Development of a Non-destructive Method to Measure the On-Site Clamping Force of Torque Shear High-Strength Bolts

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Abstract

High strength bolts are used for connection of steel structures, and these are mainly of the torque shear type, which are designed to fracture by shear force at a predetermined torque. Although the manufacturers specify the clamping load of high-strength bolts dependent on diameter, no method has been available for measuring the clamping force at the onsite, when the bolt is actually fastened. Thus, a nondestructive testing method was developed the first in the world, that can measure the clamping load when fastening the bolt to an actual steel structure joint. There are two key elements in this method: the algorithm that synchronizes the load displayed in the clamping force meter taken form the existing analog device and measures the amount of cumulative electric energy required by the electric torque wrench, which is used for fastening the bolts at the time of measurement, and the prototype of the test device that embeds this algorithm. The technique developed in this study achieved a reliability within 5%, with respect to the actual clamping load.

Keywords: *Bolt, Tension, Current, Wrench, Torque*

1. Introduction

Torque shear type high-strength bolts have been used for joining member of steel structure on construction site for more than a decade. The Korean Standard Specification (KS B2819), regarding torque shear type high-strength bolts for slip critical connection of steel member, and the Steel Structure Standard Specification specify that the range of clamping force is separately defined, depending on whether temperature conditions are normal or abnormal.

Even if a torque shear type high-strength bolt reaches the correct torque and the pin tail is broken, the proper tension might not have been applied due to the correlation between clamping force, torque, and the torque coefficient. This can lead to over-clamping or under-clamping the load. However, because no quantitative clamping method has been available, quality inspection has been performed on five samples of high-strength bolts from the same batch, instead of inspecting the ones which are actually fastened. In this respect, there has been no practical, nondestruc- tive inspection method for the clamping force of high-strength bolts used in steel connection.

Several domestic research studies have been conducted on techniques for predicting the clamping tensile force and clamping torque of high-strength bolts. However, these techniques only provided mathematical regression analysis equations, which were not applicable to the actual construction sites. Thus, as a result of recent studies, a prototype of test device was developed using embedded operation software, and an algorithm that can identify the clamping force when torque shear type high-strength bolts are fastened. Furthermore, the reliability of the device was evaluated, and the opinions of construction site workers were also considered. These opinions were that a prototype suitable for construction sites needs to be portable, well made, and produce reliable results. Therefore, the measuring instrument was manufactured to improve the reliability of the results.

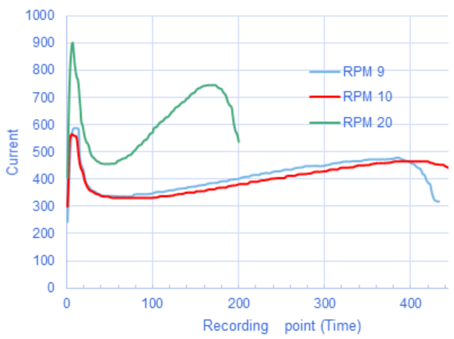

Fig.1 Electric energy curve by electric torque wrench

2. Correlation between clamping force, torque, and electric energy

2.1 Clamping force and electric energy

Torque shear type high-strength bolts are fastened by using a dedicated electric wrench. The electric energy generated when the pin tail breaks from the body makes a direct influence, by introducing an clamping force to the high- strength bolt.

Thus, the electric energy accumulated when the pin tail breaks was compared with the load measured by the existing analog meter. The experiment was conducted to develop a regression analysis equation on the correlation between clamping force and electric energy. This was based on the experimental results after setting various parameters, including the diameter of the high-strength bolts, and the type of dedicated torque wrench. Moreover, it was planned to develop prototype device that predicted the clamping force by embedding the equation-related software into the device. Because the prototype test device using this technique could identify the clamping force at the time of fastening, the test device would contribute significantly to the quality control and stability of structure.

2.2 Rotation speed of electric torque wrench

The rotation speed of a torque wrench makes a difference not only to the clamping time, but also to the starting current, the minimum current after operation, and the maximum current. Thus, software that considers various parameters, ranging from the minimum current to the maximum current, was required. When comparing electric torque wrenches with a low rotation speed (9rpm) and a high rotation speed (20rpm), among conventional electric torque wrenches, there was a time difference of approximately 5 seconds, and also a difference in maximum current, as shown in Fig. 1. The scope of this study was limited to electric torque wrenches with a similar rotation speed (9 and 10 rpm) for obtaining the measurement results, and for manu- facturing an clamping force testing technique and prototype.

2.3Correlation between clamping force and torque coefficient

The reason for this correlation is that when a bolt is fastened, the pin tail undergoes plastic deformation, and from that point, no change in clamping force can be introduced into the bolt. However, in the torque control method, the clamping load, torque coefficient, and torque are still in accordance with the following Eq. (1).

$$N = \frac{T}{kd} \tag{1}$$

where N is the clamping force (kN), T is the torque (N·m), k is the torque coefficient, and d is

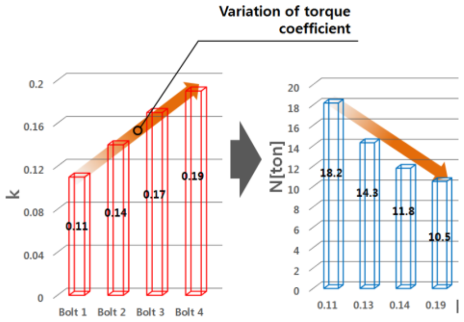

Fig.2Correlation between bolt torque coefficient and clamping force

the bolt diameter. Thus, in the case of high- strength bolts fastened with a constant torque, if the torque coefficient (k) increases in the range of 0.11 to 0.19 as shown in Fig. 2, the clamping force introduced into the bolt decreases inversely from 18.2 to 10.5 tons. As a result, bolts 2, 3, and 4 as shown in Fig. 2 could fail to meet the clamping force required by the specification.

3. Domestic and overseas research trends

Few studies have reported on the clamping force of high-strength bolts, particularly the torque shear type high-strength bolts.

Among the various studies conducted on experimental parameters to verify the variation of clamping force, clamping torque, and nut rotation angle, some studies reported on the variation of clamping force caused by the temperature param- eter. They also reported on the use of a quantita- tive regression analysis method [1-3]. Furthermore, another study revealed the error levels between on-site quality assurance inspections and labora- tory test results, by comparing and analyzing the results of clamping force variations[4]. Other studies have reported that manufacturers of bolts have stated that the clamping force of high- strength bolts varies according to the characteristics and types of lubricants used[5-7]. There was a study conducted to evaluate the bolt clamping force, according to the stress and friction force, based on the shape of the edge crack around the bolt hole[8]. To compare the clamping force according to the temperature parameter, another study experimentally and analytically evaluated the clamping force on bolt joints under both room temperature and high temperature conditions[9]. Moreover, Abdalla, Kaziolas, and Baniotopoulos [10] analyzed the variation in torque coefficients according to various conditions and different bolt lengths when lubricant was applied to the threads. The study revealed a 23% difference between the experimental and analytical results[10]. To evaluate the clamping force of one inch diameter high-strength bolts, they were compared with and without a reinforcing washer. Static and long-term tests were performed on high-strength bolts used in slotted holes, in addition to the friction characteristics. Based on these test results, the results of friction resistance characteristics over a 20-year period were estimated [11]. A clamping force test of high-strength bolt joints with hot-dip galvanized surfaces was conducted to evaluate the results [12].

4. Experimental planning and analysis

4.1Experimental planning

The high-strength bolts used in the experi- ment were type S10T M22, with a bolt diameter of 22mm, and a length of 75mm.

The high-strength bolts were fabricated by three bolt manufacturers. Three types of bolts were tested: two types of high-strength bolts coated with a conventional lubricant, and one type coated with zinc. The tensile strength of the high- strength bolts used in the tests ranged from 1,000 to 1,200 N/mm^2, and their yield strength was 900 N/mm^2. Experiments were performed at a surface temperature of 23 ℃. The device used to compare the clamping force and the cumulative electric energy comprised of a hydraulic analog tension meter (Skidmore MS-102), and two electric torque wrenches (GH-242HRZ, 9rpm and HTS 110L, 10rpm), both manufactured by TONE, Japan. The experimental variables are shown in Table 1.

Table 1 Specimen Identification

Electric tools	ID Number	Environmental condition	Quantity
rpm 10	R10-HK-22	surface temperature: 23℃	20
	R10-HKD-22	surface temperature: 23℃	20
rpm 9	R9-DW-22	surface temperature: 23℃	20
	R9-HK-22	surface temperature: 23℃	20
Total			80

4.2 Results analysis

4.2.1Clamping force due to cumulative current amount

The clamping force value was obtained from the analog clamping force meter, and the average cumulative current value was obtained from the test device using both the embedded Excel soft- ware and the algorithm constructed in this study. The regression analysis of the clamping force was obtained by incorporating the experimental results. The result of the regression analysis on the cumulative current (with respect to the clamping force) is shown in Eq. (2), and its graph is shown in Fig. 3. The coefficient of determination (R^2) in this case was 0.83.

$$T = 0.0039 \times A.C + 75.913 \qquad (2)$$

(T: Tensile force (kN), A.C: Accumulative current replacement value (A))

The average error rate of the cumulative current and the torque figure obtained from the electric torque wrenches (9 and 10rpm) was 3.2%. This error is nearly the same or smaller than that of the experimental results using a 20mm diameter bolt.

The clamping force measurements on the HK-22 bolts, using an electric torque wrench at 10rpm, ranged from 221 to 238 kN, with an average value of 229kN and a standard devi- ation of 4.8kN. The clamping force measured with the test device ranged from 219 to 245 kN, with an average value of 228 kN and a standard deviation of 8.8 kN. The average error rate of the clamping force, obtained from the test device and the analog clamping force, was 2.4%, which is 0.8% lower than the average error of 3.2% as a whole.

The clamping force measurements on the HKD-22 bolts, using an electric torque wrench at 10rpm, ranged from 192 to 272 kN, with an average value of 240kN, and a standard devi- ation of 18.2kN. This result shows that the

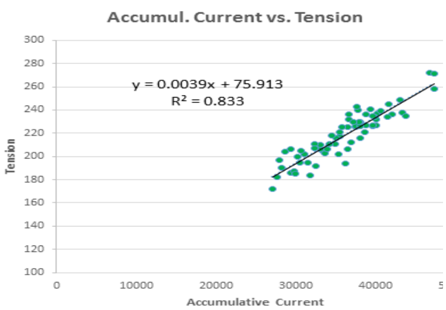

Fig. 3 Current vs Tension

average clamping force is higher than that of conventional high-strength bolts; the standard deviation was 7%. The results suggest that zinc coating applied to the bolt surface influenced the clamping force, depending on the degree of coating and the thickness. The clamping force measured with the test device ranged from 219 to 245 kN, with an average value of 233 kN, and a standard deviation of 16 kN. The average error rate of the clamping force obtained from the test device and the analog clamping force was 3.7%, which was 0.5% higher than the average error rate of 3.2% as a whole.

The clamping force measurements on the DW-22 bolts, using an electric torque wrench at 9rpm, ranged from 172 to 211kN, with an average value of 194kN, and a standard devia- tion of 10.3kN. The clamping force measured with the test device ranged from 181 to 217 kN, with an average value of 195kN, and a standard deviation of 10.3kN. The average clamping force and standard deviation from the analog clamping force meter and the test device were nearly the same. However, the error rate reached 12% in one data set, and the average error rate was 3.9%. The clamping force measurements on the HK-22 bolts, using an electric torque wrench at 9rpm, ranged from 202 to 218kN, with an average value of 211kN, and a standard devia- tion of 6.9kN. The clamping force measured with the test device ranged from 195 to 231kN, showing

Table 2 Specimen Identification

Sample ID Number	Clamping force meter (A)		Test device(B)		(A-B) Average (%)
	mean clamping force (kN)	S.D. (kN)	mean clamping force (kN)	S.D. (kN)	
R10-HK-22	229	4.8	228	8.8	2.4
R10-HKD-22	240	18.2	233	16.1	3.7
R9-DW-22	194	10.3	195	10.3	3.9
R9-HK-22	211	6.9	210	9.4	2.9
Total					3.2

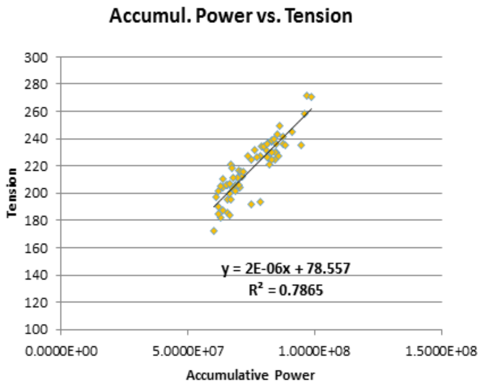

Fig. 4 Electric power vs tension

a larger clamping deviation than the data obtained from the clamping force meter. In this case, the average clamping force was 210kN, and the standard deviation was 9.4kN. The average clamping force values obtained from the clamping force meter and the testing device were nearly the same value, while their standard deviations were slightly different. The average error rate was 2.9%, which was 0.3% less than the average error rate of 3.2% as a whole.

The measured data was compiled to obtain the accumulated current. The results according to the experimental variables are summarized in Table 2. The average error rate for each experi- mental variable ranged from 2.4 to 3.9%, and the overall average error rate was 3.2%, which was very reliable.

4.2.2Clamping force due to accumulated power

The result of the regression analysis on the cumulative current, with respect to the clamping force, is shown in Eq. (3), and its graph is shown in Fig. 4. The coefficient of determi- nation (R^2) in this case was 0.78.

$$T = 2E\text{-}06 \times A.P + 78.557 \quad (3)$$

(T: Tensile force (kN), A.C: Accumulative current replacement value (A))

The clamping force due to the amount of electric power displayed a larger error rate than that of the clamping force, due to the amount of electric current. This result suggests that the electric power is the product of current and voltage, and this voltage continuously fluctuates, resulting in a large error rate in the amount of electric power.

The clamping force measured from the regres- sion analysis equation of electric power in the test device on the HK-22 bolts, using an electric torque wrench at 10rpm, ranged from 231 to 268kN, with an average value of 243 kN, and a standard deviation of 9.1kN. The average error rate of the clamping force, obtained from the test device and the analog clamping force, was 6.1%, which was 1.9 times larger than the average clamping force error of 3.2% by the current. These results indicate that the regression analysis of clamping force using current is advantageous.

The clamping force measured from the re- gression analysis equation of electric power in the test device on the HKD-22 bolts, using an electric torque wrench at 10 rpm, ranged from 228 to 276kN, with an average value of 251 kN, and a standard deviation of 13kN. The average error rate of the clamping force, obtained from the test device and the analog clamping force, was 4.6%.

The clamping force measured from the regression analysis equation of electric power in the test device on the DW-22 bolts, using an electric torque wrench at 9rpm, ranged from 199 to 235kN, with an average value of 211 kN, and a standard deviation of 8.6kN.

The average error rate of clamping force obtained from the test device and the clamping force obtained from the clamping force meter was 8.7%, which was the largest among the four experimental variables.

The clamping force measured with the test device on the HK-22 bolts, using an electric torque wrench at 9 rpm, ranged from 202 to 225 kN, which was not significantly different from the data obtained from the clamping force meter. In this case, the average clamping force was 214 kN, and the standard deviation was 6.6kN. The average clamping force, obtained from the clamping force meter and the test device, differed by 5 kN, and the average error rate was 2.6%, which was the smallest among the four experi- mental variables. This result was lower than the average error rate of 3.2% due to the amount of current.

5. Conclusion

This experiment was conducted to investigate the tendency of electric torque wrenches to intro- duce spurious tensile forces, and to develop test device to measure these introduced tensile forces in shear type high-strength bolts. Experiments on the clamping forces in high-strength bolts were conducted on torque shear type bolt, to improve analysis of the experimental results. In the case of bolts with a diameter of 22mm and a length of 75mm, the electric energies of the bolt during fracture of the pin tail were compared and analyzed by using electric torque wrenches at 9 and 10 rpm. The introduced cumulative current, and cumulative electric power, were measured to compare the clamping forces with those measured by the clamping force meter. The regression analysis equation using the cumulative current, and the regression analysis equation using the cumulative electric power, could both be obtained. The obtained results were very reliable with regard to the average error rate of 3.2%, which was the difference of clamping force with respect to cumulative current and 5.6%, which was the difference of clamping force with respect to cumulative electric power.

In the case of bolts with a diameter of 20 mm, the average error rate was less than 5%, and the results showed a similar tendency to those with a diameter of 22 mm. The test device developed in this study could produce highly reliable predictions of clamping force in high- strength bolts used for friction joining in struc- tures. In the future, with more qualitative and quantitative data, this test device could signi- ficantly influence the quality of construction and improve the reliability of structural connections.

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