AMERICAN UNIVERSITY OF BEIRUT

POST-FIRE RESPONSE OF S235 STEEL PLATES CONSIDERING DIFFERENT BOLT HOLE-MAKING PROCESSES

by
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ABSTRACT
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Title: Post-Fire Response of S235 Steel Plates Considering Different Bolt Hole-Making Processes

This study aims at investigating the effect of bolt hole-making processes on the post-fire behavior of S235 steel plates. To address this issue, a total of nine steel plates with a single bolt hole are tested in this study. The single bolt holes are fabricated using three different hole-making processes: drilling, waterjet, and plasma. Among the nine steel plates, three fabricated specimens are control specimens and are tested at ambient temperature. The six remaining steel plates with a single bolt hole are subjected to a complete heating-cooling cycle and then monotonically loaded until failure. The six fabricated specimens are first heated up to two different temperatures 800°Cand 925°C and then cooled back to the ambient prior to loading. The residual responses are characterized as load-displacement characteristics after being exposed to a complete heating and cooling cycle.
The results show that after being exposed to post-fire temperatures (800°C and 925°C), the maximum decrease in strength of the S235 steel plate was 6% (at 925°C), 14% (at 925°C), and 22% (at 800°C) when compared to the results of ambient specimens for waterjet, drilled, and plasma bolt holes, respectively. In addition, for post-fire temperature tests, drilled and waterjet bolt hole-making processes result in having approximately the same load-displacement response and both have larger strength and ductility than those obtained using plasma cutting.
This study provides preliminary data to guide the steel designers and fabricators in choosing the most suitable hole-making process for fire applications and to quantify the reduction in capacity of the S235 steel plates after fire exposure.

TABLE OF CONTENTS

ILLUSTRATIONS

Figure

TABLES

Table

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Steel structures experience residual stresses after being exposed to fire temperatures. These residual stresses can potentially act as unexpectable additional loads on the steel elements and components that reduce their strength capacity. This reduction in strength capacity can threaten the integrity of the entire structure. Therefore, it is of great importance to evaluate the residual strength capacities of different steel base materials, welds, and bolts after a fire event. However, these residual capacities are not only dependent on fire temperature exposure but also on the material grade, geometric properties, and fabrication process used to fabricate steel plate profiles and bolt holes.

Different hole-making processes used to create bolt holes in steel plates can result in varying levels of heat generation and material removal, which can influence the residual stress distribution in steel plates during a fire. By selecting a hole-making process that minimizes the risk of high local stresses and optimizing the hole size and shape, the structural integrity of steel connections can be maintained in fire conditions. In industrial applications, various hole-making processes are used, such as punching, drilling, thermal cutting, and reaming.

One of the most common methods for creating holes is drilling. Drilling a bolt hole involves using a drill bit attached to a drilling machine. This process requires centering the drill bit on the marked spot, rotating the drill, and adjusting the bit size and pressure for the desired hole size and depth. Drilling is frequently used when the plate is too thick for punching. However, as the hole becomes deeper, it is hard to regulate the heat accumulation and chip removal. The material around the hole is not significantly affected by the drilling process. Another hole-fabrication process used in industry is the punching process. Punching is the process of removing a cylindrical part from the steel plate by forcing a punch through the material in a punching die, creating a hole in the plate. Punching provides a quick and affordable alternative to drilling. This type of hole is commonly used for secondary tension members such as cross frames and angle braces in bridges. During the punching operation, the localized area surrounding the hole is severely damaged. Another method of creating holes is the water or abrasive jets. Both processes use high pressures of water to make holes in steel. The most common use of waterjets is to cut thinner steel plates since waterjets are ineffective for cutting thick plates. The same process as water jets is used by abrasive jets, but abrasive particles are inserted into the jets to allow the cutting of up to 2 to 3" thick plates. The drilling, punching, and waterjet cutting are cold cutting processes, meaning they do not produce heat-affected zones or thermal distortion.

The thermal cutting process can be performed by many techniques. The most common processes are oxy-fuel cutting, plasma cutting, and laser cutting. Oxy-fuel cutting (or flame cutting) is an old thermal cutting process that uses a high-temperature flame created by a mix of oxygen and fuel gas. During the oxy-fuel process, the metal is oxidized by the oxygen-fuel process and melted by the exothermic reaction's heat. The oxy-fuel process can cut materials from 1 to 12 inches thick. Also, it is relatively inexpensive and can be operated manually or by computer. Plasma cutting, being a fast and practical thermal cutting process, has been considered an alternative to oxy-fuel cutting. During the plasma cutting process, the metal is melted using direct heat from an electric arc resulting in a heat-affected zone around the bolt hole. Laser cutting is the most efficient process when higher accuracy and superior appearance are required. Laser cutting minimizes the heat-affected zone and removes the heat-induced distortion by concentrating the necessary energy into a tiny and dense region.

Furthermore, reaming is a hole-making process used to enlarge the hole created by sub-drilling, sub-punching, or thermal cutting using a tapered bit. Holes made by sub-punched can be reamed to remove small surface cracks and work-hardened material. Moreover, reaming a thermal cutting hole can eliminate the notches and heat-affected material. Therefore, reaming is a good process to remove the effects of different hole-making processes. In general, holes made by punching or thermal cutting have a diameter of 1/8 in. to 1/4 inch smaller than the required diameter and then reamed to the required size.

At ambient temperature, the effect of bolt hole-making processes on the mechanical properties of steel plates has been studied by many researchers. Among these previous studies, Yuan (2005) conducted an experimental investigation to study the effect of bolt hole-making processes on the strength and ductility of steel tension members. The specimens used in this study had a single bolt hole at mid-length and were made from A36 (S235) and A588 (S355) materials. The bolt holes were made by drilling, punching, and flame cutting. The specimens were tested under monotonic loadings. The results showed that the strength ratios, which are the ultimate stress divided by the maximum coupon stress, exceeded one for all bar specimens except for the punched A36 bar specimens. The ductility ratio and load-deformation responses showed that drilled specimens were the most ductile. The second most ductile specimens were the flame cut specimens, and the punched specimens were the least ductile. In addition, four specimens were tested under cyclic loadings, but the results showed that there was no decrease in strength and ductility. Another study was conducted by Hantouche et al. (2012) to investigate the effect of the common bolt hole-making processes on steel components of built-up T-stub connections. For this purpose, 10 steel plates made of A572 Grade 50 with six bolt holes at mid-length were tested under monotonic or cyclic loadings. The results showed that bolt holes fabricated by drilling and flame cutting exhibited higher ductility and slightly higher ultimate strength than those fabricated by punching, short-slotted punching, and short-slotted flame cutting. Therefore, it was recommended to use standard drilled bolt holes for detailing elements subjected to significant plastic deformation demands. However, the short-slotted bolt holes were not recommended for elements subjected to significant inelastic deformations under tension because they had poor ductility and did not offer enough elongation at failure. Furthermore, another experimental investigation was conducted by Brown et al. (2007) to study the tensile effects of punched, drilled, and slotted holes in structural steel plates and connections. Different plate thicknesses and steel grades were incorporated in this study. The results of the plate tensile tests showed that the strengths of the punched hole specimens were 5-12% less than drilled hole specimens. In addition, the strength and ductility of slotted holes created with all methods were higher than punched round hole plates but lower than drilled round hole plates. Moreover, Jiménez-Peña et al. (2019) studied the effect of the most common hole-making processes on the fatigue behavior of the high-strength steel grade S500MC (Grade 70). The results of this study showed that punched specimens had the lowest fatigue performance, and laser cutting specimens exhibited the highest fatigue performance. Drilled specimens exhibited a fatigue performance close to that of plasma specimens, and waterjet specimens had better fatigue performance than the plasma and drilled specimens.

All previous studies investigated the effect of bolt hole-making processes on the mechanical properties of steel plates at ambient temperature under different loading conditions. None of these considered the effect of bolt hole-making processes after being exposed to fire temperatures. However, many studies have been conducted to investigate the residual mechanical properties of steel base material. The results of these studies showed that the post-fire mechanical properties of many steel base materials such as S460 (Qiang et al. (2012) and Wang et al. (2015)), S690 (Qiang et al. (2012), Li et al. (2017), and Wang (2020)), and S235 (Lu et al. (2016) and Sajid and Kiran (2018)) are almost unaffected until they are exposed to temperatures exceeding 600℃. More specifically, for S235 (ASTM A36) steel, the load-displacement behavior is approximately the same for post-fire temperature below 600℃ and considerably changes for post-fire temperature above 700℃ (Lu et al. (2016) and Sajid and Kiran (2018)).

The hole-making processes have significant effects on the mechanical properties of steel plates at ambient temperature, and steel material also experiences a change in its mechanical properties after exposure to post-fire temperatures. None of the previous studies considered the effect of both the bolt hole-making processes and the post-fire temperatures on the mechanical properties of steel plates. Therefore, in this study, six specimens with drilled, plasma, and waterjet bolt holes are tested after being exposed to post-fire temperatures. The specimens are heated up to target temperatures (800°C and 925°C) and then cooled back to ambient temperature (20°C) before loading. This investigation is a step toward understanding the effect of hole-making processes on the post-fire behavior of S235 steel plates subjected to monotonic loadings. Therefore, this study provides preliminary, but necessary, data to develop recommendations for bolted connections after being exposed to fire temperature while considering the effect of different bolt hole-making processes and to guide steel designers and fabricators in choosing the most suitable hole-making process for fire applications.

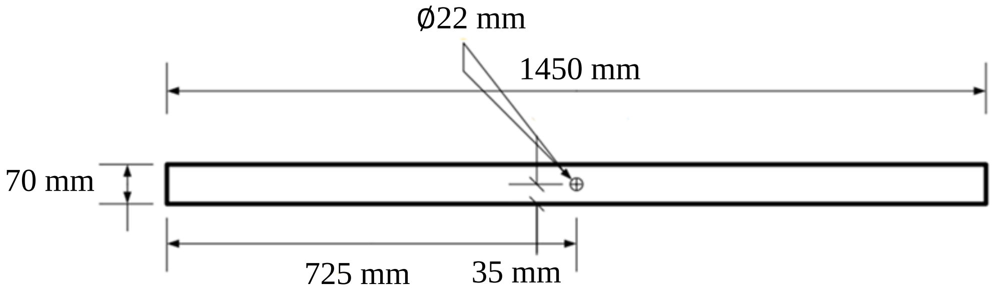
CHAPTER II

EXPERIMENTAL PROGRAM OF STEEL PLATES WITH DIFFERENT BOLT HOLE-MAKING PROCESSES

This chapter describes the procedure followed to perform the experimental tests. It consists of four sections: test specimens, setup and instrumentation, tensile testing, and test loading protocol. The test specimens section describes the steel plates used in this study, including the dimensions, material type, and fabrication process used to fabricate steel plate profiles and bolt holes. The setup and instrumentation section describes the machine used to conduct the tensile tests, the furnace used to heat the specimens, and the number, type, and location of the thermocouples. The tensile testing section describes the steps to perform the tensile tests using the Tinius Olsen Universal Testing machine. Finally, the test loading protocol section describes the heating, cooling, and testing stages.

A. Test Specimens

The steel plates used in this study had a thickness of 20 mm, width of 70 mm, and length of 1450 mm. All plate materials were made of S235 (ASTM A36), and they were cut using the plasma cutting process. Therefore, the only difference among the steel plates was the hole-making processes. Three different hole-making processes, drilled, waterjet, and plasma, were used to fabricate a 22 mm standard hole at the mid-length of the steel plates. The steel plates were designed as per ANSI/AISC 360 (2016) to fail in net section fracture at the bolt hole for both ambient and elevated temperatures. The details of the steel plates with a single bolt hole are shown in Figure 1. Figures 1(a) and 1(b) represent the plan and side views of the steel plates, respectively. In addition, a specimen of the steel plates with a single bolt hole is shown in Figure 1(c).



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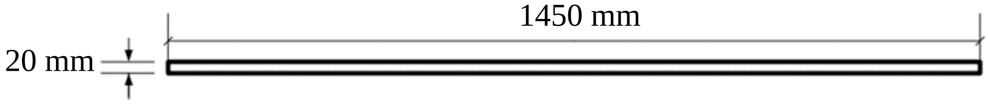

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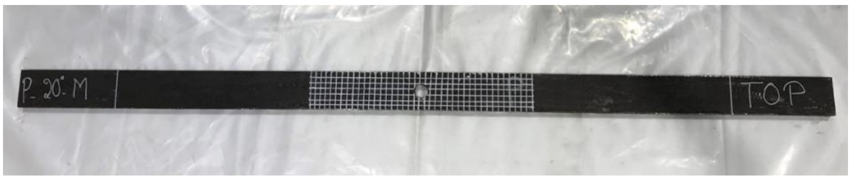
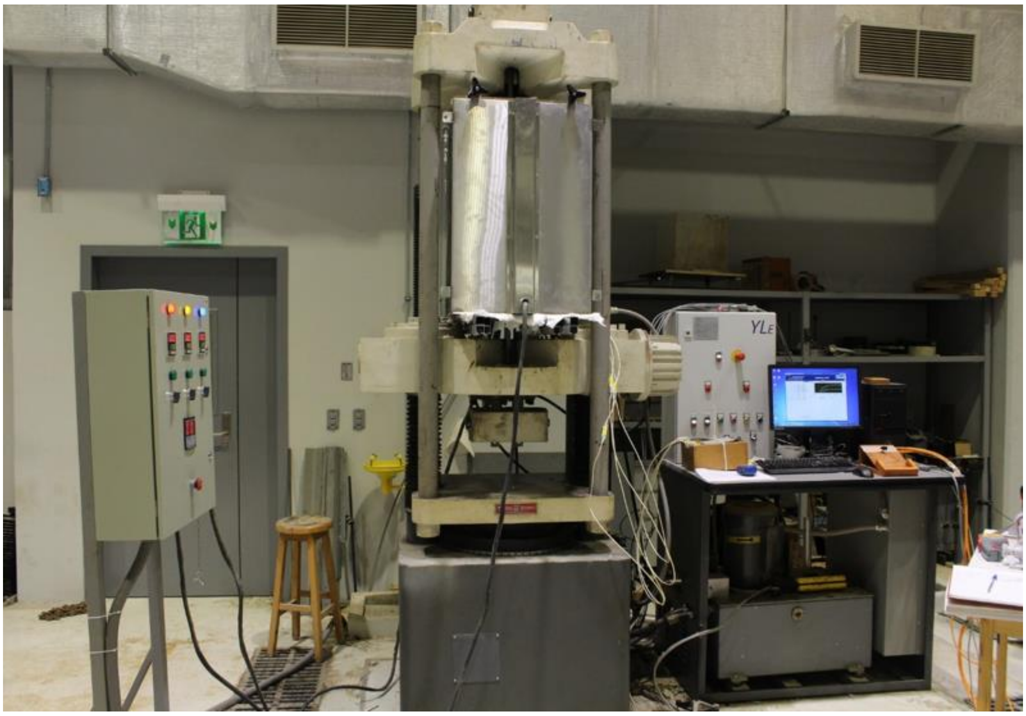


(c)

Figure 1. Layout of the steel plates with a single bolt hole: (a) Plan view, (b) Side view, (c) Specimen

B. **Setup and Instrumentation**

A 200 tons capacity Tinius-Olsen Universal Testing Machine was used to conduct the tensile testing of the steel plates with a single bolt hole after being exposed to fire temperatures. An 800 mm x 550 mm x 830 mm electric furnace was used to heat the test specimens to target temperatures. The setup instrumentation during the heating and cooling phases of the testing program is shown in Figure 2(a) and Figure 2(b), respectively.



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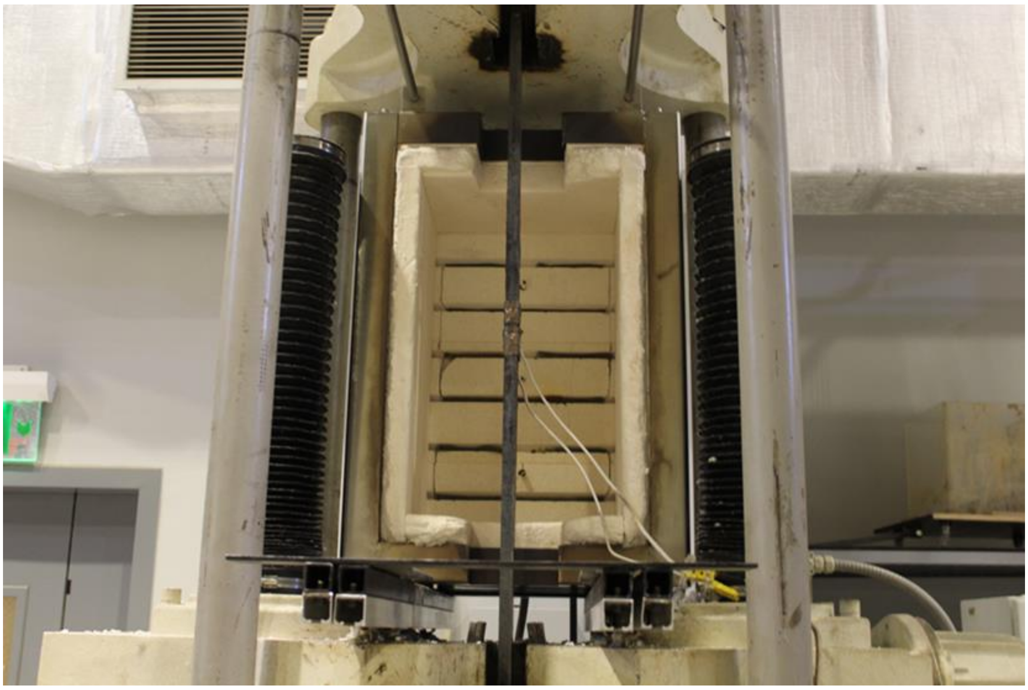


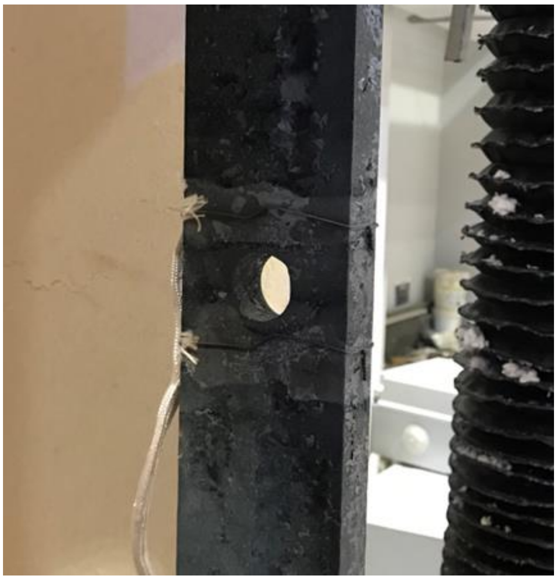
(b)

Figure 2. Tinius-Olsen Universal Testing Machine coupled with the electric furnace: (a) Heating phase, (b) Cooling phase

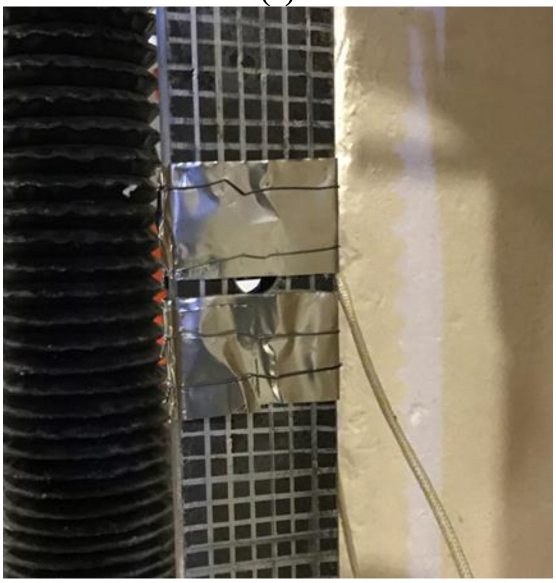
The electric furnace shown in Figure 3 is comprised of three separate heating zones, and each zone can be regulated separately by a temperature controller system (Figure 4). Insulation material is distributed all around the furnace to prevent heat loss and machine damage. Two thermocouples (type K) were used above and below the bolt hole of the steel plate as shown in Figure 5(a) to ensure a uniform temperature distribution around the bolt hole location. In addition, the specimens were covered by stainless steel foils (SSF) to protect the two thermocouples from being directly exposed to thermal radiation emitted from the furnace heating elements as shown in Figure 5(b). Note that the temperature of the specimens and the load-displacement relationship were manipulated using a data acquisition system (Figure 6).

Figure 3. Electric furnace

Figure 4. Temperature controller system



(a)



(b)

Figure 5. Thermocouple implementation: (a) Thermocouples (b) Stainless steel foil

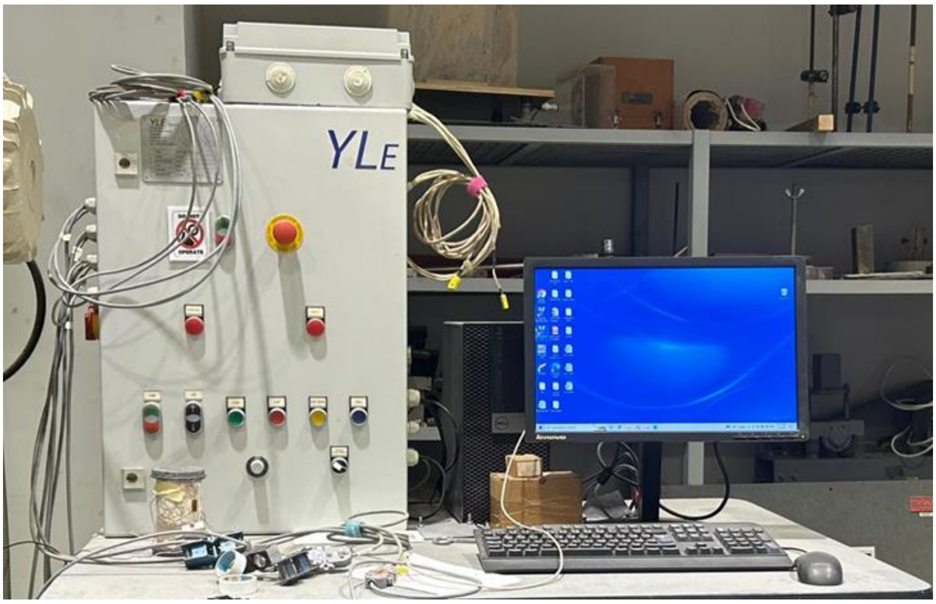


Figure 6. Data acquisition system

C. Tensile Testing Using Tinius Olsen Universal Testing Machine

Tinius Olsen Universal Testing Machine shown in Figure 7 is used to perform the tensile testing of the steel plates. Using a constant crosshead displacement, the crosshead of the testing machine is moved at a constant rate, in millimeters per minute. As the crosshead moves, it applies a tensile load to the specimen, which elongates until failure. The load, crosshead displacement, and time are recorded continuously throughout the test. The Tinius-Olsen Universal Testing Machine is connected to a data acquisition (DAQ) system, which is used to control and collect data from the test. The DAQ system provides precise control over the crosshead movement rate and enables real-time monitoring of the load and displacement. The data collected by the DAQ system can be analyzed and used to create graphs, charts, and reports that provide detailed information about the mechanical properties of the tested specimen. The steps followed to perform tensile testing using the Tinius Olsen Universal Testing Machine are:

- Set-up: The specimen is clamped in the grips of the machine and the crosshead is positioned at the starting point of the test. The LVTDs are installed on the specimen to measure its elongation. The test parameters, such as displacement rate, are set on the control panel of the machine.

- Loading: The machine applies a controlled displacement to the specimen at a constant rate while continuously measuring the force required to maintain that displacement.
- Data Collection: The machine records the load and displacement data throughout the test and the test results can be analyzed to determine the material's tensile strength, elongation, and other properties.
- Results: The tensile test results are plotted on a graph, which shows the load vs. displacement relationship. The maximum load (or peak load) reached during the test represents the material's ultimate tensile strength, while the amount of displacement at that peak load represents the material's elongation.

Figure 7. Tinius Olsen Universal Testing Machine

D. Test Loading Protocol

To study the effect of hole-making processes on the post-fire behavior of steel plates with a single bolt hole, the specimens were heated up to the desired temperature by turning on the furnace and increasing its temperature by 100°C increments. The two target temperatures were chosen as 800℃ and 925℃ since the load-displacement behavior is approximately the same for post-fire temperature below 600℃ and considerably changes for post-fire temperature above 700℃ for S235 base plate material (Lu et al. (2016) and Sajid and Kiran (2018)). In addition, the specimens were not tested at 1000℃ to avoid damaging the furnace since it is the maximum furnace temperature. After reaching a target temperature, the temperature was held constant for 60 min to ensure a uniform temperature distribution around the bolt hole location. Then, the specimens were cooled back to ambient temperature after turning off the furnace. During the cooling stage and after temperature reaches approximately 60°C, one of the furnace compartments was removed. After the temperature of the specimens cooled back to ambient, the specimens were loaded with a constant machine crosshead displacement rate of 4mm/min until failure. The test matrix of the post-fire behavior of the steel plates with a single bolt hole fabricated with different hole-making processes is presented in Table 1.

Table 1. Test matrix for the steel plates with different hole-making processes

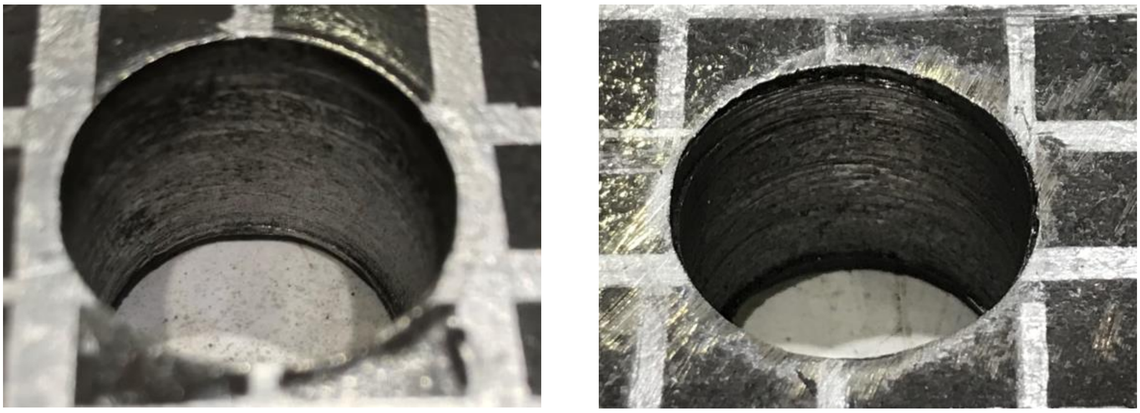
Test Number	Test Name	Hole Fabrication Process	Temperature (˚C)	Loading Protocols	Expected Failure
1	P-20˚C-M	Plasma	20	Monotonic	Net section
2	P-800˚C-M-R		800	Monotonic	Net section
3	P-925˚C-M-R		925	Monotonic	Net section
4	D-20˚C-M	Drilling	20	Monotonic	Net section
5	D-800˚C-M-R		800	Monotonic	Net section
6	D-925˚C-M-R		925	Monotonic	Net section
7	W-20˚C-M	Waterjet	20	Monotonic	Net section
8	W-800˚C-M-R		800	Monotonic	Net section
9	W-925˚C-M-R		925	Monotonic	Net section
Note that: P: Plasma, D: Drilled, W: Waterjet, R: Residual, M: Monotonic					

CHAPTER III

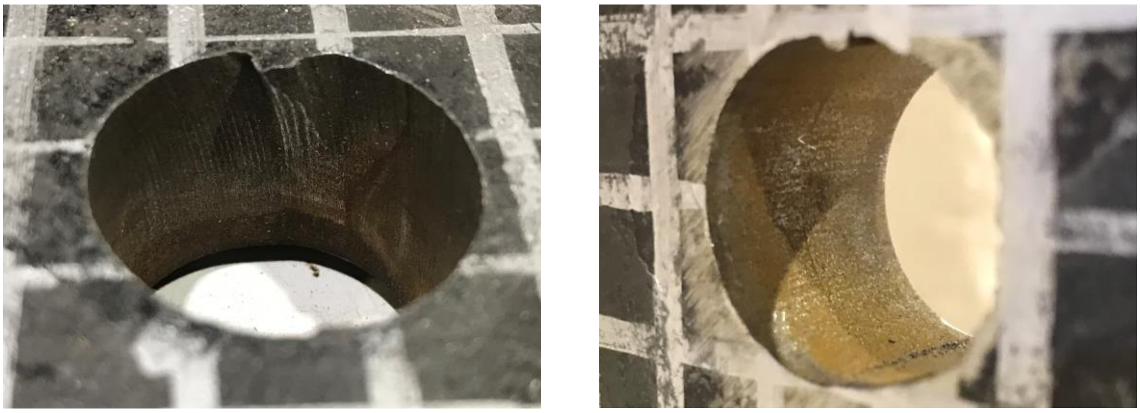
EXPERIMENTAL RESULTS OF STEEL PLATES WITH DIFFERENT BOLT HOLE-MAKING PROCESSES

A. General Observations

Bolt holes fabricated with different hole-making processes are shown in Figures 8(a), 8(b) and 8(c). It can be seen from Figure 8(a) that bolt holes fabricated by drilling had smooth and uniform surface texture throughout the inside of the hole with a regular circular shape, and the surface also had some visible ridges that correspond to the shape of the drill bit. Holes fabricated by waterjet cutting also had smooth and uniform surface texture, but Figure 8(b) shows that the edge of the waterjet holes had some imperfections caused by the initial penetration of the waterjet stream into the steel plate. It can also be seen from Figure 8(c) that bolt holes fabricated by plasma cutting had non-uniform surface texture with an irregular circular shape. During the plasma cutting process, the intense heat generated by the plasma arc disturbs the natural protective oxide layer of the steel material, making it more susceptible to corrosion. Therefore, drilling produces the smoothest holes, while plasma cutting results in irregular and distorted holes due to the direct heat usage in this process, whereas waterjet cutting produces smooth holes with some imperfections at the hole edges.



(a)

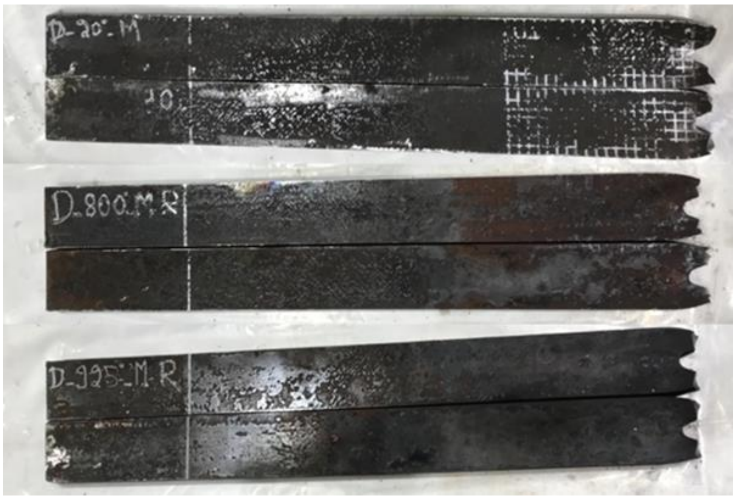


(b)

(c)

Figure 8. Hole surfaces of different bolt hole-making processes at ambient temperature for: (a) Drilled-hole, (b) Waterjet-hole, (c) Plasma-hole

After the specimens were subjected to a complete heating and cooling cycle, the exposed surfaces exhibited a change in color with the change in the exposed temperature as seen in Figure 9. More specifically, for 800°C post-fire temperature tests, the exposed surface of the specimens had a reddish-gray color, that turned to gray as post-fire temperature increased to 925°C. For post-fire structural assessment, this color change can help in identifying the temperature that steel connection experienced after being exposed to fire events.



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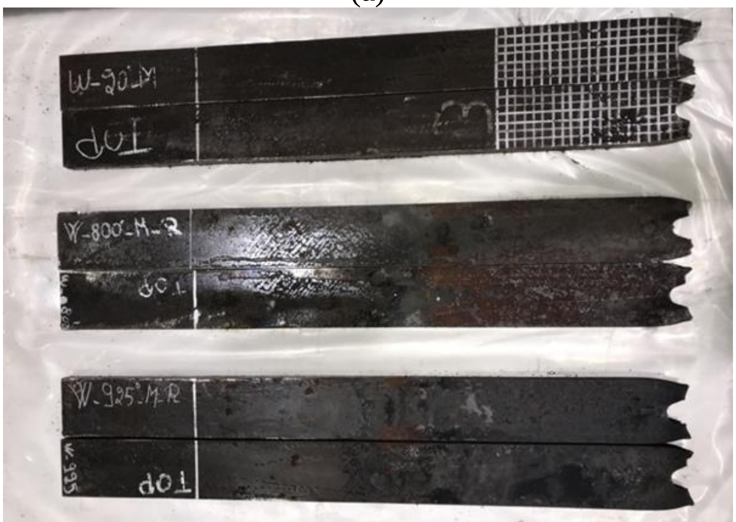

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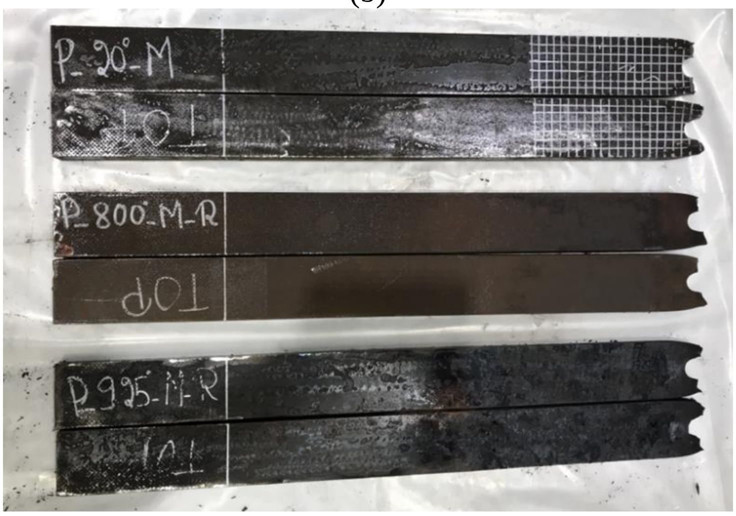
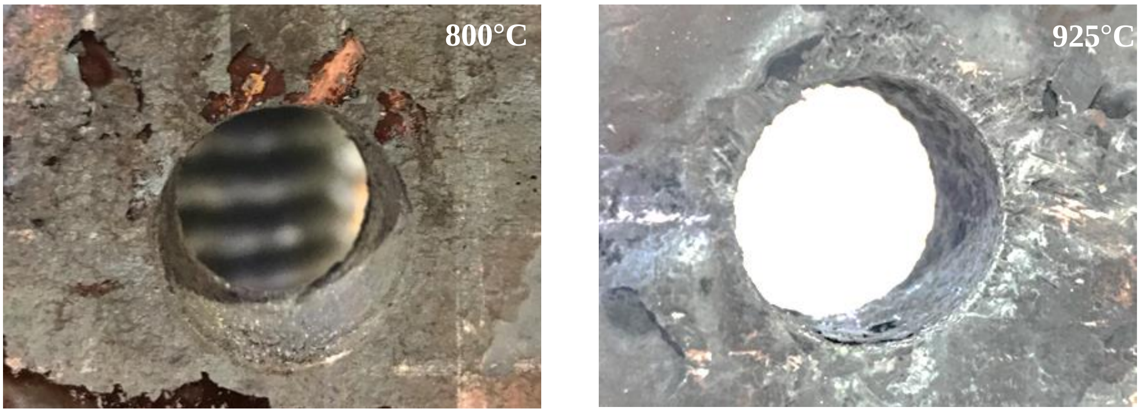


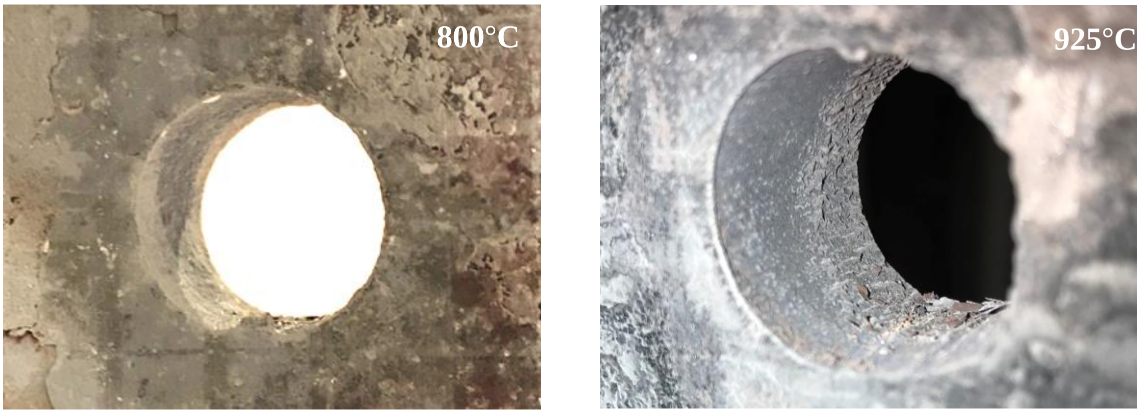
(c)

Figure 9. Failure at the net section for all test specimens at ambient and post-elevated temperatures: (a) Drilled, (b) Waterjet, (c) Plasma

In addition, Figures 10(a), 10(b), and 10(c) represent the drilled, the waterjet, and the plasma holes, respectively, after being exposed to fire temperatures. It can be seen from these figures that after being exposed to high temperatures, the surface of all these holes became slightly roughened. However, the overall shape of the bolt holes after being exposed to fire temperatures remained unchanged.



(a)



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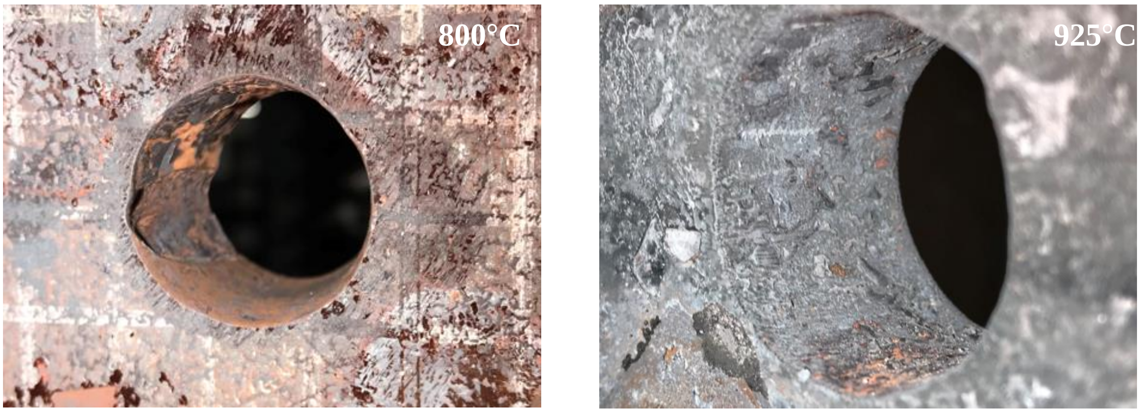
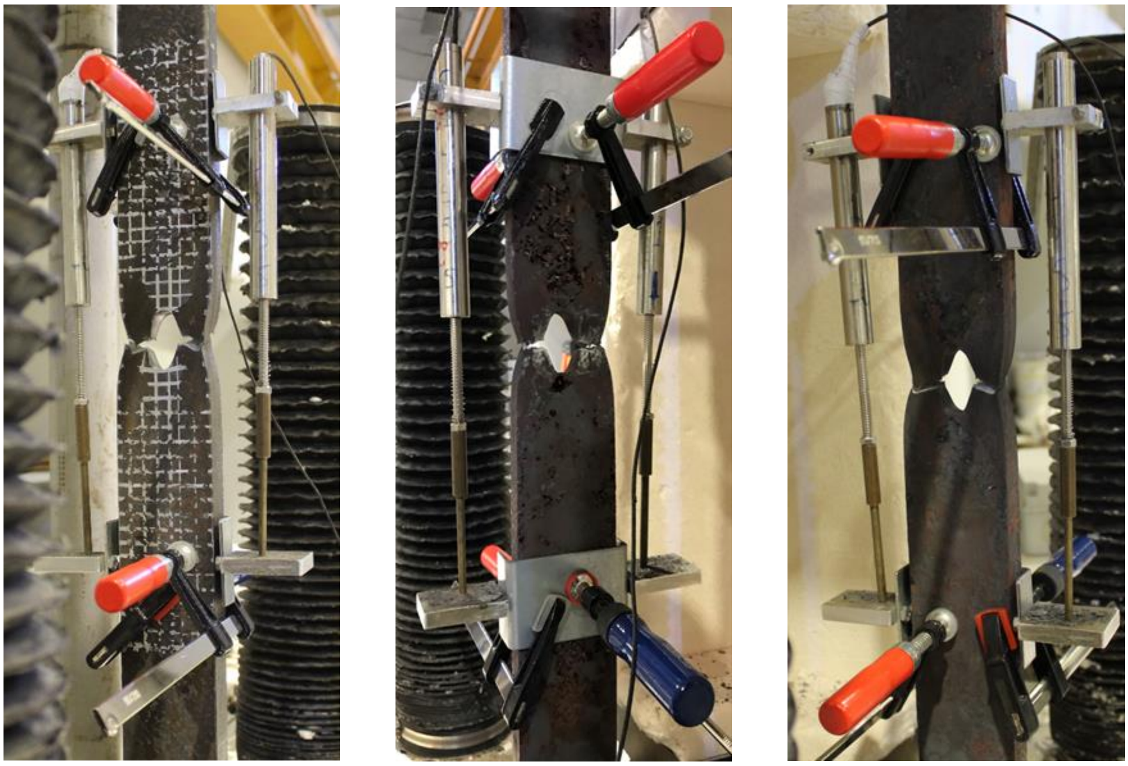


(c)

Figure 10. Hole surfaces of different bolt hole-making processes at post-fire temperatures (800°C and 925°C): (a) Drilled-hole, (b) Waterjet-hole, (c) Plasma-hole

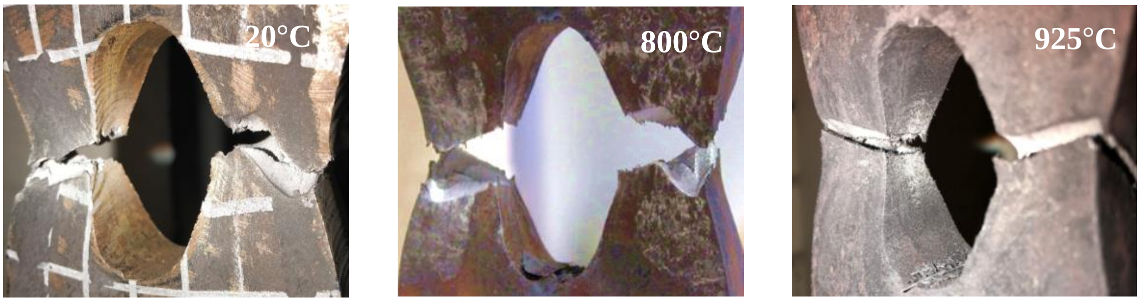
After conducting the tensile tests, the failure modes of the single bolt hole specimens at ambient and post-fire temperatures are shown in Figure 11. It can be seen that the specimens failed in net section fracture at the bolt hole for both ambient and post-fire temperatures. The net section fracture at the bolt hole for all specimens, whether having drilled (Figure 12(a)), waterjet (Figure 12(b)), or plasma (Figure 12(c)) hole, was along a line perpendicular to the direction of the tensile load.



(a) (b) (c)

Figure 11. Fracture modes of the single bolt hole specimens at ambient and post-fire temperatures: (a) 20°C, (b) 800°C, (c) 925°C

(a)



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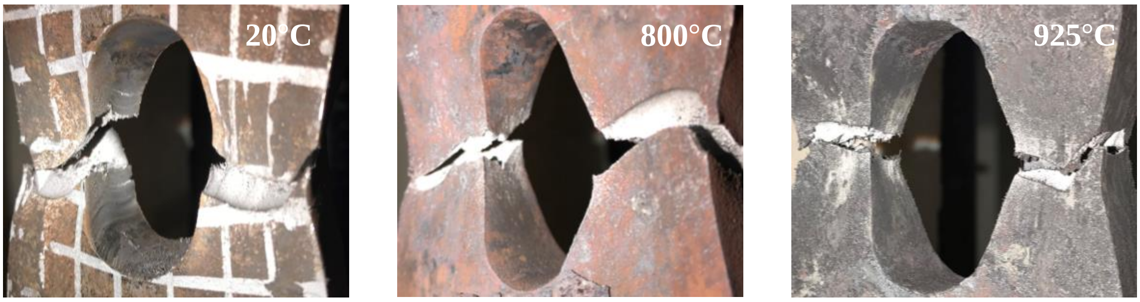
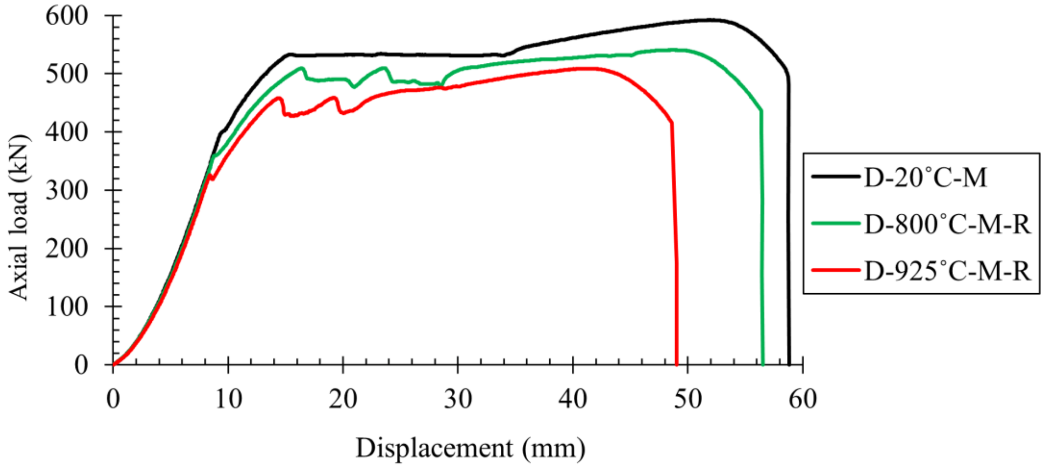


(c)

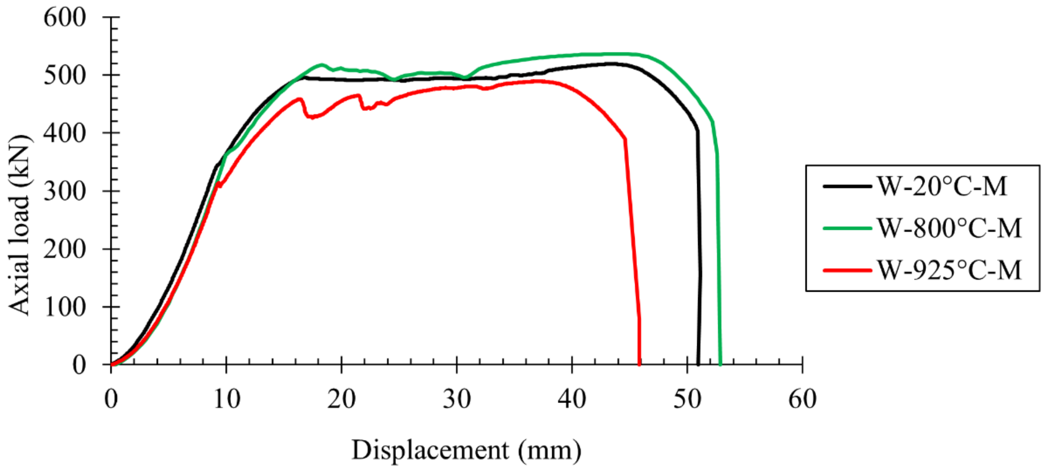
Figure 12. Failure modes for specimens with different bolt holes at ambient (20°C) and after exposed to elevated temperatures (800°C and 925°C): (a) Drilled-hole, (b) Waterjet-hole, (c) Plasma-hole

B. Residual Load–Displacement Response

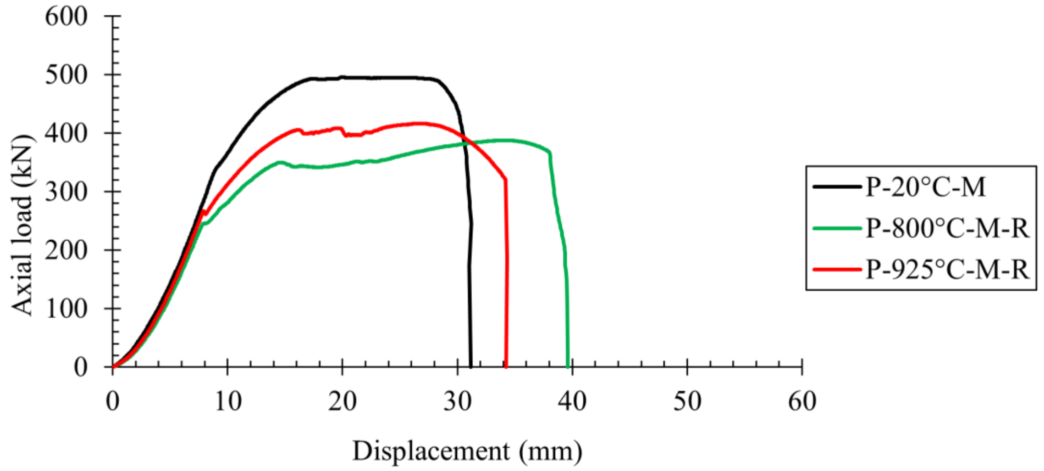
The residual load-displacement responses of the steel plates with three different bolt hole-making processes are represented in Figure 13. Figure 13(a) shows that the strength of the steel plates with a drilled bolt hole decreases with the increase in post-fire temperatures. For waterjet bolt holes (Figure 13(b)), no significant change in load-displacement characteristics occurred after being exposed to 800 °C compared to the ambient test. However, for 925°C test, the strength of waterjet specimen decreases with temperature. Interestingly, for specimens with a plasma bolt hole (Figure 13(c)), the strength of the specimen subjected to a peak temperature of 800 °C is less than the test occurred after being exposed to 925°C. Therefore, the residual strength of the steel plates with different bolt hole-making processes depends on the peak temperature exposure during the heating phase.



(a)



(b)



(c)

Figure 13. Residual load–displacement response of the steel plates with a single bolt hole: (a) drilled, (b) waterjet, (c) plasma

C. Percentage decrease in the ultimate strength

The percentages decrease in the ultimate strength of the S235 steel plates after being exposed to post-fire temperatures while considering three different bolt hole-making processes are illustrated in Figure 14.

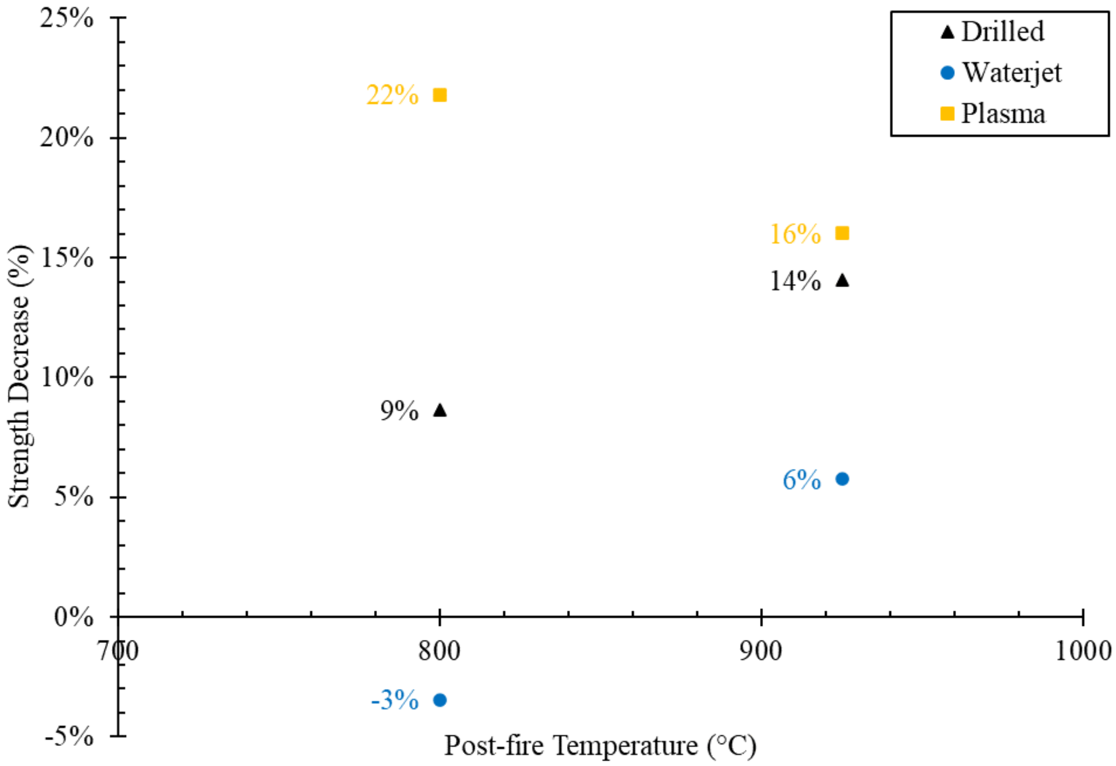


Figure 14. Percentage decrease in strength for the steel plates with three different bole-hole making processes after exposed to elevated temperature

It can be seen that the percentage decrease in strength of the specimens with a drilled bolt hole is 9% and 14% as being exposed to 800°C and 925°C post-fire temperatures, respectively. For the specimens with a waterjet bolt hole, there is no decrease in strength for post-fire temperature of 800 °C, and the percentage decrease in strength is only 6% as post-fire temperature increases to 925°C. However, for plasma bolt hole specimens the percentage decrease in strength is 22% and 16% as being exposed to 800°C and 925°C post-fire temperatures, respectively. Therefore, specimens with a plasma hole have the highest percentage decrease in the ultimate strength as exposed to post-fire temperatures compared to those with drilled and waterjet holes. In addition, a waterjet bolt hole does not affect the capacity of the S235 steel plates after fire exposure. The percentages decrease in strength for all S235 steel plates with different bolt hole-making processes after being exposed to 800°C and 925°C post-fire temperatures are tabulated in Table 2. For post-fire structural assessment, these percentages can be used to quantify the reduction in capacity of the S235 steel plates after fire exposure. The engineers can calculate the demand to capacity ratio (DCR) to decide whether the non-damaged steel plates after fires should be replaced or can be reused. The DCR is used to determine whether the remaining steel structural elements can support the expected loads. This involves comparing the expected loads that the structure will experience in its post-fire condition to the remaining capacity of the structure to withstand those loads. A DCR value of less than 1 indicates that the structure can withstand the expected loads, while a DCR value greater than 1 indicates that the structure is overstressed and may be at risk of collapse or failure.

Table 2. Test matrix and percentage decrease in strength for the steel plates with different hole-making processes after exposure to elevated temperatures

Hole-making processes	Test name	Temperature (°C)	Peak load (kN)	Strength decrease (%)
Drilled	D-20°C-M	20	592	-
	D-800°C-M-R	800	541	9 %
	D-925°C-M-R	925	509	14 %
Plasma	P-20°C-M	20	495	-
	P-800°C-M-R	800	387	22%
	P-925°C-M-R	925	416	16%
Waterjet	W-20°C-M	20	519	-
	W-800°C-M-R	800	537	-3%
	W-925°C-M-R	925	489	6%
Note that: P: Plasma, D: Drilled, W: Waterjet, R: Residual, M: Monotonic				

D. Comparison with steel base material tests available in the literature

A comparison between the percentage decreases in the ultimate strength of S235 steel plates with different bolt hole-making processes obtained from this study against post-fire coupon tests for equivalent steel base materials available in the literature is presented in Figure 15.

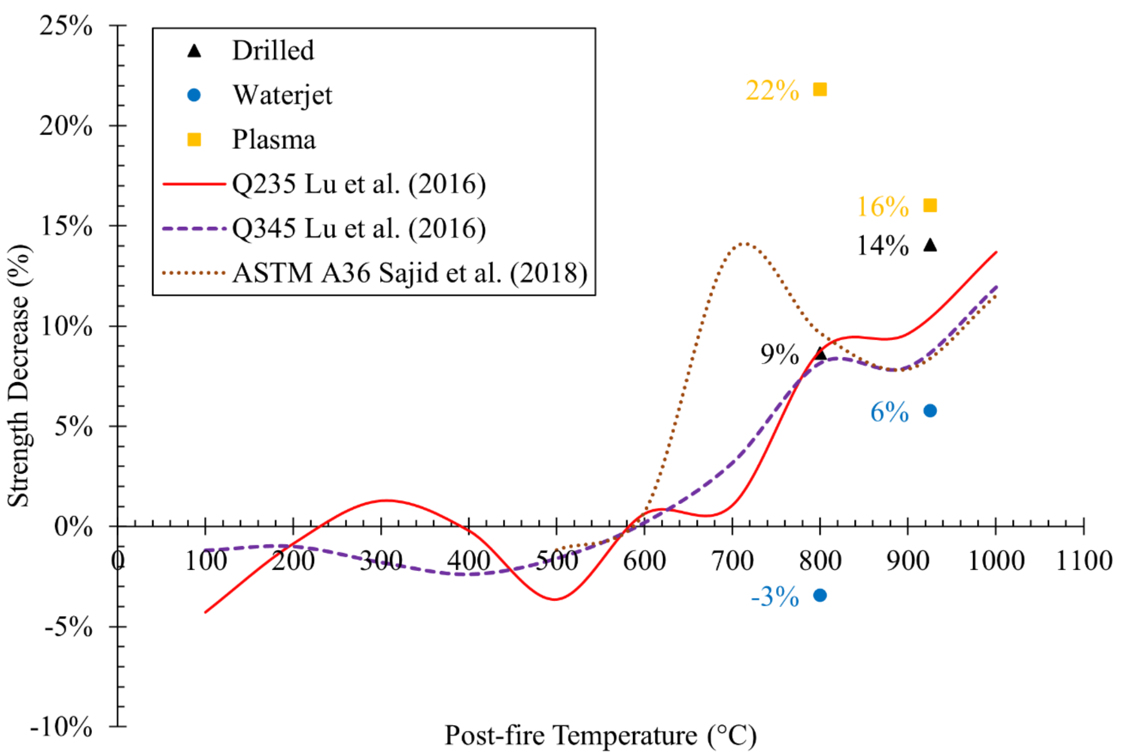


Figure 15. Percentage decrease in strength for the steel plates with three different bole-hole making processes after exposed to elevated temperature against post-fire coupon tests available in the literature

Lu et al. (2016) studied the post-fire mechanical behavior of Q235 (ASTM A36) and Q345 (ASTM A572) steel base material. Three specimens were tested after being exposed to the same post-fire temperature, and the average strength values were computed for Q235 and Q345 steel materials. Although Q345 steel material is not equivalent to S235 steel, it is still mild steel and is used in this analysis for comparison purposes. The coupon tests were conducted at different post-fire temperatures ranging from 100°C to 1000°C with 100°C increment. The results showed that for post-fire temperatures up to 700°C, there is no significant decrease in the ultimate strength of Q235 and Q345 specimens. However, beyond 700°C, the percentage decrease in strength for Q235 specimens was 9%, 10%, and 14% and for Q345 specimens was 8%, 7%, and 12%

as the specimens were being exposed to post-fire temperatures of 800°C, 900°C, and 1000°C, respectively. Moreover, Sajid et al. (2018) studied the post-fire mechanical properties of ASTM A36 steel after being exposed to targeted temperatures ranging from 500°C to 1000°C with 100°C increment. The results showed that for post-fire temperatures up to 600°C, there is no significant decrease in the ultimate strength of ASTM A36 specimens. However, beyond 600°C, the percentage decrease in strength for these specimens was 14%, 10%, 8%, and 12% after being exposed to 700°C, 800°C, 900°C and 1000°C, respectively. By comparing these results available in the literature with the results obtained in this study, it can be seen from Figure 15 that the specimens with a plasma bolt hole have a higher percentage decrease in the ultimate strength than the post-fire coupon tests obtained by Lu et al. (2016) and Sajid et al. (2018). However, for drilled and waterjet bolt hole-making processes, there are no significant changes in the residual capacity of the S235 steel plates as compared to those available in the literature. Therefore, this indicates that using plasma cutting to fabricate bolt holes significantly decreases the residual capacity of the S235 steel base material rather than those fabricated using drilling and waterjet cutting processes. This is also because using concentrated heat in the cutting fabrication of bolt holes generates residual stresses that decrease the residual capacity of the S235 steel base material.

E. Effect of different bolt hole-making processes on Load-displacement Response

To address the effect of bolt hole-making processes on the post-fire behavior of S235 steel plates with a single bolt hole, load-displacement responses for the three different bolt hole-making processes at ambient and post-elevated temperatures are represented in Figure 16. At ambient temperature as seen in Figure 16(a), the steel plates with a drilled bolt hole gain more strength and ductility than specimens with waterjet and plasma bolt hole. Whereas the waterjet bolt hole-making process provides larger strength and ductility to the steel base material than the plasma. However, for post-fire temperature tests as seen in Figure 16(b) and Figure 16(c), drilled and waterjet bolt hole-making processes result in having approximately the same load-displacement response and both have larger strength and ductility than those obtained using plasma. This difference in strength and ductility between different bolt hole-making processes is due to the influence of heat in the fabrication process. More specifically, in plasma cutting, concentrated heat with a very high temperature is used to cut the hole resulting in having a heat-affected zone around the bolt hole. As this heat-affected zone cools back to ambient it results in having residual stresses around the bolt hole that reduce the capacity of the fabricated specimen. Whereas the waterjet and drilling processes are considered cold cutting processes where their residual stresses around the bolt hole are minimal.

Since the specimens with a waterjet bolt hole had approximately the same performance as those with a drilled bolt hole, and since waterjet cutting is not practical for cutting thick plates (Yuan (2005)), therefore, for fire applications, it is recommended to use drilled bolt holes in steel plates, keeping an option for the fabricators to use waterjet bolt holes for thinner steel plates. In addition, if the fabricators need to use the plasma cutting process to cut bolt holes, which is more practical and easier, it is recommended to take into consideration the percentage decrease in strength of the S235 steel plate with a plasma bolt hole to ensure a safe design.

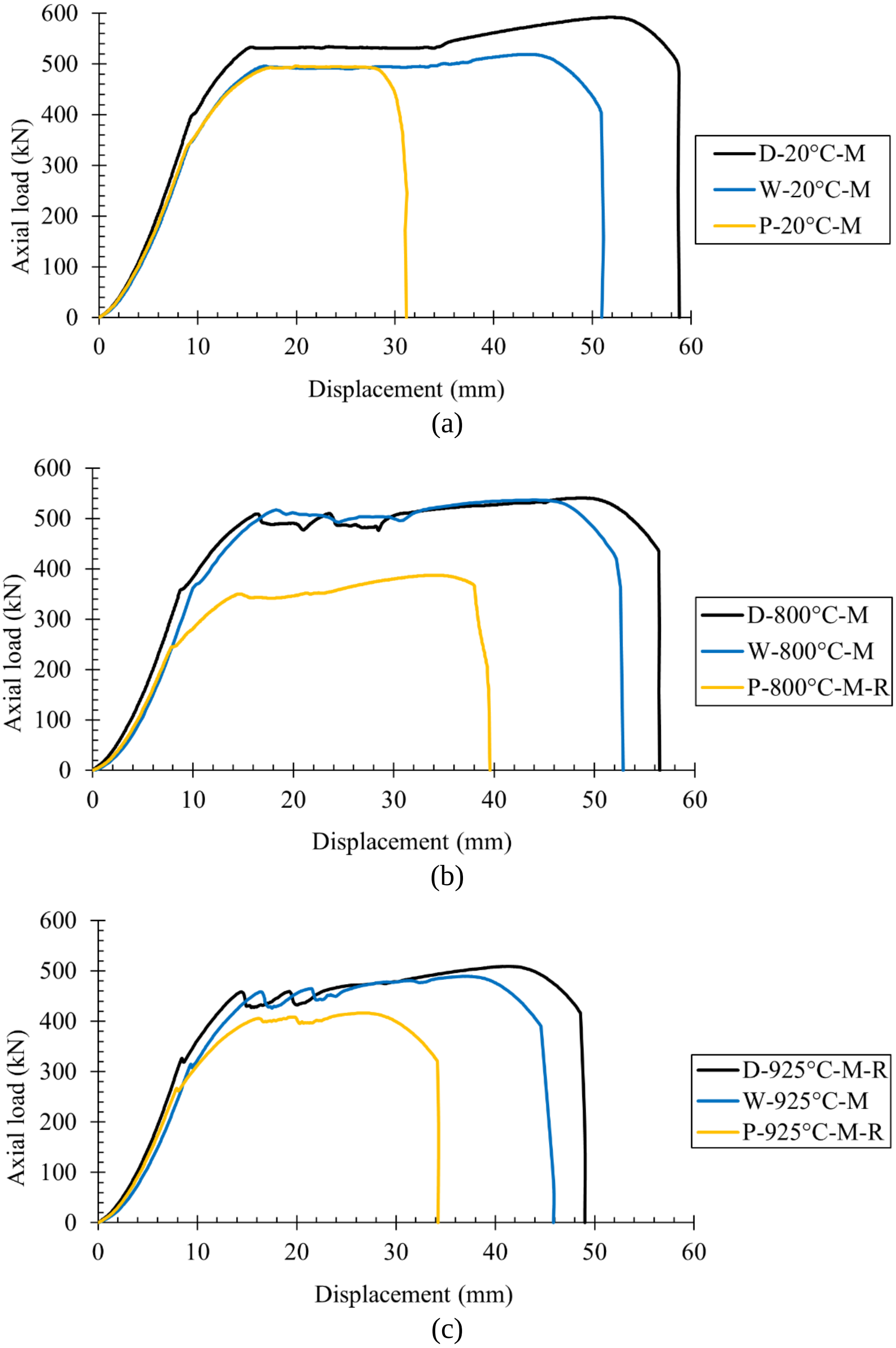


Figure 16. Residual load–displacement response of the steel plates with single bolt hole: (a) 20°C, (b) 800°C, (c) 925°C

CHAPTER IV

SUMMARY AND CONCLUSIONS

Key results of the experimental program on the effect of bolt hole-making processes on the post-fire behavior of S235 steel plates were presented. Three different bolt hole-making processes, which are drilling, waterjet, and plasma were used in this study to investigate the post-fire behavior of S235 steel plates with a single bolt hole. The following conclusions are made from this study:

- All S235 steel plates failed in net section fracture at the bolt hole for both ambient and post-fire temperatures. The exposed surface of the steel plates exhibited a change in color from reddish-gray color at 800°C to gray color at 925°C.

- At ambient temperature, drilling produces the smoothest and most consistent holes, while plasma cutting results in irregular and distorted holes, and waterjet cutting produces smooth holes with some imperfections at the hole edges. After being exposed to high temperatures, the surface of all the holes became slightly roughened, but the overall shape of the bolt holes after being exposed to fire temperatures remained unchanged.

- After being exposed to post-fire temperatures (800°C and 925°C), the maximum decrease in strength of the S235 steel plate was 6% (at 925°C), 14% (at 925°C), and 22% (at 800°C) when compared to the results of ambient specimens for waterjet, drilled, and plasma bolt holes, respectively. Therefore, specimens with a plasma hole have the highest percentage decrease in the ultimate strength as exposed to post-fire temperatures compared to those with drilled and waterjet holes, and a waterjet bolt hole does not significantly affect the capacity of the S235 steel plates after fire exposure.

- Specimens with a plasma bolt hole have a higher percentage decrease in the ultimate strength than the post-fire coupon tests of equivalent S235 steel base material available in the literature. However, for drilled and waterjet bolt hole-making processes, there are no significant changes in the residual capacity of the S235 steel plates as compared to those available in the literature. Therefore, using plasma cutting to fabricate bolt holes significantly decreases the residual capacity of the S235 steel base material rather than those fabricated using drilling and waterjet cutting processes. This is also because using concentrated heat in cutting the bolt hole generates residual stresses that decrease the residual capacity of the S235 steel base material.
- For post-fire temperature tests, specimens with a drilled or waterjet bolt hole result in having approximately the same load-displacement response and both have larger strength and ductility than those obtained using plasma. Therefore, for fire applications, it is recommended to use drilled bolt holes in steel plates, keeping an option for the fabricators to use waterjet bolt holes for thinner steel plates. In addition, since the specimens with a plasma bolt hole had the lowest strength and ductility, therefore it is recommended to avoid using plasma bolt holes in steel plates for fire applications.
- The difference in strength and ductility between different bolt hole-making processes is due to the influence of heat in the fabrication process. More

specifically, in plasma cutting, concentrated heat with a very high temperature is used to cut the hole resulting in having a heat-affected zone around the bolt hole. As this heat-affected zone cools back to ambient it results in having residual stresses around the bolt hole that reduce the capacity of the fabricated specimen. Whereas the waterjet and drilling processes are considered cold cutting processes where their residual stresses around the bolt hole are minimal.

CHAPTER V

SIGNIFICANCE, LIMITATIONS, AND FUTURE WORK

A. Significance

The hole-making processes have significant effects on the mechanical properties of steel plates at ambient temperature, and steel material also experiences a change in its mechanical properties after exposure to post-fire temperatures. None of the previous studies considered the effect of both the bolt hole-making processes and the post-fire temperatures on the mechanical properties of steel plates. To address this knowledge gap, an experimental program was conducted on S235 steel plates with different bolt hole-making processes to investigate their post-fire behavior after being exposed to high temperatures. As a result, this study provides preliminary data to guide steel designers and fabricators in choosing the most suitable hole-making process for fire applications and to quantify the reduction in capacity of the S235 steel plates after fire exposure.

B. Limitations

This study was limited to S235 (ASTM A36) base plate material with a single bolt hole fabricated by drilling, waterjet, or plasma. Further experimental data and numerical efforts are still needed to better understand the post-fire behavior of steel plates while considering different bolt hole making processes after being exposed to post-fire temperatures. This research work is considered a preliminary step toward the goal of understanding the effect of bolt hole-making processes on the post-fire behavior of S235 steel plates.

C. Future work

Future work is needed to study the effect of different hole-making processes on the residual responses of steel plates having different base plate material, thicknesses, number of bolt holes, and bolt hole diameter under a larger spectrum of targeted temperatures and cooling regimes. The future tests should be repeated at least three times to accurately estimate the residual response of steel plates while considering different bolt hole making processes after fire exposure.

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