

AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
STRUCTURAL ENGINEERING DEPARTMENT

Behavior and Design of Steel I-beam-to-Column Rigid Bolted Connections

By

Rimon Aziz Samaan

Assistant Lecturer, Structural Eng. Department

Ain Shams University

A Thesis

Submitted in Partial Fulfillment for the Requirements
of the Degree of Doctor of Philosophy
in Civil Engineering

Supervised by

Prof. Adel Helmy Salem

Former Dean, Professor (Emeritus) of Steel Structures

Structural Eng. Dept. – Faculty of Eng.

Ain Shams University

Prof. Ezzeldin Y. Sayed-Ahmed

Professor of Steel Structures

Struc. Eng. Dept. – Faculty of Eng.

Ain Shams University

Prof. Ahmed A. El-Serwi

Professor of Steel Structures

Struc. Eng. Dept. – Faculty of Eng.

Ain Shams University

Cairo – 2010

EXAMINERS COMMITTEE

- 1- Prof. Fouad Helmy Fouad** (.....)
Chairman and Professor
Department of Civil, Construction, and Environmental Engineering
The University of Alabama at Birmingham, USA

- 2- Prof. Sherif Kamal Hassan** (.....)
Professor of Steel Structures
Faculty of Engineering
Ain-Shams University

- 3- Prof. Adel Helmy Salem** (.....)
Professor of Steel Structures
Faculty of Engineering
Ain-Shams University

- 4- Prof. Ahmed Abdelsalam El-Serwi** (.....)
Professor of Steel Structures
Faculty of Engineering
Ain-Shams University

Ain Shams University
Faculty of Engineering
Structural Engineering Department

Thesis submitted by: Rimon Aziz Samaan

Title of the Thesis: Behavior and Design of Steel I-beam-to-Column Rigid Bolted Connections

Supervisors:

Prof. Adel Helmy Salem (.....)
Professor of Steel Structures
Faculty of Engineering
Ain-Shams University

Prof. Ezzeldin Y. Sayed-Ahmed (.....)
Professor of Steel Structures
Faculty of Engineering
Ain-Shams University

Prof. Ahmed Abdelsalam El-Serwi (.....)
Professor of Steel Structures
Faculty of Engineering
Ain-Shams University

Registration Date:

Examination Date:

ABSTRACT

Considerable attention has been devoted towards beam-to-column rigid bolted connections. Although different methods of design are introduced in various specifications, yet these methods are not accurate specially in calculating the bolt force and end plate capacity. In this dissertation, a general literature review of the previous studies in the field of rigid connections is presented. An experimental programme has been conducted. Ten full scale specimens for rigid connections were tested with different configurations: five specimens represented flushed end plate connections while the other five represented extended end plate connections. The material properties of the steel plates and bolts were investigated. A nonlinear finite element model which accounts for geometric and material nonlinearities is developed. In this model, 4-node shell elements are used to model steel plates, 8-node solid elements are used to model bolt shank, head and nut while contact elements capable of carrying only compressive forces are used for the contact between the column flange and the head plate. Verification of the proposed finite element model has been performed by comparing its results with the results of the performed experimental study and also with the experimental work previously performed by others. A parametric study is carried out using the verified finite element model for different connection configurations: flushed connections with one and two rows of bolts in the tension side and extended connections with and without stiffeners. Interaction curves for the studied connection configurations have been presented. The influences of bolt diameter, head plate thickness, beam height and bolts edge distances on the connection strength are presented. Furthermore, the effects of various investigated parameters on the bolt force, the prying force and the moment capacity of the connection as well as on the connection's modes of failure have been scrutinized. A comparative study between the finite element results and those using the design equations of the AISC guide No 16 (2002) is performed. Design charts for different connection configurations are also plotted. Equations to calculate the moment capacity of the connections have been proposed using regression analyses. A comparison between the connection moment capacities calculated using the proposed equations and those obtained from the finite element model has been carried out revealing good agreement between them. Conclusions are summarized and recommendations for future researches are listed at the end of the dissertation.

ACKNOWLEDGEMENTS

First and foremost, praise and thanks to our Almighty God.

The author would like to express his deepest gratitude and appreciation to his supervisor, Prof. Adel Helmy Salem for his invaluable guidance, support and encouragement.

He also greatly appreciate the help, guidance and support provided by Prof. Ezz eldin Yazeed and Prof. Ahmed Abdel-Salam throughout all stages of research.

He would like to express his heartfelt appreciation to the soul of his late father, to his beloved mother and the whole family who really helped him and provided lots of support throughout all the stages of this work.

He like to express his special thanks to his wife Marian and his sister Mariam for their precious help and support.

STATEMENT

This dissertation is submitted to Ain Shams University for the Ph.D. degree in Civil Engineering (Structural Engineering).

The work included in this dissertation has been carried out by the author in the Department of Structural Engineering, Ain Shams University, from May 2005 to March 2010.

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

Date :

Signature :

Name : Rimon Aziz Samaan

Table of Contents

Abstract	iv
Acknowledgement	v
Table of Contents	vii
List of Tables	xiv
List of Figures	xvii
Notations	xxxviii

CHAPTER 1: INTRODUCTION

1.1 Introduction	1
1.2 End-Plate Connections	2
1.3 Classification of Connections	3
1.4 General Design Comments	3
1.5 Aim of the Research	3
1.6 Methodology	4
1.7 Outline of the Dissertation	4

CHAPTER 2: LITERATURE REVIEW

2.1 General	9
2.2 End-plate Design	11
2.3 Bolt Design and Prying Force	15
2.4 Previous Numerical Models of Rigid Steel Connections	19
2.5 Behavior and Modeling of Rigid Connections	21
2.5.1 Linear Model	22
2.5.2 Polynomial Model.....	22
2.5.3 Three-Parameter Power Model	22
2.5.4 Four-Parameter Power Model	23
2.6 Comparison between Different Specifications and Actual Connection Behavior	23
2.6.1 AISC Specifications (2005)	23
2.6.1.1 Introduction	23
2.6.1.2 Calculation of Forces in Bolts Due to Eccentricity Normal to the Plane of Force of T-Stub	25

2.6.1.3 Prying Action	27
2.6.1.4 Procedures of Design for Rigid Connections According to AISC 2005 Steel Design Guide Series No. 16 (2002)	30
2.6.1.5 Factors Affecting Connection Strength	40
2.6.1.6 Limit States Check List Included in AISC	40
2.6.2 Egyptian Code of Practice (2001)	41
2.6.2.1 Allowable Forces in Bolts and Calculation of Prying Forces.	41
2.6.2.2 Determination of Head Plate Thickness or Tee Stub	42
2.6.2.3 Factors Affecting Connection Strength	43
2.6.3 EC (1993) Specification	43
2.7 Ultimate Capacity of End-Plate Connection	44

CHAPTER 3: EXPERIMENTAL PROGRAMME

3.1 General	50
3.2 Test Setup	51
3.2.1 “Beam” Description	51
3.2.2 Phase-1 Columns Description (Flushed Connections)	52
3.2.3 Phase-2 Columns Description (Extended Connections)	53
3.3 Material Properties	54
3.3.1 Bolt Properties	54
3.3.2 Steel Head Plate Properties	56
3.4 Instrumentations of the Tested Connections	58
3.4.1 Strain Gauges	58
3.4.1.1 Bolt Strains	58
3.4.1.2 Strain Gauges Used for Phase-1	59
3.4.1.3 Strain Gauges Used for Phase-2	59
3.4.2 Load Cell	59
3.4.3 Dial Gauges	59
3.5 Test Procedures	60
3.6 Test Results	60
3.6.1 Experimental Results and Discussion of Phase-1	60
3.6.1.1 Results and Discussion of Specimen F1	61

3.6.1.2 Results and Discussion of Specimen F2	61
3.6.1.3 Results and Discussion of Specimen F3	62
3.6.1.4 Results and Discussion of Specimen F4	63
3.6.1.5 Results and Discussion of Specimen F5	63
3.6.2 Experimental Results and Discussion of Phase-2	64
3.6.2.1 Results and Discussion of Specimen E1	64
3.6.2.2 Results and Discussion of Specimen E2	64
3.6.2.3 Results and Discussion of Specimen E3	65
3.6.2.4 Results and Discussion of Specimen E4	65
3.6.2.5 Results and Discussion of Specimen E5	66

CHAPTER 4: FINITE ELEMENT MODEL

4.1 Introduction	93
4.2 The Finite Element Method	93
4.3 Model Development	94
4.4 2-D Model	94
4.5 Model Description	95
4.5.1 Shell Elements	95
4.5.2 Solid Elements	96
4.5.3 Contact Elements	97
4.5.3.1 Pure Lagrange Multiplier Method	97
4.5.3.2 Pure Penalty Method	98
4.5.3.3 Lagrange Multiplier on Contact Normal and Penalty on Frictional (Tangential) Direction	98
4.5.3.4 Augmented Lagrange Method	99
4.5.3.5 The Contact Algorithm Used	99
4.6 Geometric Nonlinearity	100
4.6.1 Large Deflection Small Strain Analysis	101
4.7 Material Nonlinearity	101
4.7.1 Von Mises Yield Criterion	103
4.7.2 Modeling of Uniaxial Behavior in Plasticity	104
4.7.2.1 Stress-Strain Curve	104
4.8 Element Stiffness Matrix	105

4.9 Element Stiffness Matrix in the Global Coordinate System	105
4.10 Isoparametric Elements and Shape Functions	106
4.11 Stress-Strain Relations	107
4.12 Types of Adopted Finite Element Techniques	107
4.13 Finite Element Computer Program Adopted in the Current Study	108
4.14 Solution of the Non-Linear Equations	108
4.14.1 Static Analysis	108
4.14.2 Incremental Control Techniques	109
4.14.2.1 Force Control	109
4.14.2.2 Displacement Control	109
4.14.2.3 Arc-Length Control	109
4.14.3 Iterative Solution Methods	110
4.14.3.1 Modified Newton-Raphson (MNR) Scheme	111
4.14.3.2 Line Search Scheme	111
4.14.3.3 Termination Schemes	111

CHAPTER 5: VERIFICATION OF EXPERIMENTAL AND FINITE ELEMENT MODEL

5.1 Introduction	123
5.2 Finite Element Model of Experimental Works	123
5.3 Comparison between Finite Element model and Previous Experimental Results	124
5.3.1 Bose et al (1997) Experimental Work	125
5.3.1.1 Specimen Description	125
5.3.1.2 Experimental Procedures	125
5.3.1.3 Finite Element Mesh	126
5.3.1.3.1 Mesh Element	126
5.3.1.3.2 Mesh Sensitivity analysis	126
5.3.1.4 Failure Modes	127
5.3.1.5 Rotation Connection	127
5.3.1.6 Experimental Analysis versus Numerical Model Results ...	128
5.3.2 Jenkins et al. (1986) Experimental work	128
5.3.2.1 Specimens Description	128

5.3.2.2 Mesh Sensitivity Analysis	129
5.3.2.3 Failure Modes	129
5.3.2.4 Experimental Analysis versus Numerical Model Results ...	130
5.4 Results of the Performed Experimental programme	131
5.4.1 Meshing	131
5.4.2 Comparing Results of the Finite Element Model to the Experimental Test Results	132
5.4.2.1 Phase-1 Specimens (Flushed Connections)	132
5.4.2.1.1 Specimen F1	132
5.4.2.1.2 Specimen F2	132
5.4.2.1.3 Specimen F3	133
5.4.2.1.4 Specimen F4	134
5.4.2.1.5 Specimen F5	134
5.4.2.2 Phase-2 Specimens (Extended Connections)	135
5.4.2.2.1 Specimen E1	135
5.4.2.2.2 Specimen E2	135
5.4.2.2.3 Specimen E3	136
5.4.2.2.4 Specimen E4	137
5.4.2.2.5 Specimen E5	137
5.4.3 Experimental Program's Summary	138

CHAPTER 6: PARAMETRIC STUDY ON FLUSH END PLATE MOMENT CONNECTIONS SUBJECTED TO PURE MOMENT

6.1 Introduction	163
6.2 Connection Specimen	163
6.3 Investigated Parameters	164
6.4 Finite Element Model	166
6.5 Flush End-Plate Moment Connections	168
6.5.1 Flush Unstiffened Connection with Two Bolts in One Row	168
6.5.1.1 Beam 400mm Depth and 100 mm Horizontal Distance between Bolts	168
6.5.1.2 Beam 600mm Depth and 100 mm Horizontal Distance between Bolts	182

6.5.1.3 Beam 400mm Depth and 200mm Horizontal Distance between Bolts	184
6.5.1.4 Beam 600 mm Depth and 200mm Horizontal Distance between Bolts	186
6.5.2 Flush Unstiffened Connection with Four Bolts in Two Rows	187
6.5.2.1 Beam 600mm Depth and 100mm Horizontal Distance between Bolts	187
6.6.2.2 Beam 600mm Depth and 200mm Horizontal Distance between Bolts	193

CHAPTER 7: PARAMETRIC STYDY ON EXTENDED END PLATE MOMENT CONNECTIONS SUBJECTED TO PURE MOMENT

7.1 Introduction	231
7.2 Connection Specimen	231
7.3 Investigated Parameters	232
7.4 Finite Element Model	233
7.5 Extended End-Plate Moment Connections	234
7.5.1 Extended Unstiffened Connection	235
7.5.1.1 Beam 400mm Depth with 100mm Horizontal Distance between Bolts	235
7.5.1.2 Beam 600mm Depth and 100mm Horizontal Distance between Bolts	251
7.5.2 Extended Stiffened Connections	252
7.5.2.1 Beam 400mm Depth and 100mm Horizontal Distance between Bolts	252
7.5.2.2 Beam 600mm Depth and 100mm Horizontal Distance between Bolts	261

CHAPTER 8: PROPOSED DESIGN EQUATIONS AND CHARTS

8.1 Introduction	309
8.2 Design Charts	309
8.3 Proposed Design Equation	311
8.3.1 Equation Formation	311

8.3.2 Tabulated Values for the Proposed Equation Constants	312
8.3.2.1 Flushed Connections with Two Bolts in Tension Side	312
8.3.2.2 Flushed Connections with Four Bolts in Tension Side	313
8.3.2.3 Extended Unstiffened Connections	314
8.3.2.4 Extended Stiffened Connections	314
8.3.3 Proposed Equation Accuracy	315
8.3.3.1 Accuracy of the Proposed Equation with Respect to Finite Element Analysis Results	315
8.4 Bolt Diameter and Head Plate Thickness Relations	316

CHAPTER 9: CONCLUSIONS

9.1 Summary	335
9.2 Conclusions	336
9.3 Recommendations for Future Studies	340

APPENDIX A: PARAMETRIC STYDY ON FLUSH END PLATE MOMENT CONNECTIONS SUBJECTED TO PURE MOMENT

A.1 Flush Unstiffened Connection with Two Bolts in One Row	342
A.1.1 Beam 600mm Depth and 100 mm Horizontal Distance between Bolts	342
A.1.2 Beam 400mm Depth and 200 mm Horizontal Distance between Bolts	346
A.1.3 Beam 600 mm Depth and 200 mm Horizontal Distance between Bolts	352
A.2 Flush Unstiffened Connection with Four Bolts in Two Rows	354
A.2.1 Beam 600mm Depth and 200mm Horizontal Distance between Bolts	354

APPENDIX B: PARAMETRIC STYDY ON EXTENDED END PLATE MOMENT CONNECTIONS SUBJECTED TO PURE MOMENT

B.1 Extended Unstiffened Connection	385
B.1.1 Beam 600mm Depth and 100 mm Horizontal Distance between Bolts	385

B.2 Extended Stiffened Connections	392
B.2.1 Beam 600mm Depth and 100 mm Horizontal Distance between Bolts	392
LIST OF REFERENCES	416

LIST OF TABLES

Table 2-1a: Yield-line mechanism parameter defined for un-stiffened flushed connections	32
Table 2-1b: Yield-line mechanism parameter defined for stiffened flushed connections	33
Table 2-2a: Yield-line mechanism parameter defined for un-stiffened extended connections	34
Table 2-2b: Yield-line mechanism parameter defined for un-stiffened extended 1/3 connections	35
Table 2-2c: Yield-line mechanism parameter defined for stiffened extended 1/2 and 1/3 connections	36
Table 2 – 3: Minimum bolt pretension load	39
Table 2 – 4: Limits of using equations of Flush End Plate Connections	39
Table 2 – 5: Limits of using equations of Extended End Plate Connections	40
Table 3 - 1: Head plate thickness and bolts used in tests of Phase-1	53
Table 3 - 2: Dimensions of columns used in tests of Phase-2	54
Table 3 - 3: Dimensions and results of tension tests of bolt coupons	55
Table 3 - 4: Ultimate load and stress of tested bolts with head and nut	56
Table 3 - 5: Results of different steel coupons for all specimens	57
Table 5 - 1: Dimensions of verified specimens tested by Bose et al (1997)	125
Table 5 - 2: Output results for accuracy and processing time for different mesh sizes	126
Table 5 - 3: Modes of failure of six tested specimens by Bose et al (1997)	127
Table 5 - 4: Comparison between finite element model and experimental results ...	128
Table 5 - 5: Dimensions and modes of failure of specimens tested by Jenkins	129
Table 5 - 6: Comparison between finite element model and experimental analysis.	130
Table 5 - 7: Comparison between finite element model and experimental analysis.	138
Table 6 - 1: Values of stress and strain used in parametric study for different steel types used	165
Table 6 - 2: Values of stress and strain used in parametric study for different bolt types used	166
Table 6 - 3: Nominal moment capacity for un-stiffened flush connection with two bolts in one row with $h = 40\text{cm}$ and $g = 10\text{ cm}$	169