

Ministry of higher Education
And Scientific Research
University of Diyala
Collage of Engineering



Experimental Behaviour of simple Bolted shear Connections in Steel Plates after high Temperatures

**A Thesis Submitted to Council of College of Engineering, the
University of Diyala in Partial Fulfillment of the Requirements
for the Degree of Master of Science in Civil Engineering**

By

Qahtan Adnan Sulyiman

Supervised by

Assist. Prof. Mohammed Shihab Mahmood(PhD.)

July, 2021

IRAQ

Dhul-Hijjah, 1442

CERTIFICATION

I certify that the thesis entitled " Experimental behaviour of bolted connections in thin-walled steel plates after elevated temperatures" is prepared by " Qahtan Adnan Sulyiman “ under my supervision at the Department of Civil Engineering-College of Engineering-Diyala University in partial fulfillment of the requirements for the Degree of Master of Science in Civil Engineering.

Signature:

Supervisor:

Date: / / 2021

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

أَتُونِي زُبَرَ الْحَدِيدِ ۖ حَتَّىٰ إِذَا سَاوَىٰ بَيْنَ الصَّدَفَيْنِ قَالَ انْفُخُوا ۖ حَتَّىٰ
إِذَا جَعَلَهُ نَارًا قَالَ آتُونِي أُفْرِغْ عَلَيْهِ قِطْرًا

سورة الكهف الاية (٩٦)

Dedication
To My Family
With Respect

Acknowledgments

I would like to extend my deep thanks and gratitude to Dr. Mohammed Shihab Mahmood, who supported me and answered my inquiries.

I would like to extend my deep thanks to the members of the Civil Engineering Department / College of Engineering / University of Diyala for their support.

I would also like to thank the construction laboratory staff for their support in completing this work.

Finally, I want to thank all of my friends who have helped and supported me in my work research.

QAHTAN ADNAN SULIYMAN

Experimental Behaviour of simple Bolted shear Connections in Steel Plates after high Temperatures

By

Qahtan Adnan Suliyman

Supervised by

Ass. Prof. Mohammed Shihab Mahmood, PhD

Abstract

Steel is widely used materials due to many advantages. It offers over other construction materials. These include high strength, ductility, ease of fabrication, and speed of construction. Steel joints are a major part of steel structures; it is responsible for the transmission of loads such as shearing, tension and bending and the stability of the building. The high temperature affects the mechanical properties of the steel. Therefore, the connections are considered as one of the affected parts if the building was exposed to fire. To maintain the safety of the building, there is a need to know the behaviour of the joint after exposure to high temperatures. This study deals with the effect of high temperatures on the mechanical properties of thin steel carbon plates (2mm , 4mm), and its behaviour in bolted connections after the fire. The experimental work includes testing of thin carbon steel plate bolted connections and coupons. They were exposed to a high temperature to simulate fire conditions, at different temperatures 400°C, 700°C, and 1000°C, in different durations time(30,60,90,120 min), and cooled in water or air. The specimens and coupons were tested in a tensile. The coupons were used to find the mechanical properties (yield stress, ultimate stress, and modulus of elasticity). The specimens were used to find the ultimate load,

type of failure, axial displacement, and transverse displacement (curling). The results showed that after the steel was exposed to high temperatures there is a reduction in the thickness. The yield stress, ultimate stress, and modulus of elasticity for heated coupons dropped with increasing the duration of heating with cooled in air. The curling failure caused a reduction in the ultimate load when specimens of 2 mm thickness heated to 700 °C and 1000 °C and cooled in air. The ultimate stress for heated coupons drops with increasing the duration of heating to 400 °C, 700 °C, and 1000 °C. For coupons of 2mm and 4mm thickness, it dropped by 10%, 13% and 14% and 4%, 11%, and 15% respectively after 120 minutes of heating and cooling in air. The load-carrying capacity of the bolted connections can increase with increasing the heating temperature to 700 °C and 1000 °C for specimens of 2mm thickness by 1% and 14 % respectively after 120 minutes of heating and cooling in water. For the 4mm specimens, it improved in 400 °C, 700 °C and 1000 °C by 2%, 10%, and 9% respectively after 120 minutes of heating and cooling in water. To maintain the strength after the event of a fire in the steel structure buildings, it is recommended to use water to extinguish the fire to maintain the strength in the parts of the structure.

List of content

Subject	Page NO
Title	
Committee Decision	
Dedication	
Acknowledgments	
Abstract	I
List of Contents	III
List of Figures	VIII
List of Tables	XI
List of Symbols	XII
CHAPTER ONE INTRODUCTION	
1.1 Background	1
1.2 Connections in steel structures	1
1.2.1 Bolt Types	2
1.2.2 Welded Joints	3
1.3 Steel Properties after Elevated Temperature	4
1.4 Failure Modes of Bolted Connections	5
1.5 Aim and Objectives	6
1.6 Outline of Study	6
CHAPTER TWO LITERATURE REVIEW	
2.1 Introduction	8
2.2 Bolted Connection Tested at Room Temperature	8

2.3 Bolted Connection Tested at High Temperature	14
2.4 Bolted Connections Tested after Exposed to High Temperature.	18
2.5 Examples of Building Fires	19
2.6 Concluding Remarks	20
CHAPTER THREE EXPERIMENTAL WORK	
3.1 Introduction	22
3.2 Specimens Material and Dimension	22
3.3 Specimen Labeling	23
3.4 Heating and Cooling	28
3.4.1 Safety	28
3.4.2 Cooling the Specimens	29
3.5 Test Models (Coupons and plates)	30
3.5.1 Coupons Tests	30
3.5.2 Bolts	32
3.5.3 Strain Gauge	32
3.5.4 Specimen Test	33
CHAPTER FOUR COUPONS RESULTS AND DISCUSSION	
4.1 Introduction	35
4.2 Dimensions	35
4.3 Effect of Heating Time (400°C)	37
4.4 Effect of Heating Time (700°C)	41
4.5 Effect of heating Time (1000°C)	49
4.6 Effect of Heating Temperature (Air-Cooling)	55

4.7 Effect of Heating Temperature (Water-Cooling)	57
4.8 Post -Fire Properties	59
CHAPTER FIVE SPECIMENS RESULTS	
5.1 Introduction	62
5.2 Effect of Air-Cooling on Physicals Properties	62
5.3 Effect of Water-Cooling on Physicals Properties	64
5.4 Effect of Heating Time (400°C)	66
5.5 Effect of Heating Time (700°C)	83
5.5 Effect of Heating Time (1000°C)	99
5.7 Effect of Heating Temperature (Air-Cooling)	115
5.8 Effect of Heating Temperature (Water-Cooling)	118
5.9 Analytical Modelling	122
CHAPTER SIX CONCLUSIONS AND RECOMMENDATIONS	
6.1 Introduction	127
6.2 Conclusions	127
6.3 Recommendations	131
Reference	132
APPENDIX 1	138

List of Figures

Figure No.	Figure Title	Page No
1-1	Bolted connection	2

1-2	Welded connection	3
1.3	Stress –strain relationship of steel carbon	4
1.4	Stress –strain relationship of steel carbon after fire	4
1.5	Failure modes of bolted connection	5
2.1	Specimen in tensile test	9
2.2	Curling failure	10
2.3	Mode of failure	11
2.4	Bearing failure	12
2.5	Relationship between end distance and failure	14
2.6	Testing of bolted connections at elevated temperature	15
2.7	Specimen in furnace	16
2.8	Failure modes of bolted connections	17
2.9	Slip load test	19
2.10	Broadgate London after fire	20
3.1	Specimen geometry	22
3.2	Coupon geometry	23
3.3	Specimens labeling	24
3.4	Heating the specimens	28
3.5	Furnace, gloves, and special tool	29
3.6	Cooling the specimens	29
3.7	Specimens arrangement	30
3.8	Test Coupons	31
3.9	Bolts	32
3.10	Strain gage location	32
3.11	Specimen test	34
4.1	Change in dimensions	36

4.2	Effect of heating time and cooling method on yield and ultimate stress and elongation (2mm thickness-400°C)	39
4.3	Effect of heating time and cooling method on yield and ultimate stress and elongation (4mm thickness -400°C)	41
4.4	Effect of heating time and cooling method on yield and ultimate stress and elongation (2mm-700°C)	45
4.5	Effect of heating time and cooling method on yield and ultimate stress and elongation (4mm-700°C)	48
4.6	Effect of heating time and cooling method on yield and ultimate stress and elongation (2mm-1000°C)	51
4.7	Effect of heating time and cooling method on yield and ultimate stress and elongation(4mm-1000°C)	54
4.8	Effect of temperature and air-cooling method on yield and ultimate stress and elongation(2mm)	55
4.9	Effect of temperature and air-cooling method on yield and ultimate stress and elongation (4mm)	55
4.10	Effect of temperature and water-cooling method on yield and ultimate stress and elongation (2mm)	57
4.11	Effect of temperature and water-cooling method on yield and ultimate stress and elongation (4mm)	58
5.1	Post-fire specimens -air cooled	67
5.2	Post-fire specimens -water cooled	65
5.3	Types of failure	67
5.4	Results of 2mm thickness specimens heated to400°C and cooled in air	68
5.5	Results of 2mm thickness specimens heated to400°C and	71

	cooled in water	
5.6	Effect of heating duration on ultimate load ratio, curling displacement, ductility and curling load (400°C, 2mm thickness)	73
5.7	Results of 4mm thickness specimens heated to400°C and cooled in air	76
5.8	Results of 4mm thickness specimens heated to400°C and cooled in water	79
5.9	Effect of heating duration on ultimate load ratio, curling displacement, ductility and curling load (400°C, 4mm thickness)	81
5.10	Results of 2mm thickness specimens heated to700°C and cooled in air	84
5.11	Results of 2mm thickness specimens heated to700°C and cooled in water	87
5.12	Effect of heating duration on ultimate load ratio, curling displacement, ductility and curling load (700°C, 2mm thickness)	89
5.13	Results of 4mm thickness specimens heated to700°C and cooled in air	92
5.14	Results of 4mm thickness specimens heated to700°C and cooled in water	95
5.15	Effect of heating duration on ultimate load ratio, curling displacement, ductility and curling load (700°C, 4mm thickness)	98
5.16	Results of 2mm thickness specimens heated to1000°C	100

	and cooled in air	
5.17	Results of 2mm thickness specimens heated to1000°C and cooled in water	103
5.18	Effect of heating duration on ultimate load ratio, curling displacement, ductility and curling load (1000°C, 2mm thickness)	106
5.19	Results of 4mm thickness specimens heated to1000°C and cooled in air	108
5.20	Results of 4mm thickness specimens heated to1000°C and cooled in water	111
5.21	Effect of heating duration on ultimate load ratio, curling displacement, ductility and curling load (1000°C, 4mm thickness)	114
5.22	Effect of temperature and air-cooling method on ultimate strength, curling displacement, ductility and load -curling (2mm)	115
5.23	Effect of temperature and air-cooling method on ultimate strength, curling displacement, ductility and load -curling (4mm)	117
5.24	Effect of temperature and water-cooling method on ultimate strength, curling displacement, ductility and load -curling (2mm)	119
5.25	Effect of temperature and water-cooling method on ultimate strength, curling displacement, ductility and load -curling (4mm)	120
5.26	Mode of failure	123

List of Tables

Figure No.	Table Title	Page No
2.1	Conditions of end distance and edge distance for the occurrence of curling	9
3.1	Test program	24
4.1	Coupon results 2mm -400 °C – cooled in air	45
4.2	Coupon results 2mm -400 °C – cooled in water	45
4.3	Coupon results 4mm -400 °C – cooled in air	48
4.4	Coupon results 4mm -400 °C – cooled in water	48
4.5	Coupon results 2mm -700 °C – cooled in air	51
4.6	Coupon results 2mm -700 °C – cooled in water	52
4.7	Coupon results 4mm -700 °C – cooled in air	55
4.8	Coupon results 4mm -700 °C – cooled in water	56
4.9	Coupon results 2mm -1000 °C – cooled in air	59
4.10	Coupon results 2mm -1000 °C – cooled in water	60
4.11	Coupon results 4mm -1000 °C – cooled in air	62
4.12	Coupon results 4mm -1000 °C – cooled in water	63
4.13	Mechanical properties of specimens 2mm after fire	72
4.14	Mechanical properties of specimens 4mm after fire	73
5.1	Results of specimens (2mm-400°C - cooled in air)	67
5.2	Results of specimens (2mm-400°C - cooled in water)	70
5.3	Results of specimens (4mm-400°C - cooled in air)	75
5.4	Results of specimens (4mm-400°C - cooled in water)	78

5.5	Results of specimens (2mm-700°C - cooled in air)	84
5.6	Results of specimens (2mm-700°C - cooled in air)	87
5.7	Results of specimens (4mm-700°C - cooled in air)	92
5.8	Results of specimens (4mm-700°C - cooled in water)	95
5.9	Results of specimens (2mm-1000°C - cooled in air)	100
5.10	Results of specimens (2mm-1000°C - cooled in water)	103
5.11	Results of specimens (4mm-1000°C - cooled in air)	108
5.12	Results of specimens (4mm-1000°C - cooled in water)	111
5.13	Results of specimens 2mm by AISC code and experimental test	124
5.14	Results of specimens 4mm by AISC code and experimental test	125

List of Symbols

Symbol	Definition
F_y	yield stress
F_{yt}	post fire yield stress
F_u	ultimate stress
F_{ut}	post fire ultimate stress
F_{yt}/F_y	Means Yield stress (F_{yt}) of the coupon subjected to heating to the yield stress (F_y) of coupon tested without heating.
F_{ut}/F_u	Means dividing the ultimate stress (F_{ut}) of the coupon subjected to heating to the ultimate stress (F_u) of coupon tested without heating
F_u/F_y	Means dividing the ultimate stress (F_u) of the coupon to the

	yield stress (F_y) of coupon
T_t / T	Means the thickness of plate after fire to thickness of plate without heating
P_y	Yield load of specimen
P_u	Ultimate load of specimen
P_{yt}	post fire yield load of specimen
P_{ut}	post fire ultimate load of specimen
P_c	load that initiates curling displacement
P_{yt}/ P_y	The ratio of load at which the heated specimen is subjected to load at which the specimen is subjected without heating
P_{ut}/P_u	The ratio of ultimate load of the heated specimen to ultimate load of the specimen without heating
P_c/P_u	The ratio is the ratio of load that initiates curling displacements to the ultimate load for same specimen
A_{ns}	Net shear fracture
A_{nt}	Net tensile fracture
$P_{u an}$	Ultimate strength for equation
P_{uexp}	ultimate strength for experimental

CHAPTER ONE**INTRODUCTION****1.1 Background**

More than two centuries have passed since metals used for the first time in the construction sector. This sector was in continuous development until it became possible to use steel in many construction projects after the industrial revolution in the mid-nineteenth century. Besides, modern sections of steel that are produced in very sophisticated and accurate methods have achieved a great role in the renaissance of the construction sector. The modern steel materials and construction machines, with their high potential, widen the use of structural steel in the building industry. Steel structures are used in all types of construction including heavy industrial buildings, high-rise buildings, and bridges, towers, airport stations. (Al Manoufi, 2016). Steel is widely used due to the many advantages. It offers over other construction materials. These include high strength, ductility, and speed of construction. A major hitch of steel construction is that steel structural members possess low fire resistance due to high thermal conductivity and low specific heat of steel, as well as faster degradation of strength with elevated temperature (Agustini, et al, 2017).

1.2 Connections in Steel Structures

Connections are one of the very important structural elements in steel structures. Having suitable connections can result in perfect structural performance. The failure in the connections can risk the unity of the whole structure and finally leads to collapse (Ketabdari, et al, 2019). The

connections are mainly responsible for the transmission of loads and the stability of the structure. Connections are classified into two main classes, namely bolts and weld (Tamboli , 2009). The connections are important for assembling the parts of the steel structure, at the joints. The connection must be designed in such a way that there is no failure in the connecting area and the members because the failure of the joint is not ductile. Connections are usually the weakest components in steel structure; failure of which may cause the failure of the whole structure (Dowling, et al , 1988). Most structural failures are due to poor design or poor implementation since a large number of failures occur in the connection areas (Segua ,2007).

1.2.1 Bolt Types

Bolts are used to connect the structural elements as shown in Fig (1-1). Bolts are work for carriage Loading from beams to columns in bolted joints, Contribute to the fastness and safety of the structural system, and bearing both thermal and mechanical loads (Panga, et al, 2019). Bolts as either normal or high-strength bolts. Common bolts are graded A307 low-carbon steel with a minimum tensile strength of 60 ksi. High-strength bolts are typical of Grade A325 heat-treated medium-carbon steel with a minimum tensile strength of 120 ksi for bolts up to (1 in) diameter. (Williams , 2011).



Fig (1-1) Bolted connection. Williams , (2011)

1.2.2 Welded Joints

Welding is a method to transfer loads from one member to the other. Welded joints are mostly made by melting the base metal from the parts to be joined with the weld metal, which became a connection after cooling presented in Fig (1-2). There are two major types of welds: groove welds, which are often called butt welds and fillet welds. For building structures in general, approximately 80% of the welds are fillet welds (15%) are butt welds. The presumption underlying the structural design of welds is that welds are homogeneous properties, residual stresses and stress concentrations in the welds are least, and the connecting parts are solid with minimal deformations. This means that the stress distribution is uniform in welding. The ductility of the material leads to redistribution of stresses from residual stresses and stress concentrations, leading to decrease stress in general. Fillet welds are often preferred over butt seams because they need less equipment, fewer operator skills and less item preparation to join. In contrast, butt welds require a bit more work and preparation (Manson , 2005).



Fig (1-2) Welded connection. Manson ,(2005)

1.3 Steel Properties after High Temperatures

Steel is used in building construction due to its main properties of weight to strength ratio, high strength and good flexibility. The mechanical properties of steel are described mainly through the stress-strain relationship. This relationship is for a standard sample under stresses at ambient temperature as shown in Fig (1-3). The steel structure are lost strength and rigidity if it exposed to fire (Fig 1-4), which leads to excessive deformation of the steel parts and collapse (Sarraj, 2007).

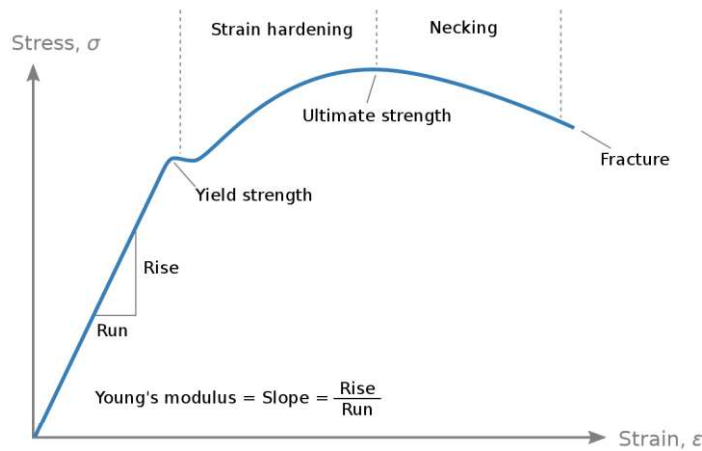
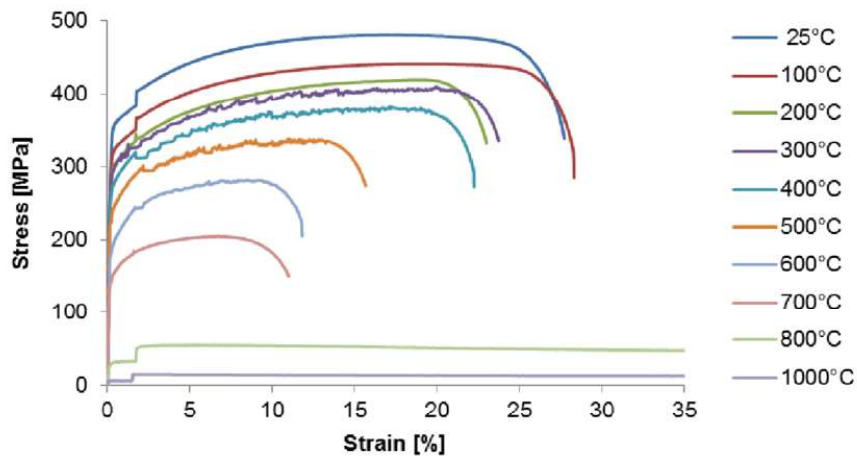


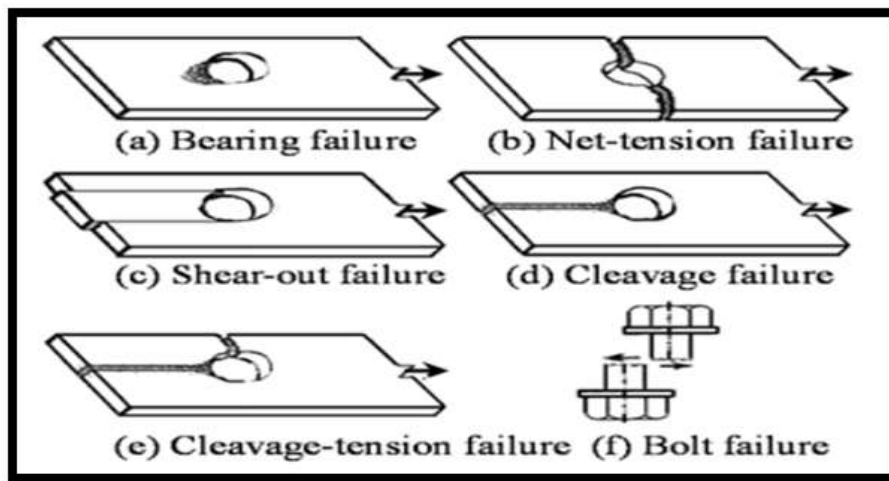
Fig (1-3) Stress –strain relationship of steel carbon. Sarraj, (2007)



(Fig 1-4), Stress –strain relationship of steel carbon after a fire. Tao, et al, (2013)

1.4 Failure Modes of Bolted Connections

Failure modes of bolted tensile connections are fundamentally net tension failure, shear failure, cleavage failure, and block shear failure, as shown in Fig (1-5-a). Net tension occurs because the cross-sectional area is reduced by the bolt hole, which causes the tensile strength to be reduced, so the plate fractures along the bolts line. Shear failure occurs when the plate becomes weak to resist shear and breaks along the shear direction. The failure of cleavage occurs in connections with a small end distance. Block shear failure occurs when shear fracture and net tensile fracture occur at the same time. In bearing failure, the bolt neck portion gradually pushes the plate as the member undergoes a load (Kim, et al, 2018). Finally In 2011, Kim reported that curling failure is shown in Fig (1-5-b) occurred in thin plates of a free edge from connection subject to tensile force. Curling accompanied by strength reduction at ultimate load (Kim, et al, 2011).



a- Failure modes of single-bolt lap-joint in-plane connection, (Kim, et al, 2018)



b. Curling failure, (Kima and Kuwamura , 2011)

Fig (1-5) Failure modes of bolted connection

1.5 Aim and Objectives

The research aims at providing a fundamental understanding on the behaviour of thin bolted connections after being subjected to hit temperature. To achieve this aim, the following objectives were set:

- 1- Studying the state of the art to the research topic.
- 2- Design a comprehensive experimental programme to investigate the effect of the influential parameters on the connection behaviour.
- 3- Perform the experimental tests.
- 4- Analyze the experimental results and observations to quantify the effect of high temperature on the connection behaviour.

1.6 Outline of Study

The thesis was divided into six chapters, and a summary of each is presented below:

- Chapter 1. Gives a general introduction on the research background and the thesis domain and outline.

- Chapter 2. This chapter contains a review of the literature that gives general introductions on the topic of the thesis. This chapter divides previous studies into three groups. The first presents specimens that tested at room temperature. The second group includes the specimens that tested at high temperatures (Fire representation). The third group presents the specimens tested after the fire.
- Chapter 3. This chapter describes the experimental programme including the dimensions of the samples (coupons and specimens). Then the chapter shows the method of heating and cooling. It also describes the instruments that were used in the experimental programme and the procedure that was adopted to record the results.
- Chapter 4. This chapter displays the changes in physical properties for coupons after heating and cooling (length, width and thickness). Comparison of coupons results after testing (yield stress, ultimate stress and elongation), at each heating temperature and different heating durations in the same cooling method with the results of coupon tested without heating were conducted.
- Chapter 5 Through this chapter, the effect of heating temperature, heating time and cooling method on the main aspects of the bolted connection is presented.
- Chapter 6. This chapter reports the conclusions and recommendations for future study.