POST-FIRE DAMAGE ASSESSMENT OF SLIP-CRITICAL CONNECTIONS

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Steel buildings may encounter fire events during their life cycle. There is a necessity of exploring the ways of assessing the remaining capacity of steel structures after exposure to high temperature. In this study, the post-fire mechanical properties of slip-critical connections and the adopted high strength bolts are experimentally studied using an electronic furnace, an electronic torsion wrench, strain gauges and a universal testing machine. Each of the slip-critical connections is composed of a single JIS F10T high strength bolt and an A36 steel PL-70x70x18 (mm) with a standard hole in the center. The test parameters are elevated temperature (400°C, 600°C and 800°C) and exposure time (60 min, 90 min and 120 min). The test items include: (1) torque strength, (2) torque coefficient, and (3) bolt pretension. The tests are made before and after the connections are exposed to high temperature. The results obtained from the above tests can be used as an important reference for judging whether a steel structure continues to be used after fire damage.

Keywords: Steel buildings, High-strength bolts, Loss of pretension, Post-fire behavior.

1 INTRODUCTION

High-strength bolts are one of the most important connecting elements in steel structures, such as bridges, industrial, office and residential buildings. When used in a slip-critical connection, the bolts are pretensioned in accordance of steel structural design standards or construction specifications, such as AISC 360-16 (2016) and AIJ (2021). Recently, the results were reported of experimental verification about the feasibility of using the loss of high-strength bolt pretension as an index for assessing the seismic damage to steel beam-to-column connections (Chen \textit{et al.} 2023).

Steel buildings may encounter several small and medium earthquakes and fires during their life time. It is also of great interest to further study the feasibility of assessing the post-fire damage to slip-critical connections and the adopted steel structures. The slip strength of a bolted connection can be calculated by multiplying the pretension of the bolts and the sliding coefficient of the faying surface (Geschwindner \textit{et al.} 2017). Accordingly, the remaining bolt pretension can be used to judge the highest temperature experienced, making the post-fire damage assessment of the steel structures. Quite recently, the test results were reported of Grade 10.9 Bolts /Class 10.9 Alloy Steel Hex Bolts/Nuts (with minimum tensile strength of 1040 MPa) that the bolts lose pretension after exposure to high temperature, but the slip coefficient increases (Lou \textit{et al.} 2015). In more detail, when the heating temperature exceeds 300°C, the bolts...
seriously lose the pretension, and the loss rate will slow down for the elevated temperature exceeds 500°C. For the sandblasted surface, the slip coefficient begins to increase when the temperature exceeds 200°C, and the coefficient increase 70% when the elevated temperature increases to 600°C and remains afterthought. The test results were also reported of Grade 10.9 Bolts as well as 8.8 Bolts (with minimum tensile strength of 800 MPa) (Liu et al. 2017). Specifically, when the heating temperature is lower than 600°C, the post-fire slip-critical and shear strengths of the bolted connections are equivalent to those at room temperature, but the strength will greatly reduce with the temperature greater than 600°C. After exposure to 900°C, for example, the slip-critical and shear strengths of the bolted connections will respectively reduce to 35% and 75% of those at room temperature.

Steel buildings may encounter fire events during their life cycle. Specific guidelines have not been established by the current steel design codes for determining the post-fire capacities of steel structures, with the exception of some recommendations proposed by the British Standards Institution (2003). According to the parametric investigation of test data, it was concluded that the most common scenario of buildings after fire events, i.e., apart from excessively distorted structures, implies considerable remaining capacity of the steel structures (Maraveas et al. 2017). In sum, there is still a necessity of exploring the ways of assessing the remaining capacity of steel structures after exposure to high temperature. High-strength bolts are commonly used in steel bridges, industrial, office and residential buildings. In most of the cases, torque is used to control the pretension forces of the high-strength bolts. Considering the fact, in the present study, torque will be used to control the pretension forces of the bolts, assessing the remaining capacity of the bolts and connections before and after exposure to high temperature. The results obtained will provide important references for judging whether a steel structure continues to be used after the fire event.

2 EXPERIMENTAL PROGRAM

2.1 Experimental Theory

The relationship between torque \( T \) (kNm), bolt diameter \( d \) (mm) and pretension \( N \) (kN) is as specified in CNS12210 with Eq. (1) (Bureau of Standards, Metrology and Inspection 1988):

\[
K = \frac{1000T}{d \times N} \tag{1}
\]

where \( K \) = torque coefficient (\( K = 0.13-0.15 \) for type A, \( K = 0.15-0.19 \) for type B). Type A means that the contact surface between the bolt and the nut has been lubricated. Type B means that the contact surface between the bolt and the nut has been not lubricated. Following the CNS 12210, in a standard torque test, the pretension force of a JIS F10T high strength bolt with a diameter \( d \) of 16 mm should range from 96.79 to 131.4 kN (Bureau of Standards, Metrology and Inspection 1988).

2.2 Specimen Details

In this study, a strain gauge was first installed in the head of a bolt and was then used to calibrate the pretension with a universal testing machine. Afterwards, the nut was turned with an electronic torque wrench, as to apply a torque \( T \) to a bolted connection assembly. The connection assembly was composed of a single JIS M16 F10T high strength bolt (i.e., \( d = 16 \) mm) and an A36 steel PL-70x70x18 (mm) with a standard hole in the center. The plate has sandblasted surfaces. The bolt pretension \( N \) was taken as 101 N, and the torque obtained by the reading of the electronic torque wrench was 302 Nm. Using Eq. (1), the torque coefficient \( K \) can be calculated and determined to be 0.187.
2.3 Test Parameters

The test parameters are elevated temperature (400°C, 600°C and 800°C) and exposure time (60 min, 90 min and 120 min). The test items include: (1) torque strength, (2) torque coefficient, and (3) bolt pretension. The tests were made before and after the connections are exposed to high temperature. Specially, each of the connection specimens was first applied with a torque and then placed in the laboratory at room temperature for one week. Then each specimen was removed to an electronic furnace, heated from the room temperature to the test temperature, remained for 1 hour (or more) and then cooled in the air. After another week, the remaining torque strength, bolt pretension and torque coefficient, were measured for each bolted connection. Figure 1 shows the pictures of the furnace and connection specimens after exposed to 400°C from 30 min to 120 min.

![Figure 1. An electronic furnace and bolted connections after exposed to 400°C for 30-120 min.](image)

3 RESULTS AND DISCUSSION

3.1 Effects of Elevated Temperature

Table 1 summarizes the post-fire torque strength ($T$), bolt pretension ($N$) and torque coefficient ($K$) for the connection specimens. For comparison, the same measurement was also made at the room temperature of 25°C. Table 2 lists the bolt pretension at elevated temperature and the percentage to that at room temperature. Table 2 also compares with the bolt pretension (percentage) reported in previous work (Liu et al. 2017). The results of the present study have shown a similar trend with those in previous work.

As mentioned in the section of introduction, when the heating temperature exceeds 300°C, the bolts seriously lose the pretension, and the loss rate will slow down for the elevated temperature exceeds 500°C (Lou et al. 2015). In the present study, as shown in Table 1, the bolt pretension ($N$) changed from 101 kN to 55.7 kN for the elevated temperature of 400°C. The pretension reduced to 20.2 kN and 21.2 kN for the elevated temperature of 400°C and 800°C, respectively. In other words, the bolt pretensions were eliminated by heating over 300 °C and decreased to about 20% for the elevated temperature equal to 600°C and higher.

As also mentioned, when the heating temperature is lower than 600°C, the post-fire slip-critical and shear strengths of the bolted connections are equivalent to those at room temperature, but the strength will greatly reduce with the temperature greater than 600°C (Liu et al. 2017). Similar observations can also be made from the post-fire torque strength ($T$) in Table 1. Specially, the torque strength of the bolted connection increased 13% for exposure to the 400°C for one hour, but
decreased to 20% and recovered to 80% for exposure to 600 °C and 800°C, respectively. In other words, the torque strength and bolt pretension seriously decreased to 20% for exposure to 600°C and higher temperature. On the other hand, coarse eroded surfaces appeared at temperatures above 650°C and that also significantly increased the torque strength (T) and coefficients (K).

Table 1. Remaining capacities of bolted connections after one-hour exposure to high temperature.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>25 °C</th>
<th>400 °C (60 min.)</th>
<th>600 °C (60 min.)</th>
<th>800 °C (60 min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque (T)</td>
<td>302 Nm</td>
<td>340 Nm</td>
<td>60.3 Nm</td>
<td>240 Nm</td>
</tr>
<tr>
<td>(100%)</td>
<td></td>
<td>(113%)</td>
<td>(20%)</td>
<td>(79%)</td>
</tr>
<tr>
<td>Bolt pretension (N)</td>
<td>101 kN</td>
<td>55.7 kN</td>
<td>20.2 kN</td>
<td>21.8 kN</td>
</tr>
<tr>
<td>(100%)</td>
<td></td>
<td>(55%)</td>
<td>(20%)</td>
<td>(22%)</td>
</tr>
<tr>
<td>Torque coefficient (K)</td>
<td>0.187</td>
<td>0.382</td>
<td>0.186</td>
<td>0.688</td>
</tr>
</tbody>
</table>

Table 2. Comparison of post-fire bolt pretension (percentage) with previous study.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>25 °C</th>
<th>400 °C</th>
<th>600 °C</th>
<th>800 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>10T M16 F bolt (Present study)</td>
<td>101 kN</td>
<td>55.7 kN</td>
<td>20.2 kN</td>
<td>21.8 kN</td>
</tr>
<tr>
<td>(100%)</td>
<td>(55%)</td>
<td>(20%)</td>
<td>(22%)</td>
<td></td>
</tr>
<tr>
<td>10.9 class M20 bolt (Liu et al. 2017)</td>
<td>153 kN</td>
<td>105 kN</td>
<td>18 kN</td>
<td>15 kN</td>
</tr>
<tr>
<td>(100%)</td>
<td>(69%)</td>
<td>(12%)</td>
<td>(10%)</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Effects of Exposure Time

Table 3 summarizes the torque (T), bolt pretension (N) and torque coefficient (K) of bolted connections exposed to 400°C for 60 min, 90 min and 120 min. As the heating duration increases from 60 min to 90 min, the bolt pretension continuously decreased but the torque coefficient gradually increased. As a total result, the torque strength changed from 113% to 85% of the room temperature. As the heating duration continuously increased to 120 min, the torque strength almost recovered to 100% of the room temperature. As the heating duration increased, the temperature distribution inside the connection specimens became more uniformly, and the increase in heating duration can hardly continue to affect the steel plates and bolts. The effects of heating duration can therefore be thought to be a minor factor. As mentioned, an electronic torque wrench was used to apply and read the torque strength of the bolted connection. Specially, the heated bolt was removed from the connection specimen and replaced by a new one preinstalled with a strain gauge. The bolt pretension can therefore be read when a specified torque was applied to the connection specimen by the same electronic torque wrench. The post-fire bolt pretension and torque coefficients became unavailable for the exposure time of 120 min. That is because permanent plastic deformations caused difficulties in replacing the bolt and in reading the pretension from the strain gauge.

Table 3. Remaining capacities of bolted connections after more than one-hour exposure to 400°C.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>25 °C</th>
<th>400 °C (60 min.)</th>
<th>400 °C (90 min.)</th>
<th>400 °C (120 min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque (T)</td>
<td>302 Nm</td>
<td>340 Nm</td>
<td>256 Nm</td>
<td>302 Nm</td>
</tr>
<tr>
<td>(100%)</td>
<td></td>
<td>(113%)</td>
<td>(85%)</td>
<td>(100%)</td>
</tr>
<tr>
<td>Bolt pretension (N)</td>
<td>101 kN</td>
<td>55.7 kN</td>
<td>35 kN</td>
<td>-</td>
</tr>
<tr>
<td>(100%)</td>
<td></td>
<td>(55%)</td>
<td>(35%)</td>
<td>-</td>
</tr>
<tr>
<td>Torque coefficient (K)</td>
<td>0.187</td>
<td>0.382</td>
<td>0.457</td>
<td>-</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS
In the present study, the post-fire mechanical properties of high-strength bolted connections have been experimentally studied. The results agree well with the main findings from previous studies. Specially, in the present study, the torque strength and bolt pretension has decreased to 20% for heating to 600°C. Moreover, coarse eroded surfaces appeared at temperatures above 650°C and that also significantly increased the torque strength and coefficients. On the other hand, the results also showed the minor effects of heating duration. Steel buildings may encounter fire events during their life cycle. The post-fire mechanical properties of structural steel and bolts still need investigating in more detail, as to further apply the research results in the damage assessment and building renovation.

Acknowledgments

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