

INVESTIGATING THE EFFECTS OF HIGH
TEMPERATURE ON THE PERFORMANCE OF
STRUCTURAL STEEL CONNECTIONS USING
FE ANALYSIS

KAMAL AHMED MOHAMMED AL-FAKIH

DOCTOR OF PHILOSOPHY

UNIVERSITI MALAYSIA PAHANG



SUPERVISOR'S DECLARATION

We hereby declare that we have checked this thesis and, in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy.

(Supervisor's Signature)

Full Name : IR.DR. CHIN SIEW CHOO

Position : SENIOR LECTURER

Date :

(Co-supervisor's Signature)

Full Name : DR. DOH SHU ING

Position : SENIOR LECTURER

Date :



STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

(Student's Signature)

Full Name : KAMAL AHMED AL-FAKIH

ID Number : PAC16001

Date :

INVESTIGATING THE EFFECTS OF HIGH TEMPERATURE ON THE
PERFORMANCE OF STRUCTURAL STEEL CONNECTIONS USING FE
ANALYSIS

KAMAL AHMED MOHAMMED AL-FAKIH

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Doctor of Philosophy

Faculty of Civil Engineering & Earth Resources
UNIVERSITI MALAYSIA PAHANG

SEPTEMBER 2019

ACKNOWLEDGEMENTS

No words could adequately indicate the acknowledgment I have for my supervisor, Dr. Chin Siew Choo, who have been a constant source of knowledge, unconditional support, and strength in difficult times. Grateful for her willingness in providing me informative ideas and recommendations that had helped me in completing this research.

I certainly would like to thank my family, especially my father for his support. I thank all the other staffs of the Civil Engineering faculty. My deepest appreciation goes to my brother Ramzi Al-Fakih for guidance through the dark period.

I also gratefully acknowledge the financial support by UMP Postgraduate Research Grants Scheme (PGRS 180313).

I would like to express my very great appreciation to all friends and teammates who gave me all the support needed throughout the research process. This research would not be completed without their help.

Finally, I greatly express my sincere appreciation to my wife, Yasmeeen, for handling all family problems and taking care of our children throughout the time of my study.

ABSTRAK

Salah satu faktor yang menyebabkan kegagalan dan kemudian keruntuhan struktur keluli adalah suhu tinggi yang sangat merosakkan ketegaran pembinaan. Oleh itu, perlu diambil kira mempertimbangkan pengenalan langkah-langkah keselamatan kebakaran dalam reka bentuk bangunan apabila mereka bentuk. Program simulasi dan analisis telah membantu meningkatkan kajian mengenai sambungan kebakaran. Untuk menilai rintangan struktur keluli kepada api, adalah penting untuk memahami kesan haba kepada tindak balas sambungan untuk memastikan keselamatan struktur keluli selepas terdedah kepada kebakaran. Dalam kajian ini, tingkah laku hubungan sudut antara rasuk dan lajur dibincangkan pada suhu yang sangat tinggi. Analisis tidak linear adalah sains yang kompleks dan tidak ada penyelesaian segera dan pantas untuk masalah ini. Semua pengiraan reka bentuk untuk pautan boleh disahkan hanya melalui ujian makmal. Ini membawa kepada kehilangan masa, usaha dan wang. Pada masa ini, dengan adanya perisian simulasi kejuruteraan dapat mengatasi masalah ini. Untuk menyediakan ciri-ciri momen-putaran semi-tegar antara rasuk dan lajur yang terdedah kepada suhu ambien dan suhu tinggi. Di samping itu, untuk mengkaji kemerosotan dalam sifat sambungan rasuk-ke-kolum keluli di bawah beban ricih dan / atau momen. Untuk mencapai matlamat ini, simulasi dilakukan untuk mengkaji kesan suhu tinggi pada sambungan sudut antara balok dan lajur menggunakan unsur terhingga (FEA) yang dikenali sebagai "ABAQUS". Empat jenis sambungan; sambungan sudut web (DWA), sambungan sudut atas dan tempat duduk (TSA), dan sambungan sudut atas dan tempat duduk dengan sambungan sudut ganda web (TSA-DWA) telah dipertimbangkan dalam kajian ini, dan sambungan plat akhir (EP). Lapan model yang berlainan dari pelbagai bahagian silang di bawah kesan pemuatan dan syarat sempadan yang berbeza telah diperiksa. 64 model telah disimulasikan dan dikaji. Bahan non-linear diperkenalkan dengan sifat definisi plastik elastik termasuk hubungan geseran antara permukaan untuk mensimulasikan keadaan sebenar. Kajian ini telah disediakan untuk mencari tingkah laku hubungan komunikasi antara jambatan dan lajur pada suhu tinggi 25 °C hingga 700 °C. Keputusan ujian menunjukkan ciri-ciri momen-putaran lengkung semi-tegar dari rasuk-ke-kolum. Hasil analisis dibandingkan dengan data empirikal yang disediakan oleh literatur. Hasil analisis dibandingkan dengan data eksperimen yang tersedia dari kesusasteraan. Selepas suhu tinggi digunakan pada jenis sambungan, ini dan lengkung momen-putaran (M-Ø) sebelum dan selepas keadaan ini dibandingkan untuk mencari momen maksimum menurun. Hasil pengesahan model menunjukkan bahawa mereka berada dalam persetujuan yang baik dengan eksperimen standard, dengan perbezaan kurang dari 5.1% untuk semua sampel. Di samping itu, hasilnya menunjukkan bahawa momen-putaran lengkung untuk semua sambungan, moment ini berkurangan dengan peningkatan suhu dan sebaliknya, yang putaran meningkat. Selain itu, sambungan pada 200 °C kehilangan daya tahannya kepada 18% dan menurun kepada 58% pada 400 °C dan sehingga 85% pada 600 °C daripada kapasiti keseluruhan dan runtuh sepenuhnya pada suhu melebihi 700 °C. Sebaliknya, kenaikan suhu menyebabkan beban paksi tensional, yang membawa kepada ubah bentuk yang lebih tinggi. Kaedah kegagalan dan corak ubah bentuk disiasat, dan lengkung rotation-moment dibentangkan dan dibincangkan.

ABSTRACT

This thesis presents a numerical investigation on the effects of elevated temperature on the performance of structural steel connections using FE analysis. One of the factors that lead to the failure, and then to the collapse of the steel structure, is the high extreme temperature that undermines the integrity of the building. Consequently, it is necessary to take into consideration the introduction of fire safety measures in the design of buildings during the designing process. To evaluate the resistance of the steel structure to the fire, it is important to understand the effects and response of the elevated temperatures, to ensure the safety of steel structure at exposure to fire. Analysis of nonlinear connections is a complex science and there is no immediate and rapid solution to the problem. All the results of the accounts of the design connections cannot be verified only through the lab tests on a large scale. This leads to the loss of a great deal of time, effort and money. At present, with the availability of engineering simulation software. It is possible to overcome these problems. The aim of this study is to provide moment-rotation characteristics and corresponding parameters of the steel beam-to-column connection exposed to the elevated temperature. To achieve the objective, a simulation was carried out to study the effect of the elevated temperature on the angles connection between beam and column using the finite element analysis (FEA). Four types of connections; double-web angles (DWA), top and seat angles (TSA), end-plate (EP), and top and seat with double-web angles connections (TSA-DWA) were considered in this study. Eight different models of various cross sections under the effect of different loading and boundary conditions were examined. Materials non-linearity was modelled with the elastic-plastic definition properties including frictional contact between surfaces to simulate actual conditions. This research investigates the behaviour of steel at an elevated temperature from 25 °C to 700 °C. The analysis of results was compared with the experimental data available from the literature. The model behaviour validation shows that the model is in good agreement with the existing experimental results. The validated FE model was used to conduct further studies with new three-dimensional (3D) loading conditions in order to produce moment-rotation curve and enhance the understanding of steel joints behaviour on fire. In addition, the results showed for that the moment-rotation curve for all connections, the moment is decreased with increasing temperatures and in contrast, the rotation increased. Moreover, the loss of total capacity of connections is 18 % at 200 °C and increased to 58 % at 400 °C. For 600 °C, it reached 85 % and completely collapsed at temperatures higher than 700 °C. In addition, it is found that the deformation capacity is controlled by the possibility of fracture in the angle connection, in the failure of the bolts and thickness of angles. Therefore, factors such as bolts diameter, type of bolts, angles thickness and properties of materials can improve the connections behaviour.

TABLE OF CONTENT

DECLARATION	
TITLE PAGE	
ACKNOWLEDGEMENTS	ii
ABSTRAK	iii
ABSTRACT	iv
TABLE OF CONTENT	v
LIST OF TABLES	ix
LIST OF FIGURES	xii
LIST OF ABBREVIATIONS	xvii
CHAPTER 1 INTRODUCTION	1
1.1 Background	1
1.2 Steel Beam to Column Connection	2
1.3 Semi-Rigid Connection	6
1.4 Problem Statement	8
1.5 Research Objectives	10
1.6 Scope of Work	10
1.7 Significance of the Research	12
1.8 Thesis Outline	12
CHAPTER 2 LITERATURE REVIEW	14
2.1 Introduction	14
2.2 Semi-Rigid Connection in Fire	15

2.2.1	Configuration and Philosophy of Structural Steel Connection Design at Elevated Temperatures.	20
2.2.2	Degradation of The Connection’s Characteristics at Elevated Temperatures	23
2.3	Numerical Study of Semi-Rigid Connection	23
2.3.1	Top and Seat Angles Connections	24
2.3.2	Double-Web Angles Connections	27
2.3.3	Top and Seat Angles with Double-Web Angles Connections	28
2.3.4	Extended End-Plate Connections	30
2.4	Experimental Study of Semi-Rigid Connection	33
2.5	Mathematical Representation of the Moment-Rotation Curve	38
2.5.1	Representations Based on Connection Characteristics	40
2.6	Models to Predict the Moment Rotation Curve	43
2.6.1	Mechanical Model	43
2.6.2	Numerical Models	44
2.7	Fire Resistant of Beam-to-Column Connections	45
2.8	Summary of Previous Related Research	47
2.9	Summary of Research Gap	51
CHAPTER 3 METHODOLOGY		53
3.1	Introduction	53
3.2	Research Study Flow	53
3.3	Planning Phase	55
3.4	Design and Implementation Phase	55
3.5	Evaluation Phase	57
3.6	Experimental Data Simulation	57
3.6.2	Top and Seat Angle Connection Specimens	58

3.6.3	Double-Web Angles Connection Specimens	61
3.6.4	Top and Seat with Double-Web Angles Connection Specimens	65
3.6.5	Extended End-Plate Connections	68
3.7	Finite Element Analysis	71
3.8	Flowchart of Modeling Process in ABAQUS	72
3.8.1	Connection Configuration	73
3.8.2	Material Properties	75
3.8.3	Properties of Materials Under Elevated Temperature	77
3.8.4	Types of Elements	79
3.8.5	Boundary Conditions	82
3.8.6	Loads	84
3.8.7	Contact Interactions	84
3.8.8	Mesh Elements	85
CHAPTER 4 RESULTS AND DISCUSSION		86
4.1	Introduction	86
4.2	Determination of Moment, Displacement and Rotation	86
4.3	Validation of Models	93
4.3.1	Top-Seat Angle Connections	94
4.3.2	Double-Web Angles Connections	98
4.3.3	Top-Seat Angles with Double-Web Angles Connections	100
4.3.4	Extended End-Plate Connections	102
4.4	Load Displacement Curves	103
4.4.1	Top-Seat Angle Connection	104
4.4.2	Double-Web Angles Connection	113
4.4.3	Top-Seat Angles with Double-Web Angles Connection	121

4.5	Connection Deformation	126
4.5.1	Top-Seat Angle Connection Deformation	126
4.5.2	Double-Web Angles Connection Deformation	131
4.5.3	Top-Seat Angles with Double-Web Angles Connection Deformation	136
4.6	Moment-Rotation Curves Under Elevated Temperature	139
4.6.1	Top-Seat Angle Connections	139
4.6.2	Double-Web Angles Connections	147
4.6.3	Top-Seat Angles with Double-Web Angles Connections	154
4.6.4	Extended End-Plate Connections	161
CHAPTER 5 CONCLUSIONS		165
5.1	Introduction	165
5.2	Conclusions	165
5.3	Recommendations and Future Work	167
REFERENCES		168
LISTED PAPERS		175

LIST OF TABLES

Table 2.1	Structural steel properties at elevated temperatures of bolts and steel members (EN 1993-1-2, 2005).	23
Table 2.2	The summary of the previous related research	48
Table 3.1	Connection geometry for TSA- connections	59
Table 3.2	Columns geometric dimensions and yield stresses	59
Table 3.3	Beams geometric dimensions and yield stresses	59
Table 3.4	Experimental data tests for specimens obtained from El-Abidi, (2012) and Stelmack et al. (1986)	60
Table 3.5	Connection Geometry for DWA-connections.	62
Table 3.6	Columns geometric dimensions and yield stresses for DWA-connections.	63
Table 3.7	Beams geometric dimensions and yield stresses for DWA-connections.	63
Table 3.8	Experimental data obtained from El-Abidi, (2012) and Lewitt et al., (1966) tests	63
Table 3.9	Connection geometry of (Azizinamini and Radziminski, 1989)	66
Table 3.10	Columns geometric dimensions and yield stresses of (Azizinamini and Radziminski, 1989)	66
Table 3.11	Beams geometric dimensions and yield stresses of (Azizinamini and Radziminski, 1989) (TSA-DWA connections)	66
Table 3.12	Experimental data obtained from (Azizinamini and Radziminski, 1989)	67
Table 3.13	Connection geometry for EP- connections	69
Table 3.14	Beams and column geometric dimensions and yield stresses for RC1	69
Table 3.15	Experimental data test for specimens obtained from Qian et al., (2008)	70
Table 3.16	Material models for elevated temperature models of steel members and bolts (EN 1993-1-2, 2005)	79
Table 3.17	Applied load	84
Table 4.1	List of calculated moments and rotations for specimen B.1/2-1	89
Table 4.2	List of calculated moments and rotations for specimen D.1/4-1	89
Table 4.3	List of calculated moments and rotations for specimen SRC-3A	90
Table 4.4	List of calculated moments and rotations for specimen FK-3	90
Table 4.5	List of calculated moments and rotations for specimen FK-5	91
Table 4.6	List of calculated moments and rotations for specimen SRC-2A	91

Table 4.7	List of calculated moments and rotations for specimen 14S1	92
Table 4.8	List of calculated moments and rotations for specimen 14S3	92
Table 4.9	Temperature distribution pursuant to time of CR1.	93
Table 4.10	Summary of the results for specimens D.1/4-1, B.1/2-1 and SRC-3A	94
Table 4.11	Summary of the results for specimens FK-3, FK-5 and SRC-2A	98
Table 4.12	Summary of the results for specimens 14S1 and 14S3	101
Table 4.13	Load versus and displacement (Dy) for TSA connections ambient temperature	105
Table 4.13	Continue	105
Table 4.14	List of calculated load and displacement for specimen SRC-3A	107
Table 4.14	Continue	108
Table 4.15	List of calculated load and displacement for specimen B.1/2-1	109
Table 4.16	List of calculated load and displacement for specimen D.1/4-1	110
Table 4.17	Load versus and displacement (Dy) for DWA connections ambient temperature	114
Table 4.18	List of calculated load and displacement for specimen SRC-2A	115
Table 4.19	List of calculated load and displacement for specimen FK-3	116
Table 4.20	List of calculated load and displacement for specimen FK-5	117
Table 4.21	Load versus and displacement (Dy)for TSA-DWA connections	121
Table 4.22	List of calculated load and displacement for specimen 14S1	122
Table 4.23	List of calculated load and displacement for specimen 14S3	123
Table 4.24	List of calculated moments and rotations for specimen B.1/2-1	140
Table 4.25	List of calculated moments and rotations for specimen D.1/4-1	141
Table 4.26	List of calculated moments and rotations for specimen SRC-3A	142
Table 4.27	Change rate for ultimate moment at elevated temperatures (TSA)	144
Table 4.28	List of calculated moments and rotations for specimen FK-3	148
Table 4.29	List of calculated moments and rotations for specimen FK-5	149
Table 4.30	List of calculated moments and rotations for specimen SRC-2A	150
Table 4.31	The change rate for ultimate moment at elevated temperatures (DWA)	152
Table 4.32	Listed of calculated moments and rotations for specimen I4S1	155
Table 4.33	List of calculated moments and rotations for specimen I4S3	156
Table 4.34	Change rate for ultimate moment at elevated temperatures (TSA-DWA)	158
Table 4.35	List of calculated moments and rotations for specimen RC1	162

Table 4.36 The change rate for ultimate moment at elevated temperatures (EP)

163

LIST OF FIGURES

Figure 1.1	Shear Connection (Clavijo and Fabian, 2016)	3
Figure 1.2	Moment Connections (Clavijo and Fabian, 2016)	3
Figure 1.3	Typical moment rotation (M- θ) curve for a different types of connections (Tamboli, 1999)	5
Figure 1.4	Connection moment-rotation behaviours (Chen et al., 1996)	6
Figure 1.5	Typical moment rotation (M- θ) curve of beam-to-column connections Chen et al., (1996)	8
Figure 2.1	The Stress-strain curve for carbon steel at elevated temperatures (EN 1993-1-2, 2005).	20
Figure 2.2	EC3 reduction factors for stress-strain curve of steel at elevated temperatures (EN 1993-1-2, 2005)	21
Figure 2.3	Stress-strain relationship at elevated temperatures for steel Grade 43,	21
Figure 2.4	Thermal elongation of carbon steel as a function of temperature (EN 1993-1-2, 2005).	22
Figure 2.5	A typical three-dimensional top and seat angles connections	25
Figure 2.6	A typical three-dimensional double-web angles connections.	27
Figure 2.7	A typical 3D top and seat angles with double-web angles connections.	29
Figure 2.8	A typical three-dimensional end plate connections.	31
Figure 2.9	Different mathematical representations of the moment-rotation curve: (a) linear; (B) bilinear; (b) Multilinear (trilinear); (c) nonlinear (Yau and Chan, 1994).	39
Figure 2.10	Trilinear approximation of the curve ($M_j-\phi$) (EC3-1-8: 2005, section 6.3.1).	41
Figure 2.11	Nonlinear approximation of the curve ($M_j-\phi$) (EC3-1-8: 2005, section 6.3.1)	42
Figure 3.1	Research flow chart	54
Figure 3.2	Typical top and seat angles connections El-Abidi, (2012).	58
Figure 3.3	Typical top and seat angles connections (Stelmack et al., 1986).	59
Figure 3.4	M- θ curves for SRC-3A (El-Abidi, 2012)	60
Figure 3.5	M- θ curves for D.1/4-1 (Stelmack et al. 1986)	61
Figure 3.6	M- θ curves for B-1/2-1 (Stelmack et al., 1986)	61
Figure 3.7	Typical double-web-angles connections El-Abidi, (2012).	62
Figure 3.8	Typical double-web-angles connections (Lewitt et al., 1966).	62
Figure 3.9	Derived M- θ curves for SRC-2A (El-Abidi, 2012)	64

Figure 3.10	Derived M- Θ curves for FK-3 (Lewitt et al., 1966)	64
Figure 3.11	Derived M- Θ curves for FK-5 (Lewitt et al., 1966)	65
Figure 3.12	Typical top and seat with double-web-angles connections (Azizinamini and Radziminski, 1989).	66
Figure 3.13	Derived M- Θ curves for 14S1 (Azizinamini and Radziminski, 1989)	67
Figure 3.14	Derived M- Θ curves for 14S3 for (Azizinamini and Radziminski, 1989)	68
Figure 3.15	Typical end plate connections Qian et al., (2008)	69
Figure 3.16	Temperature measurement points for RC1 Qian et al., (2008).	69
Figure 3.17	Temperature distribution pursuant to time of CR1 (Qian et al., 2008)	70
Figure 3.18	Modelling flow chart in ABAQUS	72
Figure 3.19	Top and seat angles connections.	74
Figure 3.20	Double-web angles connections	74
Figure 3.21	Top and seat angles with double-web angles connections	75
Figure 3.22	End plate connections	75
Figure 3.23	A typical stress-strain diagram for carbon steel (Azizinamini and Radziminski, 1989)	76
Figure 3.24	Simplified material curve (EN 1993-1-2, 2005)	78
Figure 3.25	Material properties of members under temperature (EN 1993-1-2, 2005)	79
Figure 3.26	ABAQUS element types.	80
Figure 3.27	C3D8 Solid elements	80
Figure 3.28	Angles mesh arrangement.	81
Figure 3.29	Bolt mesh arrangement.	81
Figure 3.30	Complete beam models with final arrangement.	82
Figure 3.31	Boundary conditions (El-Abidi, 2012)	82
Figure 3.32	Boundary conditions (Azizinamini and Radziminski, 1989)	83
Figure 3.33	Boundary conditions (Lewitt et al., 1966)	83
Figure 3.34	Boundary conditions (Stelmack et al., 1986)	83
Figure 4.1	Details of calculation rotation of TSA connection	87
Figure 4.2	Details of calculation rotation of DWA connection	87
Figure 4.3	Details of calculation rotation of TSA-DWA connection	87
Figure 4.4	Moment-rotation (M- Θ) curve for sample D.1/4-1	96
Figure 4.5	Moment-Rotation (M- Θ) curve for sample B.1/2-1	96
Figure 4.6	Moment-Rotation (M- Θ) curve for sample SRC-3A	97

Figure 4.7	Moment-rotation (M-Ø) curve for sample FK-3	99
Figure 4.8	Moment-rotation (M-Ø) curve for sample FK-5	99
Figure 4.9	Moment-rotation (M-Ø) curve for sample SRC-2A	99
Figure 4.10	Moment-rotation (M-Ø) curve for sample 14S1	101
Figure 4.11	Moment-rotation (M-Ø) curve for sample 14S3	102
Figure 4.12	Temperature-Time curve for sample RC1	103
Figure 4.13	Load -versus vertical displacement at ambient temperature of TSA connections	106
Figure 4.14	Load -versus vertical displacement under elevated temperature of specimen SRC-3A	112
Figure 4.15	Load -versus vertical displacement under elevated temperature of specimen B.1/2-1	112
Figure 4.16	Load -versus vertical displacement under elevated temperature of specimen D.1/4-1	113
Figure 4.17	Load -versus vertical displacement at ambient temperature of DWA connections ambient temperature	119
Figure 4.18	Load -versus vertical displacement under elevated temperature of specimen SRC-2A	119
Figure 4.19	Load -versus vertical displacement under elevated temperature of specimen FK-3	120
Figure 4.20	Load -versus vertical displacement under elevated temperature of specimen FK-5	120
Figure 4.21	Load -versus vertical displacement at ambient temperature of TSA-DWA connections	124
Figure 4.22	Load -versus vertical displacement under elevated temperature of specimen 14S1	125
Figure 4.23	Load -versus vertical displacement under elevated temperature of specimen 14S3	125
Figure 4.24	Von-Mises stress and deformation at elevated temperatures for SRC-3A	128
Figure 4.25	Von-Mises stress and deformation at elevated temperatures for D.1/4-1	129
Figure 4.26	Von-Mises stress and deformation at elevated temperatures for B.1/2-1	130
Figure 4.27	Von-Mises stress and deformation at elevated temperatures for SRC-2A	133
Figure 4.28	Von-Mises stress and deformation at elevated temperatures for FK-3	134
Figure 4.29	Von-Mises stress and deformation at elevated temperatures for FK-5	135

Figure 4.30	Von-Mises stress and deformation at elevated temperatures for 14S1	137
Figure 4.31	Von-Mises stress and deformation at elevated temperatures for 14S3	138
Figure 4.32	Moment-rotation curve at elevated temperatures for B.1/2-1	145
Figure 4.33	Moment-rotation curve at elevated temperatures for D.1/4-1	145
Figure 4.34	Moment-rotation curve at elevated temperatures for SRC-3A	146
Figure 4.35	Moment-rotation curve at elevated temperatures for FK-3	152
Figure 4.36	Moment-rotation curve at elevated temperatures for FK-5	153
Figure 4.37	Moment-rotation curve at elevated temperatures for SRC-2A	153
Figure 4.38	Moment-rotation curve at elevated temperatures for 14S1	159
Figure 4.39	Moment-rotation curve at elevated temperatures for 14S3	159
Figure 4.40	Moment-rotation curve at elevated temperatures for RC1	164

LIST OF SYMBOLS

A	Cross-Section Area of Beam Section
b_f	Width Flange of beam
d	Depth of the Beam Element
E	Young's Modulus of Elasticity
F_y	yield Strain of steel
g_1	gage distance
G	Shear modulus of the steel
h	Beam depth
L	Length of the Beam
l_p	Length of angle
M	Bending Moment
M_u	Ultimate Moment Capacity of the Connection
n	Shape factor
K_ϕ	Initial connection stiffness
t	Thickness of angle leg
t_f	Thickness of Flange
t_w	Thickness of Web
V	Shear force
\emptyset	Rotation
\emptyset_0	Reference plastic rotation
\emptyset_b	Beam rotation
\emptyset_c	Column rotation
\emptyset_j	Connection rotates
ϵ	Strain
Σ	Stress
A	The Stiffness Factor
Δx	Change of horizontal displacement
I	The length at 20 °C
ΔI	The temperature induced elongation
θ_a	the steel temperature [°C].

LIST OF ABBREVIATIONS

AISC	American Institute of Steel Construction
TSA	Top and Seat Angles Construction
TSA-DWA	Top and Seat Angles with Double-Web Angles Construction
DWA	Double-Web Angles Construction
EP	End-Plate Construction
FE	Finite Element
FR	Fully Restrained
LRFD	Load and Resistance Factor Design
PR	Partially Restrained
PRC's	Partially restrained connections
3-D	Three Dimensional
HEA-220	Column Section $H220 \times 213 \times 7 \times 10$
IPE-330	Column Section $I360 \times 170 \times 8 \times 12$

REFERENCES

- Abedi Sarvestani, H. (2017). Behaviour of corrugated webbed beams in post-tensioned semi-rigid connections. *Advances in Structural Engineering*, 20, 394-410.
- Abolmaali, A., Kukreti, A. & Razavi, H. (2003). Hysteresis behaviour of semi-rigid double web angle steel connections. *Journal of Constructional Steel Research*, 59, 1057-1082.
- Abolmaali, A., Matthys, J. H., Farooqi, M. & Choi, Y. (2005). Development of moment-rotation model equations for flush end-plate connections. *Journal of Constructional Steel Research*, 61, 1595-1612.
- Agarwal, A. & Varma, A. H. (2014). Fire induced progressive collapse of steel building structures: The role of interior gravity columns. *Engineering Structures*, 58, 129-140.
- Ahmed, A. & Hasan, R. (2015). Effect and evaluation of prying action for top-and seat-angle connections. *International Journal of Advanced Structural Engineering (IJASE)*, 7, 159-169.
- Ahmed, A. & Kishi, N. (2017). Modified Three-Parameter Power Model to Predict Moment-Rotation Curve of Top-and Seat-Angle Connection. *American Journal of Civil Engineering*, 5, 50-59.
- AISC Committee, (2010). Specification for structural steel buildings (ANSI/AISC 360-10). American Institute of Steel Construction, Chicago-Illinois.
- Aristizabal-Ochoa, J. D. (2008). Slope-deflection equations for stability and second-order analysis of Timoshenko beam-column structures with semi-rigid connections. *Engineering Structures*, 30, 2517-2527.
- Standard, A.S.T.M., (2012). A370-12a. Standard Test Methods and Definitions for Mechanical Testing of Steel Products.
- ASTM International (2011), "ASTM Standard E119-11a Standard Test Methods for Fire Tests of Building Construction and Materials", Standard E119-11a, ASTM International, West Conshohocken, PA, 2009, doi: 10.1520/E0119-11A.
- Ataei, A., Bradford, M. A. & Valipour, H. R. (2014). Moment-Rotation Model for Blind-Bolted Flush End-Plate Connections in Composite Frame Structures. *Journal of Structural Engineering*, 141, 04014211.
- Azizinamini, A. & Radziminski, J. B. (1989). Static and cyclic performance of semirigid steel beam-to-column connections. *Journal of Structural Engineering*, 115, 2979-2999.
- Bahaz, A., Amara, S., Jaspert, J. P., & Demonceau, J. F. (2018). Analysis of the behaviour of semi rigid steel end plate connections. In *MATEC Web of Conferences* (Vol. 149, p. 02058). EDP Sciences..

- Bjorhovde, R., Colson, A. and Zandonini, R., (1996). *Connections in Steel Structures III: Behaviour, Strength and Design*. Elsevier.
- Chen, W.F., (2011). *Semi-rigid connections handbook*. J. Ross Publishing.
- Chen, W.F. and Kim, S.E., (1997). *LRFD steel design using advanced analysis (Vol. 13)*. CRC press.
- Chen, W.-F., Goto, Y. & Liew, J. R. (1996). *Stability design of semi-rigid frames*, John Wiley & Sons.
- Chung, H.Y., Lee, C.H., Su, W.J. and Lin, R.Z., (2010). Application of fire-resistant steel to beam-to-column moment connections at elevated temperatures. *Journal of Constructional Steel Research*, 66(2), pp.289-303.
- Clavijo Rodriguez, F., (2016). *Desarrollo de software para diseño de conexiones en estructuras de acero bajo las especificaciones del AISC (Doctoral dissertation, Universidad Nacional de Colombia)*.
- Coelho, A. M. G. (2013). Rotation capacity of partial strength steel joints with three-dimensional finite element approach. *Computers & Structures*, 116, 88-97.
- Dai, X.H., Wang, Y.C. and Bailey, C.G., (2009). Effects of partial fire protection on temperature developments in steel joints protected by intumescent coating. *Fire Safety Journal*, 44(3), pp.376-386.
- Dai, X., Wang, Y. & Bailey, C. (2010). Numerical modelling of structural fire behaviour of restrained steel beam–column assemblies using typical joint types. *Engineering Structures*, 32, 2337-2351.
- Danesh, F., Pirmoz, A. & Daryan, A. S. (2007). Effect of shear force on the initial stiffness of top and seat angle connections with double web angles. *Journal of Constructional Steel Research*, 63, 1208-1218.
- Daniūnas, A. & Urbonas, K. (2008). Analysis of the steel frames with the semi-rigid beam-to-beam and beam-to-column knee joints under bending and axial forces. *Engineering structures*, 30, 3114-3118.
- Daryan, A. S. & Yahyai, M. (2009). Behaviour of bolted top-seat angle connections in fire. *Journal of Constructional Steel Research*, 65, 531-541.
- Díaz, C., Victoria, M., Martí, P. & Querin, O. M. (2011). FE model of beam-to-column extended end-plate joints. *Journal of Constructional Steel Research*, 67, 1578-1590.
- Drosopoulos, G., Stavroulakis, G. & Abdalla, K. (2012). 3 D Finite element analysis of end- plate steel joints. *Steel & Composite Structures*, 12, 93-115.
- El-Abidi, K. M. A. (2012). *Experimental Study of Semi-Rigid Beam to Column Connection*. University of Brawijaya Malang-Indonesia.

- El-Khoriby, S., Sakr, M. A., Khalifa, T. M. & Eladly, M. M. (2017). Modelling and behaviour of beam-to-column connections under axial force and cyclic bending. *Journal of Constructional Steel Research*, 129, 171-184.
- Elflah, M., Theofanous, M., Dirar, S. & Yuan, H. (2018). Behaviour of stainless steel beam-to-column joints—Part 1: Experimental investigation. *Journal of Constructional Steel Research*.
- Elghazouli, A., Málaga-Chuquitaype, C., Castro, J. & Orton, A. (2009). Experimental monotonic and cyclic behaviour of blind-bolted angle connections. *Engineering Structures*, 31, 2540-2553.
- Elsawaf, S. and Wang, Y.C., 2012. Methods of improving the survival temperature in fire of steel beam connected to CFT column using reverse channel connection. *Engineering Structures*, 34, pp.132-146.
- Elsawaf, S. & Wang, Y. (2013). Behaviour of restrained structural subassemblies of steel beam to CFT column in fire during cooling stage. *Engineering Structures*, 46, 471-492.
- EN 1993-1-1. (2005). Eurocode 3: Design of Steel Structures. Part 1-1: General Rules and Rules for Buildings. CEN, Brussels, Belgium.
- EN 1993-1-2, (2005). Eurocode 3: Design of Steel Structures. Part 1-2: General Rules. Structural Fire Design. CEN, Brussels, Belgium.
- Faella, C., Piluso, V. & Rizzano, G. (1999). Structural steel semirigid connections: theory, design, and software, CRC press.
- Farkas, J., Jármai, K. and Visser-Uys, P., (2003). Cost comparison of bolted and welded frame joints. *Welding in the World*, 47(1-2), pp.12-18.
- Fernandez-Ceniceros, J., Sanz-Garcia, A., Antoñanzas-Torres, F. and Martinez-de-Pison, F.J., (2015). A numerical-informational approach for characterising the ductile behaviour of the T-stub component. Part 1: Refined finite element model and test validation. *Engineering Structures*, 82, pp.236-248.
- Gerami, M., Saberi, H., Saberi, V. & Daryan, A. S. (2011). Cyclic behaviour of bolted connections with different arrangement of bolts. *Journal of Constructional Steel Research*, 67, 690-705.
- Ghindea, M., Catarig, A. & Ballok, R.-I. (2015). Semi-Rigid Behaviour Of Bolted Connections Using Angle Cleats Part 1. Development Of 3-D Finite Element Model. *Buletinul Institutului Politehnic din Iasi. Sectia Constructii, Arhitectura*, 61, 53.
- Grigonis, M., Mačiulaitis, R. and Lipinskas, D., (2011). Fire resistance tests of various fire protective coatings. *Materials Science*, 17(1), pp.93-98.
- Hadianfard, M.A. and Razani, R., (2003). Effects of semi-rigid behaviour of connections in the reliability of steel frames. *Structural Safety*, 25(2), pp.123-138.

- Hassan, M.K., Tao, Z., Mirza, O., Song, T.Y. and Han, L.H., (2014), July. Finite element analysis of steel beam-CFST column joints with blind bolts. In ASEC 2014: Structural Engineering in Australasia: World Standard: Proceedings of the Australasian Structural Engineering Conference: 9-11 July 2014, Auckland, New Zealand.
- Hasan, M.J., Ashraf, M. and Uy, B., (2017). Moment-rotation behaviour of top-seat angle bolted connections produced from austenitic stainless steel. *Journal of Constructional Steel Research*, 136, pp.149-161.
- Hean, L. S., Sulong, N. R. & Jameel, M. (2015). Effect of axial restraints on top-seat angle connections at elevated temperatures. *KSCE Journal of Civil Engineering*, 1-9.
- Hong, K., Yang, J. & Lee, S. (2002). Moment-rotation behaviour of double angle connections subjected to shear load. *Engineering Structures*, 24, 125-132.
- Hu, Y., Davison, B., Burgess, I. and Plank, R., (2009). Component modelling of flexible end-plate connections in fire. *International Journal of Steel Structures*, 9(1), pp.1-15.
- Huang, Z. (2011). A connection element for modelling end-plate connections in fire. *Journal of Constructional Steel Research*, 67, 841-853.
- Hunn, Z. D., Rassati, G. A., Swanson, J. A., & Burns, T. M. (2018). A Finite Element Study of Non-Orthogonal Bolted Flange Plate Connections for Seismic Applications. In *Key Engineering Materials* (Vol. 763, pp. 525-532). Trans Tech Publications.
- Ismail, R. E. S., Fahmy, A. S., Khalifa, A. M. & Mohamed, Y. M. (2016). Numerical Study on Ultimate Behaviour of Bolted End-Plate Steel Connections. *Latin American Journal of Solids and Structures*, 13, 1-22.
- Jiang, B., Li, G.-Q. & Usmani, A. (2015). Progressive collapse mechanisms investigation of planar steel moment frames under localized fire. *Journal of Constructional Steel Research*, 115, 160-168.
- Jiang, J. & Li, G.-Q. (2017). Disproportionate collapse of 3D steel-framed structures exposed to various compartment fires. *Journal of Constructional Steel Research*, 138, 594-607.
- King, R., Smith, V., Williams, A., Boening, M. V., Day, R. & Chen, P. (1993). *Nonlinear Dynamics and Evolutionary Economics*. Oxford University Press.
- Kong, Z. & Kim, S.-E. (2016). Numerical estimation of the initial stiffness and ultimate moment capacity of single-web angle connections. *Journal of Constructional Steel Research*, 121, 282-290.
- Kong, Z. & Kim, S.-E. (2017a). Moment-rotation behaviour of top-and seat-angle connections with double web angles. *Journal of Constructional Steel Research*, 128, 428-439.

- Kong, Z. & Kim, S.-E. (2017b). Moment-rotation model of single-web angle connections. *International Journal of Mechanical Sciences*, 126, 24-34.
- Lemonis, M. E. & Gantes, C. J. (2009). Mechanical modeling of the nonlinear response of beam-to-column joints. *Journal of Constructional Steel Research*, 65, 879-890.
- Lewitt, C. W., Chesson, E. J. & Munse, W. H. (1966). Restraint characteristics of flexible riveted and bolted beam-to-column connections.
- Liu, Y. and Glass, G., (2013). Effects of mesh density on finite element analysis (No. 2013-01-1375). SAE Technical Paper.
- Ma, Z. (2000). Fire safety design of composite slim floor structures, Helsinki University of Technology.
- Marley, M. & Gerstle, K. (1982). Analysis and tests of flexibly-connected steel frames. Report to AISC under Project, 199.
- Milke, J. A. (2016). Analytical methods for determining fire resistance of steel members. SFPE handbook of fire protection engineering. Springer.
- Pirmoz, A., Khoei, A. S., Mohammadrezapour, E. & Daryan, A. S. (2009). Moment-rotation behaviour of bolted top-seat angle connections. *Journal of Constructional Steel Research*, 65, 973-984.
- Prabha, P., Rekha, S., Marimuthu, V., Saravanan, M., Palani, G. & Surendran, M. (2015). Modified Frye-Morris polynomial model for double web-angle connections. *International Journal of Advanced Structural Engineering (IJASE)*, 7, 295-306.
- Qian, Z.H., Tan, K.H. and Burgess, I.W., (2008). Behaviour of steel beam-to-column joints at elevated temperature: Experimental investigation. *Journal of Structural Engineering*, 134(5), pp.713-726.
- Qiang, X., Bijlaard, F. S., Kolstein, H. & Jiang, X. (2014a). Behaviour of beam-to-column high strength steel endplate connections under fire conditions-Part 1: Experimental study. *Engineering Structures*, 64, 23-38.
- Qiang, X., Bijlaard, F. S., Kolstein, H. & Jiang, X. (2014b). Behaviour of beam-to-column high strength steel endplate connections under fire conditions-Part 2: Numerical study. *Engineering Structures*, 64, 39-51.
- Santiago, A., Simoes da Silva, L., Vaz, G., Vila Real, P. and Gameiro, L.A., (2008). Experimental investigation of the behaviour of a steel sub-frame under a natural fire. *Steel and Composite Structures*, 8(3), pp.243-264.
- Santiago, A., Da Silva, L.S., Real, P.V., Vaz, G., Lopes, A.G. and de Marrocos, P., (2009). Experimental evaluation of the influence of connection typology on the behaviour of steel structures under fire. *Engineering Journal*, 46(2), pp.81-98.
- Santiago, A., Da Silva, L.S. and Real, P.V., (2010). Numerical modelling of the influence of joint typologies on the 3D behaviour of a steel sub-frame under a natural fire. *Fire technology*, 46(1), p.49.

- Sarraj, M. (2007). The behaviour of steel fin plate connections in fire. University of Sheffield.
- Setia, S., Murty, C. & Sehgal, V. (2009). Configuration Analysis of Weak-Axis Connections in Seismic Steel Moment Frames. *IUP Journal of Structural Engineering*, 2.
- Shi, G., Shi, Y., Wang, Y. & Bijlaard, F. (2010). Monotonic loading tests on semi-rigid end-plate connections with welded I-shaped columns and beams. *Advances in Structural Engineering*, 13, 215-229.
- Soleimani, E. & Behnamfar, F. (2017). New moment-rotation equation for welded steel beam-to-column connections. *International Journal of Steel Structures*, 17, 389-411.
- Stelmack, T. W., Marley, M. J. & Gerstle, K. H. (1986). Analysis and tests of flexibly connected steel frames. *Journal of Structural Engineering*, 112, 1573-1588.
- Sulong, N. R., Elghazouli, A., Izzuddin, B. & Ajit, N. (2010). Modelling of beam-to-column connections at elevated temperature using the component method. *Steel and Composite Structures*, 10, 23-43.
- Tamboli, A.R., (1999). Handbook of structural steel connection design and details (pp. 451-473). New York: McGraw-Hill.
- Tsavdaridis, K.D. and Papadopoulos, T., (2016). A FE parametric study of RWS beam-to-column bolted connections with cellular beams. *Journal of Constructional Steel Research*, 116, pp.92-113.
- Wang, A. J. (2010). Finite element modelling of composite end-plate connection under elevated temperature. *Australian Journal of Structural Engineering*, 10, 191-206.
- Wang, M., Shi, Y., Wang, Y. & Shi, G. (2013). Numerical study on seismic behaviours of steel frame end-plate connections. *Journal of Constructional Steel Research*, 90, 140-152.
- Wang, Y., Davison, J., Burgess, I., Plank, R., Yu, H., Dai, X. & Bailey, C. (2010). The safety of common steel beam/column connections in fire. *Structural Engineer*, 88, 26-35.
- Wang, Y.C., Dai, X.H. and Bailey, C.G., (2011). An experimental study of relative structural fire behaviour and robustness of different types of steel joint in restrained steel frames. *Journal of Constructional Steel Research*, 67(7), pp.1149-1163.
- Wang, J., Zhang, N. and Guo, S., (2016). Experimental and numerical analysis of blind bolted moment joints to CFTST columns. *Thin-Walled Structures*, 109, pp.185-201.
- Xinwu, W. (2007) Experimental Research on Hysteretic Behaviour of top-seat and web Angles Connections. 5 th WSEAS Int. Conf. on Environment, Ecosystems, and Development, Citeseer, 77-79.

- Yahyai, M. & Daryan, A. S. (2013). The study of welded semi - rigid connections in fire. *The Structural Design of Tall and Special Buildings*, 22, 783-801.
- Yahyai, M. & Rezaeian, A. (2016). Behaviour of beams in bolted column - tree frames at elevated temperature. *Fire and Materials*, 40, 482-497.
- Yang, B. & Tan, K. H. (2012). Numerical analyses of steel beam–column joints subjected to catenary action. *Journal of Constructional Steel Research*, 70, 1-11.
- Yau, C. & Chan, S. (1994). Inelastic and stability analysis of flexibly connected steel frames by springs-in-series model. *Journal of Structural Engineering*, 120, 2803-2819.
- Yu, H., Burgess, I.W., Davison, J.B. and Plank, R.J., (2008a), May. Experimental investigation of the behaviour of flush endplate connections in fire. In *Proceedings of 5th international conference Structures in Fire*, Singapore.
- Yu, H., Burgess, I.W., Davison, J.B. and Plank, R.J., (2008b). Numerical simulation of bolted steel connections in fire using explicit dynamic analysis. *Journal of Constructional Steel Research*, 64(5), pp.515-525.
- Yu, H., Burgess, I.W., Davison, J.B. and Plank, R.J., (2009a). Development of a yield-line model for endplate connections in fire. *Journal of Constructional Steel Research*, 65(6), pp.1279-1289.
- Yu, H., Burgess, I.W., Davison, J.B. and Plank, R.J., (2009b). Experimental investigation of the behaviour of fin plate connections in fire. *Journal of Constructional Steel Research*, 65(3), pp.723-736.
- Yu, H., Burgess, I.W., Davison, J.B. and Plank, R.J., (2009c). Tying capacity of web cleat connections in fire, Part 1: Test and finite element simulation. *Engineering Structures*, 31(3), pp.651-663.
- Yu, H., Burgess, I.W., Davison, J.B. and Plank, R.J., (2009d). Tying capacity of web cleat connections in fire, Part 2: Development of component-based model. *Engineering structures*, 31(3), pp.697-708.
- Yu, H., Burgess, I.W., Davison, J.B. and Plank, R.J., (2010). Experimental and numerical investigations of the behaviour of flush end plate connections at elevated temperatures. *Journal of Structural Engineering*, 137(1), pp.80-87.
- Zhang, C., Li, G.-Q. & Usmani, A. (2013). Simulating the behaviour of restrained steel beams to flame impingement from localized-fires. *Journal of Constructional Steel Research*, 83, 156-165.