

**RETROFITTING OF PUNCHING SHEAR DAMAGED
FLAT SLABS USING CARBON FIBER REINFORCED
POLYMER (CFRP) SHEETS**

V.G.M. Priyanjani

168921 T

Master of Science Degree in Structural Engineering Design

Department of Civil Engineering

University of Moratuwa

Sri Lanka

January 2021

**RETROFITTING OF PUNCHING SHEAR DAMAGED
FLAT SLABS USING CARBON FIBER REINFORCED
POLYMER (CFRP) SHEETS**

V.G.M. Priyanjani

168921 T

Dissertation Submitted in partial fulfillment of the requirements for the
Master of Science Degree in Structural Engineering Design

Department of Civil Engineering

University of Moratuwa

Sri Lanka

January 2021

DECLARATION

I declare that this is my own work and this thesis 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 thesis, 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.

.....

.....

V.G.M. Priyanjani

Date

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

.....

.....

Prof. Mrs. J.C.P.H. Gamage

Date

Dissertation Supervisor

ABSTRACT

The punching shear failure of flat slabs is common in reinforced concrete buildings, and once the failure occurs, rectification is difficult and time consuming, which also affects building functionality. Hence, it is convenient to retrofit the flat slab structure to enhance the punching shear capacity while minimizing the disturbance to the structure. Therefore, a method was developed to retrofit punching shear damaged flat slabs using Carbon Fiber Reinforced Polymer (CFRP) sheets, considering the advantageous properties of the material, like the flexibility of usage, less weight, less thickness of material etc.

Thus, experimental and theoretical studies were carried out using 12 numbers punching shear failed flat slab panels with various repair materials and various CFRP sheet arrangements. The BS EN 1992-1-1: 2004 standard was used for theoretical analysis. A comparison of theoretical and experimental punching shear capacities concluded that the theoretical capacity is much higher than the experimental capacity, due to the difference of failure modes of the specimens.

ACKNOWLEDGEMENT

I would like to acknowledge the Department of Civil Engineering of University of Moratuwa, to provide me the opportunity for studying the Master of Science Degree Program in Structural Engineering Design. I would like to express my sincere appreciation to all the staff members of this M.Sc program for their encouragement and excellent guidance to complete my M.Sc degree in successful manner.

I am very grateful to my supervisors Prof. Mrs. J.C.P.H.Gamage of University of Moratuwa, who offered me the valuable opportunity to carry out and complete this research work and all the staff members of Department of Civil Engineering – University of Moratuwa, who gave me the fullest support to compete the work. Also, I would like to be thankful to Mrs. M.A.L. Silva for providing the cracked samples required for the experimental analysis and giving the fullest support.

Furthermore I like to express my sincere thanks and appreciation to Eng U.S. Karunaratne, the chairman of the Central Engineering Consultancy Bureau (CECB) for granting permission to carry out my Master of Engineering Degree Program and also the senior engineers of CECB who helped by sharing their knowledge and experiences.

Also, I offer my gratitude to my family members for the dedication of them for me and encouraging me to success my M.Sc degree.

Finally, I would like to extend my grateful thanks and appreciation to all who supported time to time, to achieve my goals.

TABLE OF CONTENTS

Declaration.....	i
Abstract.....	ii
Acknowledgements.....	iii
Table of Content.....	iv
List of Figures.....	vi
List of Tables.....	viii
CHAPTER 1 - INTRODUCTION	
1.1. Background.....	1
1.2. Significance of Research	2
1.3. Aim of Research	2
1.4. Objectives of Research	2
1.5. Methodology.....	3
CHAPTER 2 - LITERATURE REVIEW	
2.1. Introduction	4
2.1.1. Punching Shear of Flat Slabs	4
2.1.2. Enhancing the Punching Shear Capacity of Flat Slabs	6
2.1.3. Usage of Fiber Reinforced Polymer	7
2.1.4. Carbon Fiber Reinforced Polymer (CFRP).....	8
2.2. Punching shear behaviour of flat slabs reinforced with FRP bars.....	11
2.3. Retrofitting Flat Slabs for Punching Shear with Externally Bonded FRP Composite.....	15
2.4. Punching Shear Strengthening of Flat Slabs with FRP Dowels.....	22
2.5. Summary and Research Gaps	30
CHAPTER 3 - EXPERIMENTAL PROGRAMME	
3.1. Overview	32
3.2. Summary of Specimens	33
3.3. Material Properties	37

3.4. Methodology.....	40
3.4.1. Repairing of Cracked Specimens	40
3.4.2. Strengthening of Repaired Specimens.....	42
3.4.3. Testing	45
3.5. Test Results	46
3.5.1. Results of Specimens Repaired with Cementitious Materials.....	46
3.5.2. Test Results of Retrofitted specimens	47
3.5.3. Crack Pattern of Specimens	49
 CHAPTER 4 - THEORETICAL ANALYSIS	
4.1. Overview	52
4.2. Procedure	52
4.3. Theoretical Load Capacity – Control Sample	53
4.4. Theoretical Load Capacity – Strengthened Sample	55
 CHAPTER 5 - CONCLUSIONS AND RECOMMENDATIONS	
5.1. Summery.....	59
5.2. Discussion of Results	59
5.3. Conclusions	64
5.4. Recommendations	65
ANNEX A	ix
ANNEX B	xiv

LIST OF FIGURES

Figure 2.1. Crack Pattern in Punching Shear Failure (Osama et al., 2017).....	5
Figure 2.2. Reinforcement Arrangement (Kai et al., 2013).....	16
Figure 2.3. Configuration of Strengthening of Specimens (Kai et al., 2013).....	17
Figure 2.4. Reinforcement Detail (Silva et al., 2019)	18
Figure 2.5. Specimen Strengthening Detail (Silva et al., 2019)	19
Figure 2.6. Reinforcement Detail (Khalend et al., 2012)	21
Figure 2.7. Specimen Detail (Khalend et al., 2012)	22
Figure 2.8. Specimen Reinforcement Details	24
Figure 2.9. (a) CFRP Configuration of Type SA (b) CFRP Configuration of Type SB	24
Figure 2.10. Specimen Detail (Aghayari et al., 2015)	26
Figure 2.11. Configuration of CFRP Test Specimens (Aghayari et al., 2015)	27
Figure 2.12. Strengthening Arrangement of Slab Specimens.....	28
Figure 2.13. CFRP and GFRP stirrups Arrangement (Spacing between stirrups = 40mm)	29
Figure 2.14. Testing arrangement	30
Figure 3. 1. Details of a Specimen	32
Figure 3. 2. Details of Cracked Specimens.....	36
Figure 3. 3. Re-bound Hammer Testing	37
Figure 3. 4. Demolishing Concrete in the Cracked Area	40
Figure 3. 5. Preparation of Specimens without Epoxy Bond.....	41
Figure 3. 6. Preparation of Specimens with Epoxy Bond.....	42
Figure 3. 7. CFRP Strip Arrangements for Strengthening the Slab Panels	43
Figure 3. 8. Control Specimen	44
Figure 3. 9. Specimen with Arrangement A1	44
Figure 3. 10. Specimen with Arrangement A2	44
Figure 3.13. Testing Arrangement of Specimens	45
Figure 3. 11. Specimen with Arrangement A5	45
Figure 3. 12. Specimen with Arrangement A4	45
Figure 3.14. Dial Gauge Arrangement	46
Figure 3.15. Load – Deflection Curves of Repaired specimens – deflection is measured at ‘d’ from Column Face.	47

Figure 3.16. Load–Deflection Curve of Strengthened Specimens – deflection is measured at ‘d’ from Column Face	48
Figure 3.17. Crack Pattern of Control Specimen	49
Figure 3.18. Crack Pattern of Specimen A1	50
Figure 3.19. Crack Pattern of Specimen A2	50
Figure 3.20. Crack Pattern of Specimen A3	51
Figure 3.21. Crack Pattern of Specimen A4	51
Figure 4.1. Reinforcement Details of Specimens	53

LIST OF TABLES

Table 2.1. Constituent Material Properties of Carbon Fiber Material (ACI 440.2R-08)	9
Table 2.2. Typical Properties of Fibers (Used in FRP Systems) (ACI 440.2R-08)....	9
Table 2.3. Properties of FRP Bars (Fiber Volumes of 50 to 70%) (ACI 440.2R-08)..	9
Table 2.4. Properties of FRP Laminates (Fiber Volumes of 40 to 60%)(ACI 440.2R-08)	10
Table 2.5. Ultimate Tensile Strength Properties of Commercially Available FRP Systems (ACI 440.2R-08)	10
Table 2.6. Extract of Comparison of Results (Osama et al., 2017).....	12
Table 2.7. Specimen Detail (Jacobson et al., 2005)	14
Table 2.8. External Strengthening Arrangements with CFRP strips (Silva et al., 2019)	18
Table 2.9. Test results of Specimens (Silva et al., 2019)	20
Table 2.10. Comparison of Experimental Results and Finite Element Modeling Results (Silva et al., 2019).....	20
Table 2.11. Details of Specimen (Carlos et al., 2015).....	23
Table 2.12. Details of Specimen (Erdogan et al., 2007).....	25
Table 3.1. Properties of Cementitious Polymer Modified Concrete Repair Mortar Used for Repairing of Specimens	38
Table 3.2. Properties of Epoxy Bonding Agent Used for Repairing of Specimens..	38
Table 3.3. Properties of CFRP Sheets	39
Table 3.4. Properties of Lamination Adhesive.....	39
Table 3.5. Specimen Details	41
Table 3.6. Failure loads of repaired specimens.....	47
Table 3.7. Failure Loads for Strengthened Specimens	49
Table 4.1. Load Capacity of Strengthened Specimens	58
Table 5.1. Summary of Experimental Results of Strengthened Specimens with CFRP	60
Table 5.2. Deviation of Results from Target Load Capacity	62
Table 5.3. Comparison of Experimental and Theoretical Punching Shear Capacity	63