



**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_{um}	=	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 of 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

CERTIFICATE OF AUTHORSHIP/ORIGINALITY	i
ACKNOWLEDGEMENTS	ii
PUBLICATIONS ARISING FROM THIS DISSERTATION	v
ABSTRACT	vii
NOTATION	ix
TABLE OF CONTENTS	xiv
LIST OF TABLES	xx
LIST OF FIGURES	xxii
<i>1 Introduction</i>	<i>1</i>
1.1 Motivation for Research	2
1.2 Background Information	3
1.2.1 FRP-strengthened RC Slabs	3
1.2.2 Anchorage	5
1.3 Research Objectives	5
1.4 Layout of Dissertation	6
<i>2 Literature Review</i>	<i>15</i>
2.1 Introduction	17
2.2 Fibre-reinforced Polymer (FRP) Composites	17
2.2.1 A Brief History	17
2.2.2 Applications to Civil Infrastructure	18

2.2.3	Types and Properties	18
2.3	FRP-strengthened RC Slabs	19
2.3.1	Experimental Observations and Failure Modes	19
2.3.2	Analytical Modelling	22
2.4	FRP strengthened RC Slabs with Penetrations	26
2.4.1	Experimental Observations and Failure Modes	26
2.4.2	Analytical Modelling	29
2.5	Anchorage	30
2.5.1	Construction of FRP Anchors	32
2.5.2	Pullout Behaviour of Metal and FRP Anchors	35
2.5.3	Shear Behaviour of Metal and FRP Anchors	38
2.5.4	Pullout Model for Metal and FRP Anchors	39
2.6	Conclusions	44
3	<i>Pullout Strength and Behaviour of FRP Anchors</i>	62
3.1	Introduction	65
3.2	Experimental Details	65
3.2.1	Details of Test Specimens	65
3.2.2	Construction of Test Specimens	68
3.2.3	Test Set-up, Instrumentation and Test Procedure: Tensile Strength Tests	70
3.2.4	Test Set-up, Instrumentation and Test Procedure: Pullout Strength Tests	70
3.3	Experimental Results	72

3.3.1	Material Properties	72
3.3.2	Tensile Strength of FRP Anchors	73
3.3.3	Pullout Failure Modes: General	74
3.3.4	Pullout Failure Modes and Failure Loads of Metal Anchors	74
3.3.5	Pullout Failure Modes and Failure Loads of FRP Anchors	75
3.3.6	Load-displacement Response	77
3.3.7	Load-strain Response	78
3.3.8	Parameters Affecting Pullout Strength	79
3.4	Analytical Modelling	82
3.4.1	Experimental Database	82
3.4.2	Proposed Analytical Model	83
3.4.3	Parametric Study	90
3.5	Design Procedure	90
3.6	Conclusions	90
4	<i>Shear Strength and Behaviour of Anchored FRP-to-Concrete Joints</i>	119
4.1	Introduction	122
4.2	Experimental Details	123
4.2.1	Details of Test Specimens	123
4.2.2	Construction of Test Specimens	125
4.2.3	Test Set-up, Instrumentation and Test Procedure	129
4.3	Experimental Results	130
4.3.1	Material Properties	130
4.3.2	Failure Modes and Failure Loads	131

4.3.3	Load-displacement Responses	135
4.3.4	Load-strain Responses	137
4.3.5	Parameters Affecting the Joint Shear Strength	139
4.4	Analytical Modelling	141
4.4.1	Fundamental Derivation for Unanchored FRP-to-Concrete Joints	143
4.4.2	Fundamental Derivation for Anchored FRP-to-Concrete Joints	147
4.4.3	Comparison with Test Results	153
4.4.4	Analytical Model for Anchored FRP-to-Concrete Joints	156
4.4.5	Parametric Studies	159
4.5	Design Procedure	160
4.6	Conclusions	160
5	<i>Unanchored FRP-Strengthened RC Slabs with/without Penetrations</i>	195
5.1	Introduction	197
5.2	Experimental Details	197
5.2.1	Details of Test Specimens	197
5.2.2	Construction of Test Specimens	198
5.2.3	Test Set-up, Instrumentation and Test Procedure	201
5.3	Experimental Results	203
5.3.1	Material Properties	203
5.3.2	Failure Modes and Failure Loads	204
5.3.3	Cracking Behaviour	206
5.3.4	Debonding Behaviour	207
5.3.5	Load-displacement Responses	208

5.3.6	Load-strain Responses	209
5.4	Analytical Modelling	210
5.4.1	Critical Crack Line Analysis	211
5.4.2	Comparison of Prediction and Test Results	214
5.4.3	Parametric Study	216
5.5	Design Procedure	216
5.6	Conclusions	216
6	<i>Anchored FRP-Strengthened RC Slabs with Penetrations</i>	258
6.1	Introduction	260
6.2	Experimental Details	260
6.2.1	Details of Test Specimens	260
6.2.2	Construction of Test Specimen	261
6.2.3	Test Set-up, Instrumentation and Test Procedure	264
6.3	Experimental Results	267
6.3.1	Material Properties	267
6.3.2	Failure Modes and Failure Loads	268
6.3.3	Cracking Behaviour	271
6.3.4	Debonding Behaviour	272
6.3.5	Load-displacement Responses	274
6.3.6	Load-strain Responses	275
6.3.7	Comparison with Unanchored FRP-strengthened Slabs	276
6.4	Analytical Modelling	278
6.4.1	Ultimate Moment of Resistance along a CCL	278

6.4.2	Width of Slab for Ultimate Moment of Resistance	282
6.4.3	Comparison of Prediction and Test Results	283
6.5	Design Procedure	283
6.6	Conclusions	284
7	<i>Conclusions and Future Research</i>	310
7.1	Introduction	311
7.2	Pullout Strength and Behaviour of FRP Anchors	311
7.2.1	Summary	311
7.2.2	Future Research	312
7.3	Shear Strength and Behaviour of Anchored FRP-to-Concrete Joints	313
7.3.1	Summary	313
7.3.2	Future Research	314
7.4	Unanchored FRP-Strengthened RC Slabs with/without Penetrations	314
7.4.1	Summary	314
7.4.2	Future Research	315
7.5	Anchored FRP-Strengthened RC Slabs with Penetrations	316
7.5.1	Summary	316
7.5.2	Future Research	316
	References	318
	Appendices	329
	Appendix A: Material Properties of CFRP sheet and Epoxy	330
	Appendix B: Concrete Material Test Results	337

LIST OF TABLES

Table 2.1	Summary of pullout models	45
Table 3.1	FRP coupon tests	93
Table 3.2	FRP anchor tests	93
Table 3.3	Pullout tests – metal anchors	93
Table 3.4	Pullout tests – FRP anchors	94
Table 3.5	Tested material properties of metal anchors	95
Table 3.6	Tested material properties of concrete	95
Table 3.7	FRP coupon test results	96
Table 3.8	FRP anchor test results	97
Table 3.9	Pullout test results: metal anchors	98
Table 3.10	Pullout test results: FRP anchors	99
Table 3.11	Test database: concrete cone failure	100
Table 3.12	Test database: combined failure	101
Table 3.13	Test database: anchor rupture	103
Table 3.14	Test database: bond failure	103
Table 3.15	Calibration and performance of FRP anchor analytical models	104
Table 4.1	Shear tests	162
Table 4.2	Tested material properties of concrete	163
Table 4.3	Shear test results	164
Table 4.4	Comparison of strength enhancement of anchored specimens to control specimens	165
Table 4.5	Tested local bond-slip parameters	166

Table 4.6	Parameters of anchored joints using Case 3 model	167
Table 4.7	Test prediction: rigorous model	168
Table 4.8	Test predictions: simplified model	168
Table 5.1	Slab tests: Slabs S1 to S6	218
Table 5.2	Tested concrete material properties: Slabs S1 to S6	219
Table 5.3	Tested material properties of steel reinforcements: Slabs S1 to S6	221
Table 5.4	Slab test results: Slab S1 to S6	222
Table 5.5	Comparison of analytical predicted to test results	223
Table 6.1	Slab test: Slabs S7 and S8	286
Table 6.2	Tested concrete material properties: Slabs S7 and S8	286
Table 6.3	Tested material properties of steel reinforcement: Slabs S7 and S8	287
Table 6.4	Slab test results: Slab S7 and S8	287
Table 6.5	Average strength enhancement factor for anchored plates	288
Table 6.6	Comparison of analytical predictions to test results for Slab S7	288

LIST OF FIGURES

Figure 1.1	Slab with penetration	10
Figure 1.2	Applications of FRP composites	10
Figure 1.3	Debonding failure	11
Figure 1.4	Anchorage systems	13
Figure 1.5	Layout of dissertation	14
Figure 2.1	Typical Stress-strain response of FRP and mild steel	47
Figure 2.2	FRP-strengthened RC slab	47
Figure 2.3	Failure modes of an FRP-strengthened RC beam	48
Figure 2.4	IC debonding failures	49
Figure 2.5	Idealisation of IC debonding in FRP-strengthened RC slabs with FRP-to-concrete joints	50
Figure 2.6	Type of FRP-to-concrete joint testing	50
Figure 2.7	Stress-strain curve of concrete	51
Figure 2.8	Stress and strain over beam depth	51
Figure 2.9	FRP-strengthening schemes for one-way slabs with penetrations	53
Figure 2.10	FRP-strengthening schemes for two-way slabs with penetrations	54
Figure 2.11	FRP Rupture failure of two-way slabs with penetrations	55
Figure 2.12	Suggested opening sizes and locations in flat plates	55
Figure 2.13	Schematics diagrams of anchor systems	56
Figure 2.14	FRP anchor components	57
Figure 2.15	FRP anchors in U-jacket shear strengthening	57
Figure 2.16	Construction sequence of impregnated fibre anchors	58

Figure 2.17	Construction sequence of dry fibre anchors	59
Figure 2.18	Typical adhesive metal anchor failure modes under pullout forces	60
Figure 2.19	Typical adhesive metal anchor failure modes under shear forces	61
Figure 3.1	FRP coupon tests	105
Figure 3.2	FRP anchor construction	106
Figure 3.3	Installation of FRP anchors	107
Figure 3.4	Test set-up: tensile strength tests	108
Figure 3.5	Instrumentation: tensile strength tests	108
Figure 3.6	Test set-up: pullout strength tests	109
Figure 3.7	Instrumentation: pullout strength tests	109
Figure 3.8	Typical failure mode: tensile strength tests	110
Figure 3.9	Stress versus strain response of FRP anchors in tension tests	110
Figure 3.10	Observed anchor failure modes: pullout test	111
Figure 3.11	Load versus concrete surface displacement response	112
Figure 3.12	Load versus FRP anchor strain response	112
Figure 3.13	Pullout load versus embedment depth	113
Figure 3.14	Pullout load versus anchor hole diameter/embedment depth	114
Figure 3.15	Bond stress distribution	115
Figure 3.16	Predicted load to test load: best fit model	116
Figure 3.17	Predicted load to test load: design model	116
Figure 3.18	Parametric study: best-fit model	117
Figure 3.19	Design procedure	118
Figure 4.1	Test set-up and test specimen	169
Figure 4.2	Typical strain distribution of unanchored bonded plates with	

	150 mm bond length	170
Figure 4.3	Concrete block formwork	170
Figure 4.4	FRP anchor details	171
Figure 4.5	Anchor installation: Method 1	172
Figure 4.6	Anchor installation: Method 2	172
Figure 4.7	Plate and anchor applications sequences	173
Figure 4.8	Instrumentation	174
Figure 4.9	Debonding- Typical control specimen failure (C-3)	175
Figure 4.10	Mode 1A: Simultaneous plate debonding and anchor shear failure	176
Figure 4.11	Mode 1B: Simultaneous plate debonding and anchor fan debonding	177
Figure 4.12	Mode 2A: Plate debonding followed by anchor shear failure	178
Figure 4.13	Mode 2B: Plate debonding followed by anchor fan debonding	179
Figure 4.14	Mode 2C: Plate debonding followed by anchor pullout	180
Figure 4.15	Load-displacement responses: Control specimens	181
Figure 4.16	Load-displacement responses: First series	182
Figure 4.17	Load-displacement responses: Second series	183
Figure 4.18	Load-displacement responses: Third series	184
Figure 4.19	Load-displacement responses: Fourth series	184
Figure 4.20	Strain distribution along the FRP plate	185
Figure 4.21	Anchor distance from unbonded zone - failure load: All test specimens	186
Figure 4.22	Unanchored FRP-to-concrete joints	187
Figure 4.23	Differential element	187
Figure 4.24	Local bond-slip models	188

Figure 4.25	Anchored FRP-to-concrete joints	188
Figure 4.26	Modified local bond-slip Models	189
Figure 4.27	Relationship between shear strength enhancement and relative failure slip at failure	190
Figure 4.28	Relationship between κ and l_{anc} / l_{frp}	190
Figure 4.29	Test predictions: rigorous model	191
Figure 4.30	Test predictions: simplified model	192
Figure 4.31	Parametric study	193
Figure 4.32	Design procedure	194
Figure 5.1	Slab details: Slab type 1	224
Figure 5.2	Slab details: Slab type 2	225
Figure 5.3	FRP strengthening schemes for Slabs S2, S4 and S6	226
Figure 5.4	Reinforcing bars and formwork	227
Figure 5.5	Slab construction	228
Figure 5.6	Concrete surface preparation	229
Figure 5.7	Slabs prior to testing	230
Figure 5.8	Test set-up	231
Figure 5.9	Instrumentation: Actuator positions	232
Figure 5.10	Instrumentation: LVDTs and strain gauges: Slabs S1 to S4	233
Figure 5.11	Instrumentation: LVDTs and strain gauges: Slabs S5 and S6	234
Figure 5.12	Typical reinforcing bar strain gauges	234
Figure 5.13	Crack patterns: Slab S1	235
Figure 5.14	Crack patterns: Slab S2	236
Figure 5.15	Crack patterns: Slab S3	237

Figure 5.16	Crack patterns: Slab S4	238
Figure 5.17	Crack patterns: Slab S5	239
Figure 5.18	Crack patterns: Slab S6	240
Figure 5.19	FRP-to-concrete interface failure in concrete	241
Figure 5.20	Debonding sequence: Slab S2	242
Figure 5.21	Debonding sequence: Slab S4	243
Figure 5.22	Debonding sequence: Slab S6	244
Figure 5.23	Load-deflection responses for all slabs	245
Figure 5.24	Load-deflection responses for slab groups: Slab S1 and S2	246
Figure 5.25	Load-deflection responses for slab groups: Slab S3 and S4	247
Figure 5.26	Load-deflection responses for slab groups: Slab S5 and S6	248
Figure 5.27	Deflection along transverse lines	249
Figure 5.28	Distribution of FRP strain prior to system failure: Slab S2	250
Figure 5.29	Distribution of FRP strain prior to system failure: Slab S4	251
Figure 5.30	Distribution of FRP strain prior to system failure: Slab S6	252
Figure 5.31	Critical crack line: Slab S2	253
Figure 5.32	Critical crack line: Slab S4	254
Figure 5.33	Applied moment field and critical crack line	255
Figure 5.34	Parametric study	256
Figure 5.35	Design procedure	257
Figure 6.1	Slab details: Slab Type 1	289
Figure 6.2	FRP strengthening schemes for slabs S7 and S8	290
Figure 6.3	Typical anchor layout	290
Figure 6.4	Application of FRP anchors and plates	291

Figure 6.5	Test set-up: Schematic Representation	293
Figure 6.6	Instrumentation: Actuator positions	294
Figure 6.7	Instrumentation: Strain gauges and LVDTs	295
Figure 6.8	Slab failure: Slab S7	296
Figure 6.9	Slab cracking and failure pictures: Slab S8	296
Figure 6.10	Crack patterns: Slab S7	297
Figure 6.11	Crack patterns: Slab S8	298
Figure 6.12	Initiation of IC debonding: Slab S7	299
Figure 6.13	IC debonding sequence and CFCs: Slab S7	299
Figure 6.14	Test in progress - post IC debonding: Slab S7	300
Figure 6.15	FRP anchors failure: post IC debonding: Slab S7	300
Figure 6.16	IC debonding sequence and CFCs: Slab S8	301
Figure 6.17	Anchor pullout failure: Slab S8	301
Figure 6.18	Load-mid-span deflection responses	302
Figure 6.19	Deflection along transverse lines	303
Figure 6.20	Load-deflection responses: Slab S8	304
Figure 6.21	Distribution of FRP strain at failure	305
Figure 6.22	Comparison of Load-mid-span deflection responses	306
Figure 6.23	Schematic diagram of anchor position in relation to cracking	307
Figure 6.24	Effective anchor distance from nearer crack as well as the length of the plate	307
Figure 6.25	Critical flexural cracks and measurement of l_{anc} in moment constant region: Slab S7	308
Figure 6.26	Design procedure	309