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Evaluation of slip coefficient of slip critical joints with high strength bolts

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Abstract. A slip critical joint has various values to adopt the proper slip coefficient in various conditions of faying surfaces in the following codes: AISC, AIJ and Eurocode 3. However, the Korean Building Code still regulates the unique slip coefficient, 0.45, regardless of the diverse faying conditions. In this study, the slip resistance test, including five kinds of surface treatments were conducted to obtain the proper slip coefficients available to steel plate KS SM490A. The faying surfaces were comprised of a clean mill, rust, red lead paint, zinc primer, and shot blast treatment. The candidates for high strength bolts were torque-shear bolts, torque-shear bolts with zinc coating, and ASTM A490 bolts. Based on the test results, the specimens with a shot blasted surface and rusted surface exhibited k_s, 0.61, and 0.5, respectively. It is recommended that the specimens with zinc primer exhibit $k_s \geq 0.40$. The clean mill treated surface had prominently lower values, 0.27. For red lead painted treatment, the thickness of the coating affects the determinant of slip coefficient, so it is necessary to establish a minimum k_s of 0.2, with a coating thickness of 65 μm. During 1,000 hours of relaxation, the uncoated surfaces exhibited the loss of clamping force behind 3%, while the coated surfaces within a certain limited thickness exhibited the loss of clamping within a range of 4.71% and 8.37%.

Keywords: slip coefficient; slip critical joint; tension; high-strength bolts; relaxation.

1. Introduction

The 154 kV substations in the Republic of Korea have been changed from concrete structure to steel structure since steel structure was standardized as the typical model in 2002. Furthermore it is expected that the number of steel structure substations will increase up to 268 substations. Nowadays, the torque shear type high strength bolt substitutes for high strength hexagon bolts in the

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design of slip resistant joints. The torque shear type high strength bolt reaches the required torque when the pin-tail twists off at the end of the shank. However, this does not mean that this bolt has the required direct tension, but only that it was subjected to torqued tension (Kulak 2001). The torque coefficient affects the design strength in tension and the process of tightening by the torque control method. The tension-torque relation of the bolt is determined as followed Eq. (1)

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

where N is the bolt tension force, T is the torque, k is torque coefficient, and d is the nominal diameter of the bolt. The torque coefficient k, the decisive variable of tightening bolts is derived from Eq. (2) (Bickford 1998)

$$k = \frac{1}{2d}\left[d_n \cdot f_n + d_t\left(\frac{f_t + \cos\theta \cdot \tan\alpha}{\cos\theta - f_t \cdot \tan\alpha}\right)\right] \tag{2}$$

where d is the bolt nominal diameter, d_n is the mean diameter of the head bearing face, f_n is the friction between the bolt head and the flange, d_t is the mean thread contact diameter, f_t is the bolt thread coefficient of friction, θ is the thread flank angle, and α is the helix angle.

In order to lessen the variables of bolt torque, the direct tension indicators have been used for proper tension in the western fields (Lehman 2002). The elastic angle control method was suggested to complement the torque control in Japan (Fukuoka 2004). A study on the low preload of swaged bolts as an alternative to high strength bolts was conducted (Drean 2002). However the torque shear type high strength bolts are still dependent on ambient temperature as represented in Korean Standard B2819 (2003), which is equivalent to the newly established ASTM F2289 (2006). The torque coefficient of high strength bolts generally responded sensitively to two kinds of factors: ambient temperature and the grip length of the bolt. The pretension for the large diameter of A490 bolt was reported to be dependent on grip length (Oswald 1996). Recently, the torque-tension relation of high strength bolts was examined from the change of temperature (Nah 2008). In a similar study on temperature dependent bolts, the effect of hot-wet conditions on the load carrying capacity of pultruded GRP single bolt tension joints was examined (Turvey 2005).

Subsequently, the external load acts in a perpendicular plane to the bolt tension in the slip critical joints. For the last two decades, there have been few studies on slip coefficients on various faying surfaces in slip critical joints in comparison to both tension joints and bearing joints. The research on slip critical joints is related to the uncoated treatment of faying surfaces bolted using super high strength bolts, which have tensile strengths of 1,100~1,300 N/mm^2 and at least 990 N/mm^2 of yield strength (Kim 2001). The study on structural behavior on the friction type joint was conducted under cyclic loading (Kim 2001). The slip load due to the external load is completely determined by friction forces acting on the contacted area of the slip critical joint fastened by the bolts. In addition, the slip coefficient on a given joint geometry differs from the species of steel. The research on slip critical joints with weathering steel has been limited to uncoated faying surfaces (Park 2000). Therefore, diverse factors influencing on the friction force were examined in the following section.

2. Variables of slip critical joint

Besides the initial clamping force T_i, the slip coefficient k_s, as shown in Eq. (3), of the joint

Table 1 Slip coefficients based on the RCSC guideline/design recommendations

Type steel	Treatment	Average	Standard deviation
A7, A36, A440	Clean mill scale	0.33	0.07
	Red lead paint	0.06	-
A7, A36, Fe37	Grit blasted, exposed (short period)	0.53	0.06
	Blast-cleaned zinc sprayed (t > 2 mils)	0.40	0.04

behavior up to the slip depends considerably on the treatments and conditions of the faying surfaces. The bolt tension can be assumed to be equal in all bolts, and this reduces to

$$P_{slip} = k_s \, mn \, T_i \tag{3}$$

where P_{slip} describes the slip load of the tension plate, m is the number of slip planes, and n is the number of bolts in the joint.

The American Institute of Steel Construction (AISC), the Architectural Institute of Japan (AIJ), and Eurocode3, regulate the proper slip coefficients that result from types of steel and treatments of surfaces. Some criteria in the Research Council on Structural Connections (RCSC) are shown in Table 1.

The slip coefficient depends on the faying surface treatments and the hole sizes in the joint geometry. However, the Korean Building Code still uses a unique slip coefficient value, 0.45, without any option of faying surface treatment. This study was planned in order to suggest fundamental slip coefficient data for various surface conditions considering the domestic environment. In addition, the strain of each bolt with the specimens subjected to conditions of surfaces was measured for the long term relaxation of the initial clamping force.

3. Test program

A test was planned to determine the slip coefficient of faying surfaces under static tension loading and to determine the loss of clamping force. The main goal was to determine the shear capacity of

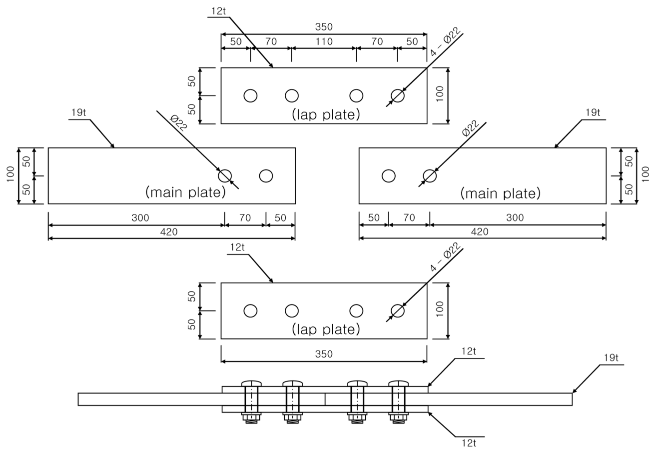


Fig. 1 Description of a double lap joint with two single holes

the connections and to evaluate the relaxation of the clamping force under service loading. The material property of base plate was composed of SM490A, and the thickness was 19 mm. The thickness of the splice plate was 12 mm. The candidates were three kinds of high strength bolts that have 1,000~1,200 N/mm^2 of tensile strength and at least 900 N/mm^2 of yield strength: torque shear bolts applied to KS B 2819 equivalent to ASTM F2289, torque shear bolts with zinc coating, and ASTM A490 bolts. Each bolt was clamped by a calibrated wrench method. The specimen was designed not to reduce the slip load due to the yielding base plate before the expected slip occurs. The test specimens had a double lap joint with two single holes, as shown in Fig. 1. The pitch of bolt hole was 70 mm, and the edge distance was 50 mm.

3.1 The preparation of specimens

There were five test parameters of faying surfaces: the clean mill, rust, red lead paint, zinc rich paint, and shot blast. The clean mill condition of the faying surface was used in the same condition in which it was delivered to the laboratory. The rust condition of faying surface was used in the condition of one month outdoor exposure after controlling the shot blast.

The nominal thickness for coated treatment was planned as 120 μm (4.7 mils). For comparison with the difference of coating thickness, at least another thickness of coating was added. Red lead paint was applied to the specimen to achieve a reddish brown color, and its average thickness was measured as 65 μm (2.5 mils) and 125 μm (4.9 mils), respectively. Galvanizing paint was applied to specimen with a spraying zinc primer, and its average thickness was 128 μm (5.0 mils), 226 μm (8.9 mils), respectively. For the specified roughness (above 50 μm), the grit size and the diameter of the shot ball ranged from 0.5 mm to 1.4 mm.

3.2 Test setup

The test setup is shown in Fig. 2. The clamping force of the high strength bolt being tested continued to reach the intended tension 178 kN after a torque of 15 kgm in the initial stage. The loading in tension was conducted to control by load until a slip occurred in order control up to fracture of specimen by displacement after slip. For measuring the strain of bolt, the strain gages on the opposite side of the bolt shank were attached after drilling holes on the head of bolt, as shown in Fig. 2.

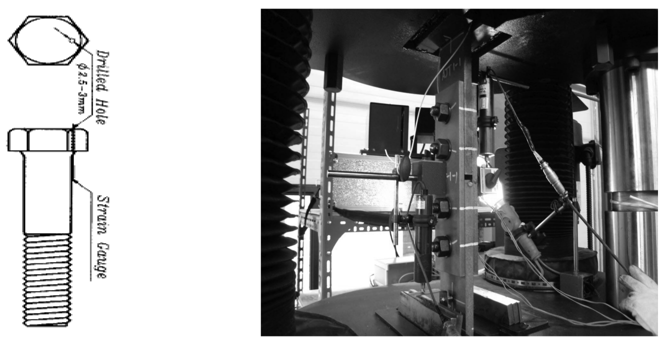


Fig. 2 Test setup for slip coefficient

Table 2 Description of specimens

Specimen I.D	Bolt Species*	Treatment of Surface Thickness : [μm(mils)]		Quantity	Remark (Bolt species*for test)
2KFM	1) KS B 2819 Torque shear bolt (M20) 2) KS B 2819 Torque shear bolt with zinc coating (M20) 3) ASTM A490 bolt (M20)	Clean mill		9	1), 2), 3)
2KFP-1		Red lead paint	65 (2.5)	3	1)
2KFP-2			125 (4.9)	6	2), 3)
2KFZ-1		Zinc primer	128 (5.0)	3	1)
2KFZ-2			226 (8.9)	2	2)
2KFR		Rust		9	1), 2), 3)
2KFB		Shot Blast		9	1), 2), 3)

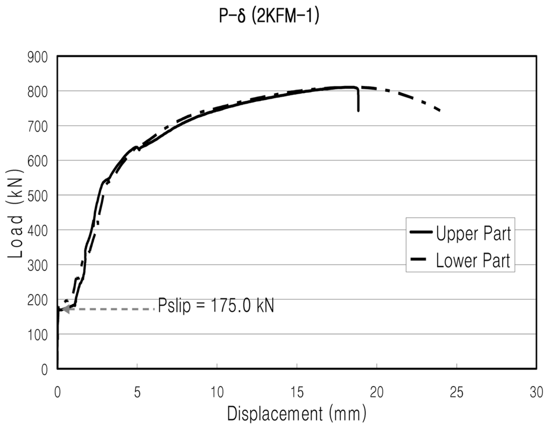
4. Test result

4.1 Slip coefficient test result

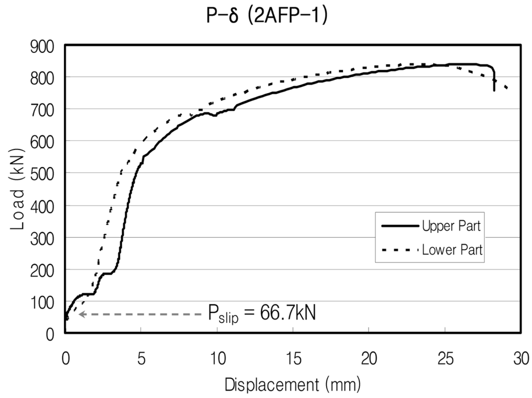
The slip load on each treatment can be traced in the load-displacement curves in Fig. 3. The specimens of the clean mill scale on the surface (2KFM Series) exhibited that the slip coefficient was from 0.23 to 0.29 with a range from 167 kN to 216 kN. This is in contrast to AISC specification for structural joints using ASTM A325 or A 490 Bolts (2000), which is suggested as 0.33, whereas it is the similar to 0.33 with a standard deviation of 0.07, as suggested by the RCSC guideline. The slip coefficient is also in the range of 0.20 to 0.35 reported by Architectural Institute of Japan (AIJ) guideline (2001). These reasons firstly come from a difference between the clamping method of direct tension and the clamping method of torque control. Secondarily, it depends on how the clean mill scale on surfaces was treated.

For specimens of red lead paint on the surface (2KFP Series), in the case of paint thickness 65 μm, the average slip coefficient was 0.21 with a standard deviation of 0.02 while the slip load ranged from 139 kN to 168 kN. This is coincided with the AIJ guideline. At the slip, the initial bolt clamping force diminished by 3% in Table 3 and Fig. 4. However, the slip coefficient of 125 μm thick paint was dropped up to 0.09 with a standard deviation of 0.01. This slip coefficient was the lowest value of the tested specimens. This result is similar to the Research Council on Structural Connections (RCSC) guideline which suggests a standard deviation of 0.06 (Kulak 2001). Primarily, this was due to thickness of coating. Secondarily it was derived from the working conditions, thickness, and formulation of the coating.

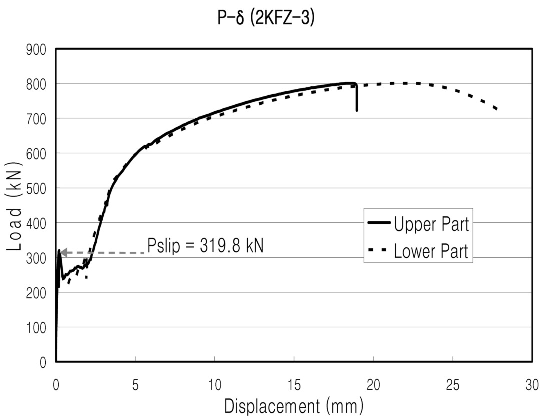
For specimens of zinc primer on the surface (2KFZ Series), the surface of the zinc thickness 128 μm exhibited that the average slip coefficient was 0.42 with a standard deviation of 0.005 while the slip load ranged from 313 kN to 326 kN. At the slip, the initial bolt clamping force loosened from 7% up to 12%, as shown in Fig. 4. The surface of zinc thickness 226 μm exhibited that the average slip coefficient was 0.45 with a standard deviation of 0.01 while the slip load ranged from 308 kN to 330 kN. This was much higher than the range from 0.1 to 0.3 suggested by the AIJ guideline and the value, whereas it was the same as 0.40 with the standard deviation of 0.04 reported by RCSC design recommendations (Kulak 2001). Unlike the red lead paint, the change of zinc primer thickness did not largely affect the slip coefficient. This behavior is believed to be due to the hardness of the metallic layer. It is also reviewed from the guide book that test results of



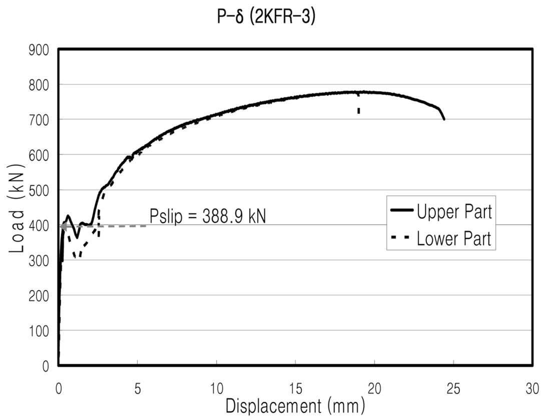
(a) Clean Mill



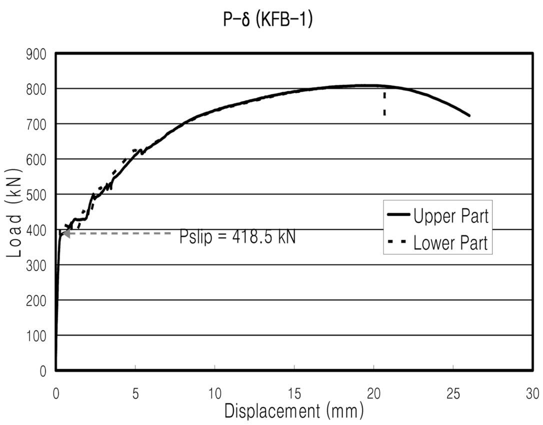
(b) Red lead paint (t=125)



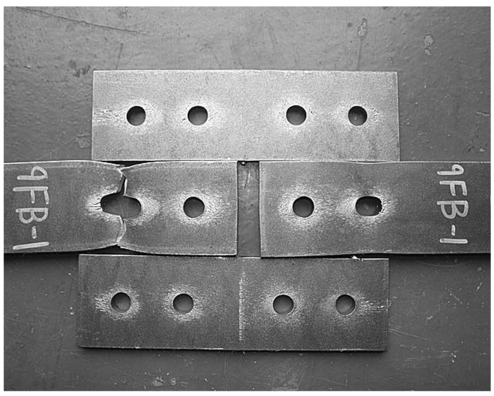
(c) Zinc Primer(t=128)



(d) Rust



(e) Shot blast



(f) Failure mode

Fig. 3 Load-displacement curve on faying surface treatment

Table 3 Test results of the slip coefficient

Surface Treatment	Clamping Force (kN)	Slip load (kN)	Mean loss of axial force on bolt (%)	Mean Slip Coefficient	Standard Deviation
Mill scale	178	170	2.5	0.27	0.01
Red lead paint (t = 65)	178	151	3.0	0.21	0.02
Red lead paint (t = 125)	178	58	1.5	0.09	0.01
Zinc primer (t = 128)	178	319	9.8	0.42	0.005
Zinc primer (t = 226)	178	322	17.0	0.45	0.01
Rust	178	390	12.5	0.61	0.07
Shot Blast	178	420	9.2	0.50	0.08

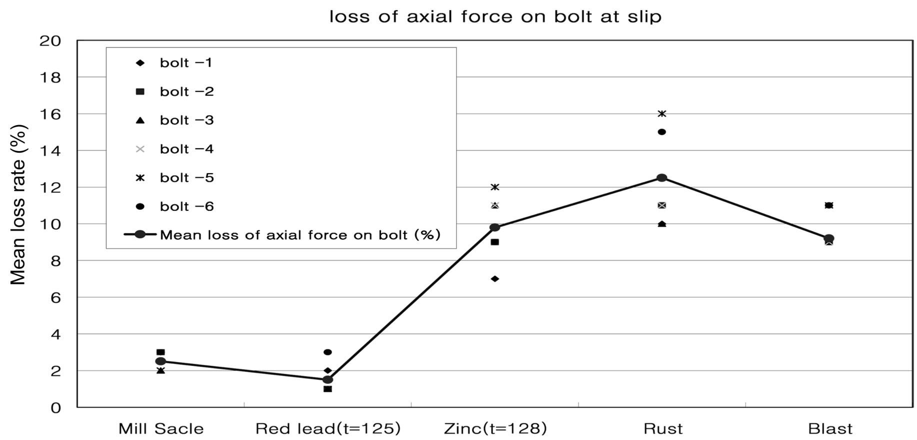


Fig. 4 Loss of axial force on bolt at slip

metallizing on surface coating were included (Kulak 2001).

The specimens rusted on the surface (2KFR Series) exhibited that the average slip coefficient was 0.61 with a standard deviation of 0.07. This value was included in the range from 0.45 to 0.7 suggested by the AIJ guideline. This value is as large as the value of both the grit blasted and exposed condition for short period, 0.53, reported by the RCSC guideline. While AISC spec regulates the slip coefficient as class B, 0.50 for rust condition, it is difficult to decide the quantitative state of rust. In the field, structural members are exposed at atmosphere for a period before erection. To simulate this field condition, the test for rust treatment condition was performed after the shot blasted plates had been exposed to an outdoor environment for a month at least. When a major slip occurred, the initial bolt clamping force dropped off from 10% to 16%, as shown in Fig. 4. In this case, the loss rate of the initial clamping force was the largest of the five treatments.

The specimens shot blasted on the surface (2KFB Series) exhibited that the average slip coefficient was 0.50 with a standard deviation of 0.08. This value was included in the range between 0.4 and 0.7 suggested by the AIJ guideline. This value was a bit lower than the value of grit blasted treatment, 0.53, which was reported by the RCSC guideline.

In case that the standard deviation both rust and blast treatment was much larger than the others. It is considered that the state of blast condition on surface was differed on the process of delivery, storage and test soon after the initial blast condition.

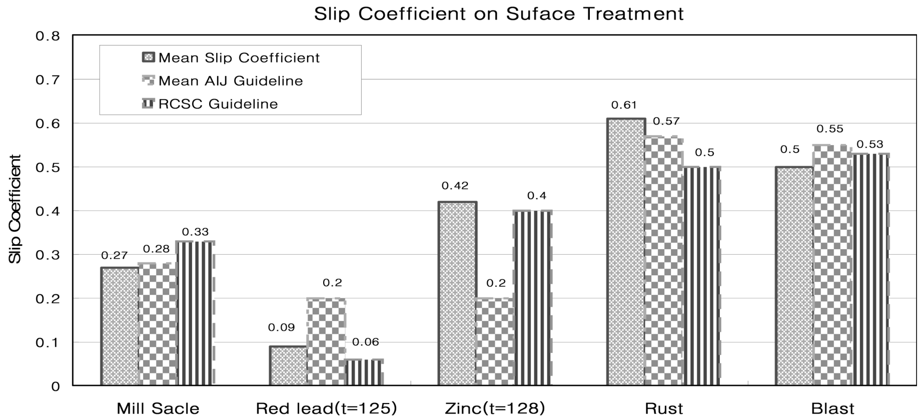


Fig. 5 Slip coefficient on faying surface treatment

The followings are the synthetic results of slip coefficient test shown in Fig. 5. Based on comparison with these tests in Fig. 5, the followings were taken: in case of uncoated treatments of faying surfaces such as clean mill scale, rust and blasted scale, the tested value showed similar trends with RCSC and the AIJ guideline within the range of standard deviation, 0.05. For comparison of material property, the type of steel used in this test, KS SM490A, is different from ASTM A36, one of the types of steel indicated in the RCSC guideline. The test result of the slip coefficient is reasonable for the calibrated wrench tightening method according to a standard deviation of k_s (mean) taken as 0.07 for $k_s \le 0.4$ and as 0.09 otherwise (Kulak 2001).

In the case of coated treatments as zinc primer and red lead primer, one among the three exhibited considerably different trends. It is surmised that the slip coefficient of the coated surface depends on the coating thickness. In this study, the coating thickness of red lead paint increased from 65 μm to 125 μm, whereas the slip coefficient was lessened abruptly from 0.2 to 0.09. Reduction in the bolt force up to 125 μm has been shown to be as large as 7.3 times that for a bare blasted surface. However, the slip coefficient for zinc primer treatment showed a stable trend from 0.42 to 0.45, regardless of increasing coating thickness from 128 μm to 226 μm. This test result was in contrast to the general view, in which the coating thickness is an effective determinant for the slip coefficient. Even though the thickness coated on the surface is the same, the slip coefficient is also affected by the formulation of the coating manufacturer and the roughness of the faying surface.

As described in the introduction of this study, it is necessary to build a diverse slip coefficient applicable to Korean standard steel. From this test, the results can be used for the fundamental data to set up the slip coefficient for steel construction in the Republic of Korea. It is also recommended that the result of this test be used to establish the criteria of the slip coefficient for slip critical joints in Korean Building Codes.

According to Korean manufacturer's recommendation for coating for steel members, the coating thickness for red lead paint is suggested as 50 μm and for zinc primer as 75 μm. For red lead paint, it is suggested that the minimum value of the mean slip coefficient k_s is 0.2 under prior conditions of coating thickness $\le$ 65 μm. For the zinc primer treatment, several tests of different thicknesses on the surface were additionally performed at 90 μm, 180 μm, and 240 μm, and the values ranged from 0.40 to 0.46. Therefore, the slip coefficient of zinc primer over thickness 90 μm is considered as $k_s \ge 0.40$.

4.2 Long term relaxation test results

A previous domestic study reported that the loss rate for the first day amounted approximately to 70% to 80% of total loss rate. For this reason, there are two standpoints from which to measure the loss rate of clamping force: 168 hours and 1,000 hours.

For clean milled scale surfaces, the average loss of the initial clamping force was 1.61% for 168 hours, 2.03% for 1,000 hours, which is in contrast to other foreign values, and 5.6% by other researcher (Yang 2000). It is different from 5% at average suggested by the researcher (Kulak 2001).

In the case of zinc primer surfaces (t = 128 μm), the mean loss of the initial clamping force was different than expected. The average loss of the initial clamping force was 7.31% for 168 hours and 8.37% for 1,000 hours. This value is different than the 12.4% mean loss for an approximately 127 μm galvanized coating surface measured by another researcher (Yang 2000). In the case of zinc primer surfaces (t = 226 μm), the average loss of the initial clamping force was 14.2% for 168 hours and 16.3% for 1,000 hours. In the case of the zinc coated surface (t = 226 μm), the loss of clamping force is 1.9 times for 7 days and 1.6 times for 42 days than the 128 μm.

For red lead painted surfaces (t = 65 μm), the loss of clamping force recorded as 4.01% and 4.71% for 168 hours and 1,000 hours, respectively. For red lead painted surface (t = 125 μm), the loss of clamping force recorded as 13% and 18.2% for 168 hours and 1,000 hours, respectively. The difference of relaxation on coated treatments is derived from the difference of coating thickness; In the case of the red lead painted surface (t = 125 μm), the loss of clamping force is 3.25 times for 7 days, 3.86 times for 42 days than the 65 μm. The main reason manipulates the relaxation of the slip critical joint is the creep behavior of the coating.

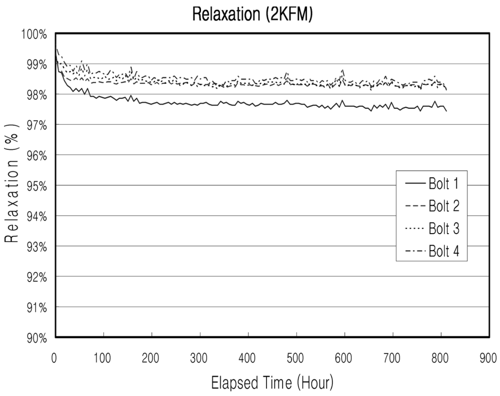
From this test, the thicker coatings results in greater loss of clamping force. It is considered that coating thickness governs coating species on the process of relaxation. It is also exhibited that the relaxation rate was different according to different coating species.

For rust surfaces, the mean relaxation was an average loss of 2.31% for 168 hours and 2.91% for 1,000 hours, as shown in Fig. 6. For shot blasted surfaces, the mean relaxation rate was the lowest of the candidate specimens, as shown in Fig. 6. These exhibited an average loss of 1.39% for 168 hours and 1.70% for 1,000 hours.

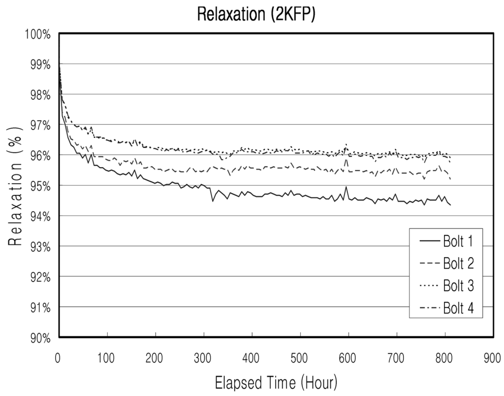
The relaxation of the synthetic test results after 168 hours and 1,000 hours are given in Fig. 7. According to this test, the loss rate of the initial clamping force for a week reaches 85% of the total loss rate. In the precedent study, the relaxation rate was reported to be within a range from 70% to 80% for the first day of 500 hours by another domestic researcher (Park 2000). In addition, Kulak reported that the relaxation of the A325 and A354 BD bolt showed 90% of this loss occurred during the first day of 21 days. It is exhibited that 90% loss occurred during the first week (Yang 2000).

This test produced an average loss of 3.33% with a range between 1.39% and 7.31% for 168 hours. The relaxation test for 1,000 hours produced an average loss of 3.94% with a range between 1.7% and 8.37%. From this test, this relaxation, 4.71% with red lead paint (t = 65) was 2.3 times larger than another relaxation, 2% for clean mill scale. Furthermore, the relaxation, 8.37% with a zinc primer coat (t = 128), was 4.1 times larger than another relaxation, which was 2% for a clean mill scale.

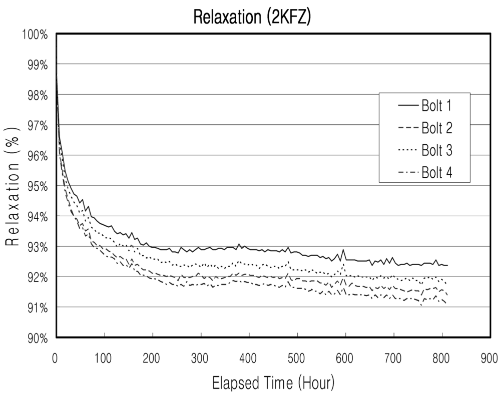
Except for red lead paint (t = 125) and zinc primer (t = 226), the losses of clamping force on various surface treatment were below 10%. In general, the coating thickness on the steel members



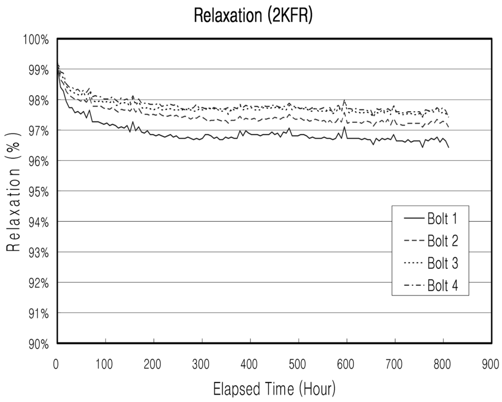
(a) Clean Mill



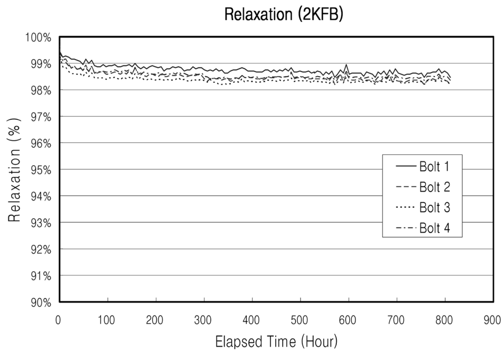
(b) Red lead paint (t=65)



(c) Zinc Primer (t=128)



(d) Rust



(e) Shot blast

Fig. 6 Relaxation rate on each treatment

in substation is below 90 μm. Therefore, the test results, except for the red lead paint and zinc primer coating, showed that it would be necessary to increase the clamping force of the bolt up to 1.1 times.

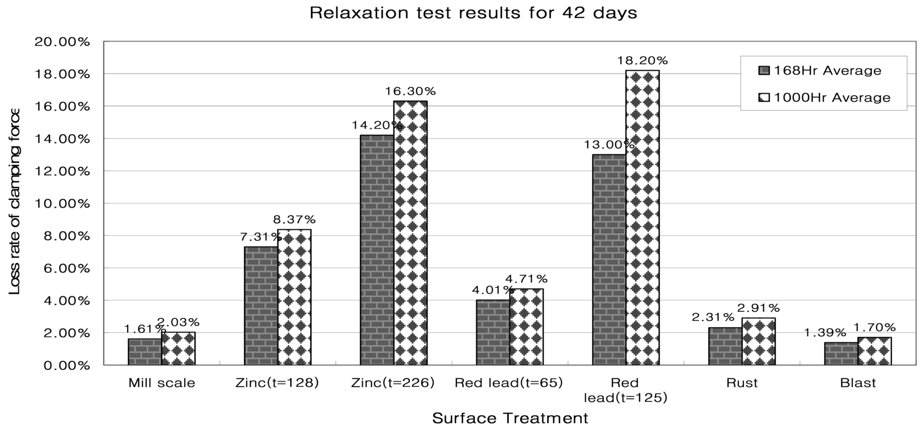


Fig. 7 Comparison between 168 hours versus 1,000 hours for relaxation

5. Conclusions

The tests were conducted on torque shear high strength bolted connections to determine how much the shear capacity is diminished by slip load and by relaxation in the clamping force for different surface treatments. The tests for slip coefficient consisted of five parameters on faying surfaces. In addition, the long term relaxation tests (1,000 hours) were performed. The following conclusions have been made for this study.

1) From the slip coefficient test, uncoated surfaces, namely the rusted surface and shot blasted surface, exhibited slip coefficients of 0.61, 0.50 respectively, exceeding the required slip resistance. For red lead surface, the slip coefficient k_s of 0.2 is considered appropriate under a prior condition of a coating thickness ≤65 μm. For zinc primer surfaces, it is considered that the slip coefficient of k_s of 0.4 can be used for zinc primer over a thickness of 90 μm.

2) The coating thickness greatly affects the loss of clamping force due to the creep behavior of the coating. From the relaxation test, it was observed that the first one week governs 85% of the total relaxation. The uncoated treatment surface exhibited the loss of clamping force below 3%, whereas the coated treatment surface exhibited the loss of clamping force with a large range between 4.7% and 18.2%. The test results of coating thickness under 90 μm showed that it would be necessary to increase the clamping force of bolt up to 1.1 times.

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