Ministry of Higher Education and Scientific Research
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A Numerical Study to Evaluate the Performance of Stainless Steel Bolted Connections During Fire

A Thesis Submitted toThe Council of College of Engineering at University of Diyala in Partial Fulfillment of the Requirements for The Master Degree of Science in Civil Engineering– Structural Engineering.

BY

Nada Shuker Mahmood

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Supervised by

Prof. Dr. Mohammed Shihab Mahmood

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Abstract

Stainless steel bolted connections are essential components of steel structures. They play an important role in load transfer and ensuring structural integrity.It is essential to understand the behavior of stainless steel bolted connections during a fire. A numerical study using 29 models using the numerical analysis ABAQUS was used to simulate the structural performance of connections during a fire. The specimens were divided into five groups. The first group consisted of six specimens to study the effect of thickness, which includes ,1.5,to, 4.5, and 4 mm, and were exposed to a temperature of 650°C. The second group consisted of eight specimens to study temperature changes which includes, 22°C to,900°C. The third group used to study the bolt spacing, consisting of four specimens with dimensions of 24, to, 48. The fourth group used to study the effect of bolt spacing, consisting of four specimens with dimensions of 36, to, 72 . The fifth group studied the effect of end spacing, consisting of seven specimens with dimensions of 18, to, 52. The results showed that the 3 mm thick specimen achieved a tensile strength 95% higher than the 1.5 mm thick specimen. The 4.5 mm thick sample had a 231% higher strength than the 1.5 mm thick specimen, indicating a significant effect of thickness.

The temperature variation results showed that the Curling displacement at 300°C was 95.5% of the curling displacement at room temperature, while it was 92.5% at 400°C, 89.5% at 500°C, 83.6% at 600°C, 70.6% at 700°C, 71.6% at 800°C, and 62.7% at 900°C. When comparing the bolt spacing of the 32 mm with the specimen strength of the 24 mm bolt spacing, the percentage was 9.28%, while the 40 mm bolt spacing specimen had a 20.15% increase compared to the 24 mm bolt spacing specimen. The 48 mm bolt spacing specimen had a 26.71% increase compared to the 24 mm bolt spacing specimen.

In comparing the bolt diameter change for the 48 mm strength with the 36 mm bolt spacing specimen, the percentage was 7.20%. The 60 mm bolt spacing specimen had a 27.11% increase compared to the 36 mm bolt spacing specimen. The 72 mm bolt spacing specimen had a 49.44% increase compared to the 36 mm bolt spacing specimen.

CHAPTER ONE

INTRODUCTION

1.1 Background

Stainless steel, developed in 1912-1913 by Brearley in the UK and Maier and Strauss in Germany, has long been a source of inspiration for architects and designers due to its durability and aesthetics. Ernest Stuart, a flatware manager, popularized the phrase "stainless steel," which now refers to corrosion-resistant iron alloys with at least 10.5% chrome (Gardner 2005). Stainless steel has different material properties than carbon steel due to its high alloy content, both at room temperature and higher temperatures. At ambient temperature, stainless steel has a more relaxed stress-strain response than carbon steel, with no acute yield point, higher ultimate-to-yield stress ratio, and more ductility. Stainless steel maintains its strength and rigidity better than carbon steel at high temperatures. Austenitic stainless steel is ideal for long-term, high-temperature industrial applications due to its strength, oxidation resistance, and elevated temperature properties. It has been used successfully at temperatures up to 550 °C for many years (Hoke JH 1997, Davies CM2009. Recent research indicates that low nickel material stainless steel can offer similar durability benefits to traditional grades at a lower cost, making it a viable option in certain situations (Theofanous and Gardner, 2006).

1.2 Types of connections in steel structures

Steel constructions rely heavily on their connections to function properly. Proper connections can ensure optimal structural performance. Failures in connections can compromise the structure's unity and lead to collapse (Ketabdari et al, 2019). Connections ensure structural stability and load transmission. connections fall into two categories: bolts and welds. Design the connection to prevent failure in both the connecting region, as joint failure may not be ductile.

1.2.1 Bolted connections

Bolt are among the most common mechanical components used in a variety of businesses and life areas. They are used for securely connecting and assembling pieces. Their kinds and forms differ based on the substance and the needed attaching technique. Bolt vary in form, cutting procedure, head type, and material composition, making each kind suitable for a certain use under certain conditions.

Bolts enable removable assembly of building components. Bolts transmit the necessary axial or preloaded forces to the sections. Controlling the axial stress or preload of bolts is crucial for structural safety and reliability. Improper or excessive loading is a prevalent cause of bolt failure at the joint (Wang et al. 2013).

Bolted connections between beams and columns improve structural security and stability by carrying temperature and mechanical forces (Pang, X. P.,et al., 2019). According to (Quan et al. 2022), bolts have a considerable impact on both the structural behavior of connected members and the overall system.

1.2.2 Welded Connections.

Welded connections are among the most common forms of connections used in metal buildings and other engineering structures, since they serve a significant role in permanently and powerfully attaching structural elements. Welding is the process of melting metal components at the locations where the pieces to be connected meet, and then permitting it to cool down and solidify, resulting in a highly efficient junction capable of transferring weights. With technical developments and the growth of production technologies, welding has replaced traditional techniques such as bolt and rivets. This is owing to its benefits, which include lowering the total weight of the building, enhancing joint resilience to environmental variables, and enhancing aesthetics and simplicity of maintenance. Various methods of welding are employed in. This is owing to its benefits, which include lowering the total weight of the building, enhancing joint resilience to environmental variables, and enhancing aesthetics and simplicity of maintenance. In metal joints, many forms of welding are utilized, including electrical arc welding, welding with gas, and friction- stir welding. The proper kind is determined by the character of the load and operating circumstances. Understanding the features and design concepts of welded joints is a crucial component of civil or mechanical engineering, since the structural strength of any facility is directly proportional to the quality and effectiveness of its joints.

1.3 Mechanical and thermal characteristics of stainless and carbon steels.

Material qualities and their reactivity to high temperatures play a crucial role in structural fire design. Important factors include high temperature stress-strain, thermal expansion, thermal conductivity, specific heat, and unit mass. The following sections provide a comparison of the qualities of stainless steel and carbon steel.

1.3.1. Stiffness and strength retention.

A material's capacity to maintain strength and stiffness at high temperatures is vital for creating fire resistant buildings. Stainless steel retains strength and stiffness better than carbon steel at high temperatures, thanks to its alloying properties. Figures (1.1) and (1.2) provide a comparison of the raised temperature properties of steel made from stainless steel and structure carbon, with data from EN 1993-1-2 (2005) from the Euro Inox/SCI Specification Manual of Structural Stainless Steel .

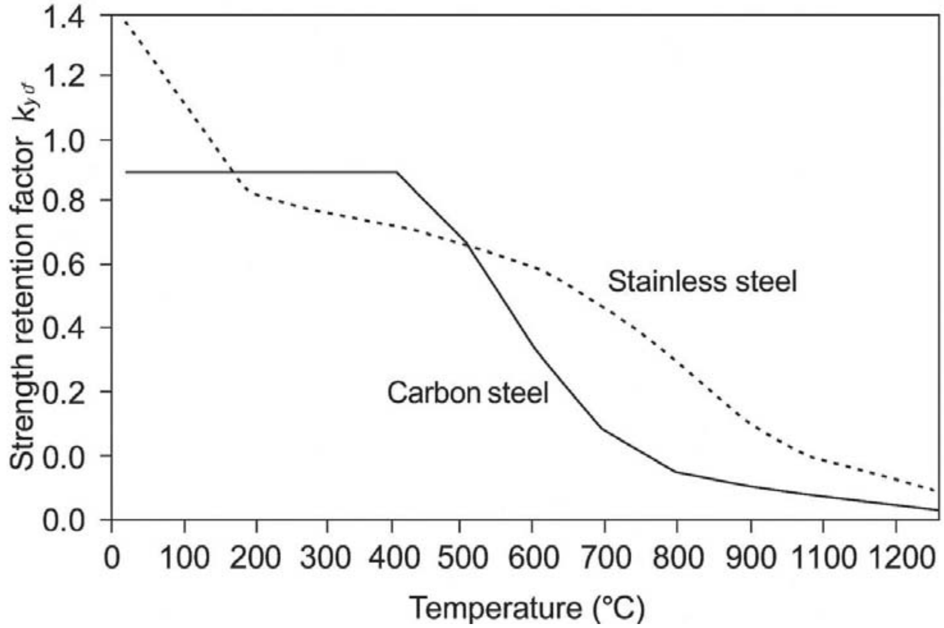


Figure (1.1) A comparison of strength decline at increasing temperatures (Gardner , 2006)

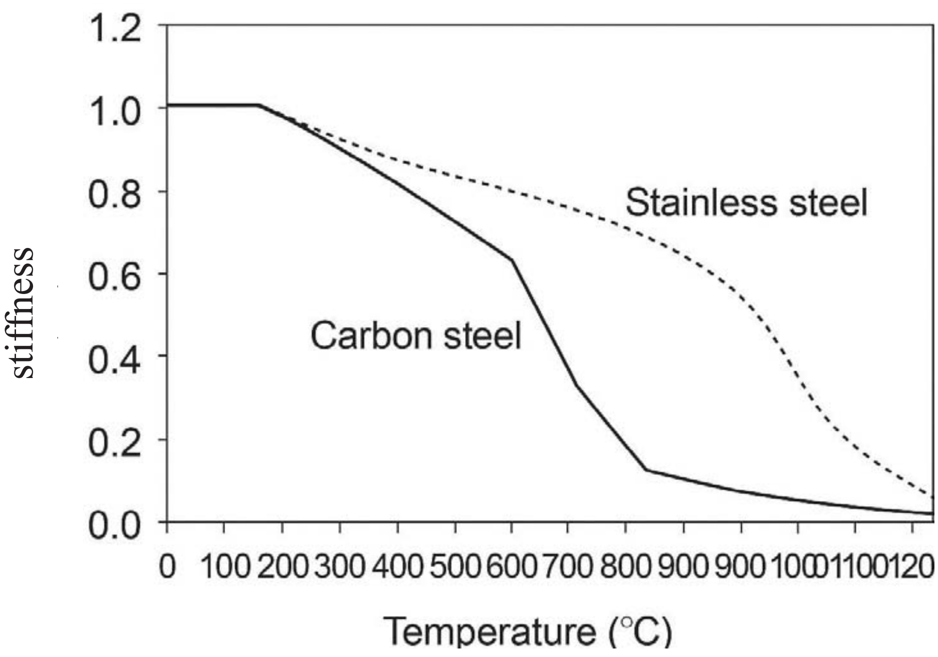


Figure (1.2) Depicts a comparison for stiffness reduction with increasing temperature (Gardner , 2006)

1.3.2 Thermal expansion.

All metals expand while heated. During fire component testing, structural elements often expand against the imposed force, resulting in no extra load. In structural frames with continuity between members and localized fires, other sections of the structure may limit thermal expansion, leading to extra member stress. Thermal expansion can cause greater axial and lateral member deformations, as well as increased forces and moments from second-order effects. Figure (1.3) compares the coefficient of thermal expansion of carbon and stainless steel based on EN 1993-1-2.

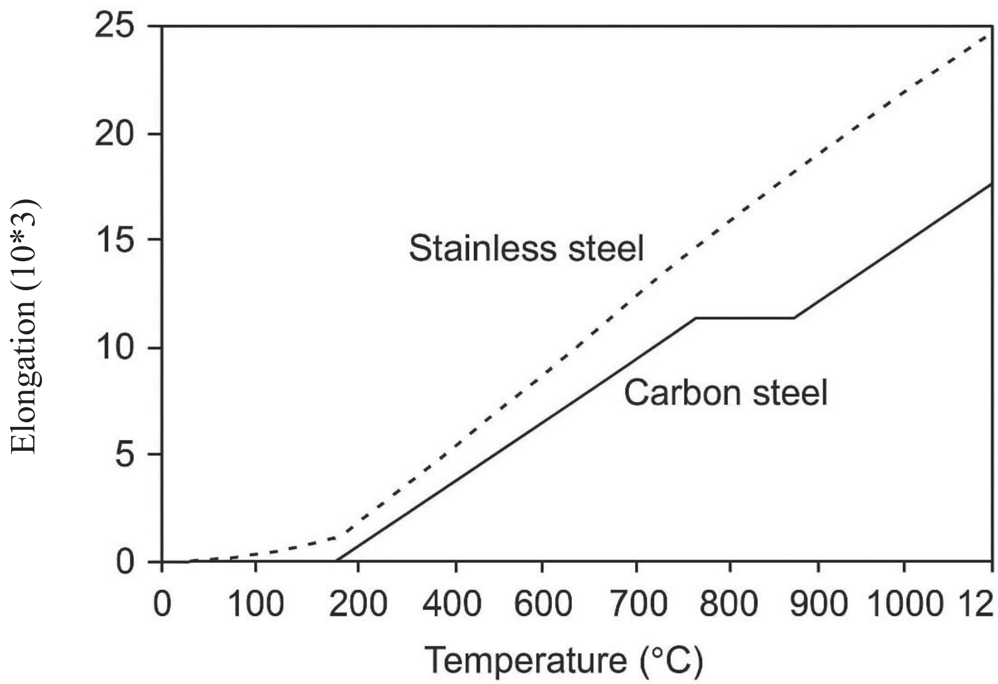


Figure (1.3) Temperature elongation in carbon and stainless steel (Gardner , 2006)

The graph indicates that stainless steel shows greater elongation than carbon steel. There has been no direct observation of the effect of increased thermal expansion on constrained stainless steel members or frameworks in fire. Restricted stainless steel structural members may suffer extra forces due to their increased thermal expansion and ability to maintain strength and stiffness at higher temperatures. The intensity of extra member forces depends on the loading arrangement and degree of rotation and translational constraint. Restrained thermal expansion can lead to greater member forces than higher stiffness and strength retention in some configurations.

1.3.3. Thermal conductivity.

Stainless steel has a substantial difference in its ability to conduct heat with temperature compared to carbon steel, as seen in Figure (1.4) EN1993-1-2 (2005).Eurocode3:designof steel structures . Carbon steel has a thermal conductivity of 53W/mK at ambient temperature, which gradually decreases to 27W/mK at 800℃. At 723℃, a phase transition occurs, resulting in constant thermal conductivity. Stainless steel has the reverse effect, increasing heat conductivity with time. Austenitic stainless steel does not undergo phase transformation when heated, resulting in a constant relationship with temperature. The value increases from 15W/mK at ambient temperature to around 30W/mK at 1200℃. At temperatures below 1000℃, stainless steel has poorer thermal conductivity than carbon steel. The difference is large at low temperatures, but insignificant beyond 700℃. Lower thermal conductivity can lead to more localized temperature development in steel frames. However, the difference in thermal conductivity among stainless steel with carbon steel is not thought to have any significant impact.

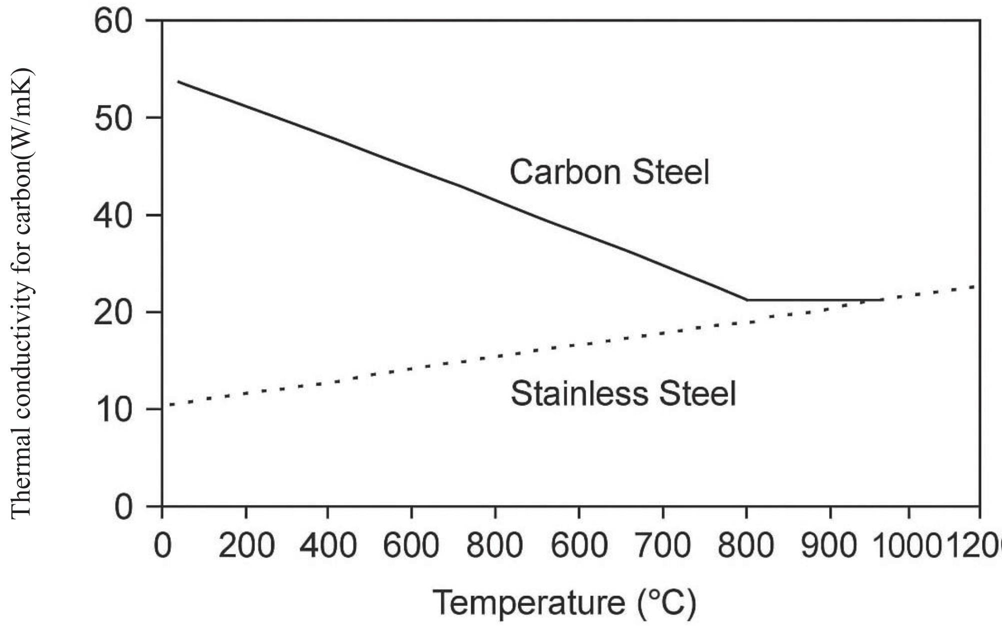


Figure (1.4) Thermal conductivity for carbon and stainless steel (Gardner , 2006)

1.3.4 Specific heat

Specific heat, also known as specific heat capacity, is the amount of heat required per unit of mass of a material to raise its temperature by 1°C. This feature is crucial for managing temperature development in structural members. Figure (1.5) shows the particular heat of stainless with carbon steel at different temperatures. Stainless steel's specific heat grows gradually with temperature, with no noticeable discontinuities (due to no phase transition). The specific heat Ca (J/kgK) for stainless steel can be calculated using Eq. (1-1) EN1993-1-2 (2005). Eurocode3 : design of steel structures , where Ca represents the temperature (100°C).

$$Ca = 450 + 0.280\,\theta_a - 2.91\times 10^{-4}\theta_a^2 + 1.34\times 10^{-7}\theta_a^3 \qquad (1\text{-}1)$$

Carbon steel has a slightly greater specific heat than stainless steel and exhibits a phase shift about 723°C. Carbon steel has a higher specific heat (600J/kgK) than stainless steel (550J/kgK). Materials with higher specific heat tend to heat up more slowly.

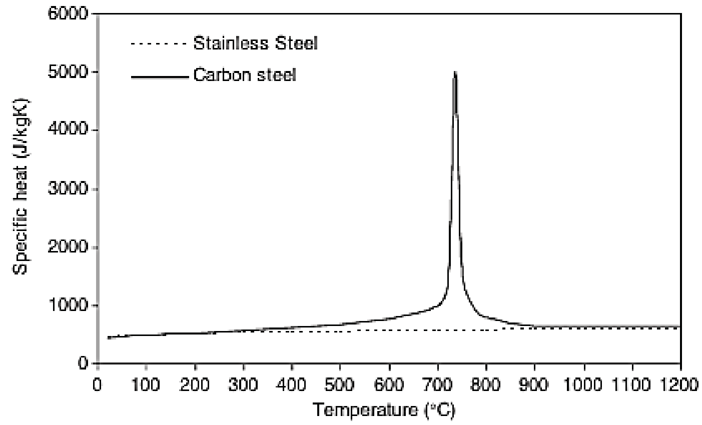
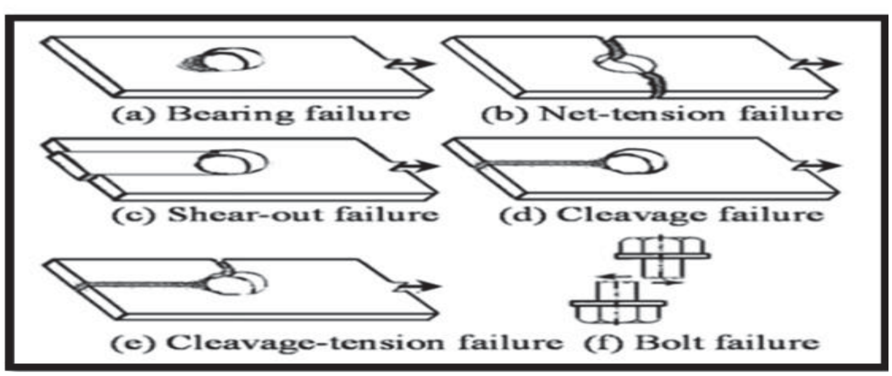


Figure (1.5) Specific heat for carbon and stainless steel (Gardner 2006)

1.4 Failure Types for Bolted Connections.

Bolted tensile connections can break due to net stress, failure of shear, cleavage failure, or block shear failure, as illustrated in Figure 1-6-a. The bolt hole reduces the cross-sectional area, resulting in lower tensile strength and plate fractures at the bolt line. Shear failure happens when a plate becomes unable resisting shear and breaks in the shear direction. Failure of cleavage happens to connection with short end distances. Block shear failure happens when shear fractures and net tensile fractures occur simultaneously. Kim et al. (2007) found that when a bearing fails, the bolt neck section gradually pulls the plate under stress. Finally In 2011, Kim observed curling failure in thin plates with a free edge from a connection under tensile tension (Fig 1-6-a-b). Kim et al. (2011) found that curling leads to a loss in strength at the ultimate load.



a- Failure types for single-bolt lap-joint in-plane connections, (Kim et al, 2011)

b. Curling Failure (Kim and Kuwamura, 2011)

Figure (1-6) Failure modes of connections with bolts.

1.5. Aim and Objectives

The research aims to provide basic knowledge on the behavior of thin-walled stainless steel bolted connections during fire. To achieve this goal, the following objectives were identified:

1. Study the effect of thickness on bolted connections at high temperatur.

2. Study the effect of temperature changes on bolted connections behaviour.

3. Study the effect of bolt spacing on bolted connections behavior during fire.

4. Study the effect of bolt spacing diameter on bolted connections behavior during fire.

5. Study the effect of end spacing on bolted connections behavior during fire.

1.6 Summary of Study

The thesis was broken into five chapters, which are summarized below:

• **Chapter One** Provides a broad introduction to the study background, thesis domain, and outline.

• **Chapter Two** This chapter provides an overview of the thesis topic through a study of relevant literature. This chapter organizes prior studies into Two divisions. The first showcases specimens examined at normal temperature. The second category consists of items evaluated under elevated temperatures .

• **Chapter Three** covers the finite element method software (ABAQUS version 2019).To understand the behavior of stainless steel during fire.

• **Chapter four** presents a case study using the finite element approach for bolt connection under temperature load, as well as a verification challenge for bolted connections.

• **Chapter five** summarizes the study's conclusions and recommendations for future research.