

**INVESTIGATION ON PERFORMANCE OF HEAVILY  
CRACKED CONCRETE BEAM STRENGTHENED  
WITH CARBON FIBER REINFORCED POLYMER  
(CFRP) SHEETS**

Prasad Dhammika Dharmaratne

(138731 H)

Dissertation submitted in partial fulfilment of the requirements for the degree Master  
of Engineering in Structural Engineering Design

Department of Civil Engineering

University of Moratuwa

Sri Lanka

December 2017

## **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).

P D Dharmaratne

Date:.....

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

Dr.( Mrs). G.C.P.H. Gamage

**Date**

Dr.( Mrs). D. Nanayakkara

**Date**

## **ACKNOWLEDGEMENT**

There are many individuals, who deserve acknowledgement for their contribution towards successful completion of this research.

First, I would like to express my gratitude to my supervisors, Dr. (Mrs.) J.C.P.H N Gamage and Dr. (Mrs.) D Nanayakkara for their valuable advice, guidance and assistance throughout the entire period of study. I am much grateful for sharing their knowledge and expertise on this field.

I am much grateful to the Head of the Department of Civil Engineering, the Course Coordinator of Master of Structural Engineering, the staff of the Department of Civil Engineering and the staff of the structural laboratory for their valuable guidance and co-operation related to all experimental works. The assistance rendered by undergraduate students Mr. Hashan Dissanayake and Miss Pamudi Ekanayake for the experimental works also gratefully acknowledged and I would like to thank to Eng (Mr.) V Aththanayake, Airow solutions(Pvt) Ltd and Mr. G M Karunarathne for their supports to make the project successful.

Secondly, my sincere acknowledgement is towards my employer, Keangnam Lanka (Pvt) Ltd for granting leaves to follow this course and other assistances provided for my research works.

My very special thanks go to my dearest wife Nilakshi for her continuous encouragement and assistance during the entire period. My research would never be successful without her tremendous support.

Lastly, there are many friends and colleagues who have not been personally mentioned here that I am much indebted to their contribution at various stages of the research to make it successful.

## **ABSTRACT**

Repair and retrofit of existing structures especially buildings, bridges, water tanks etc., have been amongst the most significant challenges in Civil Engineering. In the past construction was evolved from thousands of years back with various construction materials such as rocks, clay bricks and timber etc. There after concrete was introduced as a sustainable construction material which is most suitable than that of previously used materials.

Although concrete has high compressive strength, it is very weak in tension and become brittle under tensile loads. Because of these reasons, Engineers moved to reinforced concrete structures. Since concrete structures are long lasting structures, carrying out the rehabilitation work of existing structures becomes more vital.

Nowadays, there are different kind of problems were encountered in construction field due to original design, construction errors or poor construction supervision, damages of earthquakes etc.. That needs to be retrofitted to meet the demand usage in a more economic and effective ways. The techniques based on the externally bonded Fiber Reinforced Polymer (FRP) materials is one of the most widely application for retrofitting existing damaged structures.

The use of Carbon Fiber Reinforced Polymer (CFRP) in strengthening reinforced concrete structures has become popular retrofit technique. The technique of strengthening reinforced concrete structures by externally bonded CFRP fabric was started in 1980s and has attracted researchers around the world wide.

The aim of this research is to investigate the flexural behavior of pre cracked and non-cracked reinforced concrete beams going to be strengthened with different configurations of Carbon Fiber Reinforcement Polymer layers.

12 Nos. of Reinforced concrete beams of the width 125mm, depth 200mm and length of 1900mm were prepared and tested for this investigation. Beams were tested in accordance with ASTM C78 guidelines

Beams consist of different CFRP arrangements such as non-anchored CFRP sheet, CFRP sheet with end anchors and CFRP sheet with end and intermediate anchors at cracked locations.

FRP can be bonded to reinforced concrete elements using different methods such as external bonding, wrapping and near surface mounting. FRP sheets can be stuck to the tension face of a structural element to provide flexural strength or stuck along the web of a beam to provide shear strength.

Observation shows that increment of flexural capacity is in between 81% to 110% in beams those strengthened with CFRP sheets with respect to non-strengthened beams. Highest strength gained was observed in cracked beams strengthened with CFRP with end anchors and intermediate anchors. Similar behavior was observed in non-anchored CFRP strengthened cracked and non-cracked beams. However the flexural capacity was high in CFRP strengthened cracked beams. All the cracked beams failed in debonding. But some non-cracked beams failed by rupture of CFRP.

At the end of this dissertation, presents the experimental procedure, results, analysis and conclusion.

## TABLE OF CONTENTS

<b>DECLARATION.....</b>	<b>i</b>
<b>ACKNOWLEDGEMENT.....</b>	<b>ii</b>
<b>ABSTRACT.....</b>	<b>iii</b>
<b>TABLE OF CONTENTS.....</b>	<b>v</b>
<b>LIST OF FIGURES.....</b>	<b>vii</b>
<b>LIST OF TABLES.....</b>	<b>xxi</b>
<b>LIST OF ABBREVIATIONS.....</b>	<b>xii</b>
<b>LIST OF APPENDICES.....</b>	<b>xiii</b>
<b>1. INTRODUCTION.....</b>	<b>1</b>
1.1. Background.....	1
1.2. Objective.....	2
1.3. Methodology.....	3
1.4. Outline .....	3
<b>2. LITERATURE REVIEW.....</b>	<b>5</b>
2.1. General .....	5
2.2. Externally Bonded Reinforcement (EBR).....	5
2.3. Flexural strengthening of beams .....	6
2.4. Shear strengthening of beams.....	11
2.5. Pre- Cracked beams .....	15
2.6. Failure modes .....	15
2.7. Summary of strengthening techniques .....	18
2.8. Significance of shear span to depth ratio on failure mode .....	19
2.9. Effect of end anchors installation .....	19
2.10. Effect of length of CFRP on failure mode.....	20
2.11. Durability of adhesive used for bonding between concrete and CFRP .....	20
2.12. Summary of literature review .....	21
2.13. Research gap identification and needs .....	22

<b>3. EXPERIMENTAL PROCEDURE.....</b>	<b>24</b>
3.1. Introduction .....	24
3.2. Specimen Details .....	24
3.3. Properties of Materials .....	25
3.4. Methodology.....	28
3.5. Summary.....	37
<b>4. RESULTS AND ANALYSIS.....</b>	<b>38</b>
4.1. General .....	38
4.2. Test results of control beams .....	38
4.3. Non-cracked concrete beams strengthened with CFRP .....	40
4.4. Pre-cracked reinforced concrete beams strengthened with CFRP .....	50
4.5. Test results analysis of non-cracked (Control) strengthened beams .....	58
4.6. Test results analysis of pre-cracked strengthened beams with control beams.....	60
4.7. Deflection .....	62
4.8. Failure Pattern .....	67
<b>5. THEORITICAL ANALYSIS.....</b>	<b>69</b>
5.1. Introduction .....	69
5.2. ACI 440 design guidelines .....	69
5.3. Procedure to calculate the moment capacities of non-anchored CFRP strengthened beams.....	70
5.4. Procedure to calculate the moment capacity of anchored CFRP concrete beams with end U-wraps.....	71
5.5. Theoretical calculation .....	72
5.6. Summary of theoretical analysis .....	78
5.7. Comparison of Experimental values with theoritical values.....	78
<b>6. CONCLUSION AND RECOMMENDATION.....</b>	<b>80</b>
6.1. Introduction .....	80
6.2. Conclusion.....	80
6.3. Recommendations .....	81
<b>REFERENCES.....</b>	<b>83</b>

<b>APPENDIX.....</b>	<b>88</b>
APPENDIX - 1 .....	88
APPENDIX - 2 .....	91
APPENDIX – 3.....	95
APPENDIX - 4 .....	96



## LIST OF FIGURES

<b>Figure 2.1:</b> CFRP external bonding on beams to enhance flexural strength .....	8
<b>Figure 2.2:</b> FRP rupture .....	15
<b>Figure 2.3:</b> Concrete compression failure . .....	16
<b>Figure 2.4:</b> Diagonal shear crack at CFRP sheet end . .....	16
<b>Figure 2.5:</b> CFRP sheet interfacial de-bonding .....	16
<b>Figure 2.6:</b> CFRP sheet with concrete cover separation . .....	17
<b>Figure 2.7:</b> Crack propagation parallel to bonded plate . .....	17
<b>Figure 3.1:</b> Reinforcement arrangement of beam.....	25
<b>Figure 3.2:</b> Concrete compressive strength test.....	29
<b>Figure 3.3:</b> Prepared formwork arrangement with R/F cage and casted beam .....	29
<b>Figure 3.4:</b> Beam testing using Amsler machine .....	30
<b>Figure 3.5:</b> Crack filling .....	30
<b>Figure 3.6:</b> Air compressor.....	31
<b>Figure 3.7:</b> Sand blasting.....	31
<b>Figure 3.8:</b> Concrete surface after surface preparation .....	32
<b>Figure 3.9:</b> ‘F1’ and ‘F2’ beams.....	33
<b>Figure 3.10:</b> ‘IN1’ beam with U wrap end anchorage.....	34
<b>Figure 3.11:</b> ‘IN2’ beam without U wrap end anchorage.....	34
<b>Figure 3.12:</b> ‘M1’ and ‘M2’ beams with U wrap anchorage.....	34
<b>Figure 3.13:</b> "CF" beams .....	35
<b>Figure 3.14:</b> "CFE" beams.....	35
<b>Figure 3.15:</b> "CFI" beams.....	36
<b>Figure 3.16:</b> Installation of dial gauges .....	36
<b>Figure 3.17:</b> Fixed dial gauge to beam .....	37

<b>Figure 4.1:</b> Load Vs. deflection of control beams .....	39
<b>Figure 4.2:</b> Crack patterns in control beams.....	40
<b>Figure 4.3:</b> Failure mechanism of beam type F1 .....	40
<b>Figure 4.4:</b> Schematic diagram of loading arrangement .....	41
<b>Figure 4.5:</b> Load Vs. deflection of beam type F1 beam type F2.....	41
<b>Figure 4.6:</b> Failure mechanism of beam type F2.....	41
<b>Figure 4.7:</b> Load Vs. deflection of beam type F2.....	42
<b>Figure 4.8:</b> Failure mechanism of beam type “IN 1” .....	42
<b>Figure 4.9:</b> Load Vs. deflection of beam type “IN1” .....	43
<b>Figure 4.10:</b> Failure Mechanism of beam type “IN 2” .....	43
<b>Figure 4.11:</b> Delamination end of CFRP sheet.....	44
<b>Figure 4.12:</b> Load Vs. deflection of beam type “IN2” .....	44
<b>Figure 4.13:</b> Failure mechanism of beam type M1 .....	45
<b>Figure 4.14:</b> Delamination of U wrap end anchors .....	45
<b>Figure 4.15:</b> Load Vs. deflection of M1 .....	46
<b>Figure 4.16:</b> M2 beam after loading.....	46
<b>Figure 4.17:</b> Large flexural cracks appeared at the middle of beam .....	46
<b>Figure 4.18:</b> Load vs. deflection of M2.....	47
<b>Figure 4.19:</b> Percentage Strength gain Vs. bond arrangement.....	49
<b>Figure 4.20:</b> Average load Vs. average mid span deflection.....	50
<b>Figure 4.21:</b> Delamination of end CFRP.....	51
<b>Figure 4.22:</b> Load Vs deflection of CF1.....	52
<b>Figure 4.23:</b> CF2 beam after loading.....	52
<b>Figure 4.24:</b> Load Vs. deflection of CF2 beam .....	53
<b>Figure 4.25:</b> CFE1 beam after loading .....	53

<b>Figure 4.26:</b> Load Vs. deflection of CFE1 .....	54
<b>Figure 4.27:</b> CFE2 Beam after loading .....	54
<b>Figure 4.28:</b> Load Vs. deflection of CFE2 beam .....	55
<b>Figure 4.29:</b> CFI1 beam after loading .....	55
<b>Figure 4.30:</b> Load Vs. deflection of CFI1 .....	56
<b>Figure 4.31:</b> CFI2 beam after loading .....	56
<b>Figure 4.32:</b> Load Vs. deflection of CFI2 beam.....	57
<b>Figure 4.33:</b> IN2 type beam with IN1 type beam.....	58
<b>Figure 4.34:</b> IN2 type beam with F type beam.....	59
<b>Figure 4.35:</b> M type beam and IN1 type beam.....	59
<b>Figure 4.36:</b> Failure loads of cracked beams before and after strengthening.....	61
<b>Figure 4.37:</b> Bending moment diagram for 4 points load test.....	61
<b>Figure 4.38:</b> Deflection vs. load graph for control beams.....	63
<b>Figure 4.39:</b> Deflection vs. load graph for strengthened pre-cracked beams.....	63
<b>Figure 4.40:</b> Maximum deflection at failure, before and after strengthening .....	64
<b>Figure 4.41:</b> Deflection vs. load graph for pre-cracked and control beams .....	64
<b>Figure 4.42:</b> Deflection vs. load graph for CFE1 .....	65
<b>Figure 4.43:</b> Deflection vs. load graph for CFE2 .....	66
<b>Figure 4.44:</b> Deflection vs. load graph for CFI1 .....	66
<b>Figure 4.45:</b> Deflection vs. load graph for CFI2 .....	67
<b>Figure 4.46:</b> Deflection of beams with 0.3mm crack propagate and ultimate failure loads.....	68
<b>Figure 4.47:</b> Crack distribution of CFRP strengthened pre-cracked beams.....	68
<b>Figure 5.1:</b> Schematic diagram of forces and dimensions of anchored CFRP - concrete beam with end U wraps.....	76

## LIST OF TABLES

<b>Table 2.1:</b> Summary of strengthening techniques . . . . .	18
<b>Table 3.1:</b> Material properties of CFRP sheets.....	25
<b>Table 3.2:</b> Material properties of epoxy grout.....	26
<b>Table 3.3:</b> Technical data of epoxy resin.....	27
<b>Table 3.4:</b> Physical parameters of epoxy resin.....	27
<b>Table 3.5:</b> Mix proportion of concrete.....	28
<b>Table 3.6:</b> Summary of non-cracked beam specimens.....	33
<b>Table 3.7:</b> CFRP arrangements in heavily cracked beams.....	35
<b>Table 4.1:</b> Results of control beams.....	38
<b>Table 4.2:</b> Summary of failure modes of beam specimens.....	48
<b>Table 4.3:</b> Percentage strength gained in non-cracked beams relative to control beams.....	49
<b>Table 4.4:</b> Summary of CFRP arrangement in heavily cracked beams.....	51
<b>Table 4.5:</b> Summary of failure modes of beam specimens.....	57
<b>Table 4.6:</b> Percentage strength gain in cracked beams relative to control beams.....	58
<b>Table 4.7:</b> Failure load of pre-cracked beams with control beams.....	62
<b>Table 5.1:</b> The summarized calculation procedure of moment capacity in accordance with ACI guidelines.....	70

## LIST OF ABBREVIATIONS

CFRP	Carbon Fiber Reinforced Polymer
EB	Externally Bonded
ETS	Embedded Through Section
FRP	Fiber Reinforced Polymer
NSM	Near Surface Mounted
As	Area of tension reinforcement
Asv	Area of links at neutral axis level
b	Effective breadth of section
b <sub>v</sub>	Breadth of section for shear
d	Effective depth of the tension reinforcement
f <sub>cu</sub>	Characteristic strength of concrete
f <sub>yv</sub>	Characteristic strength of links
f <sub>y</sub>	Characteristic strength of links
M	Design ultimate resistance moment
S <sub>v</sub>	Spacing of link along the member
v <sub>c</sub>	design shear strength of concrete

## **LIST OF APPENDIX**

Appendix	Description	Page
Appendix-1	Design calculation for the flexural failure	88
Appendix-2	Expected Theoretical Calculation	91
Appendix-3	Concrete compressive strength test results	95
Appendix-4	Comparison between experimental moment and theoretical moment	96