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Develop a device to evaluate the clamping force of torque-shear high strength bolts

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ABSTRACT

This study was conducted to develop a method to identify the clamping force of high strength bolts quantitatively. The new method to identify the induced tension suggested in this study is to analyze electric energy applied to high strength bolts until the pin-tails are broken by diverse type of electric torque wrenches. Clamping force was measured and accumulated current data was obtained through various tests. Regression analysis of axial force as a function of accumulated currents was conducted with various values of bolt diameter and wrench rpm. The deviation between the values measured by an axial force meter and those estimated by a prototype of a measuring device developed in this study was within 5% when different parameter values were applied. The device including algorithms to compute load based on electricity was found reliable enough to be applied to construction sites. The prototype embedded with the algorithms for different bolt diameters and electric wrench types was upgraded through three stages. The method to determine the clamping force of a high strength bolt is deemed reasonable because total energy applied to the clamping force of the bolt is the same as the electric energy accumulated by an electric torque wrench.

1. INTRODUCTION

The bolted joint of a steel structure is designed as a slip critical joint. Currently most of the high strength bolts used in Korean construction sites are torque shear type. Unlike hexagonal head type high strength bolts, torque shear type high strength bolts are designed in a way that pin-tails are broken at certain torque. However, it is impossible to conclude that clamping force is properly induced even if proper torque is applied. It is because torque shear type high strength bolt clamping is based on torque control method. Even if torque is constant, tension changes when a torque coefficient changes. Therefore, confirming the introduction of clamping force to a high strength bold based on the fracture of its pin-tail is only valid right after it is manufactured under quality control. If the surface conditions of high strength bolt shank and threads are

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changed due to external environment such as temperature, humidity and dust while it is moved and stored, proper tension required by the specification cannot be introduced. It is why many cases of under-clamping or over-clamping exist and it is impractical to confirm how much tension is induced. Given the uncertainty described above, the purpose of this study is to determine the degree of reliability of various experiments, algorithms, and related techniques to quantitatively analyze clamping force. Subsequently, a trial product of a portable device with built-in algorithms was developed so that it can be used to quality inspection in actual construction sites.

2. Test setup

All of the candidates were torque shear high strength bolts (S10T) which were 20 mm, in diameter and 75 mm, 100mm in length to identify the tension of bolts with analog tension meter, Skidmore model, MS-102. The surface condition of high strength bolt was provided for two categories; one is plain surfaced, the other is zin coated. The applied tools for clamping bolts were electric torque wrenches made in Japan called TONE, LOCK. The revolution per minutes of tools were composed of 9 rpm for model named GH-242 HRZ, 10 rpm for model, HTS 110L, and 20 rpm for model, TWL 90L. The variables to take diverse tensions from candidate bolts were applied to conditions such as immersion of fresh water, rusted, immersion of NaCl Solution, outdoor exposure, surface temperature, no lubricant and etc. The total summary of test is as shown in Table 1.

Table.1 List of test

Torque Wrench (rpm)	Bolt Type/ Diameter	Variables	Q'ty
9 rpm	TS High Strength Bolt (S10T M20)	Temperature Immersion Lubricant	100
10 rpm	TS High Strength Bolt (S10T M20)	Temperature	45
20 rpm	TS High Strength Bolt (S10T M20)	Temperature Immersion	90

Torque shear type high strength bolts are clamped using specific electric wrenches. Electric energy induced until the fracture of the pin-tail due to shearing force directly affects the tension of the high strength bolt. The premise of study was that all the electric energy used to clamp a high strength bolt was the same as the energy induced into the shank of bolt. In order to satisfy the presupposition, it was necessary to compose diverse tensions dependent to variables and to compare these tensions with various electric energies applied to the bolts tested. The electric energy taken from an electric torque wrench was accumulated and analyzed to transform into tension within the useful range. This study is focused on the method to estimate tension by conducting regression analysis on the relation between tension measured by a tension meter and electric energy accumulated until the fracture of pin-tails and storing the result of the analysis in a measuring device.

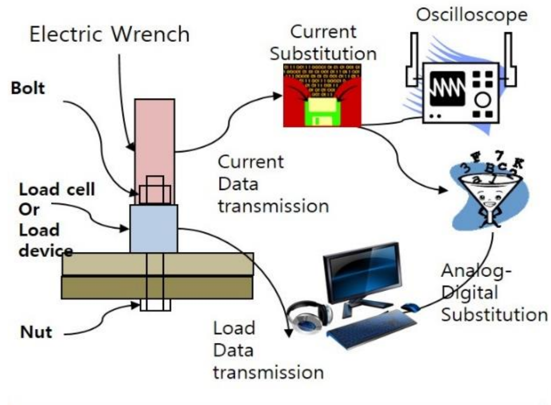

Fig.1 The process of creating data wrenches

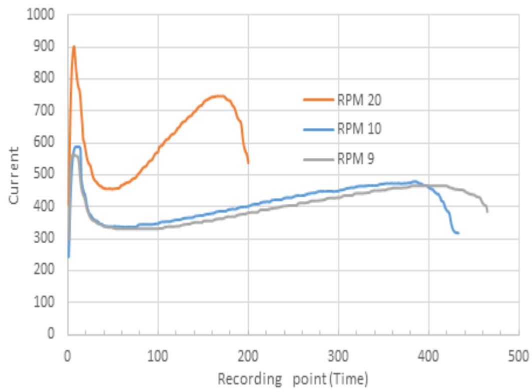

Fig. 2 Electric current curves from torque

Fig.1 shows the process of obtaining, transmitting and substituting the clamping force data of high strength bolts from an electric torque wrench. When an electric torque wrench having a speed of 9 rpm was used, the current curve continued for 8 seconds after the starting current was generated to operate the electric torque wrench and apply load as shown in Fig. 2. When an electric wrench with 20 rpm was used, fastening was completed in 3 seconds. When an electric wrench with 10 rpm was used, the electric current curve was similar to the case of 9 rpm. The magnitude of the starting current, the lowest current and the highest current were different among the three cases.
After the initial start-up current, the point where the current is the lowest indicates that clamping starts. The point of the second highest current indicates pin-tail fracture. The lowest current, the lowest power, the highest current and the highest power were determined in a general current curve. A program was configured as shown in Fig.3 to calculate the accumulated currents and accumulated power in order to determine the accumulated amount of energy from the lowest point to the highest point. All of the data measured during the tests was stored in Excel program so that the lowest current, the highest current and finally introduced tension could be displayed on the digital screen of the trial product.

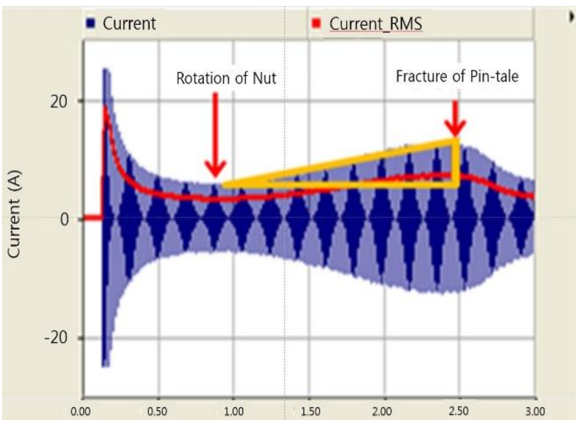

Fig. 3 Measuring electric energy from an electric torque wrench

3. Test & analysis

3.1 Test plan for electric wrench (9 rpm)

An analog tension meter (Skidmore MS-102) and an electric torque wrench (TONE, GH-242HRZ, 9 rpm) were used to measure tension and gather accumulated electric energy data. S10T M20 high strength bolts which were 20mm in diameter and 75mm, 100mm in length were used in the test. Three types of torque shear bolts from two manufacturers were chosen as specimens. Table 2 shows the list of the bolts and the variables.

Table 2 List of specimens (rpm 9)

TS High Strength Bolt	Identification	Variables	Quantity
S10T, M20 (H Co.)	HK-10	Surface temp 10 ℃	30
S10T, M20 (D Co.)	DW_IM_1	Immersion for 1 second	10
	DW_IM_24NA	Immersion for 24hours, calcium chloride	10
	DW_IM_24	Immersion for 24 hours	10
	DW_NON	No lubricant	10
S10T, M20 (Zinc Coat) (H Co.)	HKD-20	Surface temp 20 ℃	10
	HKD-IM_1	Immersion for 1 second	10
	HKD-IM_24NA	Immersion for 24hours, calcium chloride	10
Subtotal			100

3.2 Analysis result of electric wrench (9 rpm)

The tension of the bolts was measured by an analog tension meter. The average accumulated current data was retrieved from the Excel program and the trial product. Regression analysis was conducted with the test result. Eq. (1) for tension as a function of accumulated currents was obtained from the analysis. Fig. 4 is the graphical version of the analysis result.

$$T = 0.0054 \times A.C + 64.005 \quad (1)$$

(T: tension (kN), A.C: accumulated current conversion value)

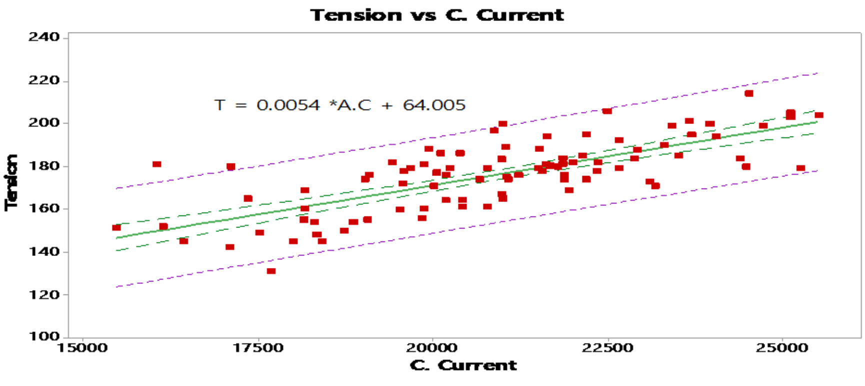

Fig.4 Tension vs. accumulated currents (9 rpm)

The regression analysis of tension as a function of accumulated power provided Eq. (2). Fig. 5 is the graphical version of the analysis result.

$$T = 0.000002 \times A.P + 64.164 \qquad (2)$$

(T: tension (kN), A.P: accumulated power conversion value)

The average deviation in the tension obtained by using accumulated currents from a 9 rpm wrench was 2.24% and the average error in the tension obtained by using accumulated power was 12.59%. The power is a value to multiply voltage by current, and voltage is fluctuated up and down at 220V sometimes as time passes. For this reason, it seemed that the range of tensions by power is larger than the range of tensions by current relatively. Therefore, it was decided to apply the relation between tension and accumulated currents to the trial product.

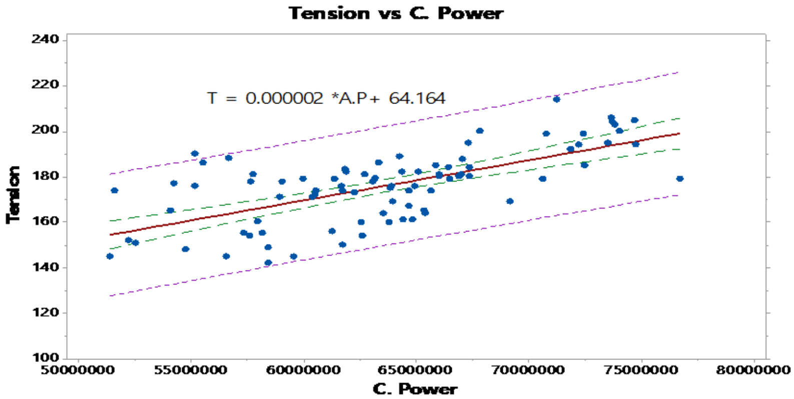

Fig. 5 Tension vs. accumulated power (9 rpm)

The highest current was observed 5.4 to 7.7 seconds after clamping started. Current data was accumulated to provide accumulated currents. The result of the analysis is shown in Table 3. The average deviation between the analysis data and the actual tension ranged between 0.04% and 7.43%. The overall average deviation was 2.24%.

Table 3 Tension analysis using an electric torque wrench (rpm 9)

Identification	Average of measured tension values (kN)	Average of accumulated currents (A)	Average of tension values from regression analysis (kN)	Average Deviation (%)
HK-10	183.2	20.974	177.2	3.28
DW_IM_1	180.2	21,648	180.9	0.39
DW_IM_24NA	187.8	22,911	187.7	0.04
DW_IM_24	164.1	20,161	172.8	5.35
DW_NON	179.3	21,484	180.0	0.40
HKD-20	160.1	19,862	171.2	7.43
HKD-IM_1	176.2	20,930	177.0	0.47
HKD-IM_24NA	160.4	18,159	162.0	1.04
Subtotal				2.24

3.3 Test Plan for electric wrench (10 rpm)

A hydraulic analog tension meter (Skidmore MS-102) and an electric torque wrench (TONE, HTS 110L, 10rpm) were used to measure tension and gather accumulated electric energy data. Three types of S10T M20 high strength bolts which were 20mm in diameter and 75mm to 100mm in length were used in the test. The test was performed at room temperature without considering various parameters since the result was expected to be similar to that obtained from the test with a 9 rpm electric wrench. Specimens in the test are shown in Table 4.

Table 4 List of specimens (10 rpm)

Bolt Species (Manufacturer)	Identification Number	Variables	Quantity
S10T M20 (H Co.)	R10-HK-20	Surface temp 23 ℃	15
S10T M20 (H Co.)	R10-HKD-20	Surface temp 23 ℃	15
S10T M20 (D Co.)	R10-DW-20	Surface temp 23 ℃	15
Subtotal			45

3.4 Analysis result of electric wrench (10 rpm)

As in the case of the previous test, measured tension values were compared with the values obtained by using accumulated current data and accumulated power data. The former provided lower deviation. Eq. (3) was obtained from the regression analysis of tension as a function of accumulated currents.

$$T = 0.0017 \times A.C + 148.02 \tag{3}$$

(T: tension (kN), A.C: accumulated currents conversion value)

The average tension obtained from the tension meter was 185.3 kN and the value obtained from Eq. (3) using accumulated currents was 183.9 kN. The deviation was as low as 1.9%. Fig. 6 shows the relationship between tension and accumulated currents.

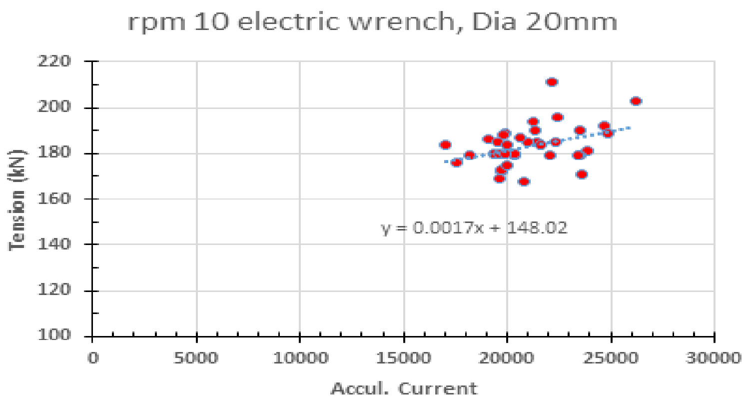

Fig. 6 Tension vs. currents (10 rpm)

The average tension of 157.4kN was achieved from the regression analysis of tension in relation to accumulated power. Standard deviation was 2.5. Fig. 7 shows the result. It was indicated that the values of tension obtained by using accumulated currents (deviation 1.9%) were much more reliable than those obtained by using accumulated power (deviation 14.9%). In fact, the deviation in the latter was too large for the values to be considered reliable. Table 5 summarizes the tension analysis using accumulated currents from an electric torque wrench with 10 rpm.

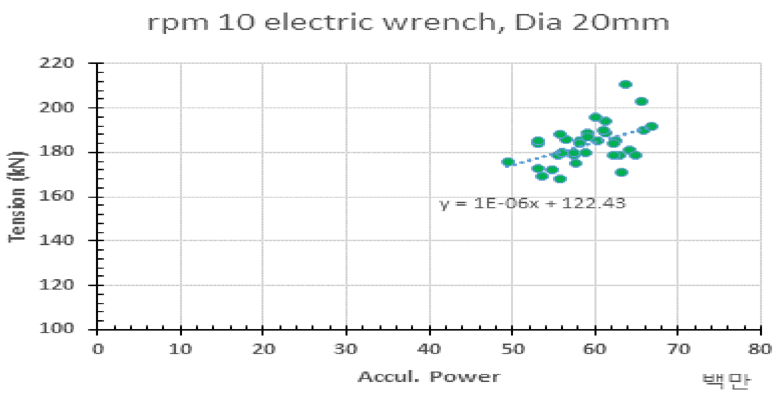

Fig. 7 Tension vs. accumulated power (rpm 10)

Table 5 Tension analysis (rpm 10)

Identification Number	measured tension (kN) (A)	Values from regression analysis		Deviation (A-B)
		Tension Aver.(kN) (B)	Standard Dev.	
R10-HK-20	185	181	7.3	1.9
R10-HKD-20	183	183	6.4	2.8
R10-DW-20	181	185	11.2	5.2
Average	183	183	8.9	3.4

3.5 Test plan for diameter 20mm bolts (20 rpm)

A hydraulic analog tension meter (Skidmore MS-102) and an electric torque wrench (TSW90L, LOCK 20 rpm) were used to measure tension and gather accumulated electric energy data. Three types of S10T M20 high strength bolts which were 20mm in diameter and 75mm to100mm in length were used in the test. Table 6 shows the specimens and the variables.

Table 6 List of specimens (rpm 20)

Bolt Type	Identification Number	Variables	Quantity
S10T M20 (H Co.)	HK-T45	Surface temp. 45 ℃	10
	HK-T20	surface temp. 20 ℃	10
	HK-T-W01	Immersion for 1 second	10
S10T M20 (D Co.)	DW-T20	Surface temp. 20 ℃	10
	DW-T43	Surface temp. 43 ℃	10
S10T M20 (H Co.)	HK-D-W24	Immersion for 24 hours	10
	HK-D-T37	Surface temp. 37 ℃	10
	HK-D-T20	Surface temp. 20 ℃	10
	HK-D-W01	Immersion for 1 second	10
Subtotal			90

3.6 Analysis result of diameter 20mm bolt (20 rpm)

The tension of the bolts was measured by an analog tension meter. The average accumulated currents were retrieved from the Excel program and the trial product. Regression analysis was conducted with the test result. Eq. (4) for tension as a function of accumulated currents was obtained from the analysis. Fig. 4 is the graphical version of the analysis result.

$$T = 0.0053 \times A.C + 97.622 \tag{4}$$

(T: tension (kN), A.C: accumulated currents conversion value)

The average deviation in the tension obtained by using accumulated currents from a 20 rpm wrench was 4.6%, which was close to the case using a 9 rpm wrench in spite of a big difference in clamping speed. Tension measured by a tension meter with the temperature variable of 50°C ranged between 179kN and 220 kN, except for two values of 156kN and 157kN.

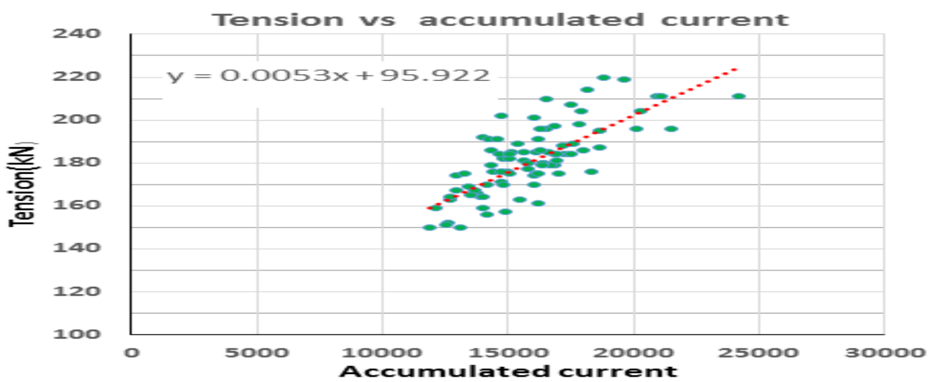

Fig. 8 Tension vs currents (20rpm)

When the temperature variable was 50℃, bolt surface temperature varied significantly due to time interval between the time of the bolts being taken out of a thermo-hygrostat and the time at which they were tested. Therefore, surface temperature was chosen as a variable. The actual surface temperatures of the bolts manufactured by C company, those manufactured by H company and zinc-coated bolts were 43℃, 45℃ and 37℃, respectively. The average tension was the highest (206kN) in specimens with the temperature variable of 43℃ and the lowest (165kN) in the specimens with the variable of immersion for 1 hour. The tension of the specimens with the surface temperature variable of 20℃ was stable, ranging between 185kN and 202kN.

The lowest current was 451A on average and the highest current was 736A on average. The number of data recorded between the lowest current and the highest current was 166 on average and time interval between the two points was less than 3 seconds. The data was accumulated to obtain the accumulated currents. The result of the analysis is shown in Table 7. The average deviations ranged between 2.58% and 7.56%.

Table 7 Result of bolt (M20) tension

Identification Number	measured tension (KN)	accumulated currents (A)	Regression Analysis (KN)	Error (%)
HK-T45	185.8	17,541	190.1	2.58
HK-T20	180.0	15,550	180.0	4.77
HK-T-W01	171.3	14.635	175.2	4.37
DW-T20	188.6	16,172	182.3	5.27
DW-T43	205.4	19,191	199.5	7.56
HK-D-W24	165.0	14,263	171.4	5.65
HK-D-T37	172.4	15,325	177.5	3.26
HK-D-T20	171.3	14,441	174.1	3.28
HK-D-W01	181	15,708	180.8	3.96
Total				4.64

Eq. (5) for tension as a function of accumulated power was obtained from regression analysis. Fig.9 is the graphical version of the analysis result.

$$T = 4E^{-06} \times A.P + 57.827 \qquad (5)$$

(T: tension (kN), A.C: accumulated power conversion value)

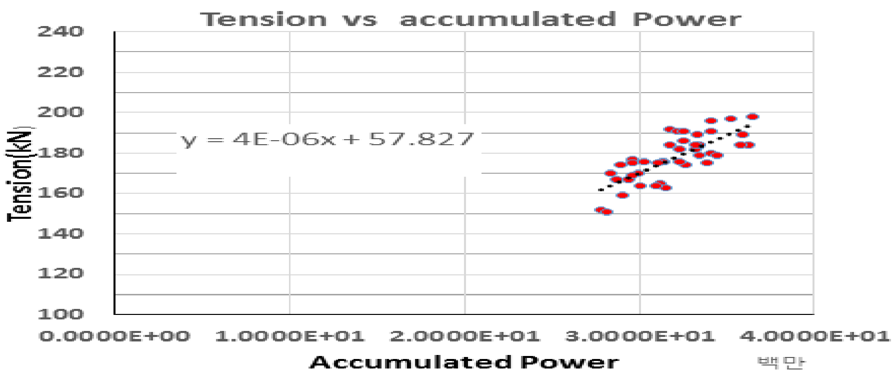

Fig. 9 Tension vs. accumulated power (20 rpm)

4. Configuration of a trial product

The trial product consists of sensing part which detects alternating current and voltage provided by an electric wrench through a current transformer; sampling part which limits the number of sensed current and voltage data to 60 per second to reduce processing time; programming part which decides the effective range (minimum value & maximum value) for measured current and voltage; programming part which decides the number of effective data to be received per second for each rpm (9~20); and part which provides information that the selected data (current or voltage) results in lower mathematic deviations. Fig. 10, 11 show the configuration. Inside the device are: part which provides regression analysis algorithms for the relation between tension and accumulated currents based on various test results; programming part which executes additional regression analysis and modifies algorithms as required by the features of an electric wrench; part which computes accumulated currents, accumulated voltages and accumulated power immediately; and part which determines tension using accumulated power as shown. Outside the device are: outlet where an tension meter and an electric wrench are connected to electricity supply; outlet where an electric wrench is connected to electricity supply; display panel for current and voltage in progress; display panel for final tension, minimum current, maximum current and accumulated current; memory card where data is stored; reset part which deletes stored or preceding data; USB part which upgrades programs; power switch; and hardware which calculates, analyzes, determines and stores measured currents & voltages and calculated power at a separate computer.

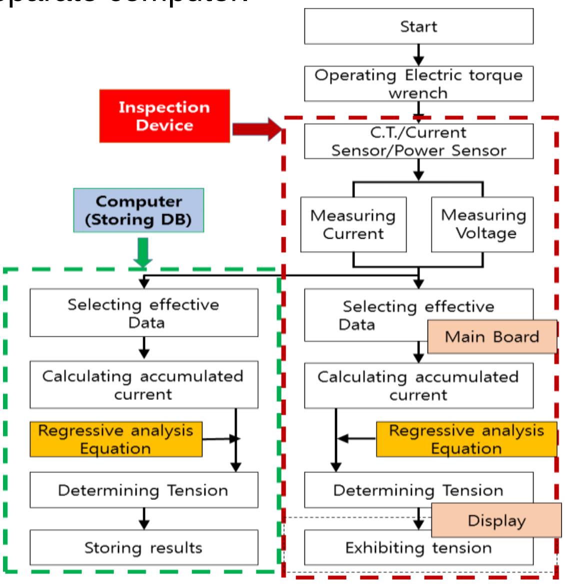

Fig. 10 Concept map of a trial product of a tension inspection device

Fig. 11 Front part of a trial product

5. Conclusions

This study was conducted to observe the measured and calculated values of tension in relation to the type of an electric torque wrench and input data in order to develop a trial product of an inspection device to measure clamping force induced to torque shear type high strength bolts. Tension tests were conducted with multiple variables on three types of high strength bolts manufactured by two companies which were 20mm in diameter and 75mm and 100mm in length. Electric torque wrenches with 9, 10 and 20 rpm were used and electric energy was analyzed until the fracture of pintails. Regression analysis was conducted to identify the relation between tension and accumulated currents and accumulated power. Equations were provided from regression analysis to calculate tension based on accumulated currents and accumulated power according to widely used diameters of bolts, rotation speed of the electric wrenches. In this study, the length of bolt, types of washer were not considered as essential elements to determine the tension.

1) Bolt diameter 20mm & rotational speed 9 rpm

$T = 0.0054 \times A.C + 64.005$

Average deviation was 2.3%.

2) Bolt diameter 20mm & rotational speed 10 rpm

$T = 0.0017 \times A.C + 148.02$

The result was similar to the case where a 9 rpm wrench was used. Average deviation was 3.4%.

3) Bolt diameter 20mm & rotational speed 20 rpm

$T = 0.0053 \times A.C + 97.622$

Average deviation was 4.6%.

As shown above, average deviation of tension values calculated by using accumulated currents were lower than 5% regardless of bolt diameter and clamping speed. The inspection method and device suggested and developed in this study estimated the clamping force of high strength bolts for friction joints. They are expected to be used for the safety assurance of bolted joints in steel structures, given extended data. The algorithms drawn from this study and the inspection device can estimate the current tension of high strength bolts clamped to existing structures by determining the initial clamping force of the bolts.

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