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Evaluating long-term relaxation of high strength bolts considering coating on slip faying surface

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Abstract. The initial clamping forces of high strength bolts subjected to different faying surface conditions drop within 500 hours regardless of loading, any other external force or loosening of the nut. This study develops a mathematical model for relaxation confined to creep on a coated faying surface after initial clamping. The quantitative model for estimating relaxation was derived from a regression analysis for the relation between the creep strain of the coated surface and the elapsed time for 744 hours. This study establishes an expected model for estimating the relaxation of bolted joints with diverse coated surfaces. The candidate bolts are dacro-coated tension control bolts, ASTM A490 bolt, and plain tension control bolts. The test parameters were coating thickness, species of coating. As for 96, 128, 168, and 226 μm thick inorganic zinc, when the coating thickness was increased, relaxation after the initial clamping rose to a much higher range from 10% to 18% due to creep of the coating. The amount of relaxation up to 7 days exceeded 85% of the entire relaxation. From this result, the equation for creep strain can be derived from a statistical regression analysis. Based on the acquired creep behavior, it is expected that the clamping force reflecting relaxation after the elapse of constant time can be calculated from the initial clamping force. The manufacturer's recommendation of inorganic zinc on faying surface as 75 μm, appears to be reasonable.

Keywords: slip critical joint; high-strength bolts; relaxation; coating; creep

1. Introduction

The clamping force of a high-strength bolt drops without any other external force or loosening of the accompanying nut immediately after tightening. It is generally known that the initial clamping force decreases sharply up to a week after application of the initial tightening (Kulak *et al*. 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 and Choi 2001). Besides the physical characteristics of the bolt itself described above, it has been shown that ambient temperature is another variable influencing the

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initial clamping force (Bickford 2008, Nah *et al*. 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 and Frank 1986, Kulak *et al*. 2001). It is known that as the coating on the faying surface becomes thicker, the clamping force of a bolt drops more severely due to the creep behavior of the coating (Frank and Yura 1981,Yang and DeWolf 2000, Kulak *et al*. 2001). After clamping high strength bolts, its pre-tension relaxation was increasing along with time, but the relaxation ratio was decreasing along with time (Hou *et al*. 2004). In case of gaskets in bolted joints, the other studies showed that the gasket creep relaxation was more important than the bolt/joint material relaxation and could not be ignored (Nassar and Alkelani 2006a, b). It was found that, after a week at temperature and subsequent cooling to room temperature, all bolts tested above 220°C showed 100% loss of prestress, whereas bolts exposed to 220°C retained around 20% of their initial prestress (Janglinski *et al.* 2007). In a similar study described above, A mathematical model was presented to predict the gasket behavior at room temperature, and an experimental procedure was established to determine the necessary gasket constants for the model (Alkerani *et al*. 2008). A loss of pretension in bolts of friction connections was monitored. To achieve a better understanding of the influences on this loss of pretension, two types of tests including relaxation are performed (Heistermann 2011).

In general, relaxation nearly stops at a step of 500 hours, while the bolt continues to constant axial force. 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. A recent study show that time dependent reduction of clamping forces of high strength bolt F13T was investigated (Jo and Seong 2009). 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 *et al*. 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 force of high strength bolt after the elapse of time. This study suggests one of models to quantitatively evaluate the induced clamping force with consideration of the relaxation of high strength bolts by coating deformation on the faying surface of slip critical bolted joints.

2. Mathematical model on relaxation

The principle factors affecting relaxation can be summarized as follows: (1) a loss of tension load resulting from elastic shortening of steel material such as with splice plates, the main plate, and the shank of a bolt; (2) creep deformation on the coated faying surface; and (3) effects of temperature of the bolt shank with the elapse of time.

A loss of initial clamping force is slightly influenced by elastic shortening, because the Young's modulus of a coating material such as zinc-rich paint is much lower than the Young's modulus of steel. For this reason, creep of the coating on the faying surface occurs long before elastic shortening of steel material. Based on the reason described above, this study is aimed at establishing a quantitative model for relaxation confined to creep behavior on the coated faying surface as time elapses.

If the creep behavior of the coating material, force equilibrium, and compatibility conditions are known, according to the correspondence principle of forces, the force (F_t) can be defined by time (t). Some mathematical approaches considering creep behavior have been derived in precedent studies (Webster 1994, Arimond and Raymond 1996). Webster studied the correlation between creep of aluminum and bolt strain by high temperature for 380 aluminum components jointed with steel bolts. Arimond's approach, meanwhile, is based on the assumption that a bolt functions as a spring with a reduced load constant; namely, the stiffness of the spring is decreased by damping force. These theories are used to establish an equation to explain the united behavior of a bolt and coated surface. Arimond proposed a mathematical model, delineated in Eq. (1), that explained the loss of clamping force as time elapsed, which results in deformation of a bolt and creep deformation of the total coating on steel plates. For estimating the induced tension force of a high strength bolt, Eq. (1) was also applied to a later study (Yang and DeWolf 2000).

$$F_t = F_o \cdot \frac{C_f + C^b}{C_f + C^b_{(t)}} \tag{1}$$

where F_t is the tension load after relaxation, F_o is the initial clamping load, C^b is the initial coating element compliance, and $C^b_{(t)}$ is the time-dependent coating element compliance. The bolt compliance C_f is the deformation of the bolt divided by the applied load. The bolt compliance can be expressed theoretically as follows

$$C_f = \frac{\sum T_{plate}}{A_{bolt} E_{bolt}} \tag{2}$$

where T_{plate} is the thickness of the steel plate, A_{bolt} is the cross sectional area, and E_{bolt} is Young's modulus of the bolt.

$$\frac{1}{E_c} = \alpha + \beta \cdot t^m \tag{3}$$

where E_c is Young's modulus of the coating, t is the elapsed time, and α, β, m are constants taken from the test results. In Eq. (3), 'm' was determined as 0.25 for the creep behavior of a general composite material (Arimond and Raymond 1996). He presented the following numerical formula for long-term relaxation related to creep of a composite material.

$$F(t) = F_o \frac{C^f + \left(\dfrac{H_o}{A_c}\right) \times a}{C^f + \left(\dfrac{H_o}{A_c}\right)\left(\alpha + \beta \cdot t^m\right)} \tag{4}$$

where C^f is the spring constant of a high strength bolt, H_o is Young's modulus for a coated material, A_c is the stress area for a high strength bolt, and 't' is the elapsed time. In the case of $d_b < D_j \leq 3\ d_b$, $T \leq 8d$, the stress area for a bolted joint is calculated with reference to Bickford and Nassar (1998).

Yang utilized Eq. (5) to calculate the required stress area

$$A = \pi/4\left[\left(d_b^2 + d_h^2\right) + \pi/8\left(\frac{D_j}{d_b} - 1\right)\left(\frac{d_b \cdot T}{5} + \frac{T^2}{100}\right)\right] \tag{5}$$

where A is the stress area for the bolted joint, d_b is the diameter of the bolt head, d_h is the diameter of the bolt-hole, D_j is the width of the plate, and T is the total thickness of the steel plates. However, for this study, in the condition of $D_j > 3\ d_b$, $T \leq 8\ d$, the stress area of the bolt was taken from the following equation presented by Bickford (1998).

$$A = \pi/4\left[\left(d_b^2 + \frac{T}{10}\right)^2 - d_h^2\right] \tag{6}$$

The following is one of the mathematical models related to the prediction of bolt forces. From Eq. (3) to estimate the long-term relaxation of bolted joints with the inorganic zinc surface, '*m*' was determined as 0.2, and the creep constants α and β from the experiment were $\alpha = 1.55 \times 10^{-3}$ and $\beta = 7.30 \times 10^{-3}$. If the variable of elapsed time is considered, the creep constant can vary as $\alpha' = 3.42 \times 10^{-12}$ and $\beta' = 1.61 \times 10^{-11}$. It was proposed that the deviation of the results from the predicted bolt forces will be smaller than ± 0.3% (Yang 1999).

$$F(t) = F_o \frac{C^f \sigma_o A + 1.55 \times 10^{-3} T}{C^f \sigma_o A + \left(1.55 \times 10^{-3} + 7.30 \times 10^{-3} t^{0.2}\right) T} \tag{7}$$

3. Test

3.1 Test program

Test specimens were fabricated as shown in Fig. 1 to investigate the relation between a modulus the elasticity and creep of coating on the faying surface. The clamping force depending on the creep behavior of the coating was measured with the elapse of 744 hours after the initial clamping force was induced. Prior to this test it was posited that a certain relation between the time dependent force and creep of coating was available. The tests depending on the time interval of 13 months were divided into two groups: joint group-1, joint group-2. For joint group-1, the test parameter was the thickness of the inorganic zinc coating on the faying surface. The required coating thickness of the faying surface was 120, 180, and 240 μm, but the actually applied thickness was different due to workmanship, as shown in Table 1. The candidate high strength bolt was a dacro-coated tension control bolt of F10T M20 on KS B 2819. The material properties of the bolts are 1,000 to 1,200 N/mm^2 tensile strength and 900 N/mm^2 yield strength.

The joint group-2 was composed to compare with the joint group-1. The test parameter of joint group-2 was the thickness, species of coating on the faying surface and species of high strength bolts as shown in Table 1. The test of joint group-2 was performed on assemblies of KS B 2819 and ASTM A490 bolts in KS SM490A steel. The physical property of bolt candidate was

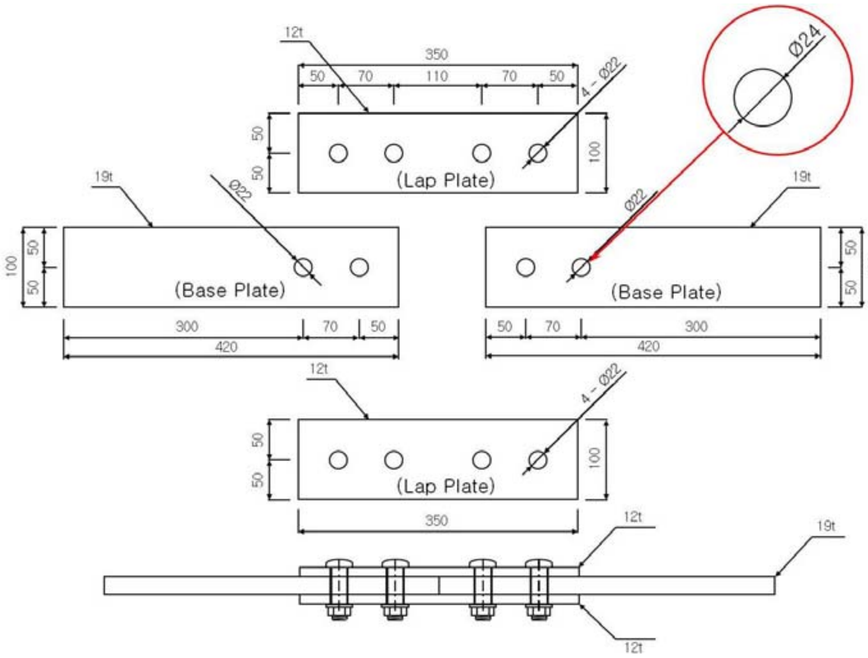

Fig. 1 Configuration of specimen

Table 1 Identification of joint specimen

Joint group	Joint specimen	Thickness (μm)		Coating species	Bolt species	Quantity		Remark
		Req'd	Actual			Joints	Bolts	
1	R2KDZ1-1	120	96	Inorganic zinc	Dacro-coated T.C. bolt	1	4	Room temperature /humidity conditions
	R2KDZ1-2	120	96	Inorganic zinc	Dacro-coated T.C. bolt	1	4	
	R2KDZ2-1	180	168	Inorganic zinc	Dacro-coated T.C. bolt	1	4	
	R2KDZ2-2	180	168	Inorganic zinc	Dacro-coated T.C. bolt	1	4	
	R2KDZ3-1	240	226	Inorganic zinc	Dacro-coated T.C. bolt	1	4	
	R2KDZ3-2	240	226	Inorganic zinc	Dacro-coated T.C. bolt	1	4	
2	R2KFP	50	65	Red lead paint	Tension control bolt *	1	4	*Constant temperature /constant humidity conditions
	R2KFZ	120	128	Inorganic zinc	Tension control bolt *	1	4	
	R2KDFP	120	125	Red lead paint	Dacro-coated T.C. bolt	1	4	
	R2AFP	120	125	Red lead paint	ASTM A490 bolt	1	4	

classified as F10T M20. The test of joint group-2 was performed on July prior to test of joint group-1. The test of joint group-1 was performed on the next June to evaluate the coating creep dependent to coating thickness in detail.

The standard joint was composed of three plates including one main plate and two lap plates, as shown in Fig. 1. The joint dimensions for the test followed the guidelines set by the Architectural Institute of Japan (2003). The dimensions of the base plate were 420 mm by 100 mm and the hole size for clamping was 24 mm. The dimensions of the splice plate were 350 mm by 100 mm. The pitch of the bolt hole was 70 mm and the edge distance was a minimum of 50 mm. The hole size for the splice plate was 22 mm, allowing a bolt diameter of 20 mm.

To measure the clamping force of high-strength bolts, strain gages were attached to each bolt shank. In some cases, washer-type load cells were also applied to the washer through each bolt shank. The sensitivity of the load cell, supplied by a Korean domestic manufacturer, is 1.345 mV/V, and its resistance is 350 Ω ± 1%. Data loggers made by Tokyo Sokki Kenkujo Co. were directly connected to the strain gages on the shank of each bolt to measure the loss of the initial clamping force induced for the group of bolts. Due to restriction of test facility, the test duration of 744 hours for joint group-1 differed from 1,000 hours for joint group-2.

3.2 Test analysis

The loss rate of bolt in tension depending on coating thickness is shown in Table 2. The test results were analyzed to accommodate the consistency of both joint group-1 and joint group-2 until 744 hours. As for joint group-1, the relaxation related to inorganic zinc exceeded 10% immediately after 168 hours. The relaxation ranged from 10.1 to 18.1% at average by 744 hours. This value is different from the mean loss, 12.4% for an approximately 127 μm galvanized coating surface measured by another researcher (Yang and DeWolf 2000). This shows that the relaxation rate depends on the coating thickness. Except for a 226 μm thick inorganic zinc coated joint (R2KDZ3-2), the initial 7 days of relaxation accounts for 91% of the total relaxation during the test duration. For 96 μm thick inorganic zinc coated joints group-1 (R2KDZ1-1, R2KDZ1-2), the clamping force of dacro-coated tension control bolt up to 168 hours was degraded with the range from 9.5% to 10.6% and the average at this stage was a 10.1% loss. The final value up to 744 hours was a 10.9% loss at average. In case of 168 μm thick inorganic zinc coated joints group-1 (R2KDZ2-1, R2KDZ2-2), the clamping force of dacro-coated tension control bolt up to 168 hours was degraded with the range from 13.2% to 15.5% and the average at this stage was a 14.4% loss. The final value up to 744 hours was a 15.7% loss at average. The loss of initial clamping force with regard to 228 μm thick inorganic zinc coated joints group-1(R2KDZ3-1, R2KDZ3-2) was from 15.5% to 16.7%, the average was a 16.1% loss at 168 hours and an 18.1% loss at 744hours.

Comparatively, for a 128 μm thick inorganic zinc faying surface of joint group-2 (R2KFZ), the clamping force of tension control bolt up to 168 hours was degraded and the average at this stage was a 10.7% loss. The final value up to 744 hours was a 12.5% loss.

For a 65 μm thick red lead painted faying joint of group-2, the relaxation ratio for 168 hours varied from 3.56% to 4.66% and the mean value was a 4.01% loss. For 744 hours, the relaxation ratio was slightly increased from 4.10% to 5.65% compared to 168 hours and the final mean value was a 4.71% loss. However, when the thickness of red lead paint was applied as nearly double from 65 μm to 125 μm, the loss of clamping force was dramatically increased. In case of a 125 μm thick red lead painted faying treatment (R2KDFP) of joint group-2, the relaxation ratio showed a 28.4% drop for 168 hours and a 32.5% drop for 744 hours. This result was nearly 7 times greater

Table 2 Relaxation results of high strength bolts

Joint group	Joint specimen	Treatment on faying surface	Coating thickness (μm)	Average relaxation (%) 168 hr.(a)	Average relaxation (%) 744 hr.(b)	(a)/(b) (%)
1	R2KDZ1-1	Inorganic zinc	96	9.5	10.1	94
	R2KDZ1-2	Inorganic zinc	96	10.6	11.6	91
		R2KDZ1 Series (Average)		10.1	10.9	93
	R2KDZ2-1	Inorganic zinc	168	13.2	14.4	91
	R2KDZ2-2	Inorganic zinc	168	15.5	16.9	91
		R2KDZ2 Series (Average)		14.4	15.7	92
	R2KDZ3-1	Inorganic zinc	226	16.7	18.3	91
	R2KDZ3-2	Inorganic zinc	226	15.5	17.9	87
		R2KDZ3 Series (Average)		16.1	18.1	89
2	R2KFP	Red lead paint	65	4.0	4.7	85
	R2KFZ	Inorganic zinc	128	10.7	12.5	85
	R2KDFP	Red lead paint	125	28.4	32.6	95
	R2AFP	Red lead paint	125	13.0	16.7	78

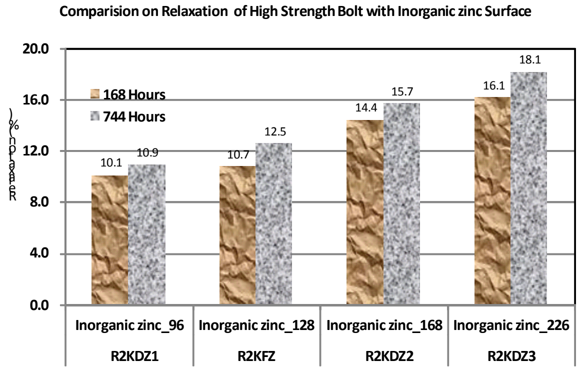

Fig. 2 Relaxation of inorganic zinc surface series

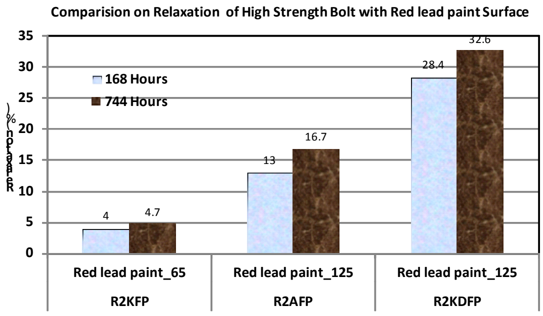

Fig. 3 Relaxation of red lead paint surface series

than 4.7% of the TC-bolted joints with the same surface conditions (R2KFP). The relaxation test for the joints clamped by dacro-coated bolts was conducted under indoor circumstances, but not in a state of constant temperature, and hence was subject to daily temperature fluctuation. For another 125 μm thick red lead painted specimen (R2AFP) of joint group-2, the clamping force by ASTM A490 bolt showed a 13.0% drop up to 168 hours, a 16.7% drop up to 744 hours. The relaxation at 168 hours amounted to 78% at 744 hours. The relaxation ratio of this joint between 168 hours and 744 hours appeared to be much lower of any other treatment on faying surface.

4. Discussion

The synthetic results subjected to faying surface parameters per each group are shown in Figs.

2 to 3. With regard to 7 joints with inorganic zinc surface series of thickness parameter as 96, 128, 168, 226 μm, it exhibited that the relaxation of high strength bolt for the first week dominated a considerable portion of the total cumulative relaxation in Table 2. The loss of the initial clamping force showed greater as the coating on faying surface was thicker as shown in Fig. 2.

In comparison with inorganic zinc series, the test for joint specimen with a 65 μm thick red lead paint (joint group-2) was performed under constant temperature and humidity environment, so the loss of bolt in tension is stable as the final mean value of 4.71% loss nevertheless coated surface. Relatively, the red lead painted joint with 125 μm coated specimens (R2KDFP, R2AFP) was conducted under indoor environment affected by temperature, humidity, and the relaxation at 744 hours was greatly different as 32.6%, 16.7% respectively. The tendency of relaxation except for 65 μm red lead painted joint, was much fluctuated not only by species of bolts, but also by coating of bolt as shown in Fig. 3. As for 125 μm coated specimens, the relaxation was influenced not only by different faying surface conditions, but also by whether the bolts were coated or not. Therefore, in case of joints such as the red lead painted surface, the guideline of ambient environment should be needed to consider creep behavior of the coating in regulating the limit of relaxation to within 10% redundancy of the direct tension.

4.1 Model for 96 μm coating for group -1

To analyze the relation between elapsed time and creep behavior with inorganic zinc thickness 96 μm on average, a descriptive statistical approach including a one-way analysis of variance, a curvilinear regression analysis was conducted with the program MINITAB. The strain of an coating derived from the test was fitted to obtain the creep formula as shown in Fig. 4. The cubic model for creep strain can be simplified as follows

$$Creepstrain_{168} = 1.0 \times 10^{-4} + 3.0 \times 10^{-5} \log_{10} t \tag{8}$$

where 't' is the elapsed time, the standard deviation (S) is 8.75×10^{-6}.

With a model, the total sum of square (TSS) is the total variation, is 3.5×10^{-6}, as shown in Table 3. The coefficient of determination (R2), is 96%, which equals the total sum of square (TSS) divided by the regression sum of square (RSS). The coefficient of determination, R^2, ranges from

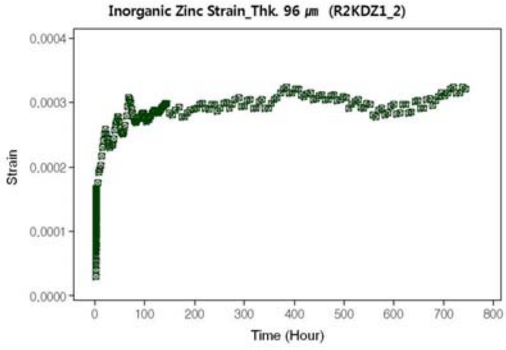

Fig. 4 Creep of inorganic zinc (t = 96 μm)

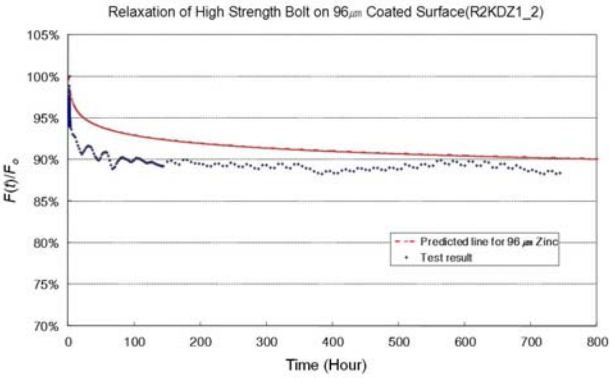

Fig. 5 Prediction and test result (t = 96 μm)

Table 3 One-way analysis of variance for coating strain (t = 96 μm)

Source	Degree of freedom	Total sum of square	Mean square	F	P
Regression	3	3.5×10^{-6}	1.2×10^{-6}	15,166	0.000
	1,694	0.1×10^{-6}	0.0×10^{-6}		-
	1,697	3.6×10^{-6}			-

‘0’ to ‘1’. As the correlation of factor between ‘time’ and ‘strain of the coating’ is higher, thecoefficient of determination is much closer to 1. On the contrary, as the coefficient of determination R^2 is nearly 0, the estimated model have less correlation between two factors. Therefore, it exhibited that 96% of the coefficient of determination described above is considerably reliable in the correlation. From the sequential one-way analysis of variance provided in Table 3, the estimated cubic model can accurately explain the variation in response under significant level (α) of 0.05.

By substituting Eq. (8), the creep formula of a 96 μm inorganic zinc layer on faying surface, into Eq. (4), the following mathematical model for the long-time relaxation of slip critical joints can be derived

$$F(t)_{96} = F_o \frac{C^f + \left(\frac{H_o}{A_c}\right) \times 1.0 \times 10^{-4}}{C^f + \left(\frac{H_o}{A_c}\right)\left(1.0 \times 10^{-4} + 3.0 \times 10^{-5} \log_{10} t\right)} \tag{9}$$

Fig. 5 presents a comparison of the time-dependent curve between the mathematical model from Eq. (9) and the test results. The test results show a sudden drop of clamping force before the elapse of 100 hours when compared with the predicted line. However, the gap between the trend line curve and the actual plot diminished gradually as time elapsed. The two lines were synchronized at nearly 500 hours.

4.2 Model of 168 μm coating for group -1

The relaxation after the initial clamping force was 13.2% at 168 hours and 14.4% at 744 hours. With respect to the test duration, the relaxation rate was governed during the first week for a 168 μm thick inorganic zinc layer as 96 μm. The regression equation derived from a curvilinear regression analysis of coating strain shown in Fig. 6 is as follows

$$Creepstrain_{168} = 2.0 \times 10^{-4} + 4.0 \times 10^{-5} \log_{10} t \tag{10}$$

where t is the elapsed time, the standard deviation (S) is 1.41×10^{-5}.

The Table 4 shows that the coefficient of determination, (R^2), is 95%, which equals the total sum of the square divided by the regression sum of the square. When substituting Eq. (10), drawn from a regression analysis on the creep of a 168 μm coating, into Eq. (4), the following quantitative model for time dependent clamping force can be derived

Table 4 One-way analysis of variance for coating strain (t = 168 μm)

Source	Degree of freedom	Total sum of square	Mean square	F	P
Regression	3	7.4×10^{-6}	2.5 × 10-6	12,296	0.000
Error	1,709	0.3×10^{-6}	0.0 × 10-6	-	-
Total	1,712	7.7×10^{-6}	-	-	-

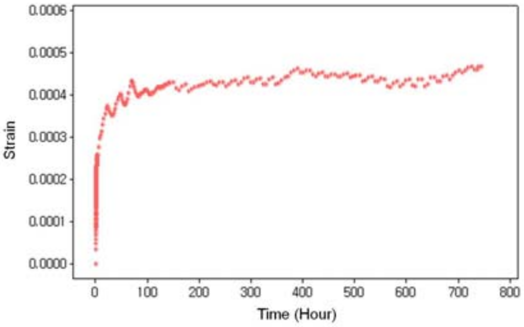

Fig. 6 Creep of Inorganic zinc (t =168 μm)

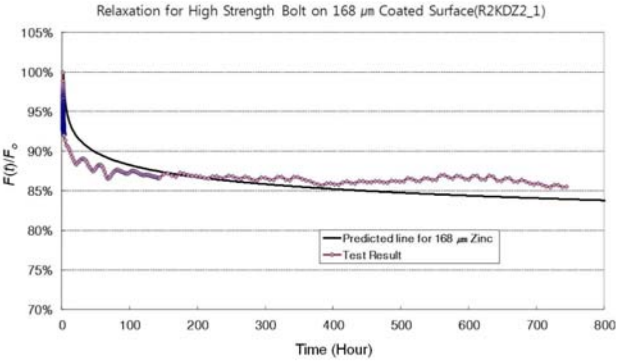

Fig. 7 Prediction and test results (t =168 μm)

$$F(t)_{168} = F_o \frac{C^f + \left(\dfrac{H_o}{A_c}\right)\times 2.0\times10^{-4}}{C^f + \left(\dfrac{H_o}{A_c}\right)\left(2.0\times10^{-4} + 4.0\times10^{-5}\log_{10} t\right)} \tag{11}$$

The regression curve was estimated from the correlation between elapsed time and creep as shown in Fig. 6. Fig. 7 shows a comparison between the mathematical model from Eq. (10) and the test results. Compared with the predicted line, the test result displays a sudden drop of clamping force by roughly 4 days. However, the gap between the trend line and the test result was lessened gradually and the two lines were synchronized as 200 hours passed.

4.3 Model for 226 μm coating for group -1

As the coating on the faying surface becomes thicker, the creep rate of the coating becomes larger. Eventually, this results in greater loss of clamping force for a high strength bolt. Similar to the different coating kinds, creep strain for the 226 μm inorganic zinc layer was taken from one way analysis of variance, as shown in Table 5. To obtain the mathematical equation correspondent to Eq. (4), an equation of coating strain measured from the test was derived by a regression analysis as follows

$$Creepstrain_{226} = 3.0\times10^{-4} + 4.5\times10^{-5}\log_{10} t \tag{12}$$

where the standard deviation is 2.16×10^{-5} and the coefficient of determination, R^2, is 96.4%.

Table 5 One-way analysis of variance for coating strain (t = 226 μm)

Source	Degree of freedom	Total sum of square	Mean square	F	P
Regression	3	6.9×10^{-6}	2.3×10^{-6}	4,898	0.000
Error	547	0.3×10^{-6}	0.0×10^{-6}	-	-
Total	550	7.2×10^{-6}	-	-	-

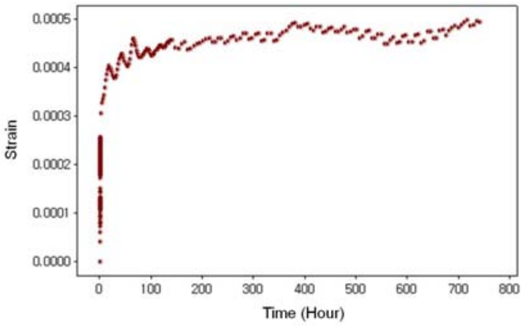

Fig. 8 Creep of inorganic zinc (t = 226 μm)

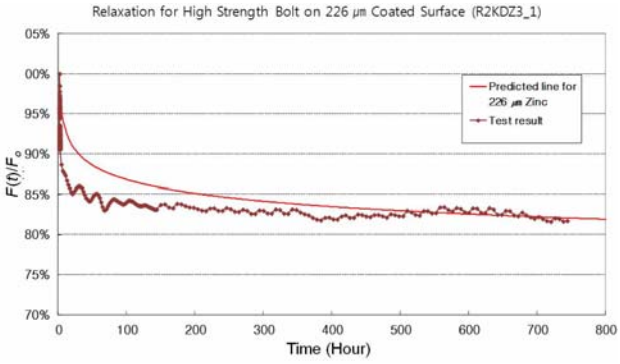

Fig. 9 Predicted line and test results (t = 226 μm)

Substituting the creep strain obtained from Eq. (12) into a mathematical model, the long-term clamping force of a high strength bolt can be estimated as follows

$$F(t)_{226} = F_o \frac{C^f + \left(\dfrac{H_o}{A_c}\right) \times 3.0 \times 10^{-4}}{C^f + \left(\dfrac{H_o}{A_c}\right)\left(3.0 \times 10^{-4} + 4.5 \times 10^{-5} \log_{10} t\right)} \tag{13}$$

The creep curve of a bolted joint with a 226 μm zinc primer is shown in Fig. 8. A comparison between the ideal model of Eq. (13) and the test results are shown in Fig. 9.

4.4 Model for 128 μm coating for group -2

The loss rate after the initial clamping force was 7.3% at 168 hours and 8.3% at 744 hours. Differently from group-1, the test of group-2 including this joint was performed at the13 months prior to performing the test of group-1. So the tendency of relaxation was slightly different from the trend curve of relaxation of group-1 due to ambient temperature, humidity and difference of indoor test facility. With respect to the test duration, the loss rate in bolt tension was governed during the first day for a 128 μm thick inorganic zinc layer as the same as relaxation of group-1. The loss of clamping force was begun to diminish after the elapse of 105 hours. During the remaining 640 hours the loss induced bolt load decreased in an exponential manner. The creep strain of the coating on faying surface shown in Fig. 9 can be taken statistically by regression analysis using MINITAB program as follows

Table 6 One-way analysis of variance for coating strain (t = 128 μm)

Source	Degree of freedom	Total sum of square	Mean square	F	P
Regression	3	1.3×10^{-5}	4.3×10^{-6}	18,128	0.000
Error	2,301	0.6×10^{-6}	0.0×10^{-6}	-	-
Total	2,304	1.3×10^{-5}	-	-	-

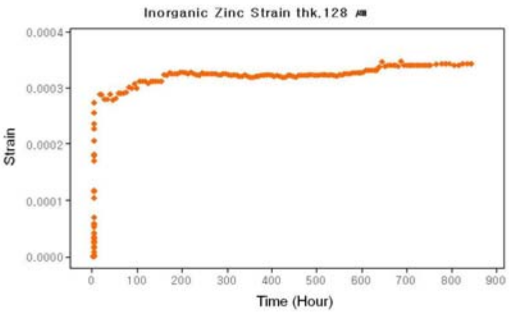

Fig. 10 Creep of inorganic zinc (t = 128 μm)

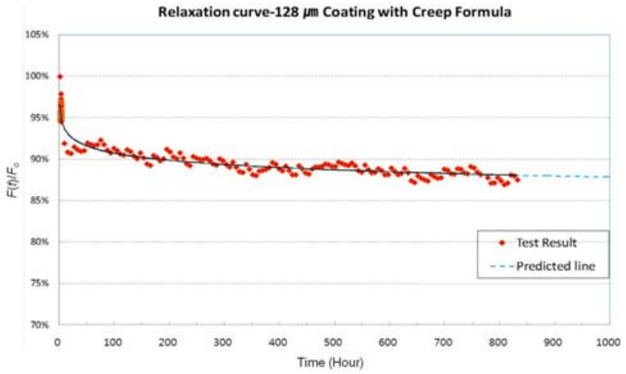

Fig. 11 Predicted line and test results (t = 128 μm)

$$Creepstrain_{128} = 1.0 \times 10^{-6} + 2.0 \times 10^{-4} \log_{10} t \tag{14}$$

where t is the elapsed time, the standard deviation is 1.54×10^{-5}

The Table 6 shows that the coefficient of determination, R^2, is 95%, which equals the total sum of the square divided by the regression sum of the square. When substituting Eq. (14), drawn from a regression analysis on the creep of a 128 μm coating, into Eq. (4), time dependent clamping force of high strength bolt is derived from the following equation

$$F(t)_{128} = F_o \frac{C^f + \left(\frac{H_o}{A_c}\right)\left(-1.0 \times 10^{-6}\right)}{C^f + \left(\frac{H_o}{A_c}\right)\left(-1.0 \times 10^{-6} + 2.0 \times 10^{4} \log_{10} t\right)} \tag{15}$$

The regression curve was estimated from the correlation between elapsed time and creep as shown in Fig. 10. Fig. 11 shows a comparison between the mathematical model from Eq. (10) and the test results. Compared with the predicted line, the test result displays a sudden drop of clamping force as 9.3% by 24 hours. The difference between the predicted line and the test result was synchronized as 100 hours passed.

4.5 Recommendation

In the case of high strength bolts on a coated faying surface, the induced clamping force of a bolt can be estimated by analyzing the creep of the coating on the faying surface. From the test

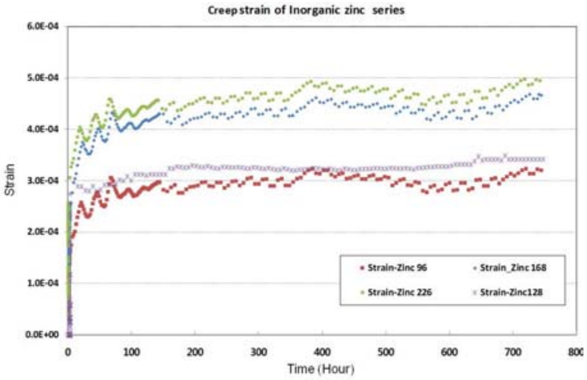

Fig. 12 Integrated test results of creep strain

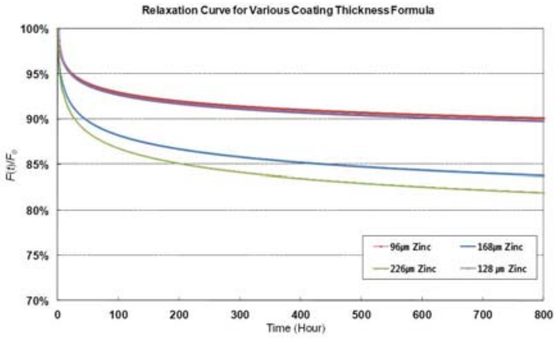

Fig. 13 Prediction of relaxation by coating thickness

Table 7 Creep constant for estimating of bolt in tension

Coating on faying Surface of a bolted joint	α	β
96 μm thick inorganic zinc	1.0×10^{-4}	3.0×10^{-5}
128 μm thick inorganic zinc	-1.0×10^{-6}	2.0×10^{-4}
168 μm thick inorganic zinc	2.0×10^{-4}	4.0×10^{-5}
226 μm thick inorganic zinc	3.0×10^{-4}	4.5×10^{-5}

results, the high strength bolts clamped on 96 μm and 128 μm thick coated joints were at a losswithin the range from 10.1% to12.5%, this loss rate is reasonable in comparison with 12% referred to the precedent guideline that the relaxation characteristics of assemblies of galvanized plates and bolts were about twice as great as plain bolts and connected material (Yang and DeWolf 2000, Kulak *et al*. 2001). However, the high strength bolts clamped on 168 μm and 226 μm thick coated joints are predicted to show at least 15% loss of the initial clamping force. The actual creep strain curves per a coating thickness were integrated as shown in Fig. 12, and the predicted relaxation curves considering creep behavior of coating can be suggested in Fig. 13. Consequently, Even the joint specimen with a 96 μm thick coating did not meet the guideline that the clamping force of a high strength bolt should be applied to the design bolt load plus 10% redundancy due to relaxation. Based on the test results, a roughly 75 μm thick to 100 μm thick inorganic zinc coating on a faying surface is critical to slip resistant joints in practice, and the general guideline that the limit of inorganic zinc on faying surface is 75 μm, appears to be reasonable. The clamping force first exerted by bolt on the joint is affected by temperature (Bickford 2008, Nah *et al*. 2009a, b). This study does not consider the creep testing at temperature equivalent to the actual temperature of the steel in service. Further research to determine the influence of temperature regarding creep shall be needed.

It is recommended that Eq. (14) or Eq. (15) should be used to estimate the clamping force considering relaxation on the faying surface as a function of the coating thickness parameter; the 96 μm thick coating was a control specimen, the 128 μm thick coating specimen showed 1.1 times of the initial clamping force, 168 μm thick specimen showed 1.7 times loss of the initial clamping force when compared to the control specimen. The 226 μm thick specimen displayed 2.3 times loss of the initial clamping force relative to the control specimen respectively. From the test results, Eq.

(8), (10), (12), and Eq. (14) can be arranged to calculate the creep strain from time, *t*. The creep constant obtained by a curvilinear regression analysis was as provided in Table 7.

$$Creep = \alpha + \beta \cdot \log_{10} t \tag{16}$$

5. Conclusions

This study established a quantitative model for estimation of the induced clamping force and relaxation of bolted joints with an inorganic zinc faying surface. The candidate bolt is a F10T M20 dacro-coated tension control bolt. The parameter of coating thickness was varied as 96, 128, 168, and 226 μm on the faying surface. As the thickness of the surface coating was increased, the relaxation ratio varied within a range of 10% to 18%. It was exhibited that the amount of relaxation up to 7 days exceeded 85% of the entire relaxation; this result accords closely with the findings of a study conducted by Kulak *et al.* (2001).

From the test results, inorganic zinc lower than 96 μm thickness on the faying surface can be applied to slip resistant joints in practice. Regardless of the type of coating on the faying surface, the equation for creep strain can be simplified as the following logarithmic function: $Creep = \alpha + \beta \cdot \log_{10} t$.

Based on the acquired creep behavior, the clamping force reflecting relaxation after the elapse of time, $F(t)$, can be suggested when the initial clamping force (F_o), is obtained as follows

$$F(t) = F_o \frac{C^f + \left(\dfrac{H_o}{A_c}\right) \times \alpha}{C^f + \left(\dfrac{H_o}{A_c}\right)\left(\alpha + \beta \cdot \log_{10} t\right)}$$

From test results, a roughly 75 μm thick to 100 μm thick inorganic zinc coating on a faying surface may be critical to induce the required tension load to slip resistant joints in practice. Korean manufacturer's recommendation of inorganic zinc on faying surface as 75 μm, appears to be reasonable.

The loss of clamping force on red lead paint joint specimen was as follows: The specimen with a 65 μm thick red lead paint was performed under constant temperature and humidity environment, so the loss of bolt in tension is stable as the final mean value of 4.71%. The tendency of the relaxation between red lead painted joints with 125 μm coated specimens was much different as 16.7%, 32.6% respectively under indoor environment only. This is why the loss of bolt in tension was much fluctuated not only by species of bolt, but also by coating of bolt. In addition, the relaxation was influenced by different faying surface condition and by whether the bolts were coated or not. The guideline of ambient environment should be needed to consider creep behavior of the coating in regulating the limit of relaxation to within 10% redundancy of the direct tension.

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