DEVELOPMENT AND VALIDATION OF A NOVEL CFRP/STEEL HYBRID CRACK REPAIRING TECHNIQUE FOR THE STEEL STRUCTURES

Sampath Abeygunasekara

(138052C)

Degree of Doctor of Philosophy in Civil Engineering

Department of Civil Engineering

University of Moratuwa
Sri Lanka

March 2023

DEVELOPMENT AND VALIDATION OF A NOVEL CFRP/STEEL HYBRID CRACK REPAIRING TECHNIQUE FOR THE STEEL STRUCTURES

Sampath Abeygunasekara

(138052C)

Thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Civil Engineering

Department of Civil Engineering

University of Moratuwa
Sri Lanka

March 2023

DECLARATION

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

Also, I hereby grant 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 work (such as articles or books).

UOM Verified Signature

Signature: Date: 01.03.2023

The above candidate has carried out research for the Doctor of Philosophy dissertation under my supervision.

Name of the supervisors: Prof. J.C.P.H. Gamage

Dr.S.Fawzia

Signature of the supervisor: *UOM Verified Signature* Date: 01.03.2023

Signature of the supervisor: *UOM Verified Signature* Date: 4/3/2023

ABSTRACT

Steel structures such as steel bridges greatly contribute to the socio economic development of the world. The current traffic demand has exhausted the service life of steel bridges paving the way for failures without prior warning due to fatigue. In fact, fatigue contributes to change the microstructure of a material which fails below the yield point. Therefore, fatigue could be considered as an issue related to materials, even though it is linked to the area of engineering. Interestingly, several unavoidable stress types on structures occur on steel bridges due to various reasons. As a result, avoiding fatigue on structures has become impossible during their service life. The result of stress fluctuation has caused crack initiation on steel structures while the initial stage is at a micro scale level and not visible to the naked eye. Thus, it should be controlled at the initial stage avoiding adverse effects later. Although the conventional crack repair techniques have extended service lives of structures they have led to numerous drawbacks too.

The crack stop hole technique could be considered as an emergency repairing technique to extend the fatigue life of a cracked steel structures that is quick, simple and economic. This technique was successfully applied in the aerospace industry primarily, however there had been irregularities due to the size of the hole with re-cracking appearing due to continuous service loads. Carbon fiber reinforce polymer (CFRP) materials have become popular as it has potential to replace the conventional repairing techniques with recent research focused on CFRP materials due to its light weight, corrosion resistivity, damping characteristics, fatigue resistivity and high tensile features. Therefore, this study proposes a crack stop hole (CSH) technique combined with a CFRP strengthening method to acquire the lost capacity due to fatigue in old structures with delaying re-cracking by further continue their services by steel bridges in the road and railway network operate at present.

An experimental test program carried out to determine the behavior of strengthened and non-strengthened CSH in steel members subjected to low cycle flexural fatigue. Overall, the test program was focused on estimating yield strength losses and yield strength gained by CFRP. Interestingly, various types of fatigue testing apparatus are available in the open market for a relatively high cost which is not affordable in a university laboratory, thus a hydro-electric controlling fatigue loading apparatus was designed and fabricated as an initiation to this research study to fulfill this vacuum. In this development process, machine operation, and development technique with finite element analysis on the test frame was investigated.

In the next phase of this research, a numerical model was developed using an advanced finite element model (FEM) and results were validated using the laboratory test results. The proposed numerical model was based on the cyclic J-integral method under the detect cyclic mode. The test results agreed with the model results consisting nine key parameters affecting the final results. This CFRP strengthened CSH technique is significantly enhanced fatigue life of the structural members. This investigation reported the yield strength losses; which are in the range of 13.4 % to 25.2 % compared to the non-conditioned and yield strength gains with CFRP; which is in the range of 32.2 % to 45.3 % compared to the non-strengthened CSH with the diameter varies from 4 mm to 25 mm. A considerable amount of strain controlled were recorded by CFRP with respect to non-strengthened CSH. When considering the critical parameter effects, the test results recorded a yield strength gain with respect to off-set distance; which was in the range of 36 % to 131 % compared to the CSH at the midpoint. The yield strength variation recorded due to the length of CFRP layer was in the range of 89 % to 223 % compared to the least length considered. This investigation recommended by CFRP strengthened technique has significantly enhanced fatigue bearing capacity of structural members with CSH. Design guidelines are developed for practical implementations.

Key words: steel members, CSH, CFRP, cyclic flexural load, Low cycle fatigue, FEM, cyclic J-integral

ACKNOWLEDGEMENTS

This research paved the way to gain valuable experience on how to apply theoretical knowledge to produce important findings for the well-being and development of the community. Therefore, my gratitude should be conveyed to a number of academics and non-academics of the university of Moratuwa for assisting me to successfully complete this research investigation and dissertation.

First, I wish to express my sincere gratitude to my principal supervisor Dr. J.C.P.H. Gamage, Professor in Civil Engineering, Department of Civil Engineering, University of Moratuwa for her supervision, enthusiastic guidance and continual encouragement throughout the course of my candidature. I am indebted to her understanding, tolerance and precious support. I am very grateful to have a supervisor that believe in my work and always provide me with guidance and valuable suggestions towards completing this thesis. Without her support and guidance none of this would be possible. Furthermore, I highly appreciate the assistance of my associate supervisor Dr. S. Fawzia, Senior lecturer in School of Urban development, Queensland University of technology, Australia, for actively coaching me with her sound knowledge for the experimental work. Her expert technical suggestions and practical assistance were indispensable in improving the quality of this research work. I would like to thank the chairperson of the progress review panel, Prof. Thishan Jayasinghe, Senior Professor and Dr. Sujeewa Lewangama, Senior Lecturer and Prof. Ashoka Perera in the Department of Civil Engineering, University of Moratuwa, guiding me with valuable instructions to progress my research as progress review panel members.

The financial burden on pursuing a PhD program was eased by the department of Civil Engineering by waiving off the course fee.

I gratefully acknowledge the support of the staff in the Mechanical workshop, the Department of Mechanical Engineering at the University of Moratuwa for their valuable support. I would also like to express my gratitude to all non-academic staff members in the department and Mr. D.M.N.L. Dissanayaka, technical officer in the Structural Testing Laboratory, Mr. Yohan technical officer in the Computational

Mechanics Laboratory, Mr. Charaka Satharasinghe, technical officer in the Computer Laboratory for their valuable support extended throughout my research period.

Moreover, I would like to thank Airow Solution (PVT) Ltd and research assistants Mr. Vimukthi, Miss Varakini, Miss. Aruga, Miss Tharika and Miss. Chamodi for their kind support throughout this period. Finally, I wish to acknowledge my wife Thanuja and my daughter Sanjalee, for their love, emotional support and encouragement.

Sampath Abeygunasekara
Department of Civil Engineering
University of Moratuwa
15.02.2023

LIST OF PUBLICATIONS AND AWARDS

International Conferences

1. Abeygunasekara.S, Gamage.J.C.P.H, & Fawzia.S. (2021a). Influence of surface preparation on CFRP/Steel bond performance. In *Proceedings of the 12th International Conference on Structural Engineering and Construction Management 2021(ICSECM-2021).* Earl's Regency Hotel, Kandy, Sri Lanka, December17–19.

2. Abeygunasekara.S, Gamage.J.C.P.H, & Fawzia.S. (2021b). Theoretical model for predicting re-cracking behavior of crack stop holes using J-integral technique. In *Proceedings of the 12th International Conference on Structural Engineering and Construction Management 2021(ICSECM-2021).* Earl's Regency Hotel, Kandy, Sri Lanka, December17–19.

3. Abeygunasekara.S, Gamage.J.C.P.H, & Fawzia.S. (2020a). Design and demonstration of a low cost small scale flextural cyclic load testing apparatus for composite materials. In *Proceedings of the the International Conference on Architecture and Civil Engineering,* Kuala Lumpur, Malasiya.

4. Abeygunasekara.S, Gamage.J.C.P.H, & Fawzia.S. (2020b). State-of-the-art review influences of envirenmental factors in CFRP steel bonding. In *Proceedings of the 11th International Conference on Sustainable Built Environment (ICSBE),* Kandy, Sri Lanka,10th – 12th December.

5. Abeygunasekera, S., Gamage, J. C. P. H., & Fawzia, S. (2019). Low cycle fatigue behaviouir of steel/CFRP composite exposed to loads with constant amplitude. In *Proceedings of the International Conference on Civil Engineering and Applications 2019.*University of Moratuwa.

6. Abeygunasekera, S., Gamage, J. C. P. H., & Fawzia, S. (2017). Effects of environmental humidity at installation phase on performance of CFRP strengthen steel I-beam. In *Proceedings of the 8th International Conference on Structural Engineering and Construction Management 2017* (pp. 18-22). *Earl's Regency Hotel, Kandy, Sri Lanka, December 13th –15th.*

7. Abeygunasekera, S., Gamage, J. C. P. H., & Fawzia, S. (2013). Bond performance of CFRP strengthened steel members subjected to axial compression. In *Proceedings of the 4th International Conference on Structural Engineering and Construction Management 2013* (pp. 161-166). Nethwin Printers (Pvt) Ltd.

Indexed journal publications

1. Abeygunasekara, S., Gamage, J.C.P.H. Fawzia. S (2018) ‘Numerical Modelling of Re-cracking Behaviour in Retrofitted Crack Stop Holes in Steel Structures, *Lecture Notes in Civil Engineering*, Volume 94. pp. 9. DOI 978-981-13-9749-3_42, © 2020

2. Abeygunasekara.S, Gamage.J.C.P.H, & Fawzia.S. (2022). Investigating the Effects of Offset Distance in CSH on Steel Plates Under Three-Point Flexural Cyclic Loads in the LCF Range. In *Lecture Notes in Civil Engineering 174* (pp. 331–345).

Journal papers (under review)

1. A novel hybrid repairing technique to delay fracture initiation and propagation of steel structures subjected to low cyclic flexural fatigue

Awards

1. Best student presentation awarded to Design and demonstration of a low cost small scale flextural cyclic load testing apparatus for composite materials at the International Conference on Architecture and Civil Engineering, Kuala Lumpur, Malasiya, March 12^{th} -13^{th}.

TABLE OF CONTENTS

DECLARATION i
ABSTRACT ii
ACKNOWLEDGEMENTS iii
LIST OF PUBLICATIONS AND AWARDS v
TABLE OF CONTENTS vii
LIST OF FIGURES xvi
LIST OF TABLES xxiv
LIST OF ABBREVIATIONS xxvii
LIST OF SYMBOLS AND NOTATIONS xxviii
LIST OF APPENDICES xxix

1. INTRODUCTION 1
1.1 Significance of the study 3
1.2 Research background 3
1.3 Problem identification and the research gap 4
1.4 Objectives 4
1.4.1 Primary objectives 5
1.4.2 Secondary objectives 5
1.5 Methodology 5
1.6 Outline of the Thesis 6

2. LITERATURE REVIEW 9
2.1 Introduction 10
2.1.1 Historical development of fatigue investigations 10
2.2 Fatigue failure 11
2.2.1 Sequence of fatigue failure 11
2.2.2 The microscopic explanation of fatigue failure .... .12
2.2.3 Material behavior with fatigue loads .... .13
2.2.4 Characteristics of fatigue .... .14

2.3 Classification of fatigue 15
2.3.1 Low cycle fatigue and high cycle fatigue 16
2.4 Prediction of fatigue life 18
2.4.1 Classification of fatigue life prediction techniques 20
2.4.2 Minor rules 21
2.4.3 Rain flow counting algorithm 22
2.5 CSH method as a repairing technique 23
2.5.1 Arrest the crack 25
2.5.2 Crack stop hole methods for crack control 27
2.5.3 Crack detection and placement of CSH 28
2.6 Mechanical treatments for CSH subjected to fatigue 29
2.6.1 The bottled CSH 29
2.6.2 The pinned CSH 30
2.6.3 The cold expanded CSH 31
2.6.4 Ancillary holes in added CSH 32
2.6.5 Comparison of different methods utilized in CSH strengthening 33
2.7 CFRP Material as a crack repairing technique 34
2.7.1 Modules of CFRP material 37
2.7.2 Flexural strength 39
2.7.3 Shear strength 39
2.8 Effects of the geometrical dimension of CRFP material 39
2.8.1 Effect of CFRP bond length 40
2.8.2 Multiple layer of CFRP material 40
2.8.3 Thickness of CFRP layer effects 40
2.9 Surface preparation 40
2.9.1 Surface preparation techniques 42
2.9.2 Steps of surface preparation 43
2.10. Adhesives and adhesive properties 44
2.10.1 Stress concentration of adhesives 45
2.10.2 Stiffness effect of adhesives 45
2.11 Effects of environmental exposure on CFRP/steel bond performance 46

2.11.1 Effects of environment moisture level on CFRP/Steel bond performance 46
2.11.2 Cyclic temperature effects on CFRP/Steel bond performance 47
2.11.3 Ultraviolet (UV) radiation effects on Steel/CFRP bond performance 49
2.11.4 Combined effects of environmental factors on Steel/CFRP bond performance 49
2.12 Different types of testing method for Steel/CFRP bond performance 51
2.12.1 Tensile load effects related investigations 51
2.12.2 Compression load effects related investigations 51
2.12.3 Combined effects of bending and compression loads 51
2.12.4 Impact load related investigations 51
2.12.5 Fatigue load related investigations 52
2.13 Testing standards 54
2.14 Behavior of fatigue 55
2.14.1 Pre-stressed and non- pre-stressed behavior of Steel/CFRP bond under fatigue load 57
2.14.2 Failure mechanism of Steel/CFRP bond under fatigue 57
2.14.3 Co-relation between geometry specimen's and fatigue 58
2.15 Field applications of CFRP strengthened material 59
2.15.1 Rectangular Hollow Section (RHS) 59
2.15.2 Circular hollow section (CHS) 60
2.15.3 Bridge repair related applications 61
2.16 Theory of material hardening 62
2.16.1 Kinematic hardening 63
2.16.2 Isotropic hardening 64
2.17 Fatigue related parameter effects on structural element 64
2.17.1 Stress intensity factor 65
2.17.2 Stress concentration 65
2.17.3 Crack tip opening displacement (CTOD) 65
2.17.4 Rate of energy release (G) 66
2.17.5 Crack growth direction 66

2.18 Summary of literature review 66

3. DESIGNING AND FABRICATING A FATIGUE LOADING APPARATUS 71

3.1 Introduction of design and fabricated fatigue loading apparatus 71

3.1.1 History of fatigue test apparatus 71

3.1.2 Types of fatigue loading 72

3.2 Classification of existing fatigue loading apparatus..................................... 73

3.2.1 Rotating bending type fatigue testing apparatus 74

3.2.2 Constant deflection amplitude cantilever bending type fatigue testing apparatus.. 75

3.2.3 Axial loading fatigue testing apparatus... 76

3.2.4 Other types of fatigue testing apparatus.. 77

3.2.5 The modern fatigue testing machine... 78

3.3 Design and detailing of fatigue loading apparatus 79

3.3.1 Considering factors for design fatigue loading apparatus.................. 80

3.3.2 Essential components of any fatigue loading apparatus 80

3.4 Designing steps of fatigue loading apparatus.. 80

3.4.1 Designing a loading frame 81

3.4.2 Loads on the loading frame.. 82

3.4.3 The machining process and assembling of testing apparatus 82

3.4.4 Selection of load applying mechanism 83

3.4.5 Designing the hydraulic circuit of fatigue loading apparatus 84

3.4.6 The controlling system of loading apparatus 88

3.5 The test setup and instrumentation of loading apparatus............................ 89

3.5.1 Measuring procedure of test apparatus 89

3.5.2 Calibration of load 90

3.5.3 Calibration of loading frequency 91

3.6 Features and benefits of the fatigue loading apparatus............................... 92

3.6.1 Cost estimation of fatigue loading apparatus.................................... 93

3.6.2 Limitations and operating range of fatigue loading apparatus........... 94

3.6.3 Safety aspects of fatigue loading apparatus 94

3.6.4 Environmental impact assessment of the fatigue loading apparatus.. 95
3.6.5 The maintenance procedure 95
3.6.6 Modification for variable loads.. 96
3.7 Summary of design and fabricated fatigue loading apparatus 97

4 EXPERIMENTAL INVESTIGATIONS 99
4.1 Introduction of experimental investigation relating with CSH/CFRP hybrid system.. 99
4.2 Material selection and specimen preparation 100
4.2.1 Selection of steel 100
4.2.2 Selection of the adhesive material 101
4.2.3 Selection of CFRP material 103
4.2.4 Procedure of CFRP installation with steel 103
4.2.5 Material properties 105
4.3 Test program.. 105
4.3.1 Test setup and instrumentation 107
4.3.2 Cyclic flexural loading setup for applying fatigue load on specimen 107
4.3.3 Tensile test setup for measuring the retained average strength on specimens 108
4.4 Behavior of steel element with respect to loading cycles........................... 108
4.4.1 Behavior of non-strengthened steel element without CSH under fatigue load... 109
4.4.2 Behavior of non-strengthened steel element with CSH under fatigue load... 111
4.4.3 Behavior of CFRP-strengthened steel element without CSH under fatigue load... 113
4.4.4 Behavior of CFRP-strengthened steel element with CSH under fatigue load... 116
4.4.5 Comparison of fatigue behavior with respect to load cycles 118
4.5 Effects of CSH diameter on LCF 121

4.5.1 Behavior of non-strengthened steel element with CSH under non conditioned 121
4.5.2 Behavior of CFRP-strengthened steel element with CSH under a non-conditioned situation 123
4.5.3 Behavior of non-strengthened steel element with CSH under fatigue load 125
4.5.4 Behavior of CFRP strengthened steel element with CSH under fatigue load 127
4.5.5 Comparison of strength variation of non-strengthened and CFRP strengthened CSH 129
4.5.6 Strain variation of non-strengthened steel element with CSH under fatigue load 131
4.5.7 The Strain variation of CFRP strengthened CSH under fatigue load 132
4.5.8 Comparison of strain behavior of non-strengthened and CFRP strengthened CSH 133
4.6 Effects due to distance from mid-point to CSH 136
4.6.1 Fatigue behavior of non-strengthened CSH with respect to distance from the mid - point 137
4.6.2 Fatigue behavior of CFRP-strengthened CSH with respect to distance from the mid-point 139
4.6.3 Comparison of fatigue behavior of CSH with respect to distance ... 141
4.6.4 Strain variation of non-strengthened CSH with respect to offset distance 143
4.6.5 Strain variation of CFRP strengthened CSH with respect to offset distance 147
4.6.6 Comparison of strain behavior of non-strengthened and CFRP strengthened CSH 150
4.7 Fatigue behavior of CFRP strengthened steel element with respect to bond length 152
4.7.1 Fatigue behavior of CFRP strengthened CSH with respect to bond length 152

4.7.2 Fatigue behavior of CFRP strengthened steel plate with respect to bond length 154
4.7.3 Comparison of CFRP length effects 157
4.8 Bond stress variation 159
4.9 Summary of experimental investigation related to the CSH/CFRP hybrid system 160

5 FINITE ELEMENT MODELLING OF FATIGUE BEHAVIOR OF CSH SUBJECTED TO CYCLIC FLEXURAL LOADING 162
5.1 Introduction of finite element modelling related to CSH/CFRP hybrid system 162
5.1.1 Background of FEM 163
5.1.2 Procedure of simulation 163
5.2 Detailed steps of simulation 165
5.2.1 Geometry of the crack model 165
5.2.2 Material properties 166
5.2.3 Assembling of geometrical components 167
5.2.4 Configuration of the FEM 168
5.2.5 Mechanical interaction between contact surfaces 168
5.2.6 Loads and boundary conditions 169
5.2.7 Meshing of the model and mesh sensitivity analysis 169
5.2.8 Analysis and model results 173
5.3 Validation of the model 174
5.3.1 Non-strengthened and CFRP strengthened CSH 176
5.3.2 FEM results compared with experimental results for non-strengthened and CFRP strengthened CSH 179
5.3.3 FEM results compared with experimental results for position change of non-strengthened and CFRP strengthened CSH (Stress based) .. 182
5.4 Summary of finite element modelling related with CSH/CFRP hybrid system 184

6. THEORETICAL APPROACH FOR EVALUATE RE- CRACKING BEHAVIOR OF CSH 186
6.1 Theoretical background of the CSH technique 186
6.2 Theory of fracture mechanics 187
6.2.1 Linear elastic fracture mechanics (LEFM) 187
6.2.2 Elastic-plastic fracture mechanics (EPFM) 188
6.2.3 The fatigue mechanism.. 189
6.3 Theoretical model to predict crack growth 191
6.3.1 Total fatigue life 191
6.3.2 The Paris law 192
6.3.3 The Power law 194
6.3.4 Comparison of Paris law and Power law 195
6.3.5 Developing a theoretical model to predict the rate of the crack growth 195
6.4 Factors that affect re-cracking of the CSH 200
6.4.1 Effects of the CSH diameter 200
6.4.2 Effects of member thickness 201
6.4.3 Effects of the crack length 202
6.4.4 Position of the CSH 203
6.4.5 Amplitude of the load 204
6.4.6 Loading frequency 205
6.4.7 Stress ratio effects 206
6.4.8 Effects of fiber direction of the CFRP 207
6.4.9 Effects of the CFRP length. 208
6.5 Summary of the theoretical model relating with the CSH 209

7 PARAMETRIC STUDY 211
7.1 Introduction of parametric study... 211
7.2 Fatigue performance of CSH varying with geometry related parameters .. 211
7.2.1 Member thickness 211
7.2.2 Crack length 214
7.3 Load related parameters 216

7.3.1 Amplitude of load 217
7.3.2 Loading frequency 219
7.3.3 The stress ratio 221
7.4 Fatigue behavior of CSH varying with Polymer material related parameters 224
7.4.1 Fiber direction angle of the CFRP 224
7.5 Summary of the parametric study relating to CSH/CFRP hybrid system . 226

8 DISCUSSION AND CONCLUSIONS 228
8.1 Conclusions 228
8.2 Contributions 230
8.3 Future research works 231
8.4 Engineering implications 232

REFERENCES 234
Appendix – A 254
Appendix – B 262

LIST OF FIGURES

Page

Figure 2 1: Main steps of fatigue 12

Figure 2 2: Crack growth with number of cycles 13

Figure 2 3: HCF to LCF transition 13

Figure 2 4: Fatigue bearing capacity variation with number of cycles 16

Figure 2 5: Various aspects of fatigue life prediction of steel structures 19

Figure 2 6: Methods of fatigue life evaluation 20

Figure 2 7: Stress variations with time linked to variable amplitude loads 21

Figure 2 8: Stress variation with number of cycles 21

Figure 2 9: Rain-flow counting methods related to (a) Pagoda roof (b) stress history 23

Figure 2 10: CSH placed at the crack tip (a) schematic view of crack stop hole (b) re-cracking of crack stop hole 25

Figure 2 11: Bolted crack stop hole 30

Figure 2 12: Pinned crack stop hole 31

Figure 2 13: Cold expanded CSH 32

Figure 2 14: Schematic diagram of the ancillary holes added CSH 33

Figure 2 15: Elephant's foot buckling failure of hollow sections 61

Figure 2 16: Uni-axial stress-strain curve 63

Figure 2 17: Kinematic hardening curve 63

Figure 2 18: Isotropic hardening behavior 64

Figure 3 1: The picture of first fatigue testing machine 72

Figure 3 2: Rotating Bending Testing Machine 75

Figure 3 3: Cantilever bending testing machine 76

Figure 3 4: Axial loading fatigue testing machine 77

Figure 3 5: Conventional fatigue testing apparatus (a) rotating cantilever bending fatigue testing apparatus (b) rotating bending fatigue testing apparatus 78

Figure 3 6: Modern fatigue testing machines 78

Figure 3 7: The layout of developed fatigue test apparatus 79

Figure 3 8: Different types of energy conversion in each step. 80

Figure 3 9: Finite element mesh and stress concentration of loading frame (a) before FEA (b) After FEA 82
Figure 3 10: Cyclic flexural test apparatus and loading frame 83
Figure 3.11: Cyclic flexural load circuit (a) simulation circuit (b) actual hydraulic circuit 87
Figure 3 12: Schematic diagram of spring return single acting cylinder 88
Figure 3 13: ARDUINO UNO, open-source electronics circuit used for fatigue test controller (a) development board (b) circuit 89
Figure 3 14: Calibration of test apparatus (a)Load measured using load cell (b) Magnifying CSH (c) A data logger with digital display 91
Figure 3 15: Complete test setup 92
Figure 4 1: Test specimen 101
Figure 4 2: Specimen preparation for testing (a) Bare steel plate (b) Grinded steel surface (c) Primer coated steel surface 101
Figure 4 3: Two part epoxy adhesive (a) before mixing (b) after mixing with hardner 102
Figure 4 4: Normal module of CFRP material 103
Figure 4 5: CFRP strengthened specimen schematic view 106
Figure 4 6: Typical test specimen 106
Figure 4 7: Cyclic flexural test setup for conditioning (a) loading frame (b) specimen fixture 107
Figure 4 8: Tensile test setup (a) schematic test layout (scale 1:4) (b) typical test fixture. 108
Figure 4 9: Schematic diagram (a) elevation (b) Plane view (c) typical specimens of non-strengthened plates without CSH 109
Figure 4 10: Variation of retained yield strength with exposure cycles for non-strengthened plate specimen 110
Figure 4 11: Failure mode of plane specimens non-strengthened plates without CSH 111
Figure 4 12: Schematic diagram (a) elevation (b) plane view (c) typical specimens of non-strengthened plates with CSH 112

Figure 4 13: Variation of retained yield strength with exposure cycles for non-strengthened plate specimen with CSH 113
Figure 4 14: Failure mode of plane specimens non-strengthened plates with CSH 113
Figure 4 15: Schematic diagram (a) elevation (b) Plane view (c) typical specimens of CFRP strengthened plates without CSH.................... 114
Figure 4 16: Variation of retained average strength with exposure cycles for CFRP-strengthened plane specimen... 115
Figure 4 17: Failure mode of CFRP strengthened plane specimens without CSH 116
Figure 4 18: Schematic diagram (a) elevation (b) Plane view (c) typical specimens of CFRP strengthened plates with CSH......................... 117
Figure 4 19: Average strength variation with number of cycles for CFRP-strengthened steel element with CSH... 118
Figure 4 20: Failure mode of CFRP-strengthened steel element with CSH 118
Figure 4 21: Variation of retained average strength with exposure cycles........... 119
Figure 4 22: Percentage of strength gain by CFRP with respect to loading cycles (a) without CSH (b) with CSH…………………………………120
Figure 4 23: Schematic view of the non-conditioned and non-strengthened specimen (Scale 1:2) (a) elevation (b) plane view (c) typical specimen 121
Figure 4 24: Retained average yield stress variation with diameter to width ratio 122
Figure 4 25: Failure mode of non-conditioned non-strengthened CSH 123
Figure 4 26: Schematic view of the non-conditioned CFRP-strengthened specimen (Scale 1:2) (a) elevation (b) plane view (c) typical specimen 123
Figure 4 27: Retained average strength variation with number of cycles for CFRP - strengthened steel element with CSH............................... 124
Figure 4 28: Failure mode of non-conditioned CFRP-strengthened specimen(a) bottom surface (b) top surface 125

Figure 4 29: Schematic view of the conditioning steel element with non-strengthened CSH specimen (scale 1:2) (a) elevation (b) plane view (c) typical test specimen 125
Figure 4 30: Retained average strength variations with the diameter to width ratio of conditioned non strengthened CSH 126
Figure 4 31: Failure mode of conditioned non strengthened steel element with CSH 127
Figure 4 32: Schematic diagram of the conditioning steel element with CFRP strengthened CSH (a) elevation (b) plane view (c) typical test specimen 127
Figure 4 33: Retained average strength variation of CFRP strengthened conditioned CSH with respect to diameter to width ratio 128
Figure 4 34: Failure mode of conditioned CFRP strengthened CSH 129
Figure 4 35: Comparison of strength gains for non-strengthened and CFRP strengthened CSH 130
Figure 4 36: Average strength with respect to diameter to width ratio (a) losses due to fatigue (b) gain by CFRP…………………………….131
Figure 4 37: Schematic view of the non-strengthened strain gauge attached CSH specimen (a) elevation (b) plane view (c) typical test specimen 132
Figure 4 38: Schematic view of the CFRP strengthened strain gauge attached CSH specimen (a) elevation (b) plane view (c) typical specimen 133
Figure 4 39: Strain variations with number of flexural cycles when d/b is ;(a) 0.1 (b) 0.2 (c) 0.3 (d) 0.4 (e) 0.5 (f) 0.6 135
Figure 4 40: Schematic view of the non-strengthened offset CSH specimen (a) elevation (b) plane view (c) typical test specimen 137
Figure 4 41: Variation of retained average strength with offset distance for strengthened samples 138
Figure 4 42: Failure mechanisms with offset distance for non-strengthened samples... 139

Figure 4 43: Schematic view of the CFRP strengthened offset CSH specimen (a) elevation (b) plane view (c) typical test specimen 140
Figure 4 44: The average strength variation with the location of the CSH 141
Figure 4 45: Failure mode of CFRP strengthened offset CSH 141
Figure 4 46: Variation of retained average strength gain with offset distance for non-strengthened and CFRP strengthened samples 142
Figure 4 47: Percentage strength gain by CFRP strengthened with respect to CSH position 143
Figure 4 48: Schematic view of the non-strengthened strain gauge attached offset CSH specimen (a) elevation (b) plane view 144
Figure 4 49: Typical specimen of non-strengthened strain gauge attached offset CSH 144
Figure 4 50: Strain variations with offset distance of non-strengthened CSH when x is; (a)20 mm (b) 40 mm (c) 60 mm (d) 80 mm (e) 100 mm 146
Figure 4 51: Schematic view of CFRP-strengthened strain gauge attached offset CSH 147
Figure 4 52: Strain variations with offset distance of CFRP-strengthened CSH when x is; (a) 20 mm (b) 40 mm (c) 60 mm (d) 80 mm (e) 100 mm 149
Figure 4 53: Comparison of strain variations with offset distance for non-strengthened and CFRP strengthened CSH when x is; (a) 20 mm (b) 40 mm (c) 60 mm (d) 80 mm (e) 100 mm.................................. 151
Figure 4 54: Schematic view of the CFRP strengthen specimen (a) elevation (b) Plane view (c) typical specimen 153
Figure 4 55: Retained average strength variation in the length of CFRP layer 154
Figure 4 56: Failure mode of CSH due to bond length variation 154
Figure 4 57: Schematic view of the CFRP strengthen specimen (a) elevation (b) plane view (c) typical specimen 155
Figure 4 58: Retained average strength varies with the length of CFRP 156
Figure 4 59: Failure mode of steel member without CSH variation with bond length.. 157

Figure 4 60: Comparison of strength variation by CFRP bond length 158
Figure 4 61: Bond stress variation with respect to (a) number of cycles (b) diameter to width ratio (c) bond length..159
Figure 5 1: A model view of the specimen after introducing contours and crack seems 165
Figure 5 2: The assembly module of the test setup (a) front view (b) plane view...167
Figure 5 3: The contour path and crack seams..168
Figure 5 4: A loading mode and boundary conditions..169
Figure 5 5: Mesh model (a) Front view of the mesh model (b) Bottom view of the mesh model (c) 8 node brick element....................................170
Figure 5 6: Mesh sensitivity anylysis with the mesh size (a) number of nodes (b) wall clock time 172
Figure 5 7: Contours with different mesh size (a) 1 mm (b) 2mm (c) 3 mm (d) 4 mm...173
Figure 5 8: The Visualization module of specimen (a) test setup (b) bottom view...174
Figure 5 9: Stress distribution near the crack stop hole 176
Figure 5 10: Average strength variation with diameter to width ratio of CSH 177
Figure 5 11: Visualization of the bottom view under fatigue load profile with diameter to width ratio of CFRP strengthened CSH specimen (a) 0.1 (b) 0.2 (c) 0.3 (d) 0.4 (e) 0.5 (f) 0.6 179
Figure 5 12: Numerical models comparing the experimental results for different diameter to width ratio (d/b) under cyclic flexural load (a) 0.1 (b) 0.2 (c) 0.3 (d) 0.4 (e) 0.5 (f) 0.6 181
Figure 5.13: Average strength variation with offset distance of CSH.................182
Figure 5 14: Visualization of the bottom view under fatigue load profile with offset distance. (a) 0 (b) 20 mm (c) 40 mm (d) 60 mm (e) 80 mm 183
Figure 6 1: Basic modes of crack deformation. (a) opening; (b) In-plane shear (c) Out- plane shear 187

Figure 6 2: Stress distribution at CSH of steel plate 190

Figure 6 3: Paris law related curve 193
Figure 6 4: Log value of rate of fatigue crack growth with cyclic J-integral 197
Figure 6 5: Comparison of Power law with laboratory test results 199
Figure 6 6: Number of cycles for crack initiation with the CSH diameter..........200
Figure 6 7: Number of cycles for crack initiation varies with the thickness to diameter ratio of the specimen...201
Figure 6 8: Number of cycles for crack initiation vary with the crack length of the specimen 202
Figure 6 9: Number of cycles for crack initiation varies with diameter to offset distance ratio 203
Figure 6 10: Number of cycles for crack initiation with respect to diameter to load ratio 204
Figure 6 11: Required number of cycle for crack initiation variations with respect to diameter to loading frequency ratio.................................205
Figure 6 12: Number of cycles for crack initiation with respect to ratio of diameter to stress ratio 206
Figure 6 13: Fiber direction with respect to the Crack direction...........................207
Figure 6 14: Number of cycles for crack initiation with respect to diameter to bond length ratio 208
Figure 7 1: Strength variation with diameter to width ratio of CSH 212
Figure 7 2: Visualization of the bottom view under fatigue load profile with diameter to width ratio of CSH specimen (a) 0.1 (b) 0.2 (c) 0.3 (d) 0.4 (e) 0.5 (f) 0.6 213
Figure 7 3: Strength variation with thickness to diameter ratio of member 215
Figure 7 4: Visualization of the bottom view under fatigue load profile with thick specimen. (a) 5 mm (b) 6 mm (c) 7 mm (d) 8 mm (e) 9 mm (f) 10 mm 216
Figure 7 5: Strength variation with diameter to crack length ratio......................217

Figure 7 6: Visualization of the bottom view under fatigue load profile with crack length from the mid- point (a) 0 (b)20 mm (c) 40 mm (d) 60 mm (e) 80 mm (f) 100 mm 218
Figure 7 7: Strength variation with diameter to offset distance ratio 219
Figure 7 8: Visualization of the bottom view under fatigue load profile with offset from the mid point. (a) 20 mm (b) 40 mm (c) 60 mm (d) 80 mm (e) 100 mm.. 221
Figure 7 9: Strength variation of CSH with load.. 222
Figure 7 10: Visualization of the bottom view under fatigue load profile with loaded specimen.(a) 2 kN (b) 4 kN (c) 6 kN (d) 8 kN(e) 10 kN....... 223
Figure 7 11: Strength variation with frequency... 225
Figure 7 12: Visualization of the bottom view under fatigue load profile with loading frequency at the mid point (a) 1 Hz (b) 2 Hz (c) 4 Hz (d) 5 Hz (e) 8 Hz (f) 10 Hz 226

LIST OF TABLES

Page

Table 2.1: Summary of results of different crack stop hole treatment methods 34

Table 2.2: Properties of CFRP material 38

Table 2.3: Characteristics of steel & CFRP 38

Table 2.4: Factors affecting the CFRP/ steel bond performance 68

Table 2.5: Summary of bond performance characteristics related studies........... 254

Table 2.6: Summary of surface preparation technology related key studies 255

Table 2.7: Key research studies related to adhesives and adhesive properties 256

Table 2.8: Summary of bonding mechanisms related to key research investigations 257

Table 2.9: Key research studies related to humidity effects on CFRP/ steel bond performance 259

Table 2.10: Summary of key research investigations related temperature and humidity combination effects on CFRP/steel bond performance 260

Table 2.11: Summary of reported bridge retrofitted with CFRP (Nisal Abeetha, 2011) 261

Table 3.1: Comparison of the hydraulic ramp and the cam mechanism................. 84

Table 3.2: List of accessories of hydraulic system 86

Table 3.3: Expenditure for the fabricate cyclic flexural load test apparatus 94

Table 4.1: Measured and manufactures provided material properties.................. 105

Table 4.2: Summary of test program 106

Table 4.3: Retained average strength of non-strengthened steel element with the number of cycles 110

Table 4.4: Retained average strength of non-strengthened steel element with CSH 112

Table 4.5: Retained average strength of CFRP-strengthened steel element without CSH.. 115

Table 4.6: Retained average strength of CFRP-strengthened plane specimen with CSH.. 117

Table 4.7: Comparison of strength gain by CFRP 119

Table 4.8: Retained average strength of non-strengthened steel element with the number of cycles ... 122
Table 4.9: Retained average strength of bare steel varies with the number of cycles ... 124
Table 4.10: Retained average strength of non- strengthened steel varies with the number of cycles ... 126
Table 4.11: Retained average strength of CFRP strengthened conditioned CSH varies with the diameter to width ratio ... 128
Table 4.12: Average strength gained by CFRP material under cyclic flexural loads ... 129
Table 4.13: Retained average strength variation with the location of the non-strengthened CSH ... 138
Table 4.14: Retained average strength variation with the location of the CFRP strengthened CSH ... 140
Table 4.15: Retained average strength, gain with CFRP strengthened offset CSH ... 142
Table 4.16: Retained average strength varies with the length of CFRP ... 153
Table 4.17: Retained average strength varies with the length of CFRP ... 156
Table 4.18: Comparison of retained average strength, variation with bond length ... 157
Table 5.1: FEM results compared with test results for CSH ... 177
Table 5.2: FEM result and test results compared with position of CSH ... 182
Table 6.1: Summary of the fracture mechanics theory ... 188
Table 6.2: Number of cycles for crack initiation by the Paris law with respect to diameter to width ratio ... 196
Table 6.3: Log values of the crack growth rate variations with diameter to width ratio of the CSH ... 197
Table 6.4: Test results comparison with the Power law approximation ... 199
Table 6.5: Number of cycles for crack initiation with respect to the diameter to width ratio ... 262
Table 6.6: Number of cycles for crack initiation with respect to the thickness to diameter ratio ... 262

Table 6.7: Number of cycles for crack initiation with respect to the diameter to crack length ratio 263
Table 6.8: Number of cycles for crack initiation with respect to the diameter to offset distance ratio 263
Table 6.9: Number of cycles for crack initiation with respect to the diameter to load ratio 264
Table 6.10: Number of cycles for crack initiation with respect to the diameter to loading frequency 264
Table 6.11: Number of cycles for crack initiation with respect to the ratio of diameter to stress ratio 265
Table 6.12: Number of cycles for crack initiation with respect to the angle of fiber direction 265
Table 6.13: Number of cycles for crack initiation with respect to the diameter to bond length ratio 266
Table 7.1: Strength variation with respect to the diameter to width ratio 212
Table 7.2: Strength variation with respect to the diameter to crack length ratio 214
Table 7.3: Strength variation with respect to the diameter to loading amplitude ratio 217
Table 7.4: Strength variation with respect to the diameter to loading frequency ratio 219
Table 7.5: Strength variation with respect to the ratio of diameter to stress ratio 221
Table 7.6: Strength variation with respect to the fiber direction 224
Table 7.7: Fatigue related design guidelines for CSH 227

LIST OF ABBREVIATIONS

Abbreviation	Description
CCF	Combined Cycle Fatigue
CFRP	Carbon Fiber Reinforced Polymer
CMOD	Crack Mouth Opening Displacement
CSH	Crack Stop Hole
CTOD	Crack Tip Opening Displacement
DB	De-bonding
DBTT	Ductile Brittle Transition Temperature
DCV	Directional Control Valve
DL	De-lamination
EPFM	Elastic Plastic Fracture Mechanics
FCGR	Fatigue Crack Growth Rate
FEM	Finite Element Model
GFRP	Glass Fiber Reinforced Polymer
HCF	High Cycle Fatigue
HLF	Hydraulic Loading Frame
HM	High Module
LCF	Low Cycle Fatigue
LEFM	Linear Elastic Fracture Mechanics
LVDT	Linear Variable Differential Transformer
MCB	Magnetic Circuit Braker
MSC	Microstructural Short Crack
NM	Normal Module
SIF	Stress Intensity Factor
UHM	Ultra High Module
UTM	Universal Tensile Machine

LIST OF SYMBOLS AND NOTATIONS

Symbol	Description	
da/dN	Rate of crack growth (mm/cycle)	mm/cycle
a	Crack length	mm
ΔK	Range of stress intensity factor	[MPa√m]
C	Paris law coefficient	
m	Paris law exponent	
ΔJ	Cyclic J-integral value	
E	Elastic modulus of the material	GNm^{-2}
J_{max}	Maximum value of J–integral	
J_{min}	Minimum value of J –integral	
A	Ramberg-Osgood coefficient	
n	Strain hardening index	
N_f	Total number of cycle of fatigue	
N_i	Number of cycles for crack initiation	
N_p	Number of cycles for crack propagation	
R	Stress ratio	
f	Loading frequency	Hz
T_g	Glass transition temperature	^0C

LIST OF APPENDICES

Appendix	Description
Appendix – A	Key finding from literature review
Appendix – B	Results of theoretical model
Appendix – C	Mechanical drawing for fatigue test apparatus
Appendix – D	Copy of publications