STRENGTHENING OF RC SLABS WITH PENETRATIONS USING UNANCHORED AND ANCHORED FRP COMPOSITES

by

Seo Jin Kim

BEng., ME.

A thesis submitted in partial fulfilment of

the requirements for the degree of

Doctor of Philosophy

School of Civil and Environmental Engineering

Faculty of Engineering and Information Technology

University of Technology Sydney

Sydney, Australia

July 2009

CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the dissertation itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the dissertation.

Production Note:
Signature removed prior to publication.

Seo Jin Kim

July 2009

ACKNOWLEDGEMENTS

The work in this dissertation was largely undertaken at the University of Technology Sydney (UTS) with the final stages being completed at The University of Hong Kong (HKU). The experimental components of the project as well as other aspects were supported by several sources, namely a UTS Research Excellence Grant as well as General Research Fund (GRF) Grants HKU 716308E and HKU 715907E of the Hong Kong Research Grants Council (RGC) which were all awarded to Dr S.T. Smith (Principle Supervisor). The author was supported by scholarships awarded by UTS in the form of an International Research Scholarship and a UTS Doctoral Scholarship as well as a supplementary scholarship awarded by the School of Civil and Environmental Engineering at UTS. In the final stages the author was supported in the form of a Research Assistantship awarded by HKU. The author is most grateful to all the various sources of funding which supported his doctoral studies as well as UTS and HKU for providing the facilities for undertaking the research.

The author is deeply indebted to his primary supervisor, Dr. Scott Thomas Smith, who provided dedicated and inspirational supervision throughout the course of his doctoral program. Dr. Smith's sincere advice on all technical aspects of the research work as well as his comments and advice on research philosophy in general are deeply appreciated. The author is honoured by the opportunity to have studied under his supervision.

The candidate is grateful to his co-supervisors, Professor Bijan Samali and Dr. Ali Saleh, who provided valuable comments and suggestions on his doctoral program. Professor Samali, Head of the School of Civil and Environmental Engineering at UTS, provided access the facilities of UTS and facilitated a friendly and supportive working environment. Professor Samali's continual support on administrative issues throughout the course of the doctoral program is deeply appreciated.

The author also wishes to thank his colleagues in the School of Civil and Environmental Engineering at UTS. Valuable comments, suggestions and support were provided by Dr. Fook Choon Choi, Dr Jianchun Li, Dr Rasiah Sri Ravindrarajah and Mr Rijun Shrestha. Dr. Fook Choon Choi's dedicated assistance on the final series of the slab testing is particularly appreciated.

The author is grateful to Dr. Ho Kyung Shon who proof read this dissertation. Dr. Shon's invaluable suggestions and critical comments are deeply appreciated.

The experimental work was undertaken at the Structural and Material Laboratories at UTS. The assistance from laboratory staff members Mr Rami Haddad, Mr Laurence Stonard, Ms Marika Mullerova, Mr David Hooper, Mr Peter Brown, Mr David Dicker, Mr Warwick Howse and Mr Nima Abdi is also gratefully acknowledged.

The author wishes to thank personal friends and family for their support and encouragement. Above all, the author's wife, Jung Hwa, is proudly acknowledged for her continual encouragement, patience and love. Without her support, this doctoral

dissertation would not have been completed. This dissertation is therefore dedicated to her.

PUBLICATIONS ARISING FROM THIS DISSERTATION

Journal Papers (Peer Reviewed)

Smith, S.T. and Kim, S.J. (2009) "Strengthening of one-way spanning RC slabs with cutouts using FRP composites", *Construction and Building Materials*, Special Issue on FRP Composites in Construction, Vol. 23, pp. 1578-1590.

Kim, S.J. and Smith, S.T. "Behaviour of FRP spike anchors under tensile load in uncracked concrete", *Advances in Structural Engineering*, APFIS-09 Special Issue, Accepted.

Kim, S.J. and Smith, S.T. "Design of FRP spike anchors under tensile load in uncracked concrete", *Journal of Composites for Construction, ASCE*, Minor Revisions required (Rereview by Editor only).

Smith, S.T. and Kim, S.J. "Fundamental behaviour and strength of FRP spike anchors in FRP-to-concrete joint assemblies", *Advances in Structural Engineering*, Accepted.

Conference Papers (Peer Reviewed)

Kim, S.J. and Smith, S.T. (2009) "Strengthening of RC slabs with large penetrations using anchored FRP composites", *Second Asia-Pacific Conference on FRP in Structures, APFIS 2009,* Seoul, Korea, 9-11 December, under review.

Kim, S.J. and Smith, S.T. (2009) "Shear strength and behaviour of FRP spike anchors in cracked concrete", *Proceedings, Ninth International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures, FRPRCS-9*, Sydney, Australia, 13-15 July, to appear.

Smith, S.T. and S.J. Kim (2008) "Behaviour of handmade FRP spike anchors", *Proceedings, Twentieth Australasian Conference on the Mechanics of Structures and Materials, ACMSM 20*, Toowoomba, Australia, 2-5 December, pp. 39-45.

Smith, S.T. and Kim, S.J. (2008) "Shear strength and behaviour of FRP spike anchors in FRP-to-concrete joint assemblies", *Proceedings (CD ROM), Fifth International Conference on Advanced Composite Materials in Bridges and Structures, ACMBS-V*, Winnipeg, Canada, 22-24 September.

Kim, S.J. and Smith, S.T. (2007) "Pullout tests on FRP anchors", *Proceedings, First Asia-Pacific Conference on FRP in Structures, APFIS 2007,* Hong Kong, China, 12-14 December, pp. 775-782.

Kim, S.J. and Smith, S.T. (2007) "Strengthening of slabs with cut-outs using FRP", *Advanced Composites in Construction Conference, ACIC 2007*, Bath, UK, 2-4 April, pp. 403-411.

ABSTRACT

Reinforced concrete (RC) slabs are one of the most commonly occurring structural forms. Penetrations (otherwise known as *openings* or *cut-outs*) in new as well as existing concrete slabs are commonly introduced due to structural and/or functional reasons. The introduction of a penetration, if large enough, may cause weakening of the slab which will then require the installation of strengthening. Traditional methods of strengthening RC slabs with penetrations, such as the addition of extra supports or bolted steel plates, can be expensive and cumbersome. Such traditional methods can however be replaced by the bonding of high strength, light-weight and durable fibre reinforced polymer (FRP) composites.

In recent years, externally bonded FRPs have become popular as a means to strengthen or rehabilitate RC infrastructure, such as the flexural, shear or torsional strengthening as well as seismic retrofitting of beams, slabs, columns and connections. The effectiveness of the FRP strengthening may however be compromised by premature debonding failure of the FRP prior to its ultimate strength being reached. In order to optimise the use of FRP composites, such premature debonding failure should be prevented or delayed. To date, several different types of anchorage systems have in turn been introduced to FRP strengthened RC members, namely embedded metal threads, U-jackets, near surface mounted rods, and anchors made using FRP. FRP anchors are particularly attractive as they are non-corrosive and can be applied to slabs and walls.

This dissertation is concerned with the strengthening of existing RC slabs with large penetrations with externally bonded FRP composites. FRP anchors are also researched and utilised in order to address the debonding issue. A review of the relevant literature is firstly given which justifies the need for the research presented herein. The remainder of the dissertation is then divided into four main sections, namely (i) pullout strength and behaviour of FRP anchor systems, (ii) shear strength and behaviour of FRP anchor systems, (iii) unanchored FRP-strengthened RC slabs with penetrations, (iv) FRP-strengthened RC slabs with penetrations with the addition of FRP anchors. In each of these four sections, experimental tests are reported. Overall, the slab strengthening schemes were found to be effective and the effectiveness of FRP anchor associated with the debonding issue was proved to be positive. Also reported in each of the four sections is the development of analytical models which have been derived from first principles and calibrated from the various test data. The results of parametric studies are then reported using the various analytical models and the influence of key geometrical and material properties identified. Design recommendations, which can be readily incorporated into existing design guidelines, are then given and future research needs are finally identified.

NOTATION

A_c	=	projected area of a single anchor
A_{eff}	=	effective area of concrete in tension
A_{frp}	=	cross-sectional area of FRP
A_{si}	=	cross-sectional area of i^{th} layer of steel reinforcement in beam
A_{st}	=	cross-sectional area of steel reinforcement in tension
A_{sx}	=	cross-sectional area of steel reinforcement in x-direction
A_{sy}	=	cross-sectional area of steel reinforcement in y-direction
b_c	=	width of concrete
b_{frp}	=	width of FRP
d	=	anchor diameter
d_0	=	anchor hole diameter
d_c	=	thickness of concrete cover
d_{frp}	=	distance from beam compressive face to centroid of FRP
d_h	=	head diameter of headed anchor
d_{si}	=	distance from beam compressive face to centroid of i^{th} layer of steel reinforcement
E_c	=	modulus of elasticity of concrete
E_{frp}	=	modulus of elasticity of FRP
E_r	=	modulus of rupture of concrete
E_s	=	modulus of elasticity of steel reinforcement
f'_c	=	concrete cylinder compressive strength
f_{ct}	=	concrete splitting tensile strength

$f_{ct.com}$	=	tensile strength of concrete based on concrete compressive strength
f_{cu}	=	concrete cube compressive strength
f_{frp}	=	FRP tensile strength
f_{su}	=	ultimate tensile stress of steel reinforcement
f_{sy}	=	yield stress of steel reinforcement
G_f	=	fracture energy of FRP-to-concrete joint
h	=	depth of beam
h_c	=	depth of concrete
h_{cone}	=	depth of concrete cone
h_{ef}	=	effective embedment depth
k	=	empirical multiplier
k_1	=	fracture energy factor of anchored FRP-to-concrete joint
k_2	=	fracture energy factor of anchored FRP-to-concrete joint
k_{c1}	=	mean stress factor
k_{c2}	=	concrete compressive force centroid factor
k_m	=	ratio of ultimate moment of resistance
L_e	=	effective bond length
l_{anc}	=	anchor position between embedded anchor and loaded end
l_{frp}	=	length of bonded FRP
l_{uanc}	=	anchor position between plate end and embedded anchor
M_n	=	ultimate moment of slab along critical crack line
M_u	=	ultimate bending moment capacity of FRP-strengthened section

$M_{u.ap}$	=	moment of resistance of anchored plate failure
$M_{u.cc}$	=	moment of resistance of concrete crushing failure
$M_{u.db}$	=	moment of resistance of IC debonding failure
$M_{u.fr}$	=	moment of resistance of FRP rupture failure
M_{un}	=	ultimate moment of resistance of slab along critical crack line
M_{ux}	=	ultimate moment of resistance of slab along longitudinal reinforcing bar
M_{uy}	=	ultimate moment of resistance of slab along transverse reinforcing bar
M_x	=	ultimate moment of slab along longitudinal reinforcing bar
M_y	=	ultimate moment of slab along transverse reinforcing bar
n	=	number of layers of steel reinforcement
N_c	=	concrete cone pullout resistance of FRP or metal anchor
N_{cb}	=	combined pullout resistance of FRP anchor
$N_{coupon,equiv}$	=	calculated tensile strength or FRP anchor based on FRP coupon test results
N_n	=	design pullout strength of FRP anchor
N_r	=	FRP rupture resistance of FRP anchor
N_s	=	ultimate tensile strength of steel reinforcement
$N_{test,anchor}$	=	tested ultimate tensile strength of FRP anchor
N_u	=	ultimate pullout strength of FRP anchor
$N_{u.test}$	=	tested ultimate pullout strength of FRP anchor
P_n	=	design shear strength of FRP plate
P_u	=	ultimate shear strength of FRP plate

$P_{u.conc}$	=	ultimate shear strength of unanchored FRP plate in anchored FRP-to-concrete joint
$P_{u.pre}$	=	predicted maximum shear strength of FRP Plate
$P_{u.test}$	=	tested maximum shear strength of FRP Plate
s_{anc}	=	FRP anchor spacing
s_{cr}	=	flexural crack spacing
t_c	=	thickness of concrete
t_{frp}	=	thickness of FRP
w_{frp}	=	width of FRP used in FRP anchor construction
x_{na}	=	distance from compressive face to neutral axis
α	=	angle of critical crack line with respect to longitudinal steel reinforcing bar
α_c	=	empirical multiplier of FRP anchor for concrete cone failure
α_{dbic}	=	empirical multiplier for intermediate crack-induced debonding
α_r	=	empirical multiplier of FRP anchor for anchor rupture failure
β_L	=	bond length coefficient
β_p	=	width coefficient
γ_c	=	partial safety factor for concrete in flexural or axial compression
Δ	=	displacement of anchored/unanchored plates
δ	=	interfacial slip (Equation 4.6)
δ_f	=	maximum interfacial slip (failure slip)
ε_{frp}	=	elongation at rupture of FRP

κ = strength enhancement factor in anchored FRP-to-concrete joint

κ_{av} = averaged strength enhancement factor offered by FRP anchor

λ' = elastic constant for Cook et al.'s (2003) pullout strength model

σ_{ap} = predicted debonding stress of anchored FRP plates

σ_c = axial stress of concrete

σ_{dbic} = predicted FRP stress at IC debonding

σ_{frp} = stress of FRP

σ_{si} = stress in i^{th} layer of steel reinforcement

τ = shear stress in adhesive layer

τ_f = maximum shear stress in adhesive layer (local bond strength)

τ_u = uniform bond stress of embedded anchor

τ_u' = design uniform bond stress of embedded anchor

$\tau_{u.max}$ = maximum value of elastic bond stress

Ψ_c = concrete strength modification factor

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES