Influence of Loading Rates on Single Shear-Bolted Lap Joints at Elevated Temperatures

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Abstract: This research investigated the effect of loading rates or implicit creep on the strength and deformation capacities of single shear-bolted lap joints subjected to elevated temperatures. To address this issue, 16 bolted lap joints were tested under two different loading rates at temperatures ranging from 400°C to 700°C. The rate- and temperature-dependent retention factors for the bolt shear capacities were compared with those from previous studies in the literature. The effects of loading rate and temperature on the bolt pretension force also were examined. The results showed that all tested bolted lap joints failed in bolt shear. The results of the slow loading rate tests indicated a larger reduction in bolt shear capacities compared with the fast tests for temperatures greater than 400°C. That is, the effect of loading rate on the bolt shear capacity ranged from 18% to 36% difference for temperatures ranging from 450°C to 700°C, respectively. Finally, a strength reduction coefficient was introduced in the bolt shear capacity equation to account for the loading rate effect when designing bolted connections in fire. **DOI: 10.1061/(ASCE)MT.1943-5533.0003435.**

Author keywords: Single shear-bolted lap joints; Loading rates; Rate-dependent behavior; Steady-state temperature conditions; Elevated temperatures.

Introduction

Structural bolts play a crucial role in transferring the applied loads between the connected components of a steel connection. This role becomes critical during fire due to the thermal expansion or contraction of the steel members leading to the development of thermal-induced forces in the beam end connections. In addition, bolts exhibit a rapid reduction in strength compared with conventional steel when temperatures exceed 400°C (Kodur et al. 2012). These factors combined can alter the controlling failure mode of bolted connections to bolt shear failure when subjected to elevated temperatures (Yu et al. 2009; Hu and Engelhardt 2012). In addition to these factors, the behavior of bolted connections can be affected by the rate at which the fire-induced load is applied (implicit creep). Therefore, understanding the behavior of bolted connections in a fire event requires accurate knowledge of the rate and thermal behavior of bolts subjected to shear forces, which can be crucial for designing such connections in fire.

Bolt shear failure is a governing failure mode in bolted connections, especially when subjected to elevated temperatures. Experimental results showed that when M24 Grade 10.9 (ASTM 2010) bolts were used in fin plate connections, the failure was due to block shear of the beam web at ambient temperature, and changed to bolt shear failure at 550°C (Yu et al. 2009). Experimental tests of a shear tab connection showed that the failure mode changed from bearing to bolt shear failure at 400°C and 500°C for tests subjected to inclined and pure tension, respectively (Hu and Engelhardt 2012). This indicates that bolt shear failure can govern the connection response during fire, and understanding its rate and thermal behavior is of great importance.

Previous experimental studies also investigated the material degradation and load-bearing behavior of structural bolts in fire (Kirby 1995; Yu 2006; Hanus et al. 2011; Yang et al. 2011; Kodur et al. 2012; Hirashima et al. 2014; Fischer et al. 2018; Peixoto et al. 2017). These studies showed the degradation of the bolt strength capacity when subjected to elevated temperatures. For instance, experimental tests were performed on Grade 8.8 (ASTM 2004) bolts subjected to tension and double shear under elevated temperatures up to 800°C (Kirby 1995). The results showed a significant loss of bolt strength when subjected to temperatures greater than 300°C. The retention factors for the bolt strength capacities presented by Kirby (1995) were adopted by Eurocode 3 (CEN 2005; Yang et al. 2011). The capacities in Eurocode 3 (CEN 2005) are included in AISC 360 Appendix 4 (AISC 2016). Tensile tests were performed on two types of coupon high-strength bolts materials, ASTM A325 (ASTM 2004) and ASTM A490 (ASTM 2010), and found that ultimate strength capacity decreased by 92% at 700°C (Kodur et al. 2012). In addition to these tests, the significance of inelastic creep strains for bolts at high temperatures was investigated by Matar (2014). Tensile creep tests conducted on ASTM A325 (ASTM 2004) bolts at 450°C, 500°C, and 550°C showed the importance of creep strains when the bolt is subjected to temperatures higher than 400°C (Matar 2014). In addition, the results indicated that the creep strain rate of the bolt material increases as temperature increases, leading to larger creep deformations for higher temperatures.

All the previous studies on bolts and bolted lap joints investigated the effect of material and some geometric parameters on the bolt strength capacity at elevated temperatures. However, none of those studies considered the effect of loading rates or implicit creep on the behavior of bolts or bolted lap joints when subjected to elevated temperatures. Therefore, this paper studied the effect of loading rates on the strength and deformation capacities of single

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shear-bolted lap joints under elevated temperatures. It provides necessary data to develop design guidelines that include the effect of loading rate or implicit creep on bolts and bolted connections for structural fire-engineering applications. Two loading rates, 1.5 mm/min (fast) and 0.1 mm/min (slow), were used to test the bolted lap joints under steady-state temperature conditions ranging from 400°C to 700°C in 50°C increments. The rate- and temperature-dependent retention factors for bolt material were presented and compared with those proposed by previous studies in the literature. In addition, the effects of loading rate and temperature on the bolt pretension force were examined. This investigation is a step toward understanding the time effect on the strength capacities and pretension force of structural bolts at elevated temperatures.

Steady-State Implicit Creep Behavior of Bolts

Implicit creep is defined as the rate-dependent behavior of the material subjected to varying load, temperature, or both. In this case, creep strains are added directly to the stress-strain curve of the material (Torić et al. 2013). In general, creep deformations are noteworthy beyond one-third of the steel melting point, which is about 400°C (Kodur and Dwaikat 2010). Therefore, this study

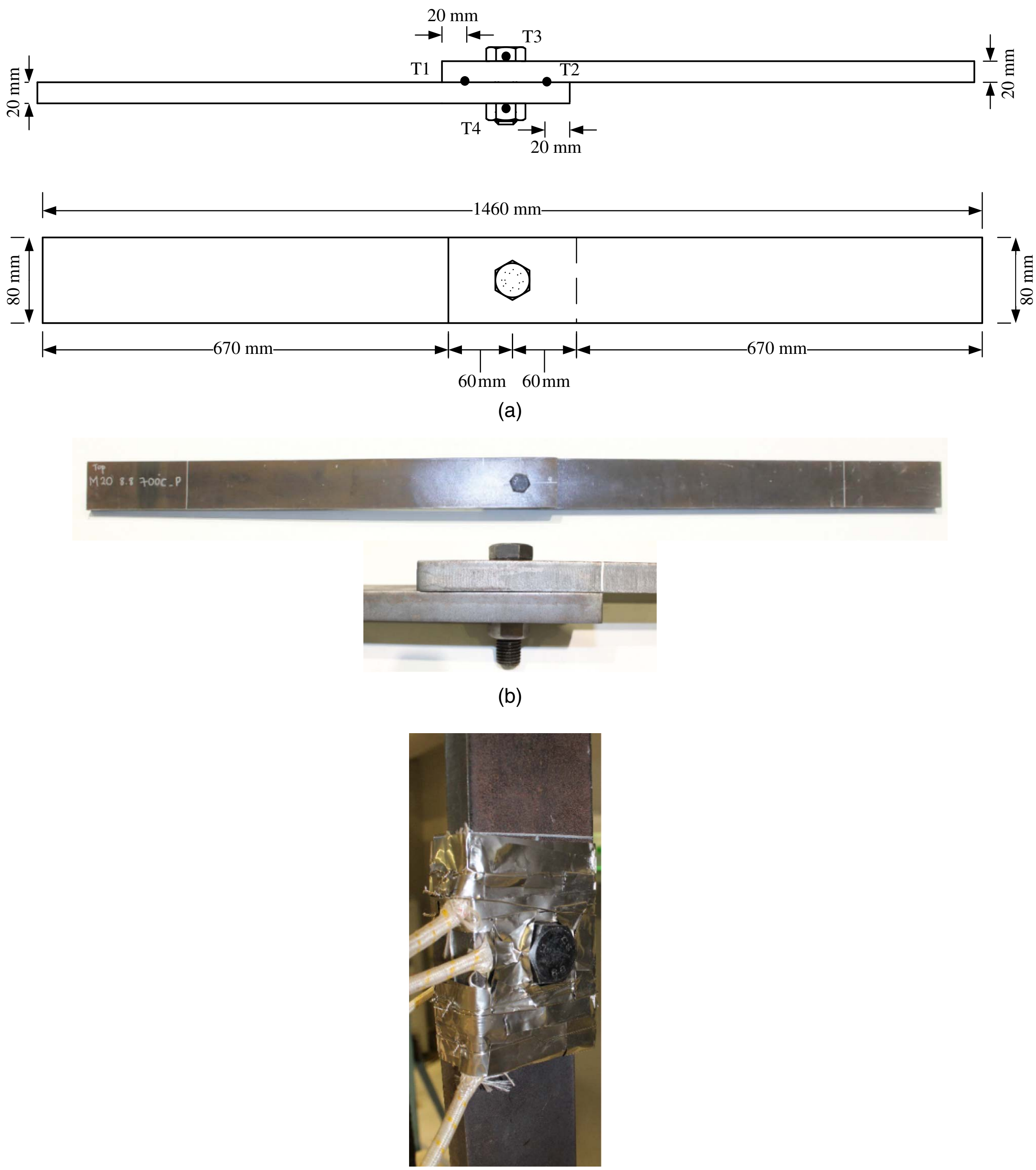


Fig. 1. Bolted lap joint specimen: (a) layout and thermocouples position; (b) elevation and top view; and (c) stainless steel foil.

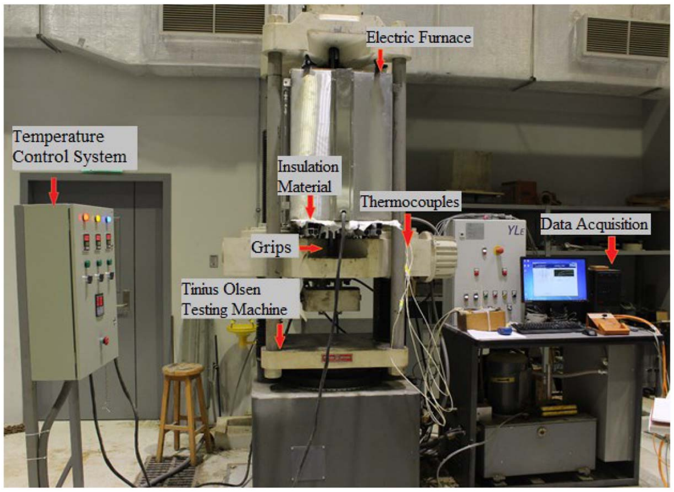


Fig. 2. Experimental setup.

investigated the implicit creep behavior of a single shear-bolted lap joint by varying the loading rate under different elevated temperatures ranging from 400°C to 700°C.

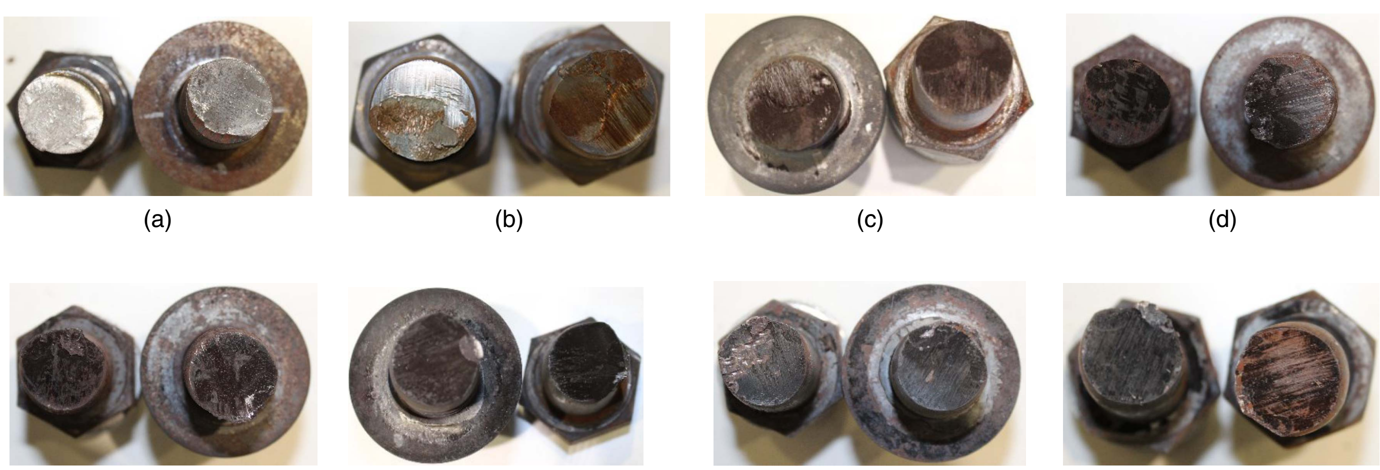
Experimental Program

Test Specimens

An experimental program was performed on single shear-bolted lap joints to measure the axial force-displacement relationship at each temperature and loading rate. The lap joints were designed as per AISC 360 (AISC 2016) such that the bolt shear failure governed the behavior of the specimen at ambient and elevated temperatures. That is, strength retention factors available in AISC 360 Appendix 4 (AISC 2016) for the steel base materials and bolts were used to calculate the elevated temperatures capacities of the bolted lap joints. Grade 8.8 (ASTM 2004) M20 X-bolts were used to connect the two S355 [ASTM A572 Grade 50 (ASTM 2018)] steel plates

(a) (b)

Fig. 3. Bolted lap joints after failure at (a) 650°C-Slow; and (b) 700°C-Slow.



(a) (b) (c) (d)

(e) (f) (g) (h)

Fig. 4. Bolt fracture surfaces in fast tests at (a) 20°C; (b) 400°C; (c) 450°C; (d) 500°C; (e) 550°C; (f) 600°C; (g) 650°C; and (h) 700°C.

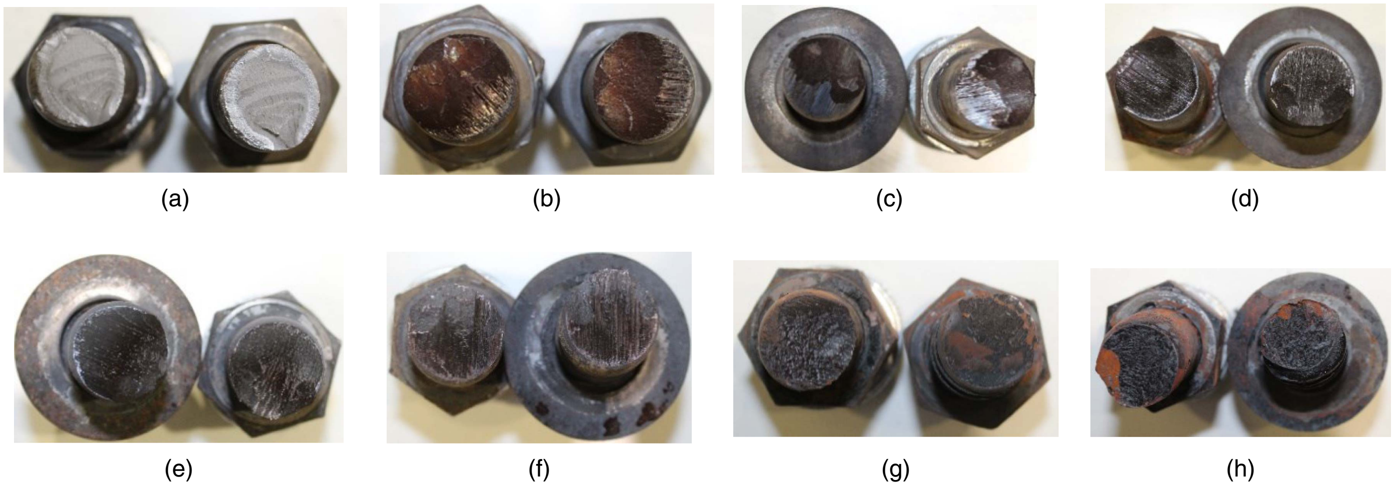


Fig. 5. Bolt fracture surfaces in slow tests at (a) 20°C; (b) 400°C; (c) 450°C; (d) 500°C; (e) 550°C; (f) 600°C; (g) 650°C; and (h) 700°C.

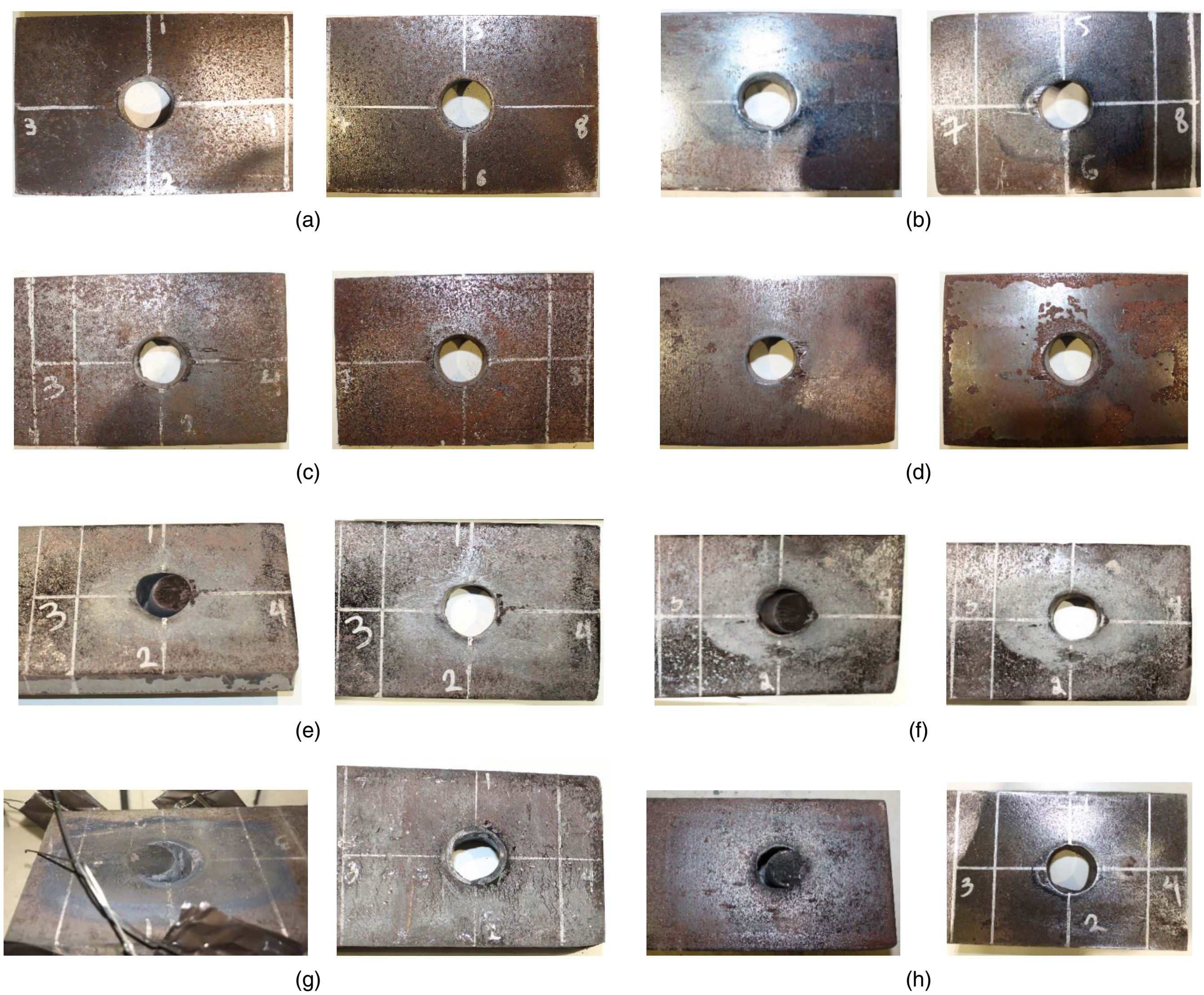


Fig. 6. Bolt holes in fast tests at (a) 20°C; (b) 400°C; (c) 450°C; (d) 500°C; (e) 550°C; (f) 600°C; (g) 650°C; and (h) 700°C.

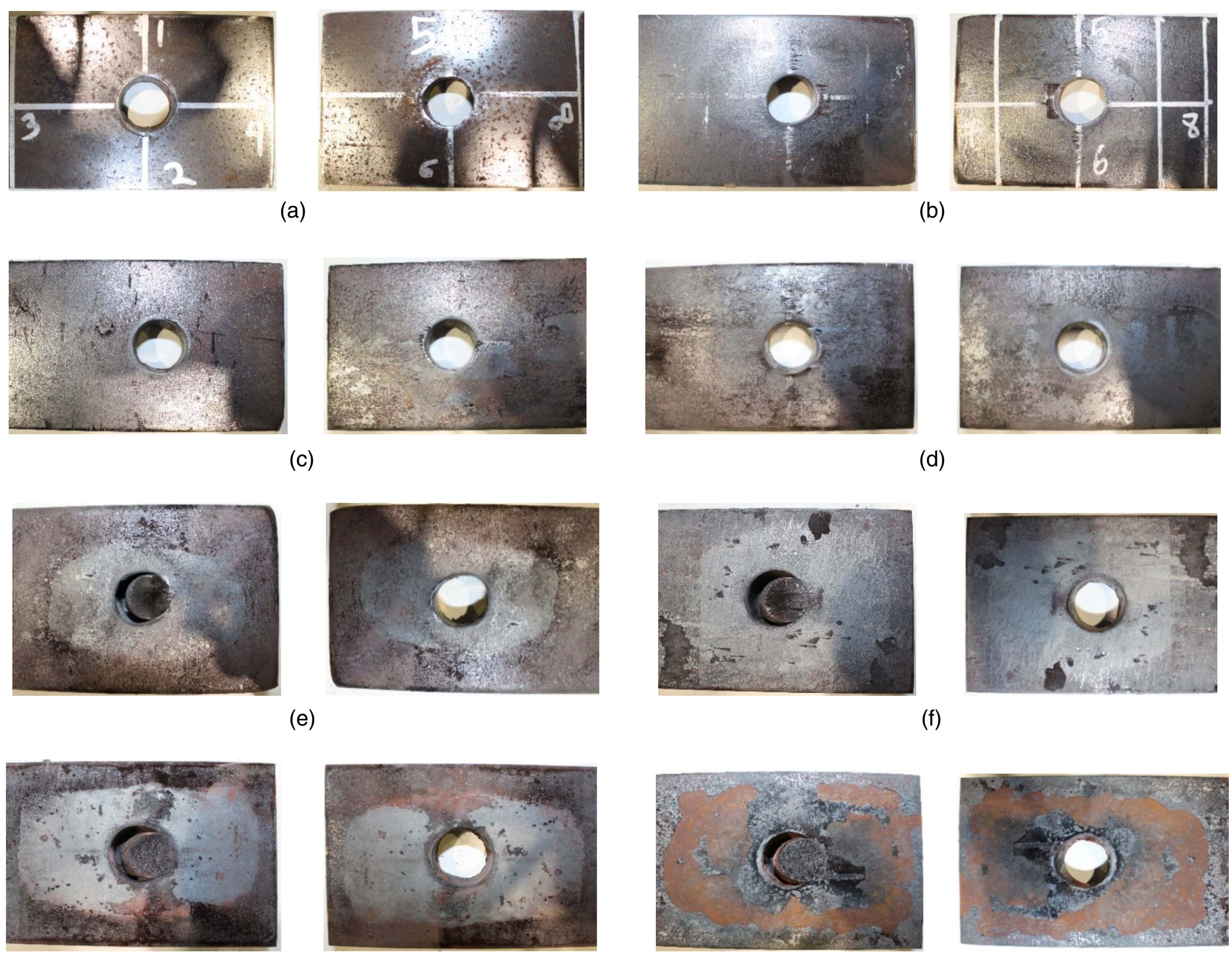
(790 × 80 × 20 mm) [Figs. 1(a and b)]. The bolts were pretensioned using a pretensioning wrench with a minimum bolt pretension force of 142 kN as per AISC 360 (AISC 2016) for all tests.

Setup and Instrumentation

A Tinius Olsen (Horsham, Pennsylvania) universal testing machine was used for the tensile testing of the bolted lap joints. An 800 × 550 × 830 mm electric furnace was used as a heating device for the elevated temperatures tests. The furnace consisted of three separate heating zones that could be controlled by a temperature control system. The bolt was pretensioned before placing four Type K thermocouples on the plates, bolt head, and bolt nut to measure their surface temperatures. Then the surfaces were wrapped in stainless steel foil (SSF) to protect the thermocouples from direct exposure to the thermal radiation emitted by the heating coils of the furnace. Fig. 1(a) shows the locations of the four thermocouples on the plate surfaces, bolt head, and bolt nut. Thermocouples T1 and T2 on the plate surfaces were placed 20 mm from the edges of the top and bottom plates, respectively. Figs. 1(b and c) show the tested specimen with and without stainless steel foil, respectively. Insulation material was used all around the furnace to prevent heat loss (Fig. 2). Neither an elevated temperature extensometer nor a camera were used inside the furnace during the tests.

Test Loading Protocol

To investigate the effect of loading rates or implicit creep on the behavior of the bolted lap joint specimens, a steady-state temperature analysis was used in this study, rather than a transient analysis. A uniform distribution of high temperature is required to perform a steady-state temperature test. The test loading protocol used comprised two phases. In the first phase, the specimen was heated up to a specific temperature and held constant for 30 min once the four thermocouples reached the same desired temperature to ensure a uniform distribution of temperature along the specimen. The second phase was the loading phase, in which a displacement-controlled load was applied to the test specimen at two different rates: fast (1.5 mm/min), and slow (0.1 mm/min). The deformations recorded by the data acquisition system were measured through the crossheads of the Tinius Olsen universal testing machine. The two loading rates used are chosen arbitrary with a factor of 15 (0.1 mm/min and 1.5 mm/min) to examine the effect of implicit creep on the bolted lap joints strength capacities and



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 7. Bolt holes in slow tests at (a) 20°C; (b) 400°C; (c) 450°C; (d) 500°C; (e) 550°C; (f) 600°C; (g) 650°C; and (h) 700°C.

deformations. The tests were stopped when the applied force reading was almost zero.

Test Results

Experimental Observation

To investigate the effect of two loading rates on single shear-bolted connections exposed to fire temperature, an experimental program was performed. The results showed that all specimens failed in bolt shear fracture at ambient and all elevated temperatures (Fig. 3). Figs. 4 and 5 show the different bolt shear fracture surfaces under all temperatures at the two loading rates. Figs. 4(a) and 5(a) show the bolt fracture surface at ambient temperatures using fast and slow loading rates, respectively. The failure mode at ambient temperature was brittle bolt shear failure at both loading rates, the bolts had smooth, gray, shiny surfaces. However, as the temperature increased to 600°C, 650°C, and 700°C, the bolts had a red-brown color with a rough surface texture, exhibiting significant ductile failure. In addition, for temperatures ranging from 400°C to 550°C, the failure surfaces of both loading rates had a combination of both textures, with a visible gray-brown color displaying less ductility. Furthermore, a pop was heard at fracture for temperatures less than or equal to 450°C. This indicates that the governing bolt shear failure changed from brittle to ductile at temperatures at about 500°C. Figs. 6 and 7 show the plate bolt holes after bolt shear failure. The bolts at temperatures greater than or equal to 550°C, at both loading rates, remained attached to the plate bolt hole after fracture occurred. Limited hole ovalization occurred at all temperatures and at both loading rates, indicating no change in failure mode.

Temperature-Dependent Behavior

Effect of Temperature on Load-Deformation Relationship

To study the temperature-dependent behavior of the Grade 8.8 (ASTM 2004) bolt, the tensile testing was conducted of the single shear-bolted lap joints at different elevated temperatures at both loading rates [Figs. 8(a and b)]. Initially, the curves increased

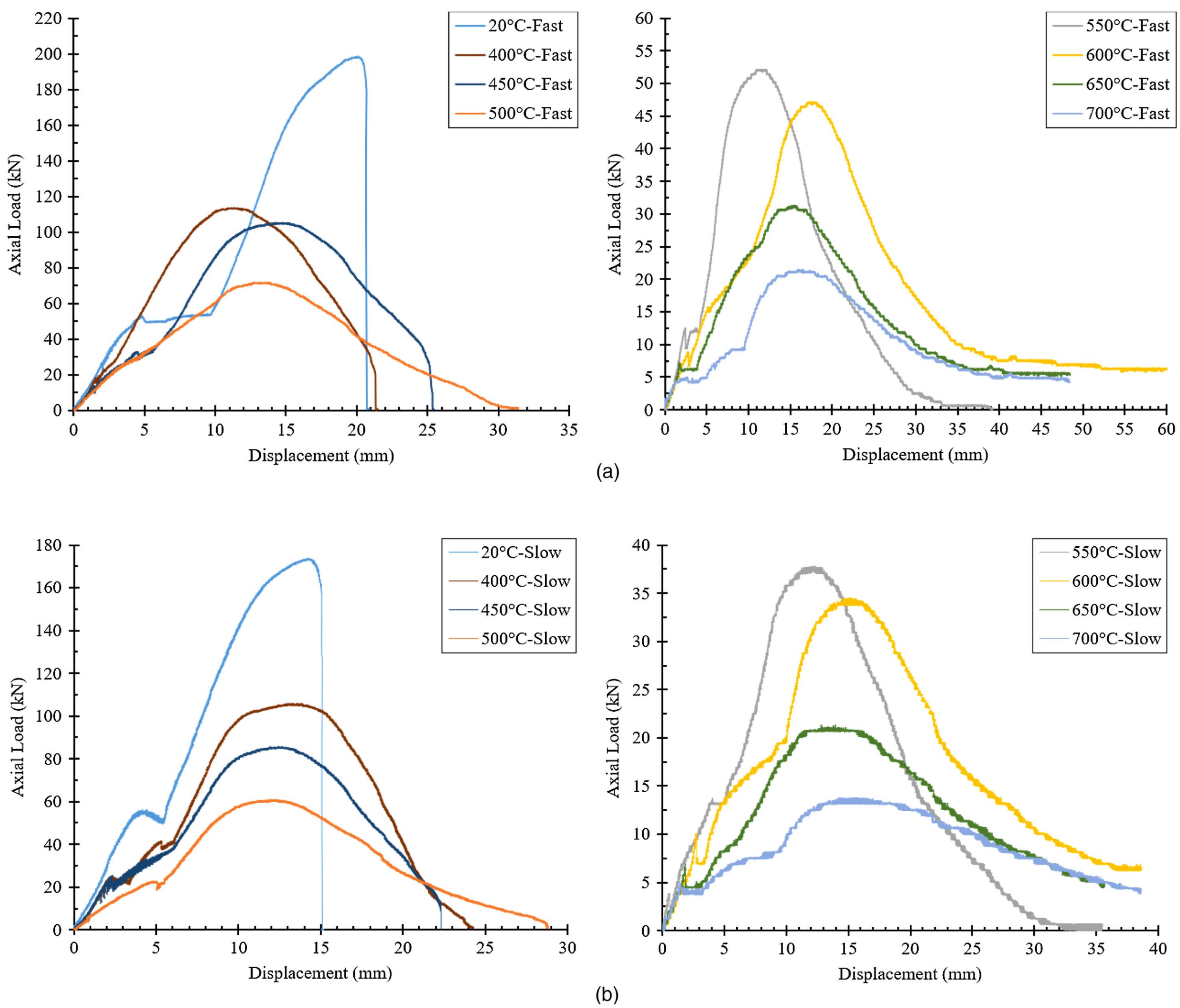


Fig. 8. Force-displacement results at (a) fast loading rate; and (b) slow loading rate.

linearly, representing the initial stiffness of the bolted lap joint at a targeted temperature. As temperature increased, initial stiffness started to degrade. The capacity of the lap joint connection decreased when temperature increased, and decreased further when the slower loading rate was applied. Table 1 presents the peak loads (P) and the maximum connection displacements (Δ) for all tested specimens at different temperatures and loading rates. The bolt strength capacities decreased sharply at temperatures between 20°C and 400°C and 400°C and 500°C at both loading rates (Fig. 8). Specifically, at 400°C, the bolt strength decreased by 42% and 39% of its initial strength capacity at ambient temperature for the fast and slow loading tests, respectively. As temperature increased to 700°C, the reduction of the bolt strength reached a maximum of 89% and 92% for the fast and slow tests, respectively. Furthermore, the increase of axial displacement as temperature increased indicates that the lap joint behaved in a more ductile manner in fire events. For instance, the maximum axial displacement at 400°C-Fast was 21.3 mm, and increased to 48.3 mm at 700°C-Fast (Table 1). Furthermore, the maximum axial displacement increased in the slow rate tests from 24.5 mm at 400°C-Slow to 38.5 mm at 700°C-Slow (Table 1).

Effect of Temperature on Bolt Pretension Force

In a slip-critical connection, the pretension forces cause the connected plates to be clamped together, producing friction forces that resist the applied shear loads (Guo et al. 2017). When the applied load reaches the slip-critical capacity of the bolt, slip occurs. Slippage in the experiments performed herein manifested in two different phenomena, either as a constant or gradual slip. In tests at 20°C-Fast, 550°C-Fast, and 650°C-Fast, constant slip occurred at forces of about 52, 12, and 6 kN, respectively (Fig. 8). However, in the other tests, slip occurred gradually within a range of lower and upper bounds. Table 2 lists the lower and upper bounds of pretension forces resulting from all tests conducted in this study. The retention factors were calculated by dividing the lower bound of the pretension force at each temperature by that at ambient temperature for each corresponding loading rate. The results indicated no major difference in the bolt pretension forces at both loading rates. Thus, the retention factors presented are the average of those obtained from the tests conducted using fast and slow rates. Fig. 9 presents the emperature-dependent retention factors for minimum bolt pretension forces of Grade 8.8 (ASTM 2004) M20 X-bolts and the corresponding proposed equation using linear regression analysis. The variation of retention factors for pretension force, K_{PT}, as a function of temperature, T, with a coefficient of determination $R^2 \simeq 0.99$, is

$$K_{PT} = -0.0009T + 0.692 \quad (1)$$

Eq. (1) is valid only for temperatures ranging from 400°C to 700°C. These retention factors can be used in the slip-resistance design Equation J3-4 in AISC 360 (AISC 2016) to predict elevated temperatures slip-critical capacities.

Time-Dependent Behavior

The effect of loading rates on a single-shear bolted lap joint subjected to different elevated temperatures was studied, and the axial force-displacement curves are illustrated in Figs. 10 and 11, which

Table 1. Test matrix and results of failure load and displacement for fast and slow rates

Test name	Temperature (°C)	Peak load, P (kN)	Failure axial displacement, Δ (mm)
20°C-Fast	20	198.4	20.1
400°C-Fast	400	113.8	21.3
450°C-Fast	450	104.5	25.7
500°C-Fast	500	71.4	31.4
550°C-Fast	550	52.1	39.1
600°C-Fast	600	47.1	60.0
650°C-Fast	650	31.2	48.3
700°C-Fast	700	21.4	48.3
20°C-Slow	20	173.3	15.2
400°C-Slow	400	105.5	24.5
450°C-Slow	450	85.5	22.4
500°C-Slow	500	60.6	28.8
550°C-Slow	550	37.8	32.2
600°C-Slow	600	34.4	36.6
650°C-Slow	650	21.3	35.6
700°C-Slow	700	13.7	38.5

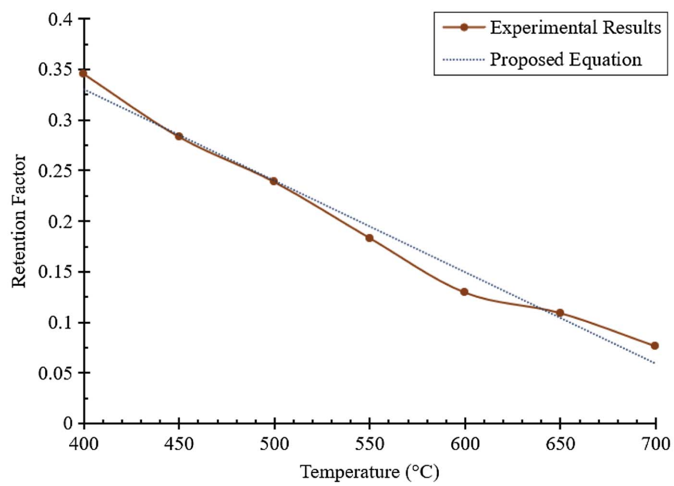


Fig. 9. Retention factors for minimum bolt pretension force of Grade 8.8 M20 bolt.

Table 2. Lower- and upper-bound pretension force (kN)

Test name	Lower-bound pretension force	Upper-bound pretension force	Test name	Lower-bound pretension force	Upper-bound pretension force
20°C-Fast	49.5	53.6	20°C-Slow	56.1	53.1
400°C-Fast	15.4	27.2	400°C-Slow	21.3	40.3
450°C-Fast	13.4	33.3	450°C-Slow	16.6	37.4
500°C-Fast	10.0	20.0	500°C-Slow	15.4	21.7
550°C-Fast	12.4	12.4	550°C-Slow	6.5	13.3
600°C-Fast	6.7	23.1	600°C-Slow	6.9	19.5
650°C-Fast	6.9	6.2	650°C-Slow	4.5	9.5
700°C-Fast	4.2	9.2	700°C-Slow	3.8	8.4

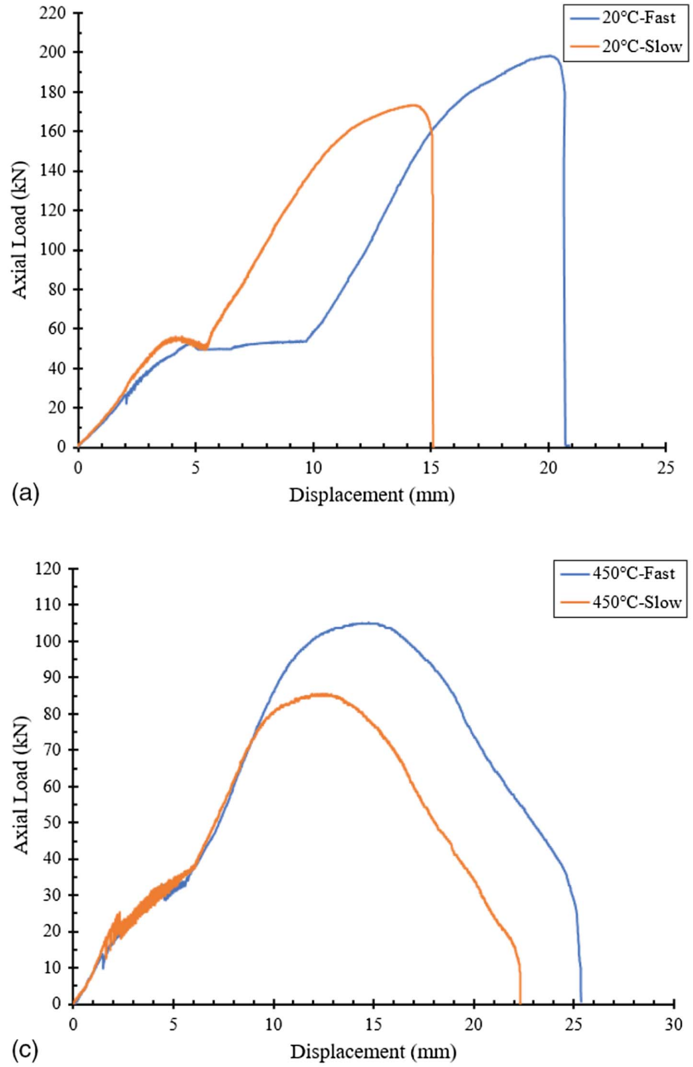


Fig. 10. Effect of loading rate on force-displacement behavior at (a) 20°C; (b) 400°C; (c) 450°C; and (d) 500°C.

compare the bolted lap joint behavior obtained at temperatures between 20°C and 500°C and between 550°C and 700°C, respectively, at both loading rates. The difference in capacities at ambient temperatures for both loading rates [Fig. 10(a)] might be due to the different material strengths, dimension tolerances, and hole diameters. However, at 400°C [Fig. 10(b)], there was no major effect on the strength capacity of the bolted lap joint when using a slower loading rate. As temperature increased to 450°C and 500°C, the difference in strength capacities became noticeable [Figs. 10(c and d), respectively]. This is because creep has no significant effect at temperatures below one-third of the melting point of steel (400°C) (Kodur and Dwaikat 2010). As temperature increased, the difference in bolt strength capacities began to increase more significantly when temperatures reached 550°C, 600°C, and 650°C [Figs. 11(a–c), respectively]. The difference in strength capacities continued to increase until it reached a maximum at 700°C, with values of 21.4 and 13.7 kN using fast and slow rates, respectively [Fig. 11(d)]. Table 3 presents the percentage decrease in bolt shear capacities for the bolted lap joints subjected to both loading rates. The percentage decrease in capacities when a slower loading rate was used showed a major effect at temperatures above 450°C. That is, the bolt shear capacity decreased by 18% at 450°C, and reached a maximum value of 36% decrease at 700°C. This reduction occurs due to the significant inelastic creep strains that initiate at temperatures slightly above the recrystallization temperature of steel (Boresi and Schmidt 2003). In addition, the results showed no major rate-dependent effect on either the pretension force or the initial stiffness, indicating that the inelastic creep strains were not significant for low stress or load levels. Figs. 11(c and d) show the force-displacement relationships for tests conducted at 650°C and 700°C, respectively, using fast and slow loading rates. The bolt shear capacities at 650°C-Slow and 700°C-Fast were the same, 21 kN. Therefore, ignoring the rate-dependent behavior of bolts in the fire design of steel bolted connections can result in unsafe predictions.

Retention Factors

The retention factors for the two loading rates are determined for the Grade 8.8 (ASTM 2004) bolt subjected to single shear. The retention factors for the bolt shear capacity was calculated by dividing the capacities at each designated temperature by that at ambient temperature. The bolt shear capacity at each elevated temperature at both loading rates was divided by the average capacity of both rates at ambient temperature, 185.9 kN. Fig. 12 compares the retention factors from this study with those in AISC 360

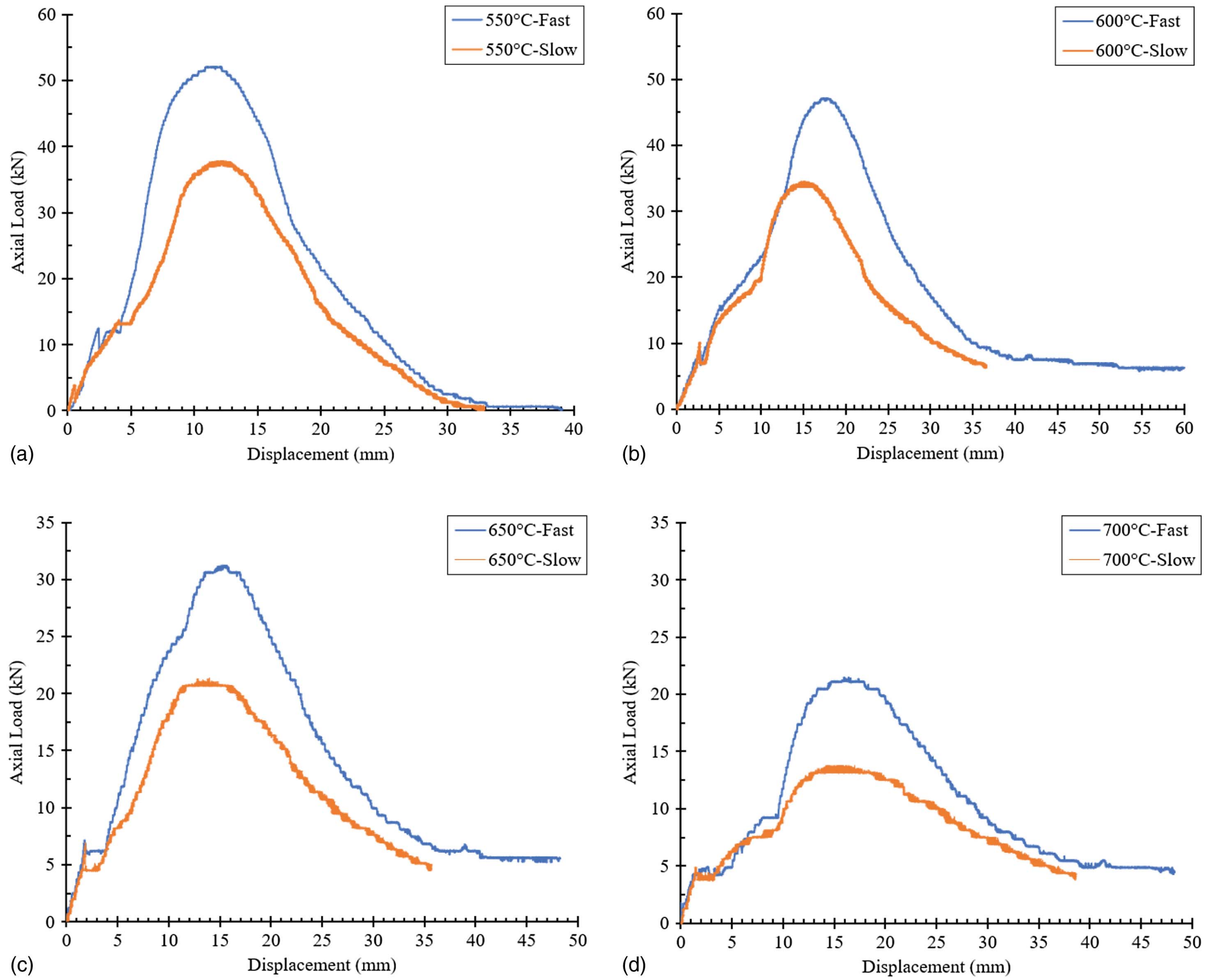


Fig. 11. Effect of loading rate on force-displacement behavior at (a) 550°C; (b) 600°C; (c) 650°C; and (d) 700°C.

Table 3. Effect of loading rate on strength capacities of single shear-bolted lap joints

Test name	Failure load, P (kN)	Test name	Failure load, P (kN)	Decrease in capacity (%)
20°C-Fast	198.4	20°C-Slow	173.3	12.3
400°C-Fast	113.8	400°C-Slow	105.5	7.3
450°C-Fast	104.5	450°C-Slow	85.5	18.0
500°C-Fast	71.4	500°C-Slow	60.6	14.7
550°C-Fast	52.1	550°C-Slow	37.8	27.4
600°C-Fast	47.1	600°C-Slow	34.4	27.0
650°C-Fast	31.2	650°C-Slow	21.3	31.7
700°C-Fast	21.4	700°C-Slow	13.7	36.0

Appendix 4 (AISC 2016), Yang et al. (2011), Kodur et al. (2012), and Fischer et al. (2018). The results show a significant effect of the loading rate on the retention factors of bolt shear strength capacity for temperatures above 450°C. This indicates that more-conservative retention factors were obtained from the slow loading rate tests than those resulting from the fast tests and all other previous studies. Furthermore, the retention factors obtained from the fast tests at temperatures up to 600°C were more conservative than those proposed by previous studies. However, above 600°C, these retention factors, as well as those available in the literature, closely matched. This indicates that neglecting the effect of loading rates might lead to unsafe and inaccurate results in predicting the bolt shear capacity of bolted connections exposed to elevated temperatures.

Proposed Retention Factors Modification

To include the effect of creep implicitly in the design of bolted connections at elevated temperatures, a strength reduction coefficient, α, is proposed and added to the bolt shear capacity Equation J3-1 in AISC 360 (AISC 2016)

$$R_n = \alpha k_{b,T} A_b F_{nv} \tag{2}$$

where R_n = single-bolt shear capacity at elevated temperatures; $k_{b,T}$ = retention factors in AISC 360 Appendix 4 (AISC 2016); A_b = unthreaded or threaded area of bolt; and F_{nv} = nominal shear strength. The strength reduction coefficient, α, is defined as the ratio of the slow rate retention factors (from tests) to the AISC

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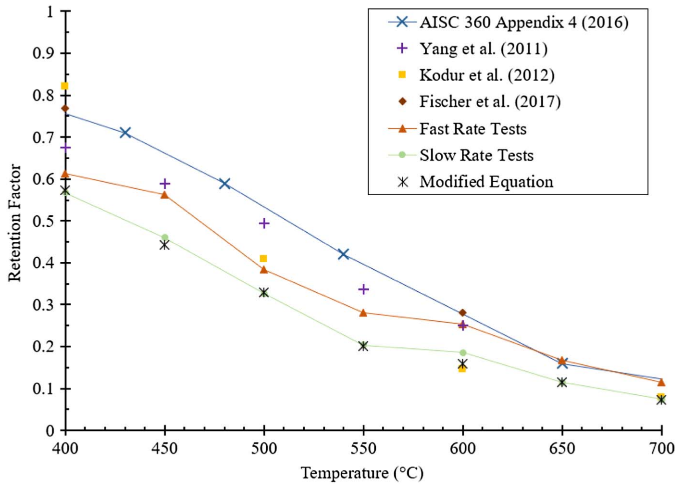

Fig. 12. Proposed bolt shear capacity retention factors compared with previous data and modified equation.

360 Appendix 4 (AISC 2016) retention factors. For temperatures from 400°C to 600°C, a linear regression analysis determined a relationship between strength reduction coefficient, α, and temperature, T, with a coefficient of determination: $R^2 \simeq 0.98$

$$\alpha = -0.0014T + 1.3 \quad (3)$$

For temperatures greater than 600°C, the value of α no longer applies for the linear relationship proposed in Eq. (3). The strength reduction coefficients (α) at temperatures 600°C, 650°C, and 700°C were found to be 0.84, 0.72, and 0.74, respectively. Therefore, the conservative value of α for temperatures greater than 600°C is considered to be 0.72. Fig. 12 shows the retention factors of the modified AISC 360 (AISC 2016) equation [Eq. (2)] versus those available in the literature (AISC 2016, Appendix 4; Yang et al. 2011; Kodur et al. 2012; Fischer et al. 2018). This proposed strength reduction coefficient, α, produces more-conservative bolt shear strength capacities at elevated temperatures when including the effect of implicit creep or loading rate.

Summary and Conclusions

This paper investigated the rate- and temperature-dependent behavior of single shear-bolted lap joints at elevated temperatures. Sixteen bolted lap joints were tested at two loading rates, fast (1.5 mm/min) and slow (0.1 mm/min), at temperatures ranging from 400°C to 700°C in 50°C increments using steady-state temperature conditions. The purpose of the experimental program was to determine the influence of loading rate or implicit creep on the bolted lap joint strength capacities, deformations, and pretension force of Grade 8.8 (ASTM 2004) bolts. In addition, this study helps to understand the rate-dependent behavior of bolts subjected to shear forces and the implications for bolted connections at high temperatures to ensure a safe design.

The experimental results showed that the tested specimens failed due to bolt shear failure at temperatures ranging from 20°C to 700°C at both loading rates. Additionally, the failure behavior shifted from brittle to ductile at about 500°C. Furthermore, limited hole ovalization occurred at all temperatures and both loading rates, indicating no change in failure mode.

Experimental results showed that as temperature increased, the bolt shear strength capacity and the initial stiffness decreased. That is, as temperature increased to 700°C, the reduction of the bolt shear strength reached an ultimate 89% and 92% decrease for the fast and slow rates, respectively. In addition, the results showed that the axial displacement increased as temperature increased, indicating that the bolted lap joint behaved in a more ductile behavior when subjected to higher temperatures.

An equation is proposed that calculates the retention factors of the minimum bolt pretension force for Grade 8.8 (ASTM 2004) M20 X-bolts. These retention factors can be used in the slip-resistance design equation of bolted connections to predict slip-critical capacities for temperatures ranging from 400°C to 700°C.

The results showed no major effect of loading rate on either the bolt pretension force or the initial stiffness, indicating that the inelastic creep strains are insignificant for low load levels. The effect of loading rate significantly initiated at 450°C with 18% decrease in strength capacity, reaching an ultimate 36% decrease at 700°C. Additionally, the tests indicated a similar strength capacity at 650°C and 700°C at slow and fast loading rates, respectively. Thus, it is necessary to consider the effect of loading rate in finite-element simulations and fire design of bolted steel connections in order to ensure a safe prediction of capacity and behavior.

The temperature- and rate-dependent retention factors for the bolt shear capacities of Grade 8.8 (ASTM 2004) bolts at both loading rates were compared with those of other studies in the literature. The retention factors obtained using the slow loading rate tests resulted in a more conservative bolt shear capacity design in bolted connections exposed to fire compared with those using the fast tests and others available in the literature.

Finally, proposed values for a strength reduction coefficient, α, were used in the bolt shear capacity fire design equation. The modified equation can help predict more-conservative bolt shear strength capacities at elevated temperatures including the effect of implicit creep or loading rate.

This study is limited to M20-Grade 8.8 (ASTM 2004) bolt material with threads excluded from the shear plane, using flame-cut bolt hole fabrication and S355 [A572 Grade 50 (ASTM 2018)] base material. Future work must be performed either numerically or experimentally to better understand the behavior of bolts and bolted connections due to the implicit creep thermal effect. Thus, the testing of different materials and failure modes at higher temperatures using different loading rates is essential to develop new design guidelines for structural fire-engineering applications of bolted connections considering the effect of rate or time.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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