



**Ain Shams University
Faculty of Engineering
Department of Structural Engineering**

Strengthening of Steel I-Section Beam-Column using Pre-Stressed CFRP Laminate

A THESIS

Submitted in Partial Fulfillment for the Requirements of the Degree of
MASTER OF SCIENCE IN CIVIL ENGINEERING (STRUCTURAL)

Submitted by

AHMED TAREK AHMED ABDELRAZIK

B.Sc. in Civil Engineering - Structural Eng.-2010

Ain Shams University – Faculty of Engineering

Supervised by

PROF. EZZELDIN YAZEED SAYED-AHMED

Professor of Steel Structures

Structural Engineering Department

Ain Shams University

PROF. AHMED ABDELSALAM ISMAIL EL-SERWI

Professor of Steel Structures

Structural Engineering Department

Ain Shams University

August 2013

Cairo-Egypt



Ain Shams University
Faculty of Engineering
Department of Structural Engineering

Examiner's Committee

Name: **Ahmed Tarek Ahmed Abdelrazik**
Thesis: Strengthening of Steel I-Section Beam-Column using
Pre-stressed CFRP Laminate
Degree: Master of Science in Civil Engineering

Name and Affiliation	Signature
Prof. Shrief Mourad Professor of Steel Structures Faculty of Engineering-Cairo University	
Prof. Abdelrahim Khalil Dessouki Professor of Steel Structures Faculty of Engineering-Ain Shams University	
Prof. Ezzeldin Yazeed Sayed-Ahmed Professor of Steel Structures Faculty of Engineering-Ain Shams University	

Date:

Curriculum vitae

Name: Ahmed Tarek Ahmed Abdelrazik

Date of Birth: August 8, 1987.

Place of Birth: Cairo, Egypt.

Nationality: Egyptian

University Degree: B.Sc. in Civil Engineering, Faculty of Engineering, Ain Shams University, 2011.

Current Job: Teaching Assistant at Structural department, Faculty of Engineering, Ain Shams University.

Statement

This dissertation is submitted to Ain Shams University for the degree of Master of Science in Civil Engineering (Structural Eng.)

The work included in this thesis was carried out by the author in the Department of Structural Engineering, Faculty of Engineering, Ain Shams University, Cairo, Egypt.

No part of this thesis has been submitted for a degree or qualification at any other university or institution.

Name: Ahmed Tarek Ahmed Abdelrazik

Signature:

Date:

Acknowledgement

I would like to thank my dear supervisor **Prof. Ezzeldin Yazeed** for his help and advice.

I am grateful to **Prof. Ahmed Abdelsalam El-Serwi** for his support.

I would like to extend my gratefulness to **Dr. Remon Aziz and Dr. Mohamed Nassar** for their valuable advices.

Also, I thank my colleague **Eng. Mostafa Atteya** for his help and support.

Finally, I want to express my regards and thanks to my father and mother for their continuous encouragement and advice all over my life since my first steps in school until now.

Abstract of M.Sc. Thesis

Ahmed Tarek Ahmed Abdelrazik, Strengthening of Steel I-section Beam-Column Using Pre-stressed CFRP Laminate, Master of Engineering Science Thesis, Ain Shams University, 2013.

Using Carbon Fibers Reinforced Polymers CFRP in strengthening steel structures' members (beams and columns) is a good method because of its significant effect on the strength. In addition, CFRP laminates can be easily connected to such members without affecting the workspace. Most of researchers, who considered this field of strengthening, concentrated their research on beams or columns and very few researches are on beam-columns. The strengthened structural members represent an extremely complex and highly indeterminate analytical problem with a large number of parameters affecting their structural behavior. Many failure modes must be taken into consideration during analysis. Not only tensile failure in either steel or laminate governs the strength but also interfacial failure probably controls the strength of such structure. Pre-tensioning the CFRP panel laminate used for strengthening increases the overall strength of the member. Present research focuses on the behaviour of steel I-section beam-columns subjected to both flexure and compression force and strengthened using pre-stressed CFRP laminate. Two failure modes are investigated in this research; the first failure mode is the steel

yielding failure criteria (mature failure), the second failure mode is the de-bonding of the CFRP laminate from the steel beam-column (pre-mature failure). Analytical model and finite element analysis are developed to investigate the strength of CFRP bonded steel beam-columns.

Keywords: steel; beam-column; I-section; strengthening; CFRP laminate; pre-stressed.

Table of Contents

<u>EXAMINER'S COMMITTEE</u>	<u>I</u>
<u>CURRICULUM VITAE</u>	<u>II</u>
<u>STATEMENT</u>	<u>III</u>
<u>ACKNOWLEDGEMENT</u>	<u>IV</u>
<u>ABSTRACT OF M.SC. THESIS</u>	<u>V</u>
<u>LIST OF FIGURES</u>	<u>XI</u>
<u>LIST OF TABLES</u>	<u>XIV</u>
<u>NOTATIONS</u>	<u>XV</u>
<u>CHAPTER 1 INTRODUCTION</u>	<u>1</u>
1.1 INTRODUCTION	1
1.2 WHY STRENGTHENING USING CFRP IS PREFERRED?	2
1.3 WHAT ARE THE OBJECTIVES?	2
1.4 HOW THESE OBJECTIVES ARE ACHIEVED?	2
<u>CHAPTER 2 BACKGROUND AND LITERATURE REVIEW</u>	<u>4</u>
2.1 GENERAL	4
2.2 STEEL BEAMS STRENGTHENED WITH BONDED CFRP LAMINATES	5
2.3 GEOMETRY MODIFIED ADHESIVE JOINTS IN STEEL BEAMS STRENGTHENED WITH CFRP LAMINATES	13
2.4 STEEL COLUMNS STRENGTHENED WITH A BONDED CFRP LAMINATES	18
2.5 BOND MODELS AND ACI LIMITATIONS	20
<u>CHAPTER 3 PROPOSED ANALYTICAL MODEL FOR LAMINATE DELAMINATION</u>	<u>23</u>

3.1 INTRODUCTION	23
3.2 ASSUMPTIONS ADOPTED FOR THE PROPOSED ANALYTICAL MODEL	24
3.3 PROPOSED ANALYTICAL MODEL	24
3.4. DERIVATION OF THE PROPOSED EQUATION	25
3.4.1 GENERAL SOLUTION FOR INTERFACIAL SHEAR STRESSES	26
3.4.2 GENERAL SOLUTION FOR INTERFACIAL NORMAL STRESSES	30
3.4.3 APPLYING BOUNDARY CONDITIONS TO THE GENERAL SOLUTION OF THE INTERFACIAL SHEAR STRESSES	33
3.4.4 APPLYING BOUNDARY CONDITIONS TO THE GENERAL SOLUTION OF THE INTERFACIAL NORMAL STRESSES	34
3.5. ESTIMATION OF THE MAXIMUM SHEAR AND NORMAL INTERFACIAL STRESSES	35
3.5.1 PROPERTIES OF THE STEEL SECTION AND THE CFRP LAMINATE	35
3.5.2 EQUATIONS' COEFFICIENTS FOR SHEAR AND THE NORMAL STRESSES AT THE END OF THE CFRP LAMINATE	36
3.5.3 MAXIMUM INTERFACIAL SHEAR AND NORMAL STRESSES	36
3.6 APPLICATIONS	36
3.6.1 MAXIMUM BEAM-COLUMN LOAD WITH NO PRE-MATURE FAILURE WHEN USING NON PRE-STRESSED LAMINATE	37
3.6.2 MAXIMUM BEAM-COLUMN LOAD WITH NO PRE-MATURE FAILURE WHEN USING PRE-STRESSED LAMINATE	38
3.7 ADOPTING THE PROPOSED EQUATIONS	40
<u>CHAPTER 4 DEVELOPING OF FINITE ELEMENT MODEL</u>	<u>43</u>
4.1 INTRODUCTION	43
4.2 DEVELOPING THE FE MODEL	43
4.2.1 TYPES OF ADOPTED ELEMENTS	43
4.2.2 GEOMETRIC NONLINEARITY	45
4.2.2.1 LARGE DEFLECTION SMALL STRAIN ANALYSIS	46
4.2.3 MATERIAL NONLINEARITY	46
4.2.3.2 MODELING OF UNIAXIAL BEHAVIOR IN PLASTICITY	52

4.3 FINITE ELEMENT COMPUTER PROGRAM USED IN STUDY	53
4.4 SOLUTION OF THE NON-LINEAR EQUATIONS	54
4.4.1 STATIC ANALYSIS	54
4.4.2 INCREMENTAL CONTROL TECHNIQUES	55
4.4.2.1 FORCE CONTROL	55
4.4.2.2 DISPLACEMENT CONTROL	56
4.4.2.3 ARC-LENGTH CONTROL	56
4.5 FINITE ELEMENT MODEL	58
<u>CHAPTER 5 VERIFICATION OF THE FINITE ELEMENT MODEL AND THE PROPOSED ANALYTICAL MODEL</u>	61
5.1 INTRODUCTION	61
5.2 VERIFICATION OF THE PROPOSED FINITE ELEMENT MODEL	61
5.2.1 SPECIMENS ADOPTED IN PREVIOUS EXPERIMENTAL STUDIES	61
5.2.2 FINITE ELEMENT MODELING OF PREVIOUS EXPERIMENTAL WORKS	67
5.2.3 COMPARISON BETWEEN EXPERIMENTAL DATA AND FINITE ELEMENT MODEL RESULTS	73
5.3 VERIFICATION OF FE MODEL INCLUDING THE PRE-STRESSING FORCE	73
5.3.1 EQUATION DEVELOPED BY AL-EMRANI AND KLIGER	74
5.3.2 PRESENT FINITE ELEMENT MODELING OF THE PRE-STRESSING FORCE	77
5.3.3 COMPARISON BETWEEN RESULTS	77
5.4 VERIFICATION OF THE PRESENT PROPOSED DESIGN EQUATIONS	79
5.4.1 VERIFICATION OF THE EQUATIONS' RESULTS	79
5.4.2 VERIFICATION OF THE TWO ASSUMED POINTS	84
<u>CHAPTER 6 PARAMETRIC STUDY</u>	86
6.1 INTRODUCTION	86
6.2 THE FINITE ELEMENT MODEL	86
6.3 STRENGTHENING BEAM-COLUMN AND EFFECT OF e/h ON ITS CAPACITY	90

6.4 PARAMETRIC STUDY	94
6.4.1 PRE-STRESSING FORCE AND ECCENTRICITY	101
6.4.2 PRE-STRESSING FORCE AND LAMINATE STIFFNESS	102
6.4.3 PRE-STRESSING FORCE AND BEAM-COLUMN STIFFNESS	103
6.4.4 PRE-STRESSING FORCE AND BEAM-COLUMN DEPTH	104
6.4.5 ECCENTRICITY AND LAMINATE STIFFNESS	105
6.4.7 ECCENTRICITY AND BEAM-COLUMN DEPTH	107
6.4.8 LAMINATE STIFFNESS AND BEAM-COLUMN STIFFNESS	108
6.4.9 LAMINATE STIFFNESS AND BEAM-COLUMN DEPTH	109
6.4.10 BEAM-COLUMN STIFFNESS AND BEAM-COLUMN DEPTH	110
6.5 DEVELOPING OF EQUATION	111
 <u>CHAPTER 7 FAILURE MODES AND DESIGN RECOMMENDATIONS</u>	 <u>113</u>
7.1 INTRODUCTION	113
7.2 INTERACTION BETWEEN THE TWO CFRP-STRENGTHENED BEAM-COLUMN FAILURE MODES AND EFFECT OF INTERFACE PROPERTIES	113
7.3 BEAM-COLUMN CAPACITY	121
7.4 CHECKING INTERFACIAL STRESSES	121
7.4.1 PROPERTIES OF THE STEEL SECTION AND THE CFRP LAMINATE	121
7.4.2 EQUATIONS' COEFFICIENTS FOR SHEAR AND THE NORMAL STRESSES AT THE END OF THE CFRP LAMINATE	122
7.4.3 MAXIMUM INTERFACIAL SHEAR AND NORMAL STRESSES	122
 <u>CHAPTER 8 SUMMARY AND CONCLUSIONS</u>	 <u>123</u>
8.1 SUMMARY	123
8.2 CONCLUSIONS	123
8.3 RECOMMENDATIONS FOR FUTURE WORK	124
 <u>REFERENCES</u>	 <u>126</u>

List of Figures

FIGURE 2-1: CFRP LAMINATES.....	4
FIGURE 2-2: CFRP SHEETS	5
FIGURE 2-3: TAPERED LAMINATE WITH AND WITHOUT ADHESIVE FILLET	14
FIGURE 2-4: DIFFERENT CONFIGURATIONS CONSIDERED IN HAGHANI ET AL. (2008)	16
FIGURE 3-1: BEAM-COLUMN STRENGTHENED USING PRE-STRESSED CFRP LAMINA.....	25
FIGURE 3-2: SHEAR STRAIN.....	26
FIGURE 3-3: FORCES IN INFINITESIMAL ELEMENT OF A SOFFIT-PLATED BEAM.	28
FIGURE 3-4: SHEAR AND NORMAL STRESS IN A PRISM OF THE ADHESIVE MATERIAL	30
3-5: P_{max1} Vs. E/H	38
FIGURE 3-6: P_{max1} & P_{max2} Vs. E/H	40
FIGURE 3-7: P_u , P_{max1} & P_{max2} Vs. E/H	41
FIGURE 4-1: NONLINEAR QUADRATIC 8-NODES SHELL ELEMENT	44
FIGURE 4-2: NONLINEAR CUBIC 20-NODES SOLID ELEMENT.....	45
FIGURE 4-3: LARGE DEFLECTION SMALL STRAIN ANALYSIS	46
FIGURE 4-4: STRESS STRAIN CURVE OF MILD STEEL	50
FIGURE 4-5: LOADING, UNLOADING AND RELOADING PATHS	50
FIGURE 4-6: STRAIN HARDENING AFTER RELOADING.....	50
FIGURE 4-7: STRAIN SOFTENING AND STRAIN HARDENING OF NON-LINEAR MATERIALS	51
FIGURE 4-8: STRESS STRAIN CURVE OF THE EPOXY ADHESIVE	51
FIGURE 4-9: STRESS STRAIN CURVE OF THE CFRP LAMINATE	51
FIGURE 4-10: IDEALIZED STRESS STRAIN CURVE OF STEEL	53
FIGURE 4-11: IDEALIZED STRESS STRAIN CURVE OF EPOXY	53
FIGURE 4-12: FAILURE OF FORCE CONTROL.....	55
FIGURE 4-13: FAILURE OF DISPLACEMENT CONTROL.....	56
FIGURE 4-14: DISPLACEMENT CONTROL TECHNIQUE	57
FIGURE 4-15: FAILURE OF FORCE AND DISPLACEMENT CONTROL	57
FIGURE 4-16: SHELL 281-ELEMENT	59
FIGURE 4-17: SOLID 95 – ELEMENT	60
FIGURE 4-18: FINE AND COURSE MESH SIZES	60
FIGURE 5-1: SCHEMATIC FOUR-POINT BENDING SETUP PERFORMED BY DENG AND MARCUS (2005).....	63

FIGURE 5-2: EXPERIMENTAL SETUP PERFORMED BY CHIEW ET AL. (2011)	65
FIGURE 5-3: SHELL 281-ELEMENT	69
FIGURE 5-4: SOLID 95 – ELEMENT	69
FIGURE 5-5: RIGID STIFFENER AND DISTRIBUTING OF LOAD	70
FIGURE 5-6: BEAM SUPPORT	70
FIGURE 5-7: FINE AND COURSE MESH SIZES.....	71
FIGURE 5-8: FULL BEAM MODELING	71
FIGURE 5-9: QUARTER BEAM MODELING.....	72
FIGURE 5-10: RESTRAINS AT LINES OF SYMMETRY	72
FIGURE 5-11: FE-MODEL OF HALF BRIDGE GIRDER IN A TWO-GIRDER RAILWAY BRIDGE STRENGTHENED WITH BONDED PRE-STRESSED LAMINATE.....	76
FIGURE 6-1: LOAD MODIFICATION.....	88
FIGURE 6-2: FINITE ELEMENT MODEL OF THE BEAM-COLUMN.....	89
FIGURE 6-3: APPLYING LOADS AND SUPPORT	89
FIGURE 6-4: EFFECT OF STRENGTHENING ON THE BEAM-COLUMN LOAD CAPACITY	92
FIGURE 6-5: EFFECT OF STRENGTHENING ON BEAM-COLUMN MOMENT CAPACITY	93
FIGURE 6-6: CHANGE IN ULTIMATE LOAD DUE TO VARIATION OF SLENDERNESS	95
FIGURE 6-7: DEPTH VARIATION WITH CONSTANT INERTIA.....	98
FIGURE 6-8: INERTIA VARIATION WITH CONSTANT DEPTH.....	99
FIGURE 6-9: EFFECT OF VARIATION OF PRE-STRESSING FORCE AND THE ECCENTRICITY TO DEPTH RATIO ON THE ULTIMATE LOAD	101
FIGURE 6-10: EFFECT OF VARIATION OF PRE-STRESSING FORCE AND LAMINATE STIFFNESS ON THE ULTIMATE LOAD	102
FIGURE 6-11: EFFECT OF VARIATION OF PRE-STRESSING FORCE AND BEAM-COLUMN STIFFNESS ON THE ULTIMATE LOAD	103
FIGURE 6-12: : EFFECT OF VARIATION OF PRE-STRESSING FORCE AND BEAM-COLUMN DEPTH ON THE ULTIMATE LOAD (ALL COLUMNS HAVE THE SAME STIFFNESS)	104
FIGURE 6-13: EFFECT OF VARIATION OF THE ECCENTRICITY TO DEPTH RATIO AND LAMINATE STIFFNESS ON THE ULTIMATE LOAD	105
FIGURE 6-14: EFFECT OF VARIATION OF ECCENTRICITY TO DEPTH RATIO AND BEAM- COLUMN STIFFNESS ON THE ULTIMATE LOAD.....	106
FIGURE 6-15: EFFECT OF VARIATION OF THE ECCENTRICITY TO DEPTH RATIO AND BEAM-COLUMN DEPTH ON THE ULTIMATE LOAD (ALL COLUMNS HAVE THE SAME STIFFNESS).....	107

FIGURE 6-16: EFFECT OF VARIATION OF LAMINATE STIFFNESS AND BEAM-COLUMN STIFFNESS ON THE ULTIMATE LOAD	108
FIGURE 6-17: EFFECT OF VARIATION OF LAMINATE STIFFNESS AND BEAM-COLUMN DEPTH ON THE ULTIMATE LOAD (ALL COLUMNS HAVE THE SAME STIFFNESS)	109
FIGURE 6-18: EFFECT OF VARIATION OF BEAM-COLUMN STIFFNESS AND BEAM-COLUMN DEPTH ON THE ULTIMATE LOAD (ALL COLUMNS HAVE THE SAME STIFFNESS)	110
FIGURE 7-1: VALUES OF THE THREE ULTIMATE LOADS FOR DIFFERENT ECCENTRICITIES VALUES FOR ADHESIVE THICKNESS EQUAL TO 1 MM.....	115
FIGURE 7-2: VALUES OF THE THREE ULTIMATE MOMENTS FOR DIFFERENT ECCENTRICITIES VALUES FOR ADHESIVE THICKNESS EQUAL TO 1 MM.....	116
FIGURE 7-3: VALUES OF THE THREE ULTIMATE LOADS FOR DIFFERENT ECCENTRICITIES VALUES FOR ADHESIVE THICKNESS EQUAL TO 0.5 MM.....	117
FIGURE 7-4: VALUES OF THE THREE ULTIMATE MOMENTS FOR DIFFERENT ECCENTRICITIES VALUES FOR ADHESIVE THICKNESS EQUAL TO 0.5 MM.....	118
FIGURE 7-5: VALUES OF THE THREE ULTIMATE LOADS FOR DIFFERENT ECCENTRICITIES VALUES FOR ADHESIVE THICKNESS EQUAL TO 0.25 MM.....	119
FIGURE 7-6: VALUES OF THE THREE ULTIMATE MOMENTS FOR DIFFERENT ECCENTRICITIES VALUES FOR ADHESIVE THICKNESS EQUAL TO 0.25 MM.....	120