AMERICAN UNIVERSITY OF BEIRUT

POST-FIRE RESPONSE OF SINGLE-SHEAR BOLTED LAP JOINTS WITH THREADS INCLUDED AND EXCLUDED FROM SHEAR PLANE

by
SARA GEORGES CHAKAR

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SARA GEORGES CHAKAR

Approved by:

Dr. Elie G. Hantouche, Associate Professor — Advisor
Department of Civil and Environmental Engineering

Dr. Georges Saad, Associate Professor — Member of Committee
Department of Civil and Environmental Engineering

Dr. Mohamed Harajli, Professor — Member of Committee
Department of Civil and Environmental Engineering

Date of thesis defense: June 3, 2022

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ABSTRACT
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Title: Post-Fire Response of Single-Shear Bolted Lap Joints with Threads Included and Excluded from Shear Plane

This study investigates the behavior of single-shear bolted lap joints with threads included in the shear plane (N-bolts) and threads excluded from the shear plane (X-bolts) after exposure to fire temperatures. To examine the post-fire performance, the lap joints are subjected to a complete heating and cooling cycle and then loaded until failure. Sixteen single bolted-lap joints are heated up to various targeted temperatures ranging from 400°C to 900°C and then cooled back to 20°C then loaded till failure. Following heating and cooling stages, the specimens are subjected to a direct tension test to determine the reduction in the shear capacity and the slip resistance of the lap joints. Post-fire reduction factors are estimated from the axial load-displacement curves to determine the residual strength of N- and X-bolted lap joints after exposure to fire temperatures. These proposed reduction factors are added to the ANSI/AISC 360 [1] equation for design purposes of bolted connections in shear after exposure to fire temperatures. The results showed that the X- bolted lap joint resulted in larger reduction in bolt shear capacities compared to those with N-bolts. The strength of lap joints with N-bolts started to degrade after 500°C exposure and reached a maximum reduction in shear strength of 40% at 900°C. However, the strength of lap joints with X-bolts started to degrade after being exposed to temperatures beyond 400°C and reached a maximum reduction in shear strength of 42% at 750°C.

Finite Element (FE) models were developed to validate the performed experimental program. The models studied the behavior, strength capacities and failure modes of bolted lap joints at post-elevated temperatures while considering the effect of the threads in the shear plane. The results show that FE models predict the force-axial displacement relationships as well as the failure mode of the lap-joints with a very high accuracy at ambient and post-elevated temperatures.

This study provides preliminary data that can support the development of design guidelines of bolted connections during and after fire exposure while considering the effect of threads in the shear plane of bolted lap-joints.

TABLE OF CONTENTS

ILLUSTRATIONS

Figure | Page

TABLES

Table Page

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Steel structures experience loss of strength as exposed to fire that might lead to a total structural collapse. However, in some cases steel structures survived the fire event and partially retained their strength and stability after the fire event. This change in strength is referred to residual strength capacities of structural components of steel buildings. Therefore, evaluating the post-fire residual mechanical properties of steel base materials, bolts, and welds is of great importance to maintain the integrity and stability of steel structures during and after fire exposure.

Simple bolted connections such as shear tab connections are commonly used in steel structures. At ambient temperatures, these connections are designed to resist shear forces due to gravity loads. The effect of bolt threads in the shear plane has a significant influence on the shear capacity of bolted connection. That is, the nominal bolt shear strength decreases by around 25% when threads are included in the shear plane as per the ANSI/AISC 360 [1]. However, during and after fire exposure the behavior of bolted connections becomes more complex due to the change in the material composition of both structural base materials and bolts.

The residual strength of bolts and bolted joints after being exposed to a complete heating and cooling cycle has been studied [2-8]. For instance, Ketabdari et al. [2] studied the post-fire behavior of Grades 8.8 and 10.9 bolts. The results indicated that for temperatures below 400°C more than 80% of the mechanical properties for both grades were recovered. Moreover, the results showed that the strength started to degrade at around 400°C and after 900 °C exposure, 40% to 60% of the mechanical properties of

Grade 8.8 and 10.9 steel bolts were recovered. Also, Grade 10.9 had a better post-fire performance and had a better ability to recover their residual strength. Yu [3] studied the residual strength of both A325 (Grade 8.8) and A490 (Grade 10.9) bolts under direct shear test. The test results showed that for post-fire temperatures lower than 400°C, the A325 bolt shear strength was fully recovered after cooling back to ambient temperature. As post-fire temperature increased up to 800°C, the A325 bolt shear strength decreased till it reached 45% of its initial strength. However, the A490 bolts tests exhibited a different behavior where the bolt kept its original strength up to a temperature of 500°C. For temperatures beyond 500°C, A490 bolt started to lose its strength linearly till it reached 60% of its initial strength after being exposed to 800ºC. Also, the post-fire slip resistance of the A490 bolted connection was studied. The slip resistance of A490 bolts dropped by 50% of its initial capacity as post-fire temperature increased from 400°C to 500°C. Whereas, as post-fire temperature increased up to 800°C, the slip resistance decreased to 10% of its original capacity. Another study was conducted by Liu et al. [4] to study the post-fire residual slip resistance and shear capacity of double shear bolted connection. Grades 8.8 and 10.9 of M16 X-bolts were used. Two different cooling modes, air cooling and water cooling, were also used. The results showed that under natural and water-cooling regimes, bolted connections with Grades 8.8 and 10.9 bolts showed same post-fire behavior in terms of slip resistance and shear capacity. The results also showed that for temperatures less than 600°C no major changes in slip resistance and shear capacity were observed. As the heating temperature exceeded 600°C, the shear capacity and slip resistance decreased quickly. The reduction factors of slip resistance and shear capacity at 900°C reached 0.35 and 0.75, respectively. Finally, two equations that correlate the reduction in the shear capacity and slip resistance with the corresponding exposure temperature were developed.

All previous studies on the post-fire behavior of bolts and bolted lap joints studied the effect of the material, cooling regimes, and some geometric parameters on the bolt shear strength capacity and slip resistance in bolted connection. However, none of these considered the effect of threads in the shear plane on the post-fire behavior of bolted connections. To address this issue, sixteen bolted lap joints with N- and X-bolts are tested after exposure to post-fire temperatures ranging from 400°C to 900°C. Then, the post-fire reduction factors for N-bolts and X-bolts are presented and compared with those proposed by previous studies available in the literature. The effect of threads in the shear plane on the post-fire slip resistance of the lap joints is also considered in this study.

Then, FE models are developed in ABAQUS (2014) and validated against the experiments performed. These models show the effect of adding the bolt strength reduction coefficient in the bolt's strength materials, on the post-fire behavior and strength capacities of lap joints after exposure to fire events.

The ability to accurately predict the fire-resistant capacities of steel connections in non-destructive steel structures following fire exposure requires a deep understanding of the post-fire material properties of bolts and steel materials. This research is a step forward towards understanding the residual behavior of bolted connections while considering the effect of threads in the shear plane after they have been subjected to fire. Different geometric and material properties of bolts and base materials still need to be considered in future works on post-fire behavior of bolts and bolted connections.

CHAPTER II

EXPERIMENTAL PROGRAM OF SINGLE SHEAR-BOLTED LAP JOINTS

A. Experimental Program

1. Test Specimens

The bolted lap joint used in this study consists of two 790 mm × 80 mm × 20 mm steel plates made of S355 (ASTM A572 Grade 50) connected to each other with Grade 8.8 M20 (N- and X-bolts) as shown in Fig. 1. All bolts were pre-tensioned with a force of 142 kN before conducting the tensile tests as per ANSI/AISC 360 [1]. The lap joints were designed such that the bolt shear failure governed the behavior of the specimens at ambient temperature.

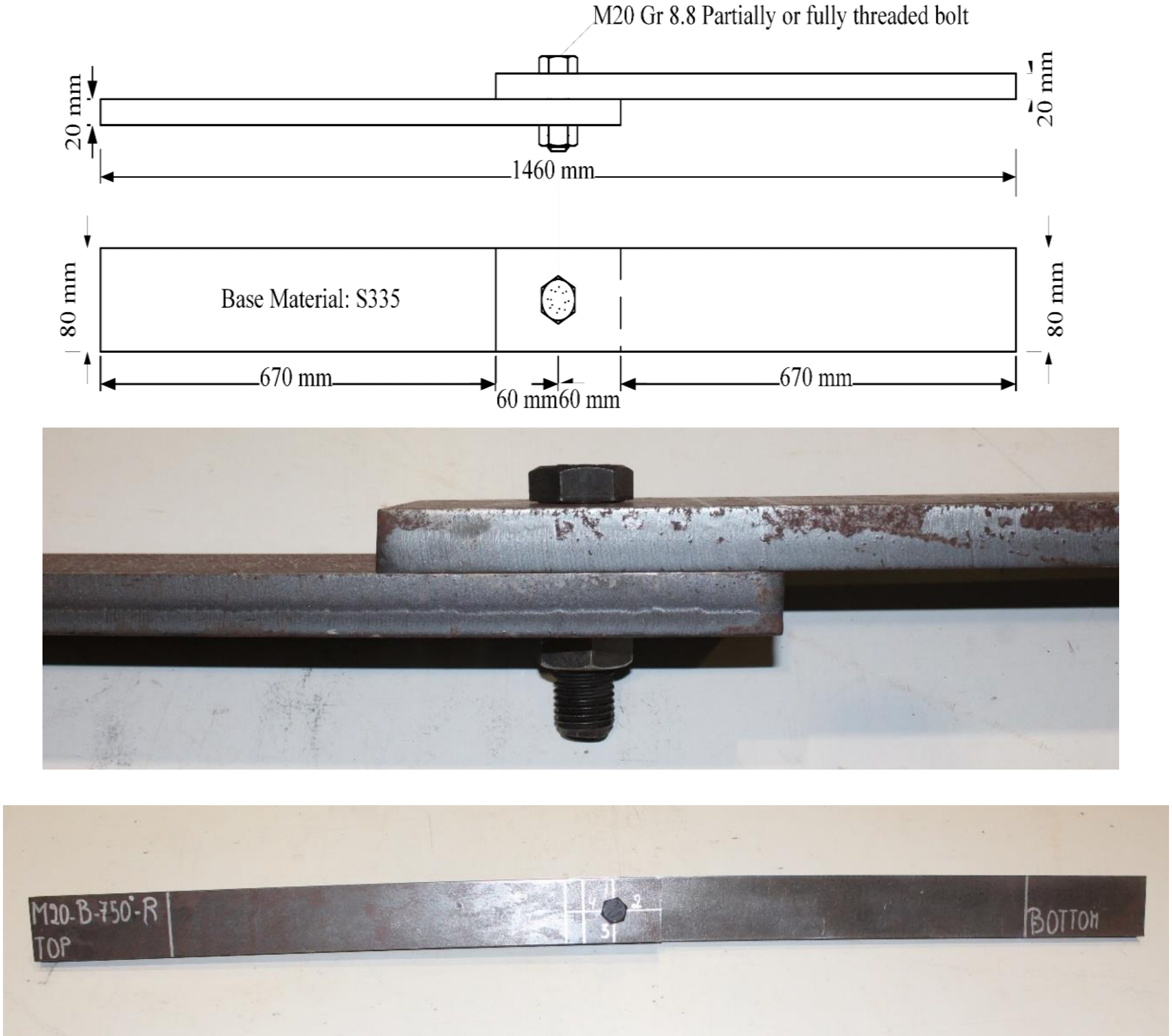
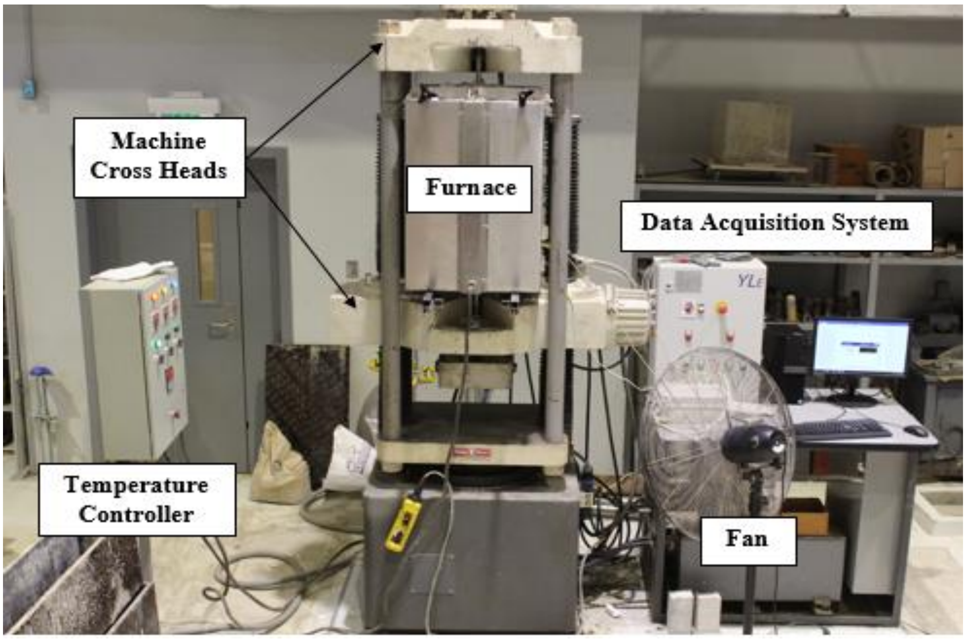


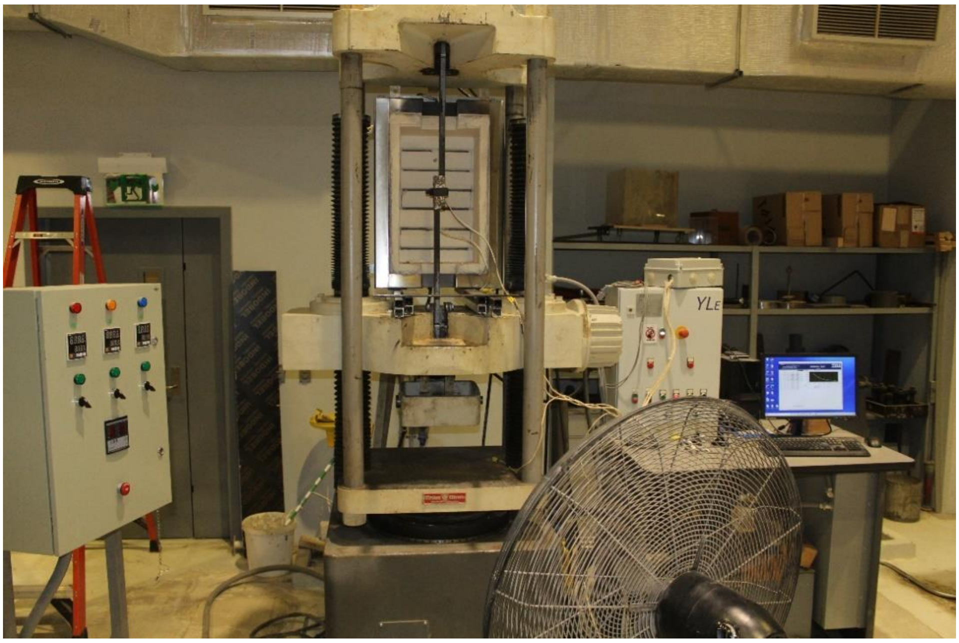
Fig 1. Bolted lap joint specimen layout

2. Setup and Instrumentation

A 200 tons capacity Tinius-Olsen Universal Testing Machine was used to perform the tensile testing of single-bolted lap joints after being exposed to fire conditions. An 800 mm x 550 mm x 830 mm electric furnace was used during the heating phase of the testing program. The setup instrumentation during the heating and cooling phases of the test program are as shown in Figs. 2(a) and 2(b), respectively.



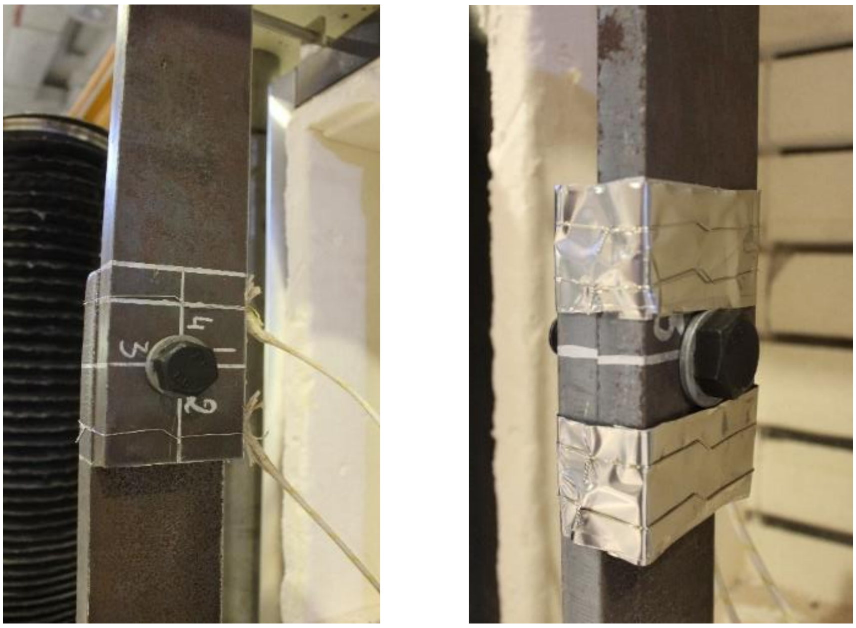
(a)



(b)

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

The furnace consisted of three separate heating zones; each zone can be controlled by a temperature controller system. Two thermocouples (Type K) were used to control the uniform temperature distribution around the bolt region as shown in Fig. 3(a). Then, the specimens were wrapped by stainless steel foils (SSF) to protect the thermocouples from direct exposure to thermal radiation emitted from heating elements of the furnace as shown in Fig. 3(b). The axial force-displacement relationships and temperatures of the thermocouples were monitored using a data acquisition system as shown in Fig. 2(a).



(a) (b)

Fig 3. Bolted lap joint specimen: (a) layout and thermocouples; (b) stainless steel foil.

3. *Test Loading Protocol*

To investigate the post-fire behavior of the single-bolted lap joints, the specimens were heated up first to a specify temperature. Then, the temperature was held constant for 60 min, to ensure a uniform distribution of temperature around the bolt region. Then the specimens were cooled back to ambient temperature. When the temperature reached around 60°C, one of the furnace compartments was removed as shown in Fig. 2(b). In some cases, when the specimen temperature reached around 40°C, the fan was switched on to accelerate the cooling phase. As the specimen temperature cooled back to ambient, displacement-control load was applied to the specimens using a constant crosshead displacement rate of 1.5 mm/min. As shown in Fig. 4, all tests were heated approximately with the same heating rate until the targeted temperature was reached, then kept constant for 60 min to ensure a uniform distribution of the temperature along the connected part of the specimen. Then the specimens were cooled down to ambient temperature. The rapid decrease in cooling rate observed at the end of the cooling phase is due to the use of the fan. The test matrix of the post-fire behavior of the single-bolted lap joint with N-bolts (NB) and X-bolts (XB) is tabulated in Table 1.

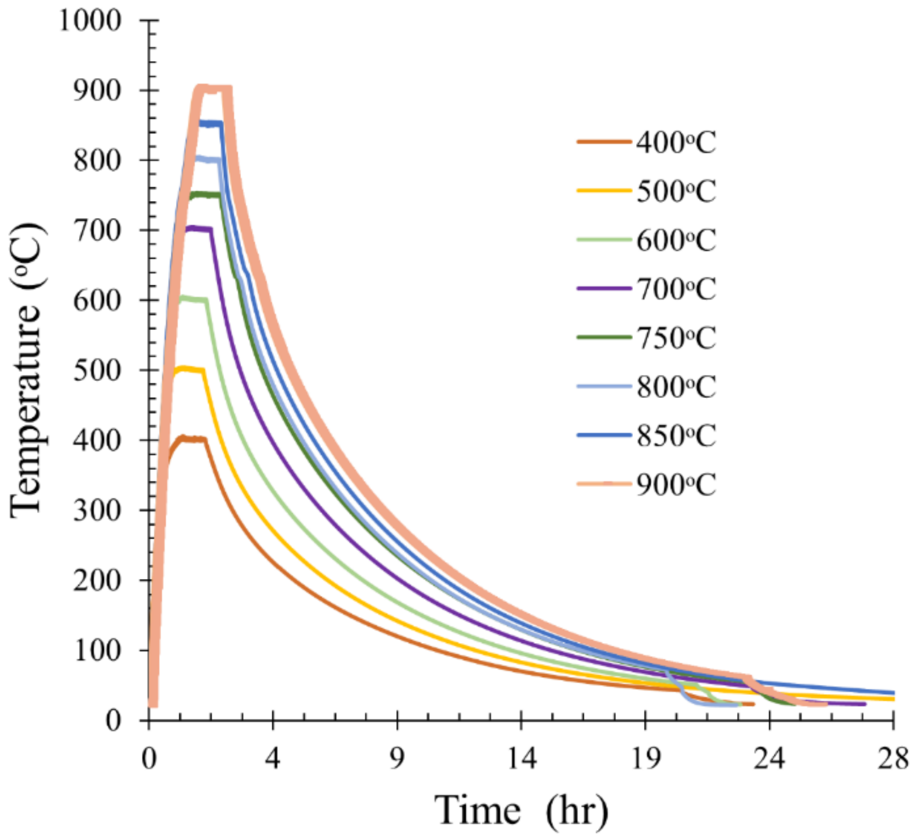


Fig 4. Temperature profile for post-fire analysis

B. Test Results

1. Experimental Observation

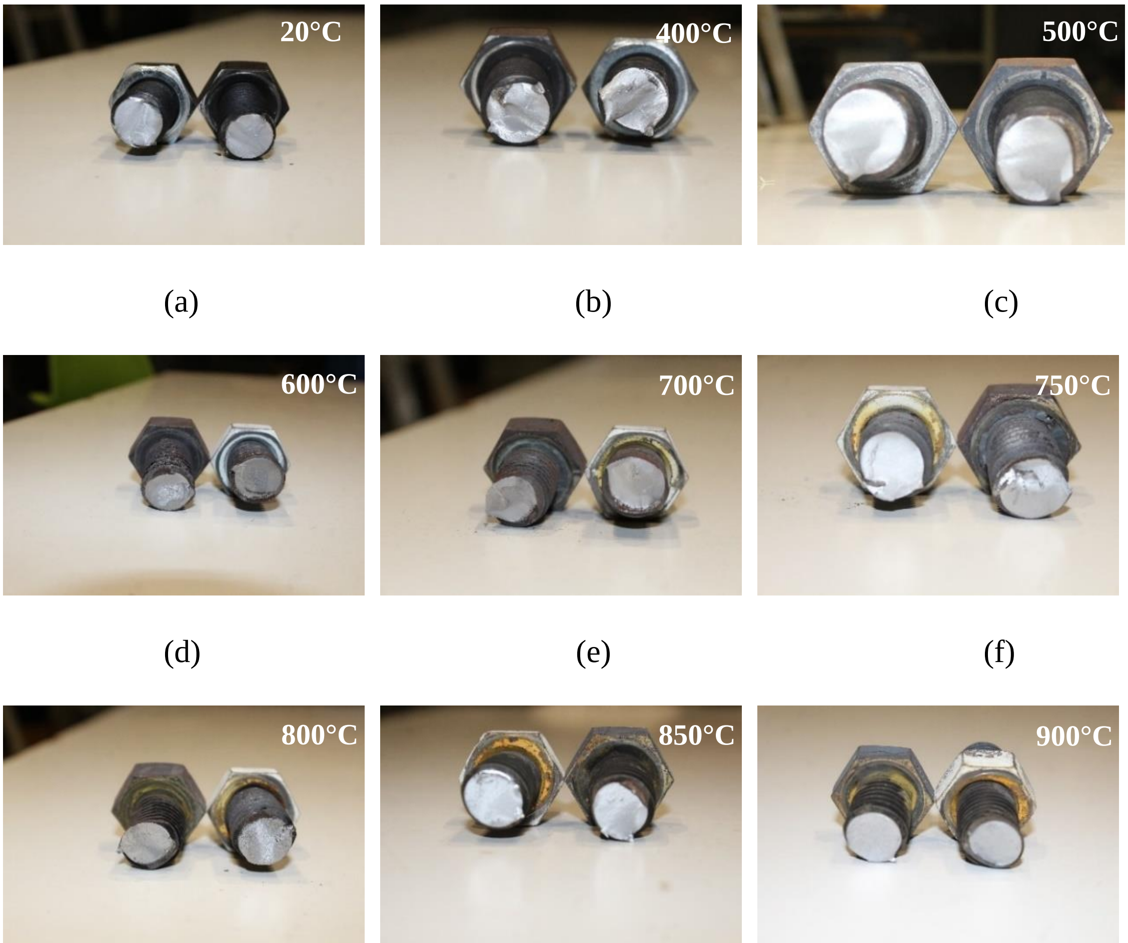
The experimental results show that all specimens failed in bolt shear fracture at ambient and post-elevated temperatures (Fig. 5).

(a)

(b)

Fig 5. Bolted lap joints with partially threaded bolt after failure at 800°C

Figures 6 and 7 show close photographs of the fracture surfaces of the N- and X-bolts, respectively, at ambient temperature and after being exposed to fire temperatures. The bolt fracture surfaces did not change with the increase of temperature and remained smooth, gray, and shiny.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Fig. 6. Bolt fracture surfaces for N-bolts at (a) 20°C; (b) 400°C; (c) 500°C; (d) 600°C; (e) 700°C; (f) 750°C; (g) 800°C; (h) 850°C; and (i) 900°C

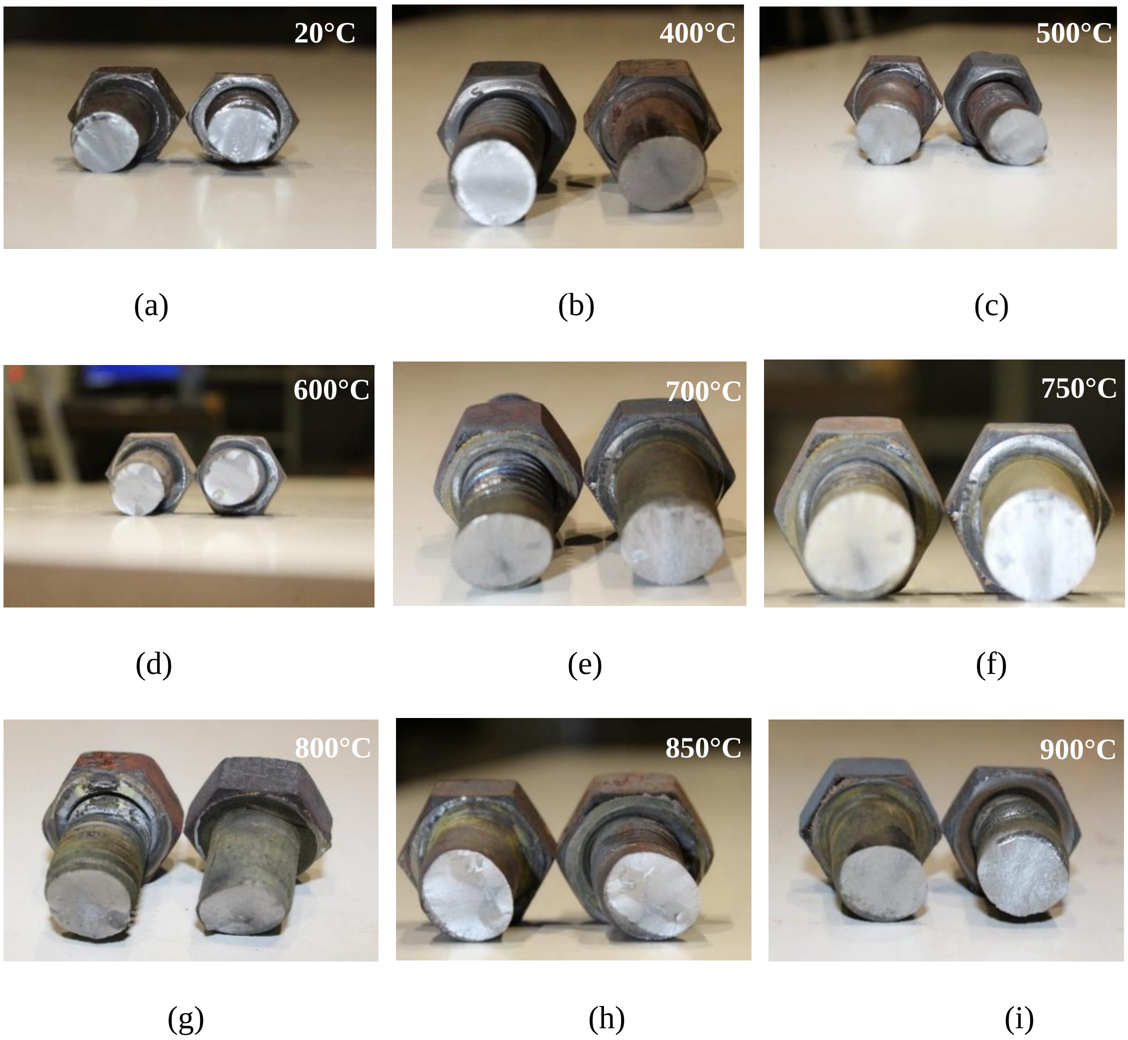


Fig. 7. Bolt fracture surfaces for X-bolts at (a) 20°C; (b) 400°C; (c) 500°C; (d) 600°C; (e) 700°C; (f) 750°C; (g) 800°C; (h) 850°C; and (i) 900°C

It can be noted from Figs. 8 and 9 that the exposed surfaces of the specimens exhibited a change in color. As the temperature increased to 500°C, the exposed surfaces exhibited a change in color to brown that turned into dark brown at 600°C. For higher temperatures like 700°C and 750°C, the surface color turned to reddish brown. As the temperature increased to 800°C, the exposed surfaces presented a reddish-gray color. Whereas, at 900°C, the steel plates exhibited a gray color.

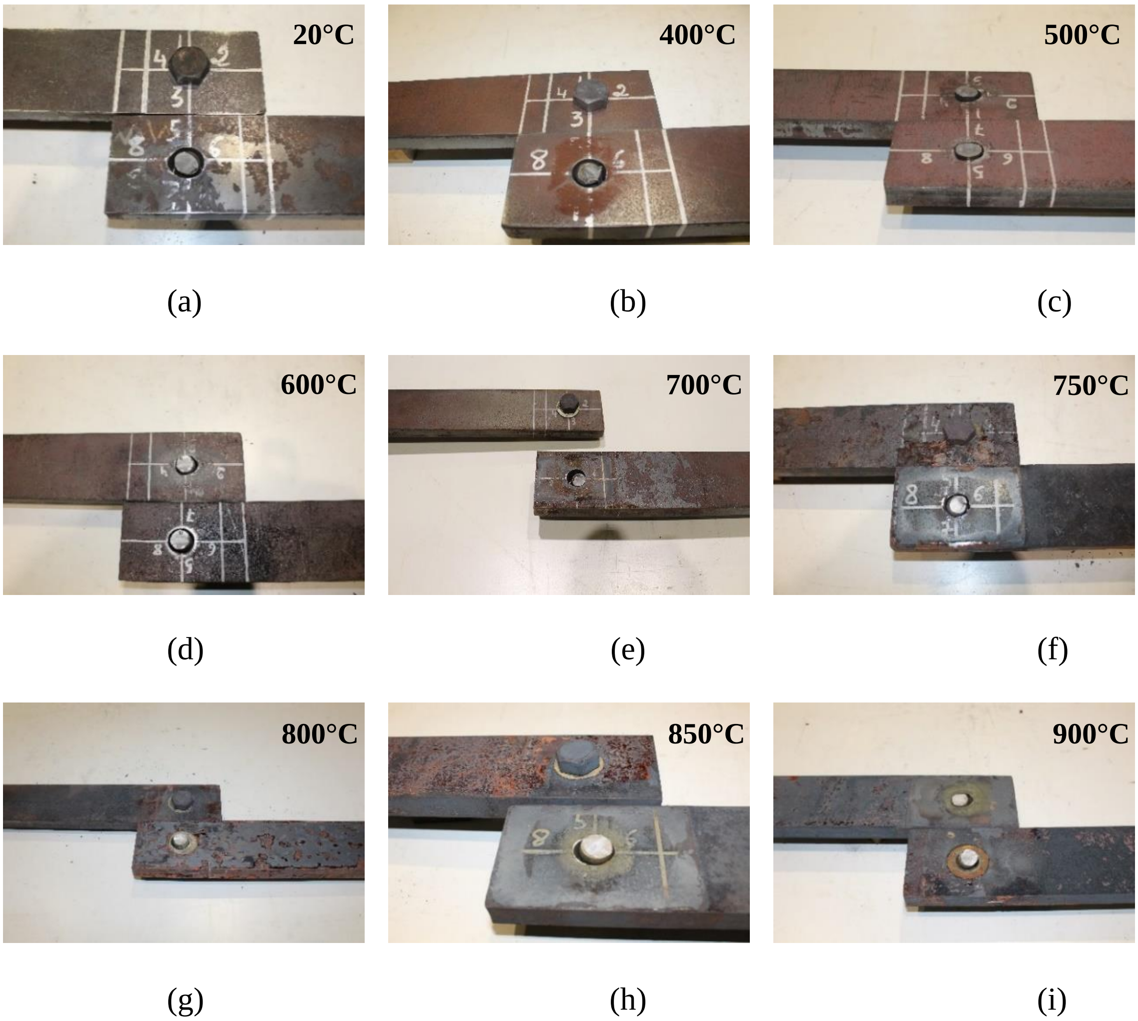
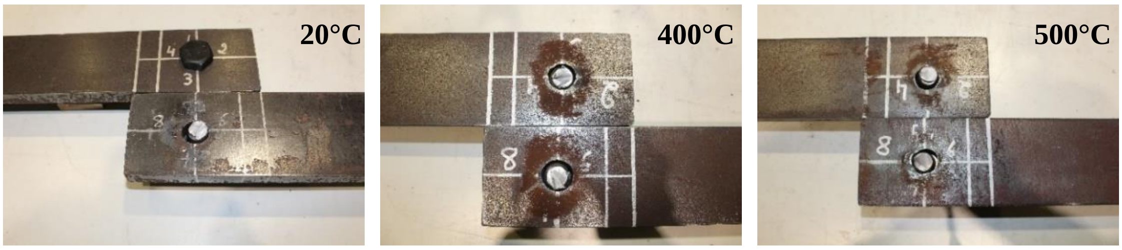
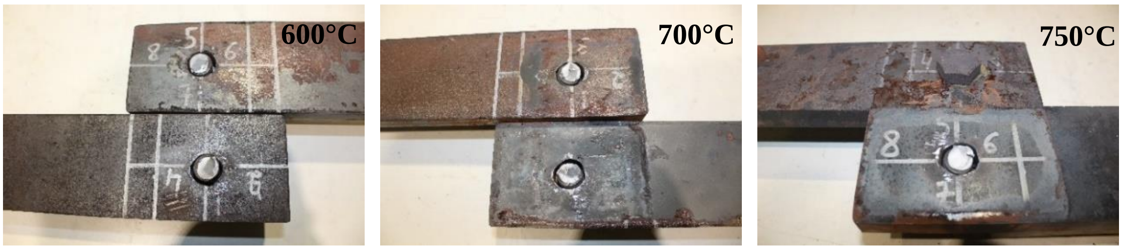


Fig. 8. Lap joints with X-bolts at (a) 400°C; (b) 500°C; (c) 600°C; (d) 700°C; (e) 750°C; (f) 800°C; (g) 850°C; and (h) 900°C.



(a) (b) (c)



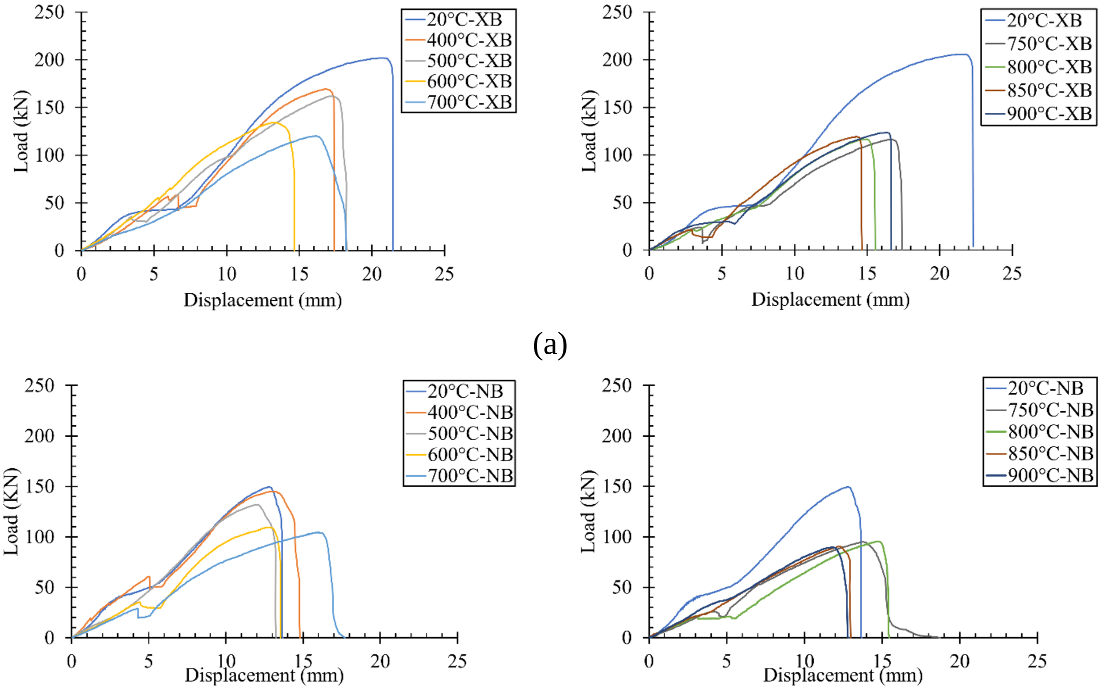
(d) (e) (f)

(g) (h) (i)

Fig. 9. Lap joints with N-bolts at (a) 400°C; (b) 500°C; (c) 600°C; (d) 700°C; (e) 750°C; (f) 800°C; (g) 850°C; and (h) 900°C.

2. *Effect of temperature on load-displacement characteristics*

Tensile testing was performed on single-shear bolted lap joints after being exposed to elevated temperatures to study the post-fire behavior of the lap-joints with N- and X-bolts. Figures 10(a) and 10(b) represent the axial load-displacement characteristics of single-shear bolted lap joints with N- and X-bolts, respectively, at ambient and post-fire temperatures.



(a)

(b)

Fig. 10. Force-displacement results with (a) X-bolts; and (b) N-bolts.

It can be seen from Fig. 10, as the post fire temperature increases, the initial stiffness starts to degrade. The shear capacity of the lap joint decreases as the post-fire temperature increases. For the same post-fire temperature, the decrease in the shear capacity of X-bolts is greater than that of N-bolts. The ultimate strength and the post-fire shear reduction factors for all specimens with N- and X-bolts after being exposed to different temperatures are tabulated in Table 1 as shown below.

Table 1. Test matrix and results of failure load and shear strength reduction factor for lap joints with N-bolts and X-bolts

Test N°	Test Name	Temperature (°C)	Ultimate strength (kN)	Shear strength reduction Factor
1	20°C-NB	20	149.6	1
2	400°C- NB	400	145.1	0.97
3	500°C- NB	500	131.5	0.88
4	600°C- NB	600	109.4	0.73
5	700°C- NB	700	104.5	0.70
6	750°C- NB	750	95.0	0.64
7	800°C- NB	800	95.5	0.64
8	850°C- NB	850	90.4	0.61
9	900°C- NB	900	89.6	0.60
10	20°C-XB	20	201.7	1
11	400°C- XB	400	169.5	0.84
12	500°C- XB	500	161.6	0.80
13	600°C- XB	600	134.1	0.67
14	700°C- XB	700	120.2	0.60
15	750°C- XB	750	116.1	0.58
16	800°C- XB	800	116.7	0.58
17	850°C- XB	850	119.3	0.58
18	900°C- XB	900	123.5	0.61

Table 1 shows that N-bolted lap joints behave differently from the X-bolted lap joints. More specifically, the X-bolt shear strength starts to degrade after being exposed to temperatures beyond 400°C. At 400°C, the shear strength of X-bolt decreases by 16% of its initial shear capacity at ambient temperature. The reduction in shear capacity increases as the post-fire temperature increases to reach 42.4% after being exposed to 750°C. For post-fire temperatures beyond 750°C, the shear strength decreases slightly to

39% at 900°C. However, for N-bolted lap joint, the shear capacity of the N-bolt starts to decrease after exposure to 500°C with 12% of its initial capacity at ambient temperature. For temperature beyond 500°C, the reduction in the shear capacity increases with the increase of the exposure temperature till it reaches 40% at 900°C.

3. Effect of threads in the shear plane on post-fire slip resistance of the bolted lap joint

The slip capacity of bolted lap joints depends on the friction between the connected plates. In case of fire, this slip capacity can be highly affected by fire temperatures since friction between the bolted plates can change with temperature. From the load-displacement curves, slippage occurred in two different phenomena, either as constant or gradual slip.

In tests 20° C-XB, 400° C-XB, 850°C-XB, 900° C-XB, 400° C-NB, 600°C-NB, 700°C-NB, and 800°C-NB slip occurred in a constant manner. Whereas, for other tests, a gradual slip with upper and lower bounds occurred. Table 2 shows the lower and upper bounds of the slip resistance force for all tests. The slip-resistance reduction factors of the lap joints with N-bolts and X-bolts are computed by dividing the lower bound of the slip resistance force at each temperature by the initial slip resistance force at ambient temperature.

Table 2. Lower- and upper-bound and reduction factor of the slip resistance

Test N°	Test Name	Lower bound of slip resistance(kN)	Upper bound of slip resistance(kN)	Slip resistance reduction Factor
1	20°C-NB	40.8	50.8	1
2	400°C- NB	60.4	50.8	1.48
3	500°C- NB	22.6	56.3	0.55
4	600°C- NB	35.6	29.6	0.87
5	700°C- NB	28.9	22.6	0.71
6	750°C- NB	26.4	20.9	0.65
7	800°C- NB	21.1	21.1	0.52
8	850°C- NB	20.8	23.3	0.51
9	900°C- NB	17.5	37.0	0.43
10	20°C-XB	42.5	42.5	1
11	400°C- XB	57.9	45.9	1.36
12	500°C- XB	35.8	31.1	0.84
13	600°C- XB	27.5	54.4	0.65
14	700°C- XB	23.9	44.2	0.56
15	750°C- XB	23.4	44.6	0.55
16	800°C- XB	21.4	44.9	0.50
17	850°C- XB	21.2	13.7	0.50
18	900°C- XB	18.1	28.4	0.43

Fig. 11 represents the post-fire reduction factors of the slip resistance of the lap joints with N- and X-bolts. The results show that the slip resistance of the lap joints with N- and X-bolts changes with temperatures. At 400°C the slip resistance of the lap joints with N- and X-bolts increases by 48% and 36%, respectively. At 500°C, a sudden decrease of 45% in the slip capacity occurs for the N-bolted lap joint. This test was repeated twice, and same result was obtained. Fig.12 shows a comparison between the two conducted test. This drop in the slip could be due to many factors such as the change in the microstructure of the material after exposure to a critical temperature. In addition, this drop in the slip resistance could be due to the alteration in the properties of the faying surface after exposure to 500°C that could affect the friction between the connected parts. Therefore, more experimental tests should be conducted after exposure to temperatures ranging from 400°C to 600°C with an increment of 25°C to study the variation in the slip resistance. Whereas for X-bolted lap joint a 16% reduction in slip capacity is observed. However, for temperatures ranging from 600°C to 800°C, the reduction in the slip resistance is higher for the X- bolted lap joints compared to those with N-bolts. For temperatures beyond 800°C, the reduction in the slip resistance of the N- and X-bolted lap joint show no significant difference and reaches 57% at 900°C.

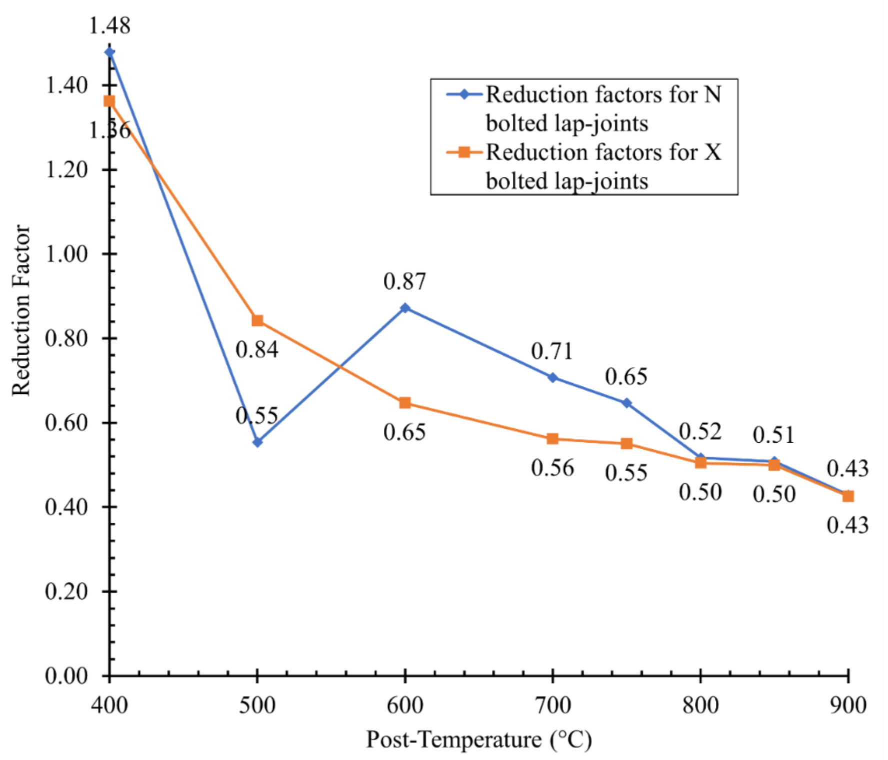


Fig. 11. Reduction factors for the slip resistance of N and X bolted lap-joints

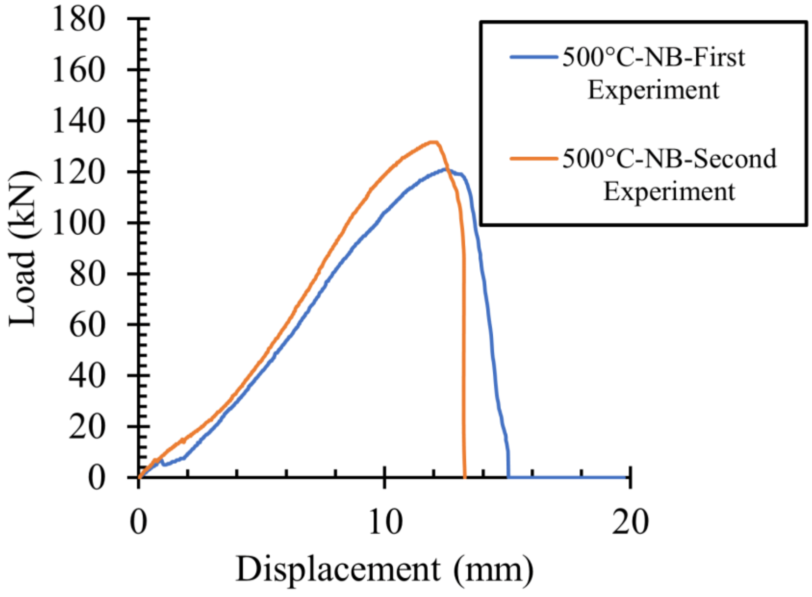


Fig. 12. Comparison between the two tests conducted after exposure to 500°C

4. Effect of threads in the shear plane on the shear capacity and slip resistance of bolted lap joints

The difference in shear capacities of N- and X-bolted lap joints at ambient temperature is due to the reduced area of the threaded portion acting in the shear plane. However, to study the effect of threads in the shear plane of bolted connections after being exposed to fire, Figs. 13 and 14 illustrate the residual axial load-displacement characteristics of N- and X-bolted lap joints at a specified post-fire temperature. It can be seen from Figs. 13 and 14, that X-bolted lap joints gain more strength and ductility than N-bolted lap joint for ambient and post-fire temperature. The percentage difference in bolt shear capacities of the bolted lap joints using N- and X-bolts is tabulated Table 3.

As illustrated in Table 3, the relative difference in the shear capacity of N- and X-bolted lap joints drop from 26% at ambient to reach 14% at 400°C. For temperatures ranging between 500°C and 800°C, the relative difference in the post-fire shear capacity increases slightly to reach an average of 18%. However, for temperatures above 800°C, the relative difference in post-fire bolt strength capacities starts to increase again till it reaches around 26%.

Table 3. Relative difference in the shear capacity (%)

Test Name	Ultimate strength (kN)	Test Name	Ultimate strength (kN)	Relative difference in the shear capacity (%)
20°C-NB	149.6	20°C-XB	201.7	26%
400°C- NB	145.1	400°C- XB	169.5	14%
500°C- NB	131.5	500°C- XB	161.6	19%
600°C- NB	109.4	600°C- XB	134.1	18%
700°C- NB	104.5	700°C- XB	120.2	13%
750°C- NB	95.0	750°C- XB	116.1	18%
800°C- NB	95.5	800°C- XB	116.7	18%
850°C- NB	90.4	850°C- XB	119.3	24%
900°C- NB	89.6	900°C- XB	123.5	27%

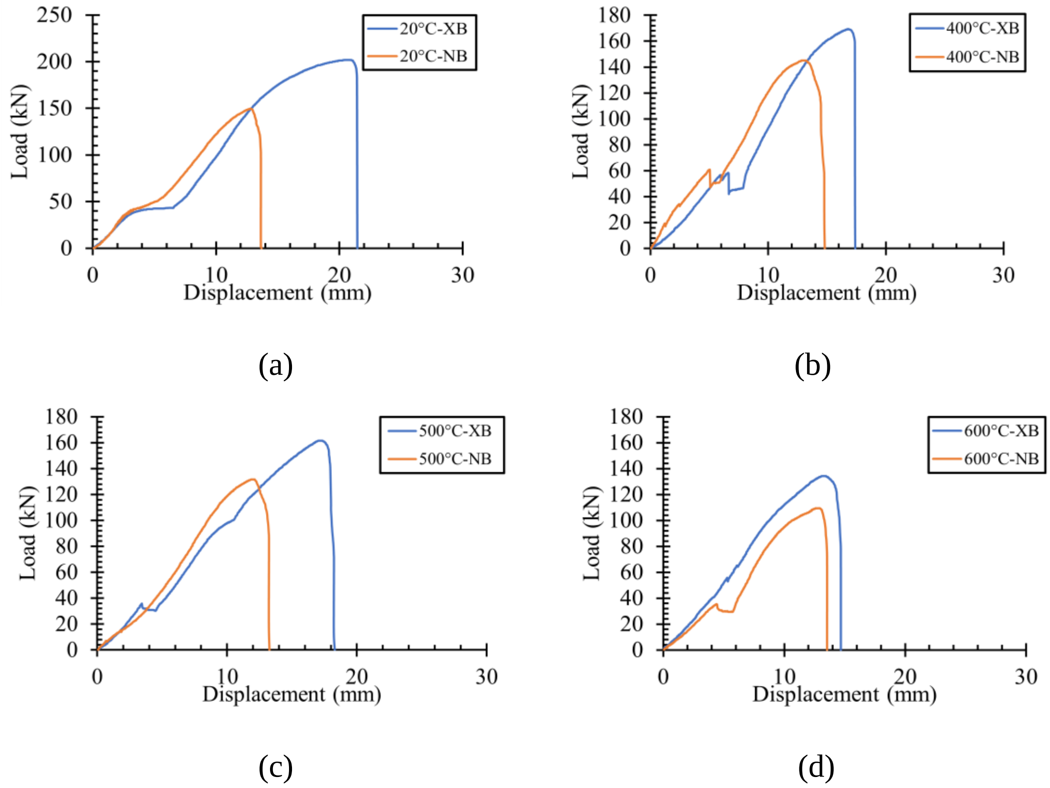


Fig. 13. Effect of the threads in the shear plane on force-displacement behavior at (a) 20°C; (b) 400°C; (c) 500°C; and (d) 600°C.

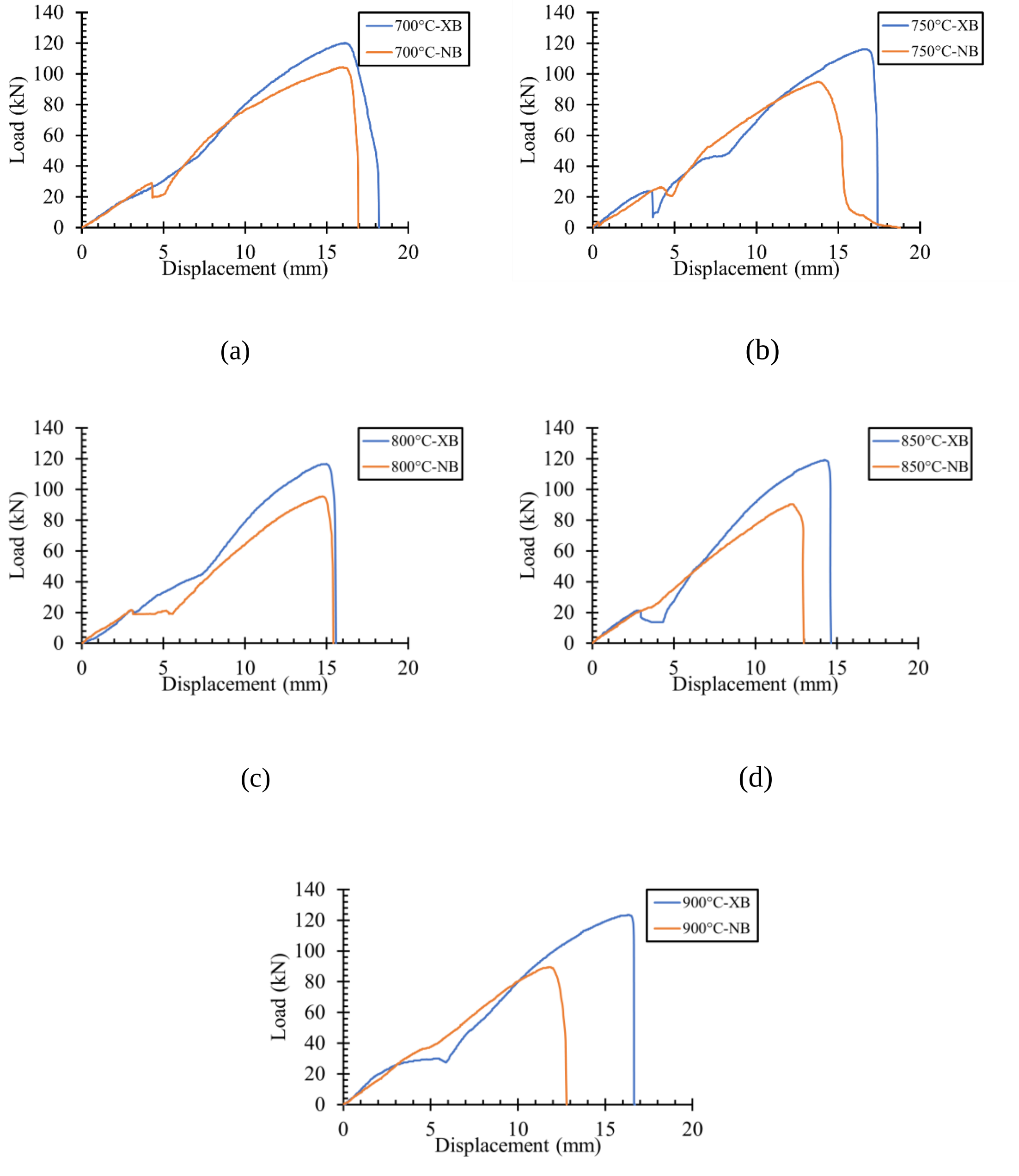


Fig. 14. Effect of the threads in the shear plane on force-displacement behavior at (a) 700°C; (b) 750°C; (c) 800°C; (d) 850°C; and (e) 900°C.

Table 4 represents the percentage difference in post-fire slip resistance of the bolted lap joints using N- and X-bolts. As shown in Table 4, for temperatures below 500°C, there is no major effect on the post-fire slip resistance of the bolted lap joint when using N- or X-bolts. As temperature increases to 500°C, the difference in slip resistance reaches a maximum value of 37%. However, for temperatures ranging between 500°C and 750°C, the effect of using N- or X-bolts on the post-fire slip of the bolted lap joint starts to decrease and reaches a difference of 13% at 750°C. For temperatures beyond 800°C, there is no major effect on the post-fire slip resistance of the bolted lap joint when using N- or X-bolts.

Table 4. Relative difference in the post-fire slip resistance (%)

Test Name	Slip Resistance (kN)	Test Name	Slip Resistance (kN)	Relative difference in the Slip resistance (%)
20°C-NB	40.8	20°C-XB	42.5	4%
400°C- NB	60.4	400°C- XB	57.9	4%
500°C- NB	22.6	500°C- XB	35.8	37%
600°C- NB	35.6	600°C- XB	27.5	30%
700°C- NB	28.9	700°C- XB	23.9	21%
750°C- NB	26.4	750°C- XB	23.4	13%
800°C- NB	21.1	800°C- XB	21.4	2%
850°C- NB	20.8	850°C- XB	21.2	2%
900°C- NB	17.5	900°C- XB	18.1	3%

C. Proposed post-fire reduction factors

The results show that all specimens failed in bolt shear fracture at ambient and post-elevated temperatures (Fig. 5). Accordingly, the shear strength reduction factors of the M20 Grade 8.8 N- and X-bolts are calculated based on the axial force-displacement curves obtained from the experimental tests. The reduction factors for the bolt shear capacity are calculated by dividing the maximum load obtained for each specimen after being exposed to a specified elevated temperature to that of ambient temperature one. The post-fire reduction factors for N- and X-bolts are illustrated in Fig. 15. It can be seen that for all post-fire temperatures the X-bolts have a larger reduction in shear strength capacities than those of N-bolts.

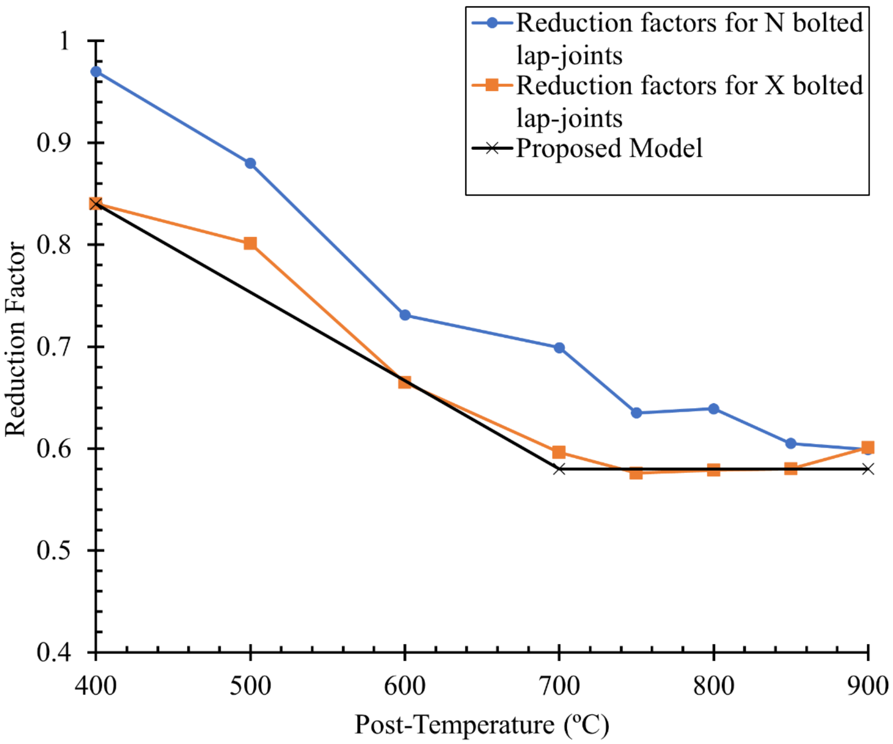


Fig. 15. Proposed reduction factors for the shear capacity of N and X bolted lap-joints

To include the reduction of the post-fire shear capacity in the design of bolted connection, a strength reduction coefficient, $\psi_{b,t}$, is proposed and added to the bolt shear capacity Equation J3-1 in ANSI/AISC 360 [1]. The proposed strength reduction factor, $\psi_{b,t}$, is defined as the envelope of the post-fire reduction factors obtained from the tests conducted on N and X bolted lap joints.

$$R_n = \psi_{b,t} \times F_{nv} \times A_b \qquad (1)$$

where Rn = post-fire single bolt shear capacity; A_b = nominal unthreaded body area of bolt or threaded part; and F_{nv} = nominal shear stress. The strength reduction coefficient, $\psi_{b,t}$, depends on the exposure temperature and the effect of threads in the shear plane. For temperatures up to 700°C, a conservative relationship between, $\psi_{b,t}$ and temperature, $T\left(°C\right)$, is proposed. The proposed reduction factors equation is presented in Eq (2) and Fig. 15.

$$\psi_{b,t} = \begin{Bmatrix} -0.0009 \times T + 1.1867 & \text{for T} \leq 700\text{°C} \\ 0.58 & \text{for T} > 700\text{°C} \end{Bmatrix} \qquad (2)$$

For temperatures greater than 700°C, the value of $\psi_{b,t}$ no longer applies for the linear relationship proposed in Eq. (2). The strength reduction coefficients ($\psi_{b,t}$) at temperatures 750°C, 800°C, and 850°C are found to be 0.58. Accordingly, the conservative value of $\psi_{b,t}$ for exposure temperatures exceeding 700°C is 0.58. This proposed strength reduction coefficient, $\psi_{b,t}$, allows to consider the reduction in the post-fire shear capacity in a more-conservative way when including the effect of threads in the shear plane. This proposed strength reduction factors, results in a more-conservative post-fire bolt shear strength capacities at post-elevated temperatures when including the effect of the threads in the shear plane of bolted lap-joints.

To include the reduction of the post-fire slip resistance in the design of bolted connection Table 2 and Fig. 11 present the reduction factors for N- and X-bolts that can be used in the slip-resistance design Equation J3-4 in AISC 360 [1] to predict post-fire slip capacities of bolted connections.

D. Comparison with other experimental tests available in the literature

Figure 16 represents a comparison between the percentage decrease in bolt shear capacity estimated in this study to those provided by Lui et al. [4]. Recall that, Lui et al. [4] computed the post-fire shear capacity of Grade 8.8 M16 X-bolted lap joints subjected to a double shear test.

It can be seen from Fig. 16, that a lower reduction in the shear capacity is obtained from the double shear test on X-bolted connections conducted by Lui et al. [4]. Moreover, X-bolted lap joints under double shear tests start to experience a reduction in the shear capacity after exposure to temperatures beyond 600°C and reach a maximum reduction in the shear capacity of 24%. However, the test conducted on Grade 8.8 M20 X-bolts result in a higher reduction in the post-fire shear capacity. For all exposure temperatures, the experimental tests show that the highest reduction in shear capacity is obtained from the shear test conducted on X-bolted lap joints with a maximum reduction of 42%. Accordingly, by conducting a double shear test, the reduction in the capacity can be eliminated for temperatures below 600ºC and can be reduced by around 50% for temperatures beyond 600ºC.

Therefore, neglecting the effect of the threads in the shear will result in unsafe prediction of the bolt shear capacity of bolted connections after exposure to elevated temperatures.

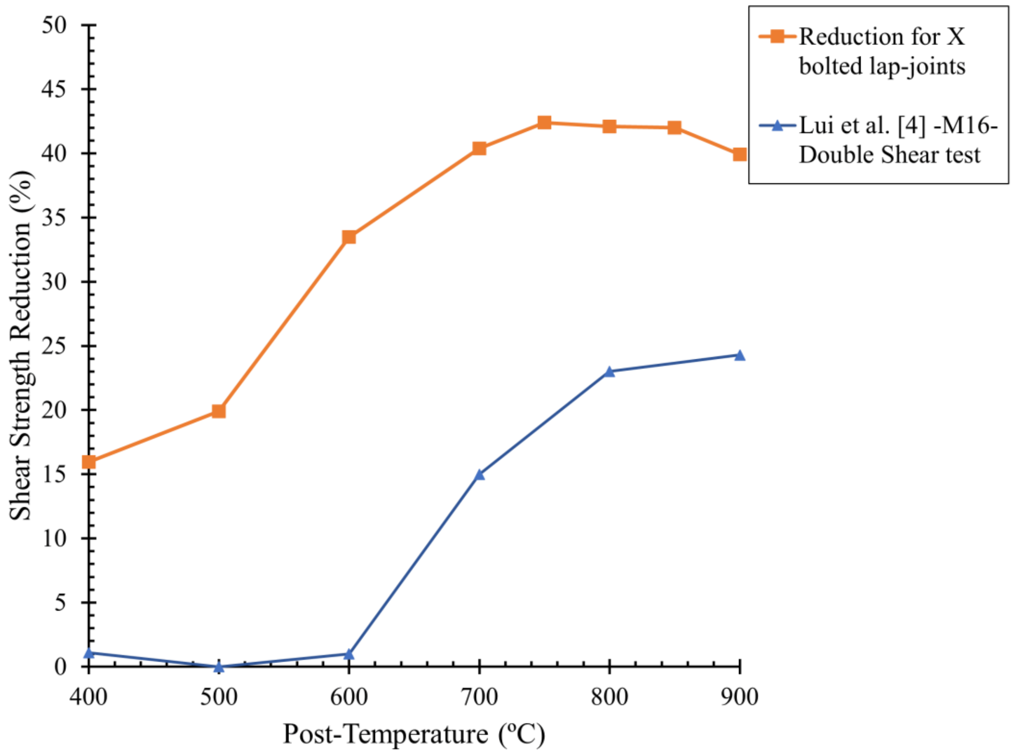


Fig. 16. Percentage decrease in the shear strength of the lap-joints with N- and X-bolts compared with previous data

CHAPTER III

FINITE ELEMENT MODELS

A. Finite Element Modelling

In this research, the finite element package ABAQUS (2014) [9] is used to reproduce the experimental program performed and to validate the FE models against the conducted experimental tests. The aim of these models is to predict the post-fire behavior of bolted lap joints while considering the effect of threads in the shear plane at post-elevated temperatures beyond 400°C.

1. Model Discretization

The elements of the lap-joint were meshed using eight-node three-dimensional solid brick elements with reduced integration (C3D8-R) as shown in Fig. 17. In the regions where the failure is most likely to occur, the bolt shank, a finer mesh was used to help predict accurate results.

Numerical results are highly sensitive to the contact properties between elements of the connection and the pretension force (Krolo et al. [10]). For all the contact surfaces, small sliding surface-to-surface discretization method was considered. The surface contact properties between the plate elements were modelled as a tangential behavior using penalty friction with the friction coefficient value of 0.3. For the normal forces between the elements, normal behavior contact properties were considered. A hard contact was used for the connection between bolt-head nut and plate elements. A frictionless tangential contact between bolt-shank and bolt-hole was considered. The bolts are usually more rigid than hot-rolled steel member, and they are usually denoted as a master surface in the contact pairs (Krolo et al. [10]).

2. Material Properties

In the finite element model, an idealized bilinear stress-strain relationship was used to model the behavior of bolts and structural steel. Yield strength and ultimate strength value of S355 steel plates are 440 MPa and 590 MPa, respectively, while its Young modulus is 210000 MPa. The stress-strain relationship of M20 (grade 8.8) high-strength bolts is bilinear. Tension bolts are M20 (grade 8.8) (F_y = 640 MPa, ε_{py}=0 and F_u = 880 MPa, ε_{pu}=0.04).

To predict the steel material properties at post-elevated temperatures, reduction factors proposed by Aziz et al. [5] are used for the base materials. However, for the bolt material, the reduction factors were calculated from the peak loads obtained from experimental tests conducted and used in the FE simulations.

3. Geometry and Boundary Conditions

All models are reproduced using ABAQUS (2014). The models are loaded in two steps. In the first step, the pretension is simulated by applying a bolt preload along the axis of the bolt-shank. Then, a displacement-controlled load is applied corresponding to the testing procedures.

The nut and the bolt-head are considered as one element with bolt-shank together. Threaded part of the bolt-shank of the bolt beyond is ignored. To consider the threaded part of the bolt-shank the effective area is used.

The effective diameter d_p is derived from the major diameter:

$$d_p = d_b - 0.9382p$$

Hexagonal shape of the bolthead and nut was replaced with a cylinder. The typical bolted joint is presented in Fig. 17.

Throughout the analysis, boundary conditions were applied to the connecting elements. As shown in Fig. 17, the specimen was attached to a spring that represented the machine stiffness during the loading step. Then, a series of FE simulations with springs of various values were conducted to evaluate the machine stiffness until the FE simulation converged toward the experimental result obtained at ambient temperature. After estimating the spring stiffness, it was employed in all FE simulations for all post-fire temperatures for all the FE simulations.

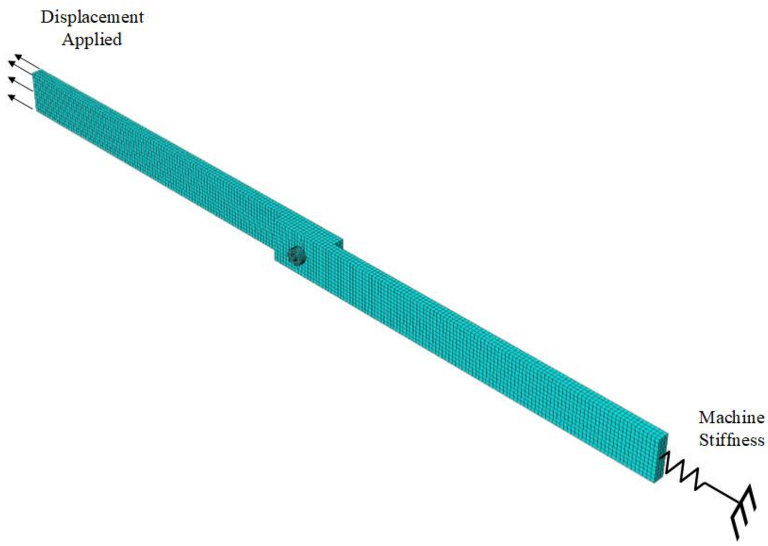
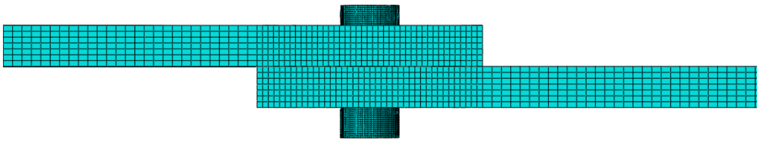


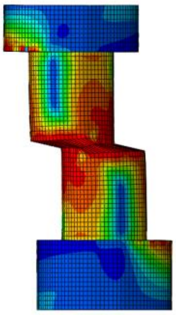
Fig. 17. X bolted lap joint model used in ABAQUS [9] simulations

B. Finite Element Validations and Results

Eighteen single shear bolted lap joints with N- and X-bolts are tested. All N- and X- bolted lap joints failed in bolt shear in the FE simulations as in the experimental results. Figs. 18 (a) and 18 (b) show the mesh of the models, and the bolt shear failure, respectively.



(a)



(b)

Fig. 18. FE results for single shear X bolted lap joint (a) Mesh, (b) Bolt Failure

Reduction factors shown in Table 2 are adopted to predict the slip-critical capacities at post-elevated temperatures, which also shows a very accurate result. Post-fire shear strength reduction factors of Grade 8.8 bolt materials presented in Table 1 are used to predict the post-fire shear capacity of N- and X- bolted lap-joints in ABAQUS (2014). As shown in Figs. 19,20,21,and 22, after adding the strength reduction coefficient, $\psi_{b,t}$, in the bolt strength capacities, the results validate the experimental force-displacement relationships of N- and X- bolted lap-joints. The FE simulations can predict closely the deformation response of the connection as well as its failure mode which is bolt shear failure.

The experimental and FE predictions are in the form of load-displacement curves at ambient and post-elevated temperatures. Figs. 19, 20, 21, and 22 show that the models predict the force-axial displacement relationships with a very high accuracy at temperatures 20°C, 400°C, 500°C, 600°C, 700°C, 750°C, 800°C, 850°C and 900°C.

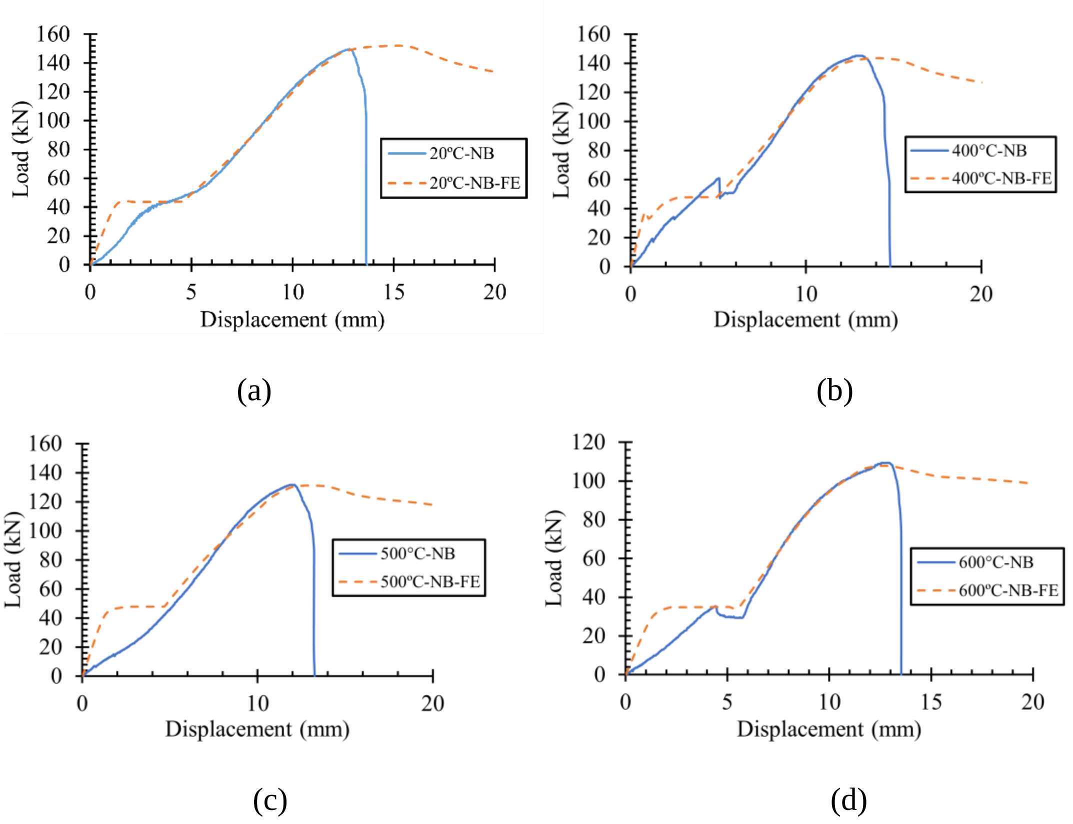
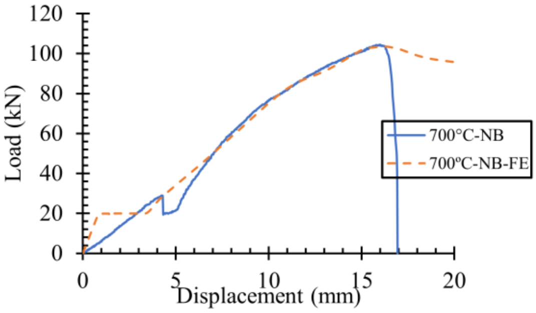
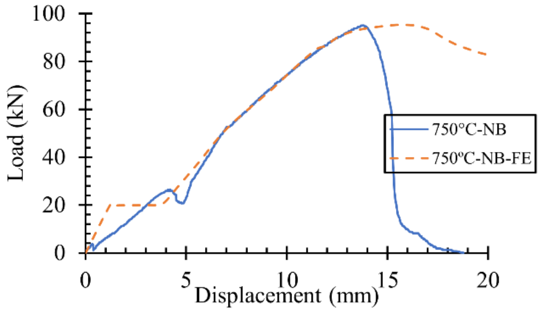


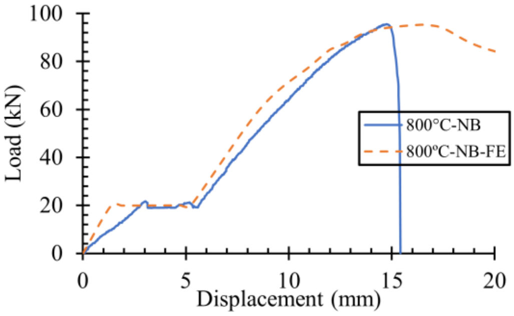
Fig. 19. Load-Displacement Validations for N bolted lap-joints at: (a) 20°C, (b) 400°C, (c) 500°C, (d) 600°C



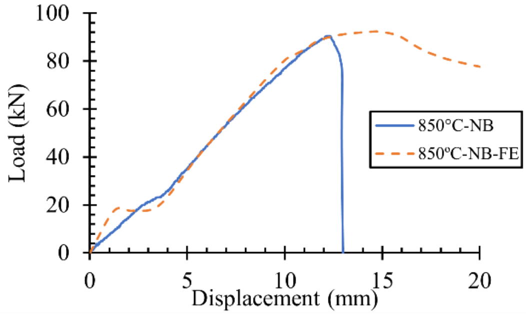
(a)



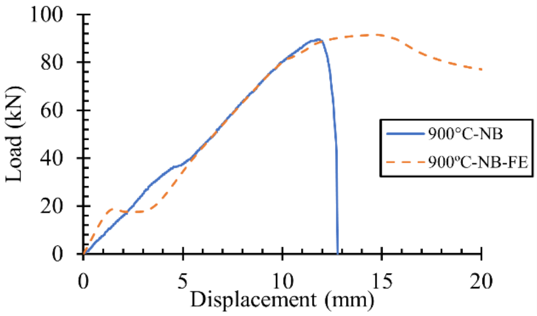
(b)



(c)



(d)



(e)

Fig. 20. Load-Displacement Validations N bolted lap-joints at: (a) 700°C, (b) 750°C, (c) 800°C, (d) 850°C, (e) 900°C

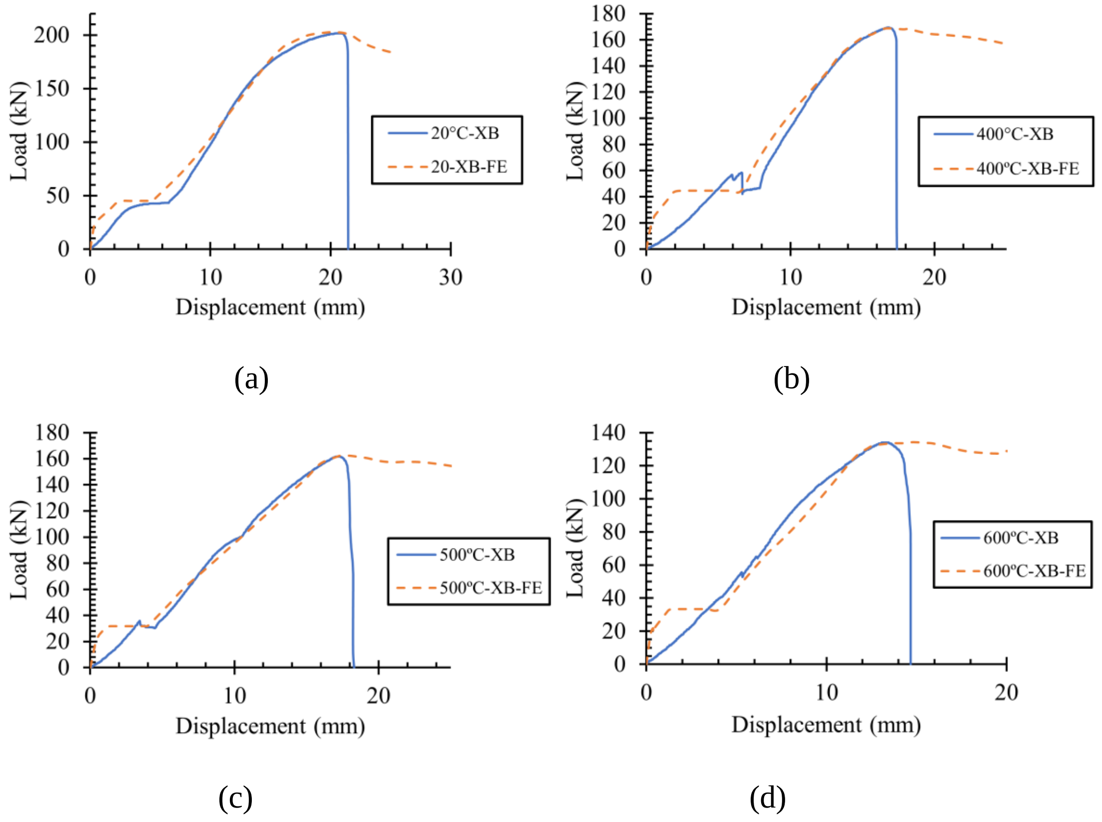


Fig. 21. Load-Displacement Validations for X bolted lap-joints at: (a) 20°C, (b) 400°C, (c) 500°C, (d) 600°C

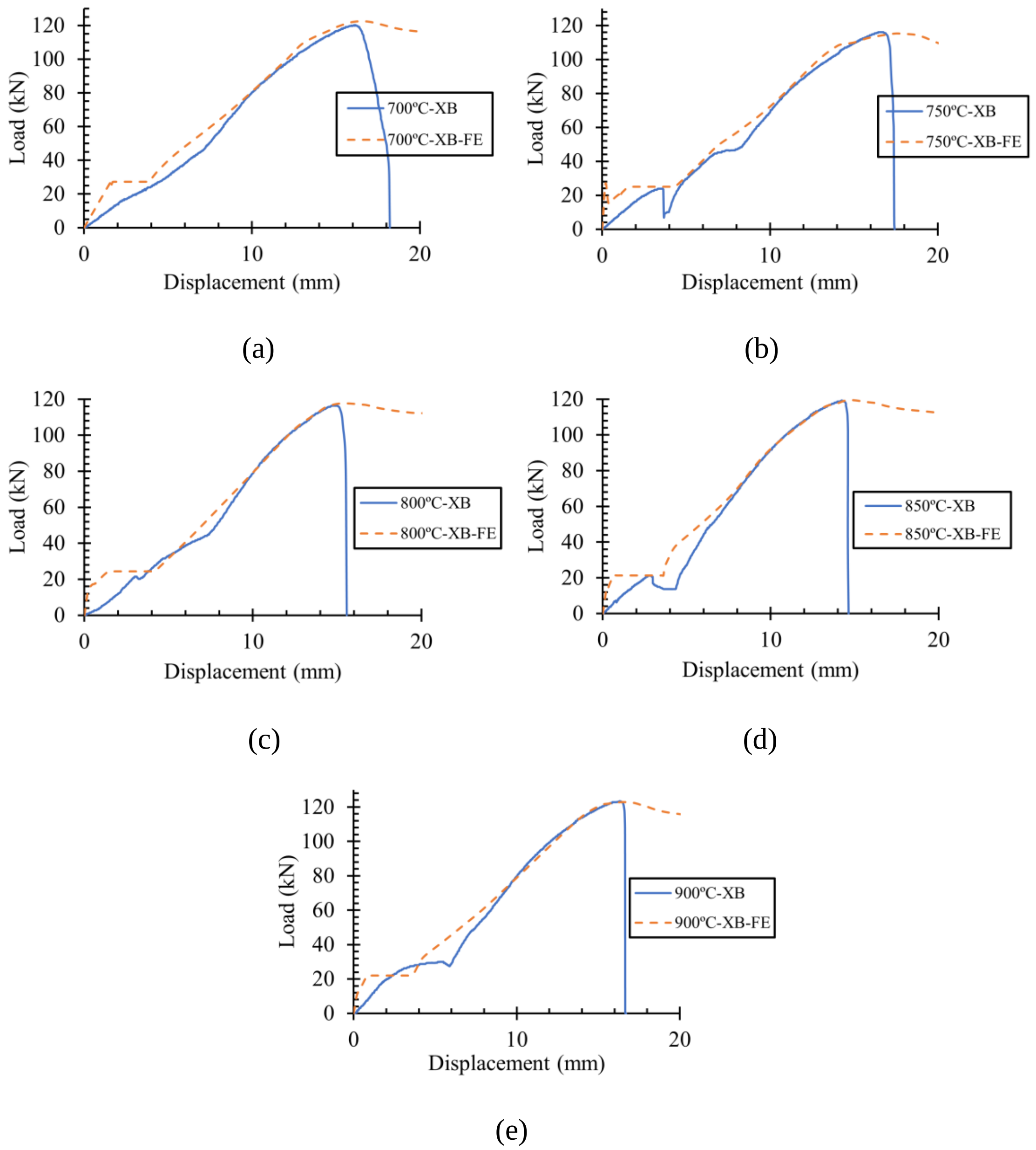
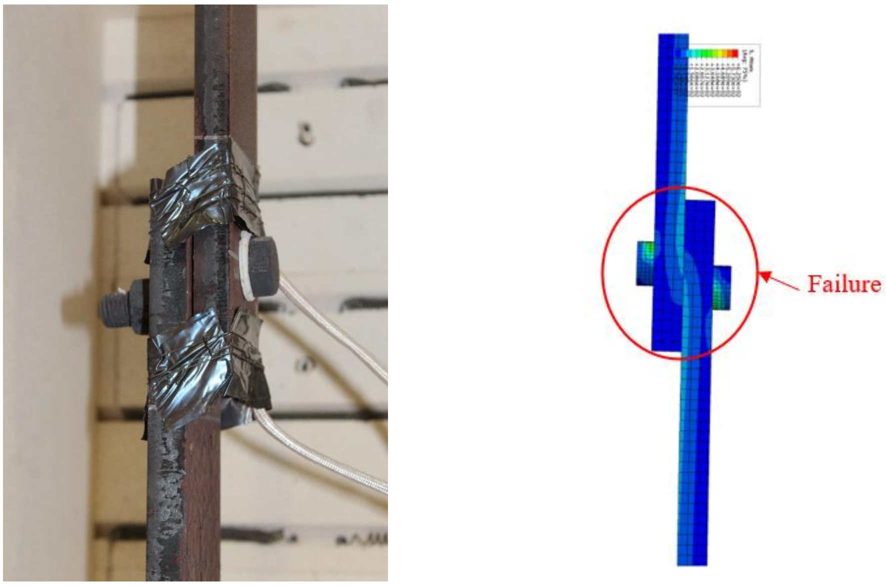


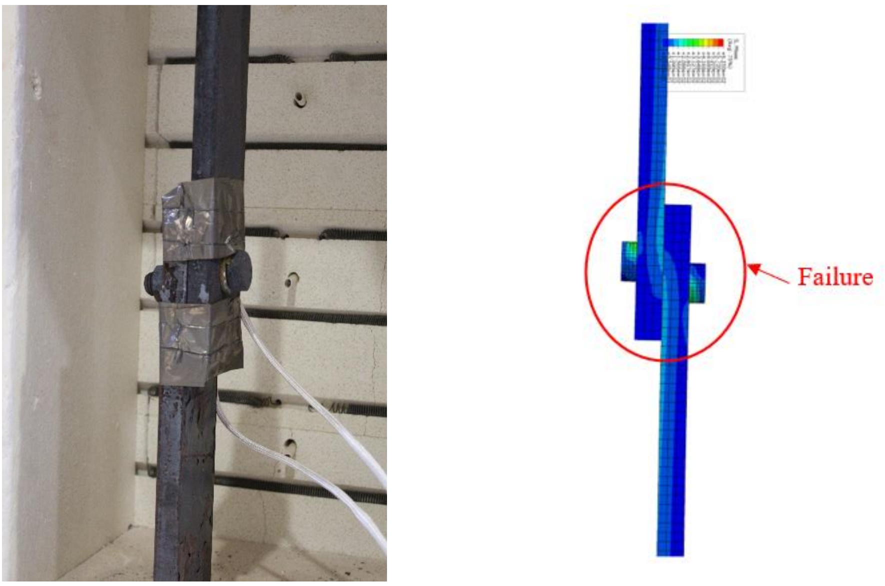
Fig. 22. Load-Displacement Validations for X bolted lap-joints at: (a) 700°C, (b) 750°C, (c) 800°C, (d) 850°C, (e) 900°C

Also, both the FE simulations and the experimental results show that all specimens failed by shear fracture at the throat of the bolts. Figs 23 (a) and 23 (b) show the failure mode observed in the experiments of X bolted lap joints performed at 700°C and 800°C, respectively, against the corresponding ones from the FE simulations. Note that, fracture modeling was not included in the simulations and the FE models were not capable to predict the behavior of lap-joint after the first component failure.

The FE simulations can predict closely the response of the connection as well as its failure mode which is bolt shear failure. This proves that neglecting the effect of threads at post-elevated temperatures might result in unsafe and inaccurate predictions of bolted lap joints strength capacities.



(a)



(b)

Fig. 23. FE versus experimental failure mode of X bolted lap-joints at: (a) 700°C (b) 900°C

CHAPTER IV

SUMMARY AND CONCLUSIONS

This study investigates the behavior of N- and X- bolted lap joints at post-elevated temperatures. Sixteen N and X bolted lap joints are tested after being exposed to temperatures ranging from 400°C to 900°C. The purpose of the experimental program is to show the effect of threads in the shear plane on the bolted lap joint strength capacity and slip resistance. Then, FE simulations are performed to validate the experimental program performed. The models show the effect of threads on N- and X- bolted lap-joints failure modes, strength capacities.

The key findings from the experimental program conducted on post-fire behavior of single shear-lap joints with N- and X-bolts are presented below:

The experimental results show that the failure mode of all bolted is bolt shear failure at ambient and post-elevated temperatures.

The exposed surfaces of the bolted lap joints exhibited a change in surface textures and colors from brown color at 500°C to gray color at 900°C. This change in color can play an important in detecting and investigating the steel temperatures in a non-destructive steel structure for repair purposes. However, the color and texture of the bolt fracture surfaces did not change when the temperature increases.

The results show that the residual peak loads for the lap joints with N- and X-bolts decrease as the targeted temperature of the post-fire analysis increases. That is, as temperature increases to 900°C, the reduction of the bolt shear strength reaches 40% and 39% of the initial strength for the lap joint with N- and X-bolts, respectively.

The effect of thread in the shear plane on the post-fire slip resistance is also studied. The results show that for temperatures ranging between 400°C and 800°C, the reduction in the slip resistance of the lap joints with N- and X-bolts are different. In addition, the results show a significant effect of the threads in the shear plane on the shear capacity of the connections. The decrease in the relative difference in shear capacity indicates that the reduction in the shear capacity of the lap joints with X-bolts is greater than those with N-bolts. However, for temperatures beyond 800°C, there is also no major effect on the post-fire behavior of bolted connections when using N- or X-bolts.

In addition, proposed values for a strength reduction coefficient, $\psi_{b,t}$ that can be used in the post-fire bolt shear capacity design equation. The modified equation can help predict more conservative post-fire bolt shear strength capacities including the effect of the threads in the shear plane. The value $\psi_{b,t}$ is incorporated in the bolt's materials of the FE validations to show the effect of threads in the shear plane on the post-fire behavior of N- and X-bolted lap joints.

The post-fire reduction factors for the bolt shear capacities of Grade 8.8 (A325) N-bolts and X-bolts are also presented and compared with other studies available in the literature. The reduction in the shear strength of X-bolted lap joints result in the lowest post-fire design of bolted connections as compared to those with N-bolts and others available in the literature.

CHAPTER V

SIGNIFICANCE, LIMITATIONS, AND FUTURE WORK

A. Significance

None of the studies available in the literature considered the effects of the threads in the shear plane on the post-fire behavior of bolted connections. To address this knowledge gap, an experimental program was conducted on N- and X-bolted lap joints to investigate their post-fire behavior after being exposed to fire temperatures. As a result, post-fire reduction factors of the slip resistance and the shear capacity of N- and X-bolts were proposed. These reduction factors can be used to develop design guidelines of bolted connections for structural-fire engineering application. After a heating-cooling cycle of a real fire and, steel in general loses its strength, however in many cases steel structures can be reused after fire events. Therefore, a deep understanding of the post-fire residual capacities of bolted connections was provided to ensure safe design of bolted connections after fire exposure. Moreover, design equations for strength capacities of N- and X- bolted lap joints were provided for post-fire analysis.

B. Limitations

This study was limited to M20-Grade 8.8 bolt material with flame-cut bolt hole fabrication and S355 (A572 Grade 50) base plate material. The governing failure mode at ambient was bolt shear failure. Further experimental data and numerical efforts are still needed to better understand the post-fire behavior of bolts and bolted connections after exposed to fire. This research work is considered a preliminary step towards the goal of understanding the post-fire behavior of bolts and bolted connection while considering the effect of threads in the shear plane. This research work was limited to one cooling regime where the specimen is cooled back to ambient in the furnace without any direct exposure to air or water. Therefore, future work is needed to study the residual responses of large-scale bolted connections having different bolt diameter, bolts and plate materials, bolt hole fabrication practices, and failure mode under a larger spectrum of targeted temperatures and cooling regimes. Future tests should be repeated at least three times to accurately understand more the residual response of bolts after fire exposure.

C. Future work

Future work should be conducted to fully comprehend the effect of threads in the shear plane on bolted connections at post-elevated temperatures. The following future works are recommended:

1. Investigate some major parameters that influence the post-fire behavior of bolted lap-joint after being exposed to fire. Such parameters are bolt diameter, bolt material, hole fabrication practice (drilling, punching, plasma-cut, etc.), and failure mode under a larger spectrum of targeted temperatures and cooling regimes. Different materials and failure modes at post-fire temperatures while using different loading rates are essential to develop new design guidelines for structural fire-engineering applications on bolted connections while considering the effect of threads in the shear plane.
2. Conduct an experimental program to investigate the post-fire behavior of the large-scale bolted connections after being exposed to elevated temperatures ranging from 400°C to 900°C and then cooled down to ambient before loading until failure.

3. Due to the drop in the slip resistance of N-bolted by 45% of its initial capacity, further experimental works should be conducted to investigate the post-fire slip resistance of N-bolted lap-joints after exposure to temperatures ranging from 400°C to 600°C with an increment of 25°C.

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