Journal of Constructional Steel Research 104 (2015) 1–8

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experimental research on slip-resistant bolted connections after fire

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ARTICLE INFO

Article history:
Received 27 January 2014
Accepted 26 September 2014
Available online 10 October 2014

Keywords:
Slip-resistant bolted connections
Post fire test
Slip factor
Bolt pre-tension force
Temperature

ABSTRACT

Slip factor and bolt pre-tension force for slip-resistant bolted connections after fire were investigated experimentally. 74 connections made up of four plates and four class 10.9 bolts were first heated to specified temperature levels, and then cooled to ambient temperature and tested. Slip load tests were conducted to obtain the slip factor and bolt pre-tension force for the post-fire connections. In case of slip factor tests the bolts in connections after fire were replaced by new bolts and the pre-tension in the new bolts was measured, so the slip factor could be determined from the post-fire slip load. While in case of bolt pre-tension tests the old bolts were kept and the residual pre-tension was calculated based on the slip factor data obtained from accompanying tests. Two friction surface treatment methods were considered which were blast-cleaning (Class A) and inorganic zincs paint coated after blast-cleaning (Class B). Nine temperature levels from 200 °C to 700 °C were considered. Test results show that heating–cooling process has significant effects on both slip factor and bolt pre-tension force. The slip factor after fire increases with increasing temperature level, and residual bolt pre-tension force decreases with increasing temperature level. The increase in slip factor for Class A friction surface is much greater than that for Class B friction surface. Tri-linear models are proposed to calculate the normalized slip factor and bolt residual pre-tension force for slip-resistant 10.9 bolted connections after fire. New suggestions are proposed for post fire checking of slip-resistant bolted connections.

1. Introduction

Steel structures may experience one or more fires in their service life. Inspection from accident fires finds that in most cases steel structures are not fatally destroyed. Structural steel may be reused after a fire provided that its mechanical properties have not been severely impaired and that the members have not been damaged [1]. The post-fire behavior of steel structures mainly depends on the following aspects: the maximum temperature each part of the steel structure has experienced; the mechanical behavior of structural steel after fire; the deformation of the structures and members; and the behavior of connection joints. Among them the deformation can be easily determined through visual examination and instrument measurement, and the other three aspects require deep research.

The maximum temperature the steel has experienced can be roughly determined by the different surface colors of hot-rolled structural steel [2] and high-strength bolt [3] affected by the attained temperature. The accurate determination of the maximum exposure temperature is based on the presumption of fire characteristic of steel structures, for which the research results of concrete structures [4–6] can provide reference. As the elevated temperature curve is known, the maximum temperature the steel has experienced can be obtained by temperature calculation method of steel member. And many researches have been conducted on the post-fire mechanical behavior of hot-rolled structural steel [2,7,8] and high-strength bolt [3,9].

Connections are of great importance to the resistance of steel structures. Due to the lack of thorough research on the post-fire behavior of bolted connections, most design codes in the world will not allow high-strength bolts to be re-used after a fire. Replacing bolts affected by fire seems to be safe on the assumption that the slip factor is not affected by the heating and cooling process. Actually the variation of slip factor after fire was found in some experimental researches. Chen [10] investigated the slip load of slip-resistant bolted connections after fire and concluded that the slip factor decreased after fire. If this is the case, only replacing the bolts will not ensure the reliability of the bolted connection. Yu [9] tested the slip load of slip-resistant bolted connections using A490 bolts after fire according to the standard slip load test method specified in the AISC Steel Construction Manual [11]. The study found that the residual post-fire slip load increased with fire temperature exposure from room temperature to 400 °C, where connection could gain 50% more slip load at most. The increase in residual post-fire slip loads was explained to be due to the increase in the surface roughness. If

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http://dx.doi.org/10.1016/j.jcsr.2014.09.018
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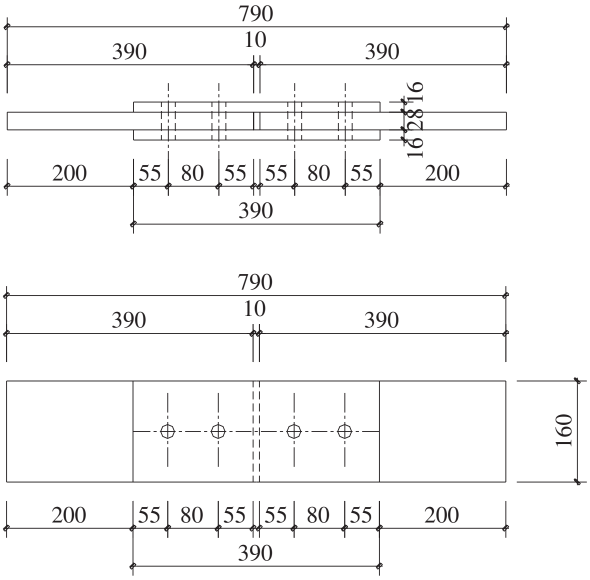


Fig. 1. Dimensions for test specimens.

this is the case, replacing the bolts tends to be over-conservative when the exposed temperature is not high.

Actually, the slip resistance of slip-resistant bolted connections is influenced by two key parameters: slip factor and bolt pre-tension force (pre-tension force in bolts). Effect of heating and cooling on slip factor and bolt pre-tension force should be investigated in order to determine the slip resistance of slip-resistant connections after fire and provide design suggestions for post-fire checking. This paper experimentally studied the behavior of slip-resistant bolted connections after fire. The effects of heating–cooling process on both slip factor and bolt pre-tension force were investigated.

2. Experimental program

2.1. Test specimens

Fig. 1 shows the dimensions of the specimens made according to the Chinese code GB50205-2001 [12]. Each specimen includes four plates (made by Q345B steel) and four class 10.9 bolts (M20). Since the intended failure mode was slip of the joint, the thickness of the cover plates and that of the inner plates were selected so as not to yield before the slip occurred.

Tables 1 and 2 give the investigated cases for slip factor tests. Totally, 60 specimens were used. Two friction surface treatment methods were considered which were blast-cleaning (Class A) and inorganic zincs paint coated after blast-cleaning (Class B). Nine temperature levels were considered which were 200 °C, 300 °C, 350 °C, 400 °C, 450 °C, 500 °C, 550 °C, 600 °C and 700 °C. The ambient temperature was also considered for comparison. Three specimens were tested at each temperature level.

Table 3 gives the investigated cases for bolt pre-tension tests. Totally, 14 specimens were used. The friction surface treatment method was blast-cleaning. Six temperature levels were considered which were 200 °C, 300 °C, 400 °C, 500 °C, 600 °C and 700 °C. The ambient temperature was also considered for comparison. For each temperature level, two specimens were tested.

2.2. Bolt pre-tension force

Bolt pre-tension force was applied by using torque wrench in accordance to Chinese code GB 50017-2003 [13]. In [13], pre-tension force for class 10.9 bolts with a diameter of 20 mm is 155 kN. Consider that heating–cooling process may affect torque coefficient, the values of pre-tension force in bolts were derived from measured strain gauges. Fig. 2 shows the location of the strain gauges on a bolt. Two strain gauges were glued on the screw to measure the tension strain. The

Table 1
Parameters and test results of blast-cleaning specimens.

Specimen	Exposure temperature T_s (°C)	Bolt pretension P_{20} (kN)	Slip load N_T (kN)	Slip factor μ_T	Average of μ_T	Experimental value of μ_T/μ_{20}	Calculation value of μ_T/μ_{20}
			Average (first/second)				
BC-20-1	20	189	342(275/408)	0.452	0.499	1.00	1.00
BC-20-2		160	327(314/340)	0.511			
BC-20-3		156	333	0.534			
BC-200-1	200	160	369(300/438)	0.577	0.523	1.05	1.00
BC-200-2		162	321(280/361)	0.495			
BC-200-3		166	330(308/351)	0.497			
BC-300-1	300	171	384	0.561	0.582	1.17	1.18
BC-300-2		155	370	0.597			
BC-300-3		151	355(280/430)	0.589			
BC-350-1	350	164	423(405/440)	0.645	0.663	1.33	1.26
BC-350-2		154	390(355/425)	0.633			
BC-350-3		140	398(391/405)	0.711			
BC-400-1	400	153	412(404/418)	0.673	0.713	1.43	1.35
BC-400-2		172	527(513/540)	0.766			
BC-400-3		160	447(436/458)	0.698			
BC-450-1	450	162	448(386/510)	0.691	0.678	1.36	1.44
BC-450-2		157	434(350/517)	0.691			
BC-450-3		165	430(380/480)	0.652			
BC-500-1	500	169	473(435/510)	0.700	0.723	1.45	1.53
BC-500-2		192	597	0.777			
BC-500-3		189	524(466/581)	0.693			
BC-550-1	550	168	514(497/530)	0.765	0.791	1.58	1.61
BC-550-2		169	537(523/550)	0.794			
BC-550-3		160	520	0.813			
BC-600-1	600	166	634	0.955	0.867	1.74	1.70
BC-600-2		162	535(424/645)	0.826			
BC-600-3		162	531(527/534)	0.819			
BC-700-1	700	169	620	0.917	0.858	1.72	1.70
BC-700-2		161	522(450/593)	0.811			
BC-700-3		159	539(520/557)	0.847			

Table 2
Parameters and test results of inorganic zincs paint coated after blast-cleaning specimens.

Specimen	Exposure temperature T_s (°C)	Bolt pretension P_{20} (kN)	Slip load N_T (kN)	Slip factor μ_T	Average of μ_T	Experimental value of μ_T/μ_{20}	Calculation value of μ_T/μ_{20}
			Average (first/second)				
PC-20-1	20	171	268	0.392	0.388	1.00	1.00
PC-20-2		171	250	0.365			
PC-20-3		147	240(200/280)	0.408			
PC-200-1	200	164	260(240/280)	0.396	0.390	1.00	1.00
PC-200-2		152	258(245/270)	0.424			
PC-200-3		161	225(220/230)	0.349			
PC-300-1	300	148	260(250/270)	0.446	0.431	1.11	1.06
PC-300-2		155	248	0.400			
PC-300-3		150	268(245/290)	0.447			
PC-350-1	350	151	248(210/285)	0.411	0.442	1.14	1.09
PC-350-2		150	283(265/300)	0.472			
PC-350-3		155	–[a]	–			
PC-400-1	400	164	297(240/353)	0.453	0.446	1.15	1.13
PC-400-2		160	280(220/340)	0.438			
PC-400-3		156	280	0.449			
PC-450-1	450	159	270(250/290)	0.425	0.416	1.07	1.16
PC-450-2		167	269	0.403			
PC-450-3		157	265(250/280)	0.422			
PC-500-1	500	166	310	0.467	0.468	1.20	1.19
PC-500-2		180	330	0.458			
PC-500-3		157	300	0.478			
PC-550-1	550	171	315	0.461	0.497	1.28	1.22
PC-550-2		155	298(275/320)	0.481			
PC-550-3		155	340	0.548			
PC-600-1	600	168	340	0.506	0.498	1.28	1.25
PC-600-2		159	330	0.519			
PC-600-3		165	310	0.470			
PC-700-1	700	162	310(290/330)	0.478	0.476	1.23	1.25
PC-700-2		166	295	0.444			
PC-700-3		160	324	0.506			

[a] Note: Test on specimen PC-350-3 failed and no slip load was obtained.

average value of the measured two strains was used to calculate the value of pre-tension force in bolts. The calculated values of pre-tension force in bolts are given in Tables 1 and 2.

2.3. Instrumentation

Three K-type thermocouples were used in each specimen to measure the inner temperatures in connections. Fig. 3a shows the location of the thermocouples. Two displacement transducers were used to measure the displacement between the outside bolts. Fig. 3b shows the location of the displacement transducers.

2.4. Test procedure and test setup

The test procedure for slip factor tests is as follows: (1) assemble the specimens and apply pre-tension force in bolts; (2) heat the specimens to desired temperature levels and maintain the temperatures for 60 min; (3) cool the specimens to ambient temperature; (4) replace the bolts in cooled specimens with new bolts, and apply pre-tension force in the new bolts; and (5) conduct slip test until specimens fail.

The test procedure for bolt pre-tension force tests is the same as for slip factor tests except that step (4) is omitted. Because the slip factor after fire can be obtained from slip factor tests, the residual bolt pre-

Table 3
Parameters and test results of specimens for bolt pretension test.

Specimen	Exposure temperature T_s (°C)	Slip load N_T (kN)	Slip factor μ_T	Bolt pretension P_T (kN)	Average of P_T (kN)	Experimental value of P_T/P_{20}	Calculation value of P_T/P_{20}
BP-20-1	20	300	0.499	150	153	1.00	1.0
BP-20-2		309		155			
BP-200-1	200	300	0.523	143	151	0.99	1.0
BP-200-2		330		158			
BP-300-1	300	328	0.582	141	144	0.94	1.0
BP-300-2		340		146			
BP-400-1	400	300	0.713	105	105	0.69	0.60
BP-400-2		297		104			
BP-500-1	500	93	0.723	32	32	0.21	0.20
BP-500-2		89		31			
BP-600-1	600	66	0.867	19	18	0.12	0.15
BP-600-2		57		16			
BP-700-1	700	43	0.858	13	15	0.10	0.10
BP-700-2		55		16			

Fig. 2. Layout of strain gauges on the bolt.

tension force is back-calculated from the slip load instead of measured. The measurement of residual bolt pre-tension force may be difficult.

Fig. 4 shows the furnace and the slip load test setup.

3. Experimental results and analysis

3.1. Load–displacement relationship and slip load

Fig. 5 shows the typical load–displacement curves for specimens using blast-cleaning method (Class A) in the slip factor tests. The load–displacement curve in Fig. 5a has a single platform, which indicates that the two connection plates slipped simultaneously during the test, while the curve in Fig. 5b has two platforms, which indicates that the two connection plates did not slipped simultaneously during the test. The reason may be due to the variation in either actual pre-tension force in bolts or friction surface treatment. For the load–displacement curve with one single platform, the slip load for the specimen is taken as the load at the platform; while for the curve with two platforms, the slip load is taken as the average of the loads at two platforms. In the tests, the load–displacement curves for most specimens have two platforms, while the curves for some specimens have one platform. Slip load values for Class A specimens are given in Table 1.

Fig. 6 shows the typical load–displacement curves for specimens using inorganic zincs paint coated after blast-cleaning (Class B) in the slip factor tests. Unlike Class A specimens, the load–displacement curves for most Class B specimens have one platform, as shown in Fig. 6a. Even for curves with two platforms, the first slip load is close to the second slip load, as shown in Fig. 6b. The little difference between the slip loads at two platforms may be due to the fact that variations in both bolt pre-tension force and friction surface treatment have little influence on the performance of Class B specimens. Slip load values for Class B specimens are given in Table 2.

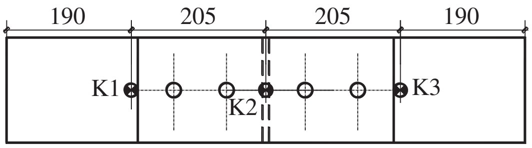
Fig. 7 shows the typical load–displacement curves for specimens in the bolt pre-tension tests. The curves have a single platform. Slip load values from bolt pretension tests are given in Table 3.

3.2. Effect of heating–cooling process on slip factor

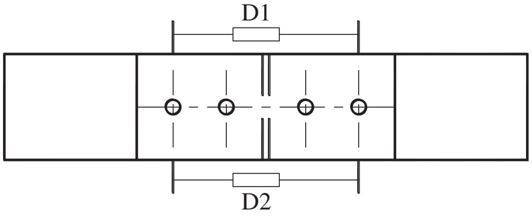
Slip factor of high-strength bolted friction-type connections after fire can be calculated as follows:

$$\mu_T = \frac{N_T}{n_f \sum P_T} \tag{1}$$

where μ_T and N_T are the slip factor and slip load of connections after exposing to temperature T_s, respectively; n_f is the number of the friction surfaces; and $\sum P_T$ is the sum of bolt pre-tension forces. The values of slip factor for Class A and Class B connections after exposed to different temperature levels are given in Tables 1 and 2, respectively. The normalized slip factors, defined as the ratio of the average slip factor for each temperature level to the average slip factor at ambient temperature, are also given in the tables.



(a) Layout of thermocouple



(b) Layout of displacement transducer

Fig. 3. Instrumentation layout.

(a) Specimen in furnac (b) Slip load test

Fig. 4. Test setup.

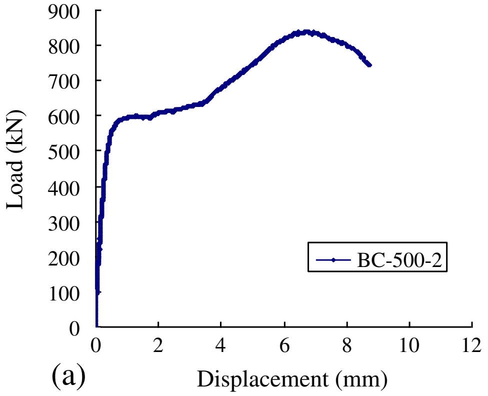


Fig. 5. Load–displacement curves of blast-cleaning specimens after fire.

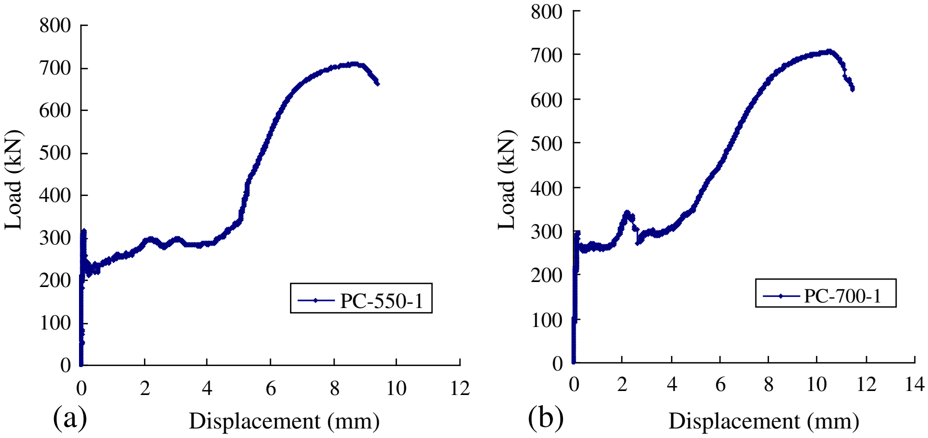


Fig. 6. Load–displacement curves of inorganic zincs paint coated specimens after fire.

Fig. 8 shows the normalized slip factor against the temperature level for Class A and Class B connections. It can be found that:

(1) The effect of heating–cooling process on the normalized slip factor for blast-cleaning (Class A) connections is greater than the effect on the normalized slip factor for inorganic zincs paint coated after blast-cleaning (Class B) connections.

(2) With increasing temperature level, the normalized slip factors first remain constant up to 200 °C, then increase linearly until 600 °C (with an exception point of 450 °C) and finally begin to decrease slightly beyond 600 °C. At 600 °C, the (maximum) normalized slip factors for Class A and Class B specimens are 1.74 and 1.28, respectively.

(3) Fluctuations at 450 °C are found in both curves for Class A and Class B specimens, as shown in Fig. 8. Fig. 9 compares the slip surfaces after slip load tests for a connection tested under different temperature levels. The color of the slip surface of the connection heated to 450 °C is quite different from that of the connection

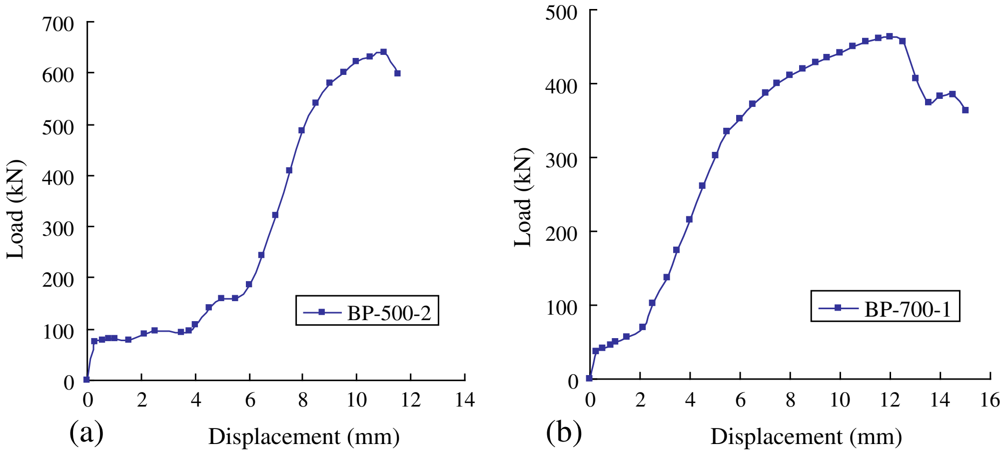


Fig. 7. Load–displacement curve of specimens for bolt pre-tension test.

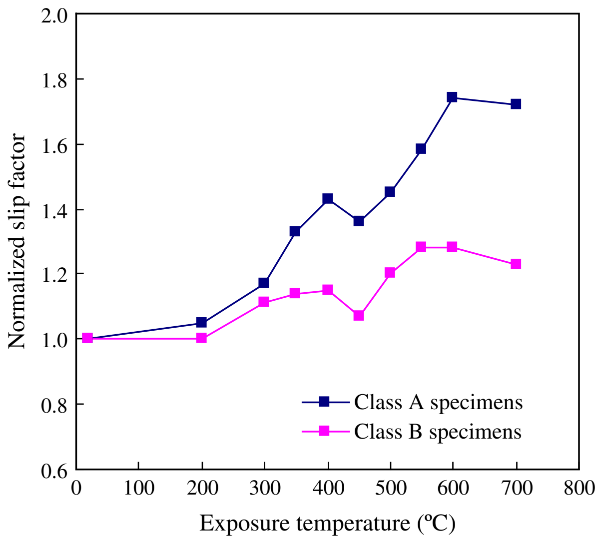


Fig. 8. Normalized factor slip after exposed to different temperatures.

heated to 200 °C. Therefore, the fluctuations of the normalized slip factor at 450 °C may be caused by blue brittleness of the steel plate.

3.3. Effect of heating–cooling process on pre-tension force in bolts

Rearrange Eq. (1) and consider $\sum P_T = 2P_T$, we get the equation to calculate the residual pre-tension force in bolts in the tested specimens,

$$P_T = \frac{N_T}{2n_f\mu_T}. \tag{2}$$

Assume that the slip factors in the bolt pre-tension tests are the same as in the slip factor tests, the residual pre-tension forces in bolts calculated by Eq. (2) are given in Table 3. The normalized pre-tension forces, defined as the ratio of the average residual pre-tension force for each temperature level to the average pre-tension force at ambient temperature, are also given in the table.

Fig. 10 shows the normalized residual pre-tension force against the temperature level for connections in pre-tension force tests. It can be found that:

(1) The effect of heating–cooling process on the normalized residual pre-tension force is significant. The normalized residual pre-tension force decreases with increasing temperature level.

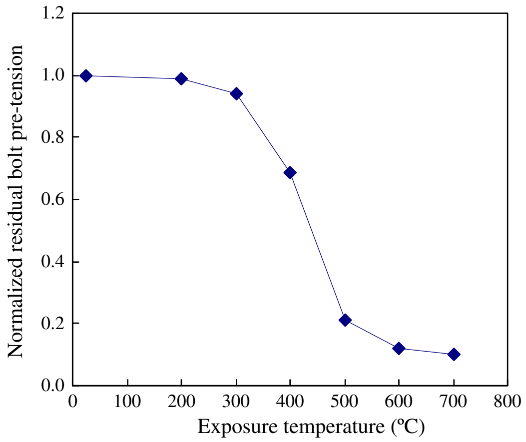
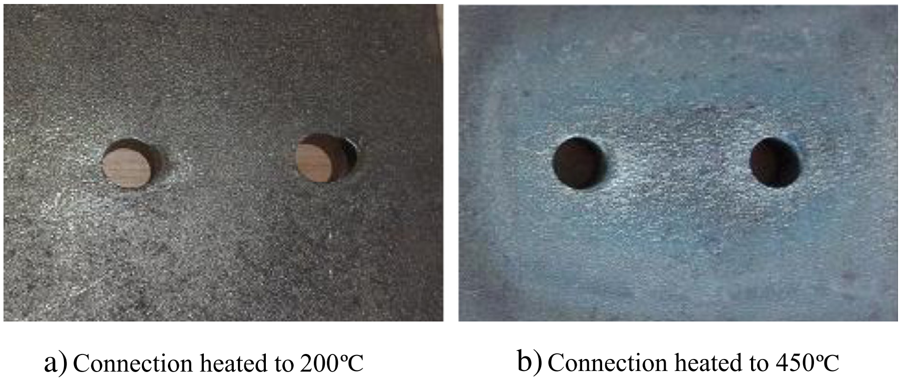


Fig. 10. Normalized residual bolt pretension of connections after exposed to different temperatures.

(2) With increasing temperature level, the normalized residual pre-tension force first decreases slightly up to 300 °C, then decreases sharply until 500 °C, and finally decreases slowly beyond 600 °C. At 500 °C, the residual pre-tension force in bolt is only 21% of its original value at ambient temperature; and when exposed to 700 °C, the residual pre-tension force is only 10% of the room-temperature value.

The loss of pre-tension forces in the bolts after heating and cooling may be explained as follows: Thermal expansion occurs in the steel when the connection is heated, which leads to the thermal expansion pre-tension loss ΔP_{TE} in the bolts. The bolt pre-tension reduces from the initial value P_{20} to the residual value $(P_{20} - \Delta P_{TE})$. When the elevated temperature is no more than 300 °C, the yielding strength and the elastic modulus of the bolts decrease progressively [14,15], so nearly no plastic deformation occurs in the bolts under the residual pre-tension force $(P_{20} - \Delta P_{TE})$. Deformation caused by thermal expansion is reversible, thus in the cooling process the thermal expansion pre-tension loss ΔP_{TE} eliminates. The bolts regain strength and stiffness on cooling [3], therefore the bolt pre-tension force can almost restore to the initial value P_{20} when the maximum exposure temperature is no more than 300 °C.

When the connection is heated to temperature above 300 °C, the yielding strength and the elastic modulus of the bolts begin to decrease rapidly [14,15], so the residual pre-tension force $(P_{20} - \Delta P_{TE})$ may cause plastic deformation in the bolts. In the cooling process thermal expansion deformation is reversible while plastic deformation is



a) Connection heated to 200℃ b) Connection heated to 450℃

Fig. 9. Slip surface of blast-cleaning connections after post-fire slip load test.

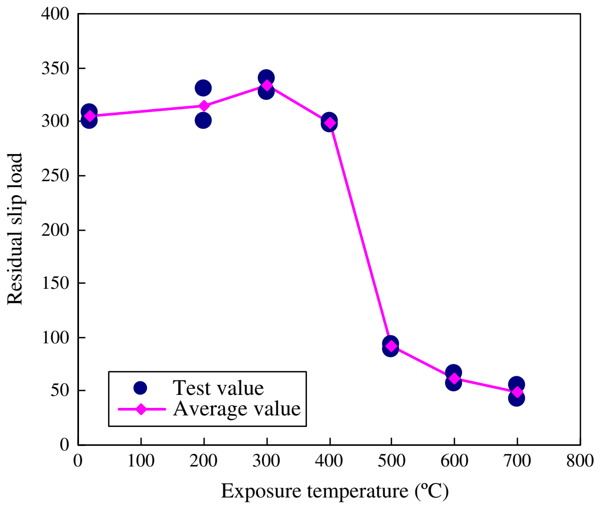


Fig. 11. Residual slip load of connections after exposed to different temperatures.

irreversible, thus the plastic deformation produced in fire results in pretension loss in the bolts after fire.

3.4. Effect of heating–cooling process on slip resistance

Measured residual slip loads for the specimens in the bolt pretension tests are also given in Table 3. Residual slip load is significantly affected by the maximum temperature (or temperature level) in the heating–cooling process as shown in Fig. 11. Residual slip load is nearly the same as that at room temperature up to 400 °C, and there is about a 10% increase at 300 °C which is due to the increase of slip factor. Then residual slip load decrease rapidly from 400 °C to 500 °C, and finally decreases slowly from 500 °C to 700 °C. At 700 °C, residual slip load is only 16% of the room-temperature value.

4. Calculation of slip factor and bolt pre-tension force after fire

4.1. Slip factor after fire

Tri-linear models derived from curve fitting of the test data were proposed to calculate the normalized slip factors for slip-resistant bolted connections after fire. For blast-cleaning slip-resistant bolted connections,

$$\begin{cases} \dfrac{\mu_T}{\mu_{20}} = 1.0 & 20^\circ\mathrm{C} \le T_s \le 200^\circ\mathrm{C} \\ \dfrac{\mu_T}{\mu_{20}} = 1 + 0.00175(T_s - 200) & 200^\circ\mathrm{C} < T_s \le 600^\circ\mathrm{C} \\ \dfrac{\mu_T}{\mu_{20}} = 1.7 & 600^\circ\mathrm{C} < T_s \le 700^\circ\mathrm{C} \end{cases} \tag{3}$$

and for inorganic zincs paint coated after blast-cleaning slip-resistant bolted connections,

$$\begin{cases} \dfrac{\mu_T}{\mu_{20}} = 1.0 & 20^\circ\mathrm{C} \le T_s \le 200^\circ\mathrm{C} \\ \dfrac{\mu_T}{\mu_{20}} = 1 + 0.000625(T_s - 200) & 200^\circ\mathrm{C} < T_s \le 600^\circ\mathrm{C} \\ \dfrac{\mu_T}{\mu_{20}} = 1.25 & 600^\circ\mathrm{C} < T_s \le 700^\circ\mathrm{C}. \end{cases} \tag{4}$$

Fig. 12 shows the curve fitting of test data using tri-linear models.

4.2. Residual bolt pre-tension after fire

A tri-linear model derived from curve fitting of the test data was proposed to calculate the normalized residual pre-tension force in class 10.9 bolts in slip-resistant connections after fire,

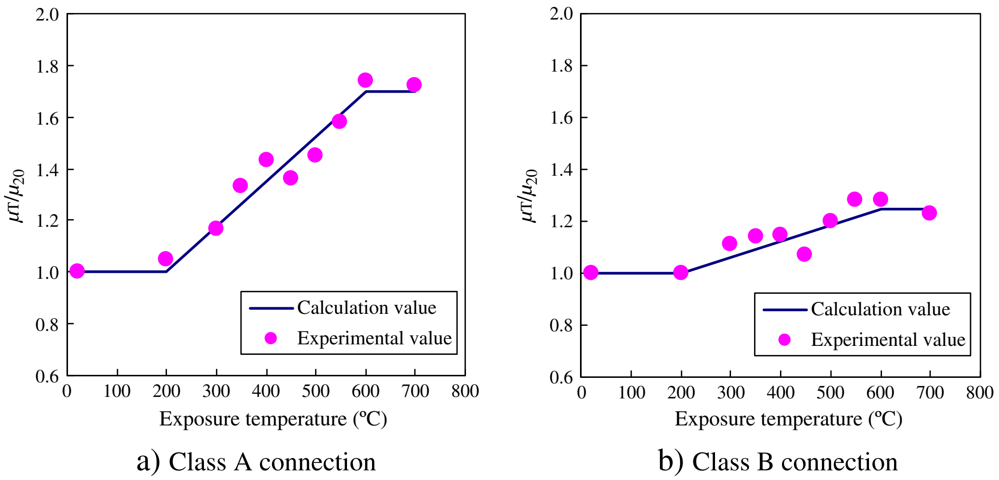
$$\begin{cases} \dfrac{P_T}{P_{20}} = 1.0 & 20^\circ\mathrm{C} \le T_s \le 300^\circ\mathrm{C} \\ \dfrac{P_T}{P_{20}} = 1 - 0.004(T_s - 300) & 300^\circ\mathrm{C} \le T_s \le 500^\circ\mathrm{C} \\ \dfrac{P_T}{P_{20}} = 0.2 - 0.0005(T_s - 500) & 500^\circ\mathrm{C} \le T_s \le 700^\circ\mathrm{C}. \end{cases} \tag{5}$$

Fig. 13 shows the curve fitting of test data using tri-linear models.

5. Conclusions

The behavior of slip-resistant 10.9 bolted connections after fire has been investigated to provide data for post fire checking. The following conclusions are reached based on the experimental results.

(1) Heating–cooling process has significant effects on both slip factor and bolt pre-tension force of slip-resistant 10.9 bolted connections.
(2) The effect of heating–cooling process on the slip factor for blast-cleaning connections is greater than the effect for



a) Class A connection

b) Class B connection

Fig. 12. Comparison of calculation value and test value of μ_T/μ_{20}.

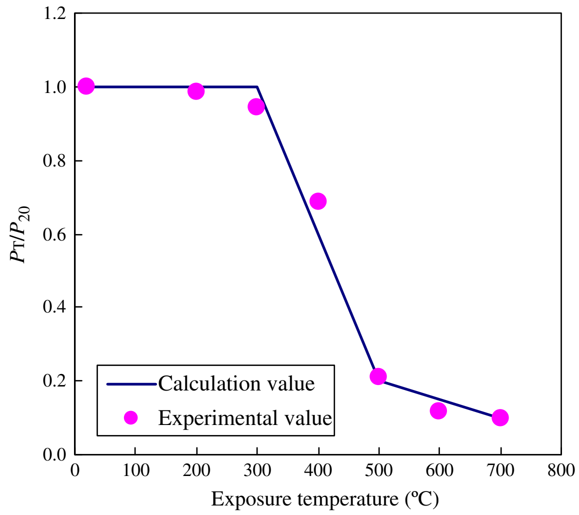


Fig. 13. Comparison of calculation value and test value of P_T/P_{20}.

inorganic zincs paint coated after blast-cleaning connections. The maximum increases in slip factors for blast-cleaning connections and inorganic zincs paint coated after blast-cleaning connections in the heating–cooling process are about 70% and 25%, respectively.

(3) With increasing temperature level (which is the maximum temperature a connection reached in the heating–cooling process), the slip factors first remain constant up to 200 °C, then increase linearly until 600 °C (with an exception point of 450 °C) and finally tend to be stable beyond 600 °C. The fact that the slip factor is enhanced confirms that the normal procedure of replacing bolts affected by fire is safe but sometimes over-conservative.

(4) With increasing temperature level, the residual pre-tension force first decreases slightly up to 300 °C, then decreases rapidly until 500 °C, and finally decreases slowly beyond 600 °C. Due to the fact that the decrease in bolt pre-tension force after exposed to 300 °C is negligible and the increase in slip factor can ensure the reliability of the slip-resistant bolted connections, it is suggested that the bolts can be re-used when the maximum exposure temperature is not in excess of 300 °C.

(5) Tri-linear models are proposed to calculate the normalized slip factor, and normalized pre-tension force in bolts for slip-resistant 10.9 bolted connections after exposing to temperature levels ranging from 20 °C to 700 °C. These equations can be used to conduct finite element analysis on post-fire behavior of slip-resistant bolted connections and to calculate the residual slip-resistance as well. Thus the damage degree of a slip-resistant bolted connection after fire can be accurately assessed and appropriate treatment measures can be performed.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (50908180), National Natural Science Foundation of China (51108265), Innovation Program of Shanghai Municipal Education Commission (12YZ080), and Leading Academic Discipline Project of Shanghai Normal University (DZL127). The financial support is highly appreciated.

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