

**BEHAVIOUR OF REINFORCED CONCRETE  
FLEXURAL MEMBERS STRENGTHENED WITH  
EXTERNALLY BONDED CARBON FIBER  
REINFORCED POLYMERS**

Batuwitage Chamila Rajeev Jayanath

(118002G)



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

Degree of Master of Philosophy

Department of Civil Engineering

University of Moratuwa  
Sri Lanka

March 2013

**BEHAVIOUR OF REINFORCED CONCRETE  
FLEXURAL MEMBERS STRENGTHENED WITH  
EXTERNALLY BONDED CARBON FIBER  
REINFORCED POLYMERS**

Batuwitage Chamila Rajeev Jayanath

(118002G)



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

Dissertation submitted in partial fulfilment of the requirements for the degree Master  
of Philosophy

Department of Civil Engineering

University of Moratuwa  
Sri Lanka

March 2013

## DECLARATION

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature:

Date:



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mru.ac.lk](http://www.lib.mru.ac.lk)

The above candidate has carried out research for the MPhil Dissertation under my supervision.

Signature of the supervisor:

Date

## ABSTRACT

Reinforced concrete structures often have to face modification and improvement of their performance during their service life. The main contributing factors are change in their use, new design standards, design errors, deterioration due to corrosion in the steel caused by exposure to an aggressive environment and accident events such as earthquakes. In such circumstances there are two possible solutions: replacement or retrofitting. It is desirable to repair and reuse reinforced concrete structures from the point of view of sustainability. Strengthening may also be needed to prolong the life of deteriorated members. Use of Fiber reinforced polymers (FRP) can be considered as one of efficient technique for such strengthening of reinforced concrete elements.

The previous research studies show the lack of field scale experimental studies and analytical studies such as finite element models (FEM) have been carried out to complete understanding of strengthening reinforced concrete structural element using FRP with respect to failure behaviour, strength enhancement, ductility assessment and deflection behaviour. Further, no studies have been carried out in Sri Lankan context to understand behaviour of FRP strengthening reinforced concrete systems and no technical data is available. This has led to less confidence of using this technique by practicing engineers in Sri Lanka. Various design guidelines shows the different approaches to design FRP strengthening system, especially the prediction of failure strains. This has led to poor understanding of safety against ultimate failure and confidence of using the existing guidelines for the designs. This study covers the above aspects with respect to strengthening of reinforced concrete flexural elements using carbon fiber reinforced polymers (CFRP).

A comprehensive experimental program has been carried out using field scale flexural strengthened reinforced concrete elements (beams and slabs) to understand failure behaviour, flexural strength enhancement, ductility assessment and deflection behaviour. A nonlinear finite element model has been developed to simulate complete experimental behaviour of CFRP strengthened reinforced concrete flexural system till failure. ACI and Japanese method of designing flexural system have been evaluated and checked with the experimental results.

It was observed that CFRP strengthened beams with u-wrapping showed about 60% load carrying capacity improvement with respect to control specimens. It was about 140% load carrying capacity increment for normal strengthened R6 slabs (reinforced with 6mm diameter mild steel) with CFRP at soffits. The load carrying capacity increment for T10 slabs (reinforced with 10 mm diameter tor steel) with CFRP was about 70% with normal wrap of CFRP. It was clear that gain in flexural enhancement has highly depend on the reinforcement ratio and the wrapping method of CFRP.

It was observed from the experimental study, a reduction in ductility of both beams and slabs strengthened with CFRP. This reduction has considerably depended on the reinforcement ratio of the elements. However, the elements still have sufficient ductility against failure.

The only failure mode observed in beam failure can be classified as cover separation with simultaneous debonding of CFRP laminates. The failure has initiated by cracks formed in the reinforced concrete elements during loading. The failure mode in the slabs is due to peeling of CFRP laminates from the slab soffit known as debonding failure. The measured strain values of CFRP for beams specimen are almost constant at failure. It was about 3570  $\mu\epsilon$ . The slabs are also constant with 2540  $\mu\epsilon$  which is independent on the reinforcement ratio. This

indicates the failure is governed by the FRP strain at failure. The difference in FRP strain at failure in beams and slabs are due to wrapping method of the laminates.

It was observed that tested specimen with flexural enhancement still satisfied the serviceability deflection criterion ( $\text{span}/300$ ) for reinforced concrete elements. Hence, these flexural enhancement designs for beams and slabs are governed by the ultimate limit state failure.

ANSYS based non-linear finite element model has been developed to simulate experimental behaviour of FRP strengthened flexural system. It has good agreement with experimental results. The calibrated material parameters has presented in this dissertation.

ACI and Japanese method of designs of flexural system are governed by the prediction of debonding strain values by empirical based formulae. It was observed that prediction of debonding strain by ACI method overestimate the value compared to Japanese method. On the other hand, it was observed that Japanese method prediction is more close to experimental CFRP strain observed at the failure in this experimental program. However, ultimate moment of resistant calculation using conventional section analysis (this method is used in both codes) indicates that both ACI and Japanese method have adequate safety margin against ultimate failure of beams whereas ACI method does not show the adequate safety margin for the slabs but Japanese method does. However, Japanese method has high safety margin against beams and less value of the slabs. This difference in strains, highly depending on the failure behaviour which is directly related to the wrapping method, has to be accounted in the prediction of the debonding strain values.

Proposed Japanese method of debonding prediction formula has been modified based experimental results. This modification has led to prediction of ultimate design moment for flexural enhanced elements (both slabs and beams) with reasonable factor of safety against ultimate failure.



University of Moratuwa, Sri Lanka  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

This study has led Sri Lankan engineers to understand complete behaviour of CFRP strengthened flexural systems. Proposed methodology can be used for the design with higher confidence.

Keywords: flexural strengthening, CFRP, debonding failure, nonlinear FEM, Design criterion

## ACKNOWLEDGEMENT

My sincere gratitude is first expressed to Dr. C. S. Lewangamage for being my principal supervisor and giving me this opportunity together with his motivation, great support and excellent guidance provided throughout this research study.

I would like to thank Professor M.T.R. Jayasinghe, former Head, Department of Civil Engineering, University of Moratuwa for being chairperson of the progress review committee and provided me good guidance while doing this study. I also thank Professor H.S Thilakasiri, research coordinator, Department of Civil Engineering, University of Moratuwa, for his support throughout the period.

My special thank should go to Senate Research Grant of University of Moratuwa (Grant no: SRC/LT/2011/26) for creating this opportunity to me by providing financial support during this research study.

I am grateful to Mr. Dhammika Wimalaratne (NAVCORP Engineering Consultants Sri Lanka) who sponsored for the Carbon Fiber Reinforced Polymer (CFRP) material during the experimental programme.

I am also thankful to Professor Mrs. C. Jayasinghe, Director of Post Graduate studies division for her help during this study.

It is worth mentioning here assistance rendered by the other members of academic staff and support given by the non-academic staff of Civil Engineering Department.

Finally, I must thank those who helped me in many ways, through by the way of material of verbal thus enabling me in reaching of the present stage of the study.

## Table of content

Declaration.....	ii
Abstract.....	iii
Acknowledgement .....	v
Table of content.....	vi
List of Figures.....	xii
List of Tables .....	xvii

### Chapter 1

#### INTRODUCTION

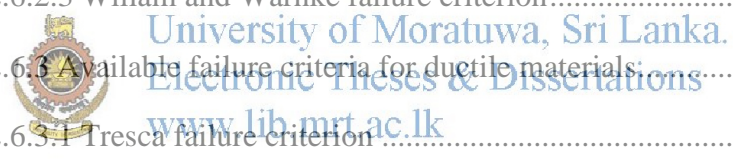
1.1 Background .....	1
1.2 Repair and rehabilitation of structural elements .....	1
1.3 Strengthening of RC flexural elements (beams/slabs) by using FRP .....	4
1.4 Scope of the study .....	6
1.5 Main results .....	7
1.6 Dissertation outline .....	8

### Chapter 2

#### LITERATURE REVIEW

2.1 Introduction .....	10
2.2 Historical development of FRP strengthening systems on RC structures.....	11
2.3 Material behaviour .....	12
2.3.1 General .....	12
2.3.2 Concrete .....	13
2.3.3 Reinforcing steel .....	13
2.3.4 FRP material.....	15

2.3.5 Bond between FRP and concrete .....	17
2.4 Associated failure behaviours of FRP strengthened flexural systems .....	17
2.5 Ductile behaviour, durability issues and wrapping methods of FRP strengthened flexural sections .....	22
2.5.1 Ductile behaviour .....	22
2.5.2 Durability issues .....	23
2.5.3 Wrapping methods .....	24
2.6 Available material's failure criteria .....	24
2.6.1 General .....	24
2.6.2 Available failure criteria for concrete.....	25
2.6.2.1 Mohr-Coulomb yield criterion .....	25
2.6.2.2 Drucker-Prager yield criterion.....	27
2.6.2.3 Willam and Warnke failure criterion.....	28
2.6.3 Available failure criteria for ductile materials.....	35
2.6.3.1 Tresca failure criterion .....	35
2.6.3.2 Von Mises yield criterion .....	36
2.6.3.3 Bresler–Pister yield criterion.....	36
2.7 Finite element modelling of FRP-concrete composite.....	38
2.8 Design guidelines for flexural strengthening with FRP .....	38
2.8.1 ACI 440.2R-08 .....	39
2.8.2 Japanese standards (JSCE recommendations).....	41
2.8.3 The Egyptian code ECP 208-2005 .....	42
2.9 Summary .....	42





### Chapter 3


#### EXPERIMENTAL STUDY

3.1 Introduction .....	45
3.2 Materials.....	46
3.2.1 FRP and epoxy .....	46
3.2.2 Concrete .....	47
3.2.3 Reinforcement .....	48
3.3 Testing of beams .....	49
3.3.1 Specimen details.....	49
3.3.2 Surface preparation of beams .....	49
3.3.3 Application of CFRP on beams.....	50
3.3.4 Testing procedure of beams .....	51
3.3.5 Measurements.....	51
3.4 Testing of slabs .....	53
3.4.1 Specimen details.....	53
3.4.2 Surface preparation of slabs .....	55
3.4.3 Application of FRP on slabs.....	55
3.4.4 Testing procedure of slabs.....	56
3.4.5 Measurements.....	57
3.5 Summary .....	58

### Chapter 4

#### EXPERIMENTAL RESULTS (flexural enhancement, failure behaviour, deflection behaviour and ductility assessment)

4.1 Introduction .....	59
4.2 Strength enhancement.....	59

4.2.1 Ultimate failure loads of beams .....	59
4.2.2 Ultimate failure loads of slabs.....	60
4.3 Failure modes .....	61
4.3.1 Failure modes of beams.....	61
4.3.2 Failure modes of slabs .....	65
4.4 Load-Deflection and Load-Strain plots.....	68
4.4.1 Load-Deflection and Load-Strain plots for beams .....	68
4.4.2 Load-Deflection and Load-Strain plots for slabs .....	69
4.5 Ductility assessment.....	73
4.5.1 Ductile behavior of beams.....	73
4.5.2 Ductile behavior of slabs.....	74
4.5 Serviceability limit deflection .....	75
4.6 Summary .....	75
<b>Chapter 5</b>  <b>NONLINEAR FINITE ELEMENT MODELING</b>	
5.1 Introduction .....	76
5.2 Element types .....	77
5.2.1 Reinforced concrete.....	77
5.2.2 Steel.....	78
5.2.3 FRP material.....	78
5.3 Material constitutive models and failure criteria .....	79
5.3.1 Concrete .....	79
5.3.2 Steel.....	82
5.3.3 CFRP .....	83
5.4 Nonlinear finite element analysis of flexural members .....	84

5.4.1 Geometry .....	84
5.4.2 Finite element discretization .....	86
5.4.3 Loading and boundary conditions .....	87
5.4.4 Nonlinear solution .....	88
5.4.5 Load steps and failure definition for FEM .....	89
5.4.6 Finite element modeling results .....	91
5.4.6.1 Load – deflection and load – strain plots for beams .....	91
5.4.6.2 Load – deflection and load - strain plots for slabs .....	93
5.4.7 First cracking loads .....	97
5.4.8 Evaluation of crack patterns .....	99
5.4.8.1 Comparison5of crack patterns.....	102
5.4.8.2 Evaluation of CFRP strain at failure .....	105
5.5 Summary .....	109
<b>Chapter 6</b>	
<b>EVALUATION OF DEBONDING STRAIN AND ASSOCIATED FACTOR OF SAFETY FOR FRP STRENGTHENED FLEXURAL SYSTEMS</b>	
6.1 Introduction .....	110
6.2 Comparison of debonding strain at failure of beams .....	110
6.3 Comparison of debonding strain at failure of slabs .....	112
6.4 Overall factor of safety.....	114
6.5 Proposed expression for debonding strain evaluation in FRP .....	117
6.6 Factor of safety for design based on proposed debonding strain .....	118
6.7 Summary .....	119



University of Moratuwa, Sri Lanka.  
 Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

**Chapter 7**

**RECOMMENDED DESIGN PROCEDURE FOR FRP FLEXURAL SYSTEMS**

7.1 Flexural design of FRP strengthened section..... 120  
7.2 Summary ..... 124

**Chapter 8**

**CONCLUSIONS AND RECOMENDATIONS**

8.1 Conclusions and recommendations..... 125  
8.2 Future prospective for further research ..... 127

**References** ..... 128

**Appendix A** ..... 136

Material properties ..... 136

**Appendix B** ..... 142

B.1 Design moment capacity for FRP strengthened beams..... 142

B.2 Design moment capacity for FRP strengthened R6slabs ..... 143

B.3 Design moment capacity for FRP strengthened T10slabs..... 144

**Appendix C** ..... 145

Design example on FRP strengthened flexural system..... 145

**VITA**..... 146



## List of Figures

Figure 1.1: Spalling of concrete from a beam due to carbonation .....	2
Figure 1.2: Cracks appeared in the beam due to a design error .....	2
Figure 1.3: Exposed corroded reinforcement in RC slabs .....	3
Figure 2.1: Uni-axial stress strain curves for concrete.....	13
Figure 2.2: Tensile stress-strain curve for steel .....	14
Figure 2.3: Idealized stress-strain curve for steel.....	15
Figure 2.4: Stress-strain curve for FRP .....	16
Figure 2.5: Compression failure.....	20
Figure 2.6: Rupture of FRP .....	20
Figure 2.7: Shear failure.....	21
Figure 2.8: Delamination of FRP .....	21
Figure 2.9: Concrete cover separation .....	21
Figure 2.10: Wrapping methods for flexural strengthening.....	24
Figure 2.11: View of Mohr-Coulomb failure surface in 3D space of principal stresses for $c = 2$ ; $\varphi = -20^\circ$ .....	27
Figure 2.12: View of Drucker-Prager yield surface in 3D space of principal stresses for $c = 2$ ; $\varphi = -20^\circ$ .....	28
Figure 2.13: Willam and Warnke 3-D Failure Surface in Principal Stress Space .....	31
Figure 2.14: Willam and Warnke failure Surface in Principal Stress Space with Nearly Biaxial Stress.....	34
Figure 2.15: Tresca-Guest yield surface .....	35
Figure 2.16: The Tresca-Guest and Von Mises yield surfaces in 3D space .....	36
Figure 2.17: a) The Bresler-Pister yield surface in 3D space; b) The Bresler-Pister yield surface in 2D space. ....	37

Figure 2.18: Analysis of cross section in flexure.....	39
Figure 2.19: Debonding failure modes associated with FRP strengthened flexural sections.....	40
Figure 3.1: Methodology for study programme.....	45
Figure 3.2: Epoxy components .....	46
Figure 3.3: Formwork and reinforcement for beams .....	47
Figure 3.4: Formwork and reinforcement for slabs .....	47
Figure 3.5: Testing of steel samples.....	48
Figure 3.6: Reinforcement and FRP arrangement for beams (not in scale).....	49
Figure 3.7: Surface preparation of beams .....	50
Figure 3.8: Saturating of CFRP layer and beam surface with epoxy.....	50
Figure 3.9: Application of CFRP on beams .....	50
Figure 3.10: Typical test set up for beams .....	51
Figure 3.11: Testing arrangement for a beam.....	52
Figure 3.12: Strain gauge locations of beams .....	52
Figure 3.13: LVDT and dial gage positions of beams .....	53
Figure 3.14: Details of slabs.....	54
Figure 3.15: After surface preparation of slabs.....	55
Figure 3.16: Laying of FRP on slabs .....	56
Figure 3.17: Applying second coating of epoxy on FRP.....	56
Figure 3.18: Test set up for slabs .....	56
Figure 3.19: Test set up for slabs .....	57
Figure 3.20: LVDT and dial gauge locations for slabs .....	57
Figure 4.1: Flexural cracks development of control beam1.....	61
Figure 4.2: Flexural cracks development of control beam 2.....	62

Figure 4.3: Flexural cracks development of control beam 3.....	62
Figure 4.4: Ultimate failure mode of a control beam.....	62
Figure 4.5: Crack initiation and CFRP debonding of TB1 .....	63
Figure 4.6: Crack initiation and CFRP debonding of TB2 .....	63
Figure 4.7: Concrete cover separation of TB3 .....	64
Figure 4.8: Concrete cover separation of TB4 .....	64
Figure 4.9: Concrete cover separation of TB5 .....	65
Figure 4.10: Crack propagation and failure of R6 control slab.....	66
Figure 4.11: Crack propagation and failure of T10 control slab.....	66
Figure 4.12: Debonded CFRP layer of R6TS1 type slab .....	67
Figure 4.13: Debonded CFRP layers of R6TS2 type slab .....	67
Figure 4.14: Debonding failure of T10TS1 type slab .....	68
Figure 4.15: Load vs mid span deflection of beams .....	68
Figure 4.16: Load vs FRP strain at mid span for beams .....	69
Figure 4.17: Comparison of load vs mid span deflection for R6 control slabs and R6TS1 type slabs .....	70
Figure 4.18: Comparison of load vs mid span strain for R6TS1 type slabs.....	70
Figure 4.19: Comparison of load vs mid span deflection for R6 control slabs and R6TS2 type slabs .....	71
Figure 4.20: Comparison of load vs mid span strain for R6TS2 type slabs.....	71
Figure 4.21: Comparison of load vs mid span deflection for T10 control slabs and T10TS1 type slabs.....	72
Figure 4.22: Comparison of load vs FRP strain at mid span for T10TS1 type slabs.	72
Figure 5.1: SOLID65 geometry and node locations .....	77
Figure 5.2: Geometry and node locations for LINK8 .....	78

Figure 5.3: Geometry and node locations for SHELL41 .....	78
Figure 5.4: Simplified compressive uniaxial stress-strain curve for concrete .....	80
Figure 5.5: Bilinear elastic model for steel .....	83
Figure 5.6: Linear elastic model for CFRP .....	84
Figure 5.7: Typical beam dimensions (not in scale) .....	84
Figure 5.8: Typical slab dimensions (not in scale) .....	85
Figure 5.9: Finite elements mesh for a control beam model.....	85
Figure 5.10: Finite elements mesh for a FRP strengthened slab model.....	86
Figure 5.11: Mesh size vs mid span deflection (convergence study) .....	86
Figure 5.12: Mesh size vs compressive stress at top (convergence study) .....	87
Figure 5.13: Pin support.....	87
Figure 5.14: Roller support .....	87
Figure 5.15: Newton-Raphson iterative (ANSYS).....	88
Figure 5.16: Reinforced concrete behaviour for control beams.....	90
Figure 5.17 Load vs mid span deflection of control beams .....	91
Figure 5.18: Load vs Deflection at mid span for FRP strengthened beams.....	92
Figure 5.19: Load vs FRP strain at mid span for FRP strengthened beams .....	92
Figure 5.20: Load vs at mid span deflection for R6 control slabs .....	93
Figure 5.21: Load vs at mid span deflection for T10control slabs.....	94
Figure 5.22: Load vs deflection for R6TS1 slabs .....	94
Figure 5.23: Load vs FRP strain at mid span for R6TS1 slabs.....	95
Figure 5.24: Load vs deflection for R6TS2 slabs .....	95
Figure 5.25: Load vs FRP strain at mid span for R6TS2 slabs.....	96
Figure 5.26: Load vs deflection for T10TS1 slabs.....	96
Figure 5.27: Load vs FRP strain at mid span for T10TS1 slabs .....	97



Figure 5.28: Integration points in concrete solid element (ANSYS).....	99
Figure 5.29: Cracking sign (ANSYS) .....	99
Figure 5.30: Cracking of a flexural member .....	100
Figure 5.31: Crack propagation of control beam .....	102
Figure 5.32: Crack pattern at failure of R6 control slab .....	103
Figure 5.33: Crack pattern at failure of R6TS1 slab .....	103
Figure 5.34: Crack pattern at failure of R6TS2 slab .....	104
Figure 5.35: Crack pattern at failure of T10 control slab.....	104
Figure 5.36: Crack pattern at failure of T10TS1 slab .....	104
Figure 5.37: Strain variation of CFRP layer in beams .....	107
Figure 5.38: Strain variation of CFRP layer in R6TS1 .....	107
Figure 5.39: Strain variation of CFRP layer in R6TS2.....	108
Figure 5.40: Strain variation of CFRP layer in T10TS1.....	108
Figure 6.1: Variation of strain at failure between design standards predicted values and experimental values .....	111
Figure 6.2: Variation of strain at failure between design standards predicted values and experimental values for slabs .....	113
Figure 6.3: Analysis of cross section in flexure.....	114
Figure 7.1: Stress and strain across the depth of a reinforced concrete section strengthened with FRP .....	120

## List of Tables

Table 2.1: Typical properties of materials .....	16
Table 2.2: Input parameters for Willam and Warnke failure criterion .....	29
Table 2.3: Environmental reduction factors for FRP suggested by ACI 440-2R .....	41
Table 3.1: Properties of CFRP and composite .....	46
Table 3.2: Reinforcement details of beams .....	49
Table 3.3: Reinforcement details of slabs .....	54
Table 4.1: Ultimate failure loads and failure modes of beams .....	59
Table 4.2: Ultimate failure loads and failure modes of slabs.....	60
Table 4.3: Cracking loads of control beams.....	61
Table 4.4: First cracking loads of slabs.....	65
Table 4.5: Ultimate displacement ratio and ductility index for beams .....	73
Table 4.6: Ultimate displacement ratio and ductility index for slabs .....	74
Table 5.1: ANSYS parameters for concrete.....	81
Table 5.2: Steel material properties for ANSYS.....	82
Table 5.3: Linear orthotropic material properties for CFRP .....	83
Table 5.4: Load step sizes for control beam model .....	89
Table 5.5: Comparisons between experimental observed and ANSYS first cracking loads of beams.....	97
Table 5.6: Comparisons between experimental observed and ANSYS first cracking loads of slabs .....	98
Table 5.7: Comparison of failure loads of beams .....	105
Table 5.8: Comparison of failure loads of slabs .....	106
Table 6.1: Comparison of ultimate debonding strain values of beams at failure.....	111

Table 6.2: Percentage variation of the proposed debonding strain values by the design standards to the experimentally measured values for beams..... 111

Table 6.3: Comparison of ultimate debonding strain values of slabs at failure..... 112

Table 6.4: Percentage variation of the proposed debonding strain values by the design standards to the experimentally measured values for slabs ..... 113

Table 6.5: Safety factors in Japanese standards ..... 115

Table 6.6: Comparison of overall FOS between ACI-440-2R and Japanese standards for beams ..... 116

Table 6.7 Design moments and safety factors based on proposed expression..... 119

Table 7.1: Environmental factor ..... 121

Table A.1: 28 days cube strength of concrete ..... 136

Table A.2: Cube strengths of concrete at the date of testing of beams and slabs .... 137

Table A.3: Tensile test results of concrete at the date of testing of beams and slabs ..... 138

Table A.4: Tensile test results for mild steel ..... 139

Table A.5: Tensile test results for tor steel ..... 139

