

# **STRUCTURAL BEHAVIOUR OF STEEL COLUMNS AND STEEL-CONCRETE COMPOSITE GIRDERS RETROFITTED USING CFRP**

By

**Amr Abdel Salam Shaat**

A thesis submitted to the Department of Civil Engineering  
in conformity with the requirements for the degree of  
Doctor of Philosophy

Queen's University  
Kingston, Ontario, Canada  
November, 2007

Copyright © Amr A. Shaat, 2007

## **Abstract**

Steel bridges and structures often need strengthening due to increased life loads, or repair due to corrosion or fatigue cracking. This study explored the use of adhesively bonded Carbon Fibre Reinforced Polymers (CFRP) flexible sheets and rigid plates in retrofitting steel columns and girders, through experimental and analytical investigations. The first part of the research program investigated the behaviour of CFRP-strengthened steel columns comprised of square Hollow Structural Sections (HSS). Fifty columns, 175 mm to 2380 mm long (i.e. with slenderness ratios ranging from 4 to 93), were tested under axial compression loads to examine the effects of number and type of CFRP layers, fibre orientation, and slenderness ratio. Transverse wrapping was shown to be suitable for controlling outwards local buckling in HSS short columns, while longitudinal layers were more effective in controlling overall buckling in slender columns. The maximum increases in axial strength observed in the experiments were 18 and 71 percent, for short and slender columns, respectively. An analytical fibre-element model and a non-linear finite element model were developed for slender columns. The models account for steel plasticity, geometric non-linearities, and residual stresses. The models were verified using experimental results, and used in a parametric study. It was shown that CFRP effectiveness increases for columns with larger out-of-straightness imperfections and higher slenderness ratios.

The second part of the research program investigated w-section steel-concrete composite girders retrofitted using CFRP materials. Three girders, 6100 mm long, were tested to study strengthening of intact girders using CFRP plates. Eleven girders, 2030 mm long,

including girders artificially damaged by completely cutting their tension flanges at mid-span, were tested to study the effectiveness of repair using CFRP sheets. The parameters considered were the CFRP type, number of layers, number of retrofitted sides of the tension flange, and the length of CFRP repair patch. The strength and stiffness of the intact girders have increased by 51 and 19 percent, respectively. For the repaired girders, the strength and stiffness recovery ranged from 6 to 116 percent and from 40 to 126 percent, respectively. Unlike flexural strength, the stiffness was not much affected by the bond length. Analytical models were developed, verified, and used in a parametric study, which showed that the higher the CFRP modulus, the larger the gain in stiffness and yielding moment, but the lower the gain in strength and ductility. In general, this study demonstrated that steel structures can indeed be successfully strengthened or repaired using CFRP material.

## Acknowledgements

First and foremost, I thank God through whom all things are possible. I would also like to recognize and thank all the people who made my time at Queen's University during the past four years unforgettable.

I would like to express my deepest gratitude to my supervisor, Dr. Amir Fam, for his unwavering support and guidance throughout this research project. His patience, leadership, and never ending encouragement gave me the confidence to focus and proceed. I owe him an unbelievable amount of gratitude for his prominent role in helping me to achieve one of the greatest accomplishments in my life.

The support of the staff has been a vital part of my success. Thanks go to Fiona Froats, Cathy Wagar, Maxine Wilson, Lloyd Rhymer, Neil Porter, Paul Thrasher, Jamie Escobar, and Bill Boulton. Special thanks go to Dave Tryon, who provided great technical experience and guidance to make the experimental part of this research runs efficiently.

I would also like to acknowledge my fellow graduate students, who helped me along the way. Thanks go to Abdul Chehab, Andrew Kong, Britton Cole, Hart Honickman, Jeff Mitchell, Siddwatha Mandal, Tarek Sharaf, Wojciech Mierzejewski, and Yazan Qasrawi.

I wish to acknowledge the financial support provided by the Natural Sciences and Engineering Research Council of Canada (NSERC). Thanks also go to Mr. Richard Shirping Sika Inc. for providing his experience in bonding the CFRP plates of phase II. I

also wish to thank Fyfe.Co.LLC, Mitsubishi Chemical, and Sika INC. for providing the FRP materials.

I could not have survived the duration of this study without my family. I would like to thank my parents, brother, and sisters for their on-going love, support and encouragement throughout my entire life. Special thanks go to my uncle, Dr. Fathy Saleh, whose example showed me the value of pursuing an academic career. Also, love and prayers of my mother-in-law will never be forgotten; to her soul I am truly thankful.

Finally, I would like to thank my wife, Dalia, for believing in me and for all her support throughout these years. For all your love, patience and dedication, I am grateful. I would also like to acknowledge my son, Ibrahim, who enlightened my life with his smile.

# Table of Contents

<b>Abstract .....</b>	<b>i</b>
<b>Acknowledgements.....</b>	<b>iii</b>
<b>Table of Contents.....</b>	<b>v</b>
<b>List of Figures .....</b>	<b>xiii</b>
<b>List of Tables .....</b>	<b>xxv</b>
<b>Notation .....</b>	<b>xxvi</b>
<b>Chapter 1 Introduction .....</b>	<b>1</b>
<b>1.1 General .....</b>	<b>1</b>
<b>1.2 Research Objectives .....</b>	<b>3</b>
<b>1.3 Scope and Contents .....</b>	<b>6</b>
<b>Chapter 2 Background and Literature Review.....</b>	<b>11</b>
<b>2.1 Introduction.....</b>	<b>11</b>
<b>2.2 Metallic Materials .....</b>	<b>12</b>
2.2.1 Cast iron.....	12
2.2.2 Steel .....	12
2.2.3 Buckling strength of steel members .....	13
2.2.4 Residual stresses in steel sections .....	14
<b>2.3 Conventional Retrofit Techniques of Metallic Structures.....</b>	<b>15</b>
<b>2.4 Retrofit of Steel Structures using FRP Materials .....</b>	<b>17</b>
2.4.1 Bond and force transfer.....	18
2.4.2 Brief review of retrofit applications .....	20
2.4.2.1 Repair of naturally deteriorated I-girders.....	21

2.4.2.2	Repair of artificially damaged I-girders .....	22
2.4.2.2.1	<i>Non-composite I-girders</i> .....	22
2.4.2.2.2	<i>Steel-concrete composite girders</i> .....	24
2.4.2.3	Flexural strengthening of intact I-girders .....	26
2.4.2.3.1	<i>Non-composite I-girders</i> .....	26
2.4.2.3.2	<i>Steel-concrete composite girders</i> .....	29
2.4.2.4	Retrofit of I-girders in shear .....	31
2.4.2.5	Flexural strengthening of tubular sections.....	32
2.4.2.6	Other special cases of strengthening and repair studies .....	35
2.4.2.7	Fatigue and cyclic load behaviour of retrofitted members .....	36
<b>2.5</b>	<b>Surface Preparation and Bond Issues.....</b>	<b>38</b>
<b>2.6</b>	<b>Analysis and Design .....</b>	<b>40</b>
2.6.1	Analysis of bonded joints .....	40
2.6.2	Analysis of steel girders strengthened with FRP bonded material .....	42
2.6.3	Design of bonded joints.....	44
2.6.4	Flexural design of CFRP strengthening of steel structures .....	45
<b>2.7</b>	<b>Durability of Steel Structures Retrofitted with FRP .....</b>	<b>46</b>
<b>2.8</b>	<b>Field Applications.....</b>	<b>51</b>
<b>Chapter 3</b>	<b>Experimental Program .....</b>	<b>65</b>
<b>3.1</b>	<b>Introduction.....</b>	<b>65</b>
<b>3.2</b>	<b>Materials .....</b>	<b>66</b>
3.2.1	Structural steel .....	67
3.2.1.1	Cold-formed HSS .....	67
3.2.1.2	Hot-rolled W-sections .....	69

3.2.2	Fibre Reinforced Polymer (FRP) .....	70
3.2.2.1	FRP sheets.....	70
3.2.2.2	FRP plates.....	70
3.2.2.3	Epoxy resins.....	71
3.2.2.4	Coupon tests of FRP sheets and plates.....	71
3.2.3	Concrete.....	72
<b>3.3</b>	<b>Experimental Phase I – Strengthening HSS Columns .....</b>	<b>73</b>
3.3.1	Test specimens .....	73
3.3.2	Fabrication of column specimens.....	75
3.3.3	Test setup .....	79
3.3.4	Instrumentation .....	80
<b>3.4</b>	<b>Experimental Phase II – Strengthening of Intact Composite Girders.....</b>	<b>82</b>
3.4.1	Test specimens .....	82
3.4.2	Fabrication of girders .....	83
3.4.3	Test setup .....	86
3.4.4	Instrumentation .....	87
<b>3.5</b>	<b>Experimental Phase III – Repair of Artificially–Damaged Composite</b>	
<b>Beams</b>	.....	<b>88</b>
3.5.1	Test specimens .....	88
3.5.2	Fabrication of beam specimens .....	90
3.5.3	Test setup .....	93
3.5.4	Instrumentation .....	93

## **Chapter 4 Experimental Results and Discussion of Phase I:**

<b>Axial Compression Members .....</b>	<b>120</b>
--	------------



<b>4.1</b>	<b>Introduction.....</b>	<b>120</b>
<b>4.2</b>	<b>Results of Group A (Slender Column Sets 1 to 6).....</b>	<b>121</b>
4.2.1	Effect of slenderness ratio on effectiveness of CFRP .....	123
4.2.2	Failure modes .....	124
<b>4.3</b>	<b>Results of Group B (Slender Column sets 7 to 11) .....</b>	<b>126</b>
4.3.1	Effect of out-of-straightness imperfection on the effectiveness of CFRP-strengthening .....	126
4.3.2	Failure modes .....	129
<b>4.4</b>	<b>Results of Group C (Short Column sets 12 to 20) .....</b>	<b>130</b>
4.4.1	Effect of CFRP strengthening on the short column specimens.....	130
4.4.2	Effect of fibre orientation .....	132
4.4.3	Effect of CFRP type, thickness, and number of layers.....	132
4.4.4	Failure modes .....	133

## **Chapter 5 Experimental Results and Discussion of Phases II**

	<b>and III: Flexural Members.....</b>	<b>155</b>
<b>5.1</b>	<b>Introduction.....</b>	<b>155</b>
<b>5.2</b>	<b>Results of Phase II – Strengthening of Intact Girders .....</b>	<b>155</b>
5.2.1	Effectiveness of the CFRP strengthening system .....	156
5.2.2	Effect of CFRP elastic modulus .....	158
5.2.3	Effect of bonded length of CFRP plates.....	160
5.2.4	Failure modes .....	161
<b>5.3</b>	<b>Results of Phase III – Repair of Artificially Damaged Beams.....</b>	<b>162</b>
5.3.1	Effect of cutting the tension flange at mid-span .....	163
5.3.1.1	Flexural behaviour .....	163

5.3.1.2	Failure modes.....	165
5.3.2	Effect of type of CFRP .....	166
5.3.2.1	Flexural behaviour.....	166
5.3.2.2	Failure modes.....	168
5.3.3	Effect of number of repaired sides of flange.....	169
5.3.3.1	Flexural behaviour.....	169
5.3.3.2	Failure modes.....	170
5.3.4	Effect of CFRP force equivalence index .....	171
5.3.4.1	Flexural behaviour.....	171
5.3.4.2	Failure modes.....	172
5.3.5	Effect of bonded length of CFRP .....	172
5.3.5.1	Flexural behaviour.....	172
5.3.5.2	Failure Modes.....	176

## **Chapter 6 Analytical and Numerical Modeling of CFRP-**

	<b>Strengthened HSS Slender Columns.....</b>	<b>202</b>
<b>6.1</b>	<b>Introduction.....</b>	<b>202</b>
<b>6.2</b>	<b>Fibre Model (Model 1).....</b>	<b>203</b>
6.2.1	Residual stresses in HSS sections .....	204
6.2.2	Meshing system .....	204
6.2.3	Force equilibrium and moments.....	205
6.2.4	Lateral displacement.....	207
6.2.4.1	Effective moment of inertia ( $I_{eff}$ ).....	210
6.2.4.1.1	<i>Bare steel column</i> .....	210
6.2.4.1.2	<i>FRP-strengthened steel column</i> .....	213

6.2.5	Axial displacement .....	215
6.2.6	Failure criteria .....	216
6.2.7	Generation of full load-displacement responses .....	218
6.2.8	Illustration of key features of the fibre model .....	220
<b>6.3</b>	<b>Finite-Element Model (FEM) (Model 2).....</b>	<b>221</b>
6.3.1	Material properties .....	222
6.3.2	Elements' types and mesh density.....	223
6.3.3	Loading and boundary conditions .....	225
6.3.4	Geometric imperfections .....	225
6.3.5	Residual stresses.....	225
<b>6.4</b>	<b>Verification of Models 1 and 2.....</b>	<b>226</b>
<b>6.5</b>	<b>Parametric Study on CFRP–Strengthened HSS Slender Columns.....</b>	<b>229</b>
6.5.1	Effect of number of CFRP layers .....	230
6.5.2	Effect of initial out-of-straightness ( $e'$ ).....	231
6.5.3	Effect of residual stresses .....	231
6.5.4	Effect of slenderness ratio.....	232
<b>6.6</b>	<b>Comparison between models 1 and 2 .....</b>	<b>232</b>

## **Chapter 7 Analytical Modeling of CFRP-Retrofitted Steel-**

	<b>Concrete Composite Girders.....</b>	<b>267</b>
<b>7.1</b>	<b>Introduction.....</b>	<b>267</b>
<b>7.2</b>	<b>Intact Steel-Concrete Composite Girders Strengthened using CFRP</b>	
<b>Materials</b>	<b>.....</b>	<b>268</b>
7.2.1	Moment-curvature relationship.....	269
7.2.2	Load-deflection behaviour.....	271

7.2.3	Verification of the model.....	271
<b>7.3</b>	<b>Parametric Study on Girder Strengthening .....</b>	<b>272</b>
7.3.1	Effect of CFRP elastic modulus .....	273
7.3.2	Effect of CFRP reinforcement ratio .....	274
7.3.3	Effect of rupture strain of CFRP .....	275
<b>7.4</b>	<b>Damaged Steel-Concrete Composite Girders Repaired using CFRP</b>	
<b>Materials .....</b>		<b>275</b>
7.4.1	Ultimate moment capacity .....	276
7.4.1.1	Intact cross section.....	276
7.4.1.2	Damaged cross section (but not repaired) .....	277
7.4.1.3	Damaged and repaired cross sections.....	277
7.4.1.3.1	<i>Cross section repaired using HM-CFRP.....</i>	<i>278</i>
7.4.1.3.2	<i>Cross section repaired using SM-CFRP.....</i>	<i>278</i>
7.4.1.4	Calibration of parameter for the neglected part of the steel web .....	279
7.4.2	Deflection at service load .....	280
7.4.2.1	Effect of stress flow in the vicinity of the crack .....	283
7.4.2.2	Calibration of the slope (z:1) .....	285
<b>Chapter 8</b>	<b>Summary and Conclusions.....</b>	<b>301</b>
<b>Summary and Conclusions .....</b>		<b>301</b>
<b>8.1</b>	<b>Summary .....</b>	<b>301</b>
<b>8.2</b>	<b>Conclusions .....</b>	<b>302</b>
8.2.1	Axially loaded members .....	302
8.2.1.1	Slender columns.....	302
8.2.1.2	Short columns .....	304

8.2.2	Flexural members .....	305
8.2.2.1	Strengthening of intact girders .....	305
8.2.2.2	Repair of damaged girders.....	306
<b>8.3</b>	<b>Recommendations for Future Work .....</b>	<b>309</b>
<b>References</b> .....		<b>311</b>

**Appendix A Measurements of Out-of-Straightness Profiles for Column**

	<b>Sets 1 to 6.....</b>	<b>326</b>
<b>A.1</b>	<b>General .....</b>	<b>326</b>

**Appendix B Estimated Out-of-Straightness Imperfections at Mid-Height for**

	<b>Column Sets 1 to 11 .....</b>	<b>336</b>
<b>B.1</b>	<b>General .....</b>	<b>336</b>

## List of Figures

Figure 1.1 CFRP-strengthening of HSS columns. ....	9
Figure 1.2 CFRP-retrofitted steel-concrete composite girders. ....	10
Figure 2.1 Residual stresses in hot-rolled and cold-formed sections. ....	54
Figure 2.2 Typical stress-strain curves for CFRP, GFRP, and steel. ....	54
Figure 2.3 Measured and predicted strain distributions along the bonded length of a double lap joint. [Miller et al., 2001] .....	55
Figure 2.4 Test setup for bonded FRP plates in flexure. ....	55
Figure 2.5 Various techniques of introducing artificial damage to steel girders. ....	56
Figure 2.6 Load-deflection responses of artificially damaged non-composite girders. ....	56
Figure 2.7 Failure modes of artificially damaged steel-concrete composite girders. ....	57
Figure 2.8 Different strengthening schemes of steel beams. ....	58
Figure 2.9 Load-deflection response of a composite girder strengthened with HM-CFRP plates. [Tavakkolizadeh and Saadatmanesh, 2003a] .....	58
Figure 2.10 Failure mode of web-strengthened beams. ....	59
Figure 2.11 Load-deflection response and failure mode of a tubular pole. ....	59
Figure 2.12 Effective bond length for steel tube strengthened with HM-CFRP. ....	60
Figure 2.13 Different strengthening schemes of rectangular HSS against bearing stresses. [Zhao et al., 2006] .....	60
Figure 2.14 Installation of CFRP sheets on cracked aluminum truss k-joint. ....	61
Figure 2.15 Degradation of mean deflection of beams under fatigue loading. ....	61
Figure 2.16 Different techniques used to reduce peeling stresses. ....	62
Figure 2.17 Stress distribution in adhesively bonded double-sided joints. ....	62
Figure 2.18 Comparisons of shear and peel stresses for plates with and without taper under UDL. [Deng et al., 2004] .....	63

Figure 2.19 Finite element analysis versus experimental load-deflection responses. ....	63
Figure 2.20 Design guidelines for steel–concrete composite beams strengthened with HM-CFRP materials. [Schnerch et al., 2007].....	64
Figure 2.21 Installation of CFRP plate on the Christina Creek bridge (I-704). ....	64
Figure 3.1 Different steel cross sections used in the experimental investigation. ....	101
Figure 3.2 Test setup of HSS stub-column. ....	101
Figure 3.3 Compressive stress-strain responses of HSS stub-columns. ....	102
Figure 3.4 Tensile stress-strain response of a coupon cut from W250x25 .....	103
Figure 3.5 Sample coupon cut from W150x22. ....	103
Figure 3.6 Tensile stress-strain responses of coupons cut from W150x22.....	104
Figure 3.7 Tension coupons and test setup of FRP materials. ....	104
Figure 3.8 Tensile stress-strain responses of different FRP materials.....	105
Figure 3.9 Test setup for concrete cylinders. ....	105
Figure 3.10 Effect of FRP on local and overall buckling of short and slender HSS columns. ....	106
Figure 3.11 Details of FRP strengthening configurations of HSS columns in Phase I..	106
Figure 3.12 Various preparation measures of the HSS columns in Phase I. ....	107
Figure 3.13 A typical out-of-straightness geometric imperfection profile of slender columns (specimen 6-3). ....	108
Figure 3.14 FRP installation on the HSS columns in Phase I. ....	108
Figure 3.15 Test setup A of columns in group A of Phase I. ....	109
Figure 3.16 Test setup B of columns in group B of Phase I. ....	110
Figure 3.17 Test setup C of columns in group C of Phase I. ....	111
Figure 3.18 A schematic and fabrication process of girders tested in Phase II.....	112
Figure 3.19 Casting concrete slabs of the girders tested in Phase II. ....	113
Figure 3.20 Test setup of girders tested in Phase II. ....	114