# LONG-TERM CREEP PERFORMNCE OF METALIZED FAYING SURFACES USED WITH SLIP-CRITICAL BOLTED CONNECTIONS

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## BIOGRAPHY

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## SUMMARY

Metalizing is evolving as a versatile corrosion protection solution for steel bridges, and designers need to know the slip resistance of metalized faying surfaces in order to eliminate the currently costly and time-consuming practice of masking off connection faying surfaces before metalizing. Will research indicating satisfactory short and long-term slip performance influence future code revisions and improve steel bridge fabrication in North America?

The present study builds on previous short duration slip tests, to evaluate the long-term creep performance of metalized faying surfaces used with slip-critical connections under sustained tension loading for the set of critical parameters of coating thickness, bolt type and bolt preload.

# LONG-TERM CREEP PERFORMANCE OF METALIZED FAYING SURFACES USED WITH SLIP-CRITICAL BOLTED CONNECTIONS IN STEEL BRIDGES

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## Abstract

Metallizing is evolving as a versatile coating solution for steel bridge elements and has seen increased recognition by multiple transportation agencies, including the U.S. Federal Highway Administration (FHWA) and the Canadian ministère des Transports du Québec. Metalizing is a term commonly used to describe the practice of thermally spraying molten zinc, aluminium or zinc/aluminium alloy on surfaces of exposed steel elements to provide both physical barrier and effective sacrificial protection through galvanic action. In order to derive the maximum benefits from metallizing, bridge designers need to know the slip resistance of metallized faying surfaces required to develop slip-critical connections in the bridge structure. This will help eliminate the current labor-intensive, time-consuming and costly practice of masking off all connection faying surfaces to preserve their conditions prepared in accordance to prevailing design standards. The broad research goal is to characterize the slip resistance of metallized faying surfaces used with slip-critical connections in view of North American design standards. The present research aims at building on previous short-duration slip tests, to evaluate the long-term creep performance under sustained tension loading for the set of critical parameters of coating thickness, bolt type and bolt preload. The results indicate satisfactory creep performance and may inspire future code revisions and improve steel bridge fabrication in North America.

**Keywords**: Metalizing, steel bridge construction, slip-critical bolted connections, long-term creep performance, bridge design standards

## Introduction

Bolted joints may be designed as either bearing-type connection or slip-critical connection. In bearing-type 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. However, when the connection is subjected to significant load reversal or fatigue as in bridges, a slip-critical design is required. Slip-critical connections possess a low probability of intolerable slip at any time during the life of the structure. The resistance to slip depends on friction between the planes of contact of the joint plies, also known as the faying surfaces, developed by the clamping action of the pretensioned bolts. Thus, the slip resistance is governed by the bolt preload and the coefficient of slip at the faying surfaces, and it is expressed mathematically as

$$V_s = \mu n_s \sum_{i=1}^{n_b} F_{b,i} \qquad (1)$$

where $V_s$ is the slip resistance, $\mu$ is the slip coefficient for the faying surface, $n_s$ is the number of the slip surfaces involved in the joint, $n_b$ is the number of bolts, and $F_{b,i}$ is the minimum bolt pretension in bolt $i$. According to the Specification on Structural Joints using High Strength Bolts, published by the Research Council on Structural Connections (RCSC), the specified minimum bolt pretension for high strength bolts is equal to 70 percent of the specified minimum tensile strength of the bolt [1].

The coefficient of slip, $\mu$, is a function of the surface condition of the connected parts. The RCSC Specifications for Structural Joints using High Strength Bolts [1] defines three classes of surface preparation: unpainted clean mill scale steel faying surfaces (or surfaces with Class A coatings on blast-cleaned steel) as Class A surfaces with $\mu$ = 0.33;

unpainted blast-cleaned faying surfaces (or surfaces with Class B coating on blast-cleaned steel) as Class B with μ = 0.50; and hot-dip galvanized and roughened surfaces as Class C surfaces with μ = 0.35. The Canadian standard CAN/CSA-S16-14 [2] specifies slip coefficients for two faying surface conditions, namely clean mill scale or blast-cleaned with Class A coatings and blast-cleaned or blast-cleaned with Class B coatings with slip coefficient values of 0.30 and 0.52 respectively. Also, a Class A slip performance is prescribed for hot-dip galvanized surfaces roughened by wire brushing. The American standard AASHTO LRFD bridge design code [3] on the other hand specifies slip coefficients for three faying surface classes, namely unpainted clean mill scale or blast-cleaned surfaces with Class A coatings (μ = 0.33), hot-dipped galvanized surfaces roughened by wire brushing (μ = 0.33); and unpainted blast-cleaned surfaces or surfaces with class B coatings on blast-cleaned steel (μ = 0.50). Essentially, the higher the slip coefficient, the lower the number of bolts needed to prevent slippage.

In many practical cases where coating is required on exposed structural steel elements to provide longevity and corrosion resistance, faying surfaces are cleaned and masked off before applying the coating to the element (see Figure 1). This exercise is labour-intensive, time-consuming and costly, and can be avoided if designers know the slip resistance of the coated faying surface.

Thermal spray coatings are a versatile technology for protecting metal surfaces in a variety of environments [4, 5]. Metalizing, which describes the thermal spray of zinc, aluminum or both on steel surfaces, is becoming a commonly used corrosion protection solution in the North American bridge industry (Figure 2) due to its effectiveness as a protective coating and inorganic character [6, 7, 8]. The coating provides protection from corrosion related problems to the steel substrate by sacrificial and barrier protection [9]. Moreover, the metalized substrate is known to be compatible with many different sealer types, used in certain parts of the United States to increase coating longevity and improve aesthetics.

The metalizing process begins with a proper surface preparation. Here, the surface profile required is a white-metal blast finish according to the Society for Protective Coatings specification SSPC-SP 5/NACE No. 1, or near-white-metal finish (SSPC-SP 10) as a minimum. Essentially, the merits of metalized coating systems for corrosion protection of steel bridge components depend on such factors as the surface preparation, coating thickness, coating type, workmanship and environmental conditions. It is worth mentioning that there is no limit to the size of structural elements that can be metallized, unlike in hot-dip galvanizing where the size of the bath containing the molten zinc imposes size limitations on galvanized steel elements.

Recent short-duration tests have revealed that metalized faying surfaces used with slip-critical connections provide higher slip coefficients than those specified by North American design standards for uncoated blast-cleaned Class B surfaces [10]. The present study evaluates the long-term creep performance under sustained tension loading of metallized faying surfaces used with slip-critical connections. A set of critical connection and coating parameters, such as coating thickness and bolt preload, observed from the short duration slip tests were investigated in the present study.

# Slip Resistance Tests Parameters

The slip resistance evaluation involves essentially three major steps (Appendix A of the RCSC Bolt Specifications). Firstly, short-duration static load tests are conducted to determine the mean slip coefficient [10]. If the evaluated mean slip coefficient values are found to be satisfactory, long-term creep tests under sustained tension loading are required to quantify the effect of creep on the slip resistance of the coated surfaces. Finally, a post-creep slip test is carried out to verify that the loss of clamping force in the bolt does not reduce the slip load below that associated with the design slip coefficient.

The research involved the use of a thermal spray coating from a 99.9% zinc wire applied through an electric arc. The steel substrate for all specimens was prepared according to the SSPC-SP 5 (white-metal blast-cleaned surface finish). The test set-up was informed by the RCSC [1], with some unique additional techniques developed to facilitate the assembling of the specimens and monitoring of the clamping force during testing. Table 1 shows the parameters studied in the work presented here.

Each specimen was uniquely identified according to the variables shown in Table 1.


Figure 1: Masking of connection faying surfaces (courtesy of Canam-Bridges, Québec)

Figure 2: Metallized interchange rehabilitation project in Québec City (courtesy of Canam-Bridges)

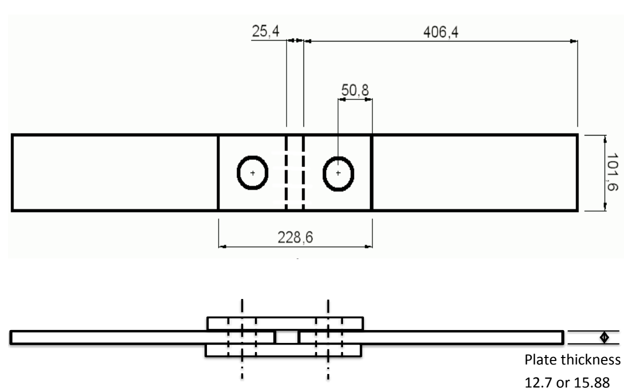
Table 1: Test variables

| # | Parameters | Variables |
|---|---|---|
| 1 | **Faying surface** | BC- commercial blast cleaned |
| | | M- metalized |
| 2 | **Thickness of coating** | 0m- uncoated |
| | | 6m- 6 mils |
| | | 12m- 12mils |
| 3 | **Clamping force** | 70% - 70% of bolt tension capacity |
| | | 90% - 90% of bolt tension capacity |

For example, Specimen M-6m-90% refers to metalized surface with a coating thickness of 6 mils under a bolt pretension equal to 90% of the tension capacity of the bolt. Similarly, BC-0m-70% represents a non-metalized blast-cleaned faying surface of an average angular surface profile of 2.6 mils under a bolt pretension equal to 70% of the bolt tension capacity. In some test plates, the surface preparation included removal of burrs around bolt holes. All specimens for the tests were assembled from steel plates prepared in a fabrication shop from 5/8 in. thick Canadian CAN/CSA G40.21 350AT cat.3 steel

## Short Duration Slip Tests

Previously, short-duration tension slip tests were designed following Appendix A of the RCSC specifications [1] to determine the mean slip coefficients of the metalized coated surfaces [10]. The specimens for the tests were assembled from 5/8 in. thick Canadian G40.21 350AT cat.3 steel plates. Each specimen consisted of two pairs of identical plates; 4 in. x 9 in. exterior plates bolted to two identical 4 in. x 16 in. interior plates (Figure 3) by two 7/8 in. diameter ASTM A325 high strength bolts. Each bolt hole measures 15/16 in. in diameter allowing for a maximum slip of 1/16 in. to occur during testing. The contact surface area per bolt of the test specimen is 4 in. x 3 in. The metalized coatings were applied in the fabrication painting shop using techniques similar to routine practice. Metalizing was applied from a 99.9% zinc wire through an electric arc. The coating thickness on each plate was measured by a Positector magnetic gage in accordance with the requirements of the Society for Protective Coatings SSPC-PA 2 standard [11]. Control specimens with non-metallized blast cleaned faying surfaces were also tested to validate the experimental set-up.



*All dimensions are in mm*

Figure 3: Test plate dimensions

The slip tests were performed on a 1500 kN MTS hydraulic Universal Testing Machine with an applied load rate of 100 kN/minute. The relative displacement (i.e. slip displacement) between the loaded middle plates and the two side plates was measured using LVDT displacement transducers. The slip load was measured as either the peak load on the load-slip curve or the load corresponding to 0.5 mm (0.02 in.) of slip, according to the RCSC.

Table 2 presents a summary of the results of the short-duration tension slip tests. The table contains slip coefficients of individual specimens tested, mean slip coefficients for the same set of parameters and associated standard deviations. The average slip coefficient for the uncoated blast-cleaned faying surfaces (with an average angular profile of 2.6 mils) was obtained as 0.36 (from a range of 0.33 to 0.37). This condition corresponds to a Class A faying surface according to both the Canadian and American standard specifications.

The same steel grade (350 AT) and plate thickness (5/8 in.) used in the short duration slip tests were selected for the long-term creep tests under sustained tension loading. Plate dimensions were based on the RCSC specifications [1]. A test specimen consisted of three identical steel plates (a middle plate and two lap plates) clamped together using a 7/8 in. diameter A490 high strength bolt, as prescribed by the RCSC. 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 [6]. 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 test plates were coated on both sides. Thus, in total, there were six layers of coating between the bolt head and the nut in each assembly. The metalized coating thickness was measured with a Positector magnetic gage on each test plate in order to mate plates with similar average coating thickness.

Table 2: Short duration slip coefficient values

| Specimen I.D. | $\mu_1$ | $\mu_2$ | $\mu_3$ | $\mu_4$ | $\mu_5$ | $\mu_{average}$ | S.D. |
|---|---|---|---|---|---|---|---|
| **BC-0m-70%** | 0.37 | 0.36 | 0.33 | | | 0.36 | 0.02 |
| **M-6m-70%** | 0.77 | 0.81 | 0.76 | 0.77 | 0.82 | 0.79 | 0.03 |
| **M-12m-70%** | 0.98 | 0.93 | 0.93 | 0.99 | 0.89 | 0.94 | 0.04 |
| **M-6m-90%** | 0.79 | 0.84 | 0.70 | 0.77 | 0.74 | 0.77 | 0.05 |
| **M-12m-90%** | 0.99 | 1.01 | 0.93 | 0.94 | 1.01 | 0.97 | 0.04 |

The metalized coated faying surfaces yielded much higher slip coefficient values than specifications for a Class B surface finish. The least mean slip coefficient was evaluated as 0.77 representing the 6 mils thick metalized coating under a clamping force equal to 90% of the bolt capacity in tension. For the same coating thickness, a reduced level of bolt preload (70%) yielded similar slip resistance (coefficient = 0.79). The same trend was also observed for the 12 mils thick metalized coating, where the slip coefficients under 70% and 90% bolt preloads were evaluated as 0.94 and 0.97, respectively. However, increasing coating thickness from 6 mils to 12 mils for both the 70% and 90% bolt preloads increased the mean slip coefficient significantly.

# Experimental Program for Creep

## Test specimens and assembly

A special device was fabricated to facilitate the assembling of the plates before testing. With this device, the necessary clearance in the bolt hole was created to permit maximum slip to occur. The bolt preload was manually applied using the turn-of-the-nut method with a hand-held ratchet to reproduce field practice. The bolt preload was monitored from the time of assembling through to the end of testing by a carefully calibrated washer-type load cell installed in series with the test assembly. The calibration was done in accordance with the manufacturer's specifications.

The same nomenclature used in the short duration tests was used to identify specimens in the present creep test. For specimen parameters, only the 12 mils metalized coating thickness at a 70% minimum bolt preload are presented in this paper. It is evident that the 12 mils thick coating is likely to experience more creep deformation than the 6 mils thick coating. In some specimens, burrs produced by the drilling process of bolt holes in test plates were left in place, while in others they were cleaned. In the specimen nomenclature, the letter ‘a’ is added to denote the former specimens (with burrs), while the letter ‘s’ is added to denote the latter (without burrs). It is noted that the heights of burrs left in place were less than 1/16 in., which represents the limit permitted by the RCSC specifications [1] and Canadian specifications [12] on joint faying surfaces.

## Instrumentation and Testing

Tension creep tests were performed using a 500 kN MTS hydraulic Universal Testing machine on six almost identical specimens assembled together in series as shown in Figure 4. The only distinction is that the top three specimens were without burrs on plate surfaces while the bottom three were with burrs. 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 specifications [1]. The sustained tension load applied during the test is the service load calculated according to Equation A4.1 of the RCSC bolt specifications, given by:

$$\text{Service Load Rs} = \frac{2\mu_t T_t}{1.5}$$

where $\mu_t$ is the design slip coefficient under consideration, and $T_t$ is the measured bolt force of the clamping bolt. The creep performance was evaluated at a design slip coefficient of 0.52, representing the largest Class B slip coefficient currently used in the North American design standards. A data acquisition system was used to monitor and record the applied loading, the extensometer and load cell measurements.

At the end of the creep test, the specimens were loaded to the design slip load for a post-creep slip test and the increase in deformation was measured and recorded for each specimen. The design slip load is calculated as the average clamping load times the design coefficient time the number of slip planes.

Figure 4: Creep test set-up

## Test Results and Discussions

The acceptable creep deformation according to the RCSC bolts specification is 0.127 mm (0.005 in.) or less. For the post-creep slip test, if the average slip deformation occurring at the design slip load is measured to be less than 0.381 mm (0.015 in.) for three identical specimens, the coated faying surface tested is considered to meet the requirements for the category of the target design slip coefficient. If any of the two conditions above is not respected, the coating is considered to have failed for the specified design slip coefficient and a new test is required to evaluate the coated faying surface for a lesser design slip resistance.

Figure 5 presents the reduction of the bolt preload over the duration of the test for both test plates with burrs in place (Figure 5a) and those with burrs removed (Figure 5b). For both sets of specimens, it is observed that significant loss of clamping force occurred essentially in the first 100 hours of sustained loading, after which the clamping force remained almost unchanged. It does also appear that the loss of clamping force is slightly greater in the test specimens with burrs on the plate surfaces, indicating that the presence of burrs (less than 1/16 in.) on faying surfaces is likely to degrade the pretension in bolts. In other words, the plates may tend to be in firmer contact in the absence of burrs and the clamping force would undergo less relaxation. It is worth recalling that the previous short duration slip tests revealed no significant effect of such burr heights on the slip coefficient of metalized joints.

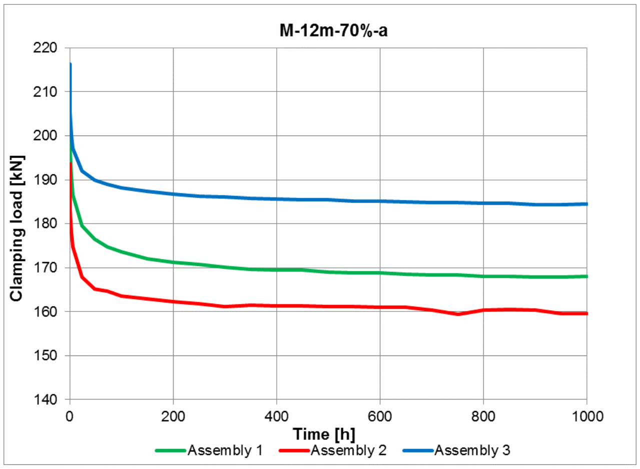



Figure 5a: Relaxation of clamping force over time (specimens with burrs)

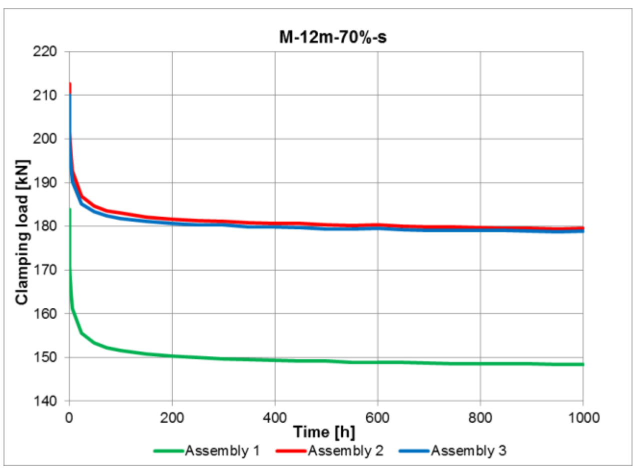



Figure 5b: Relaxation of clamping force over time (specimens without burrs)

Figure 6 shows the creep deformation measured between the first 30 minutes of sustained tension loading up until 1000 hours for both test plates with burrs in place (Figure 6a) and those with burrs removed (Figure 6b). Also shown on these figures are the creep deformation limit specified by the RCSC bolt specification [1].

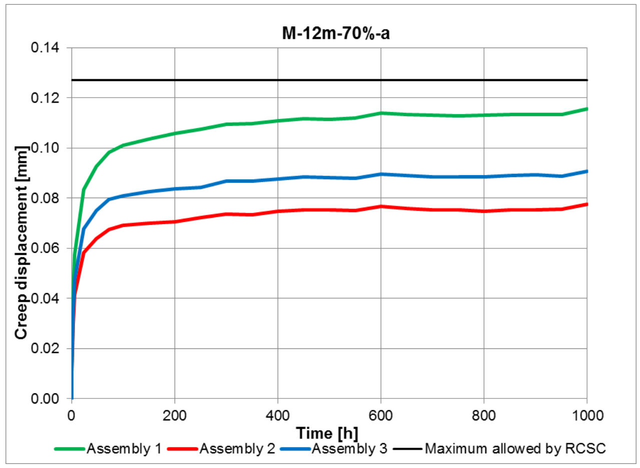



Figure 6a: Creep deformation over time (specimens with burrs)

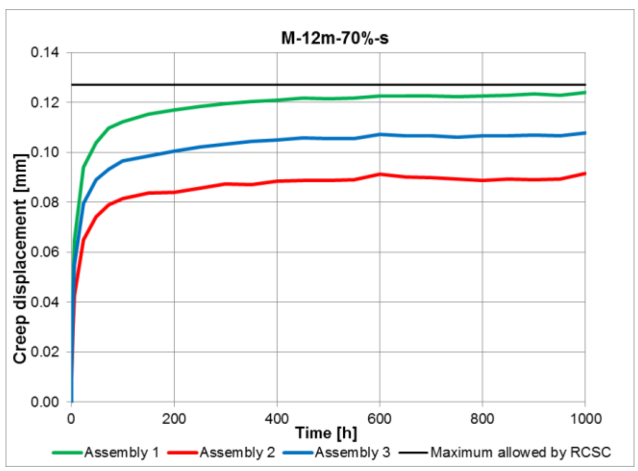



Figure 6b: Creep deformation over time (specimens without burrs)

Clearly, all the creep displacements measured were less than 0.127 mm over the 1000-hour of sustained tension loading. This indicates that all the specimens presented in this paper passed the creep test. It does, however, appear that the presence of burrs (less than 1/16 in. in height) on test plate surfaces slightly reduced the creep deformation.

The post-creep slip test under the design slip load yielded satisfactory results for all specimens tested. Table 3 shows the post-creep slip displacements for each assembly, and the average deformation for three identical specimens without and with burrs.

Table 3: Post-creep slip deformation

| Specimen I.D. | Assembly | 1000 h - creep deformation [mm] | Post-creep slip deformation [mm] | Average post-creep slip deformation [mm] |
|---|---|---|---|---|
| **M-12m-70%-s-0.52** | 1 | 0.1240 | 0.1427 | 0.1266 |
| | 2 | 0.0916 | 0.1102 | |
| | 3 | 0.1077 | 0.1270 | |
| **M-12m-70%-a-0.52** | 1 | 0.1156 | 0.1322 | 0.1106 |
| | 2 | 0.0775 | 0.0925 | |
| | 3 | 0.0906 | 0.1071 | |

Deformations in all specimen assemblies increased only minimally when loaded to the design slip load at the end of the sustained tension creep tests. Clearly, both sets of specimens with burrs on test plates and without burrs yielded average post-creep slip deformations less than the imposed limit of 0.381 mm by the RCSC specifications. Thus, the 12 mils thick metalized faying surface with a minimum clamping force of 70% of the bolt capacity in tension yielded satisfactory creep performance at a slip coefficient of 0.52.

## Conclusions

In a slip-critical connection, the pretensioned bolts develop resistance to slip through the friction on the faying surface between the connected parts. Thus, the slip resistance is a function of the condition of connection faying surfaces. With increasing use of metalizing as long-term corrosion protection solution for steel bridges, designers need to know the slip resistance of metalized faying surfaces in order to eliminate the current practice of masking off connection faying surfaces before metalizing.

Results of previous short duration tension tests indicated a much greater slip coefficient than those specified in North American design codes for uncoated blast-cleaned Class B faying surfaces. However, the full merit of these test results can be established only after a satisfactory long-term creep performance under sustained tension loading.

In the present study, a 12 mils thick metalized faying surface with a minimum bolt preload of 70% of the tension capacity of the bolt yielded a satisfactory creep performance at a slip coefficient value of 0.52 (representing the maximum Class B slip coefficient currently in the North American design standards). Both the creep deformation and the post-creep slip displacement for each assembly passed the limits of 0.127 mm and 0.381 mm, respectively, imposed by the RCSC bolt specification.

Based on results from both the short duration slip tests and the long-term creep tests under sustained tension loading reported herein, the 12 mils thick metalized faying surface with a minimum clamping force of 70% of the bolt capacity in tension can be classified as a Class B faying surface.

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