THE UNIVERSITY of ADELAIDE

AXIAL COMPRESSIVE BEHAVIOR OF FRP-CONCRETE-STEEL DOUBLE-SKIN TUBULAR COLUMNS

Butje Alfonsius Louk Fanggi

BEng and MEng (Structural Engineering)

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

2015

To my wife, Melinda Louk Fanggi-Moata

And my kids, Kayleen and Keanu Louk Fanggi

CONTENTS

ABSTRACT

A new type of composite structural system has been proposed in terms of FRP-concrete-steel double-skin tubular columns (DSTCs). This composite system consists of a steel tube inside, an FRP tube outside with concrete in between, and it combines the advantages of all three materials to achieve a high-performance structural member. This thesis is aimed at developing an improved understanding of the axial compressive behavior of DSTCs.

To this end, six experimental studies were undertaken at the University of Adelaide. In each of these studies, the key parameters that influence the axial compressive behavior of DSTCs were identified and investigated. The results of these experimental studies indicate that concrete in a DSTC system is confined effectively by FRP and steel tubes. Both the normal-and high-strength concrete DSTCs exhibited a highly ductile compressive behavior under monotonic and cyclic axial compression. However, it is found that, for a given nominal confinement ratio, an increase in the concrete strength results in a decrease in the ultimate axial strain of DSTCs. The results also indicate that increasing the inner steel tube diameter leads to an increase in the ultimate axial stress and strain of concrete in DSTCs. It is observed that the concrete-filling of the inner steel tubes of DSTCs results in an increase in the compressive strength and a slight decrease in the ultimate axial strain of concrete in DSTCs, compared to the values observed in companion specimens with hollow inner steel tubes. It is also observed that cyclically loaded normal-strength concrete (NSC) DSTCs developed similar strength and strain enhancement ratios to those of monotonically loaded NSC DSTCs. The results also show that concrete in hollow DSTCs manufactured with square inner steel tubes develops significantly lower ultimate axial stresses and strains than those of concrete in

companion hollow DSTCs with circular inner steel tubes. It is found, however, that the performance of these specimens improves dramatically when the square inner steel tube is filled with concrete.

Apart from these experimental studies, this thesis also presents analytical models that were developed to predict the compressive strength and ultimate axial strain of concrete in DSTCs. The first of these models was developed to predict the compressive strength and ultimate axial strain of concrete in hollow circular DSTCs. After undertaking additional studies to expand the test database of square and concrete-filled DSTCs a second model that is applicale both circular and square and hollow and concrete-filled DSTCs was proposed. Comparison with experimental test results show that of the proposed models are in close agreement with the test results, and the models provide improved accuracy compared to the existing models.

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.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Signed:_______________________ Date:__________________

ACKNOWLEDGEMENTS

Firstly, I would like to express my deepest gratitude to my supervisors, Dr. Togay Ozbakkaloglu and Assoc. Prof. Yung Ngothai, for their supervision, support and encouragement over the course of my PhD candidature. I would particularly like to thank Dr. Togay Ozbakkaloglu for his continual enthusiasm, vision, and determination for my research to succeed. I am also grateful to Assoc. Prof. Yung Ngothai for her help and motivation during the time of my candidature.

I acknowledge the financial support from the Government of the Republic of Indonesia through their Directorate General of Higher Education (DIKTI) Scholarships that sponsored my study at the University of Adelaide.

I would also like to thank all academics and technical staff who have helped me with this thesis in their fields of expertise. In particular, I thank Mr. Gary Bowman and Jon Ayoub who provided technical assistance throughout the experimental program and Barbara Brougham who provided technical reviews of most of the publications presented in this thesis.

I am very grateful to my fellow PhD students Mr. Thomas Vincent, Jian Lim, Mohammad Albitar, Tianyu Xie, Lei Gu, Junai Zhang, and Ms. Yunita Idris for their friendship, encouragement, and help. I would particularly like to thank Jian Lim who was always willing to help and give suggestions during development of my model papers. Many thanks also to other PhD students in the School of Civil, Environmental and Mining Engineering who have helped me throughout the course.

I would also like to thank my fellow brothers and sisters in Christ, for their continued support during the last year of my study.

Finally, and most importantly, I thank God, who put and helped me in this journey.

LIST OF NOTATIONS

B	=	Internal width of square outer FRP tube (mm)
c_1	=	Parameter in the compressive strength expression
c_2	=	Parameter in the ultimate strain expression
D	=	Internal diameter of FRP tube (mm)
D_s	=	External diameter of steel tube (mm)
E_f	=	Elastic modulus of fibers (MPa)
E_{frp}	=	Elastic modulus of FRP material (MPa)
f'_{cc}	=	Peak axial compressive stress of concrete in DSTC (MPa)
f'_{cu}	=	Ultimate axial compressive stress of concrete in DSTC (MPa)
f'_{co}	=	Peak axial compressive stress of unconfined-concrete (MPa)
f_y	=	Yield strength of steel tube (MPa)
f_u	=	Ultimate tensile strength of steel tube (MPa)
f'_{c1}	=	Axial compressive stress of concrete in DSTC at first peak (MPa)
f'_{c2}	=	Axial compressive stress of concrete in DSTC at second transition (MPa)
f_{l1}	=	Confining pressure at f'_{c1} (MPa)
f_{l2}	=	Confining pressure at f'_{c2} (MPa)
f_{lu}	=	Nominal lateral confining pressure at ultimate (MPa)
$f_{lu,a}$	=	Actual lateral confining pressure at ultimate (MPa)
f_{lo}	=	Threshold confining pressure at ultimate (MPa)
f_f	=	Ultimate tensile strength of fibers (MPa)
f_{frp}	=	Ultimate tensile strength of FRP material (MPa)
H	=	DSTC specimen height (mm)
k_1	=	Axial strength enhancement coefficient

k_2 = Axial strain enhancement coefficient

K_l = Lateral confinement stiffness (MPa)

K_{lo} = Threshold confinement stiffness (MPa)

$K_{\varepsilon,f}$ = Hoop strain reduction factor of fibers

P_T = Axial load capacity of DSTC (kN)

P_s = Axial load capacity of steel tube (kN)

P_{co} = Axial load capacity of unconfined concrete (kN)

r = Corner radius (mm)

t_f = Total nominal thickness of fibers (mm)

t_{frp} = Total nominal thickness of FRP material (mm)

t_s = Thickness of steel tube (mm)

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

ε_{cu} = Ultimate axial strain of concrete in DSTC

$\varepsilon_{h,rup}$ = Hoop rupture strain of FRP shell

ε_{l1} = Hoop rupture strain of DSTC at f'_{c1}

ε_{l2} = Hoop rupture strain of DSTC at f'_{c2}

ε_f = Ultimate tensile strain of fibers

ε_{frp} = Ultimate tensile strain of FRP material

ε_s = Ultimate tensile strain of steel tube

$Ø_F$ = Solidity factor of inner steel tube