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

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

List of Figures