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**Behaviour of RC Beam-Column Connections
Retrofitted with FRP Strips**

by

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requirements for the degree of
Doctor of Philosophy

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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.

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ABSTRACT

Reinforced concrete (RC) buildings designed prior to the implementation of seismic design codes were largely designed without structural details required for satisfactory seismic performance. These buildings are therefore more susceptible to damage in case of an earthquake and hence may require strengthening to meet current design standards. For instance, the majority of buildings that may require strengthening in Australia are those designed prior to the implementation of Australia's first earthquake design standard in 1979.

Non-seismic load designed RC framed structures may possess several inherent weaknesses when subjected to a seismic attack. One major design deficiency is inadequate or no transverse reinforcement (otherwise known as stirrups) in the joint region of the RC beam-column connections (herein referred to as connections) which may lead to joint shear failure in a seismic attack. It is important here to establish that a joint refers to the intersecting region of the column/s and beam/s while a connection refers to the joint region plus surrounding beam/s and column/s. Another inadequacy is the practice of not anchoring the bottom beam longitudinal bars which may lead to bar pull-out due to load reversal in the case of a seismic attack. The proportioning of the beam and column elements framing into the connection region may lead to the undesirable formation of a strong-beam-weak-column mechanism. In addition, plastic hinging may form in the beam or column adjacent to the joint region thus compromising the strength and integrity of the joint. Past earthquakes such as El Asnam (1980), Mexico (1985), San Salvador (1986), Loma Prieta (1989) and Turkey (1999) have shown the vulnerability of RC framed structures with inherent non-seismic load designed weaknesses to catastrophically collapse due to connection failure. The proper strengthening of connections with such inherent weaknesses is in urgent need in order to ensure the safe performance of RC connections under seismic attack.

Over the past decade or so, fibre reinforced polymer (FRP) composites have emerged as a viable solution for strengthening structures due to their superiority in strength-to-weight ratio, ease of handling and forming into shapes, and corrosion resistance when

compared with more traditional construction materials such as steel. Many experimental, analytical and numerical studies have been conducted on the strengthening of RC beams, columns, slabs and walls as well as various other structural elements with FRP. Many field applications have also been reported around the world. Significantly less research and field applications by comparison have been reported on the strengthening of RC connections with FRP composites.

Experimental studies on FRP-strengthened exterior and interior connections have demonstrated the ability of externally bonded FRP to rectify the inherent weakness of non-seismic load designed RC connections by enhancing the joint shear capacity, in addition to enhancing the flexural capacity and to also relocate the possible formation of plastic hinges in the beam away from the joint region, as well as to promote a strong-column-weak-beam failure mechanism. Most of these experimental studies, while extremely useful, have been concerned with the behaviour of the strengthened connection as a whole with less attention paid to the behaviour of the FRP strengthening itself. In addition, the distinct lack of numerical simulations and analytical models, by comparison, are hindering better understanding and the more widespread rational design of FRP-strengthened for RC connections.

The research reported in this dissertation focuses on the commonly occurring case of a shear strength deficient connection. Such connections are retrofitted or repaired with FRP strips however from herein such application of FRP will collectively be referred to as strengthening. The key aims of this project are to (i) experimentally observe and quantify the behaviour of FRP strengthening in FRP-strengthened connections, (ii) accurately simulate the experimental results produced in aim (i) using finite elements and identify the strengths and weakness of such numerical modelling, (iii) perform parametric studies with the calibrated numerical models, (iv) develop an analytical model which can rationally and reliably predict the behaviour of the FRP-strengthened connections, and (v) formulate a design approach which can be easily incorporated into future versions of existing FRP-strengthening design guidelines as well as new guidelines.

Initially a state-of-the-art review is conducted on the current state of knowledge pertaining to FRP-strengthened RC connections. Existing research is also systematically categorised for ease of reference and comparison and for identifying the various issues still requiring research attention. The experimental program then forms the heart of the project and considers the shear strengthening of virgin connections as well as the repair of damaged connections. A strength hierarchy dictating shear failure in the joint region (even after application of the FRP) is deliberately chosen in order to assess the effectiveness and limitation of the FRP strengthening. All test specimens are extensively instrumented and the majority of connections are tested under monotonic load which greatly enhances the ability to effectively monitor the behaviour of the FRP as well as the cracking behaviour of the connection. Two connections are also tested under cyclic loading in order to assess the energy absorption characteristics of the strengthening schemes.

Finite element models are developed for plain (RC connection without any FRP strengthening) and FRP-strengthened RC connections which are then used to perform parametric studies to analyse various parameters affecting the behaviour of the connections such as amount of FRP, location of the FRP strips and strength of concrete. Also, a simple analytical model is presented based on the finding of the tests which can accurately estimate the contribution of the FRP strengthening to the connection shear strength. Finally, recommendations are made for design of FRP strengthening of shear deficient RC connections and future research needs are identified.

NOTATION

β	=	orientation of FRP with respect to longitudinal axis of member
β_l	=	factor that relates magnitude of stress (or strain) in the column main bars to the average stress (or strain) at the column centre line
β_t	=	factor that relates magnitude of stress (or strain) in the beam main bars to the average stress (or strain) at the beam centre line
ε	=	strain in concrete at stress equal to σ
ε_o	=	concrete strain at ultimate compressive stress
ε_{cf}	=	concrete strain at the extreme fibre
ε_{co}	=	elastic strain limit for concrete
$\varepsilon_{F,e}$	=	effective strain of FRP at failure
ε_{frp}	=	strain in FRP at failure
ε_{frp}	=	average axial strain in the fibre direction at the peak load
ε_p	=	maximum permissible FRP strain
λ	=	ratio of maximum to effective bond length
v_n	=	the joint shear strength
θ	=	angle between the critical diagonal compression strut and column axis
θ	=	angle between critical diagonal crack and column axis
ρ	=	density of concrete
ρ_b	=	area ratio of longitudinal beam reinforcement
ρ_l	=	effective vertical reinforcement ratio
ρ_t	=	area ratio of horizontal stirrup in the joint
σ	=	concrete stress
σ_{axial}	=	column axial stress
a'_s	=	distance from compressive face to centroid of compressive steel reinforcement
A_{frp}	=	cross-sectional area of FRP

$A_{frp,i}$	=	cross-sectional area of FRP strip crossing the joint.
A_{sv}	=	cross-sectional area of steel shear reinforcement
b	=	joint width or depth of column
b_c	=	column width (i.e. the dimension of the column perpendicular to the face of the FRP strengthening)
b_j	=	joint width
C_b	=	tension force transferred to the joint region
D_f	=	stress distribution factor for FRP
d	=	joint depth
d_l	=	distance from the extreme compression fibre to the neutral axis
d_e	=	effective connection depth
d_w	=	depth of column
E_c	=	modulus of elasticity for concrete
E_F	=	modulus of elasticity of FRP
E_{frp}	=	modulus of elasticity of FRP
E_w	=	elastic modulus of the FRP
f_{by}	=	yield stress of beam reinforcement
f_c	=	concrete compressive strength
f_{cmax}	=	crushing strength of concrete
f_{ctm}	=	mean tensile strength of concrete
$f_{f,deb}$	=	maximum tensile stress in FRP sheet
f_{fl}	=	average normal stress in the FRP in longitudinal direction
f_{ft}	=	average normal stress in the FRP in transverse direction
f_{fl}	=	shear stress in the FRP
f_l	=	average stress of longitudinal reinforcement of the column at mid height of the joint
f_l^b	=	average stress in beam reinforcement
f_l^s	=	average stress in stirrup
f_{yl}	=	yield stress of column reinforcement
f_{sy}	=	yield strength of steel shear reinforcement

$f_{u,i}$	=	stress in the FRP at failure
f'_c	=	ultimate compressive stress in concrete
f'_{cf}	=	tensile strength of concrete
h	=	column depth
h_0	=	effective depth of section
h_{b0}	=	effective depth of beam (i.e. distance from compressive face to centroid of beam steel tension reinforcement)
h_c	=	total column depth (dimension in the same plane as the FRP strengthening)
h_j	=	total joint depth (equals the depth of the beam h_b)
L_b	=	distance of beam tip load from the column centre line
l_b	=	bond length
l_c	=	length of the column between the points of contra flexure
L_e	=	effective bond length
L_{max}	=	maximum bond length
$M_{b,centre}$	=	moment at the joint centre
N	=	column axial force
n	=	number of FRP layers
N_h	=	beam axial force
N_v	=	compressive axial load of the column
P_b	=	beam tip load
Q_{ij}	=	elements of FRP stiffness matrix
s	=	centre-to-centre spacing of steel shear reinforcement
T	=	tensile forces transferred to the joint
T_b	=	tension force transferred to the joint region by beam
$T_{b,s}$	=	tensile force due to steel in tension
$T_{b,frp}$	=	tensile force due to FRP
t_F	=	thickness of FRP
t_w	=	wrap thickness
V_b	=	beam shear force
V_{col}	=	column shear force
V_c	=	contribution of concrete to the joint strength

V_{frp}	=	contribution of FRP to the joint strength
V_j	=	joint shear force
v_j	=	joint shear stress
V_{jh}	=	horizontal shear force across the joint
v_{jh}	=	horizontal shear stress across the joint
V_{jv}	=	vertical joint shear force across the joint
v_{jv}	=	vertical joint shear stress
V_s	=	contribution of transverse joint reinforcement to the joint strength
V_u	=	shear strength of the joint

LIST OF CONTENTS

Certificate of Authorship/Originality-----	i
Acknowledgements -----	ii
List of Publications -----	v
Abstract -----	vii
Notation -----	x
List of Contents-----	xiv
List of Tables -----	xxi
List of Figures -----	xxiii
1 Introduction -----	1
1.1 Preamble -----	1
1.2 Background Information-----	4
1.2.1 <i>Deficiencies in Reinforced Concrete Beam-Column Connections</i> -----	4
1.2.2 <i>Strengthening, Repair and Retrofitting Techniques</i> -----	5
1.2.3 <i>Beam-Column Connection</i> -----	5
1.2.4 <i>Concept of Strong-Column-Weak Beam</i> -----	9
1.2.5 <i>Fibre Reinforced Polymer (FRP) Composites</i> -----	10
1.3 Research Objectives -----	12
1.4 Research Significance and Benefit to Society -----	14
1.5 Terminologies -----	15
1.6 Layout of the Thesis-----	16
2 Literature Review -----	19
2.1 Introduction-----	19
2.2 Experimental Investigations: RC Connections Strengthened With Non-FRP Materials -----	20
2.2.1 <i>Epoxy Injection</i> -----	20
2.2.2 <i>Concrete Jacketing</i> -----	21
2.2.3 <i>Steel Jacketing</i> -----	21

2.3	Experimental Investigations: RC Connections Strengthened with FRP Materials -----	25
2.3.1	<i>Shear Strengthening</i> -----	37
2.3.2	<i>Anchorage Strengthening</i> -----	50
2.3.3	<i>Shear and Anchorage Strengthening</i> -----	51
2.3.4	<i>Relocation of Plastic Hinge</i> -----	54
2.3.5	<i>No Deficiency</i> -----	57
2.3.6	<i>Multiple Strengthening</i> -----	58
2.3.7	<i>Critical Review</i> -----	66
2.4	Numerical Modelling of Plain RC Connections -----	67
2.5	Numerical Modelling of FRP-strengthened RC Connections -----	67
2.5.1	<i>Parvin and Granata (2000)</i> -----	67
2.5.2	<i>Mostofinejad and TaleiTaba (2004 and 2006)</i> -----	69
2.5.3	<i>Parvin and Wu (2008)</i> -----	71
2.5.3	<i>Critical Review</i> -----	71
2.6	Analytical Modelling of Plain RC Connections-----	72
2.6.1	<i>Strut and Truss Model</i> -----	72
2.6.2	<i>Stress-Strain Compatibility Model</i> -----	75
2.6.3	<i>Critical Review</i> -----	78
2.7	Analytical Modelling of FRP-strengthened RC Connections -----	78
2.7.1	<i>Stress-Strain Compatibility Model</i> -----	79
2.7.2	<i>Empirical Models</i> -----	83
2.7.3	<i>Critical Review</i> -----	86
2.8	Debonding Failure in FRP -----	87
2.8.1	<i>Bond Strength Model</i> -----	89
2.9	Concluding Remarks-----	90
3	Experimental Programme -----	91
3.1	Introduction -----	91
3.2	Test Schedule -----	92
3.3	Strengthening Schemes-----	93
3.4	Details of Test Specimens-----	95
3.5	Fabrication of Specimens -----	98
3.5.1	<i>Steel Reinforcement and Concrete</i> -----	98
3.5.2	<i>Application of FRP</i> -----	101

3.6	Strengthened Connections-----	104
3.6.1	<i>Strengthened Connection SM1</i> -----	104
3.6.2	<i>Strengthened Connection SM2</i> -----	105
3.6.3	<i>Strengthened Connection SC1</i> -----	105
3.7	Repaired Connections-----	106
3.7.1	<i>Repaired Connection RM1</i> -----	107
3.7.2	<i>Repaired Connection RM2</i> -----	108
3.7.3	<i>Repaired Connection RM3</i> -----	111
3.8	Material Properties-----	113
3.8.1	<i>Concrete</i> -----	113
3.8.2	<i>Steel Reinforcement Bars</i> -----	114
3.8.3	<i>Carbon FRP Sheet</i> -----	114
3.8.4	<i>Epoxy Saturant</i> -----	115
3.8.5	<i>Primer</i> -----	115
3.8.6	<i>Repair Mortar</i> -----	116
3.8.7	<i>Epoxy Adhesive</i> -----	117
3.9	Test Setup and Test Rig-----	118
3.10	Instrumentation-----	122
3.11	Experimental Procedure-----	127
3.12	Concluding Remarks-----	128
4	Experimental Results-----	129
4.1	Introduction-----	129
4.2	Monotonic Load Tests-----	129
4.2.1	<i>Control Connection UM1</i> -----	129
4.2.2	<i>Strengthened Connection SM1</i> -----	133
4.2.3	<i>Strengthened Connection SM2</i> -----	137
4.2.4	<i>Repaired Connection RM1</i> -----	141
4.2.5	<i>Repaired Connection RM2</i> -----	144
4.2.6	<i>Repaired Connection RM3</i> -----	147
4.3	Cyclic Load Tests-----	150
4.3.1	<i>Control Connection UC1</i> -----	150
4.3.2	<i>Strengthened Connection SC1</i> -----	155
4.4	Comparison of Load-deflection Response-----	160
4.4.1	<i>Monotonic Load Tests</i> -----	160
4.4.2	<i>Cyclic Load Tests</i> -----	163
4.4.3	<i>Monotonic versus Cyclic Load Tests</i> -----	165
4.5	Reinforcement Strain Results-----	167

4.6	Concrete Strain Results-----	172
4.7	FRP Strain Results -----	174
4.7.1	<i>Strengthened Connection SM1</i> -----	174
4.7.2	<i>Strengthened Connection SM2</i> -----	177
4.7.3	<i>Repaired Connection RM1</i> -----	179
4.7.4	<i>Repaired Connection RM2</i> -----	182
4.7.5	<i>Strengthened Connection SC1</i> -----	185
4.8	Concluding Remarks-----	190
5	Numerical Modelling: ANSYS Features and Validations -----	193
5.1	Introduction -----	193
5.2	Introduction to the Finite Element Analysis-----	194
5.3	Introduction to ANSYS -----	195
5.4	Element Types-----	196
5.4.1	<i>Concrete</i> -----	196
5.4.2	<i>Steel Reinforcement Bars</i> -----	197
5.4.3	<i>FRP Strips, Sheets and Wraps</i> -----	197
5.4.4	<i>Steel Plates</i> -----	198
5.4.5	<i>Concrete-Steel Reinforcement Interface</i> -----	199
5.5	Material Properties -----	200
5.5.1	<i>Concrete</i> -----	200
5.5.2	<i>Steel Reinforcement Bars</i> -----	202
5.5.3	<i>FRP Strips, Sheets and Wraps</i> -----	204
5.5.4	<i>Steel Plates</i> -----	204
5.5.5	<i>Bond Stress-Slip Relationship between Concrete and Steel Reinforcement Bars</i> -----	205
5.6	ANSYS Solver-----	206
5.7	Modelling Approaches and Assumptions-----	207
5.7.1	<i>Mesh Size</i> -----	207
5.7.2	<i>Concrete Behaviour</i> -----	207
5.7.3	<i>Dummy Elements</i> -----	209
5.7.4	<i>Load Steps</i> -----	210
5.8	Validation of ANSYS -----	211
5.8.1	<i>Introduction</i> -----	211
5.8.2	<i>Simply Supported RC Beam</i> -----	211
5.8.3	<i>Exterior RC Connection</i> -----	218
5.8.4	<i>Interior RC Connection</i> -----	231
5.9	Concluding Remarks-----	240

6	Numerical Modelling: Finite Element Analysis Results -----	243
6.1	Introduction-----	243
6.2	Geometry and Reinforcement Details-----	244
6.3	Material Properties -----	247
6.4	Support Conditions and Loading -----	248
6.5	FRP Strengthening-----	249
6.6	Mesh-----	249
6.7	Comparison between Finite Element Results with Experimental Results -----	254
6.7.1	<i>Plain Connection UM1</i> -----	254
6.7.2	<i>Strengthened Connection SM1</i> -----	258
6.7.3	<i>Strengthened Connection SM2</i> -----	266
6.8	Parametric Study-----	277
6.8.1	<i>Concrete Strength</i> -----	281
6.8.2	<i>FRP Quantity</i> -----	283
6.8.3	<i>Joint Transverse Reinforcement</i> -----	285
6.9	Comments-----	287
6.10	Concluding Remarks -----	288
7	Analytical Modelling -----	289
7.1	Introduction-----	289
7.2	Basic Joint Shear Strength Model -----	290
7.2.1	<i>Fundamental Derivation of Basic Joint Shear Strength Model</i> -----	290
7.2.2	<i>Consideration of FRP Stress and Strain</i> -----	293
7.3	Calculation of Applied Joint Shear Stress-----	299
7.3.1	<i>Calculation Method</i> -----	299
7.3.2	<i>Concrete Elastic State</i> -----	304
7.3.3	<i>Concrete Inelastic State I</i> -----	305
7.3.4	<i>Concrete Inelastic State II</i> -----	307
7.3.5	<i>FRP Bond Strength</i> -----	309
7.3.6	<i>Solution Procedure</i> -----	309
7.3.7	<i>Calculation of FRP Contribution to Joint Shear Stress in Tested Connections</i> -----	309
7.4	Comparison of Basic Joint Shear Strength Model with Test Results-----	310

7.5	Refined Joint Shear Strength Model-----	311
7.5.1	<i>Strain Distribution Factor</i> -----	311
7.5.2	<i>Effect of Monotonic and Cyclic Load</i> -----	313
7.5.3	<i>Crack Angle</i> -----	313
7.5.4	<i>FRP strengthening Type</i> -----	313
7.5.5	<i>Refined Joint Shear Strength Model</i> -----	314
7.6	Comparison of Refined Joint Shear Strength Model with Test Results -----	314
7.7	Comparison of Joint Shear Strength Model with other Test Results-----	316
7.8	Concluding Remarks-----	316
8	Design Recommendations -----	319
8.1	Introduction -----	319
8.2	Design Philosophy -----	319
8.3	Design Recommendations -----	320
8.3.1	<i>Calculation of Joint Forces</i> -----	320
8.3.2	<i>Calculation of Joint Capacity</i> -----	321
8.4	Detailing Recommendations-----	324
8.4.1	<i>Surface Preparation</i> -----	324
8.4.2	<i>Anchorage</i> -----	325
8.4.3	<i>Confinement</i> -----	325
8.4.4	<i>Strengthening of Three-dimensional RC Connections Possessing Transverse Beams and Slabs</i> -----	326
8.4.5	<i>Strip Spacing</i> -----	326
8.5	Concluding Remarks-----	326
9	Conclusions and Future Research -----	327
9.1	Introduction -----	327
9.2	Identification of Design Deficiencies-----	327
9.3	Classification of Different Strengthening Schemes -----	328
9.4	Effectiveness of FRP Strips and Identification of Failure Modes -----	328
9.5	Identification of Strength and Limitations of ANSYS as a Finite Element Modelling Tool for FRP-Strengthened RC Connections -----	329
9.6	Development of Simple Semi-Empirical Model -----	330
9.7	Design guidelines -----	330
9.8	Future Research Needs -----	330

References	-----	333
A.	Appendix A: Material Test Results -----	344
B.	Appendix B: Calculation Methods -----	354
	Calculation of Peak-to-peak Stiffness Using Hysteretic Curve -----	354
	Calculation of Cumulative Energy Dissipated from Hysteretic Curve -----	356
C.	Appendix C: Strain in Steel Reinforcement Bars -----	357
	Comparison of Strain in FRP-strengthened Connections, SM1 and SM2 with Control Connection, UM1 -----	358
	Comparison of Strain in Repaired Connections, RM1 and RM2 with Control Connection, UM1 -----	365
	Comparison of Strain in Cyclic Load Tested Connections, UC1 (Control) and SC1 (FRP-strengthened)-----	372
D.	Appendix D: Parametric Study -----	387
	Concrete Strength-----	387
	Amount of FRP -----	392
	Joint Transverse reinforcement -----	395

LIST OF TABLES

Table 2.1	Shear Strengthening-----	27
Table 2.2	Anchorage Strengthening -----	31
Table 2.3	Shear and Anchorage Strengthening-----	32
Table 2.4	Plastic Hinge Relocation -----	33
Table 2.5	Others (No Connection Deficiency)-----	34
Table 3.1	Summary of test connections -----	92
Table 3.2	Summary of repaired connections -----	93
Table 3.3	Summary of predicted failure loads-----	97
Table 3.4	Summary of concrete properties for tested connections -----	113
Table 3.5	Summary of reinforcement bar properties -----	114
Table 3.6	Summary of FRP properties -----	114
Table 3.7	Properties of MBrace Saturant -----	115
Table 3.8	Properties of MBrace Primer -----	116
Table 3.9	Properties of Emaco S88C -----	116
Table 3.10	Properties of Megapoxy PF-----	117
Table 4.1	Summary of load and deflection for control and strengthened connections---	161
Table 4.2	Summary of load and deflection for connections UM1, RM1 and RM2 -----	163
Table 4.3	Summary of load and deflection for cyclic load tested connections -----	164
Table 4.4	Comparison of load and deflection for cyclic and monotonic load tested connections-----	166
Table 5.1	Number of elements in plain RC beam model -----	215
Table 5.2	Number of elements in exterior RC connection model -----	225
Table 5.3	Comparison between finite element and test results for connection L1 -----	227
Table 5.4	Comparison between finite element and test results for connection FRPL3 --	229
Table 5.5	Number of elements-----	236
Table 6.1	Summary of concrete properties for tested connections -----	247
Table 6.2	Summary of reinforcement bar properties -----	247
Table 6.3	Summary of FRP properties -----	247
Table 6.4	Summary of debonding stress for FRP strips-----	247
Table 6.5	Summary of element numbers used in finite element models-----	253
Table 6.6	Comparison of finite element and test results – connection UM1 -----	254
Table 6.7	Comparison of finite element and test result – connection SM1-----	258
Table 6.8	Comparison of maximum strains in FRP strips at peak load-----	265

Table 6.9	Comparison of finite element and test result –connection SM1 -----	266
Table 6.10	Comparison of maximum strains in FRP strips at peak load -----	276
Table 6.11	Summary of parameters studied for column strips scheme -----	278
Table 6.12	Summary of parameters studied for beam strips scheme-----	279
Table 7.1	Moment of resistance of beam section (elastic state) -----	305
Table 7.2	Moment of resistance of beam section (inelastic state I) -----	307
Table 7.3	Moment of resistance of beam section (inelastic state II) -----	308
Table 7.4	Summary of joint shear stresses -----	310
Table 7.5	Comparison of proposed model predictions-----	311
Table 7.6	Comparison of proposed model predictions with test results-----	315
Table 7.7	Comparison of model predictions with test results-----	317
Table A.1	Test results for compressive strength of concrete -----	344
Table A.2	Test results for indirect tensile strength (splitting strength) of concrete -----	345
Table A.3	Test results for static chord modulus of elasticity of concrete-----	346
Table A.4	Test results for modulus of rupture of concrete-----	348
Table A.5	Test results for tensile strength of reinforcement bars-----	349
Table A.6	Tests results for tensile strength and modulus of elasticity of FRP -----	350
Table B.1	Calculation of peak-to-peak stiffness for cyclic load tested connections -----	355
Table B.2	Cumulative energy dissipation for cyclic load tested connections-----	356

LIST OF FIGURES

Figure 1.1	Typical failure of connections -----	3
Figure 1.2	Connection deficiencies -----	4
Figure 1.3	Beam-column connections -----	5
Figure 1.4	Diagonal shear cracks induced in the joint region due to shear distortion-----	6
Figure 1.5	Typical bending moment and shear force in a frame -----	7
Figure 1.6	Forces acting on a beam-column connection -----	8
Figure 1.7	Internal actions in the joint region -----	8
Figure 1.8	Collapse mechanisms of frames (Murty et al., 2003) -----	9
Figure 1.9	Cross section of a FRP sheet formed using wet lay-up process-----	10
Figure 2.1	Steel jacketing of the beam, column and the joint (Ghobarah et al. 1997) -----	22
Figure 2.2	Typical reinforcement details for connections with insufficient joint shear reinforcement (Ghobarah and Said 2001)-----	35
Figure 2.3	Typical reinforcement details for connections with insufficient anchorage of beam bar (Ghobarah and El-Amoury 2005)-----	35
Figure 2.4	Typical reinforcement details for connections with combination of insufficient joint shear reinforcement and inadequate beam bar anchorage (El-Amoury and Ghobarah 2002) -----	36
Figure 2.5	Typical reinforcement details for connections with relocation of plastic hinge (Prota et al. 2001) -----	36
Figure 2.6	Strengthening scheme tested by Ghobarah and Said (2001) -----	37
Figure 2.7	Strengthening schemes tested by Ghobarah and Said (2002) -----	38
Figure 2.8	Gergely et al.'s (2000) FRP wrapping arrangement-----	39
Figure 2.9	Strengthening schemes (Antonopoulou and Triantafillou 2003) -----	41
Figure 2.10	FRP strengthening details (Tsonos and Stylianidis 2002) -----	42
Figure 2.11	Strengthening scheme (Ouyang et al. 2003)-----	43
Figure 2.12	Strengthening schemes tested by Al-Salloum and Almusallam (2007)-----	46
Figure 2.13	FRP schemes tested by Mosallam (2001)-----	48
Figure 2.14	FRP strengthening scheme (Tsonos 2008)-----	49
Figure 2.15	Strengthening Schemes (Granata and Parvin 2001)-----	51
Figure 2.16	Strengthening schemes (El-Amoury and Ghobarah 2002) -----	52
Figure 2.17	Strengthening scheme (Ilki et al. 2008) -----	53
Figure 2.18	Strengthening schemes (Prota et al. 2004)-----	55
Figure 2.19	Strengthening scheme for relocation of plastic hinge (Mahini et al. 2004) -----	56
Figure 2.20	Strengthening scheme tested by Li et al. (1999) -----	58

Figure 2.21	Strengthening scheme for ductility specimen (Geng et al 1998)-----	59
Figure 2.22	Strengthening schemes for development specimens (Geng et al. 1998) -----	60
Figure 2.23	Strengthening schemes tested by Mukherjee and Joshi (2004)-----	61
Figure 2.24	Strengthening schemes tested by Ghobarah and El-Amoury (2005) -----	63
Figure 2.25	Strengthening schemes tested by Karayannis and Sirkelis (2002)-----	64
Figure 2.26	Strengthening schemes modelled (Parvin and Granata 2000) -----	68
Figure 2.27	Mechanisms in connection (Paulay and Priestley 1992) -----	72
Figure 2.28	External actions in an interior joint (Paulay and Priestley 1992)-----	73
Figure 2.29	Internal stresses in an interior joint (Paulay and Priestley 1992)-----	74
Figure 2.30	Stress equilibrium (Pantazopoulou and Bonacci 1992)-----	76
Figure 2.31	Equilibrium of vertical and horizontal forces (Antonopoulos and Triantafillou 2001)-----	79
Figure 2.32	Failure modes in FRP-strengthened beams (Teng et al. 2008) -----	88
Figure 3.1	FRP strengthening schemes -----	94
Figure 3.2	Geometric and reinforcement details of tested connections -----	96
Figure 3.3	Steel reinforcement cage-----	98
Figure 3.4	Application of strain gauge on steel reinforcing bars -----	99
Figure 3.5	Formwork and steel cage prior to concrete pour -----	100
Figure 3.6	Removal of weak concrete surface -----	102
Figure 3.7	Application of FRP (connection SM1)-----	103
Figure 3.8	FRP strengthening on connection SM1 -----	104
Figure 3.9	FRP strengthening on connection SM2 -----	105
Figure 3.10	FRP strengthening on connection SC1-----	106
Figure 3.11	Damage in joint region of connection RM1 prior to repair -----	107
Figure 3.12	Schematic diagram showing extent of cracks in the joint region for connection RM1 prior to repair -----	108
Figure 3.13	Connection RM1 after repair-----	108
Figure 3.14	Damage in joint region of connection RM2 prior to repair -----	109
Figure 3.15	Schematic diagram showing extent of cracks in the joint region for connection RM2 prior to repair -----	110
Figure 3.16	Connection RM2 after repair-----	110
Figure 3.17	Close-up view of connection RM2 after repair -----	110
Figure 3.18	Damage in joint region of connection RM3 prior to repair -----	112
Figure 3.19	Schematic diagram showing extent of cracks in the joint region for connection RM3 prior to repair -----	112
Figure 3.20	Connection RM3 after repair-----	112
Figure 3.21	Test Setup-----	118

Figure 3.22	Arrangement for application of load-----	119
Figure 3.23	Detailed three dimensional diagram of the test setup -----	120
Figure 3.24	Test connections prior to testing -----	120
Figure 3.25	Detailed view of the hinge support -----	121
Figure 3.26	Exploded view of the hinge support -----	121
Figure 3.27	Location of LVDT -----	122
Figure 3.28	Location of strain gauges on reinforcement bars – overall view-----	123
Figure 3.29	Location of strain gauges on reinforcement bars – close-up view-----	123
Figure 3.30	Location of strain gauges on concrete surface-----	124
Figure 3.31	Location of strain gauges on FRP strips (column strips scheme)-----	125
Figure 3.32	Location of strain gauges on FRP strips (beam strips scheme) -----	125
Figure 3.33	Measurement of gauge location for connection SM2 -----	126
Figure 3.34	Location of strain gauges on FRP strips for connection RM2 -----	127
Figure 4.1	Flexural cracks in the beam and shear crack at the beam-column corner -----	130
Figure 4.2	Load-deflection plot for control connection UM1 -----	130
Figure 4.3	Cracks in the joint region at different load levels (connection UM1)-----	131
Figure 4.4	Schematic diagram showing crack propagation at various load levels (connection UM1)-----	132
Figure 4.5	FRP strengthening scheme for connection SM1 -----	134
Figure 4.6	Cracking in the joint region at different load levels (connection SM1)-----	134
Figure 4.7	Load-deflection plot for FRP-strengthened connection SM1 -----	135
Figure 4.8	Final crack pattern for connection SM1 -----	135
Figure 4.9	Schematic diagram showing crack propagation at various load levels (connection SM1) -----	136
Figure 4.10	FRP strengthening scheme for connection SM2 -----	138
Figure 4.11	Cracks in the joint region at different load steps (connection SM2) -----	138
Figure 4.12	Load-deflection plot for FRP-strengthened connection SM2 -----	139
Figure 4.13	Final crack patterns for connection SM2-----	139
Figure 4.14	Schematic diagram showing crack propagation at various load levels (connection SM2) -----	140
Figure 4.15	Strengthening scheme applied to repaired connection RM1 -----	141
Figure 4.16	Cracks in the joint for connection RM1 corner (crack marking from previous tests can also be seen) -----	142
Figure 4.17	Load-deflection plot for repaired connection RM1 -----	142
Figure 4.18	Final crack patterns for connection RM1 -----	143
Figure 4.19	Schematic diagram showing final crack pattern in connection RM1 -----	143
Figure 4.20	Strengthening scheme applied to repaired connection RM2 -----	144

Figure 4.21	Cracking in connection RM2 (load = 40 kN) -----	145
Figure 4.22	Load-deflection plot for connection RM2 -----	145
Figure 4.23	Final crack patterns for connection RM2 -----	146
Figure 4.24	Schematic diagram showing final crack pattern for connection RM2 -----	146
Figure 4.25	Strengthening scheme applied to repaired connection RM3 -----	147
Figure 4.26	Damage in the joint region of connection RM3 -----	148
Figure 4.27	Damage in the joint region of connection RM3 -----	148
Figure 4.28	Damage in the joint region of connection RM3 -----	149
Figure 4.29	Schematic diagram showing final crack pattern for connection RM3 -----	149
Figure 4.30	Cracks in the joint region after first load cycle (connection UC1) -----	150
Figure 4.31	Cracks in the joint region after second load cycle (connection UC1) -----	151
Figure 4.32	Cracks in the joint region after third load cycle (connection UC1) -----	151
Figure 4.33	Cracks in the joint region after fourth load cycle (connection UC1) -----	151
Figure 4.34	Final crack patterns for connection UC1 -----	152
Figure 4.35	Concrete cover separation from back face of column (connection UC1) -----	152
Figure 4.36	Schematic representation of crack propagation for connection UC1 in push and pull cycles -----	153
Figure 4.37	Schematic representation final crack pattern for connection UC1 -----	154
Figure 4.38	Load-deflection plot for connection UC1 -----	154
Figure 4.39	Strengthening scheme applied to repaired connection SC1 -----	155
Figure 4.40	Cracks developed in connection SC1 -----	156
Figure 4.41	Cracks developed in connection SC1 after second cycle -----	156
Figure 4.42	Cracks generated in connection SC1 after third cycle -----	157
Figure 4.43	Cracks generated in connection SC1 after fourth cycle -----	157
Figure 4.44	Final crack patterns for connection SC1 -----	157
Figure 4.45	Load-deflection plot for connection SC1 -----	158
Figure 4.46	Schematic representation of crack propagation for connection SC1 -----	159
Figure 4.47	Schematic representation of crack propagation for connection SC1 -----	160
Figure 4.48	Load versus deflection response for connection UM1, SM1 and SM2 -----	161
Figure 4.49	Load versus deflection response for control and repaired connections -----	163
Figure 4.50	Peak to peak stiffness for cyclic load tested connections -----	164
Figure 4.51	Cumulative Energy dissipated for cyclic load tested connections -----	164
Figure 4.52	Load-deflection envelop curve for cyclic load tested connections -----	165
Figure 4.53	Location of strain gauge on internal reinforcement bars -----	167
Figure 4.54	Strain in gauge R2 for connection UM1 and SM2 -----	168
Figure 4.55	Strain in gauge R3 for connection UM1, SM1 and SM2 -----	168
Figure 4.56	Strain in gauge R2 for connections UM1, RM1 and RM2 -----	169

Figure 4.57	Strain in gauge R9 for connections UM1, RM1 and RM2 -----	169
Figure 4.58	Strain in gauge R11 for connections UM1, RM1 and RM2 -----	170
Figure 4.59	Strain in reinforcement bar at gauge R2 – push direction -----	170
Figure 4.60	Strain in reinforcement bar at gauge R7 – pull direction -----	171
Figure 4.61	Strain in reinforcement bar at gauge R13 – push direction -----	171
Figure 4.62	Strain in reinforcement bar at gauge R14 – pull direction -----	171
Figure 4.63	Comparison of concrete strain for FRP-strengthened connection SM1 with control connection UM1 at beam compression face (Gauge 1)-----	173
Figure 4.64	Comparison of concrete strain for FRP-strengthened connection SM1 and SM2 with control connection UM1 at column compression face (Gauge 2)--	173
Figure 4.65	Distribution of strain along FRP strip 1 on the joint front face -----	175
Figure 4.66	Distribution of strain along FRP strip 2 on the joint front face -----	175
Figure 4.67	Distribution of strain along FRP strip 1 on the joint back face -----	176
Figure 4.68	Distribution of strain along FRP strip 2 on the joint back face -----	176
Figure 4.69	Distribution of strain along FRP strip 1 -----	178
Figure 4.70	Distribution of strain along FRP strip 2 -----	178
Figure 4.71	Distribution of strain along FRP strip 3 -----	179
Figure 4.72	Distribution of strain along FRP strip 1 on front face of the joint -----	180
Figure 4.73	Distribution of strain along FRP strip 2 on front face of the joint -----	180
Figure 4.74	Distribution of strain along FRP strip 1 on back face of the joint -----	181
Figure 4.75	Distribution of strain FRP strip 2 on back face of the joint-----	181
Figure 4.76	FRP strain at identical positions for connections RM1 and SM1 -----	182
Figure 4.77	Distribution of strain along FRP strip 1 -----	183
Figure 4.78	Distribution of strain along FRP strip 2 -----	183
Figure 4.79	Distribution of strain along FRP strip 3 -----	184
Figure 4.80	FRP strain at identical position for connections RM2 and SM2 -----	184
Figure 4.81	Distribution of strain along FRP strip 1 (push cycle, front face) -----	186
Figure 4.82	Distribution of strain along FRP strip 1 (pull cycle, front face) -----	186
Figure 4.83	Distribution of strain along FRP strip 2 (push cycle, front face) -----	187
Figure 4.84	Distribution of strain along FRP strip 2 (pull cycle, front face) -----	187
Figure 4.85	Distribution of strain along FRP strip 1 (push cycle, back face)-----	188
Figure 4.86	Distribution of strain along FRP strip 1 (pull cycle, back face)-----	188
Figure 4.87	Distribution of strain along FRP strip 2 (push cycle, back face)-----	189
Figure 4.88	Distribution of strain along FRP strip 2 (pull cycle, back face)-----	189
Figure 5.1	SOLID65 element geometry (ANSYS 2007)-----	196
Figure 5.2	LINK8 element geometry (ANSYS 2007)-----	197
Figure 5.3	SHELL181 element geometry (ANSYS 2007)-----	198

Figure 5.4	SOLID45 element geometry (ANSYS 2007)-----	198
Figure 5.5	Interface element between nodes of bar element and concrete element-----	199
Figure 5.6	COMBIN39 element geometry (ANSYS 2007)-----	199
Figure 5.7	Stress-Strain relationship for concrete in compression -----	201
Figure 5.8	Stress-Strain relationship for steel reinforcement bars-----	203
Figure 5.9	Constitutive model for FRP -----	204
Figure 5.10	Bond stress-slip model (CEB-FIP 2000) -----	205
Figure 5.11	Non-linear solution with Newton-Raphson method (ANSYS 2007) -----	206
Figure 5.12	Effect of shear transfer coefficient on convergence of a plain RC beam-column connection -----	208
Figure 5.13	Example of dummy element mesh through out the connection model -----	209
Figure 5.14	Load-deflection plots for a connection with and without dummy element ----	210
Figure 5.15	Geometric and reinforcement details of beam tested by Kachlakev and McCurry (2000)-----	212
Figure 5.16	Schematic representation of support condition and loading point -----	213
Figure 5.17	Effect of number of elements on the load -----	214
Figure 5.18	Effect of number of elements on maximum principal stress in concrete-----	214
Figure 5.19	Effect of number of elements on maximum longitudinal stress in steel reinforcement bars -----	215
Figure 5.20	Finite element model for simply supported beam -----	215
Figure 5.21	Load versus deflection at the mid span for plain RC beam -----	216
Figure 5.22	Crack pattern at increasing load steps-----	217
Figure 5.23	Geometric and reinforcement details of exterior connections (Tsonos and Stylianidis 2002)-----	219
Figure 5.24	Schematic representation of support conditions and loading point -----	221
Figure 5.25	FRP strengthening on connection FRPL3 (Tsonos and Stylianidis 2002) ----	221
Figure 5.26	Effect of number of elements on beam tip load-----	223
Figure 5.27	Effect of number of elements on maximum first principal stress -----	223
Figure 5.28	Effect of number of elements on maximum stress in column bars-----	223
Figure 5.29	Effect of number of elements on maximum stress in beam bars -----	224
Figure 5.30	Finite element meshes-----	224
Figure 5.31	Internal Steel reinforcement mesh-----	224
Figure 5.32	Dummy element mesh -----	225
Figure 5.33	Finite element and test results for connection L1 -----	227
Figure 5.34	Crack pattern at increasing load levels for connection L1 -----	228
Figure 5.35	Finite element and test results for FRP-strengthened connection FRPL3-----	229
Figure 5.36	Crack pattern at increasing load levels for connection FRPL3 -----	230

Figure 5.37	Geometric and reinforcement details of connection BC4-----	233
Figure 5.38	Schematic diagram showing support conditions and loading point -----	234
Figure 5.39	Finite element mesh for beam-column connection BC4-----	235
Figure 5.40	Finite element mesh for reinforcement bars in connection BC4-----	235
Figure 5.41	Finite element mesh for dummy elements in connection BC4-----	236
Figure 5.42	Effect of number of elements on column end load -----	237
Figure 5.43	Effect of number of elements on maximum principal stress in concrete -----	237
Figure 5.44	Effect of number of elements on maximum stress in steel reinforcement bars -----	237
Figure 5.45	Comparison of load deflection plot for BC4-----	238
Figure 5.46	Comparison of load deflection plot for connection BC4 with results from Kwak and Filippou (1990) study-----	239
Figure 6.1	Geometric details of control connection UM1 -----	244
Figure 6.2	Geometric details of FRP-strengthened connection SM1-----	245
Figure 6.3	Geometric details of FRP-strengthened connection SM2-----	245
Figure 6.4	Reinforcement details of all connection – column section -----	246
Figure 6.5	Reinforcement details of all connection – beam section-----	246
Figure 6.6	Boundary condition for finite element models -----	248
Figure 6.7	Schematic diagrams of FRP strengthening schemes -----	249
Figure 6.8	Effect of number of elements on beam tip load -----	250
Figure 6.9	Effect of number of elements on maximum first principal stress-----	251
Figure 6.10	Effect of number of elements on maximum stress in column bars -----	251
Figure 6.11	Finite element mesh for connection UM1 -----	252
Figure 6.12	Finite element mesh for connection SM1 -----	252
Figure 6.13	Finite element mesh for connection SM2 -----	253
Figure 6.14	Finite element mesh for dummy element in connection UM1 -----	253
Figure 6.15	Comparison of beam tip load-deflection results for connection UM1 -----	255
Figure 6.16	Cracks in connection UM1 at different beam tip loads -----	256
Figure 6.17	Cracks in connection UM1 at higher beam tip loads -----	256
Figure 6.18	Comparison of crack pattern for connection UM1-----	257
Figure 6.19	Comparison of beam tip load-deflection results for SM1-----	258
Figure 6.20	Cracks in connection SM1 at different beam tip loads-----	259
Figure 6.21	Cracks in connection SM1 at higher beam tip loads -----	260
Figure 6.22	Comparison of crack pattern for connection SM1 -----	260
Figure 6.23	Stress (MPa) distribution in FRP strips at 30 kN -----	262
Figure 6.24	Stress (MPa) distribution in FRP strips at 60 kN -----	262
Figure 6.25	Stress (MPa) distribution in FRP strips at 80 kN -----	262

Figure 6.26	Stress (MPa) distribution in FRP strips at 99 kN -----	262
Figure 6.27	Comparison of strain profile along FRP strip 1 -----	263
Figure 6.28	Comparison of strain profile along FRP strip 2 -----	264
Figure 6.29	Comparison of strain profiles at peak load -----	265
Figure 6.30	Comparison of beam tip load-deflection results for SM2 -----	266
Figure 6.31	Cracks in connection SM2 at different beam tip loads -----	268
Figure 6.32	Cracks in connection SM2 at higher beam tip loads -----	268
Figure 6.33	Comparison of crack pattern for connection SM2 -----	269
Figure 6.34	Stress (MPa) distribution in FRP strips at 80 kN -----	270
Figure 6.35	Stress (MPa) distribution in FRP strips at 100 kN -----	271
Figure 6.36	Stress (MPa) distribution in FRP strips at 110 kN -----	271
Figure 6.37	Stress (MPa) distribution in FRP strips at 120 kN -----	272
Figure 6.38	Comparison of strain profile along FRP strip 1 -----	273
Figure 6.39	Comparison of strain profile along FRP strip 2 -----	274
Figure 6.40	Comparison of strain profile along FRP strip 3 -----	275
Figure 6.41	Comparison of strain profiles at peak load -----	276
Figure 6.42	Column strips scheme used in parametric study -----	280
Figure 6.43	Beam strips scheme used in parametric study -----	280
Figure 6.44	Stress profile along strip 1 with two layer FRP (column strips scheme) -----	281
Figure 6.45	Stress profile along strip 2 with two layer FRP (column strips scheme) -----	281
Figure 6.46	Stress profile along strip 1 with two layer FRP (beam strips scheme) -----	282
Figure 6.47	Stress profile along strip 2 with two layer FRP (beam strips scheme) -----	282
Figure 6.48	Stress profile along strip 3 with two layer FRP (beam strips scheme) -----	282
Figure 6.49	Stress profile along strip 1 for $f_c = 16$ MPa (column strips scheme) -----	283
Figure 6.50	Stress profile along strip 2 for $f_c = 16$ MPa (column strips scheme) -----	283
Figure 6.51	Stress profile along strip 1 for $f_c = 16$ MPa (beam strips scheme) -----	284
Figure 6.52	Stress profile along strip 2 for $f_c = 16$ MPa (beam strips scheme) -----	284
Figure 6.53	Stress profile along strip 3 for $f_c = 16$ MPa (beam strips scheme) -----	284
Figure 6.54	Stress profile along strip 1 with two layers FRP (column strips scheme) -----	285
Figure 6.55	Stress profile along strip 2 with two layers FRP (column strips scheme) -----	285
Figure 6.56	Stress profile along strip 1 with two layers FRP (beam strips scheme) -----	286
Figure 6.57	Stress profile along strip 2 with two layers FRP (beam strips scheme) -----	286
Figure 6.58	Stress profile along strip 3 with two layers FRP (beam strips scheme) -----	286
Figure 7.1	Joint portion of a reinforced concrete connection with an FRP strengthening applied at an arbitrary angle -----	291
Figure 7.2	Components of force in FRP parallel and perpendicular to column axis -----	292
Figure 7.3	Resolution of force in FRP perpendicular to the critical shear crack -----	292

Figure 7.4	Strain distribution along the length of FRP strip 1 (connection SM1)-----	296
Figure 7.5	Strain distribution along the length of FRP strip 1 in push cycle-----	296
Figure 7.6	Strain distribution along the length of FRP strip 1 (connection SM2)-----	297
Figure 7.7	Strain distribution along the length of FRP strip 2 (connection SM2)-----	297
Figure 7.8	Strain distribution along the length of FRP strip 3 (connection SM2)-----	298
Figure 7.9	RC connection dimensions and forces-----	299
Figure 7.10	Joint stress diagram -----	301
Figure 7.11	States of strain for concrete in compression -----	302
Figure 7.12	Stress-strain diagram for steel reinforcement bars -----	303
Figure 7.13	Stress-strain diagram for FRP -----	303
Figure 7.14	Stress and strain diagrams for elastic state-----	304
Figure 7.15	Stress and strain distribution for inelastic state I-----	305
Figure 7.16	Stress and strain distribution for inelastic state II-----	307
Figure 7.17	Stress distribution factor (Chen and Teng 2003a) -----	312
Figure 8.1	Forces in the joint region -----	320
Figure A.1	Geometric details of FRP coupons used to determine the tensile strength and modulus of elasticity of carbon FRP-----	351
Figure A.2	Material data sheet for MBRACE fibre -----	352
Figure A.2	Material data sheet for MBRACE fibre -----	353
Figure C.1	Location of strain gauge on internal reinforcement bars-----	357
Figure C.2	Strain in reinforcement bar at gauge R2-----	358
Figure C.3	Strain in reinforcement bar at gauge R3-----	358
Figure C.4	Strain in reinforcement bar at gauge R4-----	358
Figure C.5	Strain in reinforcement bar at gauge R5-----	359
Figure C.6	Strain in reinforcement bar at gauge R6-----	359
Figure C.7	Strain in reinforcement bar at gauge R7-----	359
Figure C.8	Strain in reinforcement bar at gauge R8-----	360
Figure C.9	Strain in reinforcement bar at gauge R9-----	360
Figure C.10	Strain in reinforcement bar at gauge R10 -----	360
Figure C.11	Strain in reinforcement bar at gauge R11 -----	361
Figure C.12	Strain in reinforcement bar at gauge R12 -----	361
Figure C.13	Strain in reinforcement bar at gauge R13 -----	361
Figure C.14	Strain in reinforcement bar at gauge R14 -----	362
Figure C.15	Strain in reinforcement bar at gauge R15 -----	362
Figure C.16	Strain in reinforcement bar at gauge R16 -----	362
Figure C.17	Strain in reinforcement bar at gauge R17 -----	363
Figure C.18	Strain in reinforcement bar at gauge R18 -----	363

Figure C.19	Strain in reinforcement bar at gauge R19-----	363
Figure C.20	Strain in reinforcement bar at gauge R20-----	364
Figure C.21	Strain in reinforcement bar at gauge R21-----	364
Figure C.22	Strain in reinforcement bar at gauge R22-----	364
Figure C.23	Strain in reinforcement bar at gauge R2-----	365
Figure C.24	Strain in reinforcement bar at gauge R3-----	365
Figure C.25	Strain in reinforcement bar at gauge R4-----	365
Figure C.26	Strain in reinforcement bar at gauge R5-----	366
Figure C.27	Strain in reinforcement bar at gauge R6-----	366
Figure C.28	Strain in reinforcement bar at gauge R7-----	366
Figure C.29	Strain in reinforcement bar at gauge R8-----	367
Figure C.30	Strain in reinforcement bar at gauge R9-----	367
Figure C.31	Strain in reinforcement bar at gauge R10-----	367
Figure C.32	Strain in reinforcement bar at gauge R11-----	368
Figure C.33	Strain in reinforcement bar at gauge R12-----	368
Figure C.34	Strain in reinforcement bar at gauge R13-----	368
Figure C.35	Strain in reinforcement bar at gauge R14-----	369
Figure C.36	Strain in reinforcement bar at gauge R15-----	369
Figure C.37	Strain in reinforcement bar at gauge R16-----	369
Figure C.38	Strain in reinforcement bar at gauge R17-----	370
Figure C.39	Strain in reinforcement bar at gauge R18-----	370
Figure C.40	Strain in reinforcement bar at gauge R19-----	370
Figure C.41	Strain in reinforcement bar at gauge R20-----	371
Figure C.42	Strain in reinforcement bar at gauge R21-----	371
Figure C.43	Strain in reinforcement bar at gauge R22-----	371
Figure C.44	Strain in reinforcement bar at gauge R1 – push direction-----	372
Figure C.45	Strain in reinforcement bar at gauge R1 – pull direction-----	372
Figure C.46	Strain in reinforcement bar at gauge R2 – push direction-----	372
Figure C.47	Strain in reinforcement bar at gauge R2 – pull direction-----	373
Figure C.48	Strain in reinforcement bar at gauge R3 – push direction-----	373
Figure C.49	Strain in reinforcement bar at gauge R3 – pull direction-----	373
Figure C.50	Strain in reinforcement bar at gauge R4 – push direction-----	374
Figure C.51	Strain in reinforcement bar at gauge R4 – pull direction-----	374
Figure C.52	Strain in reinforcement bar at gauge R5 – push direction-----	374
Figure C.53	Strain in reinforcement bar at gauge R5 – pull direction-----	375
Figure C.54	Strain in reinforcement bar at gauge R6 – push direction-----	375
Figure C.55	Strain in reinforcement bar at gauge R6 – pull direction-----	375

Figure C.56	Strain in reinforcement bar at gauge R7 – push direction -----	376
Figure C.57	Strain in reinforcement bar at gauge R7 – pull direction -----	376
Figure C.58	Strain in reinforcement bar at gauge R8 – push direction -----	376
Figure C.59	Strain in reinforcement bar at gauge R8 – pull direction -----	377
Figure C.60	Strain in reinforcement bar at gauge R9 – push direction -----	377
Figure C.61	Strain in reinforcement bar at gauge R9 – pull direction -----	377
Figure C.62	Strain in reinforcement bar at gauge R10 – push direction -----	378
Figure C.63	Strain in reinforcement bar at gauge R10 – pull direction -----	378
Figure C.64	Strain in reinforcement bar at gauge R11 – push direction -----	378
Figure C.65	Strain in reinforcement bar at gauge R11 – pull direction -----	379
Figure C.66	Strain in reinforcement bar at gauge R12 – push direction -----	379
Figure C.67	Strain in reinforcement bar at gauge R12 – pull direction -----	379
Figure C.68	Strain in reinforcement bar at gauge R13 – push direction -----	380
Figure C.69	Strain in reinforcement bar at gauge R13 – pull direction -----	380
Figure C.70	Strain in reinforcement bar at gauge R14 – push direction -----	380
Figure C.71	Strain in reinforcement bar at gauge R14 – pull direction -----	381
Figure C.72	Strain in reinforcement bar at gauge R15 – push direction -----	381
Figure C.73	Strain in reinforcement bar at gauge R15 – pull direction -----	381
Figure C.74	Strain in reinforcement bar at gauge R16 – push direction -----	382
Figure C.75	Strain in reinforcement bar at gauge R16 – pull direction -----	382
Figure C.76	Strain in reinforcement bar at gauge R17 – push direction -----	382
Figure C.77	Strain in reinforcement bar at gauge R17 – pull direction -----	383
Figure C.78	Strain in reinforcement bar at gauge R18 – push direction -----	383
Figure C.79	Strain in reinforcement bar at gauge R18 – pull direction -----	383
Figure C.80	Strain in reinforcement bar at gauge R19 – push direction -----	384
Figure C.81	Strain in reinforcement bar at gauge R19 – pull direction -----	384
Figure C.82	Strain in reinforcement bar at gauge R20 – push direction -----	384
Figure C.83	Strain in reinforcement bar at gauge R20 – pull direction -----	385
Figure C.84	Strain in reinforcement bar at gauge R21 – push direction -----	385
Figure C.85	Strain in reinforcement bar at gauge R21 – pull direction -----	385
Figure C.86	Strain in reinforcement bar at gauge R22 – push direction -----	386
Figure C.87	Strain in reinforcement bar at gauge R22 – pull direction -----	386
Figure D.1	Stress profile along strip 1 (column strips scheme – four layers)-----	387
Figure D.2	Stress profile along strip 2 (column strips scheme – four layers)-----	387
Figure D.3	Stress profile along strip 1 (column strips scheme – eight layers)-----	387
Figure D.4	Stress profile along strip 2 (column strips scheme - eight layers) -----	388
Figure D.5	Stress profile along strip 1 (column strips scheme - sixteen layers)-----	388

Figure D.6	Stress profile along strip 2 (column strips scheme – sixteen layers)-----	388
Figure D.7	Stress profile along strip 1 (beam strips scheme – four layers)-----	389
Figure D.8	Stress profile along strip 2 (beam strips scheme – four layers)-----	389
Figure D.9	Stress profile along strip 3 (beam strips scheme – four layers)-----	389
Figure D.10	Stress profile along strip 1 (beam strips scheme – eight layers)-----	390
Figure D.11	Stress profile along strip 2 with eight layer FRP (beam strips scheme)-----	390
Figure D.12	Stress profile along strip 3 (beam strips scheme – eight layers)-----	390
Figure D.13	Stress profile along strip 1 (beam strips scheme – sixteen layers)-----	391
Figure D.14	Stress profile along strip 2 (beam strips scheme – sixteen layers)-----	391
Figure D.15	Stress profile along strip 3 (beam strips scheme – sixteen layers)-----	391
Figure D.16	Stress profile along strip 1 for $f'c = 25$ MPa (column strips scheme)-----	392
Figure D.17	Stress profile along strip 2 for $f'c = 25$ MPa (column strips scheme)-----	392
Figure D.18	Stress profile along strip 1 for $f'c = 40$ MPa (column strips scheme)-----	392
Figure D.19	Stress profile along strip 2 for $f'c = 40$ MPa (column strips scheme)-----	393
Figure D.20	Stress profile along strip 1 for $f'c = 25$ MPa (beam strips scheme)-----	393
Figure D.21	Stress profile along strip 2 for $f'c = 25$ MPa (beam strips scheme)-----	393
Figure D.22	Stress profile along strip 3 for $f'c = 25$ MPa (beam strips scheme)-----	394
Figure D.23	Stress profile along strip 1 for $f'c = 40$ MPa (beam strips scheme)-----	394
Figure D.24	Stress profile along strip 2 for $f'c = 40$ MPa (beam strips scheme)-----	394
Figure D.25	Stress profile along strip 3 for $f'c = 40$ MPa (beam strips scheme)-----	395
Figure D.26	Stress profile along strip 1 (column strips scheme - four layers)-----	395
Figure D.27	Stress profile along strip 2 (column strips scheme - four layers)-----	395
Figure D.28	Stress profile along strip 1 (column strips scheme - eight layers)-----	396
Figure D.29	Stress profile along strip 2 (column strips scheme - eight layers)-----	396
Figure D.30	Stress profile along strip 1 (column strips scheme - sixteen layers)-----	396
Figure D.31	Stress profile along strip 2 (column strips scheme - sixteen layers)-----	397
Figure D.32	Stress profile along strip 1 (beam strips scheme - four layers)-----	397
Figure D.33	Stress profile along strip 2 (beam strips scheme - four layers)-----	397
Figure D.34	Stress profile along strip 3 (beam strips scheme - four layers)-----	398
Figure D.35	Stress profile along strip 1 (beam strips scheme - eight layers)-----	398
Figure D.36	Stress profile along strip 2 (beam strips scheme - eight layers)-----	398
Figure D.37	Stress profile along strip 3 (beam strips scheme - eight layers)-----	399
Figure D.38	Stress profile along strip 1 (beam strips scheme - sixteen layers)-----	399
Figure D.39	Stress profile along strip 2 (beam strips scheme - sixteen layers)-----	399
Figure D.40	Stress profile along strip 3 (beam strips scheme - sixteen layers)-----	400