Bolted Shear Connections with Painted Surfaces

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INTRODUCTION

In high-strength bolted shear connections, the load transfer between plate components is initially provided by the frictional forces developed by bolt clamping forces and friction characteristics of contact surfaces. A connection which relies on this slip resistance to transfer load is called a friction connection. When the slip resistance is exceeded, the connection slips into bearing to develop the bearing strength (bearing connection). Prior to 1974, paints on the contact surfaces were prohibited in friction connections because some early tests showed they affected adversely the slip load. The fabricator had to mask off the connection area, thus increasing the cost when friction joints and painted steel were specified. In exposed environments, the unpainted contact surfaces resulted in crevice corrosion and a subsequent deterioration of the structural painting system.

Design criteria for bolted joints are given in the *Specification for Structural Joints Using ASTM A325 or A490 Bolts* prepared by the Research Council on Structural Connections (RCSC).[7] The RCSC Specification gives allowable friction forces for nine different contact surface conditions based on a probability of slip concept developed by Fisher and Struik.[3] Three types of paint were recognized for friction surface: organic and inorganic zinc-rich paint and vinyl wash. Many coatings and painting systems, especially vinyl and epoxies, which show significant improvement in corrosion protection, have been developed. Since such coatings are not reflected in the RCSC Specification, their status for use on friction surfaces is unknown.

A statistically reliable (factorial) experimental program was developed to study the slip characteristics of four coating systems with superior corrosion protection: organic zinc-rich primer, organic zinc-rich primer with an epoxy topcoat, inorganic zinc-rich primer with a vinyl topcoat and vinyl primer with and without a vinyl base topcoat. The effects of paint curing time, clamping force, steel strength, hole size and paint thickness were considered. The research program involved hundreds of slip experiments, so a reliable and speedy slip test was developed. Some large multi-bolt connections were tested to evaluate the extrapolation of design recommendations based on small slip tests to more realistic applications. Consideration was also given to the possible difference between carefully controlled laboratory tests and joints constructed under typical field conditions. Based on the tests contained here, and those reported by others, design recommendations for friction joints are presented. This paper is a summary of the results of a research program described in detail elsewhere.[4,5]

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EXPERIMENTAL METHODS

Slip Test Arrangement

Because of the large number of slip tests required, the compression-type slip test setup shown in Fig. 1 was used to keep testing time and specimen fabrication to a minimum. It was reasoned that Poisson's ratio may lead to an increase in the slip load in a compression-type slip test.[3] This objection was eliminated by using a ⅞-in. (22 mm) rod acting through a centerhole jack to apply the clamping force. Oil pressure is applied to the ram, which forces a nut with the threads drilled out to slip along the threaded rod against the connection plate. The drilled nut provides the same contact area as the head of a bolt. The clamping force was measured by a load cell and also by monitoring pressure in the calibrated ram. The arrangement maintained the clamping force, thus eliminating the problem of bolt variations and calibrations. Two different clamping forces were applied in the study: 39 kips (173 kN) and 49 kips (218 kN). They represented the minimum tension required for ⅞-in. (22 mm) ASTM

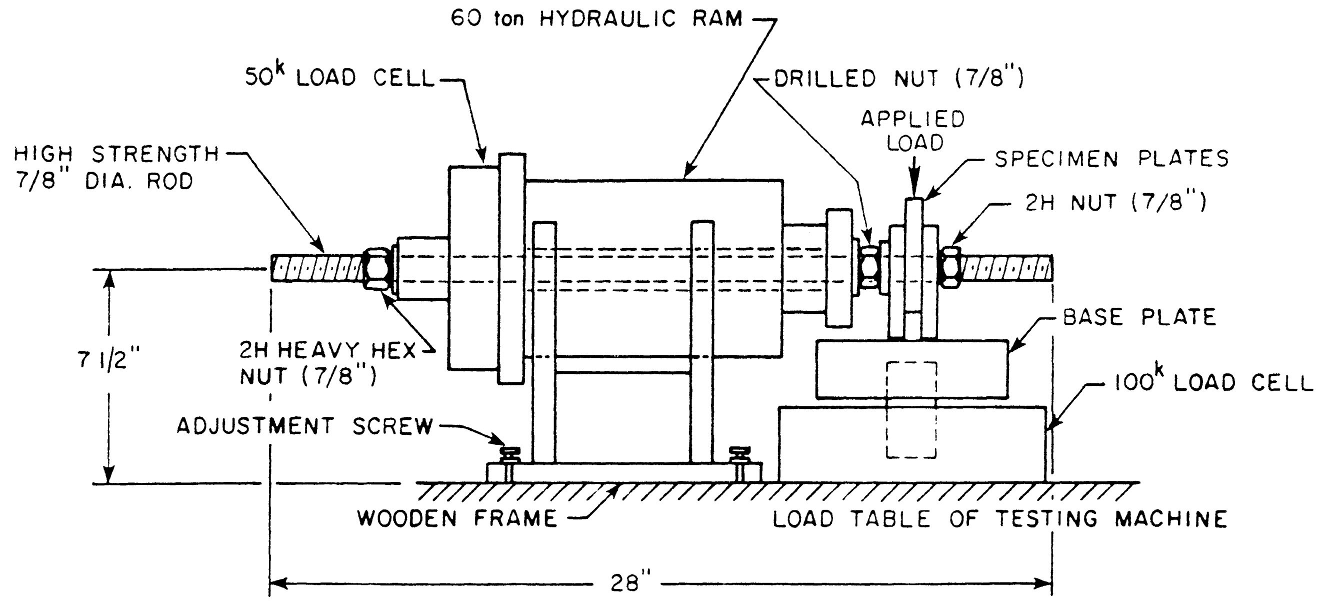

Fig. 1. Test setup schematic (1 in. = 25.4 mm)

A325 and A490 high-strength bolts, respectively. The whole arrangement was placed on the load table of a testing machine and leveled as shown in Fig. 1. For additional control, the machine load applied to the specimen was monitored by a load cell. Two electrical deflection gages were used to measure the slip. A somewhat similar "hydraulic-bolt" setup was used in Japan.[6]

The slip test specimen shown in Fig. 2 consisted of three ⅝ × 4 × 4-in. (16 × 102 × 102 mm) plates. These relatively small plates were used because pilot tests showed they produced the same results as larger specimens. The contact area was generally within 1 in. (25 mm) of the edge of the hole in the plates, independent of the plate size. An evaluation and more detailed description of the test setup and specimen is given in Ref. 4.

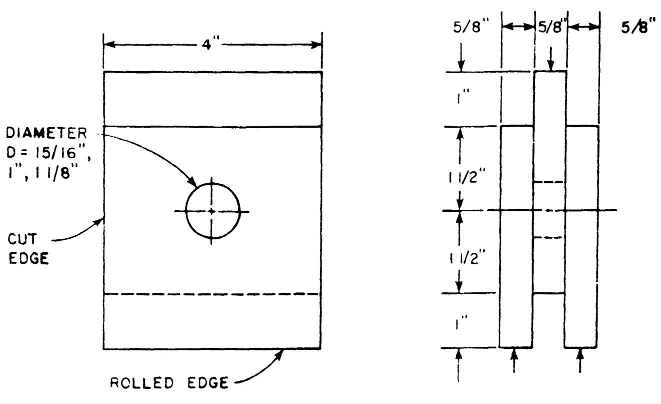

Fig. 2. Slip test specimen (1 in. = 25.4 mm)

Painting

A group of 20 to 30 specimens was dry sandblasted at the same time to a white metal finish to meet requirements of the SSPC-SP5-63.[8] Some specimens were painted by one of the selected coating systems, and the rest were used as control test specimens with blast-cleaned surfaces. Usually, for every 10 specimens there were four control specimens. The surface roughness of the control specimens was established using the Keane-Tator surface comparator. Usually the sandblasted control specimens were tested within a week after sandblasting.

All painting was done in the laboratory according to the paint manufacturer's as well as painting experts' recommendations. In many instances, multiple coats were required to build up to the desired dry film thickness. A Mikrotest gage (magnetic gage) was used to measure the dry paint thickness reported here. Usually, eight readings were taken for each plate (four on each side) or 24 readings per specimen. Under laboratory conditions, a coat could be applied to a dry film tolerance of ± 1 mil. The curing time between the application of one coat and another was usually 24 hours. However, if the specimens were to be topcoated, the primer was left to cure for a particular number of days, based on curing tests. After all the coats were applied, the specimens were placed in an air conditioned room to cure before testing. The inorganic zinc-rich paint specimens were covered by wet burlap (at least one hour after painting) to provide the recommended humid atmosphere for curing. Special racks were used to insure that both painted surfaces of the plate were not disturbed while specimens were curing.

Preliminary slip tests at an early stage in the research indicated time lapse between painting and assembling for testing was a significant parameter. Since this was not considered in the basic factorial experiment, a series of slip tests was conducted to determine the time required for the paint to cure. The paint was considered cured when the slip load was unaffected by additional curing time. The drying time for a coating system, as specified by paint manufacturers, is intended only for handling and recoating purposes, and does not imply curing of the paint. Based on the curing time experiments, the following minimum drying time shown in parentheses was used before assembling the plates for testing: organic zinc-rich (9 days); organic zinc (9 days), plus epoxy topcoat (7 days); inorganic zinc (3 days); inorganic zinc (3 days), plus vinyl topcoat (18 days); and vinyl primer (17 days).

Slip Test Procedure

Individual specimen plates were assembled so that coated surfaces which showed the smallest variation in thickness would be placed in contact. The specimen was inserted into the hydraulic bolt setup and aligned in the test machine to minimize eccentricities. A spherical head on the test machine ensured uniform compression along the edge of the plate. A slip gage was attached and the DCDT's located on each side of the specimen were connected to give the average of the two readings. The gages measured the relative displacement (slip) between the interior connection plate and the two side plates. The slip gage arrangement included axial deformation of plates in the slip measurement, but it is very small compared to the slip.

Pilot tests indicated that loading rate has an effect on the slip coefficient for some paints. Thus, it was decided to conduct all slip tests at the same load rate to achieve fair comparisons of slip coefficient and to minimize the influence of the operator on the shape of the load-slip curves. The applied loading rate was approximately 25 kips (111 kN) per minute, or 0.003 in. (0.076 mm) of slip per minute. The rate of 3 mils/min. was chosen so a test could be conducted within a reasonable amount of time. The test was terminated when the specimen came into bearing.

The slip load, determined from the connection load-deflection plot, shows some typical types in Fig. 3. The slip load was recorded as one of the following: (1) the maximum load, provided this maximum occurred before a total slip of 0.020 in. (0.51 mm) occurred; (2) the load at which the deflection rate suddenly increases, typically as seen in curve b; and (3) the load measured when the slip is 0.020 in. (0.51 mm). The latter definition controls when the load-deflection curve shows a gradual change in response, as shown by curve c. The experimental slip coefficient is calculated as

$$\text{slip coef.} = \frac{\text{slip load}}{\text{clamping force} \times \text{number of slip planes}} \qquad (1)$$

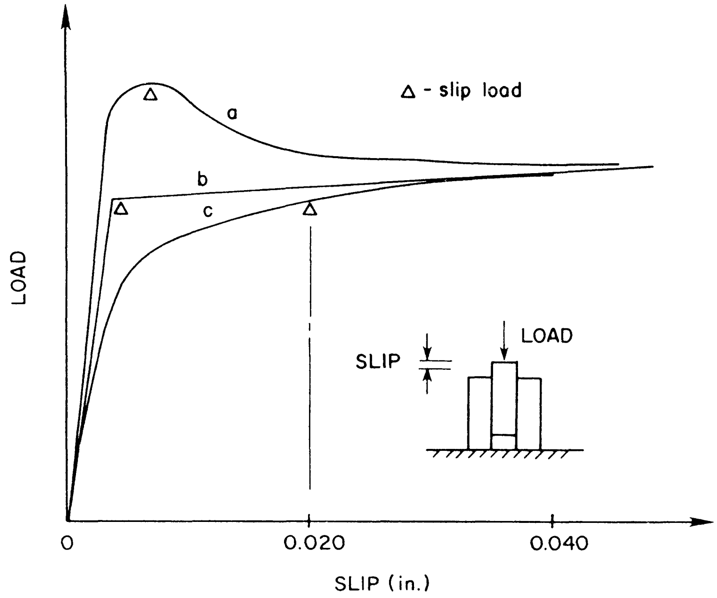

Fig. 3. Definition of slip load

FACTORIAL SLIP STUDY

The main experiment design was a factorial type. This allows a good statistical analysis of the results and provides a firm basis for design specification recommendations. In its simplest form, a factorial experiment is one in which all levels of a given factor (variable) are combined with all levels of every other factor in the experiment. Some information is obtained on possible interaction between the variables considered in the experiment. More than 400 slip tests on connections with painted contact surfaces and another 77 on blasted surfaces are summarized in this section.

The effect of the following variables on the slip behavior of friction-type bolted joints with coated surfaces was the main concern of this research.

1. *Three types of steel*: A36, F_y = 36 ksi (248 MPa); A572, F_y = 50 ksi (345 MPa); A514, F_y = 100 ksi (690 MPa).
2. *Three hole sizes for a ⅞-in. (22 mm) fastener*: standard dia. = 15⁄16 in. (24 mm), oversize dia. = 1 in. (25 mm), oversize dia. = 1 ⅛ in. (29 mm).
3. *Two magnitudes of clamping force*: 39 kips (174 kN) and 49 kips (218 kN), corresponding to the minimum specified clamping forces for ⅞ in. (22 mm), and A325 and A490 bolts, respectively.
4. *Four paint systems*: organic zinc-rich primer, organic zinc-rich primer with an epoxy topcoat, inorganic zinc-rich primer with a vinyl topcoat, and vinyl primer with and without a vinyl base topcoat. These products came from the same manufacturer to ensure compatible primers and topcoats.

5. *Three paint thicknesses on each plate in contact*: thin (~3 mils), normal (~6 mils), and thick (~9 mils).

Only one fastener size, ⅞ in. (22 mm) dia., was used throughout the research program. Five replicates with similar parameters were tested in each cell of the factorial design shown in a tabular layout of the experimental program in Refs. 4, 5.

As part of the study, a large number of blasted specimens without coated contact surfaces were tested, since surfaces had to be sandblasted before painting. These tests, considered control tests, were taken from each group of specimens sent for sandblasting. The purpose of these control specimens was to provide a base condition for determining the influence of the coating on slip behavior and provide additional needed data on A514 steel. A tabular listing of all test results is in Ref. 4.

Blasted Surfaces

The sandblasted control specimens were usually tested within a week after sandblasting. Figure 4 provides a comparison of the average slip coefficients (ASC) for the three steel types and two levels of clamping force where n is the number of tests in the sample. It is evident

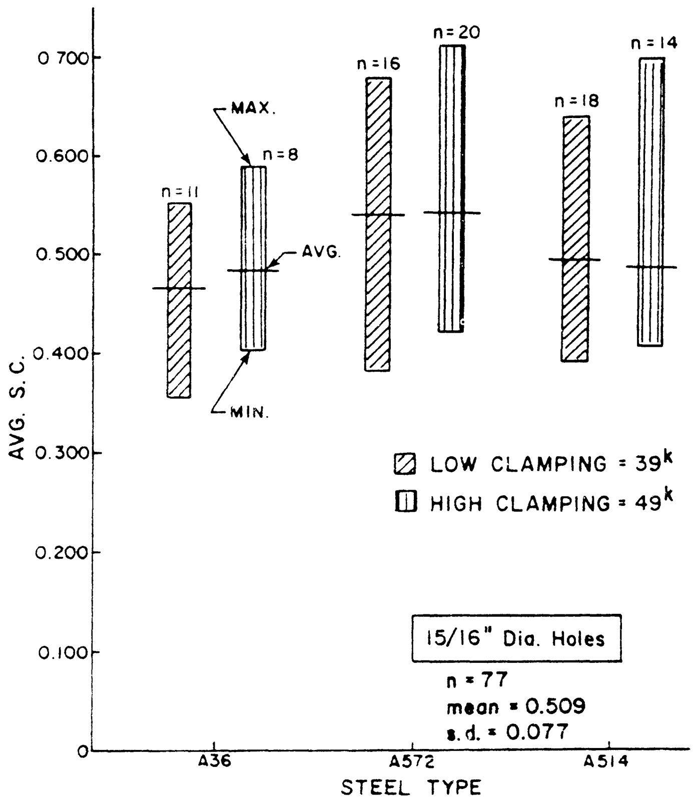

Fig. 4. Effect of steel type and clamping force, sandblasted surfaces (1 kip = 4.45 kN, 1 in. = 25.4 mm)

the ASCs for A36 and A514 are comparable. On the other hand, A572 steel has a slightly higher ASC (maximum difference about 15%). The effect of clamping force on the slip coefficient is almost negligible. The frequency distribution of the 77 test results are approximately normally distributed with a mean of 0.509 and standard deviation of 0.077. The ASC reported by Fisher[3] was 0.493 for 168 tests, and the standard deviation was 0.074, which are in close agreement with the results of this research.

Other tests reported indicated that A514 heat-treated steel provided lower resistance to slip as compared to A36 steel.[3] This was attributed to the harder surface of A514 steel that influences the roughness achieved by blast cleaning. They reported a reduction in the slip-resistance of about 33% for blast-cleaned A514 surfaces. However, the ASCs for A36 and A514 steel specimens studied here were about the same, a difference of only about 3.5%. This result seems to be reasonable, since blasted surfaces of A36 and A514 steel inspected under a powerful microscope did not exhibit any drastic differences in texture. The measured surface roughness for A36 and A514 steel plates which were blasted together did not indicate any significant differences.

A detailed statistical analysis of the results on sandblasted surfaces is presented elsewhere.[5] Evaluation of sandblasted data for specimens with different hole diameters gave no conclusive trends. Small differences observed may be attributed to scatter in the test results. Data from 15 different sandblasting groups indicated that scatter in the mean value from different sandblasting is, in most cases, less than the variation within a sample of specimens blasted at one time. An attempt was also made to correlate slip coefficient with surface roughness. The general trend indicates that there is a slight increase in slip coefficient with deeper anchor patterns. However, a definite relationship could not be established, since the roughness as measured by the Keane-Tator surface comparator is operator sensitive.

Painted Surfaces

Typical load-slip relationships for plates with painted faying surfaces are shown in Fig. 5. In some of the tests, the loading rate was doubled after a total slip of about 30 mils to determine the effect of higher loading rate on the slip coefficient. Usually a hump in the loadslip curve was formed when the loading rate was increased, indicating an increase in the slip resistance of the specimen. This increase in slip resistance was dependent on several factors, such as loading rate, curing time and paint film roughness. The slip coefficients reported are always based on the first slip load, and before increasing the load rate. The standard deviation was generally less than 10% of the mean for each group of five replicates.

For organic zinc coating, investigation of contact sur-

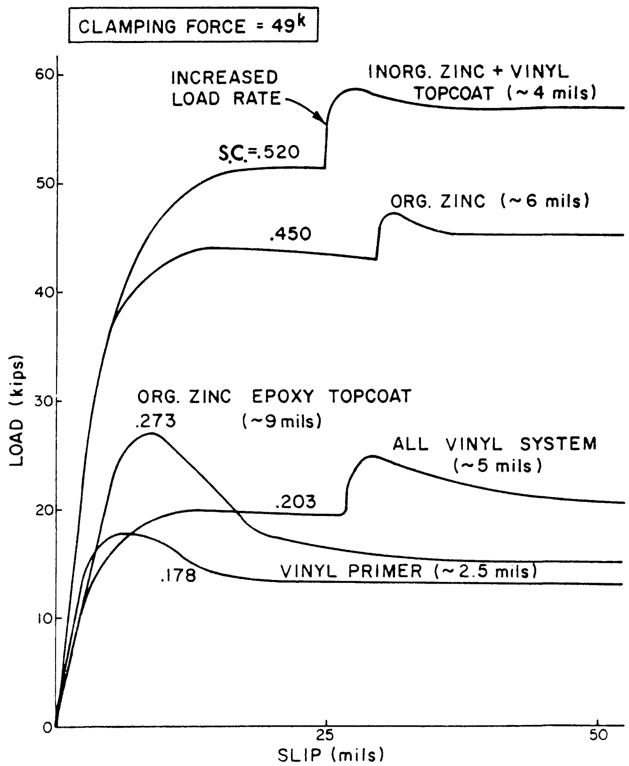

Fig. 5. Typical load-slip curves (1 kip = 4.45 kN)

faces of the specimens after slip indicated that damage to the surfaces was fairly uniform all over the contact areas. However, in some cases, severe damage was confined mostly to the areas adjacent to the holes. The histogram of the organic zinc painted A572 Gr. 50 steel data shown in Fig. 6, which considers variations in paint thickness and hole diameters, is typical of distribution and scatter for other coatings in the program.

When the organic zinc primer was topcoated with an epoxy paint, major slip was accompanied by a sudden drop in load. This indicated that dynamic friction was much lower than static friction. The loading rate did not seem to have any effect on the shape of the load-slip curve, compared to the case of specimens coated with the primer only. The smooth epoxy topcoat caused a significant reduction in slip coefficient compared to organic zinc primer alone. Investigation of the faying surfaces of specimens after testing indicated there was no damage to the hard epoxy topcoat surface.

The mean slip coefficient for inorganic zinc-rich primer with a vinyl topcoat is 0.503. The load-slip response shown in Fig. 5 is very similar to that of organic zinc-rich primer. An appreciable increase in slip resistance occurred when the loading rate was increased. Investigation of the faying surfaces of the specimens after testing indicated that, in most cases, damage to the vinyl topcoat was fairly uniform. The white vinyl topcoat peeled off, exposing the yellow inorganic zinc-rich primer.

The vinyl primer alone did not exhibit any load rate effects, but the vinyl topcoat did. Since the same thick-

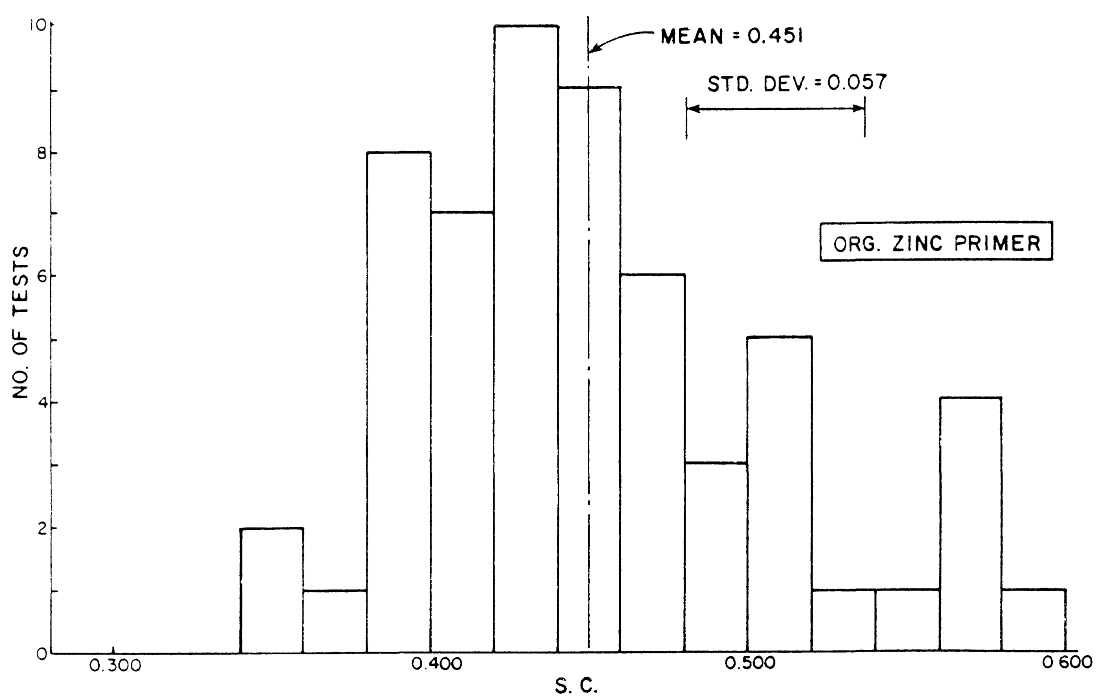

Fig. 6. Frequency distribution for organic zinc-rich coated A572 surfaces (58 tests)

Table 1. Summary of Test Results (1 in. = 25.4 mm)

Surface	Steel	Thickness			Oversize Holes		Totals
		Thin	Normal	Thick	$D = 1$ in.	$D = 1\text{-}\frac{1}{8}$ in.	
	A36		0.555*				
			(0.025)**				
Organic Zinc	A572	0.446	0.484	0.494	0.439	0.380	0.464
$n = 106$		(0.046)	(0.055)	(0.039)	(0.020)	(0.025)	(0.061)
	A514	0.355	0.479	0.470			
		(0.032)	(0.066)	(0.072)			
	A36		0.305				
Organic Zinc			(0.033)				
with Epoxy	A572	0.283	0.271	0.274	0.253	0.258	0.276
Topcoat		(0.023)	(0.023)	(0.030)	(0.011)	(0.024)	(0.031)
$n = 88$	A514	0.288	0.275	0.277			
		(0.024)	(0.030)	(0.029)			
	A36		0.512				
Inorganic Zinc			(0.075)				
with Vinyl	A572	0.468	0.493	0.550	0.555	0.548	0.510
Topcoat		(0.051)	(0.020)	(0.019)	(0.018)	(0.031)	(0.057)
$n = 94$	A514	0.445	0.507	0.515			
		(0.055)	(0.048)	(0.071)			
	A36		0.206				
			(0.015)				
Vinyl Primer	A572		0.186				(0.193)
$n = 15$			(0.012)				(0.016)
	A514		0.187				
			(0.014)				
All Vinyl	A514		0.195				0.195
System $n = 5$			(0.014)				(0.014)
Inorganic Zinc							
80% Zn, $n = 20$	A572		0.607		0.628		0.618
			(0.030)		(0.020)		(0.030)
75% Zn, $n = 5$	A572		0.507				0.507
			(0.010)				(0.010)
0% Zn (ethyl	A572		0.276				0.276
silicate base)			(0.003)				(0.003)
$n = 5$							
Sandblasted			0.521				0.521
$n = 103$			(0.077)				(0.077)

* Average slip coefficient ** Standard deviation

Editor's note: Different paint products within the same generic category give a wide range of average slip coefficients. The value reported on this and the other tables cannot be relied upon for paint products from a different manufacturer.

ness vinyl topcoat was used with the inorganic zinc primer and the vinyl primer, it is obvious from the curves in Fig. 5 that slip resistance is affected significantly by the primer. A full factorial experiment on the vinyl system was not completed because it became evident from a creep experiment[5] that the vinyl system with thicknesses greater than 2 mils was not satisfactory for slip-critical joints.

DISCUSSION OF FACTORIAL RESULTS

Table 1 gives the mean and standard deviation for each cell of the factorial experiment, the sandblasted data plus inorganic zinc slip tests, which are presented later. A computer program (AOVRNC) at the University of Texas was used to perform a statistical analysis of the test results. AOVRNC is a self-contained routine for performing fixed-effects analysis of variance requiring user-specified hypotheses. The routine could be used for analyzing factorial experiments with any number of levels. For statistical testing, a 5% level of significance was usually used. A statistical evaluation of the significance of hole size, clamping force, type of steel, paint thickness and base primer on the slip coefficient was conducted. In some instances, additional tests were performed to better isolate a particular variable.

Oversize Holes and Clamping Force

Each coating system was analyzed statistically to determine the effects of oversize holes and clamping force level on the slip coefficient. All joints were of A572 steel and had normal paint thickness (~6 mils for primer and ~3 mils for topcoat).

For the surfaces coated with organic zinc primer, the analysis indicated hole size was a significant variable, whereas clamping force was not. The organic zinc specimens with 15⁄16- and 1-in. (24 and 25 mm) hole joints had comparable ASCs (difference of about 3%), but were 14% higher than the ASC for the specimens with 1⅛-in. (29 mm) hole joints. However, friction characteristics of organic zinc primer surfaces showed sensitivity to painting in a group. This is believed to be due to slight variations in paint surface roughness resulting from different painting conditions (humidity, temperature, spray gun setting, etc.). Since the 15⁄16-and 1⅛- in. (24 and 29 mm) diameter hole joints were painted separately, it was felt that the low ASC exhibited by the 1⅛-in. (29 mm) diameter hole joints might have resulted from different painting jobs.

Therefore, an additional experiment was conducted with the hole size as the only variable, and all joints were painted at the same time. The results[5] show the effect of hole size on the ASC was insignificant [0.368 and 0.371 for 15⁄16- and 1⅛-in. (24 and 29 mm) diameter holes, respectively], and the effect of different paints was verified. A similar situation was found for inorganic zinc with vinyl topcoat, except the oversize holes showed greater slip resistance than standard holes. Again, additional tests established that hole size had no significant effect on the slip coefficient.

For specimens with organic zinc primer topcoated with epoxy, the analysis indicated that neither hole size nor clamping force was significant as a variable. The effect of different paintings on the ASC was very slight as compared to the case of the primer without topcoat. It is believed the hard epoxy topcoat provided surfaces which possess more uniform friction characteristics.

Figure 7 shows the effect of oversize holes for the different coating systems. The solid boxes for organic zinc primer only represent the additional experiment done for this paint. It may be concluded that for joints with ⅞-in. (22 mm) bolts, coated with any of the above-mentioned paint systems, there will be no decrease in the slip coefficient for oversize holes with up to ¼-in. (6 mm) clearance for ⅞-in. (22 mm) bolts.

In the RCSC Specification, a reduction of about 15% is specified for joints with oversize holes. This was based on data which showed the clamping force was reduced by about 15% for oversize holes.[3] This reduction was attributed to plate depressions occurring under bolt heads during tightening by the turn-of-nut method, so rotation of the nut does not result in the degree of bolt elongation desired. But, bolt tension was still above the minimum required tension by about 18%. Thus, if a specification is based on the minimum clamping force, no reduction should be considered, even when the turn-of-the-nut method is used. If torque-controlled bolts or load-indicating washers are used, perhaps a reduction may not exist. Further research is needed to determine if oversize holes cause reduction in the clamping force for these installation methods.

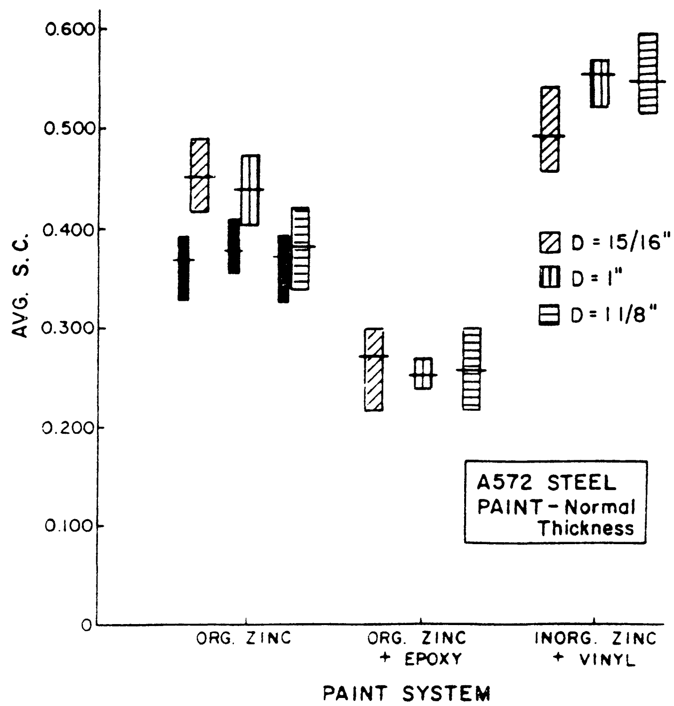

Fig. 7. Comparison of average slip coefficient for different hole sizes (1 in. = 25.4 mm)

Type of Steel

A similar experiment to that used for oversize holes was analyzed to determine the effects of steel type and clamping force on the slip coefficent. The steel types were A36 and A514, and the clamping forces were 39 and 49 kips (174 and 218 kN). All joints had 15⁄16-in. (24 mm) holes and normal paint thickness. Results of the analyses indicated that the effect of the clamping force was insignificant.

On the other hand, the analyses indicated the steel type was a significant variable for most of the coated surfaces. For the organic zinc primer, organic zinc primer with epoxy topcoat and vinyl primer coated surfaces, the ASCs for A572 and A514 steel were about the same (differences less than 1.5% for any of the three paint systems), but were noticeably lower than the ASC for A36 steel of the same paint system. The percentage increase in slip resistance provided by the A36 steel was 15%, 12%, and 11% for the three paint systems, respectively. For the surfaces coated with inorganic zinc primer with a vinyl topcoat, the analyses indicated steel type was an insignificant variable.

The increase in slip resistance provided by A36 steel for some coatings cannot be explained, since the blasted specimens and those with inorganic zinc primer with vinyl topcoat did not show a similar increase. Since the maximum observed increase was only 15%, it is recommended the steel type effect not be considered in a design specification. The small potential benefit for some coatings does not justify the complications resulting from inclusion of steel as a factor in design specifications.

Paint Thickness

Thickness of the primer was analyzed for its effect on slip. The three levels of thickness were 3, 6 and 9 mils for organic zinc primer; and 3, 7 and 11 mils for the inorganic zinc primer. All joints had 15⁄16-in. (24 mm) holes. It was found thickness was insignificant in the case of organic zinc primer with and without epoxy topcoat paint systems. For inorganic zinc primer with vinyl topcoat, the ASC for thin coatings was lower than for thick coatings by about 15%. Since the ASC for normal thickness was comparable with the ASCs for both thin and thick coatings, this suggests using the ASC based on normal thickness and eliminate the effect of thickness. Thus, based on the above discussion concerning thickness of paint, it may be concluded thickness is not an important variable.

Primer

A simple one-variable analysis was performed with the vinyl topcoats to study the effect of primers. The joints had A514 steel and 15⁄16-in. (24 mm) holes. The results indicated the vinyl primer and all vinyl systems had comparable ASCs, which were significantly lower than the ASC of the inorganic zinc primer with vinyl topcoat. The vinyl primer, which has a low ASC (0.187), still exhibited a low ASC (0.195) when topcoated with vinyl, whereas inorganic zinc, which has a high ASC (0.607), exhibited a relatively high ASC (0.489) when topcoated with the same vinyl topcoat. This behavior indicates the kind of primer considerably affects the slip resistance, even when it is topcoated.

OTHER SLIP TESTS

In this section, additional slip studies are reported on the effect of zinc content of paint, variations among organic zinc-rich paints on the market and the influence of paint curing time prior to assembly of the joint. A number of large truss-type shear joints were tested to assess the reliability of using small-joint slip coefficients in determining the slip load of large bolted joints.

Other Coatings

Inorganic zinc primer. The Steel Structures Painting Council Specification SSPC-PS-12.00 C8T requires at least 75% zinc by weight for the paint to be acceptable on exposed structural steel.[8] The zinc content of the inorganic zinc primer used in the factorial experiment contained 80% zinc. Because this percentage was greater than required, another inorganic zinc paint from the same manufacturer with the same vehicle and 75% zinc was tested. The ASC for 80% zinc was 0.62. For 75% zinc, the ASC was 0.51, an 18% reduction. These results indicate zinc paint should be agitated continuously to avoid variations in corrosion protection and slip resistance.

Additional organic zinc primers. The factorial experiment discussed earlier established an ASC of 0.46 for one particular brand of organic zinc-rich primer. In order to get an indication of the scatter to be expected within one of the current surface classifications in the RCSC Specification, two additional organic zinc primers from a different manufacturer were tested. One paint had a phenoxy base and the other an epoxy base. Two separate groups of specimens were painted for each primer. An equal number of slip specimens, as shown in Fig. 2, were prepared using 7⁄8-in. (22 mm) A325 bolts and the hydraulic bolt arrangement. The two types of tests were planned to provide a direct indication of bolt relaxation due to creep. The thickness of the paint on each surface was between 4 and 6 mils.

Originally 40 tests were planned. However, one of the painting groups showed an unusually low slip coefficient, so an additional 10 specimens were tested. The average of five replicates is summarized in Table 2.

Scatter within each group of five replicates was quite small, with the coefficient of variation usually less than 10%. It is apparent the bolted specimens give about the same result as the hydraulically bolted specimens. Group 1 of the phenoxy-base data is significantly lower than the other two samples. Apparently this was due to improper mixing and agitation of the primer during paint spraying. This incident points out one of the variables that can have a significant effect on the slip resistance which is beyond the control of the design engineer. The average of Groups 2 and 3 gave an ASC = 0.31, which is close to the ASC = 0.33 reported by others for this same paint (3- to 6-mils thick) and using a multi-bolt, tension-type setup.[2]

The test data indicate a significant difference between the ASC of the two primers. The phenoxy base, which had a zinc content of 90%, gave an ASC of 0.31 compared to 0.46 for the phenoxy-base organic zinc supplied

Table 2. Average Slip Coefficients for Additional Organic Zinc Primers

	Epoxy Base			Phenoxy Base			
Type of Test	Group 1	Group 2	Total	Group 1	Group 2	Group 3	Total*
Real bolts	0.45	0.38	0.41	0.14	0.30	0.26	0.28
Hydraulic bolts	0.44	0.42	0.43	0.12	0.30	0.32	0.31

*Only Groups 2 & 3

by another manufacturer for the factorial experiment. The average of the epoxy zinc-rich paint is 0.43. This study shows that paints within a particular category can show a wide variation in ASC.

Paint Curing Prior to Assembly

The RCSC Specification does not have any guidelines related to the amount of curing required before contact surfaces are bolted. The curing-time test results mentioned previously show paints vary in their curing requirements and, in the factorial experiment, periods from three to 21 days were used before joints were assembled. Examination of the research on coated faying surfaces reported in Ref. 3 has shown that usually a two-week period of time elapsed between painting and assembling.

From a fabricator's viewpoint, it is best to assemble the connection as soon as practical to avoid the cost of storage of clip angles, bolts, etc., or the more costly field-erection of such items. But, if the connection is assembled without the paint properly cured, the slip coefficient upon which the allowable bolt stress is based may not be achieved. It could be argued, however, that the paint can cure in place. To get some perspective on the problem, a pilot study was undertaken on one organic zinc primer.

Twenty single-bolt compression slip specimens were blasted and painted with the phenoxy zinc-rich paint used in the previous section with an ASC = 0.31. One coat, 2 mils dry, was applied first and one day later a similar final coat was applied. After applying the second coat, plates were bolted together one hour, five hours, one day and two weeks after painting. The final dry paint thickness varied between 3 and 4 mils. Five specimens were prepared within each group. Two weeks after painting, three specimens from each group were tested. One month after painting, the remaining specimens were tested. Table 3 gives the ASC.

Table 3. Effect of Curing Time on Slip Coefficient, Phenoxy Zinc Primer

Time before assembly	1 hr.	5 hrs.	1 day	2 wks.
Tested after two weeks*	0.08	0.14	0.34	0.39
Tested after one month**	--	0.24	0.36	0.39

*Average of three specimens
**Average of two specimens

The data indicate curing time prior to assembly has a significant effect on slip resistance. Five hours of curing produced only 57% of the slip resistance recorded for the two-week cured control specimens. Waiting an additional two weeks before testing gave an improved slip coefficient (0.24 vs. 0.14), but it is still less than the coefficient from the two-week control group (0.39). For the particular paint product tested, the curing time prior to assembly is a significant variable which should be considered in developing design and fabrication procedures.

Full-Size Connections

Eleven full-size truss-type connections with 40 bolts, shown in Fig. 8, were tested in compression for the slip

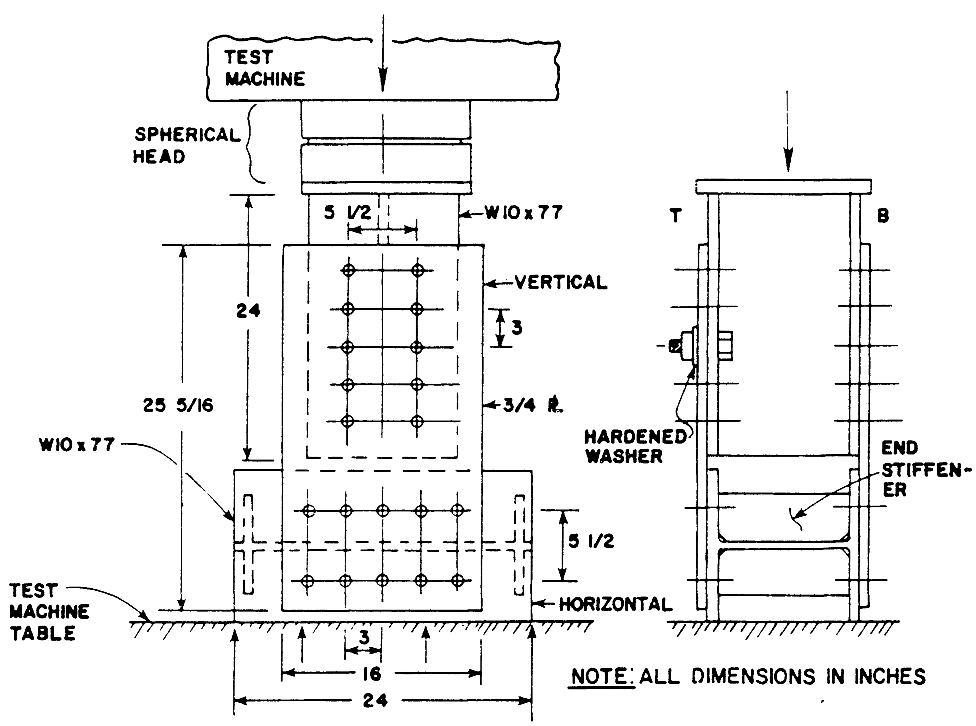

Fig. 8. Full-size slip connection (1 in. = 25.4 mm)

load. Four different joints were fabricated; after the first tests, they were sandblasted and reused twice. The purpose of the full-size tests was to provide slip data for comparison with the small slip tests, monitor any losses in clamping force due to compressive creep of paint and determine any difference between laboratory and fabricator installation techniques.

Eight of the connections were bolted in the laboratory by graduate students. Three different paint systems were applied, inorganic zinc primer, organic zinc primer and organic zinc with an epoxy topcoat. All paints were the same type used in the factorial experiment, but in some instances the paints were from different lots. Three sandblasted specimens were bolted up by fabricators. Two connections were sent to Fabricators A and B, both of whom would be considered large fabricators handling steel fabrication for construction throughout the U.S. and some foreign countries. Through the cooperation of the engineering departments of these fabricators, assurances were made that no special techniques other than normal shop practice for friction joints would be used. No quality control inspection was performed. A final specimen was connected using torque-controlled LeJeune fasteners. These were installed by a field representative of the supplier, using fasteners from a single lot. Calibration tests were performed to establish the clamping force of the fastener was 42.7 kips.

Bolt clamping forces. In the connections tightened in the laboratory, at least three bolts of each 10-bolt group in each test joint were specially prepared to monitor bolt forces. All bolts were snugged and some re-snugged before each bolt was tightened. Bolts were first installed to one-third turn from snug, the normal installation requirement. Bolt elongations were recorded and the clamping forces determined from calibration curves. The bolts were then tightened further to three-quarter turn so all bolts would be in the flat plateau of the bolt-elongation response curve (Fig. 9) to minimize scatter in the clamping force.

Histograms of bolt elongation developed for the 12 or 16 bolts in each connection are also shown in Fig. 9. The clamping-force data at one-third turn are summarized in Table 4. The average clamping force at one-third turn was 20% higher than the minimum specified. As expected, the average installed bolt tension shown in Col. 7 showed very little scatter because of the installation method (three-quarter turn). The bolt forces were monitored for two weeks before conducting the slip test. Because the paint thicknesses were only about 4 mils, only small bolt relaxation due to creep was recorded (less than 10% of the initial tension). Most of the shortening occurred within the first week after bolting.[5]

In the specimens tightened by Fabricators A and B, all 40 bolts were from the same lot and ends were machined so the bolt elongation could be monitored. The connections had similar sandblasted surfaces, but they were not sandblasted at the same time as the laboratory specimens discussed in the previous section. Fabricator A developed 23% greater clamping force than Fabricator

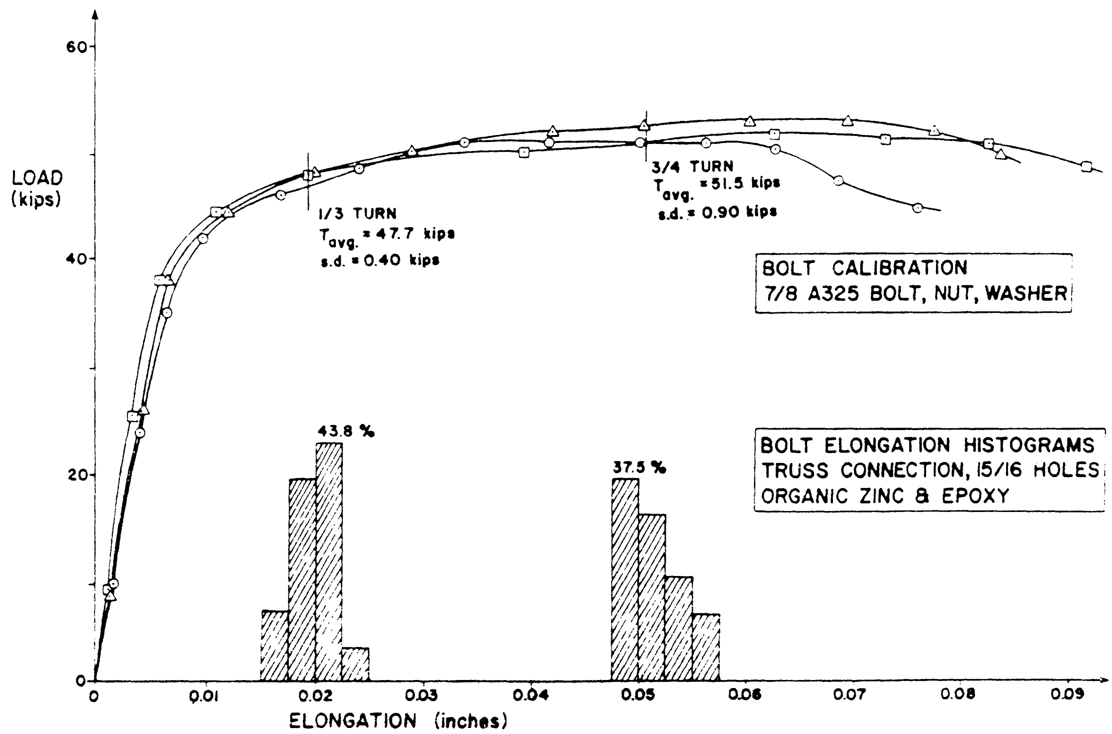

Fig. 9. Bolt force histograms and calibrations (1 kip = 4.45 kN, 1 in. = 25.4 mm)

Table 4. Measured Clamping Force for One-third Turns (1 kip = 4.45 kN, 1 in. = 25.4 mm)

Coating (1)	Size of Hole (in.) (2)	Number of Bolts Measured (3)	Maximum Torqued Tension Strength in Kips (4)	Mean Tension One-third Turn in Kips (5)	Col. (5) / 39 kips (6)	Installed Bolt Tension in Kips (7)	Col. (7) / 39 kips (8)
Organic zinc	15/16	32	52.0	47.8	1.22	51.7	1.33
Organic zinc	1-1/16	16	54.6	46.2	1.18	52.5	1.35
Organic zinc plus epoxy	15/16	16	52.0	47.7	1.22	51.5	1.32
Inorganic zinc	15/16	24	52.0	47.1	1.21	51.5	1.32
Inorganic zinc	1 1/16	12	54.6	45.6	1.17	52.0	1.33
Sand-blasted	15/16	16	52.0	46.4	1.19	51.3	1.32
				Average	1.20		

Table 5. Test Results, Full-Size Specimens

Test No. (1)	Contact Surfaces (2)	Hole Size (in.) (3)	Av. Paint Thick. (mils) (4)	Instld. Bolt Tension (kips) (5)	Loss in Clamping Force (kips) (6)	Slip Test Load (kips) (7)	Theo. Slip Load (kips) (8)	Allow. Load (kips) (9)	Col. 7 / Col. 8 (10)	Col. 7 / Col. 9 (11)
1	Inorg. Zn	15/16	4	51.4	5	466	513	354	0.91	1.32
	(0.55)*					497	513	354	0.97	1.40
2	Inorg. Zn.	15/16	3	51.5	4	446	525	354	0.85	1.26
	(0.55)					446	525	354	0.85	1.26
3	Inorg. Zn	1 1/16	3	52.0	4	434	531	300	0.82	1.47
	(0.55)					489	531	300	0.92	1.63
4	Org. Zn	15/16	4	51.8	5	445	346	252	1.29	1.77
	(0.37)					499	346	252	1.44	1.98
5	Org. Zn	15/16	4	51.6	4	438	352	252	1.24	1.74
	(0.37)					470	352	252	1.34	1.87
6	Org. Zn	1 1/16	4	52.5	5	393	352	216	1.12	1.82
	(0.37)					462	352	216	1.31	2.13
7	Org. Zn + Epoxy	15/16	4+2	51.5	7	229	214	---	1.07	---
	(0.24)					242	214	---	1.13	---
8	Blasted-Lab	15/16	-	51.3	-	533[a]	480	298	1.11	1.78
	(0.52)+					542[b]	453	281	1.20	1.93
9	Blasted-Fab. A	15/16	-	46.2	-	454	480	330	0.94	1.38
	(0.52)+					511	480	330	1.06	1.55
10	Blasted-Fab. B	15/16	-	37.7	-	288	392	330	0.73	0.87
	(0.52)+					356	392	330	0.91	1.08
11	Blasted-LeJeune	15/16	-	42.7	-	413	444	330	0.93	1.25
	(0.52)+					463	444	330	1.04	1.40

+ Average from Table 1 1 in. = 25.4 mm, 1 kip = 4.45kN [a] 18 bolts on slip surface [b] 17 bolts on slip surface

* Slip coefficient from control test

B, as shown in Table 5. The average clamping force of 37.7 kips (168 kN) developed by Fabricator B was slightly below the minimum specified 39 kips (174 kN).

The following items were observed during the installation process:

1. The connection was not brought to the snug position in the recommended manner;
2. The bolt head was not prevented from turning;
3. Wrenches were not calibrated for the bolts provided, even though the installation method resembled the calibrated wrench technique;
4. One wrench had no adjustment for controlling torque;
5. The operator could "tell by sound" when they were tight enough; and
6. There was a general unawareness of the RCSC Specification by the installers, and especially the required tightening procedure.

The LeJeune fastener installation followed the RCSC Specification. Bolts were first snugged with a small impact wrench and then the special wrench installed the bolts starting from the center of a bolt pattern and working towards the ends. Because the bolt has a twistoff end, no method was readily available to determine the actual installed clamping forces. It is assumed the clamping force is the same as that developed at twistoff in the bolt calibration, 42.7 kips (190 kN).

Slip tests. The results of the 11 full-size tests are given in Table 5. Two distinct slip loads could be detected for each specimen, except for Test 1. In Test 8, the load in the connection with 40 bolts reached the capacity of the machine without the slipping. The specimen was unloaded and two bolts removed from both sides of the vertical connection. Although this left only 16 bolts connecting the two sides of the vertical member to the plates, the first slip occurred at 533 kips (2,370 kN) on one vertical and one horizontal surface, which had 18 bolts in the slip plane. Further loading could not produce the second slip load, so an additional bolt was removed from the horizontal row. The slip load for the 17 bolts was 542 kips (2,412 kN).

The theoretical slip load in Col. 8 was determined by using Eq. 1, in which the clamping force used considered the average losses shown in Col. 6 and the actual number of bolts in the slip planes. The allowable load is based on the 1978 RCSC Specifications. When slip control specimens were not tested, the average slip coefficient was taken from Ref. 4. The control slip coefficients shown in Tests 1-7 are averages from three hydraulic bolt control specimen tests. No values of allowable load are shown for the epoxy topcoat since the RCSC Specification does not address that paint category.

Specimens with coated surfaces were disassembled for examination upon completion of the test. The significant contact zone was confined to a small area around the hole similar in size to the small compression specimen. This reinforces the premise that the slip coefficient from the small specimens can predict slip load in large connections.

Discussion of full-size tests. The ratio given in Col. 10 of Table 5 represents a comparison between the small slip test and the full-size connection. The results are quite reasonable, except for the organic zinc tests which have been underestimated significantly. This may be due to some control slip coefficients that are not representative. The average of three control organic zinc primer slip coefficients was 0.37. In Ref. 4, only seven slip coefficients out of 106 fall below this level. If the average organic zinc slip coefficient of 0.464 is used, the theoretical slip load becomes 434 kips (1,944 kN), which is in good agreement with the tests.

Col. 11 is a measure of the factor of safety against slip, but recall that the clamping force is higher than usual because of the three-quarter turn tightening procedure adopted. Since the slip load is directly related to the clamping force, then the maximum load would have been less if the recommended one-third turn approach was used. For example, Test No. 1 would have a factor of safety of $1.32 \times (47.1/51.4) = 1.21$. The factor of safety for the inorganic zinc specimen is low for Test 2. In fact, if the bolts had been installed by the turn-of-nut method using one-third turn, the average factor of safety for the six inorganic zinc tests would be 1.25. This average is consistent with the factor of safety against the mean of 1.24 derived by Fouad[4] using results in Ref. 3.

The results from connections bolted by the fabricators pointed out the shortcomings of using only laboratory data to develop design specifications. Consideration must be given to those factors which can reasonably be expected to occur in practice. The LeJeune bolts developed a clamping force 12% above the minimum specified and, with a slip coeffient of 0.52, gave a factor of safety of 1.25. This is actually consistent with the RCSC Specification, which has low factors of safety against the mean data for certain surfaces, as will be shown in the next section.

These full-size tests showed the number of control samples should be larger than three to develop reliable slip coefficients. Also, the loss in clamping force due to paint creep was greater than 10% for the 6-mil thick organic zinc with epoxy topcoat. This is consistent with other data developed from tension slip tests which are not included herein,[4] and the creep tests by others.[1,2]

The RCSC Specification requires a 15% reduction in allowable stress when oversize holes are used in the outer plies of a friction connection. This is due to a reported reduction in clamping force when turn-of-the-nut method is used to install the bolt, because of head dishing and local compression of the plates. The data for one-third turn shown in Table 4 give only a three percent reduction in clamping force, which is insignificant. There was no reduction due to oversize holes at the installed tension level because a three-quarter turn was used.

DESIGN RECOMMENDATIONS

In the 1966 RCSC Specification, the allowable bolt shear stress for friction connections of 15 ksi (103 MPa) for mill-scale surfaces was based on an ASC = 0.35, the minimum specified clamping force, and a factor of safety against slip of 1.51. Data collected since then give an ASC = 0.336 for millscale,[3] so the factor of safety using the 1966 stress level would be 1.45. The 1978 Bolt Spec has lower average factors of safety for some surface coatings, as shown in Table 6. Column 5 in the table is calculated as follows: ASC $\times$ 1.13 $\times$ specified clamping force $\div$ area of bolt = shear stress. The 1978 RCSC Specification relies on a clamping force 13% higher than the minimum specified, typical of the calibrated wrench tightening method.[3] Even with this reliance, the mean factors of safety against slip listed in Table 6 are as low as 1.20. Only a 10% probability of slip concept was used to develop the RCSC Specification, since slip was con-

Table 6. Mean Safety Factor for Different Surface Treatments

Surface Treatment (1)	Slip Coeff.* Ave. (2)	Slip Coeff.* Std. Dev. (3)	Specs Allowable Shear Stress (A325) in ksi (4)	Theo. Shear Slip Stress (A325) in ksi (5)	F.O.S. 1978 Bolt Spec. (6)
Mill scale	0.336	0.070	17.5	24.6	1.41
Blast-cleaned	0.493	0.074	27.5	36.1	1.31
Organic zinc-rich paint	0.350	0.035	21.0	26.7	1.22
Inorganic zinc-rich paint	0.500	0.050	29.5	36.6	1.24
Vinyl primer	0.270	0.023	16.5	19.8	1.20

* Ref. [3] 1 ksi = 6.9 MPa

sidered a serviceability problem, not a strength problem.

It is the authors' opinion that a dual criteria considering both the mean slip coefficient and the distribution of slip data (probability of slip) with the minimum specified clamping force be used to develop a sound allowable stress design specification *for situations in which joint slip could be detrimental to the structural integrity*. Examples of slip critical joints would be those with oversize holes, or slotted holes in the direction of applied stress, joints subjected to reversal of load and those in which both welds and bolts share the shear force. Joints with standard holes and multiple bolts subjected to static loads, such as floor live and dead loads, would not be considered slip critical because some bolts will always be in bearing, thus preventing any noticeable joint movement. Such joints should be designed on the basis of the shear capacity of the bolt and not the theoretical slip resistance of the connection.

The research summarized in this paper indicates the current RCSC Spec. for allowable bolt shear stresses in friction-type connections with painted faying surfaces is not reliable. The current format which gives allowable stresses for nine classes of surface treatment should be changed for the following reasons: First, within a paint category, the products may vary widely with respect to their frictional characteristics. For the three organic zinc primers studied herein, the ASC varied between 0.31 and 0.46. There are obviously other organic zincs which may fall outside the current bounds. Second, the variations which occur even for a particular coating do not justify three significant figures. Therefore, it is suggested the friction shear stress table be arranged as a function of slip coefficient, not particular painting groups. Four groups are suggested with slip coefficients of 0.2, 0.3, 0.4 and 0.5. The allowable stresses would be modified by factors for paint thickness, oversize holes, etc. The proposal presented above also requires development of a standard classification test which could be run by the paint manufacturers themselves to determine what category a particular product will fit. Questions related to curing time, time before assembly, etc., all have significant effects on slip resistance. Paint manufacturers must address these problems to get a paint classified. A draft of such a standard test is contained in Ref. 5.

SUMMARY AND CONCLUSIONS

The extensive research program undertaken revealed certain coatings with superior corrosion protection characteristics can be permitted on the contact surfaces of bolted joints without reducing the slip resistance below that for the base mill-scale condition. In general, coating the faying surface, or other forms of surface treatment such as blast-cleaning, reduces scatter in the slip performance of a bolted joint relative to the uncontrolled condition of a mill-scale surface. When the steel itself must be painted, more economical structures will result from the reduction of fabrication costs due to the elimination of the masking of faying surfaces. The maintenance cost of the structure will also be reduced by elimination of the unprotected edges at the periphery of a joint, which cause early coating failures.

The factorial experiments using the small compression specimens in which the clamping force was held constant during the test produced the following conclusions:

1. Paint thickness did not significantly change the slip coefficient of the coatings;
2. Hole size did not alter the slip coefficient of the coating;
3. The magnitude of the clamping force did not change the measured slip coefficient of the coating;
4. The type of steel on which the coating was applied did not change the slip coefficient of the coating;
5. The elapsed time between painting and testing influenced the slip coefficient of some coatings. Longer times, called curing time, produced higher slip coefficients. The increase in slip coefficient with time after assembling of a joint was small;
6. The slip coefficient of organic zinc paints are not single-valued, but they depend on the type of organic vehicle employed in the coating. Perhaps a similar behavior would be suspect with other generic paint categories.

The tests of large truss-type joints showed the behavior of these specimens could be predicted reliably using the small single bolt compression specimens. Significant reduction in the clamping force of the bolts was found for some coatings due to the compressive creep of the coating on the faying surface, and under the head of the bolt and nut. Truss joints tightened by turn-of-nut method in the laboratory indicated tightening to one-third turn past snug produced a clamping force 20% in excess of the minimum specified, but not as high as average for one-half turn data (35%). The joints tightened by the fabricators indicated variation in clamping force much larger than found in published literature. As a consequence of these data, it is the authors' opinion the minimum specified bolt tension be used in setting the allowable loads for slip-critical connections or proper inspection and quality control be established. Also, the use of oversize holes did not result in a significant reduction in clamping force for the ⅞-in. (22 mm) A325 bolts installed using one-third turn from snug. Current specifications imply a 15% reduction.

The results of the numerous slip tests performed on coated surfaces indicate many variables influence the performance of a coating. A slip coefficient, and consequently a design allowable stress for a coating, cannot be established reliably unless tests are performed on the particular coating. A test procedure for determining the slip coefficient is presented elsewhere.[5] Classification of surfaces into narrow slip range categories based on generic paint type as currently used in the 1978 RCSC Specification was shown to be unreliable. Different paint products within the same generic category gave a wide range of average slip coefficients. It is recommended that fewer surface categories be used, and based on slip coefficients rather than paint type. The slip resistance should only be considered for slip-critical design situations.

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