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Establishment of Slip Coefficient for Slip Resistant Connection

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Abstract: A slip critical connection has various values to adopt the proper slip coefficient in various conditions of faying surfaces in AISC, AIJ and Eurocode3. The Korean Building Code regulates the unique slip coefficient, from 0.45 to 0.5 without consideration of the diverse faying conditions in 2009. 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 slip coefficient of specimens over zinc primer thickness of 128 μm exhibit was 0.42. The clean mill treated surface had prominently lower values as slip coefficient, 0.27. For red lead painted treatment, it is suggested to setup a minimum slip coefficient, 0.21, below a coating thickness of 65 μm. The slip coefficient of one faced lap connection was higher 1.4 times than the slip coefficient of two faced lap connection.

Key words: Bolt, slip, coefficient, faying surface, coating, torque, tension.

1. Introduction

The bolted connection of steel structure of Nuclear Power Plant structures in Korea was originally designed by high-strength hexagon bolt for slip resistant connections. However, nowadays it is a general tendency that the torque shear type high strength bolt is in place for the high strength hexagon bolt at design of slip resistant connection. The Korean standard for torque shear-type high-strength bolt was initially regulated in 2003 and revised in 2005 [1]. Moreover, the related code ASTM F 2280, as used in the USA, was established in 2006 [2]. The torque shear type high strength bolt reaches the required torque when the pin tail twisted off at the end of shank. However this does not mean that even if the pin tail was properly detached from the bolt shank, this bolt has the required direct tension, but only that it was subjected to indirect tension affected by torque [3]. The torque coefficient affects on the design strength in tension when it is tightened by the torque control equipment. The induced toque is greatly varied due to accuracy of bolting method [4]. The tension is in inverse proportion to the torque due to the variation of torque coefficient.

The torque shear type high strength bolts are still dependent on ambient temperature as represented in Korean Standard B2819, which is equivalent to the newly established ASTM F2289. The torque coefficient of high strength bolts 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 [5]. Recently, the torque-tension relation of high strength bolts was examined from the change of temperature [6]. Subsequently the external load acts in a perpendicular plane to the bolt tension in the slip critical connections. The slip coefficient on a given connection geometry differs from the species of steel. The Table 1 of following section shows as to which factors are influencing on the slip coefficient.

2. Review of Slip Coefficient

Besides the initial clamping force *Ti*, the slip coefficient k_s as shown in Eq. (1) of the connection 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

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Table 1 Slip coefficients based on the RCSC guideline.

Type of 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>2mils)	0.40	0.04

Table 2 Slip coefficient of Eurocode3.

Class	Slip factor	Surface Treatments
A	0.50	· surfaces blasted with shot or grit, with any loose rust removed, no pitting · surfaces blasted with shot or grit, and spray-metalized with aluminum · surfaces blasted with shot or grit, and spray-metalized with a zinc-based coating certified to provide a slip factor of not less than 0.5
B	0.40	· surfaces blasted with shot or grit, and painted with an alkali-zinc silicate paint to produce a coating thickness of 50~80 m
C	0.30	· surfaces cleaned by wire brushing of flame cleaning with any loose rust removed
D	0.20	· surfaces not treated

this reduces to

$$P_{slip} = k_s mnT_i \tag{1}$$

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 connection.

The American Institute of Steel Construction, and Eurocode3, regulate the proper slip coefficients that results from types of steel, and treatments of surfaces. Some criteria in the Research Council on Structural Connections (RCSC) and Eurocode3 are shown in Table 1, Table 2 respectively.

The slip coefficient depends on the faying surface treatments, and the hole sizes in the connection geometry. This study was planned in order to suggest a fundamental slip coefficient data for various surface conditions considering the domestic environment.

3. Test Program

A test plan was both to determine the slip coefficient of faying surfaces under static tension loading. The material property of base plate, splice plate was composed of Korean Standard SM490A and the thickness was 19 mm. The thickness of the splice plate was 12 mm. The steel plate, SM490A with a thickness range from 16 mm to 40 mm, has the material property, which has 235 N/mm^2 of minimum yield strength, and from 400 N/mm^2 to 510 N/mm^2 of tensile strength. The candidates for high strength bolts were three kinds, 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 178 kN with a calibrated wrench. The specimen was designed not to reduce the slip load due to yielding base plate before the expected slip occurs. The test specimens had two kinds of lap connections: one is a double lap connection with two single holes as shown in Fig. 1, another is a single lap connection with two single holes as shown in Fig. 2. The dimension of base plate was 420 mm by 100 mm, the hole size for clamping was 24 mm. The dimension of splice plate was 350 mm by 100 mm. The pitch of bolt hole was 70 mm and the edge distance was 50 mm at least. The hole size for splice plate was 22 mm available to bolt diameter 20 mm. The dimension of the specimen for a test followed a suggestion from guidebook on design and fabrication of high strength bolted connections which the guideline of Architectural Institute in Japan regulates [7].

3.1 The Preparation of Specimens

There were two kinds of test parameters: One is the treatment of faying surfaces such as the clean mill, rust, red lead paint, zinc rich paint, and shot blast.

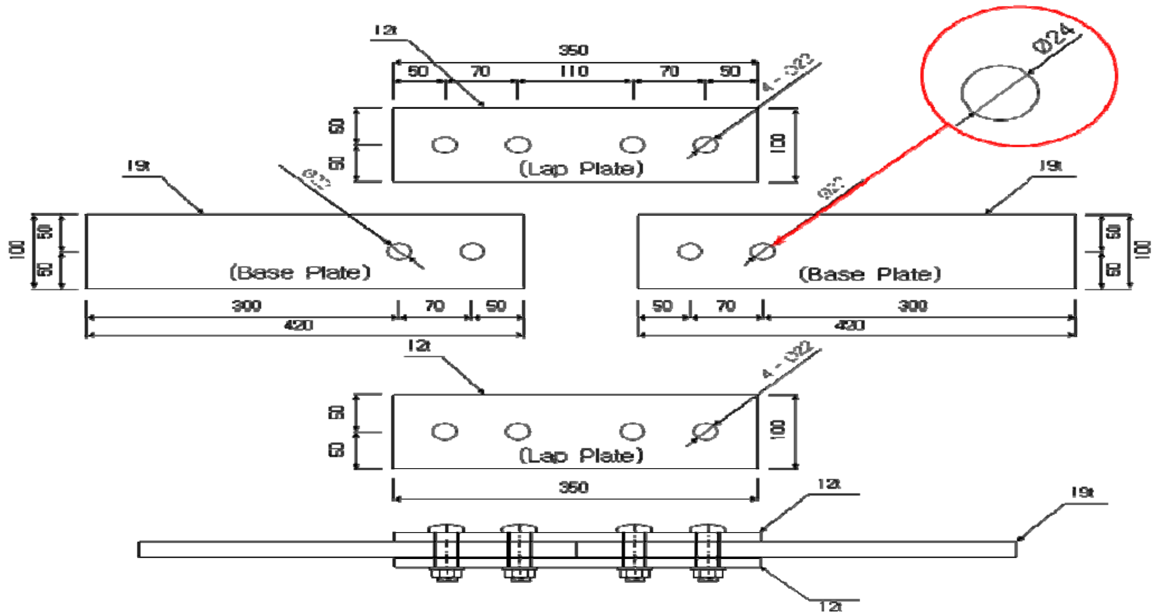


Fig. 1 Description of a double lap connection with two single holes.

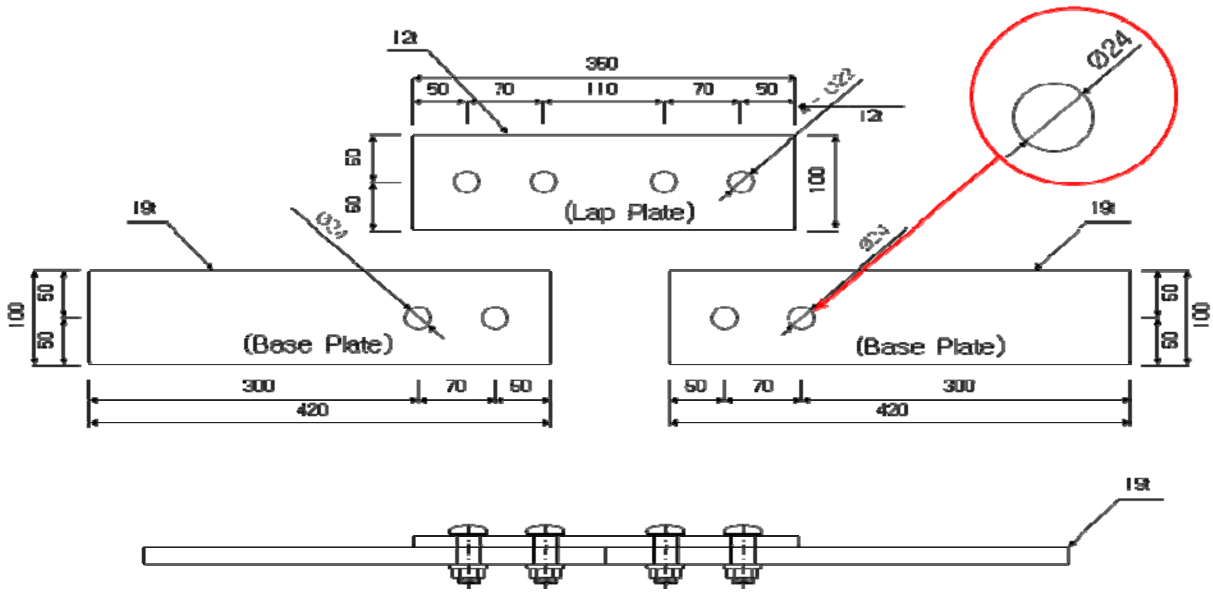


Fig. 2 Description of a single lap connection with two single holes.

Another is a number of lap plates such as one lap plate, double lap plate as shown in Fig. 1 and Fig. 2.

The clean mill condition of 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. For comparison with the difference of coating thickness, at least another thickness of coating was added. Red lead paint was applied to the specimens to achieve a reddish brown color, and its average thickness was measured as 65 μm and 125 μm respectively. Galvanizing paint was applied to specimens with a spraying zinc primer, and its average thickness was 128 μm, 226 μm respectively. The roughness of the shot blast on the surface ranged from 0.5 mm to 1.4 mm.

3.2 Test Setup

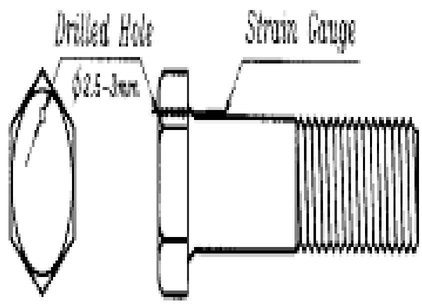
The description of specimens is shown in Table 3. The test setup is shown in Fig. 3. The clamping force of high strength bolt on test was continued to reach the intended tension of 178 kN, after preliminary torque of 15 kg m at initial stage. The loading under tension was controlled by load until a slip occurred, and then, by displacement after major slip until a fracture of specimen occurred. 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. 3.

4. Test Result & Discussion

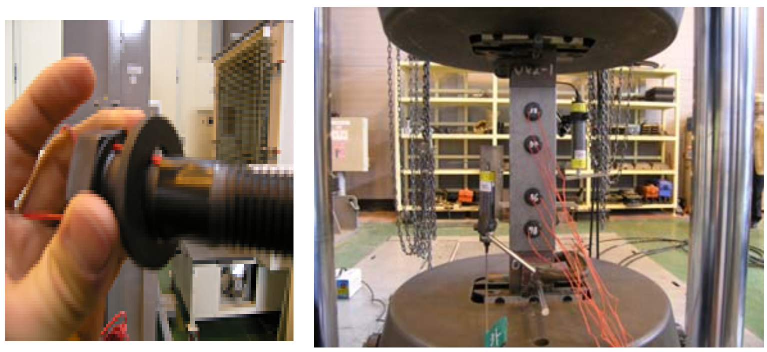
4.1 A Double Lap Connection with Two Single Holes

The slip load on each treatment can be traced in the load-displacement curves in Fig. 4. 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 connections using ASTM A325 or A 490 Bolts [8], 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 [3]. The slip coefficient is also in the range of 0.20 to 0.35 reported by Architectural Institute of Japan (AIJ) guideline [7]. The difference between test results and American criteria firstly come from a difference between the clamping method of direct tension and the clamping method of torque control. Secondarily, the difference depends on how the clean mill scale on surfaces was treated.

For specimens of red lead paint on the surface



(a) drilling hole

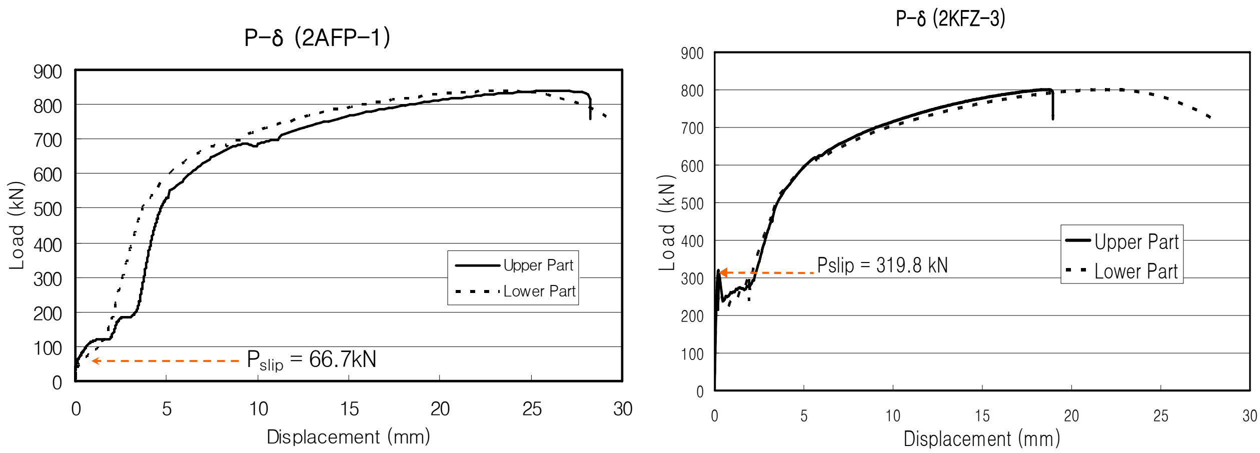


(b) Preparation of loading

Fig. 3 Test setup.

Table 3 Plant performance of winter barley cultivars at Fruita, Colorado USA in 1997, 1998, and 1999.

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)
1KFM	1) KS B 2819 Torque shear bolt (M20)	Clean mill		3	1)
1KFP		Red lead paint	65 (2.5)	3	1)
1KFZ		Zinc primer	128 (5.0)	3	1)
1KFR		Rust		3	1)
1KFB		Shot Blast		3	1)



(a) Red lead paint (t = 125)

(b) Zinc Primer (t = 128)

Fig. 4 Load-displacement curve on faying surface treatment (2 faces).

(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, as shown in Fig. 4(a) and Table 4. This is coincided with the AIJ guideline [7]. At the slip, the initial bolt clamping force diminished by 3% in Table 3 and Fig. 5. 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 [3]. Primarily, the difference between test results and American criteria was due to thickness of coating. Secondarily the difference 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(b) and Table 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 [7] and the value, whereas it was the same as 0.40 with the standard deviation of 0.04 reported by RCSC design recommendations [3]. 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.

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 barely included in the range from 0.45 to 0.7 suggested by the AIJ guideline [7]. This test result is higher than values of the grit blasted and exposed condition for short period, 0.53, reported by the RCSC guideline [3]. While AISC spec regulates the slip coefficient as class B, 0.50 for rust condition [8], 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. 5. 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

Table 4 Test results of slip coefficient (2 faces).

Specimen I.D	Surface Treatment	Clamping Force (kN)	Slip load (kN)	Mean loss of axial force on bolt (%)	Mean Slip Coefficient	Standard Deviation
2KFM	Mill scale	178	170	2.5	0.27	0.01
2KFP-1	Red lead paint (t = 65)	178	151	3.0	0.21	0.02
2KFP-2	Red lead paint (t = 125)	178	58	1.5	0.09	0.01
2KFZ-1	Zinc primer (t = 128)	178	319	9.8	0.42	0.01
2KFZ-2	Zinc primer (t = 226)	178	322	17.0	0.45	0.01
2KFR	Rust	178	390	12.5	0.61	0.07
2KFB	Shot Blast	178	420	9.2	0.50	0.08

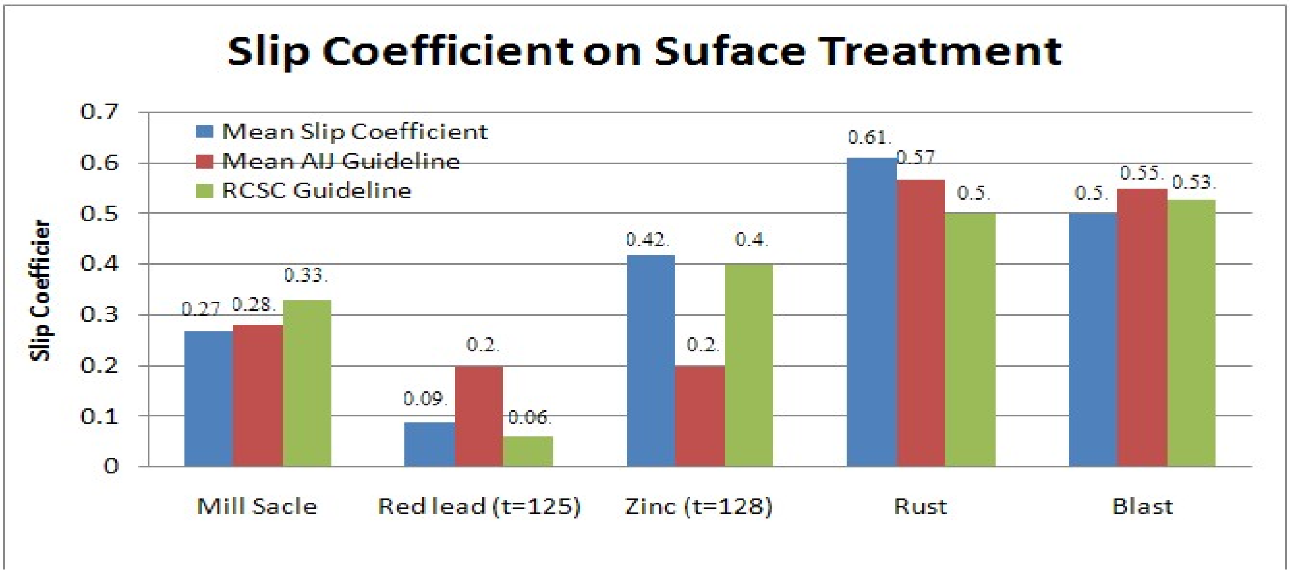


Fig. 5 Slip Coefficient on faying surface treatment (2 faces).

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 [7]. This value was a bit lower than the value of grit blasted treatment, 0.53, which was reported by the RCSC guideline [3].

In case that the standard deviation both rust and blast treatments were 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.

The followings are the synthetic results of slip coefficient test with two faced lap connection, as 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, and the tested value showed similar trends with RCSC and the AIJ guideline [7] 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 [3]. 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 $k_s \leq 0.4$ and as 0.09 otherwise [3].

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. 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 connections in steel structures of Korean Building Code.

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 0.21 under prior conditions over coating thickness of 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 0.42.

4.2 A Single Lap Connection with Two Single Holes

The specimens of the clean mill scale on the surface (1KFM Series) exhibited that the slip coefficient was 0.39 at average from 135 kN to 140 kN of the slip load as shown in Fig. 6(a). The slip coefficient of one faced lap connection was much higher than 0.27 of two faces lap connection. The fracture mode of the specimen was shear fracture of the bolt after the maximum load was reached. This is the reason why it gave rise to the out-of- plane bending of one faced lap plate by eccentric force when the load in tension was applied.

For specimens of red lead paint on the paint thickness 65 μm surface (1KFP Series), the average slip coefficient was 0.27 with a standard deviation of 0.012 while the slip load ranged from 92 kN to 100 kN. This value is 1.28 times higher than 0.21 of two faced lap connection. At the slip, the initial bolt clamping force diminished by 12% in Table 5.

For specimens of zinc primer on the zinc primer thickness 128 μm surface (1KFZ Series), it exhibited that the average slip coefficient was 0.50 with a standard deviation of 0.030 while the slip load ranged from 167 kN to 188 kN. At the slip, the initial bolt clamping force loosened from 7% up to 16%, as shown in Table 5.

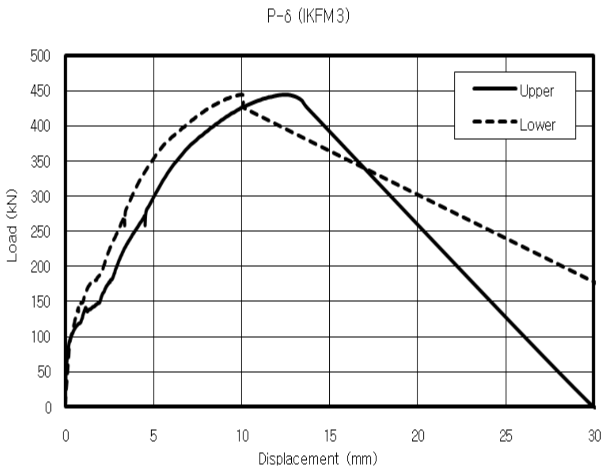
The specimens rusted on the surface (1KFR Series) exhibited that the average slip coefficient was 0.61 with a standard deviation of 0.031. This value was the same as the slip coefficient of two faced lap plate. This results included in the range from 0.45 to 0.7 suggested by the AIJ guideline [7]. The initial bolt clamping force loosened from 14% at average, this result was the lowest among the five parameters.

The specimens shot blasted on the surface (1KFB Series) exhibited that the average slip coefficient was 0.50 as shown in Fig. 6(b), the same as the specimens rusted on the surface (1KFR Series). The standard deviation was 0.054. This value was also included in the range between 0.4 and 0.7 suggested by the AIJ guideline [7].

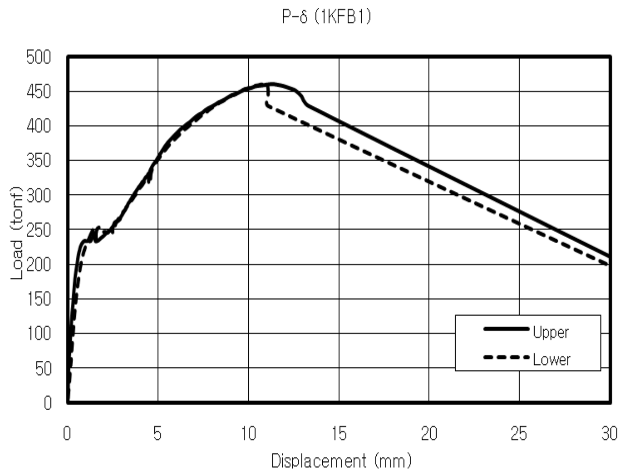
The followings are the synthetic results of slip coefficient test with one faced lap connection, compared as shown in Table 5. This concern is how much the composition of the lap connection is affected on the slip coefficient. Based on comparison with these tests in Fig. 5, the followings were taken: For rusted

Table 5 Test results of slip coefficient (1 face).

Specimen I.D	Surface Treatment	Clamping Force (kN)	Slip load (kN)	Mean loss of axial force on bolt (%)	Mean Slip Coefficient	Standard Deviation
1KFM	Mill scale	178	139	9	0.39	0.008
1KFP	Red lead paint (t=65)	178	95	7.9	0.27	0.012
1KFZ	Zinc primer (t=128)	178	178	9.8	0.50	0.030
1KFR	Rust	178	216	14.5	0.61	0.031
1KFB	Shot Blast	178	215	13.7	0.61	0.054



(a) Mill scale



(b) Blast

Fig. 6 Load-displacement curve on faying surface treatment (1 face).

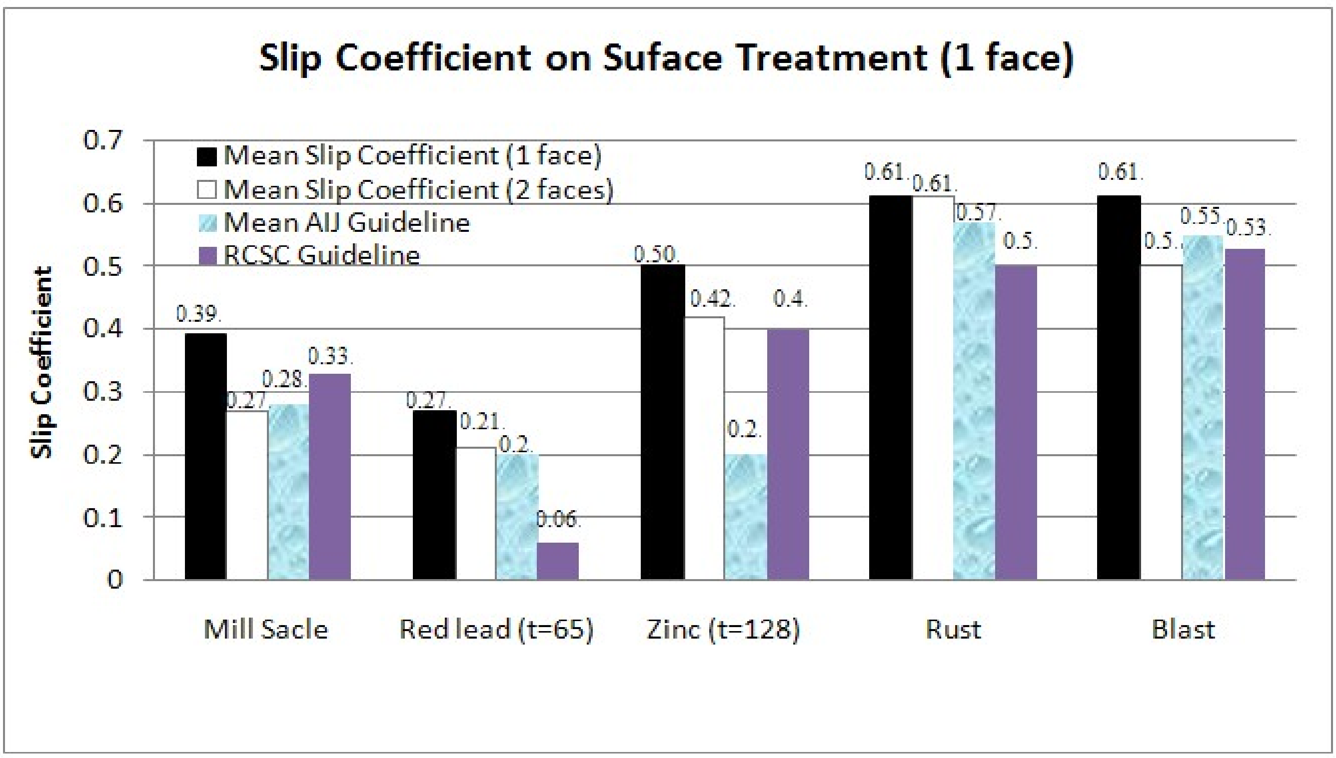


Fig. 7 Slip coefficient on faying surface treatment (1 face).

surface condition, the slip coefficient of one faced lap connection was the same as that of two faced lap connection. As for the rest parameter on surface treatments, the slip coefficient of one faced lap connection was generally higher within the range of 1.4 times than the slip coefficient of two faced lap connection in Fig. 7.

5. Conclusion

The tests were conducted on high strength bolted connections to determine how much the shear capacity is diminished by slip load due to different surface treatments. The tests for slip coefficient consisted of parameters: Both on faying surfaces and number of lap plate.

The following conclusions are made for this study.

From the slip coefficient test of two faced lap connection, 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 of 0.21 is considered appropriate under a prior condition below a coating thickness of 65 μm. For zinc primer surfaces, it is considered that the slip coefficient of 0.42 can be used for zinc primer over a thickness of 90 μm.

For reference, as for the slip coefficient test of two faced lap connection, the slip coefficient of one faced lap connection was generally higher within the range of 1.4 times than the slip coefficient of two faced lap connection.

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