrete-filled FRP tubes." *4th International Conference on Civil Engineering and Transportation (ICCET 2014)*, Xiamen, China, December 24-25.