THE UNIVERSITY
of ADELAIDE

AXIAL COMPRESSIVE BEHAVIOR OF ACTIVELY CONFINED AND FRP-CONFINED CONCRETES

Jian Chin Lim
BEng (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

THIS PAGE HAS BEEN LEFT INTENTIONALLY BLANK

CONTENTS

ABSTRACT

Since the 1920s, a significant research effort has been dedicated to the understanding of the improved compressive behavior of concrete under lateral confinement. Upon the introduction of fiber-reinforced polymer (FRP) composites to the construction industry, the use of FRP as confinement material has received much attention. To that end, a great number of studies have been conducted in the past two decades on the axial compressive behavior of unconfined, actively confined and FRP-confined concretes, resulting in the development of over 110 stress-strain models. These models are classified into four broad categories, namely design-oriented, analysis-oriented, evolutionary algorithm, and finite element models. In the present study, existing models in each category were carefully reviewed and assessed using comprehensive experimental test databases assembled through an extensive review of the literature. The databases cover more than 7000 test results of unconfined, actively confined, and FRP-confined concrete specimens from 500 studies. A close examination of the assessment results has led to a number of important findings on factors influencing the performances of existing models. For each model category possible areas for further improvement were identified and new models were proposed.

First, an empirical model in simple closed-form expressions that are suitable for engineering design purpose was developed using the database of FRP-confined concrete. The distinct feature of this design-oriented model includes its applicability to normal- and high-strength concretes with cross-sections ranging from circular to rectangular. The model also considers the observed dependency of the hoop rupture stain of the confining jacket on the material properties of the concrete and FRP. In addition, a novel concept, referred to as the confinement stiffness threshold condition, was incorporated into this model to allow for an accurate prediction of post-peak strain softening behavior of FRP-confined concrete.

Following this, using the combined database, a unified analysis-oriented model that is capable of predicting the complete stress-strain and dilation behaviors of unconfined, actively confined, and FRP-confined concretes was developed. It was found that, at a given axial strain, lateral strains of actively confined and FRP-confined concretes of the same concrete strength correspond when they are subjected to the same lateral confining pressure. However, under the same condition, concrete confined by FRP exhibits a lower strength enhancement compared to that seen in companion actively confined concrete. On the basis of this observation, a novel approach that incorporates the confining pressure gradient between the two confinement systems was established and a unified stress-strain model was developed. Other distinct features of this highly versatile model are its applicability to concretes ranging from light- to normal-weight and low- to high-strength. In addition, it is also applicable to specimens with various sizes and slenderness.

To improve the capability of handling complex databases with a large number of independent variables, a third category of model that uses evolutionary algorithm and soft computing techniques was considered. In this study, a genetic programming approach that is capable of gradually refining the solution while maintaining the versatility of the model in closed-form expressions was used to develop an evolutionary algorithm model for FRP-confined concrete.

Lastly, the finite element modeling approach was investigated. A review of the existing literature revealed that the failure criterion and flow rule considered by existing FE models for confined concretes are based on limited test results and they are not very sensitive to the variations in unconfined concrete strength and confining pressure. Based on the comprehensive experimental databases assembled, a concrete strength-sensitive finite element model applicable to concrete subjected to various confining pressure levels was developed.

Comparison with experimental test results show that the predictions of all of the proposed models are in good agreement with the test results, and the models provide improved accuracy compared to the existing models. Comparison of models in different categories indicates that model accuracy generally improves with the size of database and the complexity of modeling framework; however, the choice of models depends mainly on the suitability of their end use.

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.

19/05/2015

Signature

Date

ACKNOWLEDGEMENTS

Firstly, I would like to acknowledge the support of my supervisors, Dr. Togay Ozbakkaloglu and Dr. Alex Ching-Tai Ng, 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 Dr. Alex Ching-Tai Ng for his constant motivation and scientific insight into my research.

I would also like to take this opportunity to express my gratitude to all academics and technical staffs who have helped me with this thesis in their fields of expertise. In particular, I thank Mr. Adam Ryntjes who provided technical assistance throughout the experimental program and Barbara Brougham who provided technical reviews to most of the publications presented in this thesis.

I am very grateful to my fellow PhD students Mr. Thomas Vincent, Butje Alfonsius Louk Fanaggi, Tianyu Xie, Yongjian Chen, and Ms. Yunita Idris for their friendship, encouragement, and help. 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 wife, Eva Hooi Ying Beh, for her unwavering support and motivation.

Finally, and most importantly, I thank God, who put me on this journey, which has been challenging but in the end very rewarding.