AXIAL COMPRESSIVE BEHAVIOUR OF FRP-CONFINED HIGH-STRENGTH CONCRETE

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M.Phil. (Structural Engineering)
B.Eng. (Civil & Structural) Hons.

Thesis submitted to The University of Adelaide
School of Civil, Environmental and Mining Engineering
in fulfilment of the requirements
for the degree of Doctor of Philosophy

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.

STATEMENT OF ORIGINALITY

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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John VINCENT, Thomas — Date

ACKNOWLEDGEMENTS

I wish to extend my gratitude and appreciation to all those who have assisted me throughout my Ph.D. studies. First and foremost, I would like to thank my Primary Supervisor; Dr. Togay Ozbakkaloglu, who supported me throughout my candidature. I am especially grateful for his determination, vision, patience and encouragement. I am also grateful to my Secondary Supervisor; Prof. Michael Griffith, who supplied me with encouragement and motivation throughout my candidature. Together, their supervision has been of great value to me, and this thesis would not have been possible but for their joint contributions.

I am very grateful to the staff of the School of Civil, Environmental and Mining Engineering for their continual support and advice throughout my candidature. I wish to acknowledge the considerable effort from the laboratory technicians in performing many experimental tasks. In particular, I thank Mr. Dale Hodson who provided technical support throughout the experimental programs. In addition I wish to thank the following members of the School's technical staff: Messrs. Jon Ayoub, Ian Cates, Terry Cox, Simon Golding, Steven Huskinson, Ian Ogier and Adam Ryntjes.

I would like to take this opportunity to also acknowledge the support I have received from my fellow Ph.D. students throughout my candidature. In particular I would like to thank Messrs. Jian (James) C. Lim, Butje Alfonsius Louk Fanggi and Ms. Yunita Idris for their friendship and encouragement. My thanks extends also to other Ph.D. students in the School of Civil, Environmental and Mining Engineering who have provided me support and encouragement throughout the course of my Ph.D. studies.

Finally, I would like to acknowledge the continual support provided by my family throughout my Ph.D. studies. I will always be in debited to my parents; Tony and Helen, and my sister; Kiralee, who supplied me with unwavering encouragement and motivation to give me the strength to complete this challenging, but rewarding achievement.

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.
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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.

INTRODUCTION

It is now well-understood that the confinement of concrete with fibre-reinforced polymer (FRP) composites can lead to significant improvements in both compressive strength and ductility. Over the last two decades a significant number of experimental studies have been performed on both FRP-wrapped specimens, intended for retrofitting applications, and concrete-filled FRP-tubes (CFFTs), intended for new construction. However, the majority of these existing studies focused on normal-strength concrete with unconfined compressive strengths less than approximately 55 MPa.

The popularity of higher strength concretes in the construction industry has been on a steady incline due to the superior performance and economy offered by high-strength concrete (HSC) over normal-strength concrete (NSC) in a large number of structural engineering applications. These beneficial characteristics result in more cost-effective construction of bridges and multi-storey buildings. However, the use of higher strength concretes in seismically active regions poses difficulties because of the inherently brittle nature of the material. Confining HSC with FRP tubes is an emerging construction technique that combines two high-strength materials to form a high-performance member while eliminating the inherent brittle nature normally associated with unconfined HSC members.

Research on the compressive behaviour of FRP-confined HSC, in general, and on high-strength CFFTs (HSCFFTs), in particular, remain limited with only a few studies reported in the existing literature. The publications reported in this thesis present a significant contribution to the current literature by reporting a number of important findings from the presented experimental programs on FRP-confined HSC. In these publications a summary of the experimental programs are provided, including discussion of the specimen properties and testing procedures. Following this, results of the experimental program are presented, where the ultimate conditions of the specimens are tabulated and stress-strain responses are graphically illustrated. Finally, a detailed discussion on the important factors influencing the axial compressive behaviour is provided and key outcomes clearly summarised.

Research Overview

This research aims to improve the understanding of the axial compressive behaviour of FRP-confined HSC. Initially a comprehensive review was conducted into existing experimental tests and models development for the axial compressive behaviour of FRP-confined normal-strength concrete. This task involved the review of all current published literature until the end of 2011, which resulted in the collection of 88 models developed to predict the axial stress-strain behaviour and 730 test datasets. This comprehensive review of FRP-confined conventional normal-strength concrete (NSC) led to the identification of key confinement parameters which were subsequently examined for the lesser understood area of FRP-confined HSC. These parameters were examined by designing and conducting new experimental programs at the University of Adelaide.

The experimental programs planned and conducted as part of this research resulted in the manufacturing and testing of 282 test specimens. A close examination of this large database of experimental results has led to a number of important discoveries on the topic of FRP-confined HSC. Finally, the test results reported as part of the experimental program allowed the development of the first axial stress-strain model that is applicable to prestressed or delayed activation of confinement, caused by prestressing the confinement fibres or radial shrinkage of concrete, respectively

Thesis Overview

This thesis is structured into 10 main chapters, with each chapter consisting of a manuscript that has been submitted for publication throughout the course of this study [1-10]. *Table 1* outlines the main areas of focus for each manuscript, including the review of literature, experiment testing and model development.

The important parameters influencing the axial compressive behaviour of FRP-confined HSC outlined in *Table 1* have been investigated in this research. These key confinement parameters include:

1. Amount of confinement - specimens confined with between 1 and 6 layers of FRP confinement, resulting in a total fibre thickness between 0.117 and 0.702 mm, were experimentally examined. This range of test specimens resulted in confinement ratios (f_{lu}/f'_{co}) between 0.06 and 0.49.
2. Concrete compressive strength - the unconfined concrete compressive strength (f'_{co}) was examined by testing specimens with f'_{co} between 34.0 and 119.3 MPa.
3. Confinement method - specimens manufactured as FRP-wrapped and concrete-filled FRP tubes (CFFTs) were both experimentally investigated.
4. Specimen size - the influence of specimen size was examined by designing specimens with nominal diameters of 75, 100, 150 and 300 mm, with each specimen maintaining a 2:1 height-to-diameter ratio.
5. Fibre type - the fibre types investigated in this research included aramid, carbon and high-modulus carbon.
6. Manufacturing method - FRP confining shells were prepared with either the automated filament winding technique or manual wet layup technique.
7. Fibre orientation - the majority of specimens were prepared with fibres aligned in the hoop direction, however the orientation of the unidirectional fibres was examined by manufacturing a group of specimens with fibres aligned at 45, 60 and 75 degrees.
8. Specimen end condition - the effect of specimen end condition was examined on CFFTs and FRP-wrapped specimens by studying the influence of loading the FRP jacket on the axial compressive behaviour.
9. Specimen slenderness - test specimens manufactured with height-to-diameter ratios of 1, 2, 3 and 5 were investigated in this research.
10. Concrete shrinkage - the influence of FRP-to-concrete interface gap, caused by radial shrinkage of the concrete, on axial compressive behaviour was examined by applying a

gap of up to 0.12 mm thickness. This gap simulated shrinkage strains of up to 1600 microstrain.

11. Strain measurement method - axial strain recordings from axial strain gauges and full- and mid-height linear variable displacement transformers (LVDTs) were investigated.
12. FRP overlap - the influence of FRP overlap configuration, distribution and continuity on the axial compressive behaviour was examined in this research.
13. Lateral prestress - prestressing of the fibres in the FRP confinement shell was investigated as a potential technique to overcome the delay in confinement activation and subsequent drop in compressive strength typically experienced by FRP-confined HSC.

Table 2 provides further details on each experimental program performed as part of this research. It can be seen in this table that a total of 282 test specimens were experimentally examined with unconfined concrete strengths ranging from 34.0 to 119.3 MPa. It can also be seen in this table that the majority of the resulting publications contained an examination of the axial stress-strain response, ultimate axial stresses and strains and FRP tube hoop rupture strains. In addition to these core experimental test results, further experimental outcomes reported and examined within each paper have been provided.

Table 1. Summary of publications

	Review of literature		Parameter investigated												
	Data sets	Stress-strain models	Amount of confinement	Concrete compressive strength	Confinement method	Specimen size	Fibre type	Manufacturing method	Fibre orientation	Specimen end condition	Specimen slenderness	Concrete shrinkage	Strain measurement method	FRP overlap	Lateral prestress
Ozbakkaloglu et al. [1]	Collect and review	Collect and review	-	-	-	-	-	-	-	-	-	-	-	-	-
Vincent and Ozbakkaloglu [2]	-	-	Exp.	Exp.	Exp.	-	-	-	-	-	-	-	-	-	-
Ozbakkaloglu and Vincent [3]	-	-	-	Exp.	-	Exp.	Exp.	Exp.	-	-	-	-	-	-	-
Vincent and Ozbakkaloglu [4]	-	-	-	-	Exp.	-	-	-	Exp.	Exp.	-	-	-	-	-
Vincent and Ozbakkaloglu [5]	-	-	Exp.	Exp.	-	-	-	-	-	-	Exp.	-	-	-	-
Vincent and Ozbakkaloglu [6]	-	-	-	-	-	-	-	-	-	-	-	Exp.	Exp.	-	-
Vincent and Ozbakkaloglu [7]	-	-	-	Exp.	-	-	-	-	-	-	-	-	-	Exp.	-
Vincent and Ozbakkaloglu [8]	-	-	-	-	Sum.	-	-	-	Sum.	Sum.	Sum.	Sum.	Sum.	-	-
Vincent and Ozbakkaloglu [9]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Exp.
Vincent and Ozbakkaloglu [10]	-	-	-	-	-	-	-	-	-	-	-	Model	-	-	Model

where: Exp. denotes an experimental program was designed and performed; Sum. denotes a summary of experimental results was provided.

Table 2. Summary of experimental details examined

	Experimental details							
					Experimental results examined			
	Number of specimens	Concrete strength, f'_{co} (MPa)	Confinement method	Fibre type	Axial stress-strain behaviour	Ultimate strength and strain	FRP tube hoop rupture strains	Additional details examined
Vincent and Ozbakkaloglu [2]	55	34.6 - 112.0	FRP-wrapped, CFFTs	CFRP	yes	yes	yes	Performance of 10 existing stress-strain models was assessed against the recorded data.
Ozbakkaloglu and Vincent [3]	83	34.0 - 110.1	CFFTs	AFRP, CFRP, HMCFRP	yes	yes	yes	Due to large quantity of specimens, no additional details examined.
Vincent and Ozbakkaloglu [4]	24	49.4 - 85.9	FRP-wrapped, CFFTs	AFRP	yes	yes	yes	Axial strain measurement method examined. Hoop strain and fibre strain development compared for specimens manufactured with inclined fibres.
Vincent and Ozbakkaloglu [5]	33	55.2 - 119.3	CFFTs	AFRP	yes	yes	yes	Variation of hoop strains along specimen height and around specimen perimeter examined.
Vincent and Ozbakkaloglu [6]	30	44.8 -83.2	FRP-wrapped, CFFTs	AFRP	yes	yes	yes	Long term concrete shrinkage strains monitored. Axial and lateral strain development on FRP shell examined
Vincent and Ozbakkaloglu [7]	33	52.0 - 84.7	CFFTs	CFRP	yes	yes	yes	Hoop strain and corresponding lateral confinement pressure development examined. Effectiveness of confinement arrangement examined.
Vincent and Ozbakkaloglu [8]	n/a	n/a	FRP-wrapped, CFFTs	AFRP, CFRP	n/a	n/a	n/a	Overview of a number of less-understood parameters, a summary of previously established findings presented.
Vincent and Ozbakkaloglu [9]	24	100.2 - 110.3	CFFTs	AFRP	yes	yes	yes	Prestress application method developed. Prestress losses monitored. Specimen toughness examined.
Total	282							

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[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.

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JOURNAL ARTICLES

JOURNAL ARTICLE 1

Statement of Authorship

Title of Paper	FRP-Confined Concrete in Circular Sections: Review and Assessment of Stress-Strain Models
Publication Status	(•) Published ( ) Accepted for Publication ( ) Submitted for Publication ( ) Publication Style
Publication Details	Engineering Structures, Volume 49, Pages 1068–1088, Year 2013

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author	Dr. Togay Ozbakkaloglu		
Contribution to the Paper	Research supervision and review of manuscript		
Signature		Date	22/02/2015

Name of Co-Author (Candidate)	Mr. Jian Chin Lim		
Contribution to the Paper	Review of literature, assessment of existing models, and preparation of manuscript		
Signature		Date	22/02/2015

Name of Co-Author	Mr. Thomas Vincent		
Contribution to the Paper	Preparation of manuscript		
Signature		Date	23/2/2015.

Ozbakkaloglu, T., Lim, J. C., and Vincent, T. (2013) FRP-confined concrete in circular sections: Review and assessment of stress-strain models.
Engineering Structures, v. 49, pp. 1068-1088.

NOTE:
This publication is included on pages 12 - 32 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1016/j.engstruct.2012.06.010

JOURNAL ARTICLE 2

Statement of Authorship

Title of Paper	Influence of concrete strength and confinement method on axial compressive behavior of FRP confined high- and ultra high-strength concrete
Publication Status	(●) Published ( ) Accepted for Publication ( ) Submitted for Publication ( ) Publication Style
Publication Details	Composites: Part B, Volume 50, Pages 413 - 428, Year 2013

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author	Mr Thomas Vincent		
Contribution to the Paper	Preparation of experimental database, analysis of test results, assessment of model performance against database and preparation of manuscript		
Signature		Date	4/03/2015

Name of Co-Author (Candidate)	Dr Togay Ozbakkaloglu		
Contribution to the Paper	Research supervision and review of manuscript		
Signature		Date	4/03/2015

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: Engineering, v. 50: pp 413-428.

NOTE:
This publication is included on pages 37 - 52 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1016/j.compositesb.2013.02.017

JOURNAL ARTICLE 3

Statement of Authorship

Title of Paper	Axial compressive behavior of circular high-strength concrete-filled FRP tubes
Publication Status	(●) Published ( ) Accepted for Publication ( ) Submitted for Publication ( ) Publication Style
Publication Details	Journal of composites for construction, Volume 18, Issue 2, 04013037, Year 2103

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Co-Author (Candidate)	Dr Togay Ozbakkaloglu		
Contribution to the Paper	Design and supervision of experimental tests, and supervision of manuscript		
Signature		Date	4/03/2015

Name of Principal Author	Mr Thomas Vincent		
Contribution to the Paper	Preparation of experimental database, analysis of test results, and preparation of manuscript		
Signature		Date	4/03/2015

Ozbakkaloglu, T., and Vincent, T. (2013) Axial compressive behavior of circular highstrength concrete-filled FRP tubes.
ASCE Journal of Composites for Construction, v. 18 (2), pp. 04013037-1 – 04013037-11

NOTE:
This publication is included on pages 56 - 73 in the print copy of the thesis held in the University of Adelaide Library.

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http://dx.doi.org/10.1061/(ASCE)CC.1943-5614.0000410

JOURNAL ARTICLE 4

Statement of Authorship

Title of Paper	Influence of fiber orientation and specimen end condition on axial compressive behavior of FRP-confined concrete
Publication Status	(●) Published ( ) Accepted for Publication ( ) Submitted for Publication ( ) Publication Style
Publication Details	Construction and Building Materials, Volume 47, Pages 814 - 826, Year 2013

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author	Mr Thomas Vincent		
Contribution to the Paper	Preparation of experimental database, analysis of test results, and preparation of manuscript		
Signature		Date	4/03/2015

Name of Co-Author (Candidate)	Dr Togay Ozbakkaloglu		
Contribution to the Paper	Design and supervision of experimental tests, and review of manuscript		
Signature		Date	4/03/2015

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, v. 47, pp 814 – 826

NOTE:
This publication is included on pages 78 - 90 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1016/j.conbuildmat.2013.05.085

JOURNAL ARTICLE 5

Statement of Authorship

Title of Paper	Influence of slenderness on stress-strain behavior of concrete-filled FRP tubes: Experimental study
Publication Status	(•) Published ( ) Accepted for Publication ( ) Submitted for Publication ( ) Publication Style
Publication Details	Journal of Composites for Construction, Volume 19, Issue 1, 04014029, Year 2014

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author	Mr Thomas Vincent		
Contribution to the Paper	Supervision of experimental testing, preparation of experimental database, analysis of test results, and preparation of manuscript		
Signature		Date	4/03/2015

Name of Co-Author (Candidate)	Dr Togay Ozbakkaloglu		
Contribution to the Paper	Design and supervision of experimental tests, and review of manuscript		
Signature		Date	4/03/2015

Vincent, T., and Ozbakkaloglu, T. (2015). Influence of slenderness on stress-strain behaviour of concrete-filled FRP tubes: experimental study.
ASCE Journal of Composites for Construction, v. 19 (1), pp. 04014029-1 – 04014029-13

NOTE:
This publication is included on pages 94 - 106 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1061/(ASCE)CC.1943-5614.0000489

JOURNAL ARTICLE 6

Statement of Authorship

Title of Paper	Influence of shrinkage on compressive behavior of concrete-filled FRP tubes: An experimental study on interface gap effect
Publication Status	(●) Published ( ) Accepted for Publication ( ) Submitted for Publication ( ) Publication Style
Publication Details	Construction and Building Materials, Volume 75, Pages 144 - 156, Year 2015

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author	Mr Thomas Vincent		
Contribution to the Paper	Design of experimental tests, manufacture and laboratory testing of specimens, preparation of experimental database, analysis of test results, and preparation of manuscript		
Signature		Date	4/03/2015

Name of Co-Author (Candidate)	Dr Togay Ozbakkaloglu		
Contribution to the Paper	Supervision of experimental tests, and review of manuscript		
Signature		Date	4/03/2015

Vincent, T., and Ozbakkaloglu, T. (2015). Influence of shrinkage on compressive behaviour of concrete-filled FRP tubes: An experimental study on interface gap effect.
Construction and Building Materials, v. 75, pp 144 – 156

NOTE:
This publication is included on pages 110 - 122 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1016/j.conbuildmat.2014.10.038

JOURNAL ARTICLE 7

Statement of Authorship

Title of Paper	Influence of overlap configuration on compressive behavior of carbon FRP-confined normal- and high-strength concrete
Publication Status	(●) Published ( ) Accepted for Publication ( ) Submitted for Publication ( ) Publication Style
Publication Details	Materials and Structures, DOI 10.1617/s11527-015-0574-x

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author	Mr Thomas Vincent		
Contribution to the Paper	Supervision of experimental testing, preparation of experimental database, analysis of test results, and preparation of manuscript		
Signature		Date	4/03/2015

Name of Co-Author (Candidate)	Dr Togay Ozbakkaloglu		
Contribution to the Paper	Design and supervision of experimental tests, and review of manuscript		
Signature		Date	4/03/2015

Vincent, T., and Ozbakkaloglu, T. (2015). Influence of overlap configuration on compressive behavior of CFRP-confined normal- and high-strength concrete. *Materials and Structures, Published Online, pp. 1 - 24*

NOTE:
This publication is included on pages 127 - 150 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1617/s11527-015-0574-x

JOURNAL ARTICLE 8

Statement of Authorship

Title of Paper	Axial compressive behaviour of FRP-confined concrete columns: Investigation of less-understood influences
Publication Status	(●) Published ( ) Accepted for Publication ( ) Submitted for Publication ( ) Publication Style
Publication Details	Concrete in Australia, Volume 40, Issue 2, Page 37 - 45, Year 2014

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author	Mr Thomas Vincent		
Contribution to the Paper	Compiling test results for comparison, and preparation of manuscript		
Signature		Date	4/03/2015

Name of Co-Author (Candidate)	Dr Togay Ozbakkaloglu		
Contribution to the Paper	Review of manuscript		
Signature		Date	4/03/2015

Axial compressive behaviour of FRP-confined concrete columns: investigation of less-understood influences

Thomas Vincent and Togay Ozbakkaloglu – The University of Adelaide

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. A comprehensive experimental program has been underway at the Structures Laboratory of The University of Adelaide to investigate the influence of column parameters on the axial compressive behaviour of FRP-confined concrete columns. This paper presents important findings from these investigations by reporting and discussing the results of concrete filled FRP tubes (CFFTs) and FRP-wrapped concrete specimens selected among over 500 specimens tested. These parameters include confinement method, specimen slenderness, fibre orientation, specimen end condition and concrete shrinkage. In addition to these confinement parameters, the influence of the axial strain measurement method on the recorded results was also examined. The results indicate that specimen slenderness, fibre orientation and concrete shrinkage significantly affect the axial behaviour of FRP-confined concrete. The influence of confinement method and specimen end condition was found to be minor. The results also indicate that the axial strain measurement method can have a significant influence on the recorded axial strains.

1.0 INTRODUCTION

External confinement of concrete with fibre reinforced polymer (FRP) jackets has become widely accepted for strengthening reinforced concrete members. A large number of experimental studies into the axial compressive behaviour have been performed over the last two decades, producing over 3000 test results as discussed and assessed in the recent comprehensive review studies reported in Ozbakkaloglu et al (2013); Ozbakkaloglu & Lim (2013); Lim & Ozbakkaloglu (2014). The majority of early experimental studies focused on FRP-wrapped concrete columns (Rousakis, 2001; Berthet et al, 2005; Ilki et al, 2008; Wang & Wu, 2008; Eid et al, 2009; Ozbakkaloglu & Akin, 2012), but more recently attention has turned to the potential applications of FRP composites for new structures. One such application, the CFFTs, has recently received significant research attention (Ozbakkaloglu & Oehlers, 2008a, 2008b; Mohamed & Masmoudi, 2010; Park et al, 2011; Ozbakkaloglu, 2013a, 2013b, 2013c, 2013d; Ozbakkaloglu & Vincent, 2013; Vincent and Ozbakkaloglu, 2013a, 2013b). These recent studies on compressive behaviour of CFFTs, along with those on their seismic behaviour (Ozbakkaloglu & Saatcioglu, 2006, 2007; Saatcioglu et al, 2008; Idris & Ozbakkaloglu, 2013), demonstrated the ability of CFFTs to develop very high inelastic deformation capacities, making them an attractive alternative for construction of high performance columns.

Previous experimental studies on FRP-wrapped concrete and CFFT columns have examined the influence of critical confinement parameters such as concrete strength, amount of confinement, specimen size, specimen shape and fibre type on the axial compressive behaviour (Mirmiran et al, 1998; Lam & Teng, 2004; Silva and Rodrigues, 2006; Ozbakkaloglu, 2013a, 2013b, 2013c, 2013d; Ozbakkaloglu & Vincent, 2013; Vincent & Ozbakkaloglu, 2013a, 2013b). However, there remain additional confinement parameters that have received less research attention and associated experimental testing. A comprehensive experimental program has been underway at The University of Adelaide to address this research gap, where a wide variety of less understood confinement parameters have been investigated. This paper presents important findings from these experimental investigations that focused on the behaviour of FRP-confined normal- and high-strength concrete (NSC and HSC) columns under concentric compression. First, a summary of the test program is provided, including specimen properties and the testing procedure. Following this, a discussion on typical failure modes of the test columns is presented. Finally, comparisons of the axial stress-strain behaviours of these columns are shown and discussions on the influence of investigated parameters are provided.

2.0 EXPERIMENTAL PROGRAM

Over 500 FRP-confined concrete specimens have been manufactured and tested under concentric compression as part of an ongoing comprehensive investigation at The University of Adelaide on FRP concrete composite columns. This paper reports on the results of a group of these specimens, which were carefully selected to investigate the influence of the less understood parameters on the compressive behaviour of FRP-confined concrete columns.

2.1 Test specimens and materials

The test specimens presented in this paper were manufactured as either concrete filled FRP tubes (CFFTs) or FRP-wrapped concrete specimens. The specimen diameter varied from

Table 1: Material properties of fibres.

Type	Provided by manufacturer				Obtained from coupon tests		
	Nominal fibre thickness (mm)	Ultimate tensile stress (MPa)	Ultimate tensile strain (%)	Elastic modulus (GPa)	Ultimate tensile stress (MPa)	Ultimate tensile strain (%)	Elastic modulus (GPa)
Aramid sheet type 1	0.2 or 0.3	2600	2.2	118.2	2390	1.86	128.5
Aramid sheet type 2	0.2	2900	2.5	120	2663	2.12	125.7
Aramid filament used in wound tubes		2930	2.9	99			
Carbon	0.117	3800	1.55	240	3626	1.44	251

100 mm to 152 mm and the height varied from 152 mm to 762 mm, with the majority of the specimens having a 152 mm diameter and 305 mm height. The average compressive strength of the concrete ranged from 35 to 120 MPa with all batches of concrete mixed and cured at The University of Adelaide.

The majority of the CFFT specimens were prepared using a manual wet lay-up process by wrapping epoxy resin impregnated fibre sheets around precision cut styrofoam templates. Only the specimens with fibres oriented at an inclined angle were selected to be manufactured using an automated filament winding process, which was performed at the University of Alberta in Canada. Specimens not manufactured as CFFTs were prepared as FRP-wrapped specimens, where a thin layer of epoxy resin was applied to the concrete surface prior to manually wrapping the fibre sheets around precast concrete cylinders. All CFFTs and FRP-wrapped specimens constructed using the manual wet lay-up technique had fibre sheets oriented in the hoop direction with at least 100 mm overlap unless otherwise indicated. The CFFT specimens manufactured by an automated filament winding process had fibre winding angles of 45, 60, 75 and 88 degrees relative to the longitudinal axis to examine the influence of fibre orientation.

The type of fibre used in this experimental program included aramid and carbon FRP (AFRP and CFRP), with examples of these fibres shown in Figure 1. The epoxy adhesive consisted of two parts, epoxy resin binder and thixotropic epoxy adhesive, which were mixed at a ratio of 3:1. FRP coupons, with 25 mm width and a clear span of 138 mm length, were manufactured and tested in parallel to the FRP-confined concrete specimens in accordance with ASTM standard D3039M-08 (ASTM, 2008). Examples of the manufacturing methods of the FRP-confined concrete specimens are shown in Figure 2. The manufacturer-supplied material properties of the unidirectional fibre sheets and the fibres used in the manufacture of the filament wound tubes are shown in Table 1, together with the properties determined from coupon tests.

The specimens were prepared using two different grades of concrete, namely NSC and HSC. In this paper, unconfined concrete strength (f'_{co}) below 55 MPa is referred to as NSC and over 55 MPa as HSC. In designing the FRP confinement, due consideration was given to the well understood influence of the strength of concrete on its confinement demand (Ozbakkaloglu 2013c; Ozbakkaloglu & Vincent, 2013). This was done by selecting the number of FRP layers dependent on concrete strength with higher strength concrete specimens receiving proportionally more layers to ensure adequate confinement.

(a) (b) (c) (d)

Figure 1: Materials for manufacturing FRP-confined specimens: (a) unidirectional aramid fibre sheet; (b) unidirectional carbon fibre sheet; (c) mixing epoxy resin; (d) preparing epoxy resin for application.

(a) (b) (c) (d)

Figure 2: Manufacturing process for FRP-confined specimens: (a) impregnating carbon fibre sheet with epoxy resin; (b) wet lay-up on styrofoam mould; (c) AFRP tubes prior to concrete pour; (d) concrete filled AFRP tubes.

2.2 Instrumentation and testing

Axial deformations of the specimens were measured with four linear variable displacement transducers (LVDTs), which were mounted at the corners between the loading and supporting steel plates of the test machine. These deflection readings were used to calculate average axial strains along the heights of the specimens. In addition to the four full height LVDTs, a surface mounted LVDT cage was attached to the mid-section of each 152 mm specimen to monitor mid-height deflections of these specimens. The LVDT cage had an LVDT installed on each of its four sides and it was designed to be mounted directly on the FRP shell via surface screws. The mid-height LVDT cage had a gauge length of 175 mm and it was placed at equal distance from each end. In addition to the LVDTs, specimens were instrumented with a large number of unidirectional strain gauges to monitor strain development on the FRP shell. These strain gauges had gauge lengths of 5 mm to 20 mm and were aligned in the axial, hoop or fibre orientation direction. Examples of the instrumentation used to monitor the axial behaviour are shown in Figure 3.

The specimens were tested under monotonic axial compression, using a 5000kN capacity universal testing machine. To ensure an even loading surface, each specimen end was either ground flat using a precision grinding machine or levelled with a thin layer of capping material before testing. For the majority of the specimens, the load was applied directly to the concrete core through the use of precision cut steel discs 15 mm thick and 150 mm in diameter, thereby avoiding the loading of the FRP shell in axial compression. A group of specimens were tested without the steel discs to examine the effect of loading both the concrete core and FRP shell in axial compression. The test setup and instrumentation are shown in Figure 4.

3.0 TEST RESULTS AND DISCUSSION

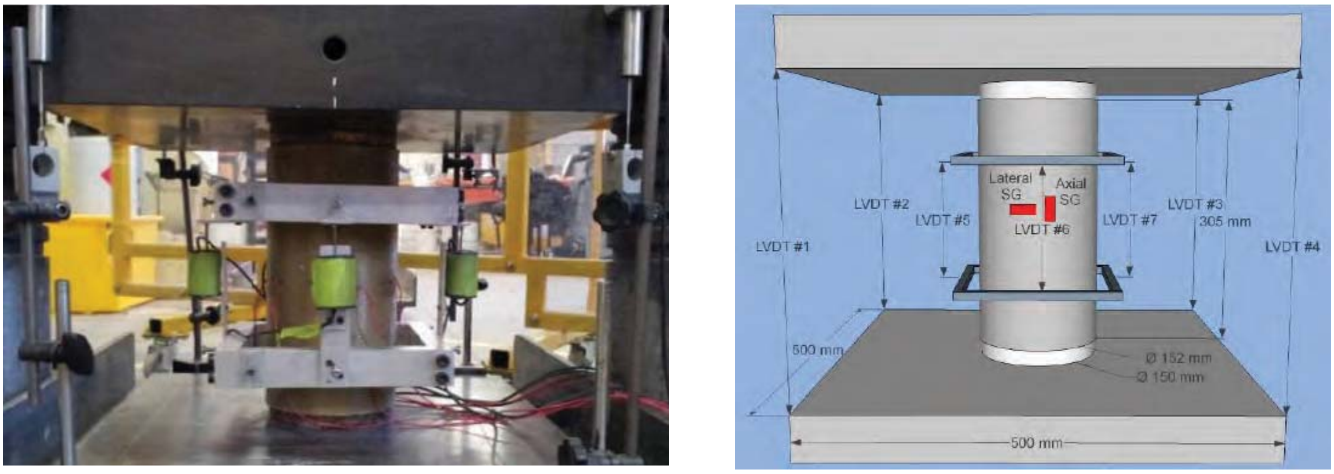
Important findings from the experimental program are presented and discussed in this section. Initially a summary of specimen failure modes is presented followed by discussion on the influence of investigated parameters on the compressive behaviour of FRP-confined concrete columns.

3.1 Failure modes of FRP-confined concrete columns

Typical failures of FRP-confined concrete specimens are shown in Figure 5 where it is evident that in all specimens, failure resulted from a rupture of the FRP tube. For specimens with fibres aligned in the hoop direction, FRP rupture was typically vertical and resulted in an instantaneous loss of applied load. The observed FRP rupture for specimens with height-to-diameter (H/D) ratio of 1 or 2 was characterised by either continuous rupture of the FRP tube from top to bottom or localised segmented rupture. Examples of these two failure modes can be seen in Figure 5(a) and (b) respectively. Specimens with higher height-to-diameter ratios (ie H/D = 3 or 5) were not observed to fail with a continuous rupture and as such displayed only localised segmented rupture, as displayed in Figure 5(c). Specimens manufactured with inclined fibres were found to have a tendency to exhibit gradual ductile failure as the fibre orientation was increased

(a) (b) (c)

Figure 3: Specimen instrumentation: (a) application of strain gauges; (b) example of strain gauges attached to FRP surface; (c) mid-height LVDT cage.



(a) (b)

Figure 4: Specimen test setup: (a) specimen before testing; (b) technical illustration.

relative to the hoop direction. These specimens experience a slow fracture of the FRP shell as individual fibres progressively ruptured and caused tearing and splintering throughout the FRP tube, as seen in Figure 5(d).

3.2 Axial compressive behaviour of FRP-confined concrete columns

3.2.1 Influence of confinement method

To examine the influence of confinement method on axial behaviour, specimens with 152 mm diameter and 305 mm height were prepared as either CFFTs or FRP-wrapped specimens. These specimens were manufactured as either NSC or HSC, with test day concrete strengths of 35 and 65 MPa respectively, and they were confined by CFRP tubes having 0.234 mm nominal fibre thickness. Figure 6 presents a comparison of the axial stress-strain behaviour of specimens manufactured by different confinement methods. It can be seen in this figure that both NSC and HSC can exhibit highly ductile behaviour when confined by either FRP tubes or wraps. A comparison of these graphs reveals similar axial performance with only minor visible differences between CFFT and FRP-wrapped specimens with otherwise identical parameters. This observed similarity in axial behaviour of CFFTs and FRP-wrapped specimens was also reported in Vincent and Ozbakkaloglu (2013a) where a large database and in-depth assessment are presented.

3.2.2 Influence of specimen slenderness

The influence of specimen slenderness on axial compressive behaviour was examined by preparing 152 mm diameter CFFTs with H/D of 1, 2, 3 and 5, as shown in Figure 7. Both NSC and HSC mixes were used, with average test day compressive strengths of 55 and 115 MPa, respectively. All CFFTs were manufactured with Type 1 aramid FRP (AFRP), with material properties supplied in Table 1. NSC and HSC specimens were confined by FRP tubes having a total nominal fibre thicknesses of 0.4 mm and 1.2 mm respecitvely. Examples of the axial stress-strain behaviour of the NSC and HSC specimens can be seen in Figures 8a and 8b respectively.

It can be seen in Figure 8 that H/D ratio has a significant influence on axial stress-strain performance for both NSC and HSC specimens. This comparison indicates that CFFTs manufactured with a H/D ratio of 1 display significantly higher

(a) (b) (c) (d)

Figure 5: Example failure modes of FRP-confined concrete specimens: (a) full height rupture; (b) mid-section rupture; (c) top section rupture; (d) progressive failure of inclined fibre specimen.

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ultimate stress and ultimate strain compared to companion specimens. The higher performance of CFFTs with a H/D of 1 can be attributed to the end plate confining effect. It is well established that the friction at the loading surface supplies additional confining pressures (Rousakis, 2001; Tamuzs et al, 2006). These additional confining pressures are localised to regions close to the specimen ends and this effect reduces substantially as the distance from specimen end increases. A comparison of CFFTs with H/D = 2 to 5 in Figure 8 reveals similar ultimate axial stress performance. On the other hand, it can be seen that H/D ratio has a significant effect on the axial strain performance, with an increase in H/D ratio resulting in a reduction in ultimate axial strains.

3.2.3 Influence of specimen end condition

A comparison of axial stress-strain relationships for specimens with and without end plates can be seen in Figure 9, where CFFT and FRP-wrapped specimens are presented separately. All specimens were 152 mm in diameter and 305 mm in height, had concrete compressive strengths of 49 MPa and were confined by Type 2 aramid fibres with a total nominal fibre thickness of 0.6 mm. It is evident from the similar compressive behaviours of the specimens shown in Figure 9 that loading of the FRP jacket during testing does not influence the behaviour noticeably. However, upon close inspection it can be seen that the inclusion of end plates slightly increases the ultimate axial strain and decreases peak stress. As can be seen in Figure 9, this effect is most noticeable in CFFT specimens.

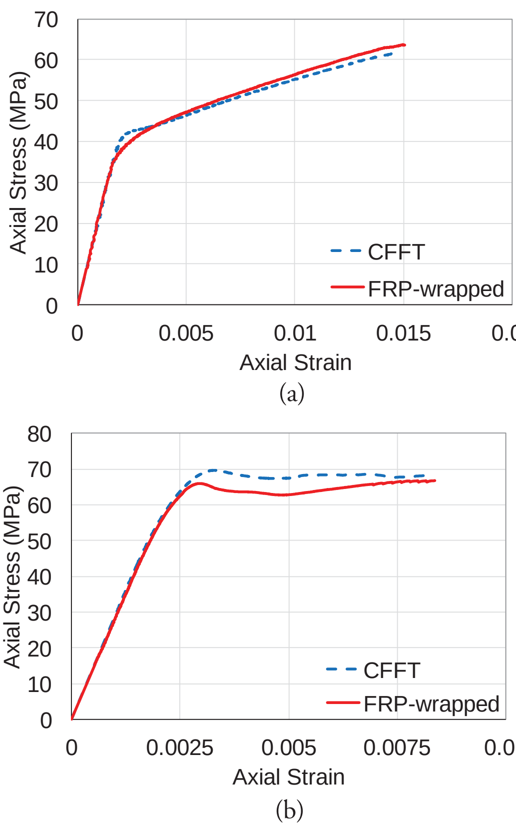

Figure 6: Effect of confinement method on axial compressive behaviour: (a) NSC confined by 2 layers of CFRP; (b) HSC confined by 2 layers of CFRP.

Figure 7: CFFT specimens prepared with H/D ratios of 1, 2, 3 and 5.

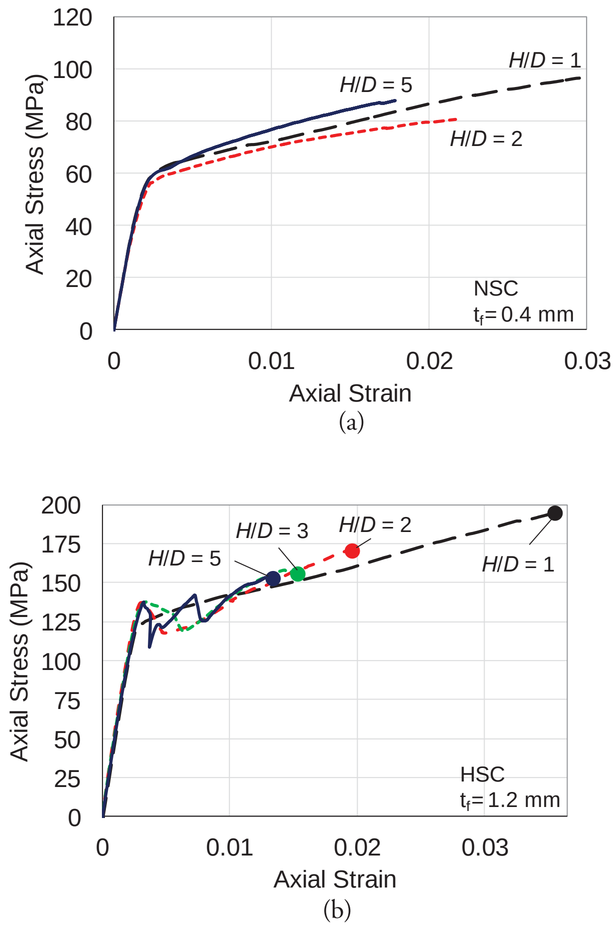

Figure 8: Effect of specimen slenderness on axial compressive behaviour: (a) NSC CFFTs; (b) HSC CFFTs.

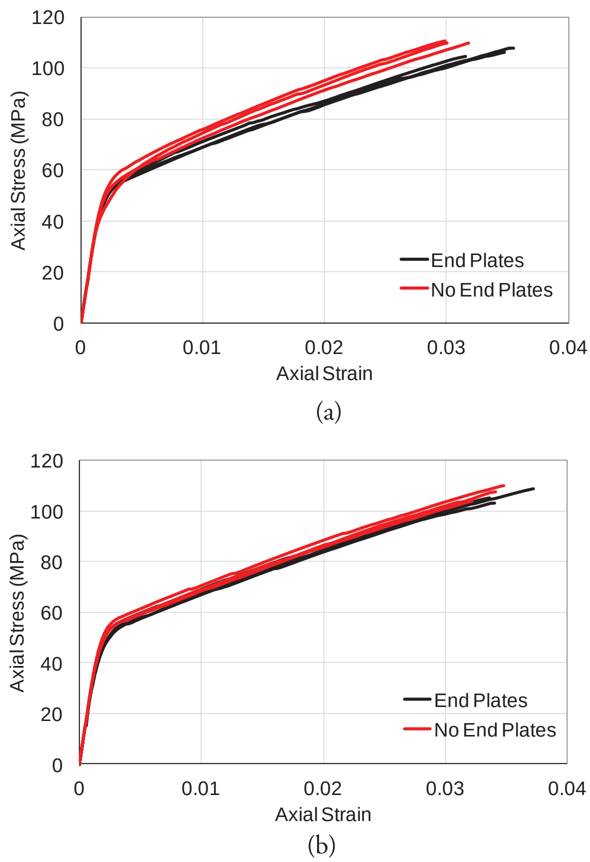

Figure 9: Influence of specimen end condition on axial stress-strain behaviour of: (a) CFFT specimens; (b) FRP-wrapped specimens.

3.2.4 Influence of fibre orientation

To examine the influence of fibre orientation, a group of CFFT specimens were manufactured using an automated filament winding technique with FRP tubes having 0.6 mm total nominal fibre thickness. These specimens were 100 mm in diameter and 200 mm in height, and they were manufactured using a HSC with 81 MPa test day concrete strength. As explained previously, CFFTs manufactured with inclined fibres can display significantly different failure modes compared to CFFTs with fibres aligned in the hoop direction. Figure 10 illustrates this observation by presenting example specimens with fibres aligned at 45, 60, 75 and 88 degrees with respect to the longitudinal axis. It can be seen in this figure that CFFTs with fibres oriented at low angles (ie 45 and 60 degrees) exhibit a gradual ductile failure with no catastrophic failure observed. CFFTs with fibres oriented at 75 or 88 degrees displayed a distinct rupture of the FRP shell accompanied by an instantaneous loss of applied load, similar to behaviour observed from CFFTs with fibres aligned in the hoop direction.

It can be seen from the axial stress-strain relationships presented in Figure 11(a) that fibre orientation has a significant influence on axial stress-strain behaviour of CFFTs. CFFTs with fibres oriented at 45 and 60 degrees show no clear signs of catastrophic failure and as such, experienced large axial strains. However, these axial strains were only experienced after substantial strength loss. CFFTs with fibres oriented at 75 and 88 degrees displayed ascending stress-strain curves indicating highly ductile behaviour.

As mentioned previously, CFFTs with inclined fibre orientation had strain gauges installed on the FRP tube at the inclined orientation. Figure 11(b) presents a comparison of axial stress-orientation strain relationships for CFFTs with inclined fibres. It can be seen in this comparison that substantial differences exist between the relationships of specimens with different fibre orientations, with only the CFFTs with hoop oriented fibres developing orientation strains close to the fibre ultimate tensile strain of 0.029 reported by the manufacturer.

This observation indicates that fibres used for FRP-confinement of concrete are most effective when aligned in the hoop direction, with fibre efficiency reducing significantly with an increase in fibre alignment with respect to the hoop direction.

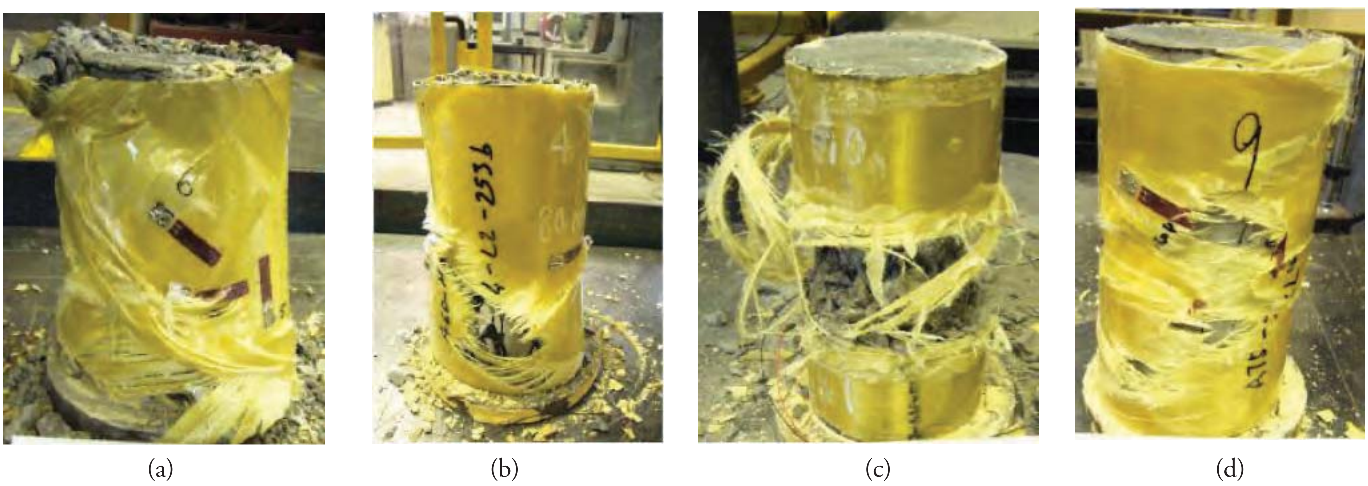

Figure 10: Failure of CFFT specimens with inclined fibre orientation: (a) 45 degree fibre angle; (b) 60 degree fibre angle; (c) 75 degree fibre angle; (d) 88 degree fibre angle.

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3.2.5 Influence of concrete shrinkage

Concrete shrinkage may pose a concern for CFFTs, as in these members the curing of concrete takes place inside the FRP tube. To study the influence of concrete shrinkage on the axial behaviour of CFFTs, specimens with 152 mm diameter and 305 mm height were prepared with a gap of up to 0.12 mm thickness at the FRP-to-concrete interface, simulating 1600 microstrain of shrinkage in the radial direction. NSC and HSC mixes were used with average test day concrete compressive strengths of 45 and 83 MPa respectively. Specimens were manufactured with Type 1 AFRP, with NSC and HSC specimens confined by FRP tubes having total nominal fibre thicknesses of 0.4 mm and 0.8 mm respectively. It can be seen from the axial stress-strain relationships presented in Figure 12 that the curves of all specimens exhibited overall ascending behaviour for both NSC and HSC. However, it can be observed in these figures that as the interface gap increased so did the tendency for a slight loss in axial stress near the location of the unconfined concrete peak stress. This behaviour can be attributed to the increased interface gap causing a delayed activation of the confinement mechanism, during the rapid expansion of the concrete core. As can be seen in Figure 12, this behaviour was temporary and was followed by strength recovery and further performance gains.

The influence of concrete shrinkage on the ultimate condition can also be examined from the behaviour illustrated in Figure 12. As evident from this figure, an increase in FRP-to-concrete interface gap leads to a slight decrease in ultimate stress for both NSC and HSC. On the other hand, an increase in interface gap results in a significant increase in ultimate strain for both concrete grades.

3.2.6 Influence of axial strain measurement method

Axial strain recordings were compared on specimens instrumented with three different measurement methods: axial strain gauges, and full- and mid-height linear variable displacement transformers (LVDTs). This comparison was performed for both NSC and HSC specimens, with compressive strengths of 49 and 103 MPa respectively. All specimens were 152 mm in diameter and 305 mm in height and manufactured with Type 2 AFRP. NSC and HSC specimens were confined by FRP tubes having total nominal fibre thicknesses of 0.6 mm and 1.2 mm respectively. The stress-strain behaviour of the NSC and HSC specimens can be seen in Figures 13 and 14, respectively. It can be seen in Figure 13 that both LVDT readings are similar along the full curve, while strain gauge readings record slightly lower strain values near ultimate condition. This observation indicates that for NSC specimens, LVDTs mounted along the entire height of the specimen record similar axial strains to those by LVDTs mounted at the specimen mid-height. However, axial strains determined from strain gauges are significantly lower than strains determined by their LVDT counterparts, suggesting that the axial strain gauges are incapable of accurately capturing the full specimen deformation.

A comparison of the results for HSC specimens in Figure 14 reveals that the difference in axial strains measured using

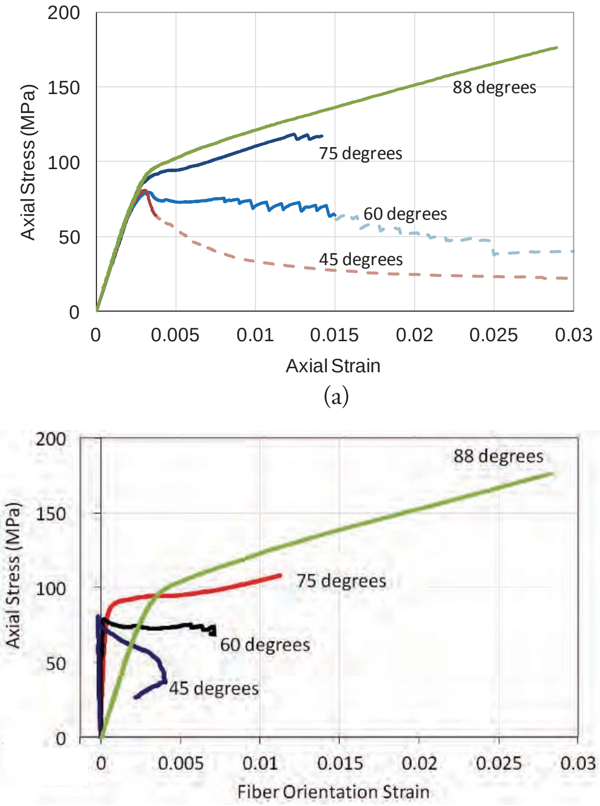

Figure 11: Influence of fibre orientation angle on compressive behaviour of CFFTs: (a) axial stress-strain response; (b) axial stress-fibre strain response.

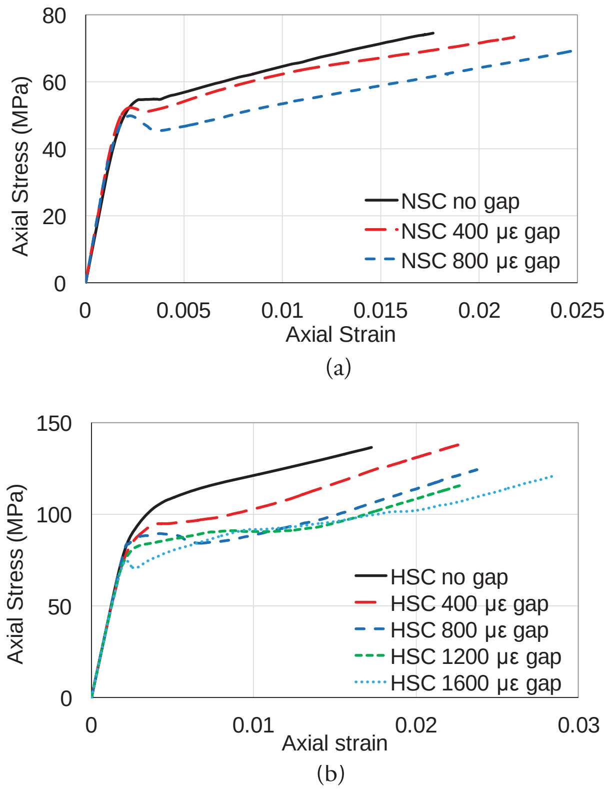

Figure 12: Effect of shrinkage on compressive behaviour of CFFTs: (a) NSC; (b) HSC.

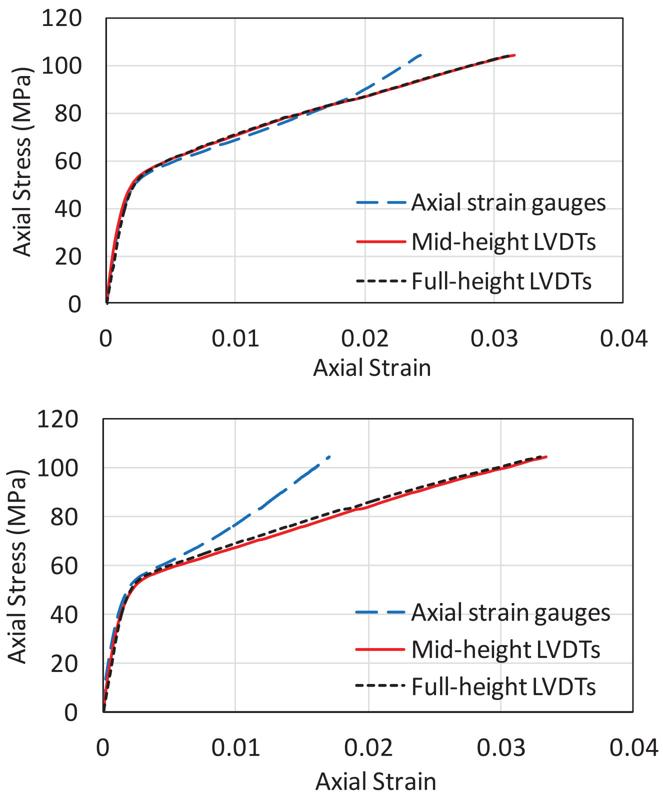

Figure 13: Influence of axial strain measurement method on stress-strain curves of FRP-confined NSC.

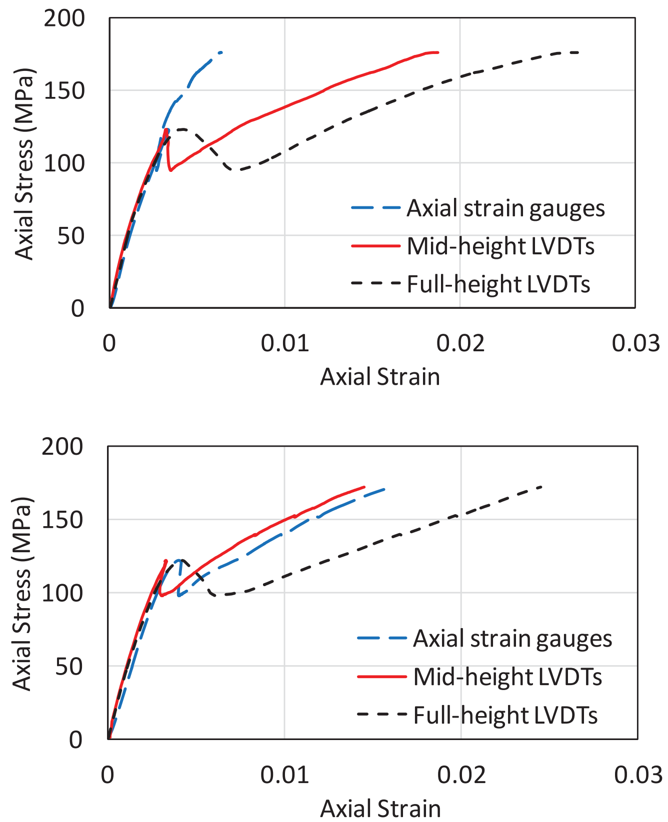

Figure 14: Influence of axial strain measurement method on stress-strain curves of FRP-confined HSC.

different methods becomes more significant with an increase in concrete strength. This outcome can be attributed to the increase in concrete brittleness associated with an increase in concrete strength, which alters the concrete crack patterns from heterogenic microcracks to localised macrocracks. This finding is in agreement with those previously reported in Ozbakkaloglu & Lim (2013) based on an investigation of an extensive test database. These observations indicate that the axial strain measurements of FRP-confined HSC are highly sensitive to the instrumentation arrangement and significant differences occur in the results obtained from different measurement methods. It is recommended, therefore, in the interpretation of the results of FRP-confined HSC specimens, due consideration be given to the influence of instrumentation methods.

4.0 CONCLUSIONS

This paper has presented important findings from an ongoing investigation at The University of Adelaide to investigate the less understood column parameters on the axial compressive behaviour of FRP-confined NSC and HSC columns. Based on the results and discussion presented in this paper, the following conclusions can be drawn:

- Specimens with a H/D ratio of 1 exhibit significantly higher ultimate axial stress and ultimate axial strain than companion specimens with H/D = 2 to 5 due to the beneficial influence of the end plate confinement effect. For specimens with a H/D ratio of 2 to 5, H/D ratio has no significant influence on ultimate axial stress; however, an increase in H/D ratio from 2 to 5 causes a decrease in ultimate axial strain.
- Specimen end condition does not have a significant effect on axial stress-strain behaviour. It was observed that the inclusion of end plates slightly increased the ultimate strain and decreased peak stress, with this effect more noticeable in CFFTs than FRP-wrapped specimens.
- The axial compressive behaviour of CFFTs is highly sensitive to the fibre orientation. Fibres used for FRP-confinement of concrete are most effective in enhancing the concrete compressive behaviour when aligned in the hoop direction. Fibre efficiency reduces significantly with an increase in fibre alignment with respect to the hoop direction.
- An increase in FRP-to-concrete interface gap results in a slight decrease in ultimate axial stress, whereas it leads to a significant increase in ultimate axial strain. It was observed that the interface gap affects the ultimate axial stress and strain of NSC and HSC in a similar manner, suggesting that the influence is independent of concrete compressive strength.
- In NSC specimens, axial strains determined from full height LVDTs and mid-height LVDTs are similar. However, axial strains obtained from strain gauges are much lower and they do not accurately capture the full height deformations of specimens. For HSC specimens, axial strains determined from full height LVDTs, mid-height LVDTs or strain gauges differ significantly from each other. This indicates HSC columns are highly sensitive to the instrumentation arrangement used in the measurement of these strains.

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JOURNAL ARTICLE 9

Statement of Authorship

Title of Paper	Compressive behavior of prestressed high-strength concrete-filled aramid FRP tube columns: Experimental observations
Publication Status	(•) Published ( ) Accepted for Publication ( ) Submitted for Publication ( ) Publication Style
Publication Details	Journal of Composites for Constructions, DOI: 10.1061/(ASCE)CC.1943-5614.0000556 , 04015003, Year 2015.

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author	Mr Thomas Vincent		
Contribution to the Paper	Design of experimental tests, manufacture and laboratory testing of specimens, preparation of experimental database, analysis of test results, and preparation of manuscript		
Signature		Date	4/03/2015

Name of Co-Author (Candidate)	Dr Togay Ozbakkaloglu		
Contribution to the Paper	Supervision of experimental tests, and review of manuscript		
Signature		Date	4/03/2015

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, v. 19 (6), pp. 04015003-1 – 04015003-13

NOTE:
This publication is included on pages 168 - 180 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1061/(ASCE)CC.1943-5614.0000556

JOURNAL ARTICLE 10

Statement of Authorship

Title of Paper	Stress-strain model for concrete-filled FRP-tubes incorporating prestressing and delayed activation of confinement
Publication Status	◯ Published ◯ Accepted for Publication ◯ Submitted for Publication ◉ Publication Style
Publication Details	

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author	Mr Thomas Vincent		
Contribution to the Paper	Model development, preparation of manuscript		
Signature		Date	4/03/2015

Name of Co-Author (Candidate)	Dr Togay Ozbakkaloglu		
Contribution to the Paper	Supervision of model development, review of manuscript		
Signature		Date	4/03/2015

LATERAL STRAIN-TO-AXIAL STRAIN RELATIONSHIP FOR CONCRETE-FILLED FRP TUBE COLUMNS INCORPORATING INTERFACE GAP AND PRESTRESSED CONFINEMENT

Thomas Vincent[1] and Togay Ozbakkaloglu[2]

ABSTRACT

Concrete-filled fiber-reinforced polymer (FRP) tube (CFFT) columns have received significant research attention over the past decade. Accurate prediction of the lateral strain-to-axial strain relationship is of vital importance in predicting the behavior of these members under various loading conditions, as the confinement pressure generated by FRP on the concrete core depends on the lateral expansion of concrete. A recent review of the literature revealed that while lateral-to-axial strain models exist for FRP-confined concrete, a model that is applicable to CFFT columns with prestressed FRP tubes or an interface gap caused by radial shrinkage of concrete is not yet available. The aim of the present study is to address this research gap by developing an accurate lateral-to-axial strain model based on the experimental observations from two test databases. Analyses of the experimental databases that consisted of 24 specimens manufactured with FRP-to-concrete interface gap and a further 23 specimens prepared with lateral prestress is presented and discussed in this paper. Based on close examination of the ultimate conditions of the column specimens and hoop strain development on the FRP confining shell, expressions to predict strain reduction factors and lateral-to-axial strain relationships are proposed. The comparison of the proposed model with the experimental results of specimens prepared with an interface gap or prestressed FRP tubes showed good agreement.

KEYWORDS: High-strength concrete (HSC); Fiber reinforced polymer (FRP); Concrete-filled FRP tube (CFFT); Confinement; Lateral strain; Axial strain; Prestress; Shrinkage; Gap; Dilation.

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INTRODUCTION

It is well established that lateral confinement of concrete enhances its axial strength and deformability (Fam and Rizkalla 2001, Lam and Teng 2004; Bisby et al. 2005; Smith et al. 2010; Rousakis and Karabinis 2012; Vincent and Ozbakkaloglu 2013a,b; Wu and Jiang 2013; Ozbakkaloglu and Vincent 2014). In recent years, a great number of studies have been conducted to understand and model the behavior of FRP-confined concrete. These studies were recently reviewed in Ozbakkaloglu et al. (2013), where it was revealed that over 200 experimental studies have been conducted in the last two decades resulting in the development of more than 80 axial stress-strain models. These models have been categorized into two categories: design-oriented models presented in closed-form expressions, and analysis-oriented models, which predict stress-strain curves from lateral strain-to-axial strain behavior using an incremental procedure.

The majority of design-oriented models focus on the prediction of the ultimate condition of FRP-confined concrete and they are not able to provide a complete stress-strain relationship. Analysis-oriented models, on the other hand, are capable of establishing the full axial stress-strain and lateral-to-axial strain relationships of the FRP-confined concrete on the basis of the interaction mechanism between the external confining shell and the internal concrete core. As previously discussed in detail in Teng et al. (2007), Ozbakkaloglu et al. (2013), and Lim and Ozbakkaloglu (2014) the accuracy of the analysis-oriented models, therefore, depend greatly on the prediction of the lateral-to-axial strain relationship of the FRP-confined concrete. The relationship between the axial strain, lateral strain, and confining pressure has been established in a number of studies using experimental test results from both actively confined and FRP-confined concrete (e.g., Teng et. al., 2007 and Lim and Ozbakkaloglu, 2014). However, no model to date has been developed to predict the behavior of FRP-confined concrete with an interface gap or prestressed FRP tubes, resulting from radial shrinkage of concrete or lateral prestressing of the FRP fibers, respectively. As recently discussed in an experimental study by Vincent and Ozbakkaloglu (2015a) concrete shrinkage poses a concern for concrete-filled FRP tubes (CFFT) columns, as in these columns the curing of concrete takes place inside the FRP tube. This concrete shrinkage was found to delay the activation of the FRP confining shell and influence the compressive behavior of the CFFT columns. As such, it is important to understand this influence for successful design and construction of these columns. The same also applies to FRP-confined concrete columns with prestressed confinement, a high performing system recently investigated by Vincent and Ozbakkaloglu (2015b). In this study, lateral prestressing of the confining FRP shell was achieved through the use of an expansive mineral admixture that was added into the concrete mix to cause an early activation of the FRP confining shell. This lateral prestressing of the FRP shell was observed to result in significant performance benefits for FRP-confined HSC. However, these recent developments in experimental testing are yet to be incorporated into existing models to predict compressive behavior.

The work presented in this paper was motivated by the need to develop a model applicable to FRP-confined concrete with an interface gap or prestressed FRP tubes, resulting from shrinkage of concrete or prestressing of the FRP fibers, respectively. To this end, firstly two databases of specimens prepared with either an interface gap or lateral prestress are presented and discussed. Based on an assessment of the test results from these two databases, changes in the compressive behavior of FRP-confined concrete with an interface gap or lateral prestress were investigated, and influential parameters identified. Finally, through an examination of the results in the databases, a lateral-to-axial strain model that is applicable to FRP-confined concrete with an interface gap or lateral prestress was developed.

EXPERIMENTAL TEST DATABASE

Two carefully prepared test databases used in the development of the proposed models are summarized in this section. These test databases were selected for development of the models described in this paper, as together they provide a wide array of test results for FRP-confined concrete columns with both delayed and early activation of confinement. The first test database includes specimens prepared with different amounts of FRP-to-concrete interface gap which lead to delayed activation of the FRP confinement shell. This FRP-to-concrete interface gap simulates varying amounts of radial shrinkage of the internal concrete, which is of concern for concrete-filled FRP tubes (CFFTs) as for these members curing of concrete occurs inside the FRP tubes. The second test database includes specimens prepared with different amounts of lateral prestrain in their FRP confinement shells, which create early activation of the FRP shell. As recently discussed in Vincent and Ozbakkaloglu (2015b) this early activation of the confinement mechanism results in significant improvements on axial compressive behavior of FRP-confined HSC columns, with benefits also reported for FRP-confined NSC columns (Mortazavi et al. 2003).

Database of Specimens with Interface Gap

The database of specimens with an interface gap consisted of 24 test specimens, all with a 152 mm diameter (*D*) and a 305 mm height. These specimens were prepared with varying amounts of gap at the FRP-to-concrete interface, simulating the change in interface conditions due to radial shrinkage of concrete. As was recently shown in Vincent and Ozbakkaloglu (2015a), concrete shrinkage delays the activation of confinement mechanism, and as such these specimens are labeled in this paper as specimens with delayed confinement activation. Two different concrete mixes with average compressive strengths of 44.8 and 83.2 MPa were used, which are labeled in this paper as normal- and high-strength concrete (NSC and HSC), respectively. The specimens were manufactured with aramid FRP sheets using a wet lay-up technique, which involved wrapping epoxy resin impregnated fiber sheets around precast concrete cylinders. The interface gap was achieved by wrapping low strength polyethylene sheets around the concrete during the manual wet lay-up procedure of the aramid fiber sheets, to create a boundary gap between the concrete and FRP shell. The specimens were manufactured as FRP-wrapped specimens, instead of CFFTs, because this allowed simulation of CFFTs experiencing a constant level of shrinkage in a controlled manner.

To ensure adequate confinement the NSC and HSC specimens were wrapped with two and four layers respectively of aramid fiber sheets with a nominal fiber thickness of 0.2 mm per layer. The NSC specimens were prepared with nominal shrinkage levels of 0, 400 and 800 με, whereas the HSC specimens were allocated additional shrinkage levels; 0, 400, 800, 1200 and 1600 με, due to the potential of higher levels of shrinkage associated with higher strength concretes (Bissonnette et al., 1999; Kwan et al., 2010). The details of these 24 test specimens are given in *Table 1*, and a more thorough description of the experimental program can be found elsewhere (Vincent and Ozbakkaloglu, 2015a).

Database of Specimens with Lateral Prestress

The database of FRP-confined concrete with lateral prestress consisted of 23 specimens, all manufactured with a 152 mm diameter (D) and a 305 mm height. These specimens were manufactured with different levels of lateral prestress controlled by the amount of an expansive mineral admixture added into the concrete mix. The average compressive strengths of the concrete mixes ranged from 100.2 to 110.3 MPa and they are labeled as HSC in this paper. The specimens were manufactured as concrete-filled FRP tubes (CFFTs) with aramid FRP sheets using a wet lay-up technique, which involved wrapping epoxy resin impregnated fiber sheets around Styrofoam templates. As was recently shown in Vincent and Ozbakkaloglu (2015b), lateral prestress results in activation of confinement mechanism prior to application of the axial compressive load, as such these specimens are labeled in this paper as specimens with early confinement activation. All specimens were prepared using four layers of aramid fiber sheets with nominal fiber thicknesses of either 0.2 or 0.3 mm/layer to manufacture specimens that are referred to in this paper as lightly- or well-confined, respectively. The details of these 23 test specimens are given in *Table 1*, and a more thorough description of the experimental program is presented elsewhere (Vincent and Ozbakkaloglu, 2015b).

PROPOSED MODEL

Hoop Rupture Strain of the FRP Shell

It is now understood that the hoop rupture strain of the FRP shell ($\varepsilon_{h,rup}$) is often smaller than the ultimate tensile strain (ε_f) of fibers in the FRP material, and it can be estimated from the material properties using a strain reduction factor (k_ε) determined from *Eq. 1*. Recent comprehensive experimental studies on strain reduction factor (e.g. Vincent and Ozbakkaloglu 2013; Lim and Ozbakkaloglu 2014; Ozbakkaloglu and Vincent 2014) have demonstrated that the two key parameters influencing k_ε are concrete compressive strength (f'_{co}) and elastic modulus of fibers (E_f). The influence of these key parameters on strain reduction factor was recently modeled by Lim and Ozbakkaloglu (2014), with the expression provided here in *Eq.* 2.

$$k_\varepsilon = \frac{\varepsilon_{h,rup}}{\varepsilon_f} \tag{1}$$

$$\varepsilon_{h,rup} = (0.9 - 2.3f'_{co} - 0.75E_f \times 10^{-6})\varepsilon_f \tag{2}$$

where $\varepsilon_{h,rup}$ is the ultimate hoop rupture strain of FRP shell; ε_f is the ultimate tensile strain of FRP material; f'_{co} is the peak unconfined concrete strength in MPa; and E_f is the elastic modulus of the fiber material in MPa.

Two expressions being proposed in the present study for determining the strain reduction factor (k_ε) for FRP-confined concrete with prestressed FRP tubes or an interface gap are presented separately in the following sections.

A recent experimental study on the compressive behavior of FRP-confined concrete with an FRP-to-concrete interface gap (Vincent and Ozbakkaloglu, 2015a) demonstrated that amount of interface gap has a minor influence on strain reduction factor (k_ε). The results of that study indicates that FRP-confined concrete members with delayed activation experience an increase in k_ε, independent of the amount of delay. Based on these experimental observations the variation of k_ε has been modeled in the present study using a similar equation form that was previously proposed by Lim and Ozbakkaloglu (2014). This expression is presented in *Table 2*.

Figure 1 shows a comparison of the model prediction of the strain reduction factor (k_ε) with experimentally recorded test results for specimens with interface gap. A total of 22 specimens were included in this assessment with 2 datasets omitted due to unreliable strain gauge readings, caused by instrumentation problems or partial strain gauge debonding due to localized damages. It is worth mentioning that the proposed expression was applied only to predict the behavior of specimens manufactured with gaps. The behavior of the specimens manufactured without gaps was predicted using the model proposed by Lim and Ozbakkaloglu (2014). It is clear from this figure that the Lim and Ozbakkaloglu (2014) model has a tendency to underestimate values of k_ε for specimens with an interface gap, while the proposed model provides an accurate prediction.

The influence of prestressing the fibers of the FRP shell on strain reduction factor (k_ε) was recently experimentally examined in Vincent and Ozbakkaloglu (2015b) where it was reported that prestressing the confinement leads to a significant increase in k_ε. This experimental observation was attributed to the influence of crack formations on strain reduction factors (k_ε), where prestressed specimens experienced a significant reduction in macrocracking accompanied by a significant increase in k_ε. The influence of concrete cracking behavior on hoop strain efficiency of the FRP shell was investigated by Ozbakkaloglu and Lim (2014) during development of the model presented here as *Eq. 2*. The second term of this equation (i.e., $-2.3f'_{co}$) describes the observed decrease in strain reduction factor (k_ε) resulting from changes in concrete cracking pattern with an increase in concrete strength. Typical FRP-confined NSC specimens experience gradual and controlled expansion of the concrete core as the applied load reaches the level that corresponds to the unconfined concrete compressive strength (f'_{co}), leading to the development of heterogeneous microcracks. On the other hand, FRP-confined HSC specimens experience rapid and uncontrolled expansion of the HSC core leading to the development of localized macrocracks (Vincent and Ozbakkaloglu 2013; Lim and Ozbakkaloglu 2014) and a subsequent reduction in strain reduction factor (k_ε). It was observed in Vincent and Ozbakkaloglu (2015b) that prestressing the fibers of the FRP shell results in a more controlled and progressive expansion of the HSC core, similar to what is typically experienced by non-prestressed FRP-confined NSC. Based on the summarized observations in this paper it is proposed that the second term of *Eq.* 2 is not required when predicting the behavior of FRP-confined concrete manufactured with lateral prestress. For these specimens, the crack formations and expansion rate of the concrete core are altered under the presence of lateral prestressing such that prestressed FRP-confined HSC exhibits cracking patterns that resemble those of non-prestressed NSC counterparts. The proposed model for determining strain reduction factor (k_ε) for specimens with prestressed FRP shells is presented in *Table 2*.

Figure 2 shows a comparison of the model prediction of the strain reduction factor (k_ε) with experimentally recorded test results for specimens with prestressed confinement, where once again the proposed expression was only applied to predict the behavior of specimens manufactured with lateral prestress. In this comparison of model predictions with experimental test results all 23 specimens presented in *Table 1* were included in the assessment. Similar to the results presented for specimens manufactured with interface gap, it can be seen in *Fig. 2* that the Lim and Ozbakkaloglu (2014) model has a tendency to underestimate values of k_ε, whereas the proposed model provides a more accurate prediction.

Dilation Behavior

The expression given in *Eq.* 3, which was proposed by Lim and Ozbakkaloglu (2014) to predict the lateral-axial strain relationship of both actively confined and FRP-confined concrete, is adopted for the same purpose in the present study.

$$\varepsilon_c = \frac{\varepsilon_l}{\upsilon_i\left[1+\left(\varepsilon_l \big/ \upsilon_i\varepsilon_{co}\right)^n\right]^{\frac{1}{n}}} + 0.04\varepsilon_l^{\,0.7}\left[1+21\left(\frac{f_l}{f'_{co}}\right)^{0.8}\right] \tag{3}$$

$$f_l = \frac{2E_f t_f \varepsilon_l}{D} = K_l \varepsilon_l \tag{4}$$

$$\varepsilon_{co} = \frac{f'^{\,0.225k_d}_{co}}{1000} k_s k_a \tag{5}$$

$$k_a = \left(\frac{2D}{H}\right)^{0.13} \tag{6}$$

$$k_d = \left(\frac{2400}{\rho_{c,f}}\right)^{0.45} \tag{7}$$

$$k_s = \left(\frac{152}{D}\right)^{0.1} \tag{8}$$

$$\upsilon_i = 8\times10^{-6} f'^{\,2}_{co} + 0.0002 f'_{co} + 0.138 \tag{9}$$

$$n = 1 + 0.03 f'_{co} \tag{10}$$

where the confining pressure (f_l) can be calculated using *Eq. 4*; K_l = confinement stiffness of FRP shell; ε_{co} = axial strain corresponding to the compressive strength of unconfined concrete, can be calculated using *Eq. 5*; k_d, k_s and k_a, respectively, are the coefficients to allow for concrete density, specimens size and specimen aspect ratio as proposed by Lim and Ozbakkaloglu, (2014) to be calculated using *Eqs. 6, 7* and *8*, respectively; v_i = initial Poisson's ratio of concrete, to be calculated using *Eq. 9* as proposed by Candappa et al. (2001) and n = curve shape parameter, to be calculated using *Eq. 10*.

Based on the experimental observations from specimens prepared with an interface gap and prestressed FRP tubes, presented in Vincent and Ozbakkaloglu (2015a) and Vincent and

Ozbakkaloglu (2015b) respectively, *Fig. 3* is presented to illustrate the characteristic lateral strain-axial strain relationships for these specimens. It can be seen in this figure that, as expected, FRP-confined concrete columns with an interface gap experience an initial delay in the development of lateral strains. During this stage the FRP-confined concrete undergoes a significant amount of axial strain before lateral strains start to develop in the FRP shell, with this amount of axial strain defined here as ($\varepsilon_{c,initial}$). On the other hand, columns manufactured with lateral prestress exhibit an initial lateral strain prior to axial loading, with this lateral prestrain defined here as ($\varepsilon_{l,initial}$). A comparison of the characteristic curves presented in *Fig. 3* reveals that the curves of conventional FRP-confined concrete display similar slopes to those of interface gap or lateral prestress for the full lateral-to-axial strain relationship. However, a close examination of the experimental data reveals slight differences among these curves, which are discussed in detail in the following sections.

Figure 4 presents the experimentally recorded lateral strain-axial strain relationships for FRP-confined concrete columns with interface gap, where the initial development of the lateral strain-axial strain relationship is displayed to closely examine the behavior when the concrete core rapidly expands and engages the confining shell. In these graphs the delay in development of lateral strains can be observed for the range of tested specimens detailed in *Table 1*. It is evident from the curves presented in *Fig. 4(a)* and *Fig. 4(d)* that specimens with no interface gap display instantaneous development of lateral strain with increasing axial strain. On the other hand, a noticeable delay in the development of lateral strain can be seen in the curves of the remaining specimens. It can also be observed in the presented experimental data that the initial axial strain development ($\varepsilon_{c,initial}$) in the specimens prior to the development of hoop strains in the FRP shell is not influenced by the amount of interface gap. This observation can be attributed to the rapid expansion of unconfined concrete as the axial strain approaches the strain corresponding to the compressive strength of unconfined concrete. This rapid expansion results in an almost instantaneous activation of the confining shell, independent of the amount of interface gap, as the concrete core rapidly dilates and closes the gap at the FRP-to-concrete interface. The proposed expression for determining the initial axial strain development ($\varepsilon_{c,initial}$) is presented in *Eq. 11*.

$$\varepsilon_{c,initial} = 0.8\varepsilon_{co} \tag{11}$$

where ε_{co} = axial strain corresponding to the compressive strength of unconfined concrete, to be calculated from *Eq.* 5.

It is worth noting that this expression is based on the results from specimens with 400 to 1600 microstrain of shrinkage and as such, the proposed model covers the maximum anticipated values of shrinkage strains that can be experienced by concrete in a CFFT column in typical construction.

In addition to the reported influence of interface gap on the delay in the development of hoop strains, Vincent and Ozbakkaloglu (2015a) also reported that an increase in interface gap leads to a significant increase in the ultimate strain (ε_{cu}) of FRP-confined concrete for both NSC and HSC. This can be seen in *Fig. 5,* where a comparison is presented for the NSC and HSC specimens separately. It is evident from the figure that the increase in the ultimate strain (ε_{cu}) is due to the reduction in the slope of the lateral-to-axial strain relationship (i.e., reduced dilation rate) with an increase in FRP-to-concrete interface gap. A close examination of the experimental data presented in *Fig. 5* revealed that this increase in the ultimate strain (ε_{cu}) is dependent on the unconfined concrete strength (f'_{co}) and, to a lesser extent, on the amount of interface gap. Based on these observations, a model for determining axial strain (ε_c) for columns with delayed activation of confinement is proposed, which is presented in *Eqs. 12* and *13*. These expressions were developed by regression analysis of the experimental test results from Vincent and Ozbakkaloglu (2015a) and they were based on the equation proposed by Lim and Ozbakkaloglu (2014), shown previously in *Eq.* 5. In *Eq. 12* the coefficient k_{sh} is introduced to account for the increase in the ultimate strain (ε_{cu}) and it is to be determined using *Eq. 13*.

$$\varepsilon_c = \varepsilon_{c,initial} + 0.04 k_{sh} \varepsilon_l^{0.7} \left[1 + 21 \left(\frac{f_l}{f'_{co}} \right)^{0.8} \right] \quad (12)$$

$$k_{sh} = 1 + f'_{co} \, \varepsilon_{sh}^{0.8} \quad (13)$$

where $\varepsilon_{c,initial}$ is the magnitude of axial strain in the column prior to development of corresponding hoop strain in the FRP shell; k_{sh} = coefficient to allow for FRP-to-concrete interface gap; f'_{co} is the peak unconfined concrete strength in MPa; ε_{sh} = radial shrinkage of the concrete.

Figure 6 shows a comparison of the model prediction of the lateral strain-axial strain behavior to the experimentally recorded results from specimens with an interface gap. It can be seen in *Fig. 6* that the predictions of the proposed model are in good agreement with the full range of experimental test results.

It was previously demonstrated in Vincent and Ozbakkaloglu (2015b) that amount of prestress has a significant influence on the lateral strain-axial strain relationship (i.e., dilation behavior). It was shown that prestressing the fibers in the FRP shell leads to an almost constant dilation rate for these specimens, compared to the non-linear dilation behavior observed in non-prestressed specimens with increased dilation rates near the transition region between the first and second branches. *Figure 7* presents a comparison of the dilation rates for specimens manufactured with lateral prestress, with lightly- and well-confined specimens presented separately. It can be seen in this comparison that a generally linear lateral strain-axial strain relationship was evident for the dilation behavior of both lightly- and well-confined HSC specimens. A close examination of the dilation rates of these specimens revealed that the slope of the lateral-to-axial strain was dependent on the confinement stiffness (K_l), while the influence of amount of lateral prestress was negligible. Based on these experimental observations, *Eq. 14* is proposed to predict the lateral strain-axial strain relationship for FRP-confined concrete members with prestressed FRP tubes.

$$\varepsilon_c = \left(\frac{K_l}{1000}\right)^{0.8} \left(\varepsilon_l - \varepsilon_{l,initial}\right) \quad (14)$$

where $\varepsilon_{l,initial}$ is introduced to represent the amount of lateral prestrain in the FRP shell, and K_l is the confinement stiffness of FRP shell in MPa, which is to be determined by *Eq.* 4.

Figure 8 shows a comparison of the model prediction of the lateral strain-axial strain behavior to the experimentally recorded results for specimens with prestressed FRP tubes. It can be seen in *Fig. 8* that the proposed model, presented in *Eq. 14*, is in good agreement with the full range of experimental test results.

COMPARISON WITH EXPERIMENTAL RESULTS

Table 3 presents a comparison of the performance statistics for the proposed model against a total of 6 existing strain enhancement ($\varepsilon_{cc}/\varepsilon_{co}$) models developed for predicting the performance of traditional FRP-confined concrete. Three of these models (Lim and Ozbakkaloglu 2014; Miyauchi et al. 1997; Xiao et al. 2010) were selected from a recent review study reported in Lim and Ozbakkaloglu (2014) and are intended for predicting strain enhancement ($\varepsilon_{cc}/\varepsilon_{co}$) of FRP-confined NSC or HSC. For completeness of the model comparison, in addition to the models applicable to HSC, three of the best performing models (i.e., Albanesi et al. 2007; Tamuzs et al. 2006; Teng et al. 2009) out of the 88 NSC models reviewed in Ozbakkaloglu et al. (2013) are also included in the performance comparison. In *Table 3* performance statistics are provided separately for specimens with interface gap, lateral prestress and those manufactured without gap or prestress which are referred to as control specimens. In the assessment shown in *Table 3*, the mean square error (*MSE*), average absolute error (*AAE*) and mean (*M*) were used as the statistical indicators to evaluate the accuracy and consistency of model predictions. The values of *MSE* and *AAE*, determined by *Eqs. 15* and *16* respectively, were used as statistical indicators of modeling accuracy where lower values indicated better model performance. The value of mean (*M*), determined by regression analysis, was used to describe the associated average overestimation or underestimation of the model, where an overestimation is represented by a value greater than 100%.

$$AAE = \frac{\sum_{i=1}^{n} \left| \frac{\text{mod}_i - \exp_i}{\exp_i} \right|}{N} \tag{15}$$

$$MSE = \frac{\sum_{i=1}^{n} \left(\text{mod}_i - \exp_i \right)^2}{N} \tag{16}$$

where *mod* is the model prediction, *exp* is the experimental value and *N* is the total number of datasets.

In addition to the statistical indicators presented in *Table 3*, a graphical illustration of the model performances is presented in *Fig. 9*. This figure presents a comparison of model predictions to experimental values, where the 45 degree line corresponds to perfect agreement between the predictions and the test results. A trend that spans above the 45 degree line represent overestimation of the experimental results by model predictions, whereas a trend that spans below the reference line indicates an underestimation of the test result.

As expected, it can be seen in this comparison that all models perform well when predicting strain enhancement of control specimens maintaining values of *MSE* and *AAE* below 1.1 and 14.0%, respectively. It can also be seen in this model assessment that in general, accuracy for existing model predictions of $\varepsilon_{cc}/\varepsilon_{co}$ degrade when applied to specimens manufactured with interface gap or lateral prestress, with this observation more pronounced for specimens with interface gap. However, it is evident from *Table 3* that the NSC models appear to accurately predict the behavior of specimens manufactured with lateral prestress recording significantly low values of *MSE* and *AAE*. This outcome can be attributed to the inability of these model to account for the decrease in strain enhancement for higher strength concretes coupled with the increase in strain enhancement due to the lateral prestressing which unintentionally results in an accurate final prediction of ultimate strain. An examination of *Fig. 9* and the corresponding values of mean (*M*) presented in *Table 3* reveals that the existing models underestimate and overestimate the performance of interface gap and lateral prestress specimens, respectively. This outcome can be attributed to the increase and decrease in ultimate strain due to the influence of interface gap and lateral prestress respectively, which is not considered in the existing models. It can be seen from the results given in *Table 1* that the proposed model is able to maintain its accuracy for the full range of specimens, which indicates that the model adequately accounts for the influences of an interface gap and lateral prestressing of confinement.

It should be noted that in the evaluation of model predictions, the experimentally recorded hoop rupture strains ($\varepsilon_{h,rup}$) were used for consistency rather than the values or expressions recommended by the original models for the calculation of $\varepsilon_{h,rup}$. It is also worth noting that values of the axial strain corresponding to the compressive strength of unconfined concrete (ε_{co}) were determined according to the expression provided in Lim and Ozbakkaloglu (2014) and presented here as *Eq. 5*.

CONCLUSIONS

This paper has presented the results of an investigation into the lateral-to-axial strain behavior of FRP-confined concrete columns with an interface gap or prestressed FRP tubes. Two databases of experimental results of FRP-confined concrete manufactured with either simulated radial shrinkage or lateral prestress have been described and presented. On the basis of these databases, new lateral-to-axial strain models have been developed and summarized in this paper. These models are applicable to FRP-confined concrete columns with delayed or early activation of confinement, and they incorporate the important factors identified from the close examination of the results reported in the databases. A comparison of the models predicting the lateral-to-axial strain curves to the experimentally recorded curves shows good agreement for the full range of test specimens. As revealed by the results of the performance assessment, the proposed models adequately account for the influence of FRP-to-concrete interface gap and lateral prestress on the strain enhancement ratio of FRP-confined concrete columns.

NOMENCLATURE

AAE	Average absolute error
D	Diameter of concrete cylinder (mm)
exp	Experimental value
E_f	Modulus of elasticity of the fibers (MPa)
f_l	Lateral confinement pressure for FRP confined concrete (MPa)
f_l^*	Lateral confinement pressure for actively confined concrete (MPa)
K_l	Confinement stiffness of FRP shell (MPa)
k_a	Coefficient to allow for specimen aspect ratio
k_d	Coefficient to allow for concrete density
k_s	Coefficient to allow for specimen size
k_{sh}	Coefficient to allow for FRP-to-concrete interface gap
k_ε	FRP strain reduction factor determined from strains outside overlap region
M	Mean value
mod	Model predicted value
MSE	Mean square error
n	Curve shape parameter
N	Total number of datasets
r	Concrete brittleness
t_f	Total fiber thickness of FRP confinement (mm)
$\varepsilon_{c,i}$	Axial strain corresponding to the inflection point of the descending branch of the stress-strain curve

$\varepsilon_{c,initial}$ Amount of initial axial strain developed in the FRP shell prior to development of corresponding lateral strains.

ε_{co} Axial compressive strain of unconfined concrete at f'_{co}

ε_{cu} Ultimate axial compressive strain of confined concrete

$\frac{\varepsilon_{cu}}{\varepsilon_{co}}$ Ultimate strain enhancement

ε_{f} Ultimate tensile strain of fibers

$\varepsilon_{h,rup}$ Hoop rupture strain of FRP shell recorded outside overlap region

$\varepsilon_{l,initial}$ Amount of lateral prestrain of the fibers in the FRP shell prior to axial loading

ε_{sh} Amount of radial shrinkage for the internal concrete

$\rho_{c,f}$ Density of concrete (kg/m^3)

v_i Initial Poisson's ratio of concrete

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Table 1. Experimental test databases

Experimental Database	Concrete type	Average f'_{co} (MPa)	f_{lu}/f'_{co}	Fiber thickness, t_f (mm)	Shrinkage gap (με)	Lateral prestress, $\varepsilon_{f,i}/\varepsilon_{fu}$	Number of specimens
Specimens with interface gap	NSC	44.8	0.31	0.4	0	n/a	3
		44.8	0.31	0.4	400	n/a	3
		44.8	0.31	0.4	800	n/a	3
	HSC	83.2	0.33	0.8	0	n/a	3
		83.2	0.33	0.8	400	n/a	3
		83.2	0.33	0.8	800	n/a	3
		83.2	0.33	0.8	1200	n/a	3
		83.2	0.33	0.8	1600	n/a	3
Specimens with lateral prestress	HSC	110.3	0.25	0.8	n/a	0%	3
		100.2	0.27	0.8	n/a	19%	3
		100.2	0.27	0.8	n/a	26%	3
		100.2	0.27	0.8	n/a	32%	3
		110.3	0.37	1.2	n/a	0%	3
		100.2	0.41	1.2	n/a	14%	3
		100.2	0.41	1.2	n/a	19%	3
		100.2	0.41	1.2	n/a	22%	2

Table 2. Expressions for predicting dilation behavior of FRP-confined concrete with delayed or early activation of confinement

Parameter	Proposed model		
	Delayed activation of confinement (Interface gap)	Typical activation of confinement	Early activation of confinement (Lateral prestress)
Strain reduction factor (k_ε)	$k_\varepsilon = \frac{\varepsilon_{h,rup}}{\varepsilon_{fu}} = 1.15\left(0.9 - 2.3f'_{co} - 0.75E_f \times 10^{-6}\right)$	$k_\varepsilon = \frac{\varepsilon_{h,rup}}{\varepsilon_{fu}} = 0.9 - 2.3f'_{co} - 0.75E_f \times 10^{-6}$	$k_\varepsilon = \frac{\varepsilon_{h,rup}}{\varepsilon_{fu}} = 0.9 - 0.75E_f \times 10^{-6}$
Axial strain (ε_c)	$\varepsilon_c = \varepsilon_{c,initial} + 0.04k_{sh}\varepsilon_l^{0.7}\left[1+21\left(\frac{f_l}{f'_{co}}\right)^{0.8}\right]$ $\varepsilon_{c,initial} = 0.8\varepsilon_{co}$ $k_{sh} = 1 + f'_{co}\,\varepsilon_{sh}^{0.8}$	$\varepsilon_c = \frac{\varepsilon_l}{\upsilon_i\left[1+\left(\varepsilon_l/\upsilon_i\varepsilon_{co}\right)^n\right]^{\frac{1}{n}}} + 0.04\varepsilon_l^{0.7}\left[1+21\left(\frac{f_l}{f'_{co}}\right)^{0.8}\right]$	$\varepsilon_c = \left(\frac{K_l}{1000}\right)^{0.8}\left(\varepsilon_l - \varepsilon_{f,i}\right)$ $K_l = \frac{2E_f t_f}{D}$

where E_f, f'_{co}, and f_l are in MPa

Table 3. Statistics on performances of models in predicting strain enhancement ratios of FRP-confined columns with interface gap and lateral prestress.

Model	Database	Prediction of $\varepsilon_{cc}/\varepsilon_{co}$		
		MSE	*AAE* (%)	*M* (%)
Albanesi et al. (2007)*	Interface gap	7.8	27.0	73.0
	Lateral prestress	0.5	9.9	106.9
	Control	1.0	12.7	102.0
	All combined	3.5	17.4	92.3
Lim and Ozbakkaloglu (2014d)	Interface gap	3.8	18.2	85.1
	Lateral prestress	2.9	25.7	125.7
	Control	0.5	7.4	98.4
	All combined	2.7	18.6	103.4
Miyauchi et al. (1999)	Interface gap	11.5	34.5	65.5
	Lateral prestress	1.5	13.8	86.7
	Control	1.1	14.0	86.0
	All combined	5.4	22.1	78.1
Tamuzs et al. (2006)*	Interface gap	6.1	23.7	76.3
	Lateral prestress	0.5	10.4	110.2
	Control	0.6	9.6	91.8
	All combined	2.8	15.5	92.6
Teng et al. (2009)*	Interface gap	11.2	33.8	66.2
	Lateral prestress	0.2	5.8	101.1
	Control	1.2	14.6	85.4
	All combined	4.8	19.0	83.6
Xiao et al. (2010)	Interface gap	2.2	12.9	93.4
	Lateral prestress	8.3	43.4	143.4
	Control	0.9	12.1	110.2
	All combined	4.2	24.3	116.0
Proposed model	Interface gap	1.5	10.9	100.4
	Lateral prestress	0.5	8.6	101.7
	Control	0.5	7.4	98.4
	All combined	0.9	9.2	100.5

where * indicates models intended for use with FRP-confined NSC

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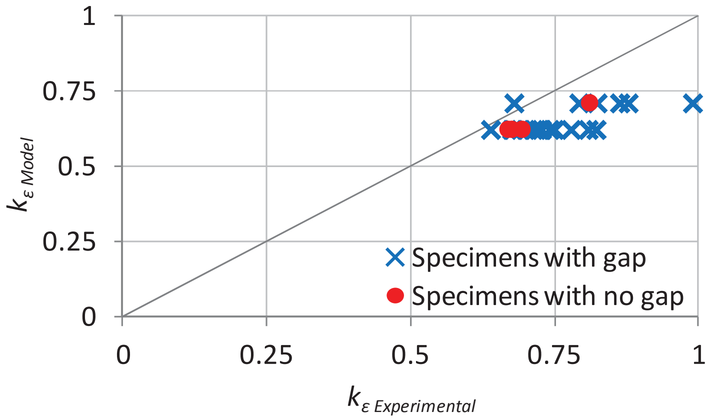

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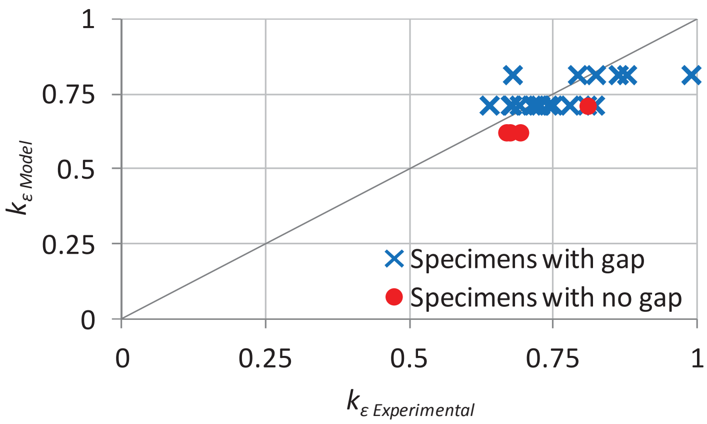
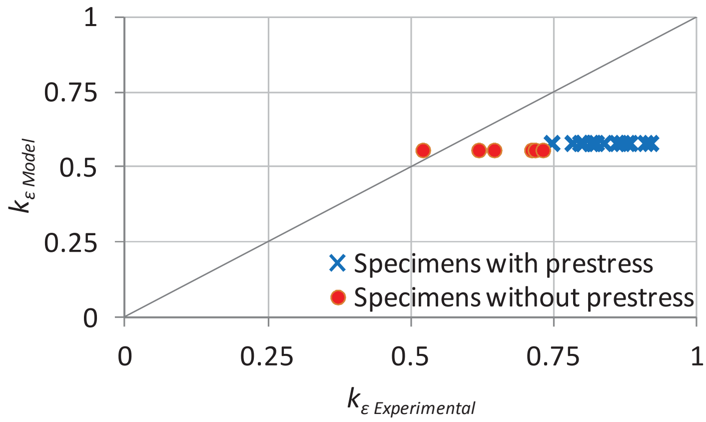


b)

Figure 1. Comparison of model predictions with experimentally recorded strain reduction factors (k_ε) for specimens with interface gap: a) original model by Lim and Ozbakkaloglu 2014; b) proposed model



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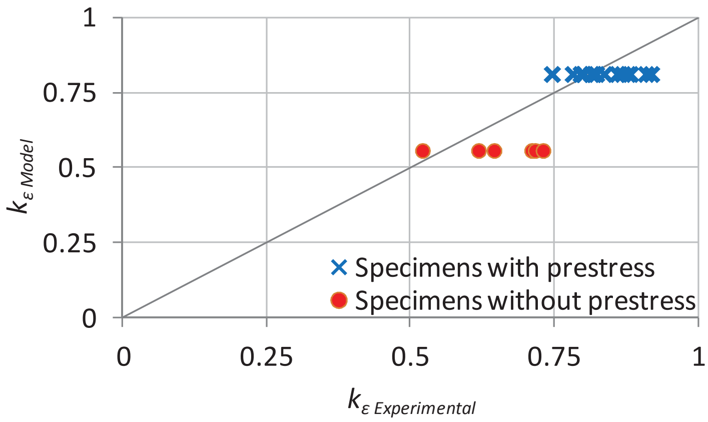


b)

Figure 2. Comparison of model predictions with experimentally recorded strain reduction factors (k_ε) for specimens with lateral prestress: a) original model by Lim and Ozbakkaloglu 2014; b) proposed model

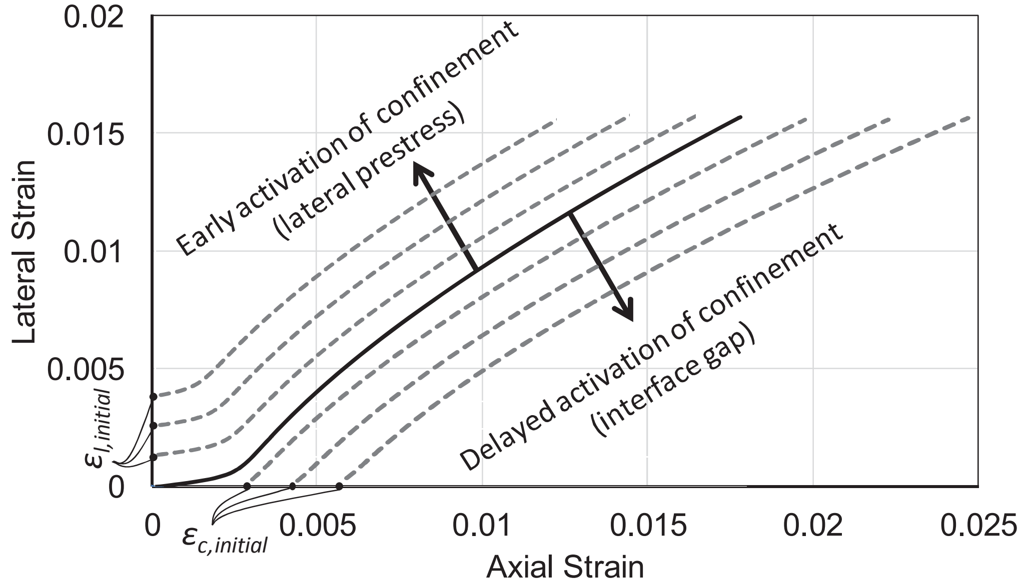


Figure 3. Dilation behavior of FRP-confined concrete under axial compression with early or delayed activation of confinement.

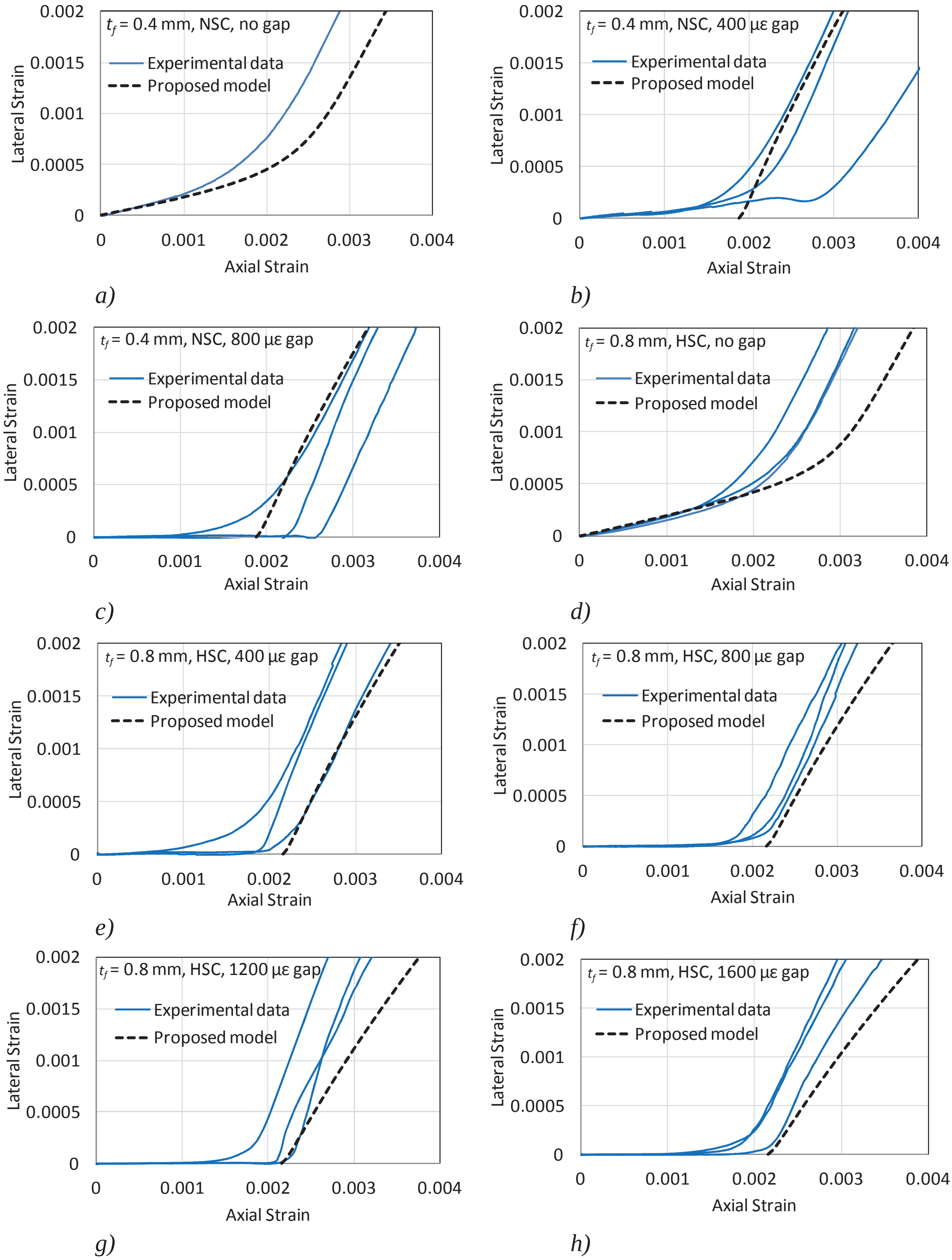
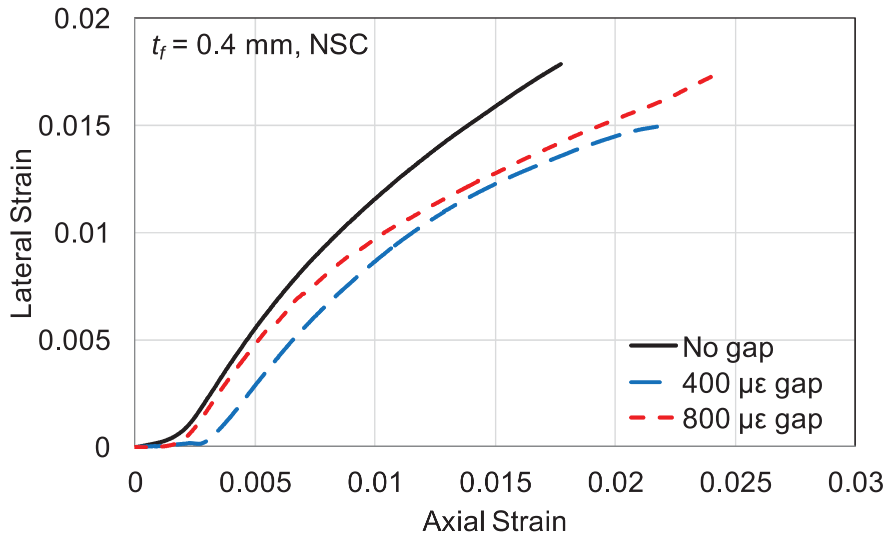


Figure 4. Comparison of model predictions with experimentally recorded lateral-to-axial strain behavior for the initial branch of specimens with interface gap: a) t_f = 0.8 mm with no interface gap; b) t_f = 0.8 mm with 400 με gap; c) t_f = 0.8 mm with 800 με gap; d) t_f = 1.2 mm with no interface gap; e) t_f = 1.2 mm with 400 με gap; f) t_f = 1.2 mm with 800 με gap; g) t_f = 1.2 mm with 1200 με gap; h) t_f = 1.2 mm with 1600 με gap



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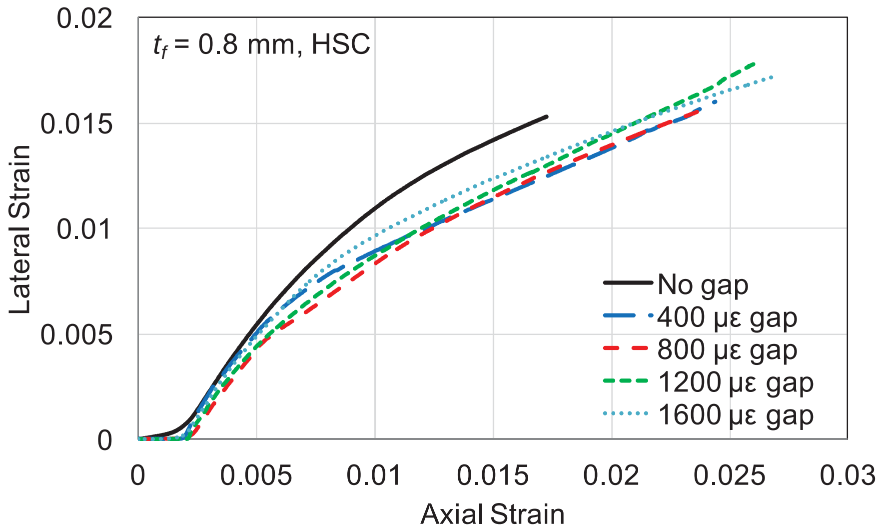


b)

Figure 5.Comparison of lateral-to-axial strain behavior for specimens with interface gap: a) NSC; b) HSC

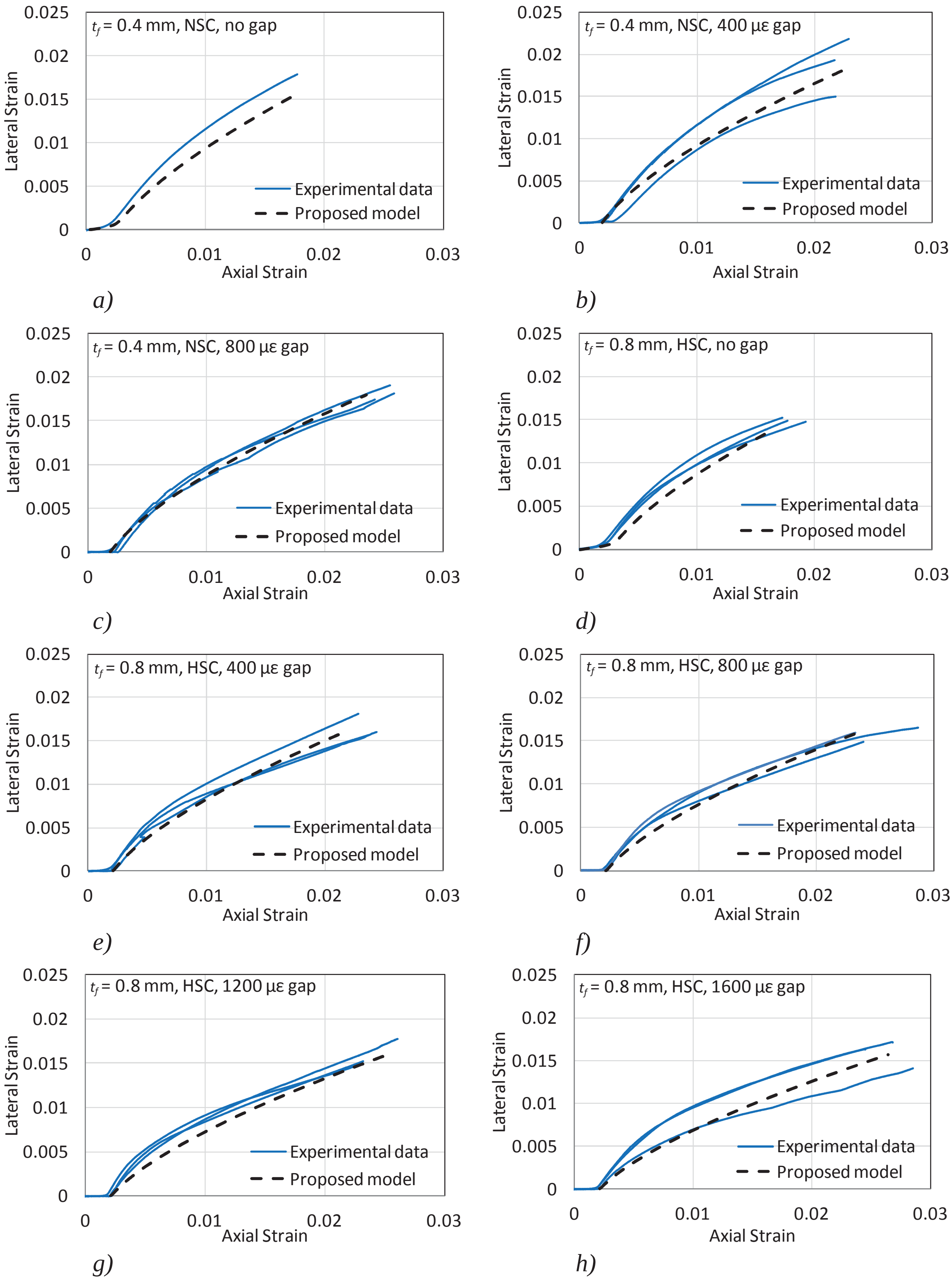
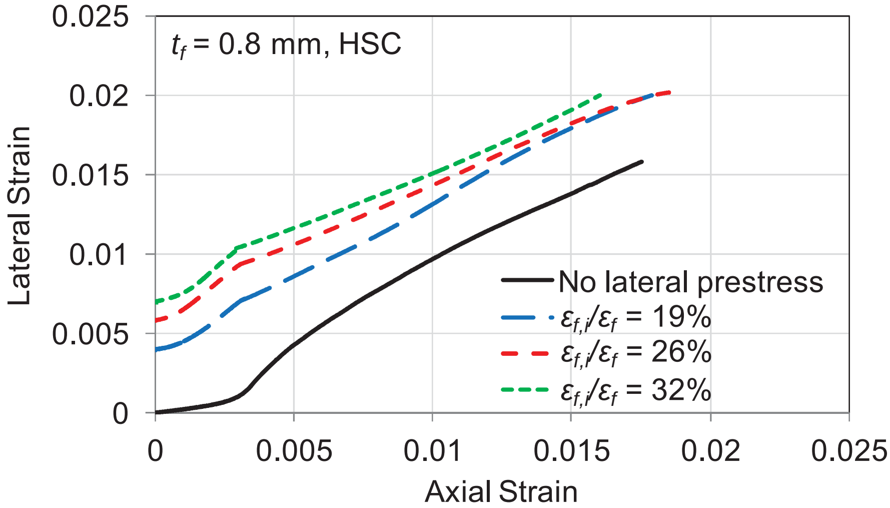


Figure 6. Comparison of model predictions with experimentally recorded lateral-to-axial strain behavior for specimens with interface gap: a) $t_f = 0.4$ mm with no interface gap; b) $t_f = 0.4$ mm with 400 με gap; c) $t_f = 0.4$ mm with 800 με gap; d) $t_f = 0.8$ mm with no interface gap; e) $t_f = 0.8$ mm with 400 με gap; f) $t_f = 0.8$ mm with 800 με gap; g) $t_f = 0.8$ mm with 1200 με gap; h) $t_f = 0.8$ mm with 1600 με gap



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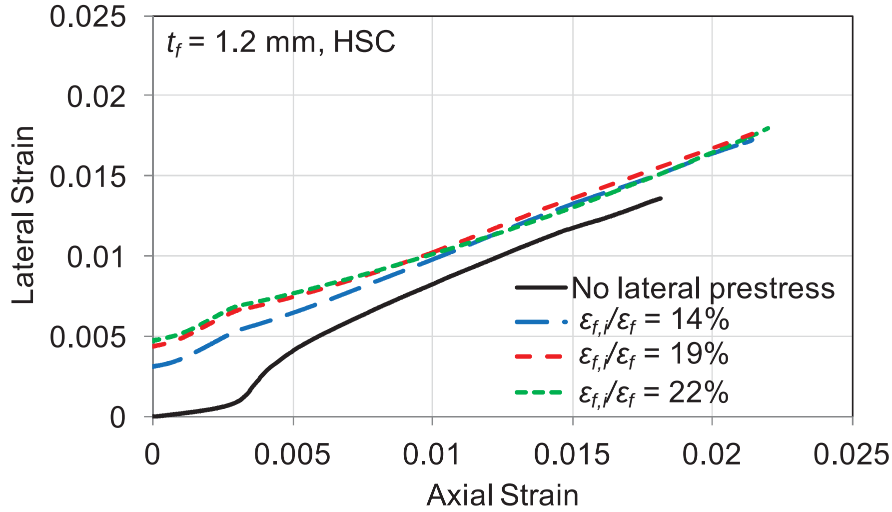


b)

Figure 7.Comparison of lateral-to-axial strain behavior for specimens with lateral prestress: a) lightly-confined; b) well-confined

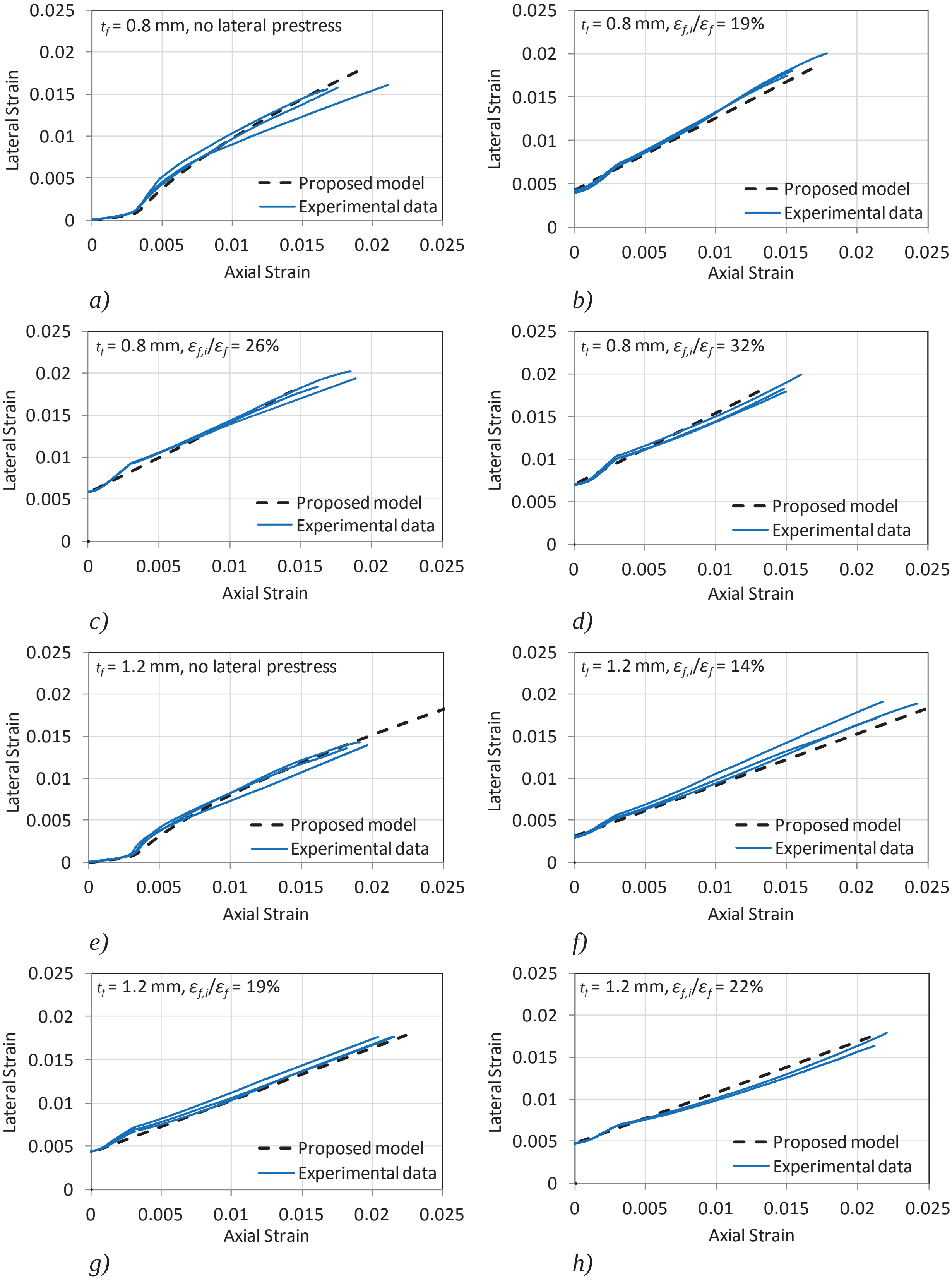
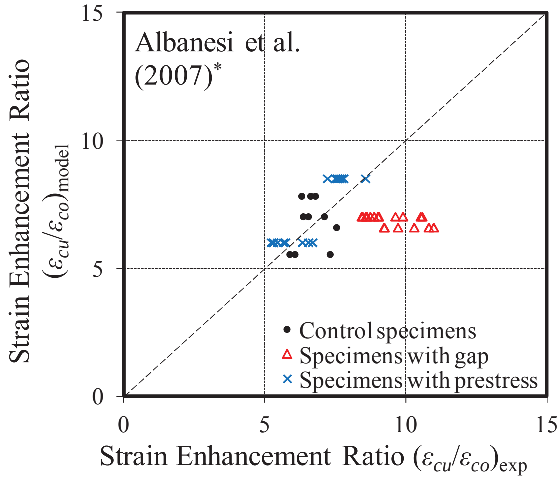
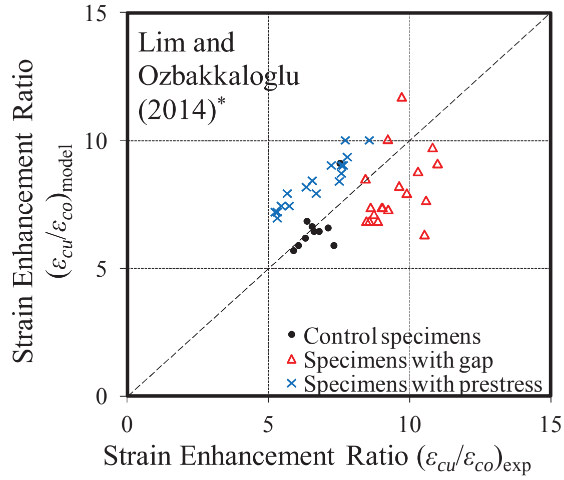


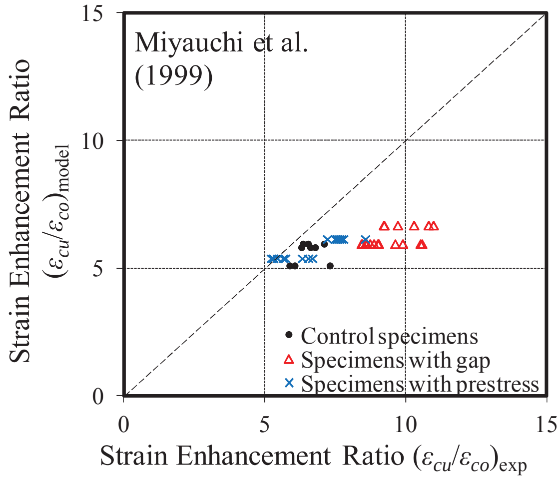
Figure 8. Comparison of model predictions with experimentally recorded lateral-to-axial strain behavior for specimens with lateral prestress: a) t_f = 0.8 mm with no lateral prestress; b) t_f = 0.8 mm with $\varepsilon_{f,i}/\varepsilon_f$ = 19%; c) t_f = 0.8 mm with $\varepsilon_{f,i}/\varepsilon_f$ = 26%; d) t_f = 0.8 mm with $\varepsilon_{f,i}/\varepsilon_f$ = 32%; e) t_f = 1.2 mm with no lateral prestress; f) t_f = 1.2 mm with $\varepsilon_{f,i}/\varepsilon_f$ = 14%; g) t_f = 1.2 mm with $\varepsilon_{f,i}/\varepsilon_f$ = 19%; h) t_f = 1.2 mm with $\varepsilon_{f,i}/\varepsilon_f$ = 22%


Albanesi et al. (2007)*
Control specimens
Specimens with gap
Specimens with prestress
Strain Enhancement Ratio $(\varepsilon_{cu}/\varepsilon_{co})_{model}$
Strain Enhancement Ratio $(\varepsilon_{cu}/\varepsilon_{co})_{exp}$
0
5
10
15

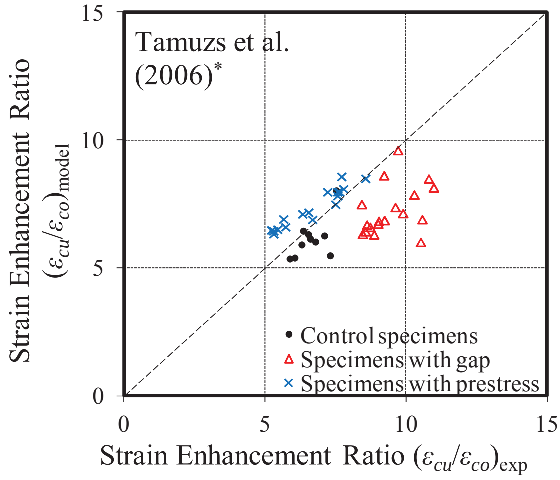
a)


Lim and Ozbakkaloglu (2014)*
Control specimens
Specimens with gap
Specimens with prestress
Strain Enhancement Ratio $(\varepsilon_{cu}/\varepsilon_{co})_{model}$
Strain Enhancement Ratio $(\varepsilon_{cu}/\varepsilon_{co})_{exp}$
0
5
10
15

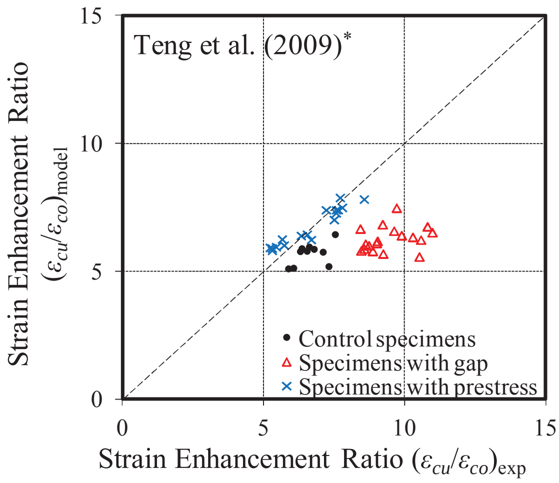
b)


Miyauchi et al. (1999)
Control specimens
Specimens with gap
Specimens with prestress
Strain Enhancement Ratio $(\varepsilon_{cu}/\varepsilon_{co})_{model}$
Strain Enhancement Ratio $(\varepsilon_{cu}/\varepsilon_{co})_{exp}$
0
5
10
15

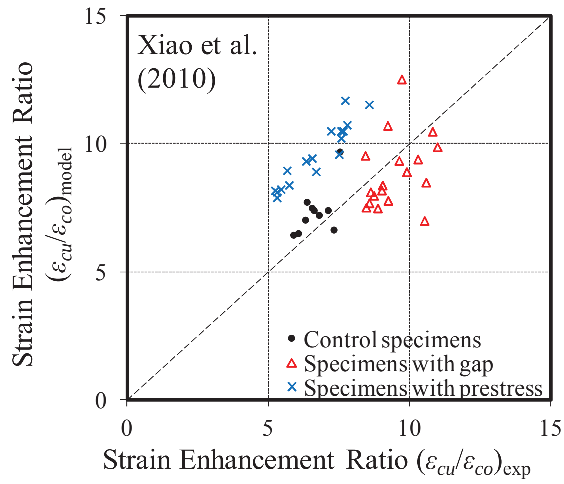
c)


Tamuzs et al. (2006)*
Control specimens
Specimens with gap
Specimens with prestress
Strain Enhancement Ratio $(\varepsilon_{cu}/\varepsilon_{co})_{model}$
Strain Enhancement Ratio $(\varepsilon_{cu}/\varepsilon_{co})_{exp}$
0
5
10
15

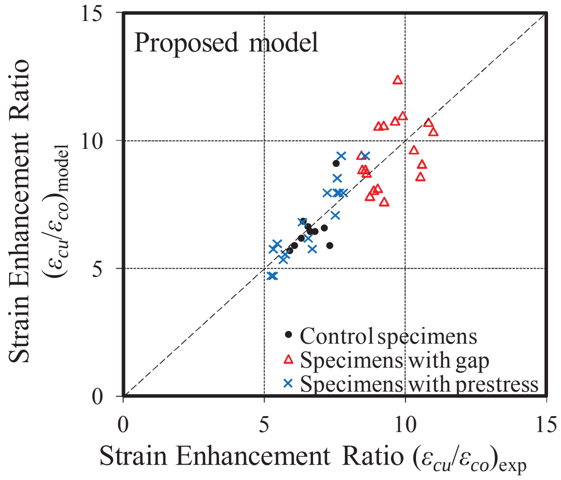
d)


Teng et al. (2009)*
Control specimens
Specimens with gap
Specimens with prestress
Strain Enhancement Ratio $(\varepsilon_{cu}/\varepsilon_{co})_{model}$
Strain Enhancement Ratio $(\varepsilon_{cu}/\varepsilon_{co})_{exp}$
0
5
10
15

e)


Xiao et al. (2010)
Control specimens
Specimens with gap
Specimens with prestress
Strain Enhancement Ratio $(\varepsilon_{cu}/\varepsilon_{co})_{model}$
Strain Enhancement Ratio $(\varepsilon_{cu}/\varepsilon_{co})_{exp}$
0
5
10
15

f)



g)

Figure 9. Comparison of model predictions of strain enhancement ratios ($\varepsilon_{cu}/\varepsilon_{co}$) with experimental data

CONCLUSIONS

This thesis has presented the results of an investigation into the axial compressive behaviour of FRP-confined high-strength concrete. Initially, an extensive review of FRP-confined normal-strength concrete (NSC) was performed to summarise the current published literature until the end of 2011, and present a unified framework for future reference. This comprehensive review of FRP-confined conventional normal-strength concrete (NSC) led to the identification of key confinement parameters which were subsequently examined for the lesser understood area of FRP-confined HSC. Research gaps were identified from the review of current literature and these experimental parameters were systematically examined by designing and conducting new tests at the University of Adelaide. The parameters that have been examined in this research include: 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. A close examination of the test results from these experimental programs has lead to a number of important findings for the axial compressive behaviour of FRP-confined HSC. In addition to these experimental findings, the development of an analysis-oriented model is presented in this thesis that is applicable to prestressed or delayed activation of confinement, caused by prestressing the confinement fibres or radial shrinkage of concrete respectively.

The research presented within this thesis presents a significant contribution to the current literature by reporting a large number of experimental datasets and corresponding discussions and assessments for an investigation into monotonically loaded FRP-confined HSC columns. The specific research contributions for each journal article, presented here as chapters of this thesis, have been listed and summarised in *Table 1*.

Table 1. Summary of research contribution

Publication	Contributions
Ozbakkaloglu et al. [1]	A systematic performance assessment of existing design-oriented and analysis-oriented models for FRP-confined concrete using an up-to-date database has been presented in this paper. Based on the review study, factors influencing the performances of exiting models and recommendations for modelling improvements have been outlined.
Vincent and Ozbakkaloglu [2]	This paper presented the results of an experimental study that examined the influence of concrete strength and confinement method on axial compressive behaviour of FRP confined high- and ultra high-strength concrete. In addition to contributing a significant number of experimental datasets for future use, a statistical assessment of existing stress-strain models was presented.
Ozbakkaloglu and Vincent [3]	As the first experimental study on the axial compressive behaviour of circular high-strength concrete-filled FRP tubes confined by AFRP, CFRP, or HMCFRP, a number of unique conclusions were presented. The axial compressive behaviour of 83 test specimens is presented which led to the discussions on the influence of fibre type, concrete strength, specimen size and FRP tube manufacturing method.
Vincent and Ozbakkaloglu [4]	This paper presented the results of the first experimental study to systematically investigate the influence of fibre orientation on the axial performance of FRP-confined concrete. In addition to this, the effect of specimen end condition was examined on both CFFTs and FRP-wrapped specimens.
Vincent and Ozbakkaloglu [5]	This paper presented a number of unique conclusions as it was the first experimental study to examine the influence of specimen slenderness on the compressive behaviour of FRP-confined HSC. In addition to reporting the axial compressive behaviour, discussion were presented on the variation of hoop strain along specimen height and around specimen perimeter.
Vincent and Ozbakkaloglu [6]	This paper presented the first study on FRP-confined concrete to experimentally examine the influence of amount of concrete shrinkage on axial compressive behaviour. The experimental program discusses a unique specimen manufacturing technique designed to apply a constant level of shrinkage in a controlled manner.
Vincent and Ozbakkaloglu [7]	As the first comprehensive experimental study to examine the influence of FRP overlap region length, continuity and distribution on the axial compressive behaviour of carbon FRP-confined NSC and HSC, a number of unique conclusions were presented. In addition to this, the experimental study reported in this paper was the first to examine the influence of overlap configuration on strain reduction factor for either NSC or HSC.
Vincent and Ozbakkaloglu [8]	This paper presents a discussion on the confinement parameters that have received less attention and associated experimental testing. This paper presents a collection of important findings from previous experimental investigations that focused on the behaviour of FRP-confined normal- and high-strength concrete (NSC and HSC) columns under concentric compression.
Vincent and Ozbakkaloglu [9]	This paper presented a number of unique conclusions as it was the first experimental study to examine the influence of prestressing the confining shell. A unique method to control the level of applied lateral prestress was developed as part of this research. Prestressing of the confining shell was found to supply significant benefits for FRP-confined HSC including overcoming the strength loss problem at the transition region, increasing ultimate conditions and specimen toughness.
Vincent and Ozbakkaloglu [10]	On the basis of the two databases presented in previous papers ([6] and [9]), a lateral-to-axial strain model is developed. This model is the first to accurately describe the dilation behaviour of FRP-confined concrete columns with early or delayed activation of confinement, caused by prestressing the confinement fibres or radial shrinkage of concrete, respectively.

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