Long-Term Slip Resistance of Metallized Faying Surfaces used with High Strength Bolted Connections

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Abstract: Metallizing is becoming a commonly used corrosion protection solution for steel bridge members. Bridge designers need to know the slip resistance of metallized faying surfaces in order to eliminate the currently costly and time-consuming practice of masking off connection faying surfaces before metallizing. The slip resistance evaluation involves essentially two major processes. Firstly, short-duration static load tests are conducted to determine the mean slip coefficient. If the evaluated slip coefficient values are found to be satisfactory, long-term sustained tension creep tests are required to quantify the effect of creep on the slip resistance of the coated surfaces. A post-creep slip test is finally carried out as part of the evaluation. Earlier tests have revealed significant slip coefficients for metalized faying surfaces beyond those specified by North American design standards for uncoated blast-cleaned surfaces. The present study evaluates the long-term sustained tension creep performance of metallized faying surfaces used with slip-critical connections. Results of this study have shown a very good performance for slip and creep. This will likely to influence future code revisions and impact steel bridge fabrication in North America.

1 INTRODUCTION

1.1 Context of the Study

Steel bridge elements are exposed to harsh conditions from ambient environment and human activities such as the spread of salt on roadways. Durability of structures can be significantly improved by applying a surface coating that provides a protection against wear and corrosion. Nowadays, metallization, a term commonly used to describe thermal spray metal coatings of zinc or aluminium alloys, of steel bridge members is a popular way to protect the structural integrity of these members while reducing the number of maintenance cycles. The sacrificial action of the zinc or aluminum alloys produces an efficient protection against corrosion (Bayliss and Deacon 2002). The metallized coating also produces zero volatile organic compound emission (Chang et al. 1999).

Bolted joints may be either bearing connection or slip-critical connection. In bearing connections, the applied load is transferred through the bolt to the connected members, and the resistance is governed by bolts shear or plates in bearing against the bolts. Consequently, the conditions of the surfaces of the connected members do not affect the resistance of the joint. However, when the connection is subjected to load reversal or fatigue as in bridges, slip-critical connections are required. In this joint type, the load is transmitted by friction of the faying surfaces of the connected elements and slip in the connection is prohibited at the serviceability limit state. The friction is developed by the clamping action of the bolts on the connected members. Thus, the preparation of the surfaces is a critical parameter for the resistance of the joint. If the slip resistance of the joint is reached, the joint slip into bearing. The slip resistance (V_s) of slip-critical connections can be obtained from:

$$V_s = k_s \times m \times \sum_{i=1}^{n_b} F_{bi} \quad [1]$$

where k_s is the slip coefficient of the faying surfaces, m is the number of slip planes, n_b is the number of bolts and F_{bi} is the bolt preload in bolt i. The magnitude of the bolt preload is required to evaluate the slip resistance. According to the Specification on Structural Joints using High-Strength Bolts, published by the

Research Council on Structural Connection (RCSC 2009), hereafter named RCSC bolt specification, the minimum bolt preload must be equal to 70% of the tensile strength of the bolt for slip-critical connections.

The slip coefficient k_s of the faying surfaces is an important parameter in the evaluation of the slip resistance. The value of k_s depends on the preparation and condition of the faying surfaces. The Canadian standard CAN/CSA-S06-06 (CSA 2006) specifies slip coefficients for three faying surface conditions, namely clean mill scale or blast-cleaned with Class A coatings; blast-cleaned or blast-cleaned with Class B coatings, and Hot-dip galvanized with wire brushed surfaces. The corresponding slip coefficients are 0.33, 0.5 and 0.4 respectively. The AISC Specifications (AISC 2010) on the other hand provide mean slip coefficients for two steel surface classes, namely unpainted clean mill scale or blast-cleaned with class A coatings ($k_s = 0.30$) and unpainted blast-cleaned surfaces or blast-cleaned surface with class B coatings ($k_s = 0.5$). Other standards such as the Eurocode 3: Design of Steel Structures, Part 1.8: Design of Joints (2005) describe similar surface conditions with their associated slip factors.

Design standards do not specify slip coefficient for metallized faying surfaces. Bridge fabricators are compelled to mask off all faying surfaces before metallizing (see Figure 1). This process is therefore time consuming and laborious intensive. Moreover, touch-ups of exposed areas are often required after assembling. The work associated with masking can be eliminated if coated faying surfaces are appropriately characterized in light of the prevailing design standard for slip-critical joints. Appendix A of the RCSC bolt specification (RCSC 2009) provides a widely used methodology to determine the slip resistance of a coated faying surface. This method consists of two parts: the first is a short-duration static test to determine the mean slip coefficient. If the mean slip coefficient is found to be satisfactory, a long-term sustained tension creep test is carried out ensure that the coating will not undergo significant creep. In general, the slip coefficient value depends on the characteristics of the coating, i.e. the thickness and its composition.

Chiza et al. (2013) conducted a number of short duration slip tests to evaluate the mean slip coefficient for zinc-based metallized faying surfaces used with high strength bolted connections. A number of important parameters were investigated, e.g. coating thickness, bolt preload, plate sizes and substrate preparation. In the present study, creep tests are conducted under sustained tension service-load. At the end of the creep test, the load is increased in order to verify if the loss of clamping force in the bolt reduces the slip load below that associated with the design slip coefficient.

Figure 1: Masking off the faying surfaces in shop

1.2 Nomenclature

Table 1 contains the parameters of the specimens tested. Each specimen has been identified following the variables used in Table 1. For example, specimen 6m-70 refers to a faying surface with a 6 mils thick zinc-metallized coating and a preload equal to 70% of the tension capacity of the bolt.

Table 1: Important parameters

#	Parameters	Variables
1	Thickness of coating	6m - 6 mils 12m - 12 mils
2	Clamping force	70 - 70% of bolt capacity 90 - 90% of bolt capacity

1.3 Short-Term Static Loading Tests Results

Static short-term tests were conducted by Chiza et al. (2013) following appendix A of the RCSC bolt specification (RCSC 2009). Slip coefficients of zinc-metallized faying surfaces for 5/8 inch thick plates were obtained and are presented in Table 2. For each set of parameters, results were obtained for five replicates. The mean slip coefficients are also shown in Table 2, together with the standard deviations. The mean slip coefficient of 0.91 was obtained for 12 mils metallized coating thickness with a 90% bolt preload. When the bolt preload is reduced to 70%, the mean slip coefficient was observed as 0.85 for 12 mils metallized coating thickness. For a 70% bolt preload, the mean slip coefficient was obtained as 0.82 for a 6 mils metallized coating thickness. These results are significantly greater than the specify slip coefficient of value of 0.50 for Class B faying surfaces by both Canadian and American standards.

Table 2: Results of short-term static loading test

Specimen	k_1	k_2	k_3	k_4	k_5	$k_{average}$	Standard deviation
6m-70	0.88	0.81	0.77	0.80	0.84	0.82	0.04
12m-70	0.80	0.76	0.91	0.92	0.86	0.85	0.07
12m-90	0.89	0.89	-	0.91	0.94	0.91	0.02

2 EXPERIMENTAL PROGRAM

2.1 Specimen Characteristics and Preparation

Test assemblies were machined from 5/8 inch thick steel plates, grade 350AT. The plate dimensions were chosen in accordance with the RCSC bolt specification (RCSC 2009). An assembly consists of three identical steel plates (a middle plate and two lap plates) clamped together using a 7/8 inch diameter A490 high strength bolt. A test setup consists of three assemblies connected in series. The 1-inch bolt-hole diameter prescribed by the specification allowed for sufficient clearance required for slip or significant creep to occur during testing. The test plates were fabricated and zinc-metallized in the shop under controlled environmental conditions. Burrs were removed before metallizing.

Thermal spray coating was applied from a zinc wire through an electric arc in accordance with SSPC-CS 23.00/AWS C2.23M/NACE No. 12 (SSPC/AWS/NACE 2003). The steel substrate for each plate was prepared to white metal finish SSPC-SP 5 and the angular profile depth was measured to ensure compliance. All plates were coated on both sides. Thus, there are six layers of coating between the bolt head and the nut in each assembly. Thickness of the coating was measured with a Positector magnetic gage on each test plate in order to mate plates with similar average coating thickness. Five different readings were taken on each plate faying surface in accordance with the Society for Protective Coatings SSPC-PA 2 (SSPC 2012) standard and the average thickness was determined. Table 3 presents the nominal coating thicknesses as well as the range of thicknesses measured for each specimen.

Table 3: Test and thickness of the coating

Specimen I.D.	No. of specimens	Nominal coating thickness [mils]	Range of thickness [mils]	Average thickness [mils]	Standard deviation
6m-70	3	6	6.4 - 7.7	7.3	0.5
12m-70	3	12	12.1 - 13.4	12.5	0.4
12m-90	3	12	12.0 - 12.9	12.4	0.3

2.2 Tension Creep Tests

Each specimen consists of a double lap joint and three specimens are pinned in series. Figure 2 shows a special device fabricated to facilitate the assembling of the plates before testing. The device permits the creation of the necessary clearance in the bolt hole to permit a maximum slip or creep to occur.

Figure 2: Assembly of the specimens

The applied clamping force or bolt preload needs to be known since it is an important parameter in the evaluation of the slip resistance of the joint (see Equation 1). In this research, the bolt preload was manually applied by using a hand-held ratchet to reproduce the field practice. This was continuously monitored from the time of assembly through to the end of testing by using a carefully calibrated washer-type load cell of 500 kN Omega installed in series with the clamped test plate assembly. The calibration was made in accordance with the manufacturer's specification using a 1500 kN MTS hydraulic Universal Testing Machine. A special washer was designed and used in series with the plate assembly to simulate the pressure transmitted on the test plates with a structural washer. ASTM A490 high strength bolts were used as recommended by the RCSC bolt specification (RCSC 2009).

Tension creep tests were performed on a 500 kN MTS hydraulic Universal Testing machine as shown in Figure 3. For each specimen, the relative displacement between the middle plate and the two lap plates was measured using two MTS extensometers, on each side of the assembly. The displacement recorded is the average of the two measurements. Creep deformation measurements were recorded after the first 30 minutes of loading and measurements continued under sustained tension loading for 1000 hours in compliance to the RCSC bolt specification (RCSC 2009). The sustained tension load applied during the test is the service load calculated according to equation 5.7 of the RCSC bolt specification (RCSC 2009):

[2] $$\mathrm{Service\ Load} = \mathrm{k_s} \times \mathrm{D} \times \mathrm{T_m} \times \mathrm{N_b} \times m$$

where k_s is the design slip coefficient, D is a slip probability factor (equal to 0.80), T_m is the minimum bolt pretension specified (equal to 218 kN for A490 bolts), N_b is the number of bolts (equal to 1 in the present tests), and m is the number of slip planes (equal to 2). The design slip coefficient selected for this study is 0.50. This was to verify whether the metallized coating can achieve a Class B by North American standards. A data acquisition system was used to monitor and record the applied loading, the extensometers measurements and the load cells measurements.

Figure 3: Test setup

According to the RCSC bolts specification (RCSC 2009), the acceptable creep deformation is 0.127 mm (0.005 inch) or less. The assembly was subsequently loaded in tension up to a load that is equal to the average clamping load times the design slip coefficient times the number of slip planes (= 2). If the average slip deformation that occurs at this load level is less than 0.381 mm (0.015 inch) for three specimens, the assemblies with zinc-metallized faying surfaces tested are considered to meet the requirements for the Class B design slip coefficient. If any of the above two requirements are not respected, the zinc metallized coating is considered to have failed for the specified Class B slip coefficient and a new test can be performed with a lesser design slip resistance.

3 RESULTS AND DISCUSSIONS

A total of 3 creep tests, consisting of 9 metallized specimens, were conducted in this study. For each set of parameters studied, three identical specimens were tested in series in a single column. By continuously monitoring the bolt-clamping load in each assembly from the clamping of the plates to the post-creep slip test, it was possible to evaluate the long-term relaxation of the coating. Table 4 shows the average relaxation which occurred during the creep test for each set of parameters studied. It is evident that there is an increased relaxation with increasing thickness of coating. Specimens with 12 mils thick metallized coating with a bolt preload of 70% of bolt tension capacity underwent a greater relaxation, nearly twice as much as specimens with 6 mils thick metallized coating under the same bolt preload.

Table 4: Average test relaxation

Specimen	Mean test relaxation [%]
6m-70	6.42%
12m-70	13.74%
12m-90	9.57 %

Figure 4 shows the average clamping force over time for each set of specimens. It is evident that the loss of clamping force is larger for thicker coatings. Also, the loss of clamping force is observed to occur mainly in the first 100 hours of the test. After this time, the clamping force remains almost constant
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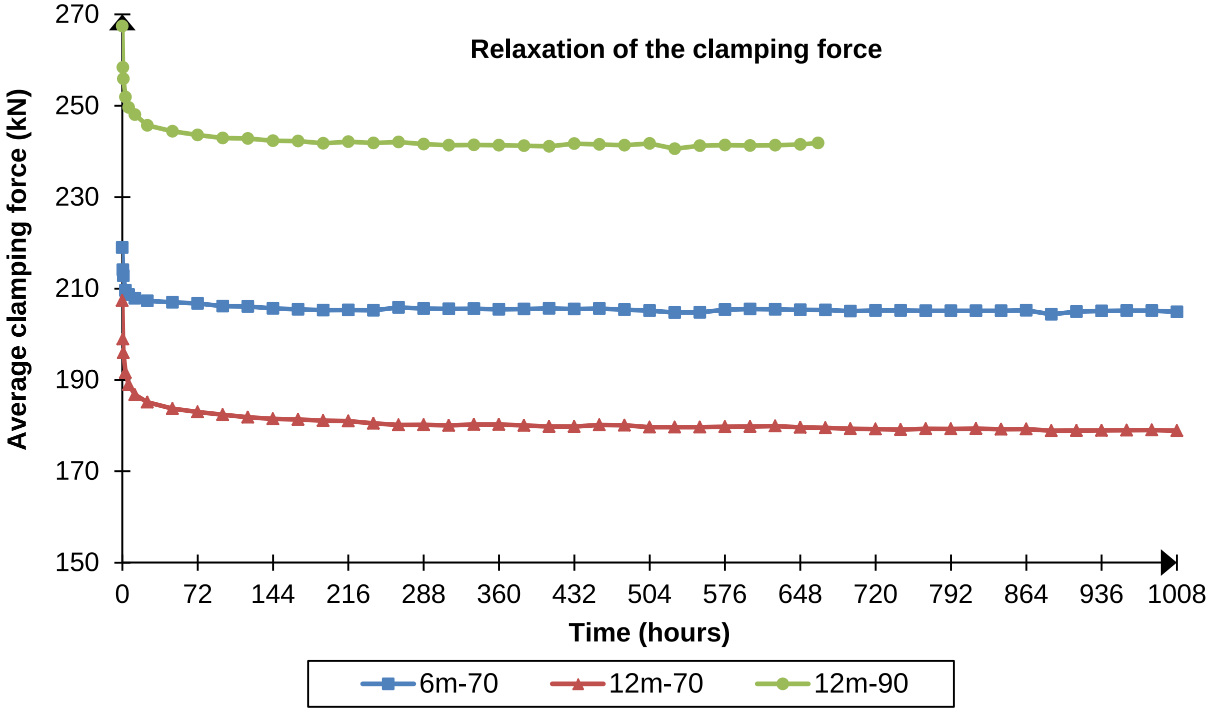

Figure 4: Average clamping force over time

As indicated in Equation 2, the sustained tension service load applied to the assemblies is function of the slip coefficient. The target slip coefficient was selected as 0.50, a Class B category according to the North American standards.

Figure 5 shows the average connection slip between 30 minutes and 1000 hours of testing, also referred to as creep deformation. Also shown on this figure is the creep deformation limit specified by RCSC bolt specification (RCSC 2009). Clearly, all the specimens considered in the study passed the creep test.

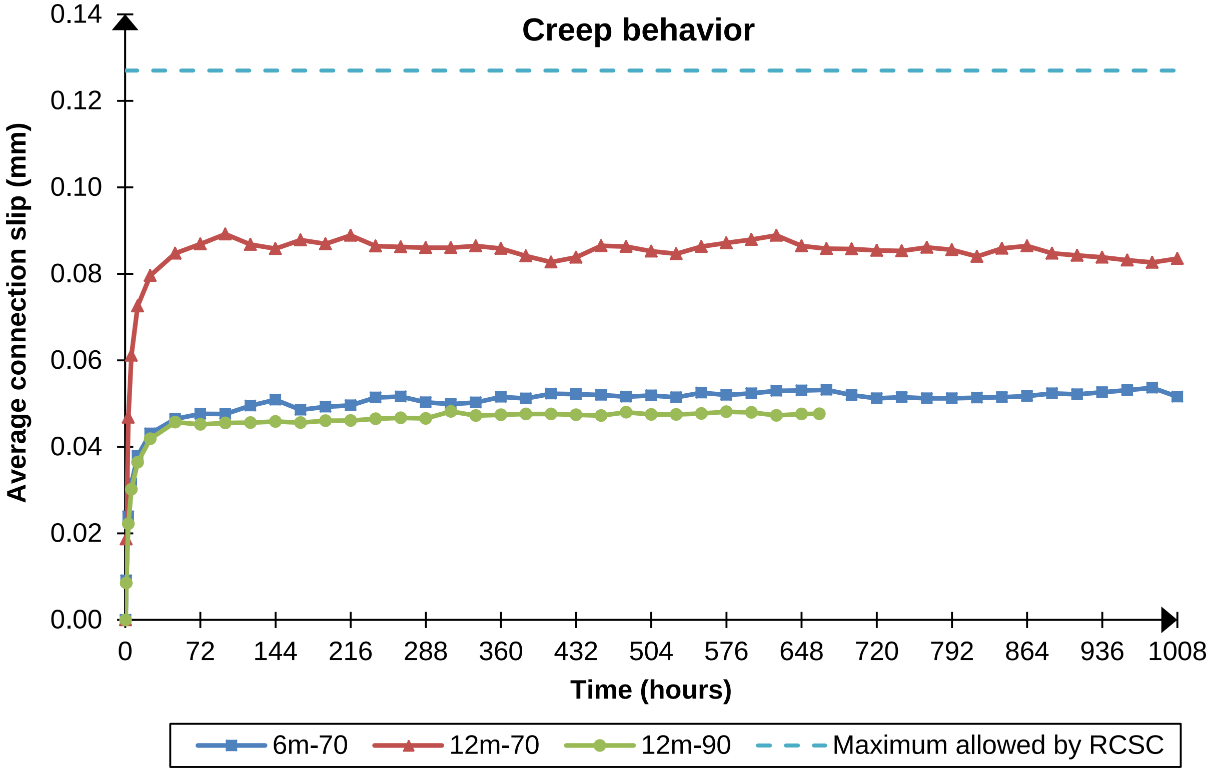

Figure 5: Average connection slip under the tension sustained load

Table 5 contains the creep deformation recorded for each assembly. In each case, the metallized coating yielded a good creep performance and fell within the limit of 0.127 mm (0.005 inch) prescribed by the RCSC bolt specification (RCSC 2009) for Class B. The largest creep deformation obtained was 0.0991 mm, which occurred in the 12 mils thick metallized coating and a bolt preload equal to 70% of the bolt tension capacity. This creep deformation is equal to 78% of the specified limit. For the 6 mils thick coating, the largest creep deformation obtained was 0.0570 mm.

It is observed that the test conducted for specimens 12m-90 was accidentally terminated at 665 hours of testing. However, based on the results of the other tests which were completed, the creep deformation observed for this test is nearly conclusive. Comparing the creep deformation of the 12 mils thick metallized coatings with clamping force of 70% and 90% of bolt tension capacity, it does appear that a higher level of bolt preload leads to a lesser creep deformation. The least creep displacement was obtained as 0.0483 mm for the 12 mils specimens clamped at 90% of the bolt tension capacity, and was obtained as 0.0991 mm for those clamped at 70% of the bolt tension capacity.

When loaded to the design slip load at the end of the creep test, all the test assemblies increased only slightly in deformation. The maximum average final deformation was obtained as 0.0934 mm representing the 12 mils thick metallized coating and 70% bolt preload. This was within the limit of 0.381 mm (0.015 inch) specified by the RCSC. For the 6m-70 and 12m-70 specimens, the average increase of deformation during the post-creep slip test was 0.0084 mm and 0.0104 mm respectively.

Table 5: Tension creep results

Test	Assembly	Creep deformation [mm]	Reload to design slip load [mm]	Average final deformation [mm]
6m-70	1	0.0449	0.0613	0.0682
	2	0.0570	0.0749	
	3	0.0556	0.0685	
12m-70	1	0.0702	0.0848	0.1012
	2	0.0798	0.0999	
	3	0.0991	0.1189	
	4	0.0845[1, 2]	---	---
12m-90	1	0.0483[1]	---	---
	2	0.0470[1]	---	

[1] Deformations took at 665 hours.
[2] Third assembly of 12m-90 clamped at 70% of bolt capacity instead of 90% due to a difficulty in laboratory.

It is observed from Table 5 that data for the final post-creep test for specimen 12m-90 is not available since the test was terminated early at 665 hours. The termination, however, resulted in an instantaneous rise of the hydraulic tension load until failure of all the specimens. When this happened, the loose bolt (bolts hand tightened) in contact with the plates between the assemblies caused the failure of the plates, and the pretensioned bolt in each slip-critical connection did not slip into bearing against the plates. Figure 6 and Figure 7 show the faying surface after testing of two different specimens. For the test that was aborted (Figure 7), the middle plate yielded on the side of the bearing connection (loose bolt) and the bolt did not touch the plate on the side of the slip-critical connection (pretensioned bolt). Thus, the ultimate limit state of the connection was reached before the limit state of serviceability.

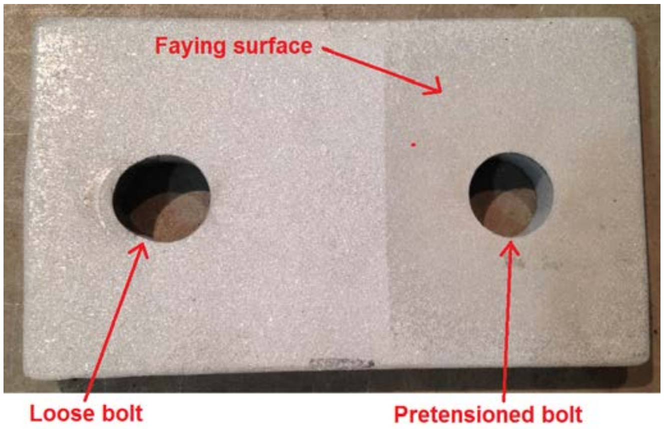

Figure 6: Typical faying surface of a middle plate after creep test - 12m-70

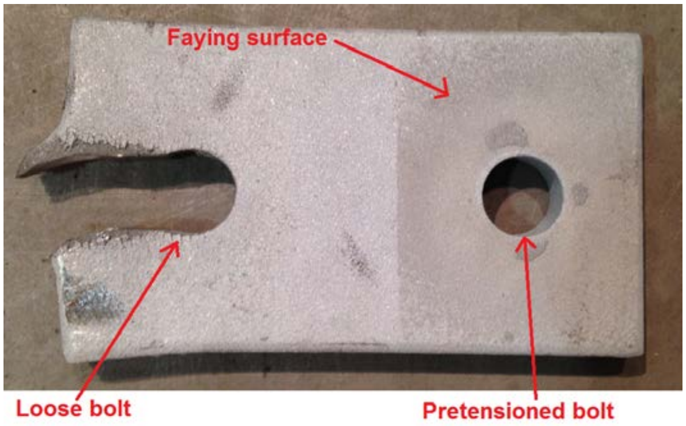

Figure 7: Faying surface of a middle plate after the yielding of the middle plate due to the rise of the hydraulic load – 12m-90

4 CONCLUSIONS

Slip resistance in steel bridge connection is critical when the structure undergoes repeated or reversal of loads. As metallization is becoming a commonly used corrosion protection method for steel bridge members, designers need to know the slip coefficient of zinc-metallized faying surfaces to be used. In this study, long-term creep performance is evaluated for metallized coating following Appendix A of the RCSC bolt specification (RCSC 2009). Overall, test results showed a good creep performance of the metallized faying surfaces for a Class B slip resistance. More specific conclusions are summarised as follows:

1. The metallized faying surfaces exhibited very good creep performance for both 6 and 12 mils coating thickness for a design slip coefficient of 0.50. Class B of both the Canadian and American design standards is therefore respected for these surfaces.
2. Creep performance was similar for the two coating thicknesses considered in this study.
3. Relaxation in the bolts increased with increasing coating thickness.
4. Relaxation of the bolt clamping force and creep deformation occurred in the first 100 hours; thereafter, no significant creep deformation was observed.

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