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Estimation on clamping load of high strength bolts considering various environment conditions

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Abstract. Of high strength bolts, the torque shear type bolt is known to be clamped normally when pin-tails are broken. Sometimes the clamping loads on slip critical connections considerably fluctuate from the required tension due to variation of torque coefficient. This is why the viscosity of lubricant affects the torque coefficient by temperature. In this study, the clamping tests of high strength bolts were performed independently at laboratory conditions and at outdoor environment. The temperatures of outdoor environment candidates were ranged from -11℃ to 34℃ for six years. The temperature at laboratory condition was composed from -10℃ to 50℃ at each 10℃ interval. At outdoor environment conditions, the clamping load of high strength bolt was varied from 159 to 210 kN and the torque value was varied from 405 to 556 Nm. The torque coefficients at outdoor environment were calculated from 0.126 to 0.158 when tensions were measured from 179 to 192 kN by using tension meter. The torque coefficients at outdoor environment conditions were analyzed as the range from 0.118 to 0.152. From these tests, the diverse equations of torque coefficient, tension dependent to temperature can be acquired by statistic regressive analysis. The variable of torque coefficient at laboratory conditions is 0.13% per each 1℃ when it reaches 2.73% per each 1℃ at outdoor environment conditions. When the results at laboratory conditions and at outdoor environment were combined to get the revised equations, the change in torque coefficient was modified as 0.2% per each 1℃ and the increment of tension was adjusted as 1.89 % per each 1℃.

Keywords: high strength bolt; torque; tension; torque-coefficient; estimation

1. Introduction

The clamping load of a high-strength bolt drops without any other external load or loosening of the accompanying nut immediately after tightening. It is generally known that the initial clamping load decreases sharply up to a week after application of the initial tightening (Kulak 2001). Relaxation results from elastic recovery of the fastener components and the surface roughness, locally plastic deformation from eccentricity, geometry inconformity, and creep of the shank of the bolt (Kim 2001). Besides the physical characteristics of the bolt itself described above, it has been shown that ambient temperature is another variable influencing the initial clamping load (Bickford 2008, Nah 2009a), and it ultimately affects relaxation. Furthermore the effects of diverse factors such as type of coating, thickness of coating, and clearance of bolt-holes on the relaxation of bolted connections independently or interactively have not been clarified (Polyzois 1986, Kulak 2001). It is known that as the coating on the faying surface becomes thicker, the clamping load of a bolt drops more severely due to the creep behavior of the coating (Yura 1981, Yang 2000, Kulak 2001). In general, relaxation nearly stops at a step of 500 hours, while the bolt continues to constant tension load. However, relaxation of the bolted joint proceeds 1,000 hours if the coating behavior on the faying surface is considered. As a result, the additional creep deformation is negligible after 1,000 hours. To date, there have been few reports presenting a quantitative evaluation of relaxation considering coating deformation on the faying surface under Korean construction contexts (Nah 2009b, 2010). In general, the Korean manufacturer recommends that, for coating on steel members, the guideline of coating thickness for red lead paint should be 50 μm and inorganic zinc primer should not be more than 75 μm. However, it is not known how much worse the coating thickness above the required thickness on faying surface is affected by the clamping load of high strength bolt after the elapse of time. This study suggested one of models to quantitatively evaluate the induced clamping load with consideration of the relaxation of high strength bolts by coating deformation on the faying surface of slip critical bolted joints. The tensile characteristics of a friction connection using a high-strength bolt, based on the clamping force loss developed by sectional corrosion damage to the bolt head, was examined. (Kim *et al*. 2016)

In many countries, specific washers are used with high strength bolts in slip-critical connections to ensure that specified tension loads are achieved, while clamping using torque is hardly employed. In Korea and Japan, torque shear high strength bolts (hereafter "TS" high strength bolts)

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rather than hexagon-headed high strength bolts have been mainly used since 2000s due to the break of pin-tails. Workers and even managers at construction sites look the break of a pin-tail as the sign of appropriate tension load. However, various environmental conditions of sites including the viscosity of lubricant applied to screw threads and washers and alien substances change torque coefficients and result in insufficient tension loads or over-clamping. The seriousness and frequency of the problem has not been checked or verified. The purpose of this study was to estimate the tension loads of high strength bolts associated with the change in site temperature by analyzing and comparing the data collected from the tests conducted under both laboratory and site conditions. During last five years in Korea, the tension loads of TS high strength bolts used at construction sites were measured and the changes in tension loads associated with temperature condition and rainfall were analyzed.

2. Overseas studies

While studies conducted in Japan pointed temperature change as the major cause of the change in the torque coefficient of surface-treated high strength bolts, the numerical values differed significantly among them. The relationships between torque coefficient and temperature were identified by linear regression analyses in the studies and the results showed that torque coefficient decreased when temperature rose in the range of -20℃~40℃. Studies conducted by Japanese researchers respectively provided quite different values as to the change in torque coefficient: 0.6~0.7%/℃, 0.48%/℃ and 0.31%/℃. Studies conducted in the U.S. (Kulak *et al*. 2001, Tambori 1999, Bickford 1998) reported that the clamping loads of high strength bolts varied depending on the manufacturer-specific properties and type of lubricant. Vand conducted a test comparing torque coefficients of high strength bolts with the variable of whether lubricant was applied to screw threads or not (Vand *et al*. 2008). Research has been established the effect which the clamping force, resulting from torque tightening a nut and bolt, has on the fracture strength and the stress intensity

geometry factor of a fastener hole containing a symmetrical pair of edge cracks (Chakherlou *et al*. 2009). The torque coefficient of lubricant-applied high strength bolts was 0.205, which showed the difference of 0.04 when compared with the value obtained from the bolts without lubricant. Abdalla analyzed torque coefficient in relation to the properties of lubricant and the length of bolts. The study found the difference of approximately 23% between test result and analysis result (Abdalla *et al*. 2011). A series of tests of bolted joints after clamping normally was conducted at room temperature and elevated temperature. (Yang *et al*. 2011). A series of tests were performed to evaluate the effect of a hardened washer placed between the turned element and a direct tension indicator (DTI) with curved protrusions. Configurations with 1.0 inch diameter bolts with and without hardened washers were evaluated (Cleary *et al*. 2012). The effects of long open slotted holes and friction properties on the bolt forces are investigated in static and long term tests. A characteristic resistance function of the lap joint with long opened slotted holes for a period of 20 years is extrapolated based on the long term tests (Heistermann *et al*. 2013). Hot dip galvanized bolts on metal sprayed surfaces were conducted to confirm the induced axial force. On the basis of tightening bolt tests, the clamping force was evaluated (Minami *et al*. 2013). As mentioned so far, clamping loads differed depending on test conditions and analysis results also varied. In Korea, a few clamping tests have been conducted with high strength bolts under laboratory conditions, while not a single test conducted under actual site conditions has been reported (Nah *et al*. 2009, 2014).

3. The setup of test

3.1 Technical standards

The Korean Industrial Standards for TS high strength bolts were established in 2003 and ASTM F 2280, the international equivalent of KS F10T and KS S10T, was established in 2006. Technical standards for high strength bolts such as KS F10T were laid down in Korea and overseas only approximately 10 years ago. Although TS high strength bolts are designed in a way that pin-tails are broken at specified torque values, they are based on Torque Control Method. In North America, technical standards for the clamping load of TS high strength bolts are prescribed in terms of tensile load. In Korea, however, the specifications and technical standards for high strength bolts are based on tensile load due to the influence of Japan, while the application of the bolts in construction sites follows Torque Control Method.

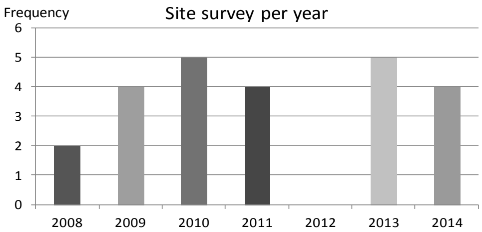
3.2 Test material and method

Torque shear high strength bolts (S10T) which were 20 mm in diameter and 7 mm in length were provided to identify the clamping loads of bolts used for slip critical connection. In the laboratory, the tension loads of bolts were measured by using various methods such as load cells, direct tension indicators (DTIs) and bolt extensometers. The standard specification, ASTM F 959, provides specific quantitative requirement to apply DTIs to indicate the achievement of a specified tension load in a bolt. However Korean-manufactured product for DTI was not still available by now, imported product made in the State was applied. Ten of high strength bolts were chosen for each of the temperature levels ranging between -10 and 50℃ as shown in Table 1.

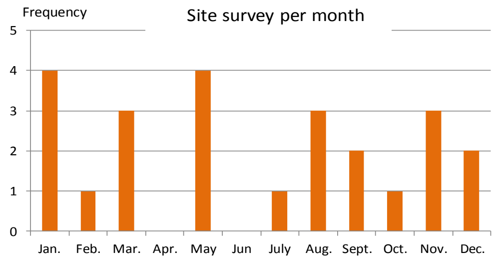
The tension loads, torque values and torque coefficients of high strength bolts obtained from twenty four construction sites between 2008 and 2014 were analyzed. Torque shear high strength bolts (S10T) used at the sites were 20

Table 1 Specimen for indoor environment

Temp. (℃)	-10	0	10	20	30	40	50
Number of specimen	10	10	10	10	10	10	10



(a) Site survey from 2008 to 2014



(b) Site survey per season

Fig. 1 Outline of site inspection

Table 2 Identification of sites

Site	Temp. (℃)	Date	Site	Temp. (℃)	Date
No. 1	-11	2013. 1	No. 3	15	2010. 3
No.24	3	2013. 1	No.13	20	2010.10
No. 2	3	2011. 1	No.17	21	2011. 5
No. 6	4	2008.11	No.14	23	2009. 3
No. 4	5	2010. 2	No.18	25	2013. 5
No. 5	5	2010. 3	No.16	25	2009. 9
No. 7	5	2014.12	No.21	26	2014. 5
No. 8	8	2009. 1	No.15	27	2011. 9
No.12	11	2010. 5	No.20	30	2011. 8
No.10	12	2014.11	No.19	32	2009. 7
No. 9	13	2008.12	No.22	34	2013. 8
No.11	14	2014.11	No.23	34	2013. 8

mm in diameter and 70, 75, 85, 90 and 95 mm in length. At least 5 bolts tested for the purpose of quality inspection were analyzed and the difference in length was not taken into consideration. The temperature conditions at the construction sites were measured and kept on record. Bolt extensometer and DTIs measured tension loads. There were significant differences observed between the temperatures kept on record by the Korea Meteorological Administration (KMA) and those measured at the sites. Therefore, the temperatures of the dates when the bolts were inspected were used in the analysis, which ranged between -11 and 34℃. The outline of sites inspected from 2008 to 2014 is as shown in Fig. 1.

Table 2 shows the temperatures and inspection dates of 24 construction sites. The sites were scattered diversely over Korean peninsula except for Jeju Island. Korea has four seasons, so the temperature differs what season the inspection for the clamping load of bolts was conducted at site. Onsite measurements were made 4 times in January and May, while none of them were in April and June as shown in Fig. 1.

4. Analysis of clamping loads

4.1 Analysis of laboratory test

In case of 20 mm diameter for high strength bolt applied slip critical connection, the specification says that the

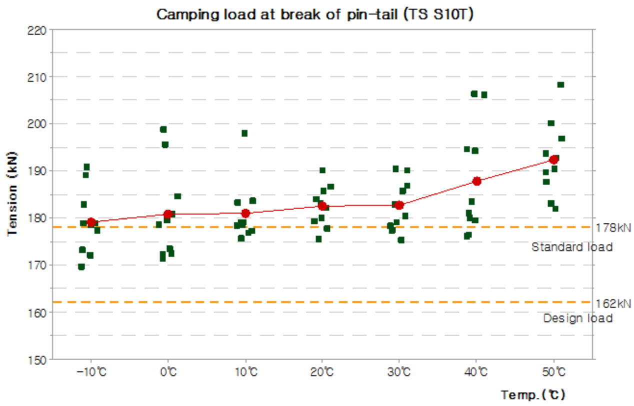


Fig. 2 Tension trends of lab. test

Table 3 Indoor test results

Temp. (℃)	-10	0	10	20	30	40	50
Tension	179.2	180.8	180.9	182.5	182.7	187.8	192.5
Standard deviation	6.9	9.7	6.5	4.4	5.3	11.6	7.9

required design load is 162 kN and the standard load is given as 178 kN in consideration of 10% relaxation after clamping. Fig. 2 shows the trend of tension with the limitation of these criteria. The average tension load of the bolts increased as the temperature rose, from 179.2 kN at -10℃ to 192.5 kN at 50℃. The standard deviation of the data ranged between 4.4 kN and 11.6 kN. Fig. 2 and Table 3 show tension trends at the point of pin-tail break and average tension load associated with the temperature, respectively. Fig. 3 shows the normal distribution of applied tension at each temperature.

Since tension loads were measured under constant temperature and humidity conditions in the laboratory, the result was more reliable than the data measured at the construction sites. Eq. (1) was achieved from the linear regression analysis of temperature and tension load based on the result.

$$N = 0.1985 \times t + 179.8 \qquad (1)$$
$$(\text{N: tension},\ \ t: \text{temp.}\ (℃))$$

The coefficient of determination (R^2) of the regression model was 0.83, meaning that it was highly reliable. The change in tension load associated with 1℃ change was 0.11%.

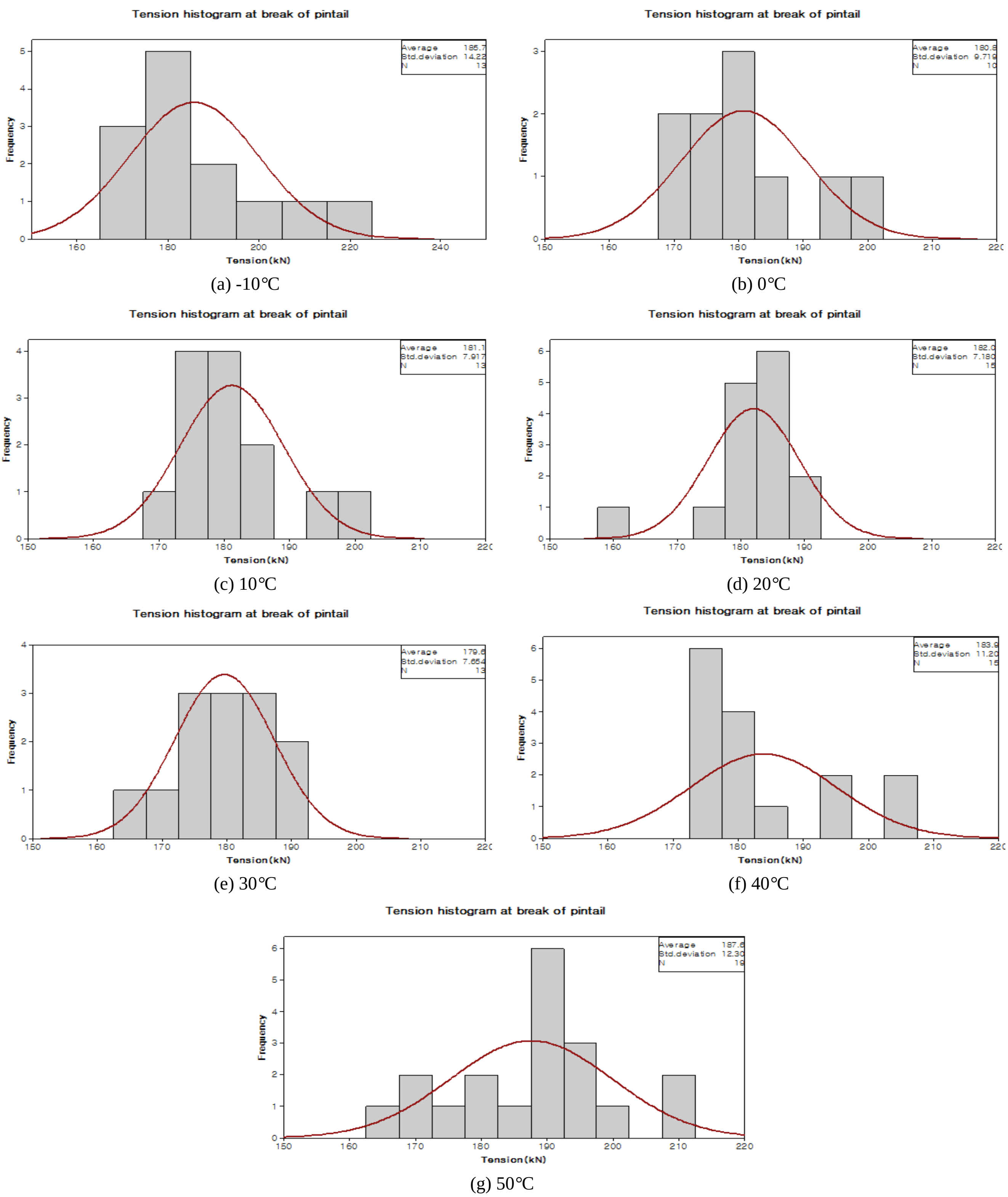


Fig. 3 Histogram of tension at indoor test

4.2 Analysis of onsite test

The torque coefficients for TS z`high strength bolts used in slip-critical connections are not clearly stated in KS industrial standards and are just assumed to be 0.110~0.150, equivalent to the torque coefficients for type-A hexagon-headed high strength bolts. In this study, the tension and torque values of the high strength bolts acquired at the construction sites were estimated to determine torque coefficients. The average temperatures of measurement day were above 0℃ with the lowest being 3℃, except for -11℃.

Fig. 4 shows the distribution of tension loads in relation to the temperature of the sites. Tension loads measured at the sites sharing similar temperature conditions, normal temperatures within the range from 10 to 30℃ or abnormal temperatures, were compared. First, the average of the tension loads measured at Hyunjeo site (No. 16) where the temperature was 11.5℃ was 173 kN and the average at Nopo site (No. 13) where the temperature was 13℃ was 183 kN. It is deduced that the tension loads of Hyunjeo site deteriorated to some extent since the lubricant was diluted by 0.5mm rainfall and rust was formed on the bolts due to moisture. It is implied from the observation that tension loads under identical temperature conditions can vary due to other variables except temperature. Second, the tension loads at Myungji site (No. 5), New Kimpo site (No. 6) and New Paju site (No. 3), in which the temperature was 5℃, 5℃ and 4.6℃, respectively, were 184 kN, 184 kN and 183 kN, respectively. KS B 2819 classifies temperature ranges for TS high strength bolts into normal temperature condition and abnormal temperature condition. Therefore, the comparison of tension loads was made under both temperature conditions in this study. 12 construction sites fell into normal temperature condition within the range from 10 to 30℃. Fig. 5 shows the relationship between temperature and the average tension load at the sites. Since constant temperature and moisture conditions as in the laboratory test did not exist at the construction sites and the data measured at the sites for the last 5 years were used, it was difficult to make a simple comparison between onsite data and laboratory data. Average tension load of the normal temperature sites was 187 kN with a standard deviation of 5.2 kN. Average torque was 504 N·m with a standard deviation of 31.1 N·m. Torque coefficient was 0.13 with a standard deviation of 0.009. The tension load in design for high strength bolts prescribed in the Korean Building Construction Standard Specification is 178 kN. Average tension loads at the construction sites were within the range of 178 kN ±10%. The regression analysis of the data collected at normal temperature sites provided Eq. (2).

$$N = 0.5213 \times t + 176.9$$
$$(N\text{: tension}, \quad t\text{: temp. (℃)}) \tag{2}$$

The coefficient of determination (R^2) of the regression model was 0.35. The change in tension load associated with 1℃ change was 0.29%, which was greater than what was obtained from the laboratory test. 12 construction sites fell into abnormal temperature condition as shown in Fig. 6. Average tension load of the sites was 179 kN with a standard deviation of 9.1 kN. Average torque was 513 N·m with a standard deviation of 30.1 N·m. Torque coefficient was 0.14 with a standard deviation of 0.01. Average tension load under abnormal temperature was approximately 5% lower than what was obtained under normal temperature sites.

The regression analysis of tension loads measured under normal temperature condition provided Eq. (3).

$$N = 1.4308 \times t + 174.5$$
$$(\text{N: tension}, \quad t\text{: temp. (℃)}) \tag{3}$$

The coefficient of determination (R^2) of the regression model was 0.71. The change in tension load associated with 1℃ change was 0.82%, which was 0.53% higher than what was obtained from normal temperature sites. While tension load increased as temperature rose, the relationship between the two was not linear. However, the increase in tension load was more noticeable at higher temperatures. The regression analysis of the data including both normal and abnormal temperature conditions provided Eq. (4) for the relationship between temperature and tension load.

$$N = 0.5558 \times t + 175.06$$
$$(N\text{: tension}, \quad t\text{: temp. (℃)}) \tag{4}$$

The coefficient of determination was 0.61. The change in tension load associated with 1℃ change was 0.31%, which was 2.8 times of that obtained from the laboratory test.

4.3 Integration of laboratory test and onsite test

As noticed from Eqs. (1) to (4), the change in tension load associated with temperature change varied depending on environmental conditions and temperature conditions. The conditions in the construction sites were more

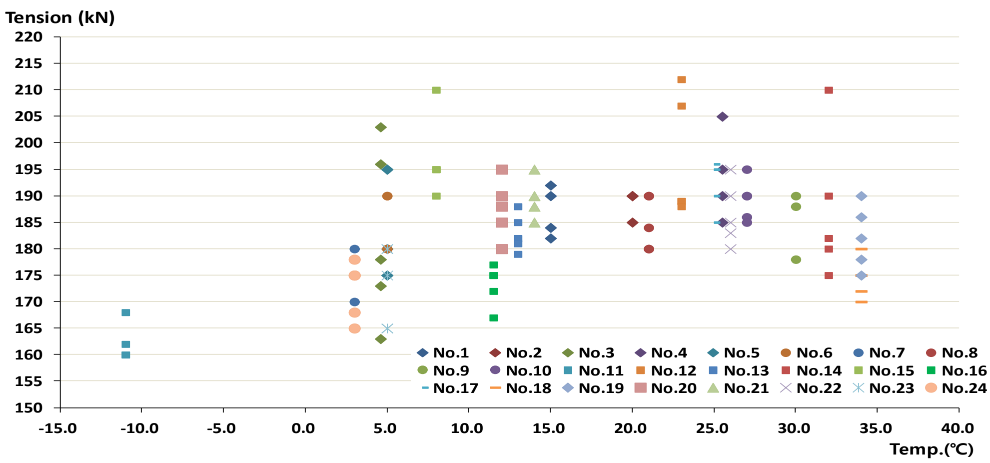


Fig. 4 Tension at onsite test

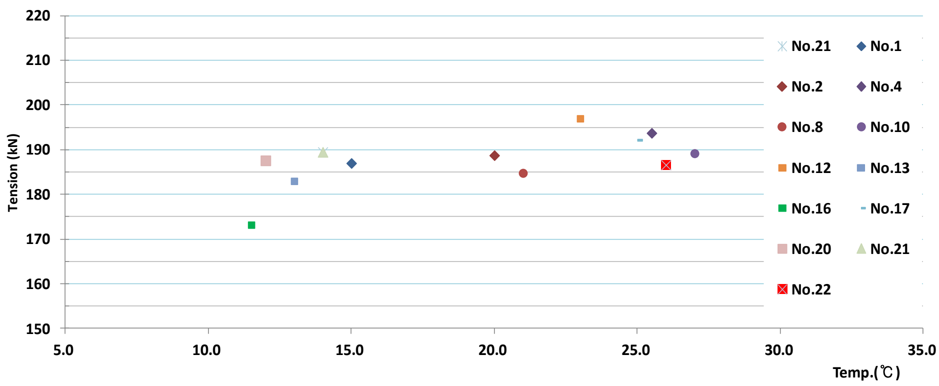


Fig. 5 Tension under normal temperature

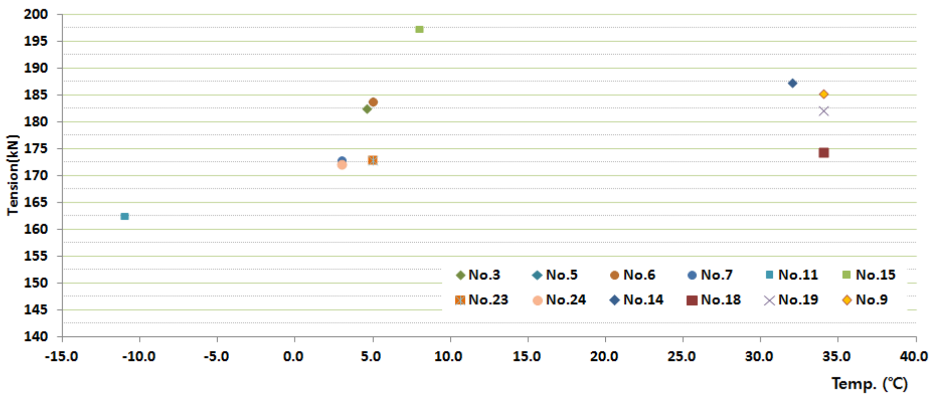


Fig. 6 Tension under abnormal temperature

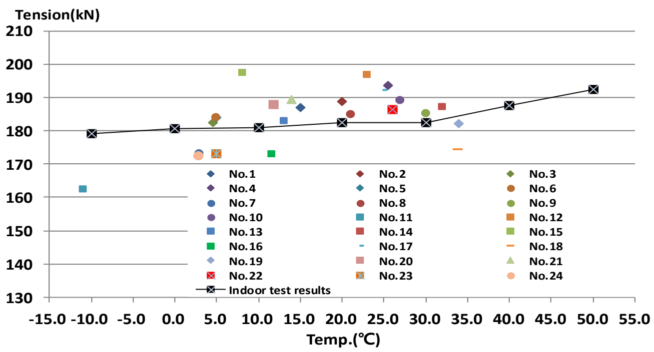


Fig. 7 Comparison of two test results

complicated than laboratory conditions. In order to improve reliability in estimating the tension loads of TS high strength bolts, data from the construction sites and laboratory test were combined as shown in Fig. 7.

The result obtained from the regression analysis of the integrated data can be summarized as Eq. (5).

$$N = 0.3373 \times t + 177.72$$
$$(N: \text{tension}, \quad t: \text{temp.} (℃)) \tag{5}$$

The change in tension load associated with temperature change was 0.18%/℃, which was 0.07%/℃ higher than that obtained from the laboratory test and 0.13%/℃ lower than that from onsite measurement.

5. Analysis of torque and torque coefficient

5.1 Analysis of laboratory test

The average torque of TS high strength bolts at pin-tail break ranged between 524 Nm and 537 Nm. The highest torque at average was recorded both at -10℃ and 0℃. This trend of torque was similar to the trend of tension at -10℃ and 0℃. The result of the laboratory test showed that the average torque of the bolts decreased as the temperature rose as shown in Fig. 8. Torque coefficients at pin-tail break ranged between 0.126 and 0.158. Since torque coefficient is in inverse relation to clamping load, it decreased as the temperature increased as shown in Fig. 9. The standard deviation of torque coefficient ranged between 0.004 and

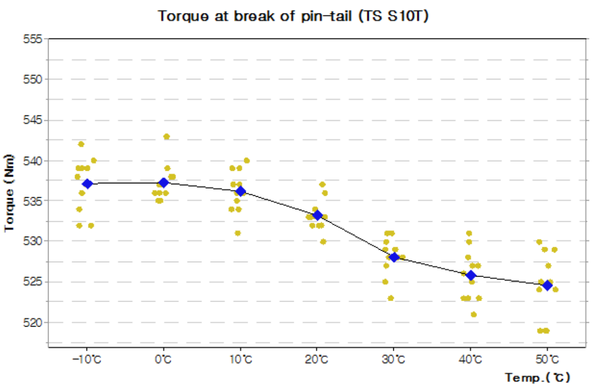


Fig. 8 Torque of indoor test

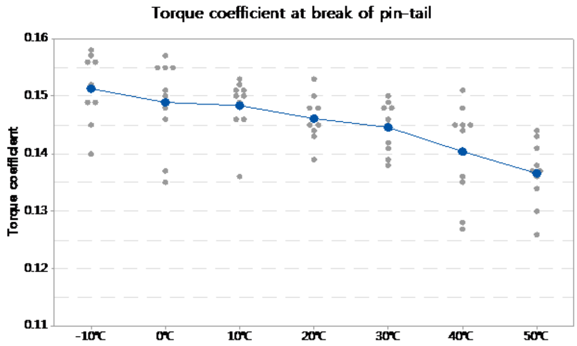


Fig. 9 Torque coefficient of indoor test

0.008, which satisfied 0.01 required for hexagon-headed high strength bolts.

Eq. (6) for torque coefficient was obtained from regression analysis. The coefficient of determination (R^2) was 0.92 and the change in torque coefficient associated with 1℃ change was 0.13%.

$$k_{\_in} = -0.0002 \times t + 0.1497 \quad (k\text{: torque coefficient}, \ \ t\text{: temp. (℃)}) \tag{6}$$

Fig. 10 shows the normal distribution of calculated torque coefficient at each temperature.

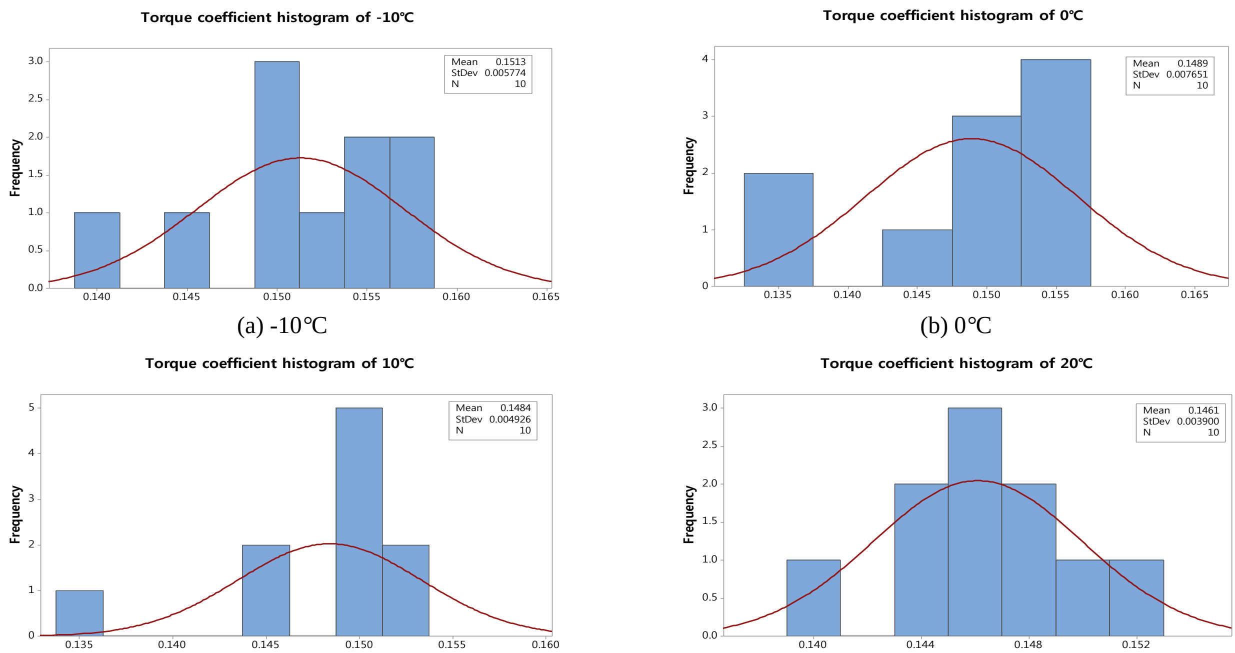
5.2 Analysis of onsite test

The average temperatures of the 24 construction sites ranged between -11℃ and 34℃. In order to observe the relationship between temperature and torque coefficient, torque values were plotted on a graph as shown in Fig. 11. Torque coefficients were obtained from the torque values measured at the sites.

The average torque of each site ranged between 447 N·m and 554 N·m. The average torque and average torque coefficient of the 24 sites were 509 N·m and 0.13 respectively. Fig. 10 shows torque coefficients obtained from the data collected at the construction sites for the 5 years. The standard deviation of torque coefficients was 0.01. Torque coefficients at pin-tail break ranged between 0.118 and 0.152. A wider variation was observed due to the complex combination of variables besides temperature such as bolt length, humidity and rainfall in the sites. Eq. (7) was obtained from the regression analysis of temperature and torque coefficients.

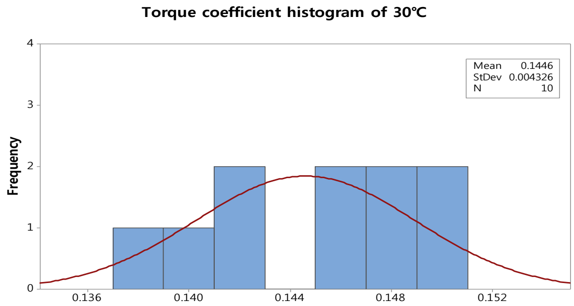
$$k_{\_out} = -0.0042 \times t + 0.1539 \quad (k\text{: torque coefficient}, \ \ t\text{: temp. (℃)}) \tag{7}$$

The change in torque coefficient associated with the change of 1℃ was 2.73%, which was significantly greater

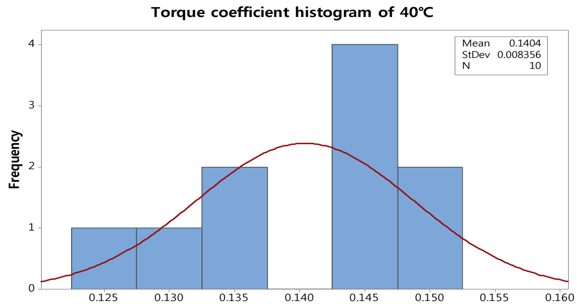


(a) -10℃ (b) 0℃ (c) 10℃ (d) 20℃

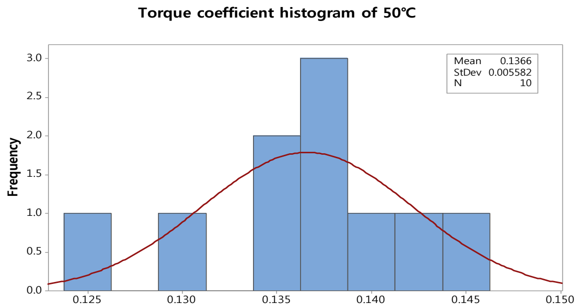
Fig. 10 Torque coefficient histogram at each temperature of indoor test



(e) 30℃



(f) 40℃



(g) 50℃

Fig. 10 Continued

than what was obtained from test data as in the case of tension load.

5.3 Integration of laboratory test data and onsite test data

As seen in the analysis of tension loads, there were differences in torque values and torque coefficients between laboratory test data and onsite test data due to not only complex environmental conditions but also storage condition, warehousing date and the level of quality inspection at the sites. Therefore, laboratory data and onsite data were integrated to improve the reliability in the estimation torque coefficients as shown in Fig. 11. The regression analysis of the integrated data found that the change in the torque coefficient of TS type high strength bolts associated with the temperature change of 1℃ was 1.89%. Eq. (8) was obtained from the analysis as shown in Fig. 12.

$$k_{\_inc} = -0.0029 \times t + 0.1531$$
$$\big(k: \text{torque coefficient},\ \ t: \text{temp.}\,(℃)\big) \tag{8}$$

This study identified the tension loads, torque values and torque coefficients of TS high strength bolts based on the break of pin-tails. Since the overseas studies tested hexagon –headed high strength bolts and were conducted many years ago, it was not easy to make a simple comparison between the results. The change in torque coefficient at laboratory, 0.13%/℃ obtained from this study was lower than 0.31%/℃ obtained from a study conducted by Yamamoto. However the change in torque coefficient at onsite, 2.73%/℃ and incorporation data, 1.89%/℃ were much higher than that of laboratory result.

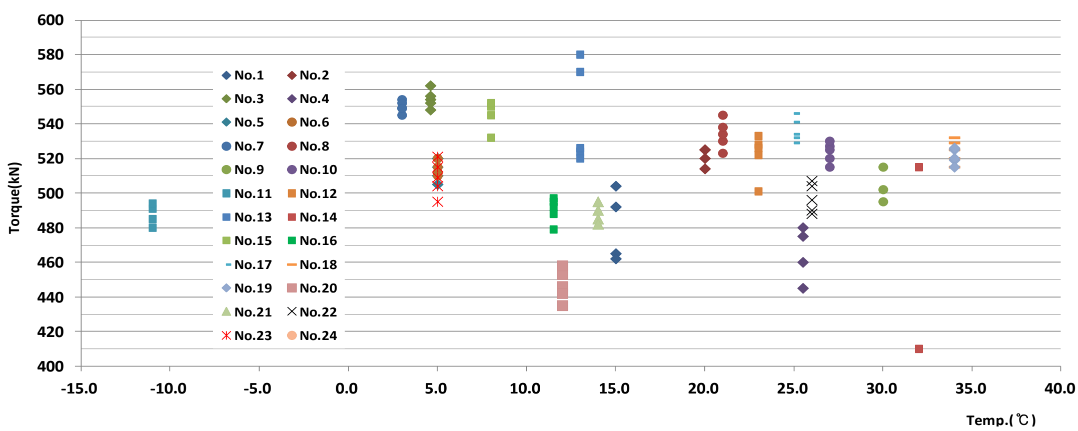


Fig. 12 Torque coefficient of onsite test

6. Conclusions

In this study conducted to estimate the tension load of TS high strength bolts with the conditions of construction sites taken into consideration, laboratory test data and the data from 24 construction sites collected at pin-tail break for quality inspection for the last 5 years were compared and analyzed. The subjects of the tests were S10T TS high strength bolts which were 20mm in diameter. The relationships among tension loads, torque values and torque coefficients were analyzed from the onsite data and laboratory data and regression analyses were conducted to produce Eq. for clamping load in relation to temperature changes. In the laboratory test, 10 bolts apiece were tested at -10, 0, 10, 20, 30, 40 and 50℃. In the analysis of onsite data, 5 bolts at least were selected for each of the temperature levels.

- The temperatures of the construction sites ranged between -11℃ and 34℃. Bolt in tension ranged from 159 to 210 kN and torque values ranged from 405 to 556 N·m. The regression analysis of the data including both normal and abnormal temperature conditions showed that the change of the tension load associated with the temperature change of 1℃ was 0.31%. The following Eq. was obtained from the analysis.

$$N = 0.5558 \times t + 175.06$$

- Laboratory test showed the average tension load of 179.2 kN at -10℃ and 192.5 kN at 50℃. Standard deviations ranged between 4.4 kN and 11.6 kN. The change in tension load associated with the temperature change of 1℃ was 0.11%. The following Eq. was obtained from the analysis of the data.

$$N = 0.1985 \times t + 179.8$$

- The regression analysis of the data integrating onsite measurement and laboratory test result provided the following Eq. for the relationships between temperature and tension load.

$$N = 0.3373 \times t + 177.72$$

The change in tension load associated with the temperature change of 1℃ was 0.18%, which was 0.07% higher than what was found in the analysis of laboratory data.

The findings about torque coefficients obtained from the analyses of laboratory data and onsite data conducted to identify the temperature-dependency of TS high strength bolts are as follows.

- 10 high strength bolts were tested at each temperature level in a laboratory. The change in torque coefficient associated with the temperature change of 1℃ was 0.13%. The following Eq. was obtained from the analysis of the laboratory test data.

$$N = -0.0002 \times t + 0.1497$$

- The following equation was obtained from the regression analysis of the data collected at construction sites for the last 5 years. The change in torque coefficient associated with the temperature change of 1℃ was 2.73%.

$$N = -0.0042 \times t + 0.1539$$

- The regression analysis of the data integrating onsite measurement and laboratory test result showed that the change in torque coefficient associated with the temperature change of 1℃ was 1.89%. The following equation was obtained from the regression analysis.

$$k_{\_inc} = -0.0029 \times t + 0.1531$$

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