SLIP BEHAVIOR OF BOLTED FRICTION-TYPE JOINTS WITH COATED CONTACT SURFACES

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SLIP BEHAVIOR OF BOLTED FRICTION-TYPE JOINTS WITH COATED CONTACT SURFACES

by

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THESIS

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ABSTRACT

About 600 friction-type bolted joints were tested to evaluate the slip characteristics of five different coating systems on the contact surfaces and to study the influence of several variables on their slip behavior. The coating systems were: organic zinc-rich primer, organic zinc-rich primer with an epoxy top coat, inorganic zinc-rich primer with a vinyl top coat, powder epoxy, and a vinyl system. The variables considered were: the hole size (15/16, 1, and 1-1/8 in. diameter holes for a 7/8 in. diameter bolt), steel type (A36, A572, and A514), clamping force (39 and 49 kips), and paint thickness (thin, normal, and thick).

As a part of the testing program, curing time tests were conducted to determine the time required by each coating system to guarantee reasonable curing. Also, blast-cleaned uncoated surfaces were tested and the effect of the various variables on their slip behavior was studied.

The studies indicated that hole size, clamping force level, and paint thickness were insignificant variables and had very slight effect on the slip behavior of the joints. Joints of A36 steel showed a slight increase in the slip resistance compared to the A572 and A514 steel joints which provided about the same slip resistances.

Based on the test results, allowable bolt shear stresses for friction-type joints with coated contact surfaces are provided. Comparisons are made with current bolt specifications.

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CHAPTER 1

INTRODUCTION

1.1 General

High-strength bolted friction-type connections are designed to transmit service load shears by friction produced between the faying (contact) surfaces by the clamping action of the bolts. For this type of joint, slip constitutes failure. Movement of the connected parts is not tolerated because of the detrimental effects on the behavior of the structure.

Because early tests showed that paint on the contact surfaces reduced the slip resistance, coatings were prohibited on contact surfaces of friction-type joints. When applying protective coatings to structural steel, the contact surfaces were masked-off, thus increasing the cost. In severe environments the unpainted contact surfaces resulted in crevice corrosion. In some instances this corrosion caused separation of the plates and elongation of the fasteners.

A solution to these problems would be to coat the faying surfaces with a corrosion inhibitive paint during shop fabrication, provided satisfactory slip resistance could be developed. However, data on the slip characteristics of joints coated with these special paints are limited and show considerable scatter.

In summary, significant monetary savings should accrue to the owners of structural steel bridges or other steel structures as the result of an acceptable coating for contact surfaces of friction-type joints. These benefits would be due to reduced maintenance and a reduction in initial paint application costs.

1.2 Historical Review of Structural Steel Coatings

Corrosion protection for exposed steel structures has been the aim of engineers for many years. The annual expenditure for protecting the structural steel on interstate highways, a large part of which consists of bridges, has been estimated to be more than two billion dollars [1]*. An estimated one million highway bridges exist in the United States. Coatings provide corrosion protection for these structures and make valuable contributions to their safety and appearance. Painting is the principal method of protecting steel structures.

Until about fifteen years ago, alkyd paints or linseed oil loaded with red lead were the standard ways to protect exposed steel. Five to seven years was the typical life before repainting was required. Recently, zinc-rich coatings have come into prominence because they can effectively protect the steel up to twenty years. Zinc protects steel by electrolytic or galvanic action, because of its high position in the galvanic series. In a corrosive atmosphere zinc sacrifices itself slowly (oxidizes) and leaves the steel surface protected. In recent years, zinc dust has been used more and more for heavy anticorrosive service in primers based on a growing array of organic and inorganic binders.

Another distinguished coating material is vinyl. It is a high performance coating for use in corrosive environments and its life expectancy is fifteen years or more. Excellent epoxy coatings have also been developed. They are highly abrasion resistant and have excellent corrosion protective qualities. Their outdoor life is from fifteen to twenty years.

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*Numbers in brackets refer to the references in the Bibliography.

Most coatings are used in systems usually consisting of a primer coat, one or more intermediate coats, and a top coat. The primer coat is used to link the substrate to the coat or coats that provide the greater part of the protection. Intermediate coats are usually of the same material as the primer coat. The top coat protects the underlying coats, provide a mechanical barrier and in some instances add aesthetic value.

A good example to show the effectiveness of the above-mentioned coatings is the Golden Gate Bridge [2]. About three to six years was all the Golden Gate Bridge's paint system was good for, before repainting was required. This was considered a good performance, since the bridge has one of the worst salt-air environments on the West Coast. However, studies were undertaken and a new paint system consisting of a zinc-rich primer and a vinyl wash tie coat was selected. It was estimated that this new system will last for at least twenty years, thus increasing the paint life expectancy by three to six times.

1.3 Current Practice

Most specifications, until 1974, prohibited the use of any type of coatings on contact surfaces of friction-type joints. As an example of such specification is the American Association of State Highway and Transportation Officials (AASHTO) Specifications of 1973 [3]. However, in 1975 AASHTO adopted a revised specification which permitted certain coatings of the contact surfaces [4]. The permissible coatings were: hot-dip galvanizing, inorganic zinc-rich paints, and metallized zinc or aluminum. Tests have indicated that these coatings have slip resistances higher than uncoated blasted surfaces. In February 1976, the Research Council on Riveted and Bolted Structural Joints revised their Specifications for Structural Joints Using ASTM A325 or A490 Bolts (Bolt Specification) [5]. For friction connections the new Bolt Specification recognizes that the type of surface affects the friction characteristics, and hence the allowable shear stresses, as shown in Table 1.1, which is a reproduction of Table 2a in the Bolt Specification (1976) [5]. This table was developed mainly from the research summary by Fisher and Struik [6]. In some instances the allowable stresses were based on just a few tests, as well as certain limitations. For example, tests done on organic zinc-rich paint were very few and involved very small paint thicknesses (0.8 to 1.2 mils*), while, in fact, paint specifications [7] require thickness of at least 3 mils. No tests were done on coated friction joints with oversize holes. Values listed in the table for oversize holes for different surface treatments were based on uncoated mill scale test joints. The values as listed for A325 and A490 bolts are in the ratio of the minimum specified clamping forces of the bolts. Effect of the clamping force level on the slip characteristic was not studied. Also, there were no tests on paint systems with top coats, although such systems are used extensively due to the better corrosion protection they offer. The Bolt Specification considers only a vinyl wash, while, in fact, vinyl primers and vinyl systems are very popular.

There is a need for an experimental study to investigate the effects of variables such as paint thickness, top coats, oversize holes, etc., on the slip behavior of friction-type joints. Such studies may lead to a better and more reliable specification for friction-type joints.

1.4 Objective and Scope

The objective of this research is to experimentally evaluate the slip resistance of friction-type structural connections with corrosion inhibiting coatings on the contact surfaces. Five coating systems, three of which had top coats, were selected for study and

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*1 mil = 0.001 in.

TABLE 1.1 ALLOWABLE WORKING STRESSES, KSI, BASED UPON SURFACE CONDITION OF BOLTED PARTS, FOR FRICTION-TYPE SHEAR CONNECTIONS

Class	Surface Condition of Bolted Parts	Standard Holes		Oversize Holes and Short Slotted Holes		Long Slotted Holes	
		A325	A490	A325	A490	A325	A490
A	Clean mill scale	17.5	22.0	15.0	18.5	12.5	15.5
B	Blast-cleaned carbon and low alloy steel	27.5	34.5	23.5	29.5	19.5	24.0
C	Blast-cleaned quenched and tempered steel	19.0	23.5	16.0	20.0	13.5	16.5
D	Hot-dip galvanized and roughened	21.5	27.0	18.5	23.0	15.0	19.0
E	Blast-cleaned, organiz zinc rich paint	21.0	26.0	18.0	22.0	14.5	18.0
F	Blast-cleaned, inorganic zinc rich paint	29.5	37.0	25.0	31.5	20.5	26.0
G	Blast-cleaned, metallized with zinc	29.5	37.0	25.0	31.5	20.5	26.0
H	Blast-cleaned, metallized with aluminum	30.0	37.5	25.5	32.0	21.0	26.5
I	Vinyl wash	16.5	20.5	14.0	17.5	11.5	14.5

Source: Reference 5, Table 2a.

evaluation. A description of the coating systems and the basis of their selection is given in Chapter 2. This research will also evaluate the effect of some of the factors affecting joint slip, such as the steel type, paint thickness, clamping forces, and hole size. A sufficiently large number of tests were planned so that these various factors could be evaluated using reliable statistical techniques. The statistical design of the experimental study is given in Chapter 3.

A test setup was developed for the efficient experimental evaluation of the slip resistance. It is discussed in detail in Chapter 4. A total of about 600 tests were performed to determine the curing time for the different paints and to obtain the desired data on the painted and blasted surfaces. Results of the tests are presented in Chapters 5, 6, and 7. The discussion of the test results is given in Chapter 8. Chapter 9 provides a summary of important results and conclusions, and establishes design recommendations for friction-type joints.

CHAPTER 2

COATING SYSTEMS

2.1 General

In this research work, several different coating systems were evaluated with respect to their friction characteristics when applied on structural joint contact surfaces. These coating systems were chosen to have excellent corrosion protection properties and a longer life expectancy before repainting.

A literature survey was undertaken to determine the five systems to be used in the bolt friction-type connection tests.

2.2 Literature Survey

The American Association of State Highway and Transportation Officials (AASHTO) recently adopted a revised specification [4] which permits the use of selected materials for coating the contact surfaces of structural steel friction-type joints. The permissible coatings are: (1) hot-dip galvanizing, (2) inorganic zinc-rich paints, and (3) metallizing by zinc or aluminum. Tests have shown that these materials have greater slip resistance than unpainted blast-cleaned steel. Therefore, an extensive literature search was made to help select other coating systems which are highly corrosion resistant but are not currently approved for the contact surface of friction-type bolted connections by the AASHTO Specification.

In 1974 the National Bureau of Standards (NBS) reported on the suitability of various coating systems for protecting steel reinforcing bars against corrosion [8]. Forty-seven different coating materials were studied to identify those which would provide both adequate coating protection for bridge deck reinforcing steel and satisfactory structural performance. Four powdered epoxy coatings were recommended which were deemed to contain the necessary qualities. The recommended optimum film thickness of epoxy films on steel reinforcing bars was about 7 ± 2 mils. Also, the results of the NBS project indicated that a polyvinyl chloride coating, if properly applied, should adequately protect steel reinforcing from corrosion. However, only the epoxy coated bars had acceptable bond and creep characteristics when embedded in concrete.

While the NBS work indicated the superiority of powdered epoxy coatings, such coating have a significant drawback for large structural joints. The steel joints are dipped in a bath of epoxy, which restricts the application of such coatings to small structural pieces that will fit in the epoxy tanks. Another drawback of epoxy coatings is the high curing temperatures, controlled atmosphere, and the special equipment they require.

The literature pertinent to the offshore structures industry was surveyed to determine the organic coatings most extensively used in protection of offshore structures. The American Petroleum Institute is currently developing corrosion specifications for use on offshore structures [9]. Three of the approved systems are: (1) a zinc-rich primer (inorganic or organic) with an epoxy top coat, (2) a zinc-rich primer (inorganic or organic) with a vinyl top coat, and (3) a wash primer with a vinyl top coat. The components of these approved systems were studied by NBS and have established a satisfactory performance record of corrosion resistance.

The Steel Structures Painting Council (SSPC) [7] was a valuable source of information on current painting systems. The SSPC (1973) Paint System Specifications contains specifications for a wide variety of steel structures and conditions of use and exposure. The purpose of these systems is to outline a limited number of complete schemes of suitable procedures and paints that will result in satisfactory paint performance. These Paint System Specifications give surface preparation, paint application procedures, type of material for each coat, film thickness, and special procedures and requirements. The most appropriate general types of paint systems for a particular painting service or exposure can usually be selected from tables. Four of the recommended paint systems by SSPC are:

(1) Zinc-rich coating systems [SSPC-PS 12.00] which are recommended for use under conditions of high humidity or marine atmospheric exposures, and for fresh water immersion. By proper topcoating, they may be used in seawater immersion and for exposure to chemical fumes.

(2) Epoxy paint systems [SSPC-PS 12.00] which are recommended for industrial exposure, marine environment, fresh and salt water immersion, and areas subject to chemical exposure such as acid and alkali.

(3) Vinyl paint systems [SSPC-PS 4.00] which are recommended for very severe exposures, including most chemical atmospheres, water immersion, and corrosive environments.

(4) Alkyd paint system [SSPC-PS 2.00] which is recommended for severe weather exposure. It has limited resistance to strong chemical environments and complete immersion in fresh or salt water.

The National Cooperative High Research Program Report 74 on "Protective Coatings for Highway Structural Steel" [1] provides a summary of painting practice in most states. Three of the most recommended coating systems are:

(1) Zinc-rich primer with a finish coat such as vinyl [recommended SSPC-Paints 8 or 9]. This system is recommended for environments frequently wet by salt water.

(2) Zinc-rich primer with a finish coat such as epoxy [for example SSPC-Paint 16]. This system is recommended for environments subject to chemical exposures.

(3) Four coats of vinyl paint for a total dry film thickness of at least 4.5 mils. This system is recommended for environments frequently wet by fresh water.

Discussions were held with paint manufacturers, highway department experts, and steel fabricators to obtain opinions on specific paint products, application of paints, surface preparation, field experience, pain film thickness measurement, and cost. Based on these discussions and the limited number of systems to be studied, it was decided to use paint products from a single manufacturer (Carboline, Inc.). This permitted the study of compatible primers and top coats.

2.3 Selected Coating Systems

The literature search indicated that there are several types of corrosion inhibiting coating systems which should be considered for use on structural joint contact surfaces. The following protective coating systems were first considered to be serious candidates for testing:

(1) organic zinc-rich primer
(2) organic zinc-rich primer with an epoxy top coat
(3) inorganic zinc-rich primer with a vinyl top coat
(4) powder epoxy
(5) vinyl

According to present painting practice, top coats are usually applied after erection. However, as painting technology advances, there will be a trend to shop-applied primer and single top coat and one field coat or field-applied top coat before erection. This was the main reason for selecting systems with top coats in this study, since the present practice of masking-off the contact surfaces of the bolted friction joints when applying top coats is costly. Also, previous research work on coated friction joints did not consider paint systems with top coats on the contact surfaces.

2.4 Discussion of Selected Coating Systems

The five painting systems described previously are discussed in detail in this section. Since some tests were conducted on inorganic zinc-rich primer, this system will also be discussed.

2.4.1 Organic Zinc-Rich Primer. Organic zinc-rich paints have a minimum zinc content of 80 percent by weight of the nonvolatile portion according to SSPC Specification (SSPC-PS 12.00-68T). Simply, they are an organic primer with large quantities of zinc dust. They require a near-white metal blast-cleaned surface for best results, and are usually applied in one coat with a minimum average dry film thickness of about 3.5 mils over the cleaned steel, according to the SSPC Specification. Compared with the inorganics, the organic coatings are generally more tolerant of variation in surface preparation quality. They tend to have better compatibility with top coats and to be more flexible.

Organic zinc-rich paints are mainly intended for use under conditions of high humidity or marine atmosphereic exposures and for fresh water immersion. They are commonly used on bridges in severe environments.

Current specifications and practice require at least a 3 mil thickness (Texas Department of Highways and Public Transportation requirements are 3.5 mils minimum to 10 mils maximum). However, most of the friction-type joint tests which have been conducted up to the present time by other researchers used thicknesses which were less than 1.5 mils. Thus, the effect of increased thickness on the friction characteristics is not known.

2.4.2 Organic Zinc-Rich Primer with an Epoxy Top Coat.

The epoxy polyamide widely used as a top coat is a two-component system and is usually applied in one coat at a thickness of 3 to 6 mils. This coating is capable of providing long-term protection to steel surfaces in environments involving fresh or seawater immersion, tidal and splash zone exposure, condensation, burial in soil, and exposure to brine, crude oil, alkalis, chemical fumes, and chemical splashings.

The organic zinc-rich primer with an epoxy top coat system has been used successfully for protecting offshore oil drilling platforms and is recommended by the American Petroleum Institute (API) for use on offshore structures. No friction-type joint tests have been conducted with this system on the faying surfaces of the joints.

2.4.3 Inorganic Zinc-Rich Primer with a Vinyl Top Coat.

The inorganic zinc-rich primer must have a minimum zinc content of 75 percent by weight of the nonvolatile portion (SSPC-PS 12.00 6BT). Usually the coating is supplied with the zinc dust packaged separately to be mixed at the time of application with the inorganic vehicle, i.e., silicates, silicate esters, or phosphates. As in the case of organic zinc-rich primers, inorganic coatings have outstanding ability to withstand exposure to solvents, oils, and most petroleum products, and are very resistant to high humidity, splash, and spray. However, they are unsuitable for acidic or alkaline service without overcoating, and should be top-coated for prolonged continuous salt water exposure.

The vinyl top coat is suitable for fresh water immersion, industrial, rural, and marine atmospheres, and chemical exposures. It is applied at thicknesses of 3 to 5 mils in one coat.

The inorganic zinc-rich primer with a vinyl top coat system is also recommended by the API in its corrosion specification.

The reason for selecting this system is to study the effect of the top coat and its friction characteristics, since most of the previous research considered only the inorganic zinc-rich primer without a top coat.

2.4.4 Vinyl System. The Steel Structures Painting Council recommends this system for highway bridges exposed mainly to fresh water. Vinyl paint systems are excellent for very severe exposures, including most chemical atmospheres, and are highly recommended for complete or alternate immersion in fresh or salt water, high humidity, and condensation, and exposure to the weather. Usually the vinyl system is required in three or four coats as a minimum, according to the severity of the exposure, and is applied with a dry film thickness of about 1.5 mils per coat. This system does not require as careful a surface preparation as systems described in Secs. 2.4.2 or 2.4.3.

Joint tests have been conducted with faying surfaces treated with a vinyl wash (less than 1 mil thick). No tests have been conducted for thickness approaching the recommended values. In this research, both a vinyl primer applied in two coats, and a vinyl primer applied in two coats with a vinyl top coat were studied. Thickness ranges from 3 mils for the former system to 6 mils for the latter system (all-vinyl system).

2.4.5 Powder Epoxy System. Initially, this system was selected as one of the main systems in this study, since powdered epoxies proved to be the best performers in the rebar study conducted by NBS. However, there is some question related to the practicality of the system for large structural components, since high heat and controlled atmosphere is required. Cross sections up to 4 ft. x 4 ft. can only be handled by specialists. Thus, powdered epoxy was eliminated from being one of the main coating systems extensively tested in this research work.

Preliminary tests on specimens coated with powder epoxy (Scotchkote #202 - approved AASHTO coating for steel reinforcing bars) gave slip coefficients which were too small to provide a reasonable shear strength in a friction-type bolted joint. Thus, the powder epoxy system was not considered seriously in this research and only a few tests were conducted.

2.4.6 Inorganic Zinc-Rich Primer. (This system was described briefly in Sec. 2.4.3.) The inorganic zinc-rich system (silicate base) has been tested for friction-type bolted joints by several researchers. Tests by W. H. Munse at the University of Illinois found that this type of coating gives a satisfactory slip coefficient under static loading. These findings were confirmed by G. C. Brookhart at the University of Washington [10], who concluded that inorganic zinc-rich paint sprayed on a sandblasted surface gives a slip coefficient slightly superior to that for untreated sandblasted surfaces. In addition, inorganic zinc-rich coatings are currently permitted by AASHTO Specifications. Thus, this system was not considered seriously in this research, and only a few tests were conducted on inorganic zinc-rich coated specimens for comparison purposes and for the sake of determining the curing time of this coating (see Chapter 5).

2.5 Summary

Based on the literature survey, four paint systems were selected to be studied and tested with respect to their firction characteristics when applied on the contact surfaces of friction-type bolted structural joints. The four paint systems are:

(1) Organic zinc-rich primer
(2) Organic zinc-rich primer with an epoxy top coat
(3) Inorganic zinc-rich primer with a vinyl top coat
(4) Vinyl system

These selected systems have superior corrosion protection properties and are usually recommended for highway bridges and important steel structures.

It should be noted at this early stage of the report that current trends for protecting steel against corrosion involve paint systems at least 4 mils thick. The paint thickness on the faying surfaces of friction-type structural joints tested to date has been usually less than 1.5 mils, conforming to past painting practices. Therefore, for all the above-discussed coating systems, a paint thickness of at least 3 mils is used on each plate in contact.

CHAPTER 3

DESIGN OF THE EXPERIMENTAL STUDY

3.1 Research Program

The effect of several variables on the slip behavior of friction-type bolted joints with coated contact surfaces was the main concern of this research. The basic variables which were considered are:

(1) Types of steel: A36 (F_y = 36 ksi), A572 (F_y = 50 ksi) A514 (F_y = 100 ksi).

(2) Hole sizes for 7/8 in. fastener: Standard D = 15/16 in., Oversize D = 1 in., Oversize D = 1-1/8 in.

(3) Clamping forces: 39 kips and 49 kips, corresponding to the minimum specified clamping force for 7/8 in. A325 and A490 bolts, respectively.

(4) Paint systems: four paint systems as described in Chapter 2.

(5) Paint thickness: thin (~ 3 mils), normal (~ 6 mils), thick (~ 9 mils).

Only one fastener size, 7/8 in. diameter, was used throughout the research program. These variables were studied statistically, using a factorial experiment design.

3.2 Factorial Experiment Design

The experiment design was a factorial design. This will allow a statistical analysis of the results and provide a firm basis for the 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 the levels of every other factor in the experiment. It should be pointed out that a factorial experiment design is more efficient than a one-factor-at-a-time experiment, since it requires a smaller number of tests to be performed. Also, in a factorial experiment design, some information is gleaned on possible interaction between the variables considered in the experiment.

The typical factorial experiment designs are shown in Tables 3.1, 3.2, and 3.3.

TABLE 3.1 STEEL TYPE FACTORIAL EXPERIMENT

Clamping Force	Steel Type		
	A36	A572	A514
39^k	5	5	5
49^k	5	5	5

TABLE 3.2 PAINT THICKNESS FACTORIAL EXPERIMENT

Clamping Force	Steel Type					
	A572			A514		
	Thickness Type			Thickness Type		
	Thin	Normal	Thick	Thin	Normal	Thick
39^k	5	5	5	5	5	5
49^k	5	5	5	5	5	5

TABLE 3.3 HOLE SIZE FACTORIAL EXPERIMENT

Clamping Force	Hole Size (in.)		
	15/16	1	1-1/8
39^k	5	5	5
49^k	5	5	5

Table 3.1 shows a data layout for the "steel type" experiment. The number 5 in each box represents the number of replications per cell. The experiment is a 3 x 2 factorial experiment and was repeated for each of the four selected coating systems. In this experiment the paint thickness and hole size were not variables; that is to say, all specimens for a paint system had the same hole size (15/16 in.) and about the same paint thickness (normal ~ 6 mils). Table 3.2 shows a data layout for the "paint thickness" experiment. This experiment is a 2 x 3 x 2 factorial experiment, and was repeated for each of the selected paint systems (excluding the vinyl system). It should be pointed out that Columns 2 and 5 concern tests which were already considered in Columns 2 and 3 in the "steel type" experiment. Thus, no additional testing was done in this case; that is, Columns 2 and 5 in Table 3.2 shared the same test data with Columns 2 and 3 in Table 3.1 for each paint system. Table 3.3 shows a data layout for the "hole size" experiment. This experiment is a 3 x 2 factorial experiment and was repeated for each of the selected paint systems (excluding the vinyl system). Again, Column 1 in this experiment shared test data with Column 2 in Table 3.1.

The program described above was the main experiment design. An additional experiment was performed to study the effect of the percentage of zinc by weight in inorganic zinc-rich coating on the slip behavior. The experiment design was a one-factor design, as shown in Table 3.4.

TABLE 3.4 PERCENTAGE ZINC BY WEIGHT

	Percent	
80	75	0
10*	5	5

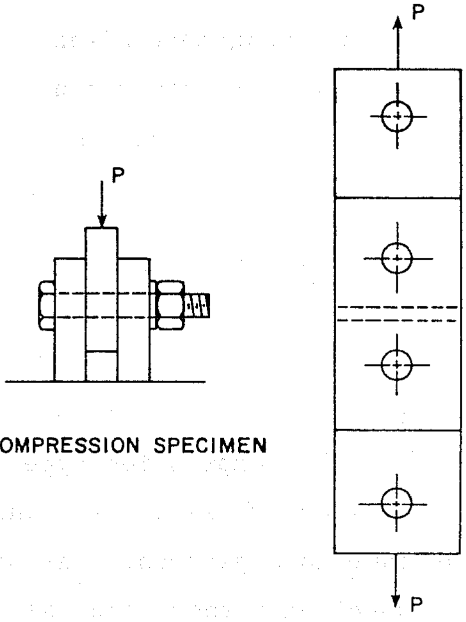
*Number of tests.

The total of about 400 tests was required to complete the factorial experiment arrangement given in Tables 3.1 through 3.4. An additional 200 tests were conducted to study uncoated blast-cleaned surfaces and paint curing time. The order of experimentation was randomized within practical limits.

3.3 Test Arrangement and Specimen Design

Because of the large number of slip tests required, the test setup was designed to keep testing time and specimen fabrication to a minimum. The compression-type slip setup shown in Fig. 3.1(a) accomplished these goals. This setup requires three plates with the same hole pattern. The shearing load is applied directly to the specimen without the use of the additional end fixtures usually required for the tension arrangement shown in Fig. 3.1(b). Hechtman [11] reported slip tests using both the tension and compression arrangements which showed that the compression setup produced slightly higher mean slip resistance compared to the tension setup (12 percent for mill scale surfaces). However, Hechtman attributed this difference to normal scatter in the test results, which are approximately 10 percent of the mean.

It has been reasoned that in a compression-type slip test, the Poisson's ratio effect may lead to an increase in the bolt force and consequently an increase in the slip load [6]. This objection was eliminated in the test setup shown in Fig. 3.2, where the clamping force is applied by means of a high-strength steel rod acting with a centerhole hydraulic jack. The actual details of this simulated bolt arrangement are discussed in Sec. 4.2. This setup provided the same contact surface clamping conditions as a standard bolted connection, with the added advantage of clamping force control which eliminated the bolt variations and calibrations encountered by other researchers. It might also be noted that a similar



(a) COMPRESSION SPECIMEN

(b) TENSION SPECIMEN

Fig. 3.1 Schematic of test specimens

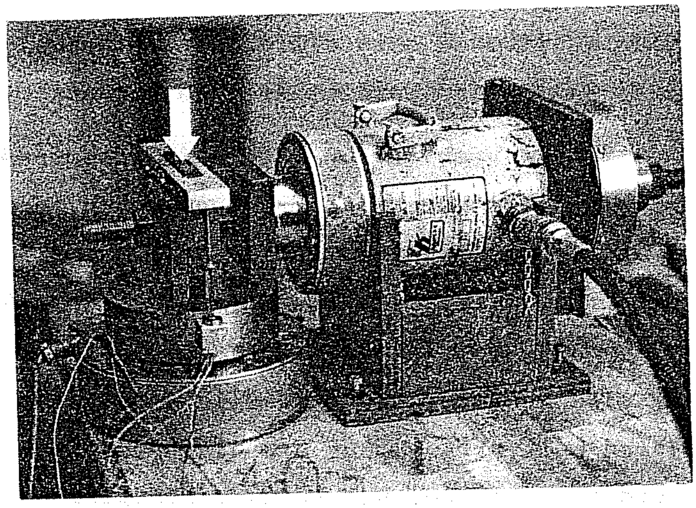


Fig. 3.2 Test setup

setup was used in Japan [12]. Thus, it was expected that the compression slip test with the "hydraulic bolt" would not result in higher slip resistance compared to a tension type test.

Pilot tests were conducted to compare results from the adopted test setup with results previously reported from tension-type tests and to finalize the plate size for the compression specimens. These tests are discussed in the next section.

3.4 Pilot Tests

The main purpose for conducting the pilot tests was to check the suitability of the test arrangement and to aid in choosing the specimen size. Tests were performed on clean mill scale specimens and on blast-cleaned specimens. Two specimen sizes were considered: a 4 x 4 in. and a 5 x 6 in. specimen size.

The test setup performed very well. The results of the slip tests were evaluated and found to give values which were consistent with the work of other researchers. Results of the 4 x 4 in. specimens were compared with the results of the 5 x 6 in. specimens and were found to be almost identical (mean slip load of 47.4^k vs. 50.1^k, respectively, for sandblasted clean surfaces). The contact areas for both specimen sizes were marked and measured after testing, and it was found that they were about the same.

Based on the pilot tests, the test setup was judged to give reliable results. Also, it was decided that a 4 x 4 in. specimen would be used. The smaller specimen size was chosen because it was expected to have less error of form and to be more practical.

CHAPTER 4

TEST PROGRAM

4.1 Specimens

4.1.1 Description. The test specimens for this study were double lap joints with one bolt hole, and had the geometry shown in Fig. 4.1. Each joint consisted of three identical plates which were bolted up by a steel rod 7/8 in. in diameter using the test setup. The clearance in the holes was either 1/16 in. (standard), 1/8 in. or 1/4 in. (oversize holes).

The joints were fabricated from three types of steel: A36, A572, and A514. The three steel types were cut from plates 5/8 in. thick, 4 in. wide, and 20 ft. long.

4.1.2 Fabrication. The test specimens were fabricated in the Civil Engineering Structures Research Laboratory (CESRL) at The University of Texas at Austin's Balcones Research Center, under the direct supervision of the writer.

Each plate length (5/8 in. x 4 in. x 20 ft. long) was cut into square plates 4 in. x 4 in. using a power hacksaw, and the sharp cut edges were filed. The three square plates (4 x 4 in.) which formed a specimen were chosen from the same plate length. An index, which was punched on the edge of the plates, was used to describe the experimental condition of the particular specimen (see Appendix A). Each group of three plates forming a specimen was aligned and clamped together in a vice prior to drilling. Then, a pilot hole 3/8 in. in diameter was drilled through them in one operation. The required holes (either 15/16 in., 1 in. or 1-1/8 in.

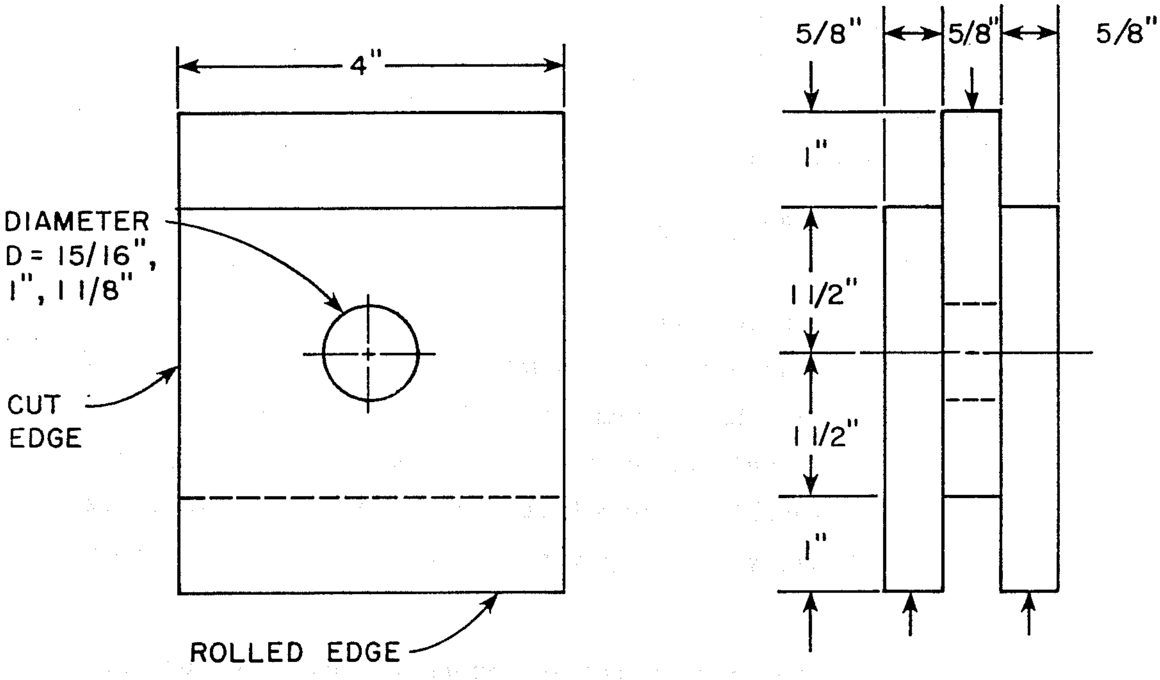


Fig. 4.1 Test specimen

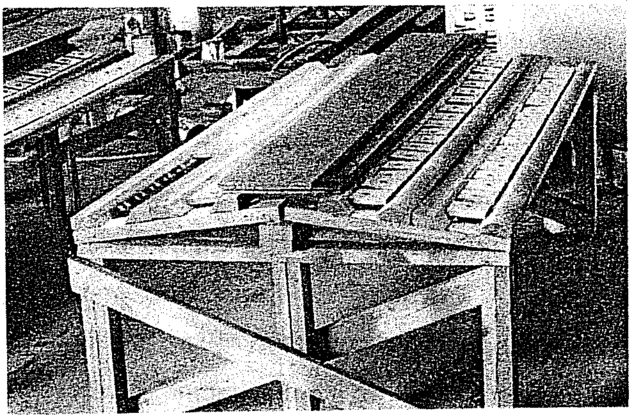


Fig. 4.2 Painting racks

diameter) were then drilled through each plate separately. This operation was repeated for every specimen and assured proper alignment of holes. The edges of the drilled holes were countersunk to remove burrs. During all the phases of fabrication, the steel was in the as-received mill scale surface condition.

4.1.3 Preparation and Painting Procedure. Specimens were sent in groups to be sandblasted at a local sandblasting shop. The steel surfaces were specified to be blast-cleaned to a white metal finish by dry sandblasting and meeting the requirements of the SSPC-SP5-63 [7]. Each group consisted of twenty to thirty specimens; some were to be painted by one of the selected coating systems, and the rest were used as control test specimens with blast-cleaned surfaces. Usually, for every ten specimens there were four control specimens.

After the specimens were brought back from the sandblasting shop, all surfaces were cleaned off with acetone to remove any sand particles or dust and were then ready for painting. The surface roughness of the control specimens was studied using the Keane-Tator surface comparator (discussed in detail in Chapter 6). Usually the sandblasted control specimens were tested within a week from sandblasting.

All painting was done in the laboratory according to the paint manufacturer's as well as painting experts' recommendations. A Devilbiss MBC-510 spray gun and a pressure cup were used for all the painting. Figure 4.2 shows the specially designed racks which were built to control overspraying of the specimens and to minimize surface disturbance of the painted surfaces. Directly before every painting of a group of specimens, several cold formed steel panels (1/16 x 4 x 4 in.) with smooth surfaces were used for practice spraying in order to achieve a good spraying pattern, to set the valves of the spray gun, and to develop a spraying tempo which would give the required wet film thickness. This operation usually consumed about thirty minutes. Some of the steel panels were also placed on the racks with the original specimens so that the dry film thickness could be measured using a destructive paint-measuring device (Tooke gage) as explained in the next section.

The wet film thickness used provided a dry film thickness of 3 mils per coat at most. This was based upon recommendations from paint experts.

The curing time between the application of one coat and another was usually 24 hours (minimum time specified by paint manufacturers was usually less than that). However, if the specimens were to be top-coated, the primer was left to cure for a particular number of days, based on the curing tests discussed in Chapter 5. After all the coats were applied, the specimens were placed in an air conditioned room (at room temperature) to cure before testing, as explained in Chapter 5. It might also be mentioned that the inorganic zinc-rich paint required a humid atmosphere to cure well. Thus, the painted specimens were covered by wet burlap (at least one hour after painting) to provide the recommended atmosphere.

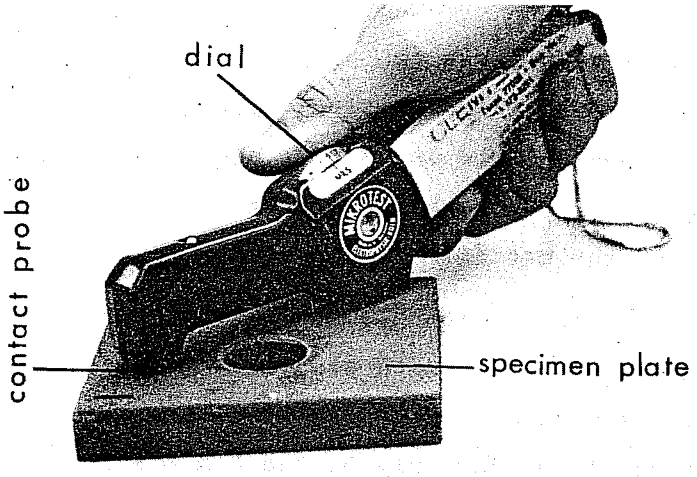
On an average, a group of twenty to thirty specimens was sent every week for sandblasting. A group of this size was found to be most practical both in handling and in painting.

4.1.4 Paint Film Thickness Measurement. The paint film thickness was one of the important variables considered in this research study; therefore, an investigation of available film-thickness measurement procedures and techniques was undertaken. The SSPC Manual (Vol. I, pp. 122-124) [7] and the NCHRP report on "Protective Coatings for Highway Structural Steel" [1] were valuable sources of information on film-thickness measurement devices. Based on this literature survey, three instruments which are most commonly used were used for measuring the film thickness in this research study. A brief description of the three film thickness gages and the principle of their operation is given below.

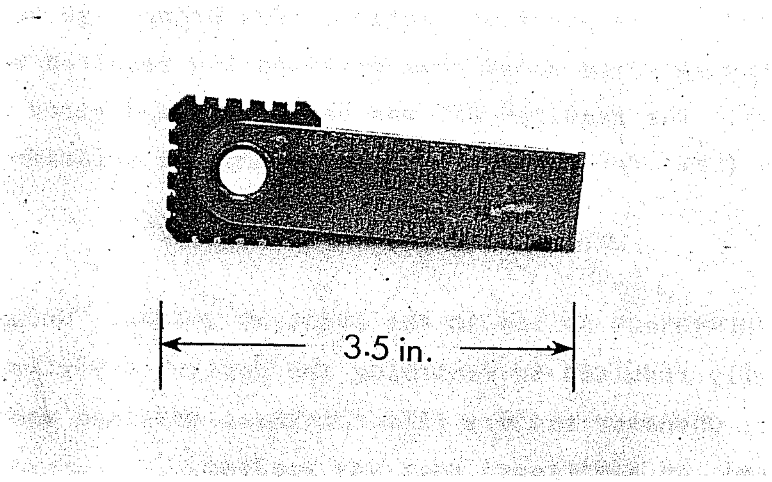
(1) Tooke Gage. This is a scratch-type gage which is slightly destructive. It operates on the principle of cutting the coating film at a predetermined angle, normally 45°, magnifying the view of the cut, and comparing the cut edge of film to a calibrated scale viewed in the eyepiece (see Fig. 4.3). The Tooke gage is an indispensable tool when multiple coats at specified thickness are used, because the thickness of each coating can be determined, provided there is a color contrast between coatings.

(2) Mikrotest Gage. It is a nondestructive magnetic gage used only to measure nonmagnetic coatings on ferrous substitutes. The Mikrotest utilizes one contact probe and measures the magnetic flux between this probe and a ferrous substitute by means of a balanced mechanism. To measure a coating thickness using the Mikrotest gage, the dial should be turned to maximum reading and the contact probe is placed on the surface to be measured. The dial should then be slowly rotated toward decreasing thickness until the magnetic contact breaks. At this point, a click will be heard. The coating thickness can then be read on the dial indicator (see Fig. 4.3).

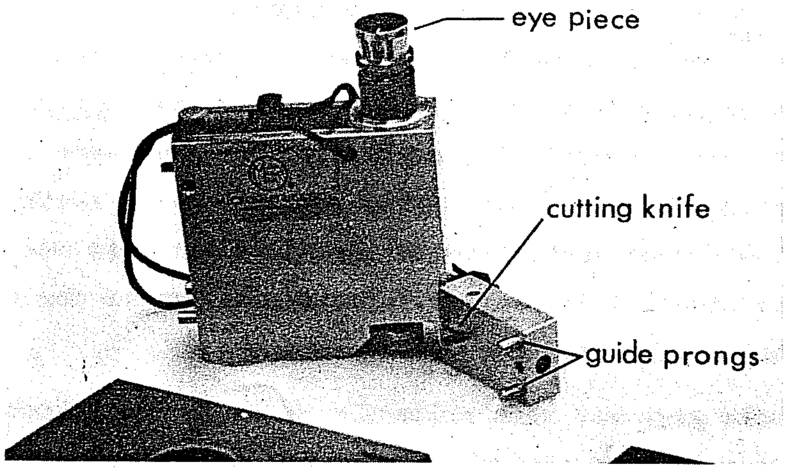
(3) Prong Gage (wet thickness). As shown in Fig. 4.3, the two outside prongs form a reference plane. The inner prongs are machined to various distance variations from this reference plane. The distance or gap between the prongs and reference plane is marked on the prongs in mils. To determine wet film thickness with the prong-type gage, both side prongs should be pressed firmly against the substrate while maintaining the gage perpendicular to the surface. The tips of the measuring prongs are then observed. If the face of a prong is partially coated with paint, the marking on that prong indicates the thickness of the coating. If a prong is completely coated, and the next prong is not coated, the thickness lies between



Mikrotest gage



Prong gage



Tooke gage

Fig. 4.3 Paint film thickness gages

the thickness indicated by these two prongs. The prong gage should be used directly after paint application, within a few seconds, since some paints contain appreciable amounts of highly volatile thinners that evaporate rapidly. Consequently, a late reading will not give a true indication of the wet film thickness.

The above-mentioned paint film-thickness gages were used extensively throughout this research study. The wet film-thickness gage (prong gage) was used during the painting process. It was not used on the specimen plates but only on the 4 x 4 x 1/16 in. control panels mentioned in the previous section. The prong gage was used to determine the spraying speed that provided the required wet film thickness (WFT). The required WFT was based on the desired dry film thickness (DFT) for the applied coat using the relation

$$\text{WFT} = \text{DFT}\ (\frac{100}{V})$$

in which V = percentage solids in the paint by volume. Using this procedure usually resulted in achieving the desired dry film thickness. However, whenever the dry film thickness obtained was smaller than the desired, an additional coat was applied.

The Mikrotest gage was used to measure the paint thickness of the cured specimens. Usually eight readings were taken for each plate (four on each side) or twenty-four readings per specimen. These readings were recorded, for every specimen, and were the basis for slecting the plate sides which were to be in contact. Sides which showed less variations in the Mikrotest gage readings and at the same time had an average thickness closer to the desired dry film thickness were chosen to be in contact.

The Tooke gage was used primarily to check the Mikrotest readings. Specimens were randomly chosen for the check. The scratch was made near the edges of the specimen plates in order not to disturb the actual contact surface. The Tooke gage was also used to measure the thickness at particular points marked by pencil on the painted control panels, which were already measured by the Mikrotest gage, in order to check the calibration of the Mikrotest gage. The results of both gages were always consistent. Thus, only results of the Mikrotest gage are reported herein.

4.2 Test Setup

The test setup consisted of a high strength steel rod 7/8 in. in diameter with threaded ends, a 50 kip load cell, a 60-ton centerhole hydraulic jack, three 2H 7/8 in. heavy hex nuts, one with the threads drilled out, and a test specimen, as shown in Fig. 4.4. The 7/8 in. steel rod slipped through the load cell, hydraulic jack, drilled nut, and the test specimen. The whole arrangement was held together by two outer 7/8 in. heavy hex nuts at the threaded ends of the steel rod. A hardened washer was placed between the test specimen and the drilled nut to simulate the condition of a joint tightened by the calibrated wrench method [5]. When the specimen was of A36 steel and the clamping force was 49 kips, another hardened washer was placed between the outer nut and the specimen, as required by the 1976 Bolt Specification, Section 5(b). The hydraulic jack, operated by a handpump, induced a tension in the steel rod, thus clamping the specimen plates together. This simulated the clamping force of a real high strength bolt. The arrangement maintained the desired clamping force, thus eliminating bolt variations. The clamping force was measured by the 50-kip load cell. Two different clamping forces were applied in the study: 39 kips and 49 kips. They represented the minimum tension required from a 7/8 in. ASTM A325 and A490 high strength bolts, respectively.

The whole arrangement was placed on the load table of a 120-kip hydraulic testing machine. The two outer specimen plates rested on a specially machined and hardened circular steel base plate, as shown in Fig. 4.4. The base plate transmitted the load

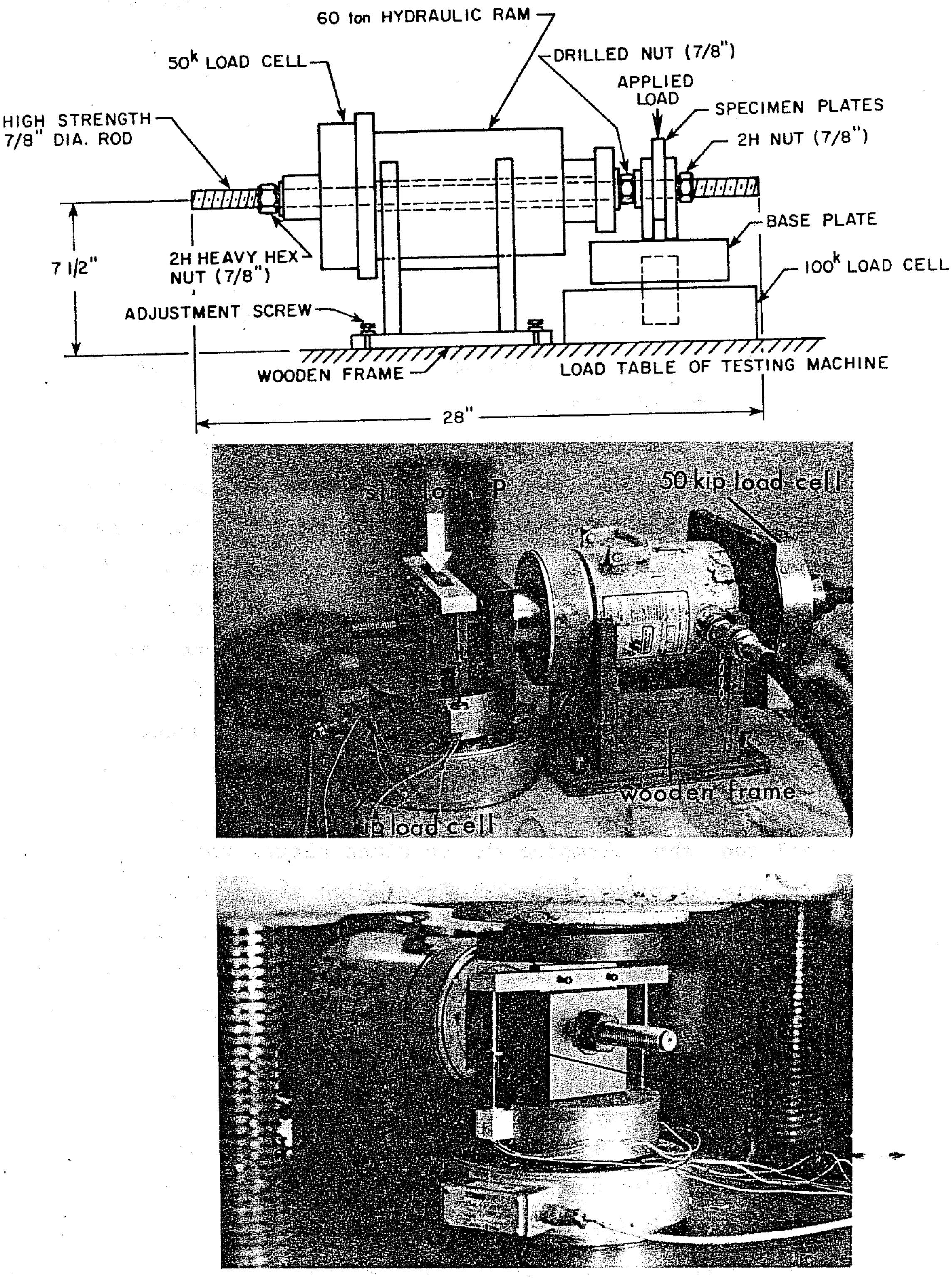


Fig. 4.4 Test setup

from the specimen to a 100-kip centerhole load cell, resting directly on the load table of the testing machine, through a 2 in. diameter threaded rod. The 100-kip load cell was used to measure the compressive load applied to the specimen by the testing machine. A wooden frame supported the hydraulic jack and was placed on the load table of the testing machine. The frame had four screws for horizontal adjustment of the setup and to provide ease in aligning the specimen. Plate washers as well as additional hardened washers were used where appropriate, as shown in Fig. 4.4, to allow for rigidity and compactness of the test setup.

4.3 Instrumentation and Data Acquisition

The test setup was instrumented to provide automatic data acquisition.

The 120-kip hydraulic testing machine was calibrated using special calibration equipment which consisted of an SR-4 strain indicator and a highly sensitive load cell. Testing machine loads were considered accurate within 0.100 kips. The compressive load applied to the specimen by the testing machine was measured by the 100-kip calibrated load cell. Loads at slip were recorded from both testing machine and 100-kip load cell. No differences of over 2 percent between load readings were observed; therefore, only slip loads from the load cell are reported as they are considered to be the most accurate.

The clamping force was measured by the 50-kip calibrated load cell. As a rough check on the clamping force, a reading was taken from a pressure gage connected to the hydraulic pump everytime a specimen was clamped. No large discrepancies between pressure gage readings for the same clamping force were ever observed. This indicated the accuracy in reproducing the desired clamping force for all specimens.

Two electrical deflection gages (DCDT) were used to measure the slip. The gages were supported by aluminum holders attached by glue to the base plate on which the two lap plates of the specimen rested (see Fig. 4.4). The two plungers of the deflection gages bore against the head of brass thumb screws connected to an aluminum fixture that could be mounted and dismounted easily on the middle plate of the specimen by means of screws. The DCDT measured the relative movement between the middle specimen plate and the base plate.

An electronic x-y plotter was connected to the 100-kip load cell and to the two electrical deflection gages. The compressive load, as measured by the load cell, and the average slip, as measured by the two gages, were plotted automatically on the y and x axes, respectively. The chosen scale for plotting the load-slip curve permitted the slip to be read to the nearest 0.50 mils, and the load to the nearest 0.50 kips. Figure 4.5 shows the x-y plotter; Fig. 4.6 shows a typical plot.

A voltmeter, connected to the x-y plotter, was used to monitor the rate of slip, since a constant rate was desired for the slip tests.

4.4 Test Procedure

The test setup permitted a one-man testing operation. The testing procedure may be summarized in the following steps:

(1) Specimen edges were cleaned using sand paper to remove any dry paint. This dry paint could cause an apparent slip at low load.

(2) Specimen contact (faying) surfaces were chosen according to the Mikrotest readings, as explained previously.

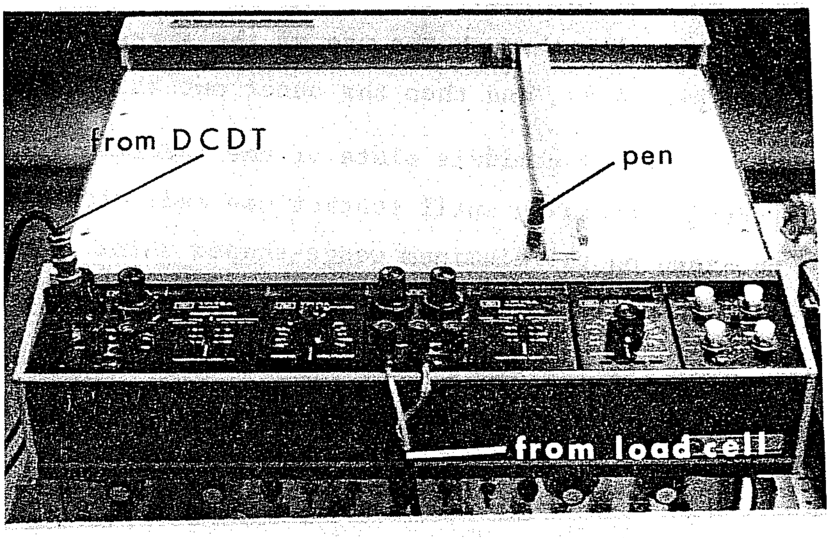


Fig. 4.5 X-Y plotter

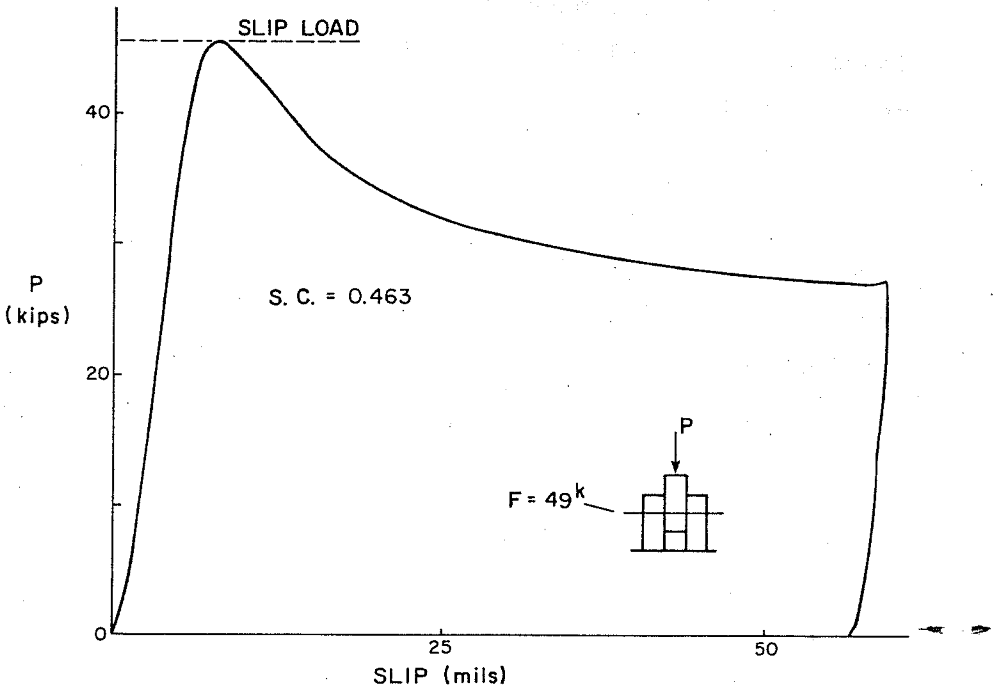


Fig. 4.6 Typical load-slip curve

(3) The specimen was placed in the setup, aligned geometrically through the use of the screws in the wooden frame (see Fig. 4.4), and then the outer nut tightened by hand.

(4) The middle plate of the specimen (butt plate) was lifted vertically until contact was made with the 7/8 in. rod, and retained on two aluminum wedge-shaped shims. This permitted a total slip which is equal to the hole clearance.

(5) The exact clamping force, as measured by the 50-kip load cell, was applied through the hydraulic jack by operating the hand pump.

(6) The aluminum wedge-shaped shims supporting the middle plate were removed. Further alignment of the specimen was done to achieve good contact of the outside (lap) plates of the specimen with the base plate.

(7) The two plungers of the electrical deflection gages were inserted in the cylindrical part of the gage. The fixture was mounted on the middle plate of the specimen and aligned to bear against the plungers.

(8) The testing machine head was lowered to contact the middle plate. Specimens were loaded to about 5 kips at most and then unloaded. This was to ensure good contact of the specimen with the base plate.

(9) The x-y plotter was adjusted and set for plotting.

(10) The specimen was loaded and the load versus slip curve was plotted automatically. The testing machine loading dials were continuously adjusted in order to maintain a rate of slip of 3 mils per minute. The test was terminated at a slip of about 1/16 in., which is the maximum clearance for standard 15/16 in. holes.

Pilot tests indicated that the rate of slip (or deformation) has an effect on the slip coefficient for some paints. Thus, it was decided to conduct all the slip tests at the rate of 3 mils per minute to achieve fair comparisons of slip coefficient and to minimize the influence of the operator of the testing machine on the shape of the load-slip curves. The rate of 3 mils/min was chosen because of its practicality, since a test could be conducted within a reasonable amount of time (20 minutes). In recent research conducted in Australia (1977) [13], slip tests were performed using displacement as a control parameter. The loading rate (slip rate) was 10 mils/min, which is about three times faster than the rate used in the research described herein.

(11) After the test was terminated, the specimen was dismantled and examined. Any unusual disturbances of the contact surfaces were recorded. The slip coefficient was defined as SC = P/NF, in which SC = slip coefficient, P = slip load, F = clamping force (39 kips or 49 kips), and N = 2 = number of slip planes. For joints that had sudden and definite slip, slip load was defined as the highest load the joint resisted before sudden drop in load accompanied by major slip, i.e., the peak of the load-slip curve. For joints that had no definite drop in load, the slip load was defined when the load-slip curve became flat--usually at 0.02 in. total slip movement.

The above eleven steps summarize the exact procedures followed when testing a specimen. A specimen was tested in about one-half hour or less.

It should be pointed out that the load-slip curve as obtained by the x-y plotter is, in fact, a load-deformation curve, since it includes the effect of axial strains in the plates. However, since the axial strains are negligible compared to the slip, the curve will always be referred to throughout the text as "load-slip" curve for simplicity.

CHAPTER 5

CURING TIME EXPERIMENTS

5.1 Objective and Scope

A possibility exists that friction-type joints may experience a reduction in the slip coefficient if the paint on the faying surfaces is not completely cured. However, since no experimental data were available to establish the significance of paint curing on the slip coefficient, several tests were conducted on each coating system. The main purpose of conducting the curing time experiments was to define the time (in days) required by each different coating system to guarantee its reasonable curing. This curing period will ensure an unbiased estimate of the slip coefficient by eliminating the reduction in the slip coefficient caused by incomplete curing of the paint.

5.2 Test Results

5.2.1 Organic Zinc-Rich Primer. Eight slip specimens of A36 steel with 15/16 in. diameter holes were sandblasted to a white metal finish according to SSPC-SP5-63, then coated with two coats of organic zinc-rich paint with an average dry film thickness of 5 mils (0.005 in.). The individual plates were cured at room temperature before they were clamped together for testing. Specimens were then tested, two at a time, after 3, 5, 7, and 9 days curing, respectively.

Table 5.1 summarizes the results of the tests. A summary of the observed slip coefficients as a function of the curing time is shown in Fig. 5.1. In the figure, slip coefficients after

TABLE 5.1 CURING TIME TEST RESULTS--ORGANIC ZINC-RICH PRIMER

Specimen* No.	Average Thickness (mils)	Curing Time** (days)	Slip Load (kips)	Slip Coef.
1	5.3	3	33.3	0.427
2	5.9	3	33.4	0.428
3	5.0	5	36.7	0.471
4	5.6	5	35.6	0.456
5	4.6	7	38.4	0.492
6	4.5	7	36.9	0.473
7	5.5	9	39.0	0.500
8	5.0	9	42.6	0.546

*A36 steel, clamping force = 39^k.

**Paint aging in days before assembly and testing of the specimen.

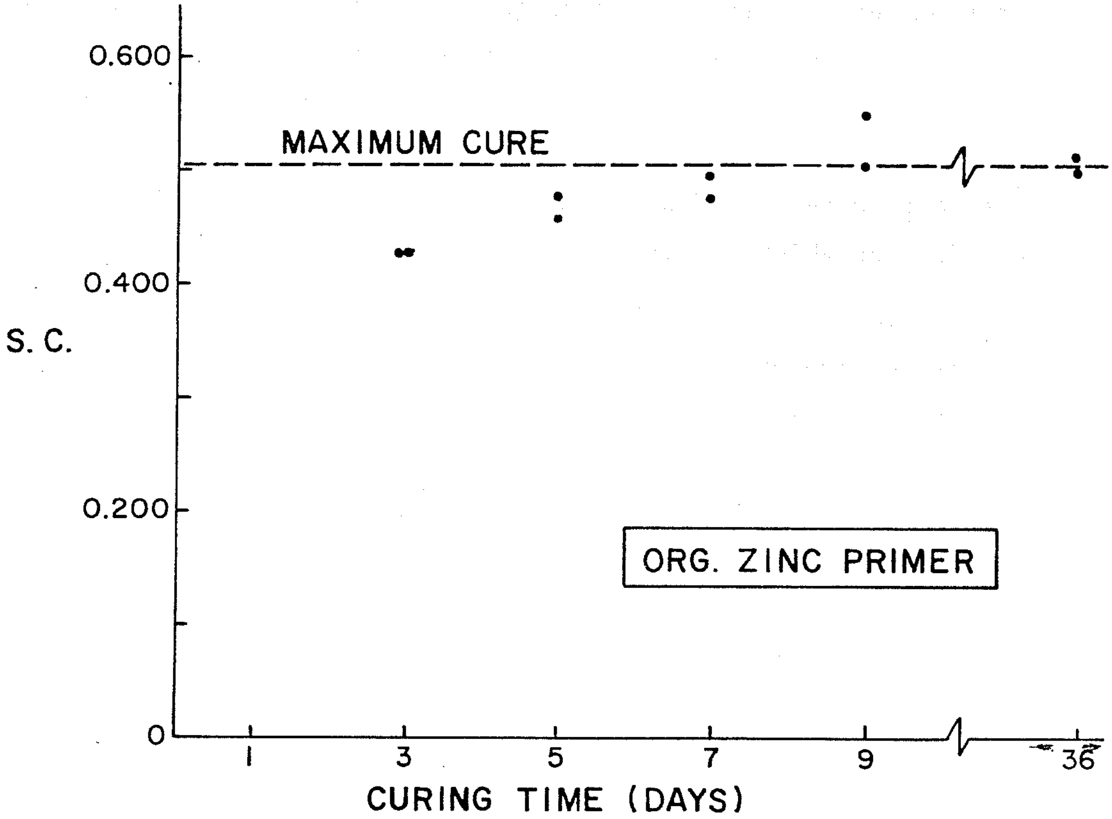


Fig. 5.1 Comparison of slip coefficients

36 days were obtained from another set of specimens (A36 steel and 15/16 in. diameter holes), which was coated at a different time. These slip coefficients were used in determining the required curing period before testing, since it was felt that the data available up to 9 days curing was not sufficient to establish a reliable curing period. The general trend of Fig. 5.1 indicates that a 9-day period will be a sufficient reasonable time for the organic zinc-rich primer to cure.

5.2.2 Organic Zinc-Rich Primer with an Epoxy Top Coat. Fourteen slip specimens of A36 steel with 15/16 in. diameter holes were sandblasted to a white metal finish according to SSPC-SP5-63, then coated with two coats of organic zinc-rich primer with an average dry film thickness of 6.5 mils. The specimens were left to cure at room temperature for 9 days (as indicated in Sec. 5.2.1) and then were top-coated by an epoxy polyamide paint with an average dry film thickness of 2.5 mils. The specimens were tested, two at a time, after 5, 9, 12, and 18 days curing, respectively. The remaining six specimens were tested after 44 days and yielded an average slip coefficient which was less than that after 9 or 12 days.

The results of the tests are presented in Table 5.2. A summary of the observed slip coefficients as a function of the curing time is shown in Fig. 5.2. The results of the six specimens tested after 44 days are not listed in the table nor shown on the figure, since their results were of no significance in establishing the curing period. It was concluded that a 9-day primer cure followed by a 7-day curing period for the top coat would be sufficient to cure the specimens prior to testing.

5.2.3 Inorganic Zinc-Rich Primer. Ten specimens of A572 steel with 1 in. diameter holes were sandblasted to a white metal finish, then coated with two coats of inorganic zinc-rich paint, with a total average dry film thickness of 6 mils. The specimens

TABLE 5.2 CURING TIME TEST RESULTS--ORGANIC ZINC-RICH PRIMER WITH AN EPOXY TOP COAT

Specimen* No.	Average Thickness (mils) Primer	Top Coat	Curing Time** (days)	Slip Load (kips)	Slip Coef.
1	4.2	2.8	5	24.8	0.318
2	4.6	2.0	5	26.6	0.333
3	6.3	2.0	9	32.3	0.414
4	7.5	2.3	9	30.4	0.388
5	7.6	2.2	12	32.1	0.412
6	6.7	3.2	12	31.2	0.400
7	5.2	2.2	18	25.8	0.331
8	7.8	2.5	18	32.6	0.417

*A36 steel, clamping force = 39^k.

**Paint aging in days before assembly and testing of the specimen.

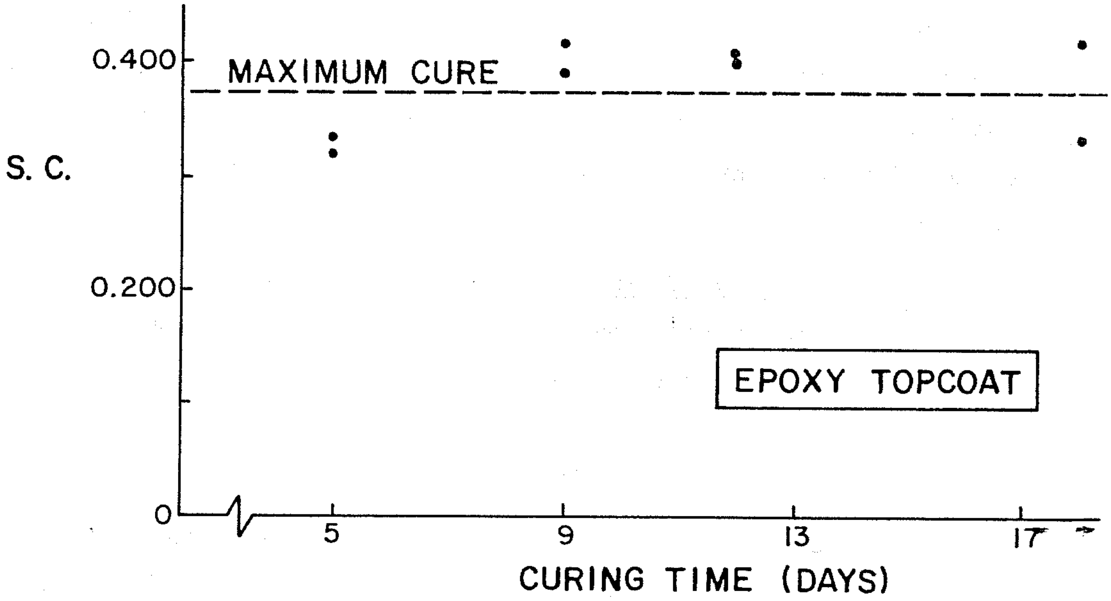


Fig. 5.2 Comparison of slip coefficients

were tested two at a time, after 3, 5, 7, 9, and 11 days curing, respectively.

Table 5.3 and Fig. 5.3 summarize the results of the tests. Comparing the average slip coefficients obtained at different testing days, it was found that the average slip coefficient at 3 days is approximately equal to that at 11 days. A 3-day curing period was chosen before applying a top coat.

5.2.4 Inorganic Zinc-Rich Primer with a Vinyl Top Coat. Ten slip specimens of A36 steel with 15/16 in. diameter holes were sandblasted to a white metal finish, then coated with two coats of inorganic zinc-rich paint with a dry film thickness of 7 mils. The specimens were left to cure at room temperature for 3 days (as indicated in Sec. 5.2.3) and then were top-coated by a vinyl paint with an average dry film thickness of 2 mils. The specimens were tested after 9, 11, 14, 16, 20, and 26 days curing, respectively.

Table 5.4 and Fig. 5.4 summarize the results of the tests. The slip coefficient does not follow a trend with time. Slip coefficients obtained at 16 days are low for some reason. Slip coefficient at 14 and 20 days are higher than those at 16 days. It was concluded that a 3-day primer cure followed by an 18-day curing period for the vinyl coat was sufficient to cure the specimens before testing.

5.2.5 Vinyl Primer. Six slip specimens of A572 steel with 15/16 in. diameter holes were sandblasted to a white metal finish, then coated with four coats of the vinyl primer with a final average dry film thickness of 4 mils. Specimens were tested after 17, 19, and 21 days curing, respectively.

The test results are given in Table 5.5. Figure 5.5, which summarizes the observed slip coefficients as a function of the curing time, indicates that curing time did not affect the slip

TABLE 5.3 CURING TIME TEST RESULTS--INORGANIC ZINC-RICH PRIMER

Specimen* No.	Average Thickness (mils)	Curing Time** (days)	Slip Load (kips)	Slip Coef.
1	6.4	3	49.4	0.633
2	6.1	3	48.8	0.626
3	5.8	5	47.5	0.609
4	5.9	5	45.8	0.587
5	6.1	7	48.4	0.621
6	6.6	7	50.6	0.649
7	6.2	9	51.3	0.658
8	5.5	9	49.1	0.629
9	5.7	11	49.5	0.635
10	6.2	11	49.0	0.628

*A572 steel, clamping force = 39^k.

**Paint aging in days before assembly and testing of the specimen.

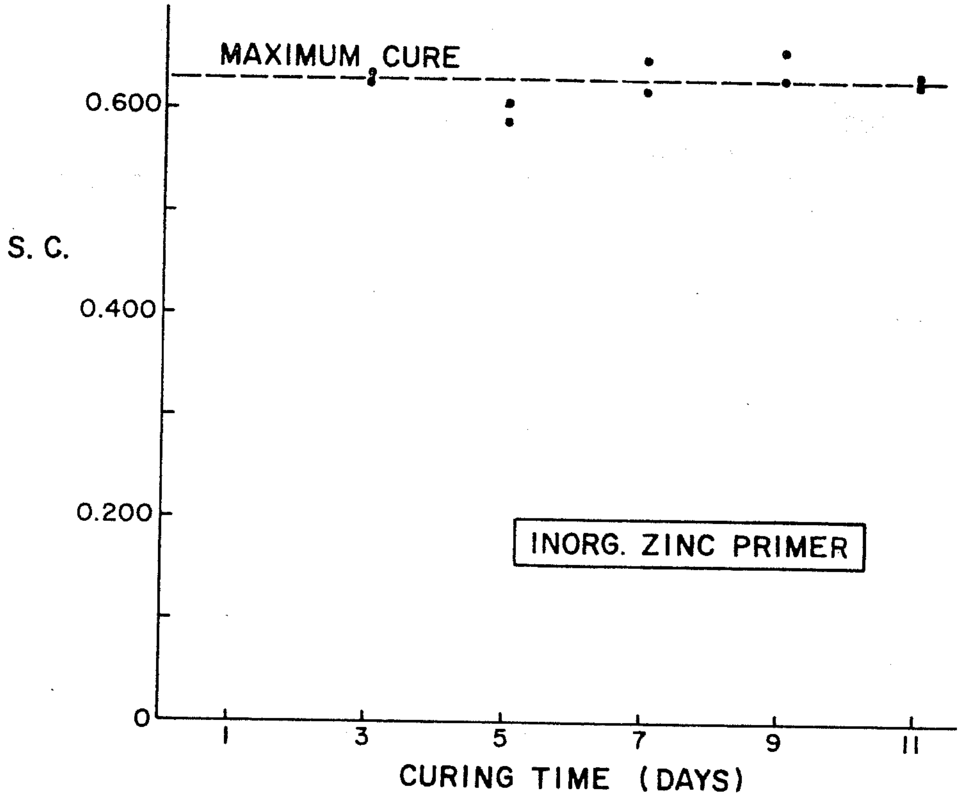


Fig. 5.3 Comparison of slip coefficients

TABLE 5.4 CURING TIME TEST RESULTS--INORGANIC ZINC-RICH PRIMER WITH A VINYL TOP COAT

Specimen* No.	Average Thickness (mils) Primer	Average Thickness (mils) Top Coat	Curing Time** (days)	Slip Load (kips)	Slip Coef.
1	7.7	1.7	9	30.8	0.395
2	6.8	1.9	9	32.4	0.415
3	6.6	2.0	9	30.5	0.391
4	7.3	1.4	11	34.9	0.447
5	6.5	2.3	11	33.0	0.423
6	6.8	1.9	14	41.5	0.526
7	7.0	2.1	16	36.6	0.469
8	6.7	2.6	16	35.7	0.458
9	6.4	2.1	20	47.5	0.609
10	8.3	1.7	26	42.7	0.547

*A36 steel, clamping force = 39^k.

**Paint aging in days before assembly and testing of the specimen.

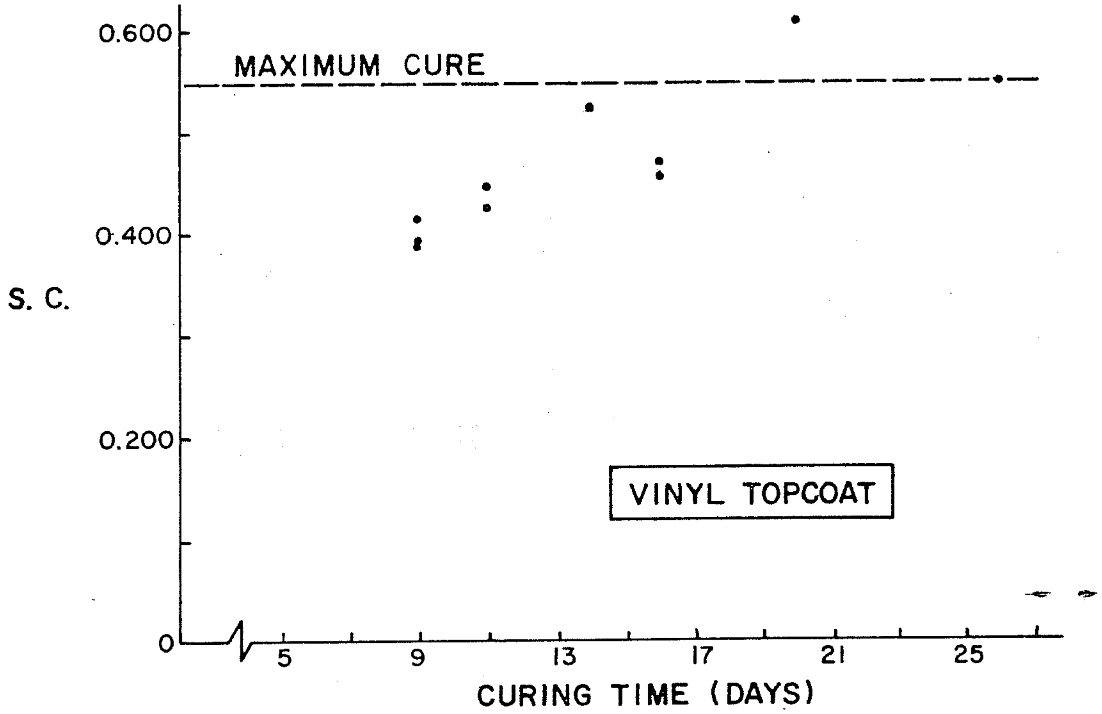


Fig. 5.4 Comparison of slip coefficients

TABLE 5.5 CURING TIME TEST RESULTS--VINYL PRIMER

Specimen* No.	Average Thickness (mils)	Curing Time** (days)	Slip Load (kips)	Slip Coef.
1	4.3	17	21.1	0.215
2	4.0	17	19.7	0.201
3	3.7	19	20.6	0.210
4	3.8	19	21.6	0.221
5	3.8	21	20.8	0.311
6	4.4	21	21.5	0.219

*A572 steel, clamping force = 49^k.

**Paint aging in days before assembly and testing of the specimen.

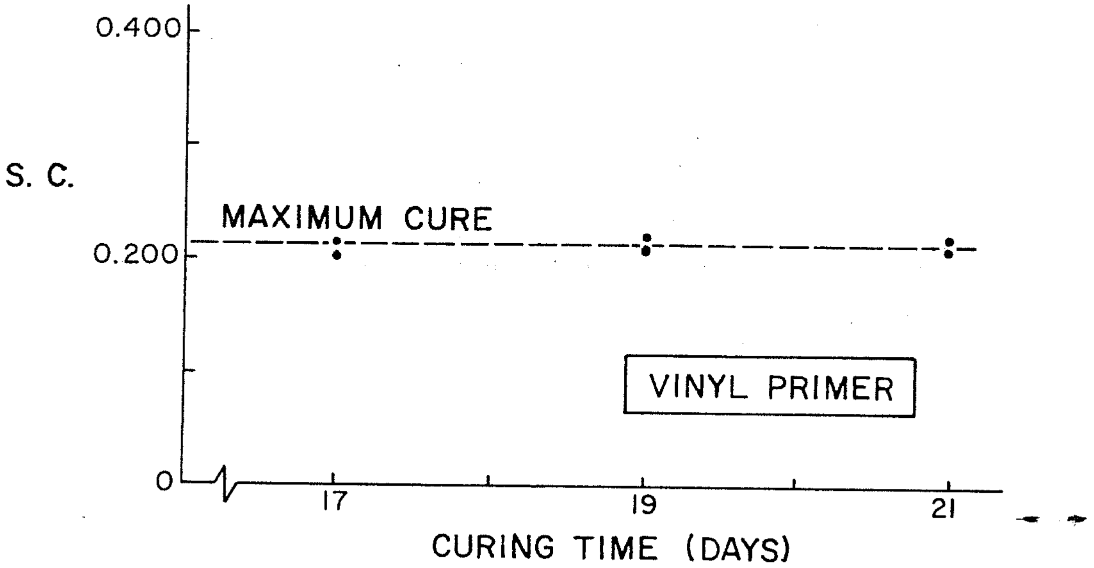


Fig. 5.5 Comparison of slip coefficients

coefficient. However, no tests were conducted on specimens with less than 17 days curing, so the minimum curing time could not be established. Since specimens would be cured after 17 days, this time interval was chosen for the test program.

5.3 Summary

Slip tests were conducted to determine the reasonable time limit during which the painted faying surfaces should be left unclamped in order to allow for paint curing. The curing period will ensure that the effect of incomplete paint curing on the test results is reduced to a practical minimum.

The following listing gives the minimum curing time used for each coating system:

Coating System	Minimum Curing Time (days)
1. Organic zinc-rich primer	9
2. Organic zinc-rich primer with an epoxy top coat	9 + 7
3. Inorganic zinc-rich primer	3
4. Inorganic zinc-rich primer with a vinyl top coat	3 + 18
5. Vinyl primer	17

It should be understood that 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.

CHAPTER 6

TEST RESULTS--BLASTED SURFACES

6.1 General

Slip behavior of blast-cleaned uncoated surfaces have been studied by other researchers. Extensive test data were reported by both Fisher (1975) [6] and the Office of Research and Experiments of the International Union of Railways (ORE) (1974) [14]. With the wealth of data already available, this research project was directed toward a study of slip behavior of coated surfaces. Nevertheless, a large number of blast-cleaned uncoated surfaces were tested that will be referred to as "control specimens" throughout this study. The purpose of these control specimens was to provide a base condition for determining the influence of the coating on the slip behavior and provide additional needed data on A514 steel.

Specimens were sent in groups to a local sandblasting shop to be sandblasted. Usually, each group of 14 specimens contained 4 control specimens. Blast-cleaned control specimens were usually tested within a week after sandblasting. All specimens were sandblasted to a white surface finish according to SSPC-SP5-63. This surface preparation is highly recommended by the SSPC and paint manufacturers for coated steel exposed to severe environments. The surface roughness of the control specimens was measured before testing, since it was felt that it might be directly related to the slip coefficient. The surface roughness of the control specimens served as an indicator of the base metal roughness of the coated specimens of the same group. The procedure for measuring the surface roughness is explained briefly in the following section.

6.2 Surface Roughness Measurement

The surface roughness or in other words the anchor pattern profile depth of the sandblasted surfaces was determined using the Keane-Tator Surface Profile Comparator shown in Fig. 6.1. It consists of a reference disc and a magnifier with a magnetic disc holder. The reference disc is composed of five sections, each with a different anchor pattern depth which is marked in mils (1/1000 in.). The comparator disc was used as a visual as well as a tactile reference. As a visual reference, the disc was centered on the bottom of the magnifier and then the magnifier placed on the sandblasted surface. The reference section most closely approaching the roughness of the sandblast was selected. Comparing the sandblasted surface in the "V" notch separating two reference segments usually provided a greater accuracy. As a tactile reference, the roughness

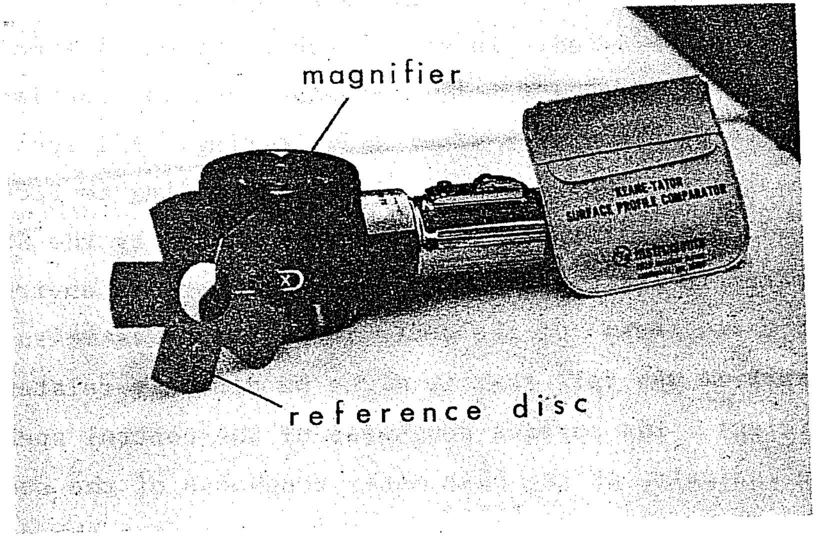


Fig. 6.1 The Keane-Tator surface profile comparator

of the sandblasted surface as felt by one's fingertip, or a plastic card, was compared with the roughness of a segment on the comparator disc. The surface roughness was measured for the three plates of a specimen. Two readings for each plate were recorded, each representing the roughness of one of the plate's sides. Based on these readings, the specimen's plates were so arranged that the average roughness for the contact surfaces was about the same. The average surface roughness of a specimen as reported in Table 6.1 of the next section was calculated by averaging the roughness of the four surfaces in contact.

6.3 Results of Tests on A36, A572, and A514 Steel Surfaces

The data of all tests conducted on blast-cleaned control specimens are summarized in Table 6.1 In the table, lines are drawn separating each group of specimens blasted at one time. Tested control specimens were of A36, A572, and A514 steels and had standard holes (15/16 in. diameter) as well as oversize holes (1 in. and 1-1/8 in. diameter).

The specimen index, listed in Col. 1 of the table is explained in Appendix A. Column 2 reports the average surface roughness of the specimens. The slip load, as obtained from the load-slip curve, and the calculated slip coefficient are listed in Cols. 3 and 4.

Pilot tests indicated that the speed of testing has no effect on the slip coefficient for sandblasted surfaces as compared to some coated surfaces. Nevertheless, all control specimens were loaded at a slip rate of 3 mils per minute (same as for coated surfaces) up to the slip load. When the slip load was reached, the specimen slipped rapidly and suddenly and it was difficult to control the rate of slip. Figure 6.2 shows a typical load-slip relationship for a blast-cleaned steel surface. The shape of the

TABLE 6.1 SUMMARY OF TEST RESULTS

Specimen* No.	Average Roughness (mils)	Slip Load (kips)	Slip Coefficient
1AL6	2	38.5	0.494
2AL7	2	43.2	0.553
3AH4	3	56.4	0.576
4AH5	3	57.7	0.589
3CL8	3	39.9	0.508
4CL9	3	37.3	0.478
2CH2	3.5	48.7	0.497
1CH1	3	39.8	0.406
Average			** 0.513(0.059)
3AL8	2	29.2	0.374
3AL9	2	35.2	0.451
4AH12	2	39.4	0.402
4AH11	2	43.3	0.442
Average			0.417(0.040)
2CL7	1.5	44.2	0.567
5CL10	3	50.0	0.641
3CH3	3	68.4	0.698
4CH4	3	48.4	0.494
1BL9	2	37.4	0.479
2BL10	3	53.0	0.679
1BH1	3	61.0	0.622
2BH2	2	52.6	0.537
Average			0.590(0.083)
2BL12	3	29.6	0.379
1BL11	2	33.5	0.429
1BH3	2	46.3	0.472
2BH4	2	52.6	0.537
Average			0.454(0.067)
4BL13	3	48.0	0.615
5BL14	3	40.1	0.514
4BH5	2.5	41.2	0.420
5BH6	2	49.8	0.508
1AL20	3	37.8	0.485
2AL21	2.5	27.7	0.355
1AH18	2	49.8	0.508
2AH19	2.5	43.4	0.443
Average			0.481(0.077)
4AL15	3	36.7	0.471
4AL16	3	41.4	0.531
4AH13	3	42.0	0.429
4AH14	3	47.1	0.481
7BL19	2.5	35.5	0.455
8BL20	2.5	34.8	0.446
7BH17	2.5	43.4	0.443
8BH18	2	47.9	0.489
Average			** 0.468(0.032)
1AL1	2	35.4	0.454
2AL2	2	33.5	0.429
2AL3	2.5	36.9	0.473
Average			0.452(0.020)
7BL21	2	43.9	0.563
7BL23	2.5	48.4	0.621
1CL6	2.5	35.5	0.455
5CL5	2	40.5	0.519
Average			0.540(0.070)
7BL27	3	40.3	0.517
8BL28	3.5	42.9	0.550
Average			0.534(--)
8BH22	2	61.0	0.610
8BH24	2.5	50.4	0.514
2CH21	3.5	44.9	0.458
7CH22	3	41.6	0.424
Average			0.502(0.081)
4BH8	2	48.5	0.495
6BH7	2.5	58.1	0.593
2CH23	Rusted	45.6	0.465
7CH24	3	47.2	0.482
Average			0.509(0.057)
12BH1	2.5	53.3	0.544
10BH2	2.5	57.8	0.590
1CH17	All Rust	47.6	0.486
7CH18	3	47.9	0.489
Average			0.527(0.050)

TABLE 6.1 (Continued)

Specimen* No.	Average Roughness (mils)	Slip Load (kips)	Slip Coefficient
12BH37	3.5	54.4	0.555
13BH38	3.5	54.8	0.559
8BH26	3.5	58.8	0.600
7BH25	3.5	69.6	0.710
12BL39	3.5	44.4	0.569
13BL40	3.5	42.5	0.545
6CH37	3.5	50.6	0.516
6CH38	3.5	45.4	0.463
Average			0.565(0.071)**
6BL15	2	48.4	0.620
4BL16	2.5	51.3	0.658
1CL19	3	30.5	0.391
7CL20	3	30.6	0.392
Average			0.515(0.140)
11BH33	2.5	48.9	0.499
12BH34	2	53.8	0.549
4CH29	2.5	45.5	0.464
3CH25	3	47.5	0.485
Average			0.499(0.036)
4BLD84	2	35.9	0.460
2BLD86	2.5	31.2	0.400
2BHD81	2.5	41.6	0.424
4BHD82	2.5	42.0	0.429
Average			0.428(0.025)
7BLD811	1.5	35.4	0.454
8BLD812	1.5	37.0	0.474
7BHD89	1.5	42.0	0.429
8BHD810	2	40.0	0.408
Average			0.441(0.029)
5BHD81	2	40.9	0.417
6BHD82	2	50.3	0.513
5BLD83	2	49.5	0.635
6BLD84	2.5	41.3	0.529
Average			0.524(0.089)**
10BHD99	2	47.8	0.488
11BHD910	2	61.2	0.624
10BLD911	2	46.0	0.590
11BLD912	2	49.7	0.637
Average			0.585(0.067)
11BLD831	3	52.6	0.674
10BLD832	3	51.7	0.663
Average			0.669(--)
2BHD92	2	63.8	0.651
6BHD96	2	63.2	0.645
1BHD91	3	60.4	0.616
7BHD95	3	69.2	0.706
1BLD93	2.5	47.4	0.608
6BLD98	3	49.7	0.637
2BLD94	3	53.7	0.688
7BLD17	3	52.0	0.667
Average			0.652(0.034)

*See Appendix A.

**Number in parenthesis is the standard deviation.

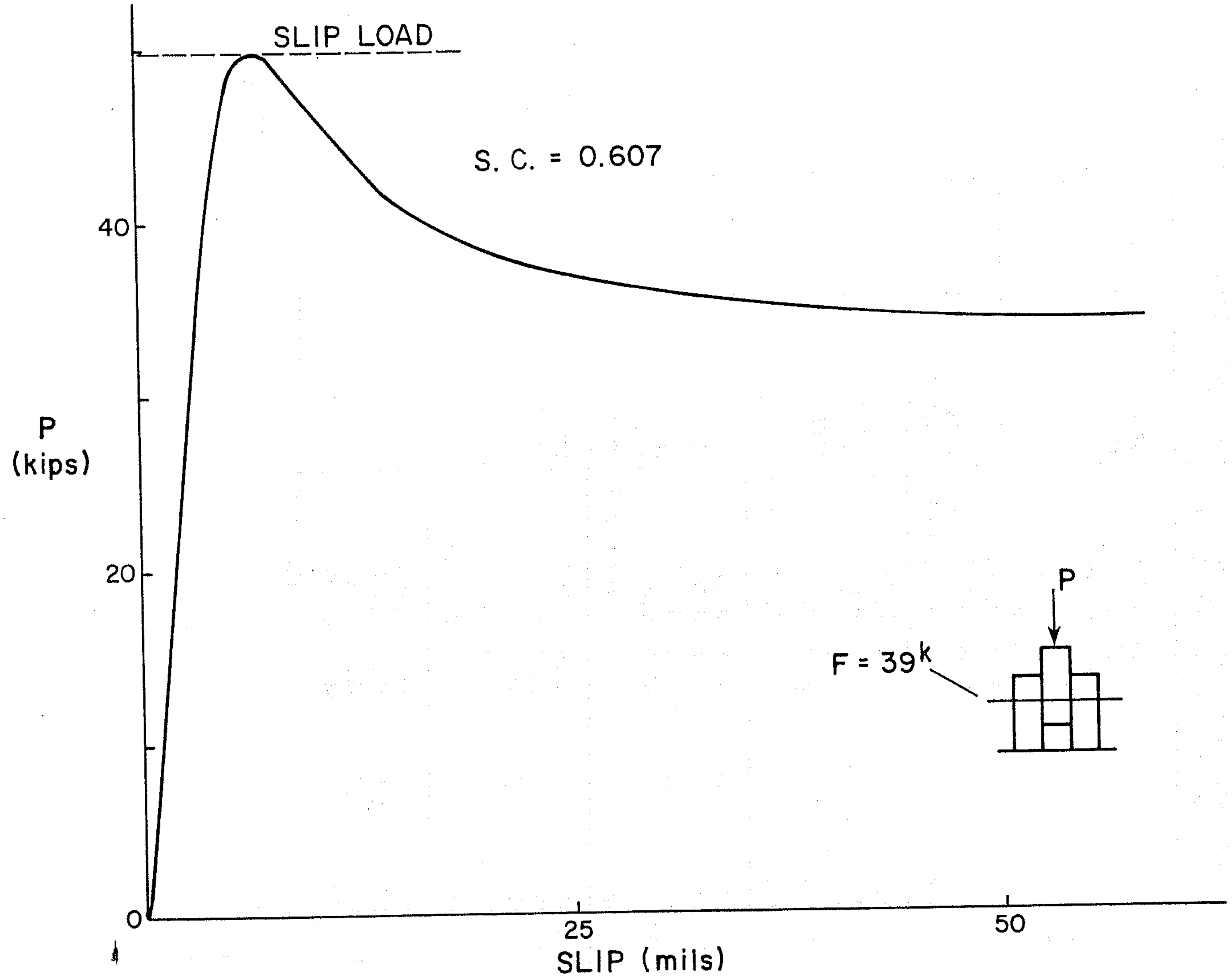


Fig. 6.2 Typical load-slip curve for sandblasted surfaces

response curves was not affected by steel type or size of hole. The load-slip response is almost linear until the load approaches the slip load. The slip load was defined as the highest load the specimen could resist (peak of curve), and usually corresponded to a total slip movement of 5 to 10 mils, as shown in the figure. At this point the load drops suddenly and the plates slip with extreme rapidity. The test was terminated after a total slip of about 1/16 in. occurred.

6.4 Summary of Test Results

The following figures and tables summarize the individual data of Table 6.1. Table 6.2 and Fig. 6.3 provide a comparison of the average slip coefficient (ASC) for the three steel types. They also compare the average slip coefficients (ASCs) for 39 kip and 49 kip clamping forces. It is evident that the ASCs for A36 and A514 are comparable (difference less than 4 percent). On the other hand, A572 steel has a slightly higher ASC (maximum difference about 15 percent). It seems that the effect of clamping force on the slip coefficient is almost negligible. The test results for all the steels are grouped together in Fig. 6.4; it seems reasonable to conclude that the clamping force had no significant effect on the slip coefficient. The two clamping forces gave approximately the same ASC (difference less than 2 percent).

Table 6.3 and Fig. 6.5 compare the ASC for specimens with different hole diameters. The ASC for 15/16 in. diameter holes (standard size holes) is higher than that for 1 in. diameter holes and lower than that for 1-1/8 in. diameter hole specimens. There is not any clear explanation for these differences, especially since the load-slip response for the three hole sizes was identical and the contact areas observed after testing were about the same. Although the number of tests for specimens with oversize holes (1 in. and 1-1/8 in. diameter holes) is too few to be conclusive,

TABLE 6.2 STEEL TYPE EFFECT--BLASTED SURFACES
(15/16 in. dia. holes)

Steel Type / Clamping Force	A36			A572			A514		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping F = 39.0^k	11	0.461	0.059	16	0.540	0.087	8	0.494	0.085
High Clamping F = 49.0^k	8	0.484	0.069	20	0.542	0.067	14	0.488	0.067
TOTAL	19	0.471	0.063	36	0.541	0.075	22	0.490	0.072

TABLE 6.3 HOLE SIZE EFFECT--BLASTED SURFACES (A572 Steel)

Hole Diameter / Clamping Force	1 in.			1-1/8 in.			15/16 in.		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping F = 39.0^k	8	0.536	0.107	6	0.638	0.036	16	0.540	0.087
High Clamping F = 49.0^k	6	0.437	0.038	6	0.622	0.073	20	0.542	0.067
TOTAL	14	0.494	0.097	12	0.630	0.055	36	0.541	0.075

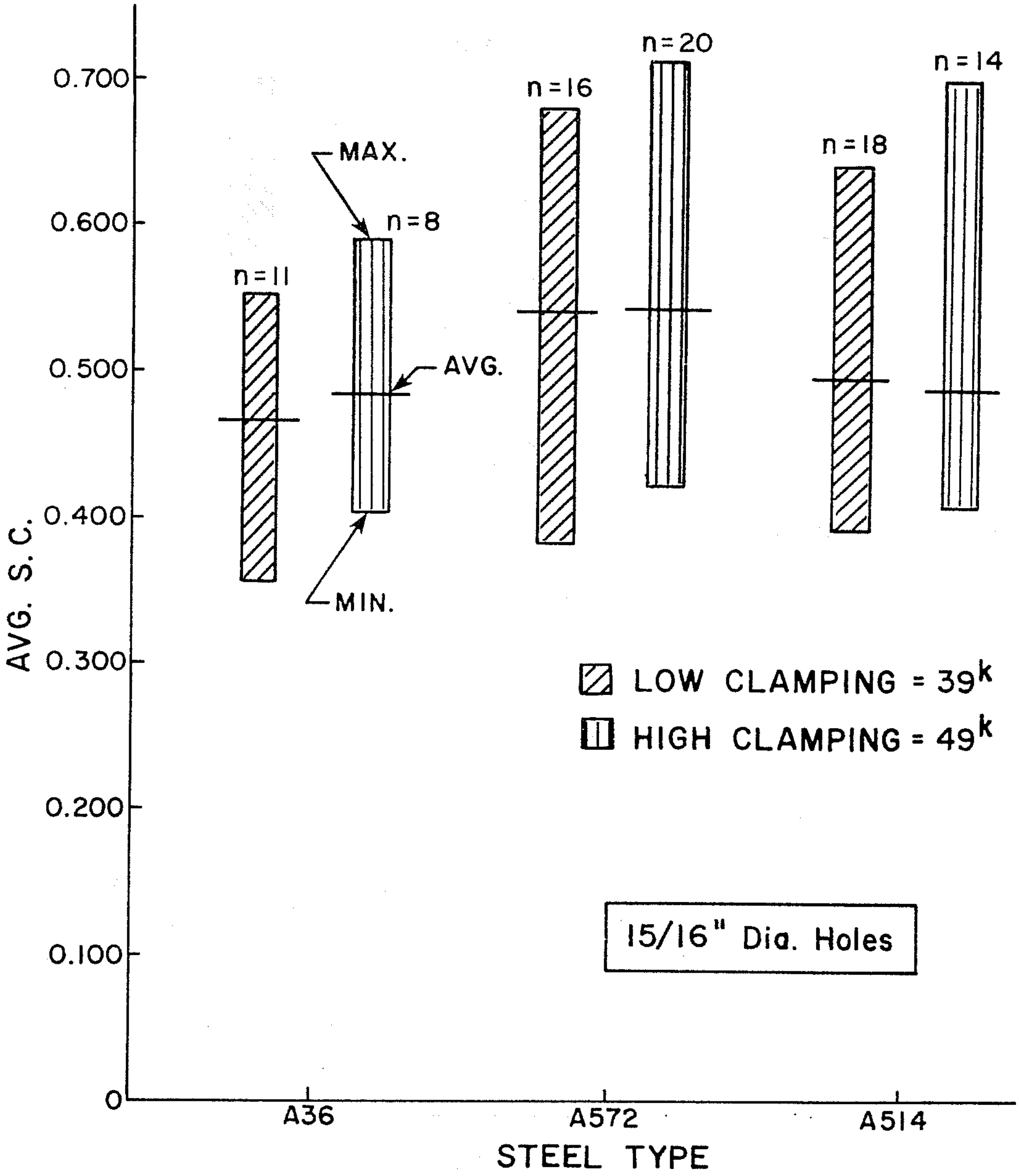


Fig. 6.3 Effect of steel type and clamping force (n = number of tests)

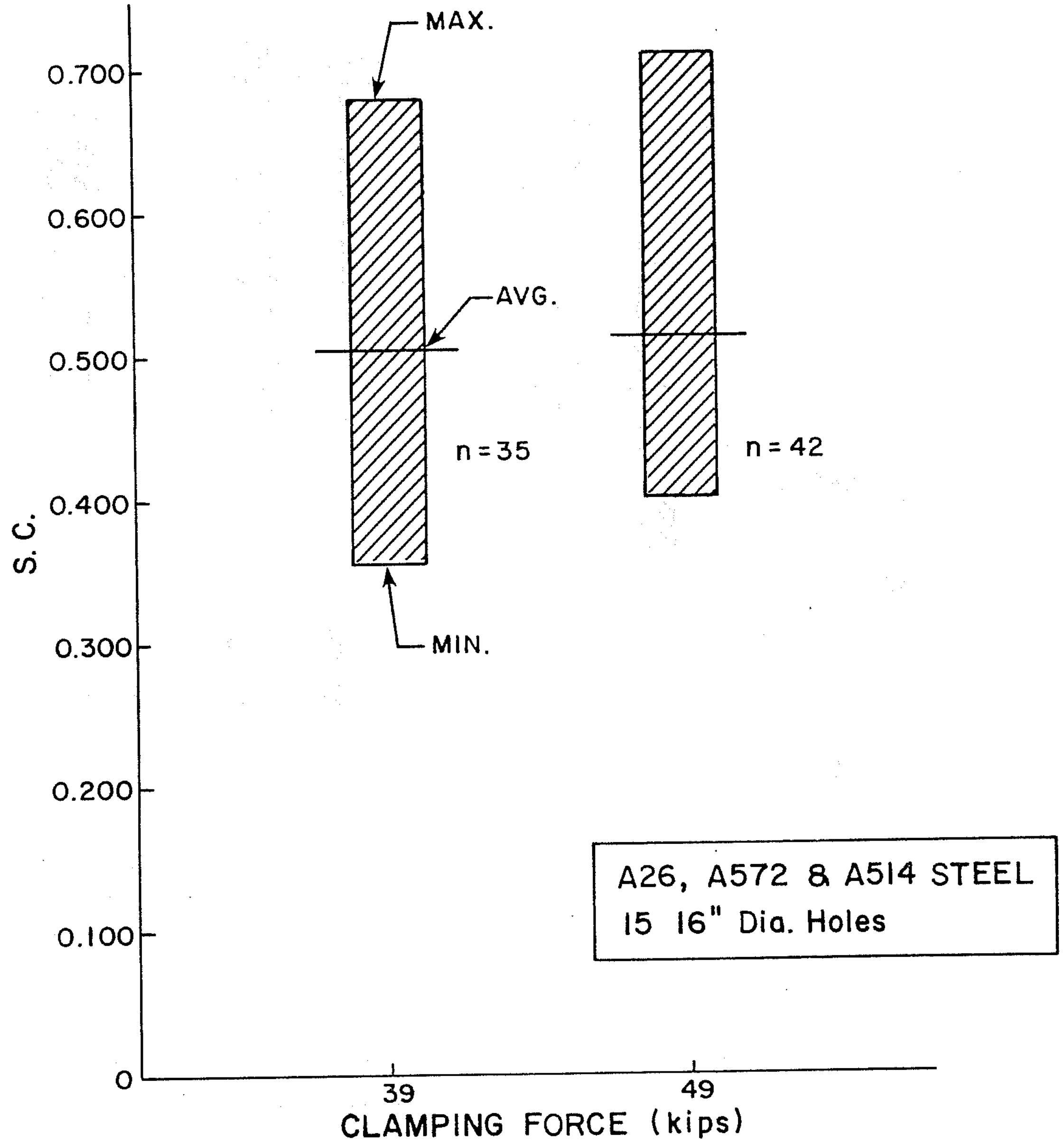


Fig. 6.4 Effect of clamping force
(n = number of tests)

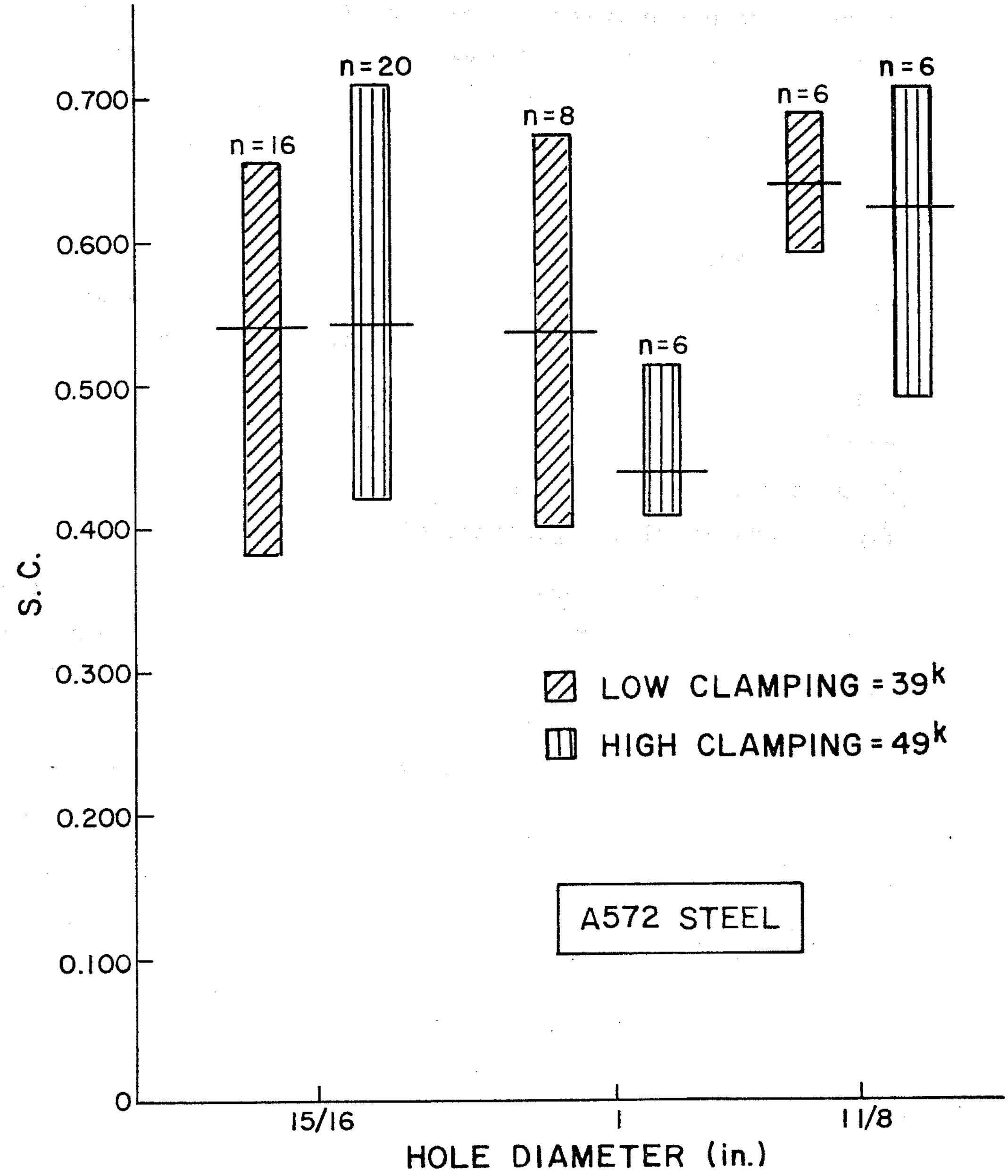


Fig. 6.5 Effect of hole size and clamping force (n = number of tests

no relationship between the slip coefficient and the hole diameter seems to exist. The differences observed may be attributed to scatter in the test results, as well as due to the fact that the results of 1-1/8 in. diameter holes were obtained from two sandblastings only.

Figure 6.6 shows the frequency distribution of the test results as derived from 77 tests with 15/16 in. diameter holes and three steel types (A36, A572, and A514 steel). The test results are approximately normally distributed with mean of 0.509 and standard deviation of 0.077. The ASC reported by Fisher [6] was 0.493 for 168 tests and the standard deviation was 0.074. These figures are in close agreement with the results of this research.

Figure 6.7 shows a comparison of the ASCs as obtained from each sandblasting. The standard deviation for each sandblasting sample is also shown. The average of these ASCs is 0.504, with a standard deviation of 0.045. Comparing the standard deviations, it is apparent that the scatter due to different sandblasting is most of the time less than that of a sample of specimens sandblasted at one time.

A summary of the observed slip coefficients as a function of the surface roughness is shown in Fig. 6.8. The general trend indicates that there is a slight increase in slip coefficent with deeper anchor pattern. However, a definite relationship cannot be established, since it is felt that the roughness as measured by the Keane-Tator surface comparator is very sensitive to the influence of the person taking readings.

The statistical analysis of the results of sandblasted surfaces is briefly discussed in Chapter 8. The recommendations in Chapter 9 are based on both the observations of this chapter as well as the statistical inferences of Chapter 8.

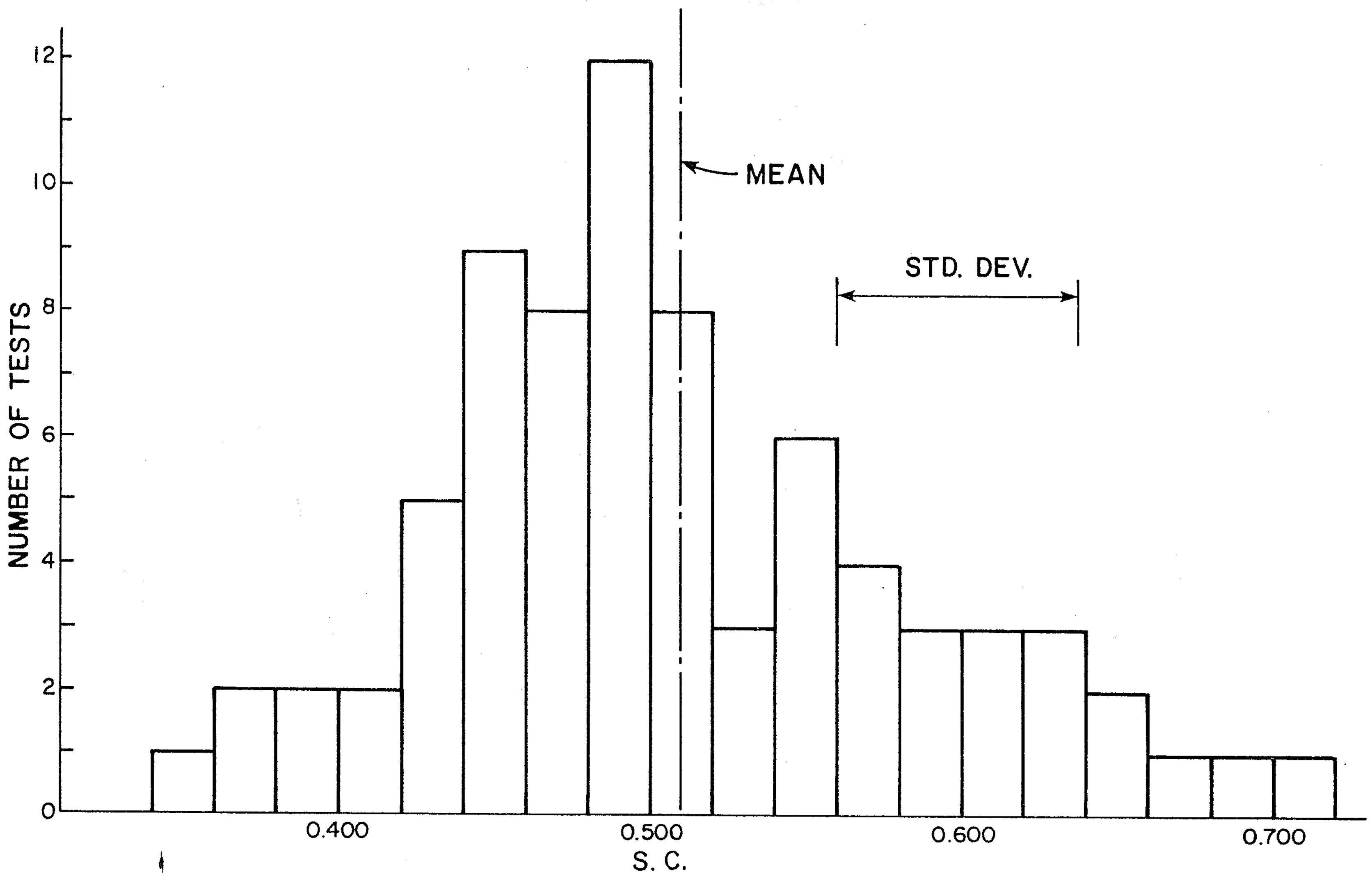


Fig. 6.6 Histogram of slip coefficient for sandblasted surfaces (sandblasted surfaces: A36-A572-A514 steels; 15/16 in. diameter holes; number of tests, 77; average, 0.509; standard deviation, 0.077)

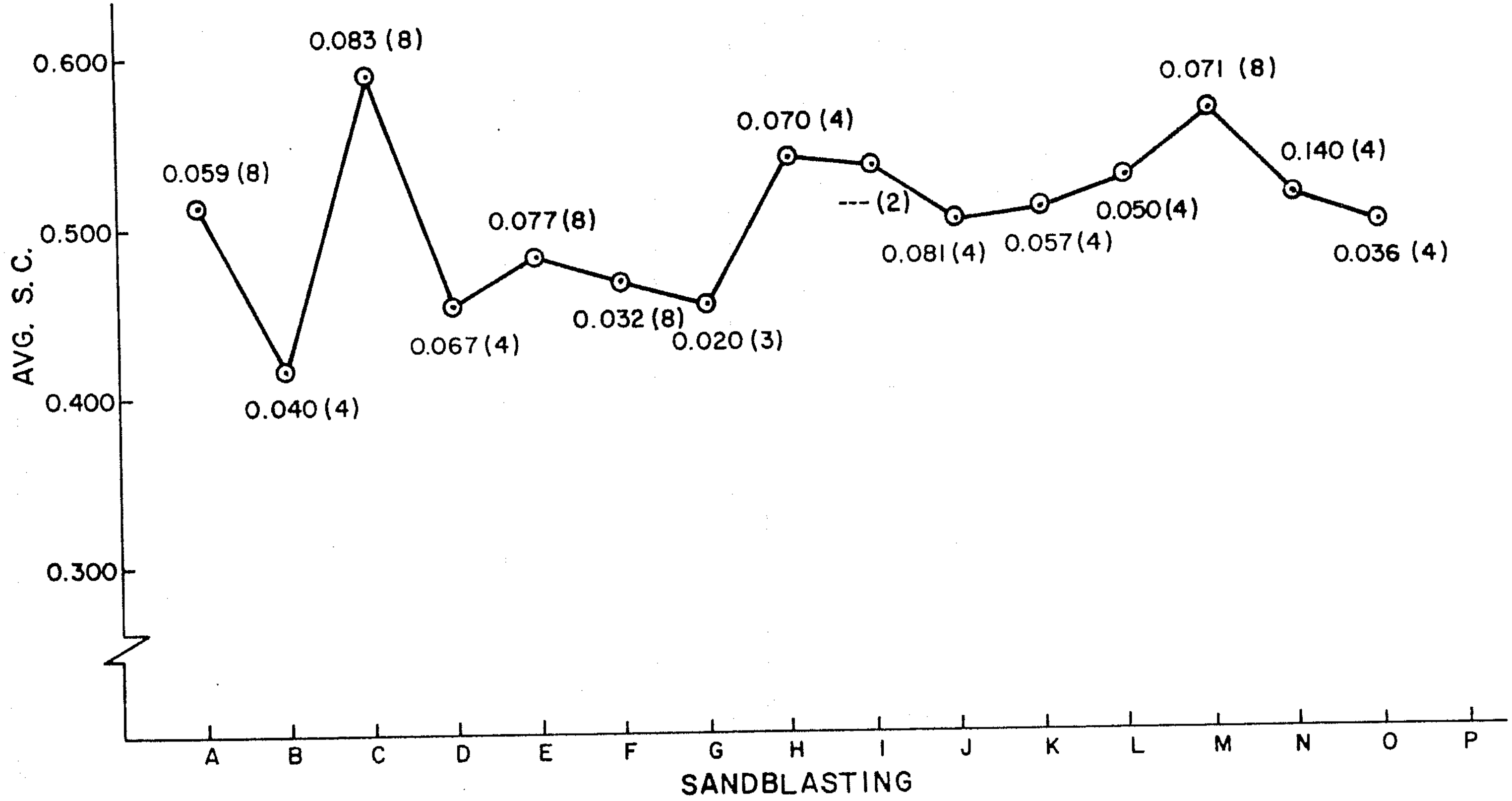


Fig. 6.7 Effect of sandblasting on the average slip coefficient (standard deviation and number of tests are given for each sandblasting)

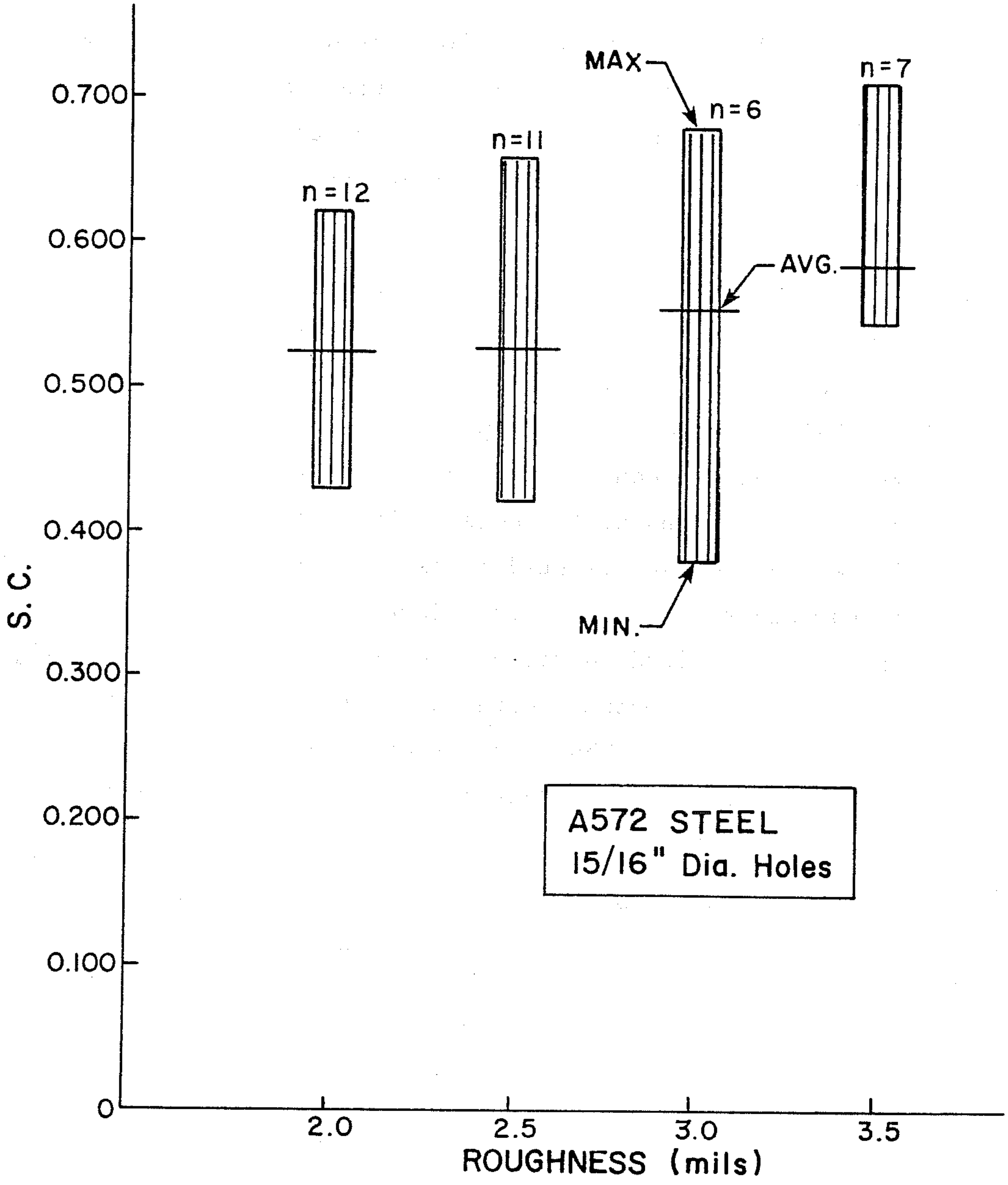


Fig. 6.8 Comparison of average slip coefficients for different surface roughness (n = number of tests)

6.5 Other Observations

Plates of specimens fabricated out of A514 steel had ridges at the rolled edges. The plates were reasonably flat through most of their width, but at both rolled edges the thickness increased (gradually) 1/32 in. Nevertheless, the plates satisfied all specifications.

Some pilot tests were conducted on coated as well as uncoated sandblasted surfaces to observe the effect of out-of-flatness on the slip coefficient. Test results indicated that the out-of-flatness was large enough so that approximately 80 percent of the surface area was not in contact after clamping the specimen. Most contact was at the ridges at the edges. This did not affect the slip coefficient of the sandblasted surfaces. The tests yielded results comparable to previous work. However, test results proved unsatisfactory for coated surfaces. The slip coefficient was significantly reduced. The specimens with the most contact area had the highest slip coefficient. Thus, it was concluded that it necessary to mill or grind off the high edges on the plates in order to obtain valid test data on the different coatings considered.

The edges were ground using a grinding wheel mounted on a radial arm saw. This left the surface undisturbed in the vicinity of the hole.

Six tests were conducted on sandblasted surfaces which had the edges ground off after sandblasting. The tests yielded an average slip coefficient of 0.356, with a standard deviation of 0.050. The specimens did not slip suddenly and rapidly as most sandblasted surfaces did; rather, the slip was slow and smooth. This was due to the smooth edge surfaces resulting from grinding. The value of 0.356 was felt to be rather low when compared to the average slip coefficient for specimens tested with the out-of-flatness not corrected, which was 0.472 with a standard deviation of 0.046. Therefore, it was decided to grind off the edges first and then sandblast the plates. The results of the tests which had edges ground off after sandblasting are not included in Table 6.1, since they are not considered valid data.

CHAPTER 7

TEST RESULTS--PAINTED SURFACES

7.1 General

The slip resistance of a bolted joint is a function of its slip coefficient and the bolt clamping force. The slip coefficient has been defined as: $SC = P/NF$, and is dependent on the treatment and condition of the contact surfaces. The scatter of the slip coefficient is attributable to the condition of the treatment of the contact surfaces.

In the relation $SC= P/NF$, the slip load, P, was defined according to the load-slip response of the coated specimens. For specimens that had sudden and definite slip, slip load was defined as the highest load the specimen resisted before the sudden drop in load accompanied by rapid slip of the specimen (major slip). For specimens that had no definite drop in load, the slip load was defined when the load-slip curve became flat, usually at a total slip value of approximately 20 mils (0.020 in.). All tests were performed at a loading rate of 3 mils per minute.

In this chapter the test results of all the coated surfaces are presented and summarized. Each of the following sections considers one coating system.

7.2 Organic Zinc-Rich Primer

The slip coefficients for each of the specimens coated with organic zinc-rich paint are summarized in Table 7.1. A typical load-slip relationship is shown in Fig. 7.1.

TABLE 7.1 TEST RESULTS--ORGANIC ZINC PRIMER

Specimen Index*	Avg. Thick. (mils)	Slip Load (kips)	Slip Coef.
1ALZ6	6.0	43.0	0.551
1ALZ7	5.6	45.2	0.579
2ALZ8	5.0	42.6	0.544
3ALZ9	4.7	40.1	0.514
3ALZ10	6.0	43.7	0.560
1AHZ1	5.4	50.6	0.516
1AHZ2	6.2	52.5	0.536
2AHZ3	4.8	52.6	0.537
3AHZ4	6.2	57.4	0.586
2AHZ5	5.7	54.9	0.560
4ALZ10	5.6	44.5	0.571
2ALZ7	5.5	45.6	0.585
3AHZ4	5.4	57.5	0.587
4AHZ17	6.1	53.5	0.546
1BLZN6	2.9	34.6	0.444
1BLZN7	3.0	35.9	0.460
1BLZN8	2.7	34.2	0.438
2BLZN9	2.5	31.5	0.404
2BLZN10	3.4	35.8	0.459
1BHZN1	2.8	41.9	0.428
1BHZN2	2.6	38.5	0.393
1BHZN3	3.2	39.9	0.407
1BHZN4	3.0	38.0	0.388
2BHZN5	4.1	39.9	0.407
1CLZN6	3.4	33.0	0.423
2CLZN7	3.8	27.0	0.346
3CLZN8	3.3	27.0	0.346
4CLZN9	3.0	24.3	0.312
5CLZN10	3.3	25.7	0.329
1CHZN1	3.6	35.5	0.362
2CHZN2	3.9	35.9	0.366
4CHZN4	3.6	35.1	0.358
3BLZ6	7.4	35.8	0.459
3BLZ7	6.1	38.2	0.490
4BLZ8	6.2	38.8	0.497
5BLZ9	6.8	35.3	0.453
6BLZ10	5.9	32.5	0.417
3BHZ1	6.1	42.9	0.438
3BHZ2	6.7	43.5	0.444
4BHZ3	6.4	44.1	0.450
5BHZ4	7.0	41.1	0.419
6BHZ5	7.0	45.8	0.467
3BLD83	5.9	34.0	0.436
3BLD87	5.9	36.0	0.462
3BLD88	5.6	36.7	0.471
3BLD89	5.7	34.1	0.437
3BLD810	5.7	36.9	0.473
3BHD81	5.8	41.4	0.422
3BHD82	6.2	39.5	0.403
3BHD83	6.6	42.1	0.430
3BHD84	5.6	40.3	0.411
3BHD85	5.1	43.3	0.442
10BLZK9	7.7	45.4	0.582
10BLZK10	8.0	43.9	0.563
9BHZK4	8.0	50.6	0.516
10BHZK5	7.3	49.3	0.503
4CLZK9	8.3	45.4	0.582
5CHZK10	8.3	48.0	0.490
4CHZK4	7.6	54.9	0.560
5CHZK5	8.7	49.8	0.508
6BLZ1	6.0	43.7	0.560
7BLZ2	5.5	45.1	0.578
6BLZ3	6.1	56.2	0.573
7BLZ4	6.0	51.9	0.530
8BLZN5	2.6	42.1	0.540
6BLZN6	3.5	39.8	0.510
6BLZN7	2.8	45.9	0.468
6BLZN8	2.8	49.9	0.499
1CLZK6	9.1	30.2	0.387
2CLZK7	8.9	35.5	0.455
3CLZK8	8.8	39.5	0.506
1CHZK1	8.7	42.5	0.434
2CHZK2	10.2	35.5	0.362
3CHZK3	8.8	40.4	0.412
7BLZK6	8.8	39.3	0.504
8BLZK7	9.0	35.1	0.450
9BLZK8	8.8	39.0	0.500
7BHZK1	8.8	43.0	0.439
8BHZK2	9.1	43.3	0.442
9BHZK3	9.0	42.7	0.436
2ALZK21	9.3	39.0	0.500
1ALZK20	8.8	39.9	0.512
2AHZK19	9.2	44.0	0.449
2AHZK2	10.3	42.7	0.436
1CLZ6	5.8	32.2	0.413
2CLZ7	6.0	31.6	0.397
1CHZ1	5.0	40.0	0.408
2CHZ2	5.6	38.8	0.396
4CLZ9	7.9	41.5	0.532
5CLZ10	7.1	40.3	0.517
4CLZ10	7.7	40.5	0.519
3CHZ3	7.7	55.0	0.561
4CHZ4	7.8	51.4	0.524
5CHZ5	7.7	51.4	0.524
1BLZD96	6.1	32.9	0.422
2BLZD97	6.1	29.8	0.382
3BLZD98	6.5	29.9	0.383
4BLZD99	6.2	31.1	0.399
5BLZD910	6.3	30.6	0.392
1BHZD91	5.4	38.8	0.396
2BHZD92	5.9	35.6	0.363
3BHZD93	5.6	38.9	0.397
4BHZD94	6.0	33.4	0.341
5BHZD95	6.0	34.0	0.347

*See Appendix A

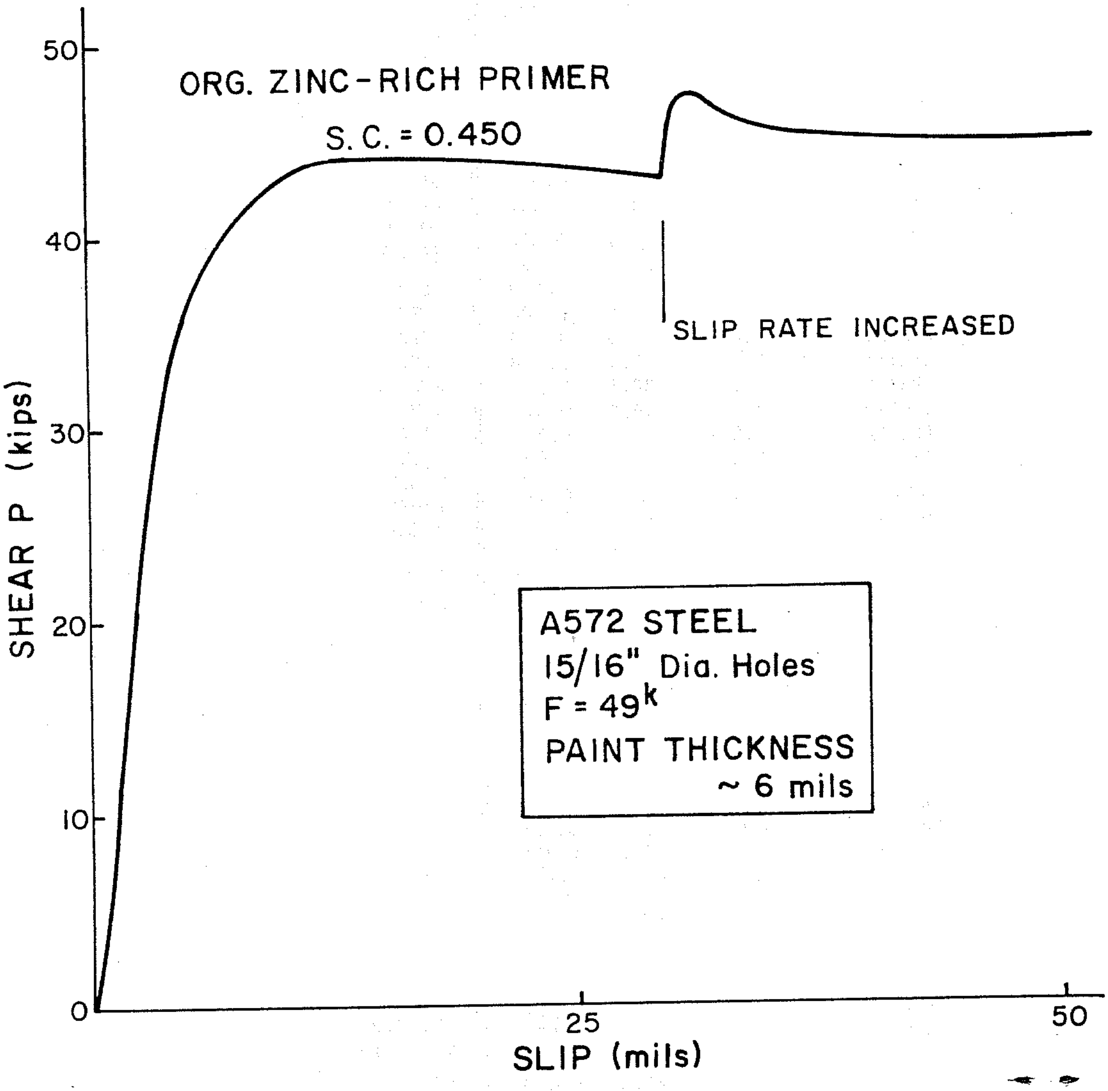


Fig. 7.1 Typical load-slip curve

In general, the load-slip response was linear up to about 80 percent of the slip load. Then, the load-slip relationship became nonlinear and eventually a flat plateau was formed which was used to define the slip load. In some of the tests, the loading rate was increased after a total slip of about 30 to 40 mils to determine the effect of higher loading rate on the slip coefficient. Usually, by increasing the loading rate, a hump was formed, indicating an increase in the slip resistance of the specimen, as shown in Fig. 7.1. This increase in slip resistance was dependent on several factors, such as the loading rate, curing time, and the paint film roughness. The slip coefficients reported herein were always based on the first slip load and before increasing the loading rate. The slip coefficients obtained are rather conservative, since most researchers conducted their tests at higher loading rates. In recent research conducted in Australia (1977), Vitelleschi and Schmidt [13] performed their slip tests at a rate of 10 mils per minute, which is about three times the rate used in this research.

Investigation of the contact surfaces of the specimens indicated that damage to the organic zinc painted surfaces was fairly uniform all over the contact areas. However, in some cases the severe damage was confined mostly to the areas adjacent to the holes. This is in accordance with the theory that the areas immediately adjacent to the holes of a bolted joint are the areas of highese contact pressure and, therefore, provide most of the slip resistance.

Tables 7.2 through 7.5 summarize the test results listed in Table 7.1 in a factorial form. Table 7.6 is a summary of an additional experiment which was conducted to study more carefully the effect of hole size on the slip coefficient. In this experiment all specimens were coated at the same time. This provided a fair comparison, since it was observed that the slip coefficient is affected by the painting process in the case of organic zinc-rich

TABLE 7.2 STEEL TYPE EFFECT--ORGANIC ZINC PRIMER
(5/16 in. dia. holes; normal paint thickness)

Steel Type / Clamping Force	A36			A572			A514		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping F = 39.0k	7	0.558	0.024	7	0.493	0.058	5	0.476	0.060
High Clamping F = 49.0k	7	0.553	0.026	7	0.474	0.055	5	0.483	0.075
TOTAL	14	0.555	0.025	14	0.484	0.055	10	0.479	0.066

TABLE 7.3 PAINT THICKNESS EFFECT--ORGANIC ZINC PRIMER
(A572 steel; 15/16 in. dia. holes)

Paint Thickness / Clamping Force	Thin ~ 3 mils			Normal ~ 6 mils			Thick ~ 9 mils		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping F = 39k	5	0.441	0.023	5	0.463	0.030	5	0.520	0.053
High Clamping F = 49k	5	0.405	0.016	5	0.444	0.020	5	0.467	0.039
TOTAL	10	0.423	0.027	10	0.453	0.030	10	0.494	0.039

TABLE 7.4 PAINT THICKNESS EFFECT--ORGANIC ZINC PRIMER
(A514 steel; 15/16 in. dia. holes)

Paint Thickness / Clamping Force	Thin ~ 3 mils			Normal ~ 6 mils			Thick ~ 9 mils		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping F = 39^k	5	0.351	0.043	5	0.476	0.060	5	0.484	0.071
High Clamping F = 49^k	3	0.362	0.004	5	0.483	0.075	5	0.455	0.079
TOTAL	8	0.355	0.032	10	0.479	0.066	10	0.470	0.072

TABLE 7.5 HOLE SIZE EFFECT--ORGANIC ZINC PRIMER
(A572 steel; normal paint thickness)

Hole Diameter / Clamping Force	15/16 in.			1 in.			1-1/8 in.		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping F = 39.0^k	5	0.463	0.030	5	0.456	0.020	5	0.396	0.016
High Clamping F = 49.0^k	5	0.444	0.020	5	0.422	0.015	5	0.369	0.027
TOTAL	10	0.453	0.030	10	0.439	0.020	10	0.382	0.025

TABLE 7.6 HOLE SIZE EFFECT--ORGANIC ZINC PRIMER
(A572 steel; normal paint thickness)

Hole Diameter / Clamping Force	15/16 in.			1 in.			1-1/8 in.		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
High Clamping $F = 49.0^k$	5	0.368	0.026	5	0.379	0.021	5	0.371	0.025

primer. Figure 7.2 is a histogram for all A572 Grade 50 steel data.

7.3 Organic Zinc-Rich Primer with Epoxy Top Coat

Test results are presented in Table 7.7. Tables 7.8 through 7.11 provide summaries for the test results in factorial form. Figure 7.4 is a histogram for all Grade 50 steel data. A typical load-slip relationship is shown in Fig. 7.3.

The load-slip response was linear up to about 95 percent of the slip load. Unlike organic zinc-rich primer, when the slip load was reached a sudden drop in load accompanied by major slip occurred. In most cases the drop in load amounted to about 50 percent of the slip load. This indicated that the dynamic friction was much lower than the static friction. The loading rate did not seem to have any effect on the shape of the load-slip curve, as compared to the case of specimens coated with the primer only.

Investigation of the faying surfaces of the specimens after testing indicated that there was no damage to the epoxy top coat surface. Theepoxy top coat was so hard that it was barely affected by slip.

7.4 Inorganic Zinc-Rich Primer with Vinyl Top Coat

Test results are presented in Table 7.12. Tables 7.13 through 7.16 provide summaries for the test results in factorial form. Figure 7.6 is a histogram of all Grade 50 steel date. Figure 7.5 shows a typical load-slip relationship.

The load-slip response was linear up to about 80 percent of the slip load. Then, the relationship became nonlinear and eventually a flat plateau was formed. There was no drop in the slip load and its value was almost constant during slip. The

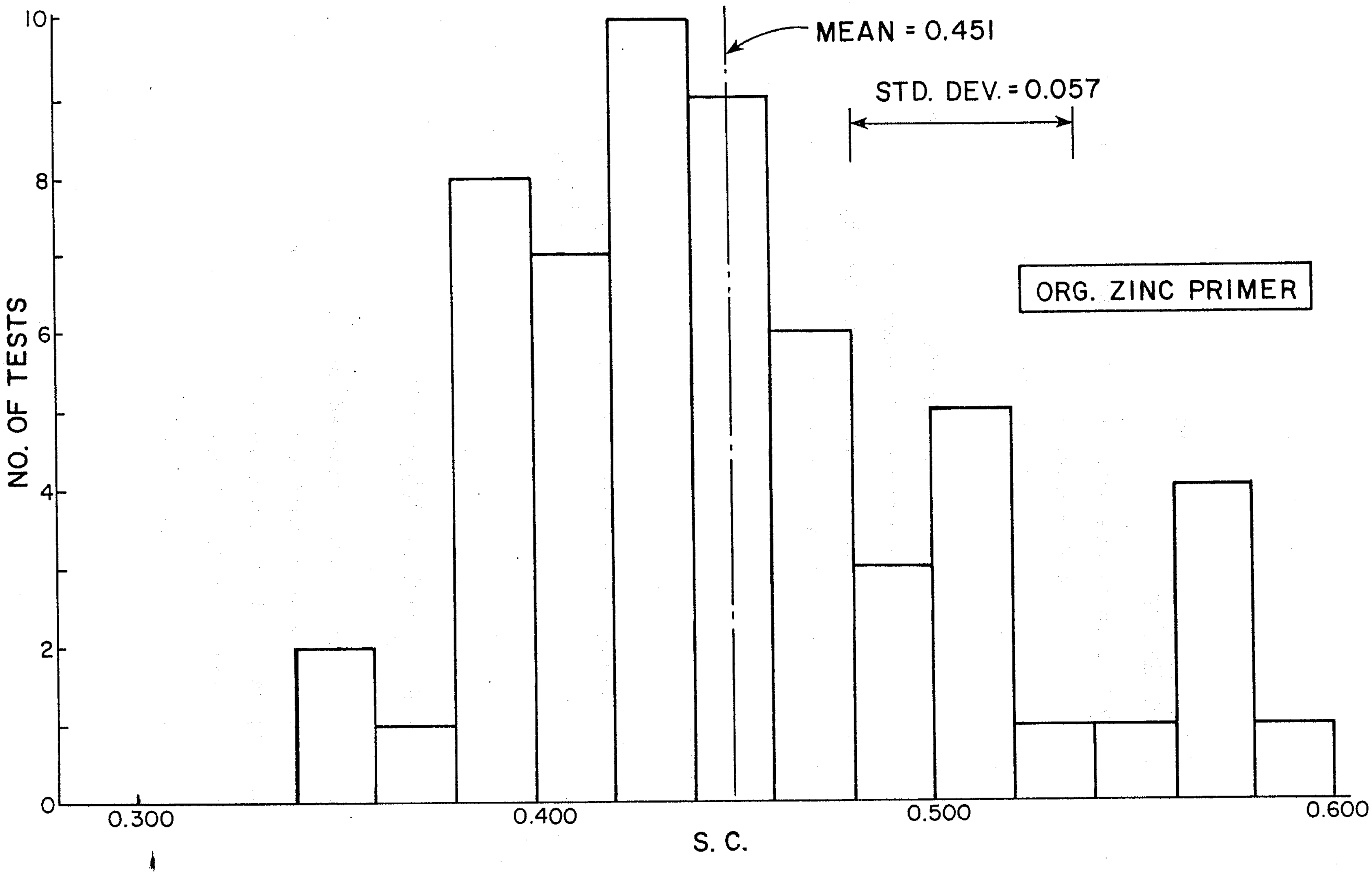


Fig. 7.12 Frequency distribution for organic zinc-rich coated surfaces (hole dimensions: 15/16, 1, and 1-1/8 in. diameter; steel: A572; paint thickness: 3, 6, and 9 mils; number of tests, 58)

TABLE 7.7 TEST RESULTS--ORGANIC ZINC PRIMER WITH EPOXY TOP COAT

Specimen Index*	Average Thick. (mils) Primer	Average Thick. (mils) Top Coat	Slip Load (kips)	Slip Coef.
3ALE7	5.2	2.9	25.4	0.326
4ALE8	5.9	3.9	23.9	0.306
1AHE1	5.1	3.4	26.4	0.269
3AHE3	5.5	3.3	26.0	0.265
4BLE6	5.8	3.5	22.5	0.288
4CLE7	5.9	3.3	23.4	0.300
3BHE1	6.2	3.6	24.4	0.249
4BHE2	5.9	3.5	26.5	0.270
2CLE7	6.0	3.0	23.3	0.299
3CLE8	5.7	3.2	22.4	0.287
3CHE3	6.1	2.9	32.6	0.333
8CHE5	5.5	3.9	26.8	0.273
5BLE8	5.8	3.2	20.7	0.265
5BLE9	6.1	3.2	22.6	0.289
6BLE10	5.8	3.5	21.9	0.281
4BHE3	6.2	2.6	27.6	0.282
5BHE4	5.4	2.9	26.0	0.265
6BHE5	5.9	2.7	21.5	0.219
1CLE6	6.0	2.9	19.3	0.247
4CLE9	6.7	2.5	20.7	0.265
5CLE10	6.2	3.6	22.0	0.282
1CHE1	6.7	2.7	21.4	0.218
2CHE2	6.4	2.4	26.8	0.273
4CHE4	5.7	3.0	26.8	0.273
9BLEN6	3.7	2.5	23.9	0.306
9BLEN7	3.0	2.9	23.5	0.301
10BLEN8	3.4	2.7	24.2	0.310
9BHEN1	3.0	2.3	29.2	0.298
9BHEN2	3.6	2.4	28.9	0.295
10BHEN3	3.1	2.1	24.3	0.248
6CLEN6	3.5	2.6	23.1	0.296
6CLEN7	3.2	3.1	22.3	0.286
6CLEN8	3.2	2.4	24.0	0.308
6CHEN1	3.6	2.6	29.1	0.297
6CHEN2	3.6	3.4	27.1	0.277
7CHEN3	3.5	2.8	25.6	0.261
11BLEK6	7.6	2.3	21.6	0.277
12BLEK7	9.5	2.5	24.7	0.317
13BLEK8	8.3	3.5	21.4	0.218
11BHEK1	8.3	2.4	27.8	0.284
12BHEK2	9.2	2.3	25.6	0.261
13BHEK3	8.4	3.4	26.1	0.266
1CLEK6	9.4	3.4	20.4	0.262
2CLEK7	9.7	2.9	24.9	0.319
3CLEK8	8.3	3.2	19.7	0.253
6CHEK1	9.4	3.0	22.9	0.234
6CHEK2	9.1	3.2	30.2	0.308
7CHEK3	8.6	3.5	28.4	0.290
2ALE6	7.6	3.0	20.0	0.256
4ALE9	7.2	2.8	27.3	0.350
4ALE10	7.0	3.5	27.0	0.346
3AHE2	7.4	3.0	29.2	0.298
4AHE5	6.6	2.9	29.7	0.303
4AHE13	6.8	2.5	32.2	0.329
10BLEN9	3.8	2.9	21.2	0.272
11BLEN10	3.0	2.4	20.8	0.267
10BHEN4	4.2	3.1	24.6	0.251
11BHEN5	3.8	2.8	27.7	0.283
8CLEN9	4.6	2.7	24.1	0.309
8CLEN10	2.8	2.4	18.9	0.242
8CHEN4	4.0	3.2	18.4	0.188
8CHEN5	5.0	2.8	30.9	0.315
13BLEK9	9.1	2.7	22.4	0.287
13BLEK10	8.9	2.6	23.9	0.306
13BHEK4	9.4	3.0	28.6	0.292
13BHEK5	8.7	3.5	23.1	0.236
4CLEK9	9.3	4.0	22.4	0.287
5CLEK10	8.9	2.8	22.8	0.292
8CHEK4	8.5	3.4	23.0	0.235
5CHEK5	8.9	3.0	28.2	0.288
12BLED86	5.6	2.7	18.7	0.240
12BLED87	6.0	2.5	19.9	0.255
11BLED88	6.0	2.2	19.4	0.249
11BLED89	5.0	2.8	19.2	0.246
9BLED810	5.2	2.3	20.6	0.264
11BHED81	5.5	2.3	24.2	0.247
12BHED82	5.9	2.5	17.8	0.182
11BHED83	6.3	2.5	23.6	0.241
12BHED84	5.6	2.4	26.5	0.270
13BHED85	5.5	2.5	26.2	0.267
3BLED96	5.7	2.9	23.4	0.300
4BLED97	5.7	3.4	21.2	0.272
5BLED98	6.1	2.6	20.6	0.264
6BLED99	5.7	3.2	19.3	0.247
7BLED910	6.3	2.6	17.5	0.224
3BHED91	6.2	2.3	26.6	0.271
4BHED92	7.3	1.8	25.5	0.260
5BHED93	6.2	3.2	21.4	0.218
6BHED94	6.2	2.6	26.9	0.274
7BHED95	5.9	2.0	24.5	0.250

*See Appendix A

TABLE 7.8 STEEL TYPE EFFECT--ORGANIC ZINC PRIMER WITH EPOXY TOP COAT (15/16 in. dia. holes; normal paint thickness)

Steel Type / Clamping Force	A36			A572			A514		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping $F = 39.0^k$	5	0.317	0.038	5	0.285	0.013	5	0.276	0.020
High Clamping $F = 49.0^k$	5	0.293	0.026	5	0.257	0.024	5	0.274	0.040
TOTAL	10	0.305	0.033	10	0.271	0.023	10	0.275	0.030

TABLE 7.9 PAINT THICKNESS EFFECT--ORGANIC ZINC PRIMER WITH EPOXY TOP COAT (A572 steel; 15/16 in. dia. holes)

Paint Thickness / Clamping Force	Thin ~ 6 mils			Normal ~ 9 mils			Thick ~ 12 mils		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping $F = 39.0^k$	5	0.291	0.020	5	0.285	0.013	5	0.281	0.039
High Clamping $F = 49.0^k$	5	0.275	0.024	5	0.257	0.024	5	0.268	0.022
TOTAL	10	0.283	0.023	10	0.271	0.023	10	0.274	0.030

TABLE 7.10 PAINT THICKNESS EFFECT--ORGANIC ZINC PRIMER WITH EPOXY TOP COAT (A514 steel; 15/16 in. dia. holes)

Paint Thickness / Clamping Force	Thin ~ 6 mils			Normal ~ 9 mils			Thick ~ 12 mils		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping F = 39.0^k	5	0.288	0.028	5	0.276	0.020	5	0.283	0.026
High Clamping F = 49.0^k	4	0.288	0.024	5	0.274	0.040	5	0.271	0.034
TOTAL	9	0.288	0.024	10	0.275	0.030	10	0.277	0.029

TABLE 7.11 HOLE SIZE EFFECT--ORGANIC ZINC PRIMER WITH EPOXY TOP COAT (A572 steel; normal paint thickness)

Hole Diameter / Clamping Force	15/16 in.			1 in.			1-1/8 in.		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping F = 39.0^k	5	0.285	0.013	5	0.251	0.009	5	0.261	0.028
High Clamping F = 49.0^k	5	0.257	0.024	4	0.256	0.014	5	0.255	0.023
TOTAL	10	0.271	0.023	9	0.253	0.011	10	0.258	0.024

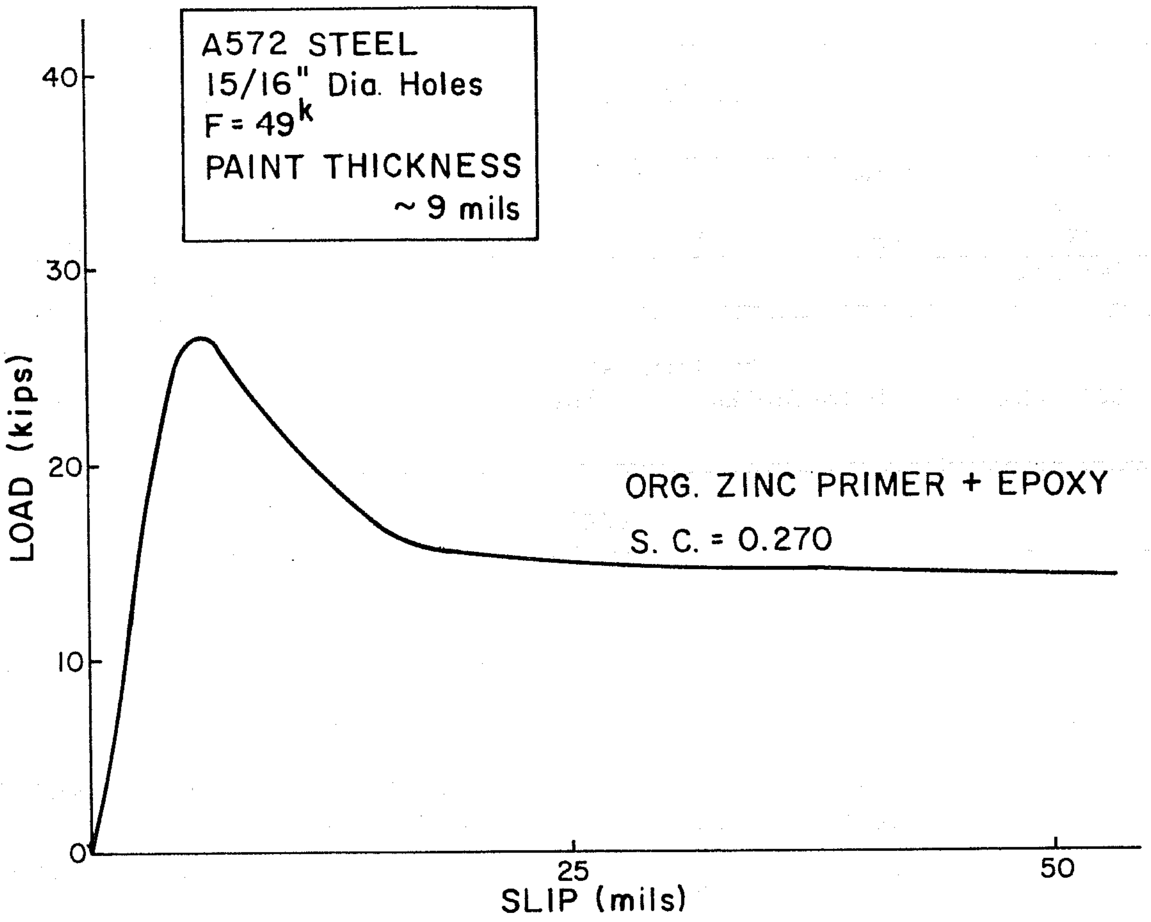


Fig. 7.3 Typical load-slip curve

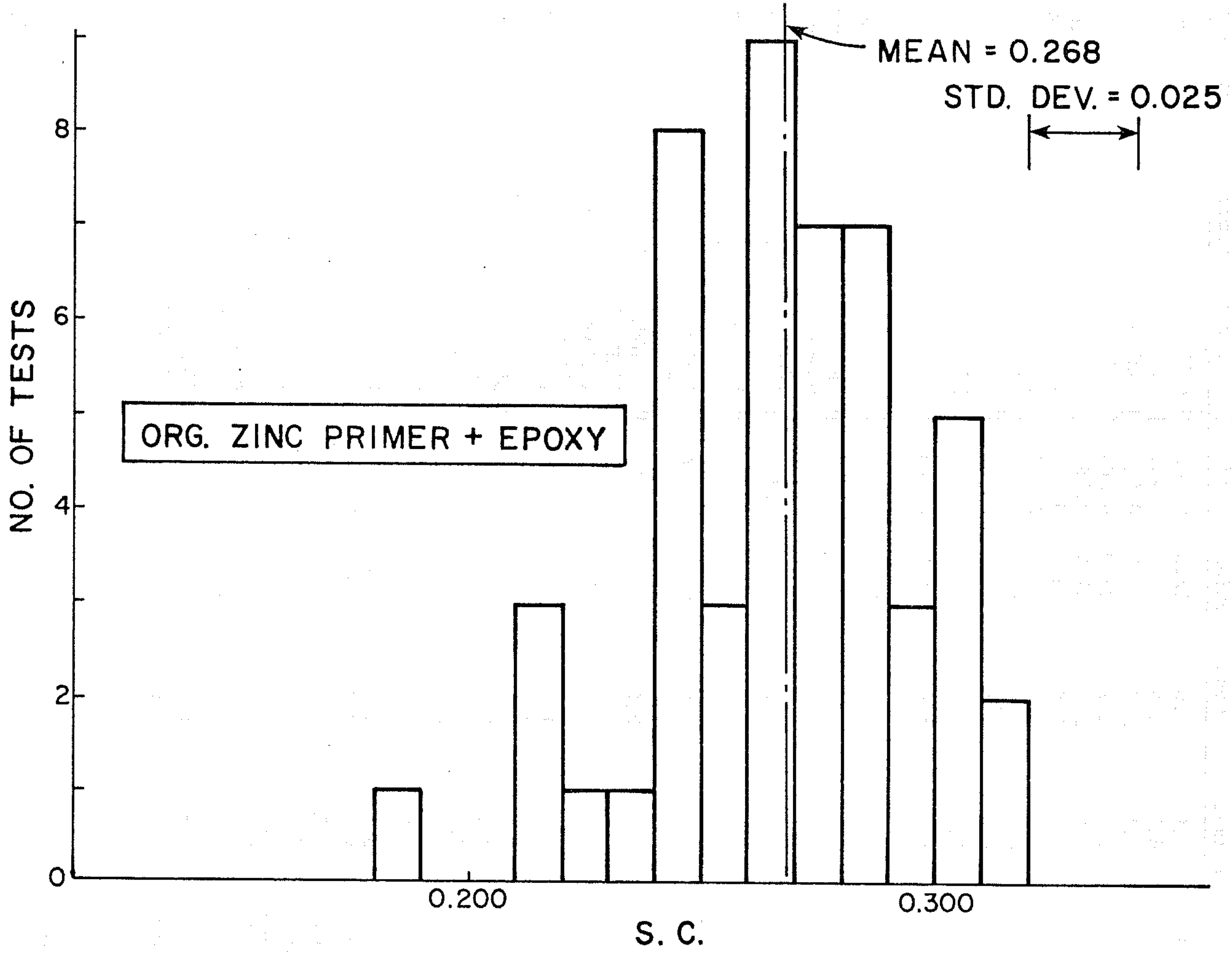


Fig. 7.4 Frequency distribution for organic zinc-rich with epoxy top coat painted surfaces (hole diameters 15/16, 1, and 1-1/8 in.; steel, A572; paint thickness, 6, 9, and 12 mils; number of tests, 49)

TABLE 7.12 TEST RESULTS--INORGANIC ZINC PRIMER WITH VINYL TOP COAT

Specimen Index*	Average Thick. (mils) Primer	Average Thick. (mils) Top Coat	Slip Load (kips)	Slip Coef.
6BLV6	7.8	1.6	42.3	0.542
6BLV7	6.9	2.4	37.5	0.481
6BLV8	7.1	2.5	37.8	0.485
7BLV9	7.1	2.1	39.0	0.500
8BLV10	6.9	2.4	37.5	0.481
6BHV1	7.7	2.5	46.1	0.470
6BHV2	8.0	2.0	49.5	0.505
6BHV3	7.6	1.8	50.9	0.519
7BHV4	7.8	1.9	47.6	0.486
8BHV5	8.0	2.5	44.8	0.457
1ALV6	7.9	2.8	29.9	0.383
1ALV7	7.4	2.4	30.5	0.391
1ALV1	7.2	2.6	35.6	0.456
3ALV5	7.5	2.7	34.6	0.444
6CLV6	7.4	2.2	34.6	0.444
6CLV7	7.4	1.6	34.0	0.436
6CHV2	6.7	3.0	31.8	0.324
7CHV4	6.6	2.1	46.3	0.472
1CLVN6	3.2	2.4	31.0	0.397
2CLVN7	2.6	2.0	33.2	0.426
1CHVN1	2.9	1.9	33.5	0.342
2CHVN2	2.7	2.0	39.9	0.407
6CLVK6	11.3	2.6	34.8	0.446
6CLVK7	11.8	2.8	31.6	0.405
6CHVK1	11.8	1.7	47.7	0.487
6CHVK2	12.5	2.0	41.0	0.418
7BLVN6	2.7	1.8	34.5	0.442
8BLVN7	2.9	1.9	35.5	0.455
7BHVN1	2.9	2.5	39.5	0.403
8BHVN2	2.6	2.1	36.3	0.418
3CLVN8	3.2	2.1	37.5	0.481
4CLVN9	3.3	2.2	40.9	0.524
5CLVN10	3.1	2.2	39.3	0.504
3CHVN3	3.3	2.1	43.9	0.448
4CHVN4	2.8	2.3	42.5	0.434
5CHVN5	2.1	2.1	47.7	0.487
7CLV8	6.7	1.9	42.8	0.549
7CLV9	6.7	1.3	44.7	0.573
8CLV10	6.8	1.6	42.7	0.548
6CHV1	6.9	1.9	50.5	0.515
7CHV3	6.7	1.9	51.5	0.526
8CHV5	6.8	1.9	49.1	0.501
7CLVK8	11.3	1.3	44.9	0.576
7CLVK9	9.5	2.3	45.0	0.577
8CLVK10	10.1	1.5	46.4	0.595
7CHVK3	10.2	1.6	55.3	0.564
7CHVK4	11.1	2.0	52.6	0.537
8CHVK5	10.5	1.8	53.7	0.548
2ALV8	6.6	2.3	40.8	0.523
3ALV9	7.0	1.5	46.2	0.592
3ALV10	6.1	2.1	44.1	0.565
1AHV2	5.8	2.3	53.3	0.544
2AHV3	5.7	2.0	53.6	0.547
3AHV4	5.8	2.2	52.7	0.538
9BLVN8	3.0	1.5	40.1	0.514
10BLVN9	3.2	1.6	41.2	0.528
10BLVN10	2.8	2.4	39.6	0.508
9BHVN3	3.1	2.0	48.4	0.494
9BHVN4	2.9	1.8	47.1	0.481
10BHVN5	3.1	1.8	47.5	0.485
11BLVK6	10.1	1.6	43.9	0.563
12BLVK7	9.9	1.8	44.0	0.564
12BLVK8	10.8	2.1	43.1	0.553
12BLVK9	9.2	2.6	42.9	0.550
13BLVK10	11.0	1.8	41.5	0.545
11BHVK1	10.5	1.2	55.2	0.563
11BHVK2	10.1	1.4	56.5	0.577
12BHVK3	9.5	1.9	51.0	0.520
12BHVK4	11.5	2.4	51.0	0.520
13BHVK5	9.6	1.6	52.9	0.540
5BLED86	6.0	2.6	44.0	0.564
4BLED87	6.5	2.3	43.9	0.562
4BLED88	6.3	2.4	44.4	0.569
5BLED89	7.1	2.2	44.0	0.564
5BLED810	6.7	2.1	43.4	0.556
5BHED81	7.0	2.0	51.2	0.522
4BHED82	6.7	2.4	55.6	0.567
6BHED83	6.4	2.6	54.0	0.551
5BHED84	6.9	2.3	52.2	0.533
5BHED85	6.7	2.1	54.7	0.558
8BLVD96	7.0	2.5	46.3	0.594
8BLVD97	6.8	2.4	40.4	0.518
8BLVD98	6.8	2.7	44.1	0.565
9BLVD99	6.5	2.2	44.0	0.564
10BLVD910	6.8	1.8	45.7	0.586
8BHVD91	6.5	2.2	48.7	0.496
8BHVD92	6.7	2.6	53.2	0.543
9BHVD93	6.9	2.7	50.8	0.518
9BHVD94	6.1	2.3	53.8	0.548
10BHVD95	5.7	2.1	53.6	0.547

*See Appendix A

TABLE 7.13 STEEL TYPE EFFECT--INORGANIC ZINC PRIMER WITH VINYL TOP COAT (15/16 in. dia. holes; normal paint thickness)

Steel Type / Clamping Force	A36			A572			A514		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping F = 39.0^k	9	0.501	0.085	5	0.498	0.030	5	0.510	0.065
High Clamping F = 49.0^k	3	0.543	0.005	5	0.487	0.030	4	0.504	0.023
TOTAL	12	0.512	0.075	10	0.493	0.020	9	0.507	0.048

TABLE 7.14 PAINT THICKNESS EFFECT--INORGANIC ZINC PRIMER WITH VINYL TOP COAT (A572 steel; 15/16 in. dia. holes)

Paint Thickness / Clamping Force	Thin ~ 6 mils			Normal ~ 10 mils			Thick ~ 14 mils		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping F = 39.0^k	5	0.489	0.038	5	0.498	0.030	5	0.555	0.008
High Clamping F = 49.0^k	5	0.446	0.057	5	0.487	0.030	5	0.544	0.026
TOTAL	10	0.468	0.051	10	0.493	0.020	10	0.550	0.019

TABLE 7.15 PAINT THICKNESS EFFECT--INORGANIC ZINC PRIMER WITH VINYL TOP COAT
(A514 steel; 15/16 in. dia. holes

Paint Thickness / Clamping Force	Thin ~ 6 mils			Normal ~ 10 mils			Thick ~ 14 mils		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping $F = 39.0^k$	5	0.466	0.053	5	0.510	0.065	5	0.520	0.088
High Clamping $F = 49.0^k$	5	0.424	0.054	4	0.504	0.023	5	0.511	0.059
TOTAL	10	0.445	0.055	9	0.507	0.048	10	0.515	0.071

TABLE 7.16 HOLE SIZE EFFECT--INORGANIC ZINC PRIMER WITH VINYL TOP COAT
(A572 steel; normal paint thickness)

Hole Diameter / Clamping Force	15/16 in.			1 in.			1-1/8 in.		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
Low Clamping $F = 39.0^k$	5	0.498	0.030	5	0.563	0.005	5	0.565	0.030
High Clamping $F = 49.0^k$	5	0.487	0.030	5	0.546	0.018	5	0.530	0.023
TOTAL	10	0.493	0.020	10	0.555	0.018	10	0.548	0.031

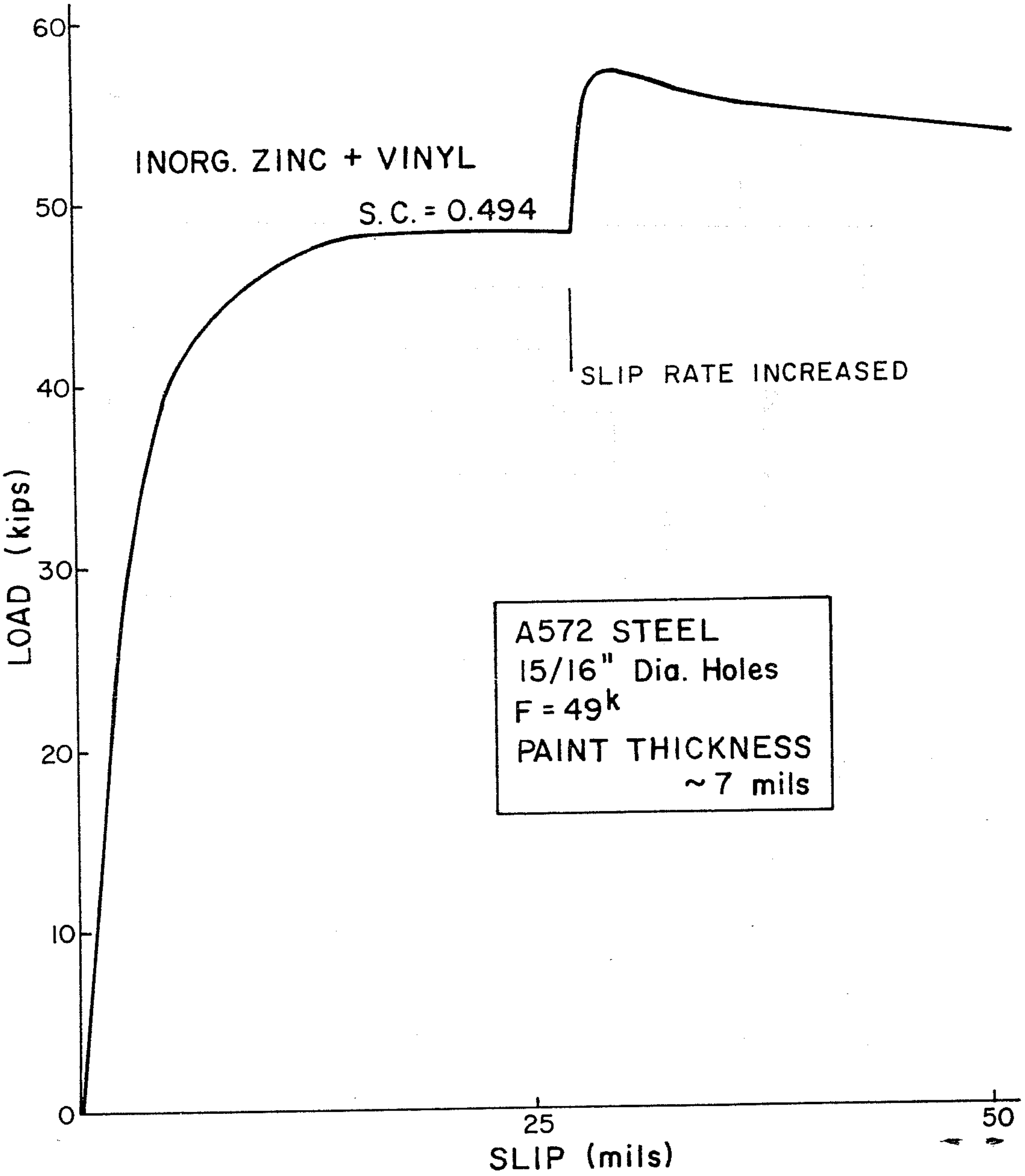


Fig. 7.5 Typical load-slip curve

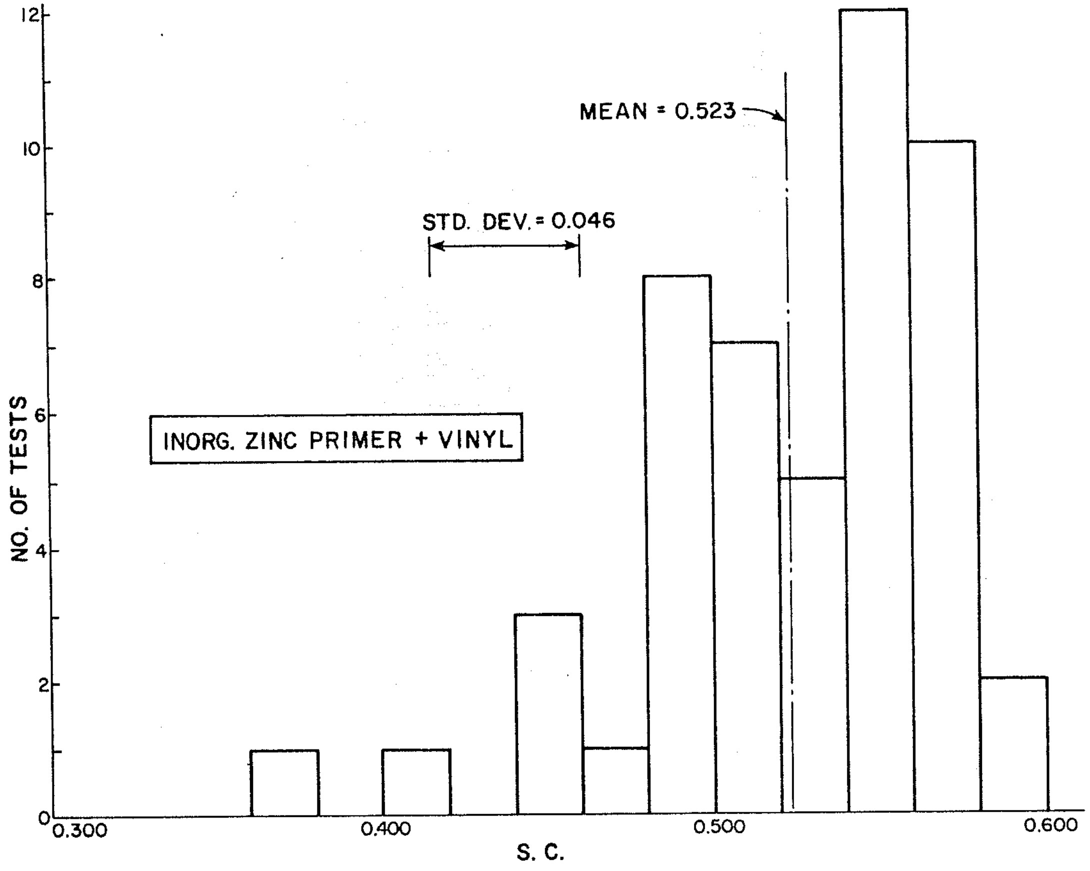


Fig. 7.6 Frequency distribution for inorganic zinc-rich with vinyl top coat painted surfaces (hole diameters, 15/16, 1, and 1-1/8 in.; steel, A572; paint thickness, 6, 10, and 14 mils; number of tests, 50)

loading rate had an effect on the shape of the load-slip curve. An appreciable increase in slip resistance occurred when the loading rate was increased. The behavior of this coating system is very similar to that of organic zinc-rich primer.

Investigation of the faying surfaces of the specimens after testing indicated that in most cases the damage to the vinyl top coat was fairly uniform. The white vinyl top coat peeled off, exposing the yellow inorganic zinc-rich primer.

7.5 Vinyl Primer and All-Vinyl System

Test results are presented in Table 7.17. Tables 7.18 and 7.19 provide summaries of test results in factorial form. Figure 7.7 shows typical load-slip relationships.

For vinyl primer, the load-slip response was linear up to about 85 percent of the slip load. When the slip load was reached, a drop in load occurred accompanied by major slip (rapid slip of specimen). The specimens did not exhibit any loading rate effects. Surface inspection after testing indicated that most contact was confined around the holes. Damage of the paint was negligible.

For the all-vinyl system (vinyl primer with vinyl top coat), the load-slip response was linear up to about 70 percent of the slip load. Then, the load-slip relationship became nonlinear and eventually a flat plateau was formed without any drop in load. Increasing the loading rate increased the slip resistance. Surface inspection after testing indicated that in most cases the white vinyl top coat was damaged (peeled off) exposing the dark red vinyl primer.

7.6 Powder Epoxy

Test results are presented in Table 7.20 and Fig. 7.8 shows a typical load-slip relationship. The extremely low values of slip

TABLE 7.17 TEST RESULTS--VINYLS

Specimen Index*	Average Coating Thickness (mils) Primer	Average Coating Thickness (mils) Top Coat	Slip Load (kips)	Slip Coefficient
3AHX4	2.1	-	21.2	0.216
4AHX5	2.3	-	18.2	0.186
1AHX6	2.5	-	22.0	0.224
2AHX8	2.4	-	19.6	0.200
1AHX10	2.5	-	20.2	0.206
Average	2.4			0.206(0.015)**
11BHX1	2.7	-	19.2	0.196
12BHX2	2.6	-	18.8	0.192
13BHX3	2.3	-	19.3	0.197
13BHX4	2.3	-	17.3	0.177
13BHX5	2.4	-	16.7	0.170
Average	2.5			0.186(0.012)
1CHX1	2.3	-	17.4	0.178
2CHX2	2.6	-	17.1	0.174
3CHX3	2.4	-	17.4	0.178
4CHX4	2.3	-	20.1	0.205
3CHX7	2.4	-	19.4	0.198
Average	2.4			0.187(0.014)
1CHA6	2.5	2.5	18.6	0.190
2CHA7	2.6	2.5	20.8	0.212
3CHA8	2.3	2.3	19.9	0.203
4CHA9	2.5	2.3	17.1	0.174
5CHA10	2.8	2.4	19.3	0.197
4CHA99	2.4	2.1	19.2	0.196
Average		2.4		0.195(0.014)

*See Appendix A.

**The number in parenthesis is the standard deviation.

TABLE 7.18 STEEL TYPE EFFECT--VINYL PRIMER (15/16 in. dia. holes; paint thickness ~ 2.5 mils)

Steel Type / Clamping Force	A36			A572			A514		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
High Clamping $F = 49.0^k$	5	0.206	0.015	5	0.186	0.012	5	0.187	0.014

TABLE 7.19 COMPARISON OF AVERAGE SLIP COEFFICIENT FOR SYSTEMS INVOLVING VINYL TOP COAT (A514 steel; 15/16 in. dia. holes)

Paint / Clamping Force	Vinyl Primer			Vinyl Primer with Vinyl Top			Inorganic Zinc Primer with Vinyl Top		
	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.	No. of Tests	Avg. SC	Std. Dev.
High Clamping $F = 49.0^k$	5	0.187	0.014	6	0.195	0.014	29	0.489	0.066

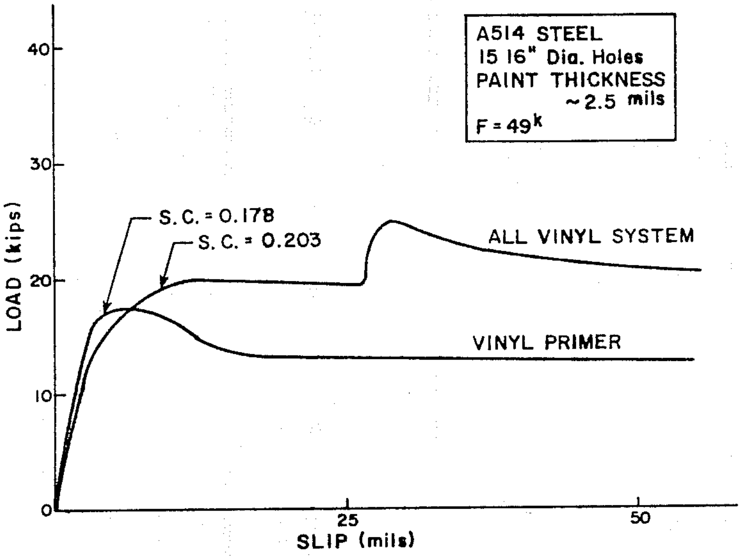


Fig. 7.7 Typical load-slip curve

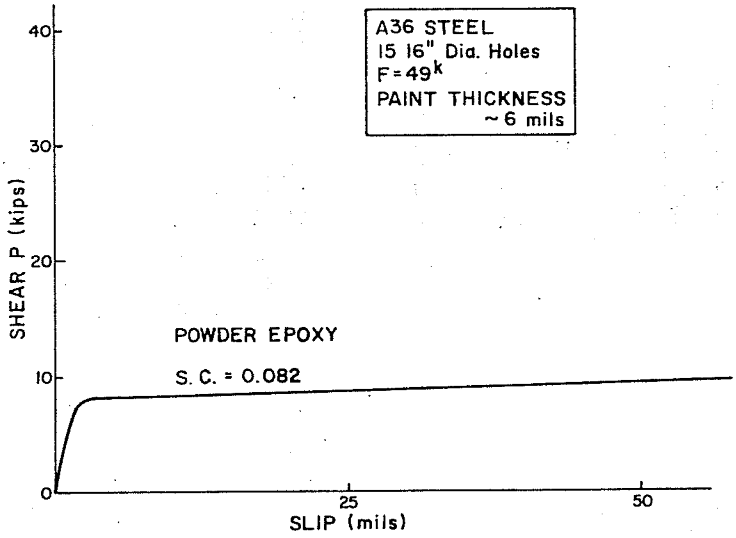


Fig. 7.8 Typical load-slip curve

TABLE 7.20 TEST RESULTS--POWDER EPOXY

Specimen Index*	Average Coating Thickness (mils)	Slip Load (kips)	Slip Coefficient
1ALP6	5.9	5.6	0.072
2ALP7	6.0	6.4	0.082
2ALP8	6.1	4.5	0.058
3ALP9	6.2	5.5	0.071
4ALP10	5.9	6.6	0.085
1AHP1	6.3	9.4	0.096
2AHP2	6.1	9.0	0.092
2AHP3	5.8	7.1	0.072
3AHP4	5.9	7.4	0.076
4AHP5	5.7	8.0	0.082
Average	6.0		0.079(0.01)**

*See Appendix A.

**The number in parenthesis is the standard deviation.

coefficients may be attributed to the very hard and smooth powder epoxy surface. Faying surfaces were unaffected by slip.

7.7 Inorganic Zinc-Rich Primer

Test results are presented in Table 7.21. Figure 7.9 shows typical load-slip relationships for primer with different percentage of zinc.

The load-slip response for inorganic zinc-rich primer was linear up to about 85 percent of the slip load. When the slip load was reached, the specimen slipped slowly with a gradual drop in load. A larger reduction in load occurred in the case of the 75 percent zinc primer as compared to the 80 percent zinc primer (see Fig. 7.9). For the ethyl silicate base (0 percent zinc), there was no drop (reduction) in the slip load, while the flat plateau was formed. The 80 percent zinc primer showed a different behavior. After a total slip of about 30 mils to 40 mils, a banging noise was heard. The sound was low at first, and then became louder as slip progressed. This led to the cyclic pattern on the load-slip curve shown in Fig. 7.9.

Investigation of the faying surfaces after testing indicated that damage to the inorganic zinc-rich primer was fairly uniform. Sometimes the damage was mostly around the holes. In case of the zincless paint (ethyl silicate base), slip caused the faying surfaces to become shiny and smooth. However, no damage occurred to the surface.

7.8 Summary

Table 7.22 is a summary of all of the results on the different coated surfaces. The statistical analyses and the discussion of the test results are given in Chapter 8.

TABLE 7.21 TEST RESULTS--INORGANIC ZINC-RICH PRIMER

Specimen Index*	Percentage Zinc	Average Coating Thickness (mils)	Slip Load (kips)	Slip Coefficient
1BLI6	80	7.5	48.8	0.626
1BLI7	80	7.0	51.4	0.659
2BLI8	80	7.4	50.7	0.650
2BLI9	80	7.1	48.1	0.617
2BLI10	80	7.1	42.6	0.546
1BHI1	80	7.3	60.4	0.616
1BHI2	80	8.0	59.4	0.606
2BHI3	80	7.7	56.6	0.578
2BHI4	80	6.8	56.9	0.581
2BHI5	80	7.6	58.2	0.594
Average		7.4		0.607(0.03)**
12BHI1	75	7.1	48.2	0.492
13BHI2	75	6.9	49.3	0.503
11BHI3	75	7.2	50.1	0.511
13BHI4	75	6.7	50.0	0.510
13BHI5	75	6.9	50.8	0.518
Average		7.0		0.507(0.01)
12BHS6	0	3.6	26.9	0.274
11BHS7	0	3.6	27.3	0.279
8BHS8	0	3.3	27.2	0.278
9BHS9	0	3.0	27.0	0.276
9BHS10	0	3.7	26.6	0.271
Average		3.4		0.276(0.003)

*See Appendix A.

**The number in parenthesis is the standard deviation.

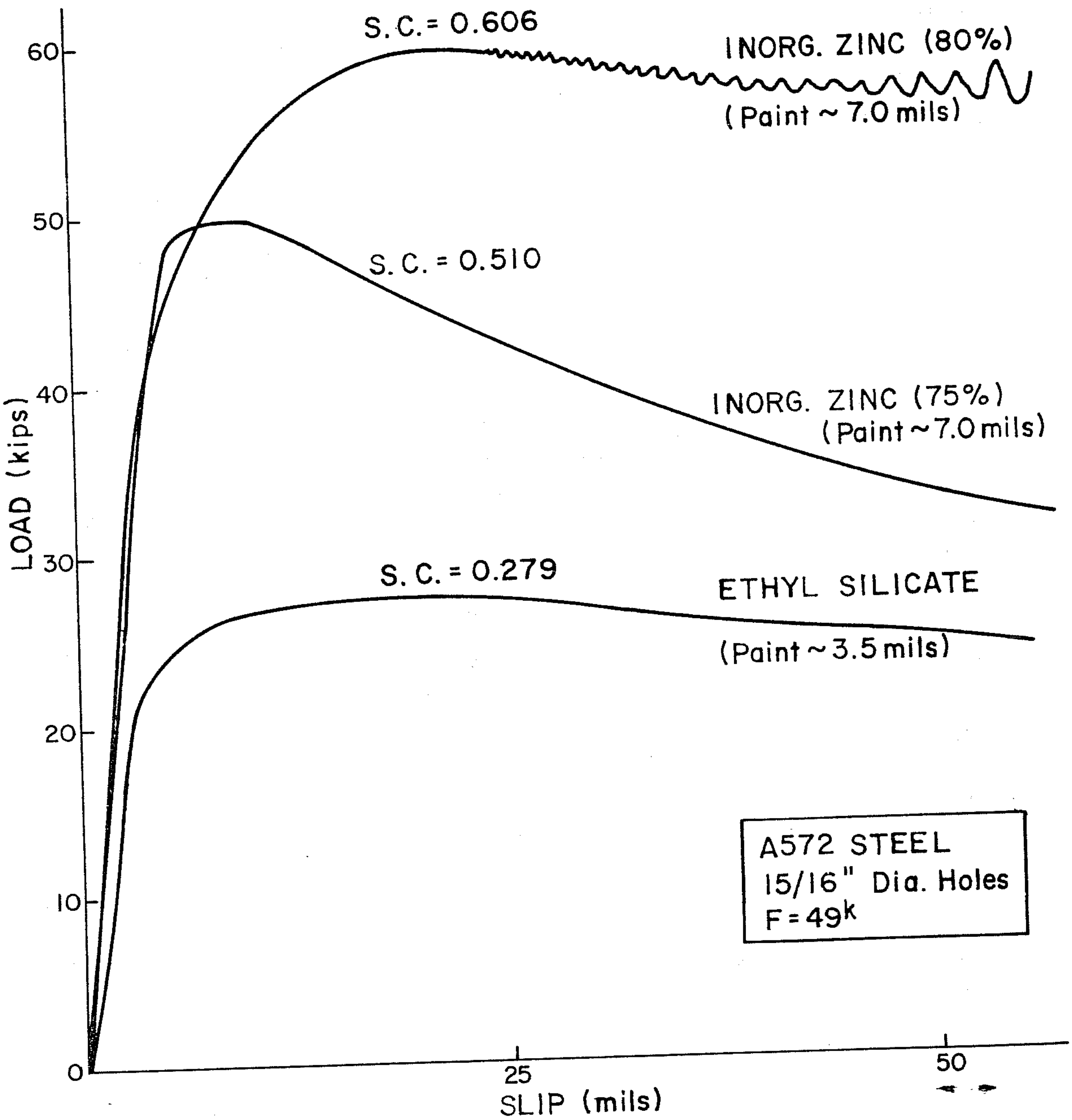


Fig. 7.9 Typical load slip curves

TABLE 7.22 SUMMARY--ALL TEST RESULTS

		Thickness			Oversize Holes	
		Thin	Normal	Thick	D = 1"	D = 1-1/8"
Organic Zinc	A36		0.555* (0.025)**			
	A572	0.446 (0.046)	0.484 (0.055)	0.494 (0.039)	0.439 (0.020)	0.380 (0.025)
	A514	0.355 (0.032)	0.479 (0.066)	0.470 (0.072)		
Organic Zinc with Epoxy Topcoat	A36		0.305 (0.033)			
	A572	0.283 (0.023)	0.271 (0.023)	0.274 (0.030)	0.253 (0.011)	0.258 (0.024)
	A514	0.288 (0.024)	0.275 (0.030)	0.277 (0.029)		
Inorganic Zinc with Vinyl Topcoat	A36		0.512 (0.075)			
	A572	0.468 (0.051)	0.493 (0.020)	0.550 (0.019)	0.555 (0.018)	0.548 (0.031)
	A514	0.445 (0.055)	0.507 (0.048)	0.515 (0.071)		
Vinyl Primer	A36		0.206 (0.015)			
	A572		0.186 (0.012)			
	A514		0.187 (0.014)			
All Vinyl System	A514		0.195 (0.014)			
Inorganic Zinc (A572)	80% Zinc		0.607 (0.030)		0.628 (0.020)	
	75% Zinc		0.507 (0.010)			
	0% Zinc (ethyl silicate base)		0.276 (0.003)			
Powder Epoxy			0.079 (0.010)			

*Average slip coefficient
**Standard deviation

CHAPTER 8

DISCUSSION OF TEST RESULTS

8.1 Method of Analysis

A statistical study was made of the test results given in Chapters 6 and 7 to investigate the effects of the different variables considered in this study. A computer program (AOVRNC) available at The University of Texas at Austin computer library was used. AOVRNC is a self-contained routine for performing fixed-effects analyses of variance requiring user-specified hypotheses. The routine could be used for analyzing factorial experiments with any number of factors at any number of levels. It can also handle situations where the number of replications in each cell is not equal. Appendix B gives a listing of a sample data and sample output for a 2 x 3 x 2 factorial experiment. For statistical testing, a 5 percent level of significance was usually used. In comparing means, this indicates a 5 percent chance of falsely assuming a mean to be significantly different from the population studied. The Scheffé test on means, which is a conservative test for protection against the probability of making a Type I error, was also performed at the 5 percent level. Type I error is the rejection of the hypothesis which states that all the means are equal when the hypothesis is actually correct.

8.2 Blasted Surfaces

A 3 x 2 factorial experiment was analyzed statistically to determine the effect of oversize holes and clamping force level on the slip resistance of A572 steel. The hole size was at three levels (15/16, 1, and 1-1/8 in. diameter), while the clamping force was at two levels (39 and 49 kips). Results of the analysis indicated that at a 5 percent level of significance the hole size exhibited significant contrasts, whereas the clamping forces' contrast was insignificant. The average slip coefficient (ASC) for 15/16 and 1 in. diameter holes was comparable, but was noticeably lower than the ASC for 1-1/8 in. diameter holes. The ASC for the 1-1/8 in. diameter hole was about 20 percent higher than the ASC for both 15/16 and 1 in. diameter holes. This increase in slip resistance provided by the 1-1/8 in. diameter hole specimens could not be explained, especially since the load-slip response for the three hole sizes was identical and the contact areas observed after testing were about the same. However, test results on the 1-1/8 in. diameter hole specimens were obtained from two sandblastings only, as compared to the test results on 15/16 in. diameter hole specimens which were obtained from a total of twelve sandblastings. Because of the considerable scatter in the test results, due to different sandblastings (see Fig. 6.7), it is a reasonable possibility that the imposed restriction on the 1-1/8 in. diameter hole joints (two sandblastings only) may have led to the higher slip resistance. However, it may be confidently concluded that for 7/8 in. diameter bolts, there is no decrease in the slip coefficient for oversize holes with up to 1/4 in. clearance. This conclusion is in agreement with the work done by Allan and Fisher on mill scale joints with oversize holes [15].

Similar statistical analysis of a 3 x 2 factorial experiment was performed to evaluate the effect of steel type on the slip resistance. Only joints with 15/16 in. diameter holes were used. Steel types were A36, A572 Grade 50, and A514. Clamping force was at the two levels, 39 and 49 kips. This analysis confirmed that clamping force was an insignificant variable. The statistical analysis was a double check. It was apparent from the test results

(Figs. 6.3 and 6.4) that the ASC was almost unaffected by the level of force (39 or 49 kips) at which the specimen was clamped. This may lead to the conclusion that regardless of steel type or hole size used (within the limitations of this study), the ASC is not affected for all practical reasons by the level of the clamping force. On the other hand, the analysis indicated that steel type was a significant variable. The ASC for A36 and A514 steel was about equal (0.471 and 0.490, respectively), but was noticeably lower than the ASC for A572 steel (0.541), as shown in Fig. 6.3. The slip resistance offered by A572 steel was only about 12.5 percent higher than that of A36 and A514 steel. It is debatable if this modest increase in slip resistance should be taken into consideration in the design, since each steel type tested came from a single heat.

It might also be mentioned that tests reported by Fisher and Struik [6] indicated that A514 heat treated steel provided lower resistance to slip as compared to A36 steel. This was attributed to the harder surface of A514 steel that influences the roughness achieved by blast cleaning. The reduction in the slip resistance was about 33 percent for blast-cleaned surfaces. However, the ASCs for A36 and A514 steel specimens studied herein were about the same , a difference of about 3.5 percent. 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 also, when compared for A36 and A514 steel plates which were blasted together, did not indicate any significant differences.

A simple one-variable analysis of variance was performed to study the effect of surface roughness on the slip coefficient. A572 steel joints with 15/16 in. diameter holes were grouped into four groups according to roughness (2, 2.5, 3, and 3.5 mils). Each group represented an average anchor pattern profile depth as measured by the Keane Tator surface comparator. As can been seen in Fig. 6.8, the ASC tends to increase slightly as the surface gets rougher. However, the statistical test at 5 percent significance level indicated that roughness was insignificant.

Another similar simple analysis was done to find out if different sandblastings significantly affected the ASC. For each steel type a separate analysis was done to compare the ASCs as obtained from each sandblasting. It was concluded that for any of the three steel types considered, the ASC is not significantly affected by different sandblasting. The ASC, as a function of sandblasting time, is given in Fig. 6.6. This conclusion is helpful in design since sandblasting is eliminated as a variable. This means that in spite of the fact that the joints in a structure might be blasted at different times, still the ASCs for all joints will be about the same.

8.3 Coated Surfaces

8.3.1 Oversize Holes and Clamping Force. A 3 x 2 factorial experiment for each coating system was analyzed statistically to determine the effects of oversize holes and clamping force level on the slip coefficient. The hole sizes were 15/16, 1, and 1-1/8 in. in diameter; the clamping force was at the two levels, 39 and 49 kips. The coating systems used were organic zinc primer, organic zinc primer with an epoxy top coat, and inorganic zinc primer with vinyl top coat. All joints were of A572 steel and had normal paint thickness (~ 6 mils for primer and ~ 3 mils for top coat). For the surfaces coated with organic zinc primer, the analysis indicated that hole size was a significant variable, whereas the clamping force was not. The 15/16 and 1 in. diameter hole joints had comparable ASCs (difference of about 3 percent) which were higher than the ASC for 1-1/8 in. diameter hole joints by about 14 percent. However, the friction characteristics of organic zinc primer coated surfaces showed ample sensitivity to painting. For each group of joints (specimens) painted at a single time, the standard deviation was very low (~ 0.020) and was about equal for all the groups. But, the average slip coefficient exhibited large differences from one painting job to another, amount to about 15 percent. This is believed to be due to the slight variations in paint surface roughness resulting from different painting conditions (humidity, temperature, spray gun setting, etc.). The results of the joints with different hole sizes were not obtained all from one painting job. The 15/16 and 1 in. diameter hole joints were painted at the same time, whereas the 1-1/8 in. diameter hole joints were painted separately.

Thus, it was felt that the low ASC exhibited by the 1-1/8 in. 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 the joints were painted at the same time. The results summarized in Table 7.6 show that the effect of hole size on the ASC was insignificant (0.368 and 0.371 for 15/16 and 1-1/8 in diameter holes, respectively) and the effect of different paintings was verified.

As for the organic zinc primer top-coated with epoxy, the analysis of the 3 x 2 factorial experiment 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 top coat. It is believed that the hard epoxy top coat provided surfaces which possess more uniform friction characteristics.

For the inorganic zinc primer with a vinyl top coat, the analysis indicated that hole size as well as clamping force was significant at the 5 percent level. The clamping force exhibited insignificant contrasts at the 1 percent level. This indicated that the clamping force effect was very small. The maximum difference in the ASC due to clamping force level was about 6 percent for the 1-1/8 in. diameter hole joints. The low clamping force (39 kips) always offered the higher slip resistance. The ASCs for 1 and 1-1/8 in. diameter hole joints were about equal (1 percent difference), but were noticeably higher than the ASC for the 15/16 in. diameter hole joints (12 percent difference). The relatively high value of the ASC for the joints with oversize holes cannot be fully explained. However, it is very possible that the observed differences were due to different paintings. The joints with 1 and 1-1/8 in. diameter holes were painted at the same time and provided comparable ASCs. Joints with 15/16 in. diameter holes were painted separately and provided a lower ASC. However, an additional experiment, as in the case of the organic zinc primer, was not designed since the oversize holes, contrary to the previous case, offered a higher slip resistance. Some additional tests were conducted on inorganic zinc (no top coat) coated surfaces with 15/16 and 1 in. diameter holes (A572 steel and a clamping force of 39 kips) which yielded ASCs of 0.620 (five tests) and 0.628 (ten tests), respectively. The values are about equal and indicate very clearly the insignificance of hole size as a variable. Figure 8.1 shows the effect of oversize holes for the different coating systems. The narrow black boxes shown in the figure for organic zinc primer represent the additional experiment done for this paint. From the above discussion, it may be concluded that for joints coated with any of the above-mentioned paint systems, there will be no decrease in the slip coefficient for oversize holes with up to 1/4 in. clearance (for 7/8 in. diameter bolts).

In the 1976 Bolt Specification [5] (Table 2a), a reduction of about 15 percent is specified for joints with oversize holes. This was based on data which showed that the clamping force is expected to be reduced by about 15 percent for oversize holes [6]. This reduction was attributed to plate depressions occurring under the bolt heads during tightening by the turn of the nut method.

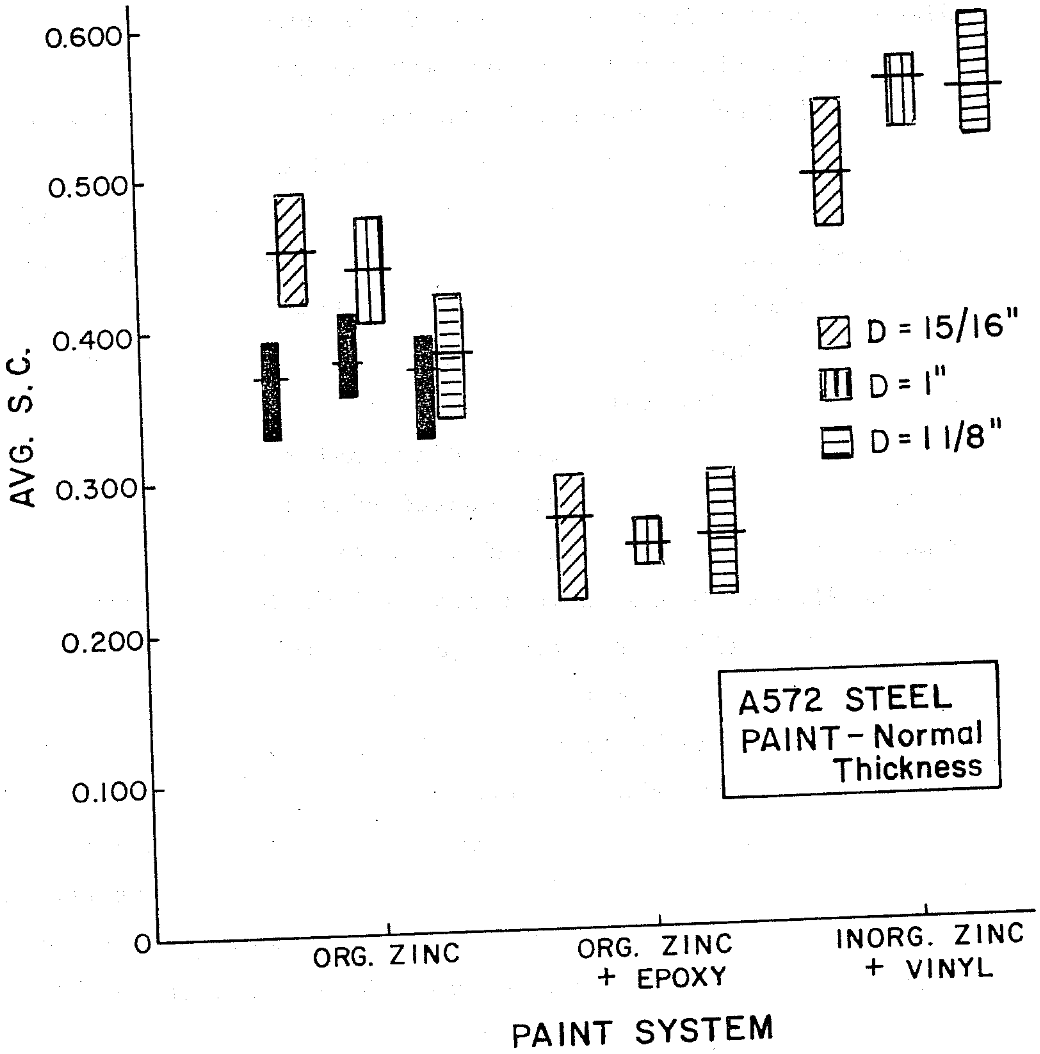


Fig. 8.1 Comparison of average slip coefficient for different hole sizes

Thus, rotation of the nut does not result in the degree of bolt elongation desired. However, if the calibrated wrench or the load indicating washer method is used in tightening the bolts, perhaps this reduction may not exist. Further research is needed to determine if oversize holes cause reduction in the clamping force for these tightening methods. Also, it should be pointed out that the reduction in clamping force (when using turn of the nut method) was 15 percent lower than the average tension that resulted in joints with a 1/16 in. hole clearance. But, bolt tension was still above the minimum required tension by about 18 percent. Thus, in a specification based on the minimum clamping force, no reduction should be considered, even when turn of the nut method is used.

8.3.2 Type of Steel. A similar experiment to that of the oversize holes was analyzed to determine the effects of steel type and clamping force on the slip coefficient of the joints. The steel types were A36, A572, and A514, and the clamping forces were 39 and 49 kips. The coating systems used were organic zinc primer, organic zinc primer with an epoxy top coat, inorganic zinc primer with a vinyl top coat, and a vinyl primer. All joints had 15/16 in. diameter holes and normal paint thickness. Results of the analyses for the different paint systems indicated that the effect of the clamping force was insignificant. Usually, the low clamping force (39 kips) offered a slightly higher slip coefficient than the high clamping force (49 kips). The maximum difference amounted to about 6 percent in the case of the organic zinc primer with epoxy top coat. However, the statistical analyses suggested that the differences are too small and are mainly due to estimate of the variance and scatter in the test results. No real differences exist between the 39 kip and 49 kip ASCs.

On the other hand, the analyses indicated that the steel type was a significant variable for most of the coated surfaces. For the organic zinc primer, organic zinc primer with epoxy top coat, and vinyl primer coated surfaces, the ASCs for A572 and A514 steel were about the same (differences less than 1.5 percent 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 percent, 12 percent, and 11 percent for the three paint systems, respectively. As for the surfaces coated with inorganic zinc primer with a vinyl top coat, the analysis indicated that steel type was an insignificant variable. The maximum percentage difference of the ASC for any of the three steel types did not exceed 4 percent. Figure 8.2 shows a comparison of the ASCs for the different steel types and paint systems. In the figure, it can be seen that the ASC of A36 steel always plots slightly higher than the ASCs of A572 and A514 steel.

The increase in slip resistance provided by A36 steel for some coatings cannot be explained, since the blasted specimens did not show a similar increase. Also, the inorganic zinc primer with vinyl top coat did not show an increase in the slip resistance. Since the maximum observed increase was only 15 percent, it is recommended that 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 the inclusion of steel as a factor in design specifications.

8.3.3 Paint Thickness. A 2 x 3 x 2 factorial experiment was analyzed to determine the effect of paint film thickness on the slip coefficient of the joints. The factorial experiment was also used to check the possibility of interaction between steel type at two levels--A572 and A514 steel, paint thickness at three levels--thin, normal, and thick, clamping force at two levels--39 and 49 kips. The same three paint systems were considered; namely, organic zinc primer with and without an epoxy top coat, and the inorganic zinc primer with vinyl top coat system. Top coats (epoxy or vinyl) had constant thickness of about 3 mils. Thickness of the primer was

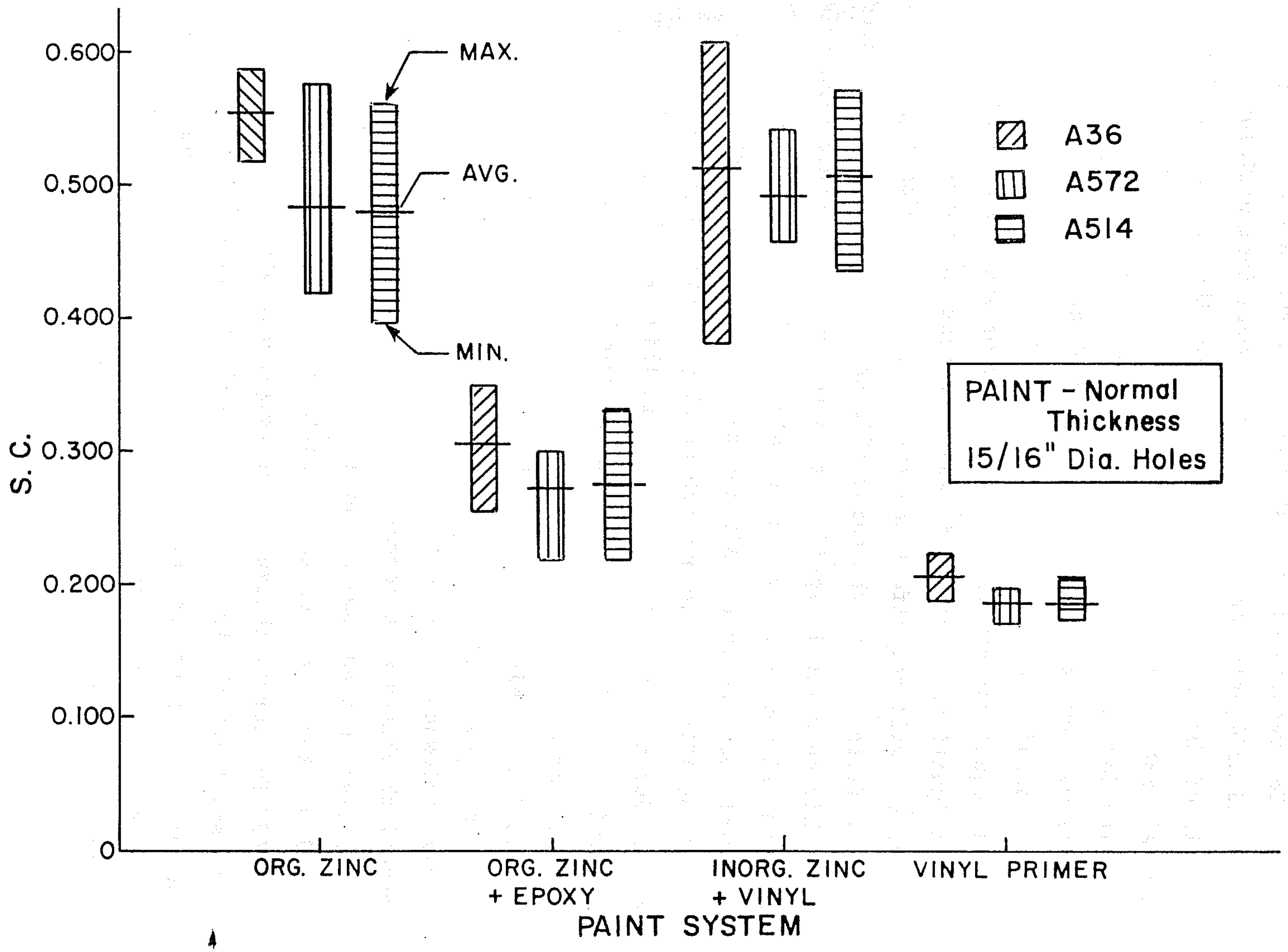


Fig. 8.2 Comparison of average slip coefficient for different steel types

the variable. 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. diameter holes.

The results of the analyses confirmed that steel type (A572 and A514 only) and clamping force were insignificant variables for all of the three paint systems. Also, the analyses indicated that all interaction effects between the three variables (steel, clamping force, and paint thickness) were insignificant. These results were expected since (1) the steel type experiment discussed above concluded that the ASCs for A572 and A514 steel were practically equal for any of the paint systems and the clamping force was insignificant, and (2) it was felt that the paint thickness as a variable will not affect the steel type or the clamping force level effects. As to the paint thickness, the analyses indicated that thickness was insignificant in the case of organic zinc primer with and without epoxy top coat paint systems. Table 7.4 shows an apparent decrease in the ASC for thin thickness of organic zinc primer on A514 steel joints (about 25 percent). However, this was mainly due to edge effects present in this set of eight specimens. A verification for this reasoning is provided by the A572 steel joints that have no edge effects and did not exhibit this reduction in ASC due to thin thickness. For inorganic zinc primer with vinyl top coat, statistical analysis indicated that the ASCs for thin and normal thickness were comparable. Also, the ASCs for thick and normal thickness were comparable. But, the ASCs for thick and thin thicknesses showed some differences. The ASC for thin thickness was lower than that for thick thickness by about 15 percent. Since the ASC for normal thickness was comparable with the ASCs for both thin and thick thicknesses, this would suggest 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 that thickness is not an important variable and its effect on the slip resistance of the joint for all practical reasons is negligible. Figure 8.3 shows the effect of paint thickness on the ASC for A572 and A514 steel joints.

8.3.4 Other Variables. A simple one variable analysis was performed to compare between the following paint systems: vinyl primer (~ 2.5 mils), vinyl primer with a vinyl top coat (all vinyl system)(~ 2.5 + 2.5 mils), and inorganic zinc primer with vinyl top coat (~ 7 + 2.5 mils). All joints were of A514 steel and had 15/16 in. diameter holes. The results indicated that the vinyl primer and all vinyl system had comparable ASCs, which were significantly lower than the ASC of the inorganic zinc primer with vinyl top coat. The all vinyl system and the inorganic zinc primer with vinyl top coat had the same top coat. However, the slip resistance of the all vinyl system was 60 percent lower. It is quite apparent that the vinyl primer, which has a low ASC (0.187), when top-coated with vinyl still exhibited a low ASC (0.195), whereas the inorganic zinc which has a high ASC (0.607) when top-coated (with the same vinyl top coat) exhibited a relatively high ASC (0.489). This behavior indicates that the kind of primer considerably affects the slip resistance even when it is top-coated. Figure 8.4 clearly shows this phenomenon.

A similar analysis was performed to investigate the effect of the percentage of zinc in inorganic zinc primer on the slip resistance. The percentages of zinc (by dry weight) were 80 percent, 75 percent, and 0 percent. Figure 8.5 illustrates the effect of percentage of zinc on the ASC. Results of the tests are given in Table 7.21. It is clear that the percentage of zinc considerably affects the slip resistance. The ethyl silicate base (0 percent zinc) provided the least ASC. The reduction in ASC was 55 percent compared to the 80 percent zinc primer. No tests were done to investigate the effect of the percentage of zinc between 0 percent and 75 percent. Therefore, it is felt that further study is needed

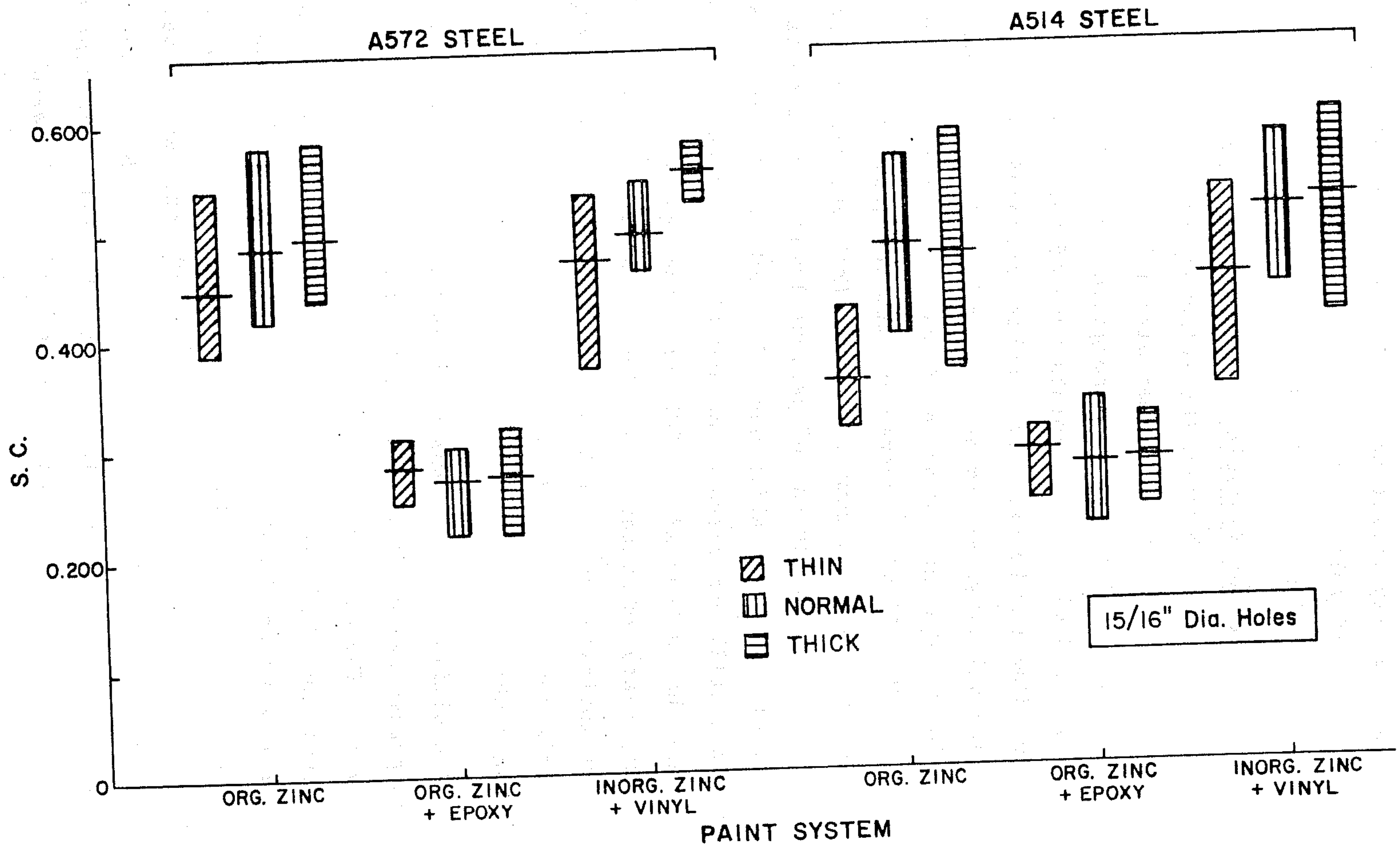


Fig. 8.3 Comparison of average slip coefficient for different paint thickness

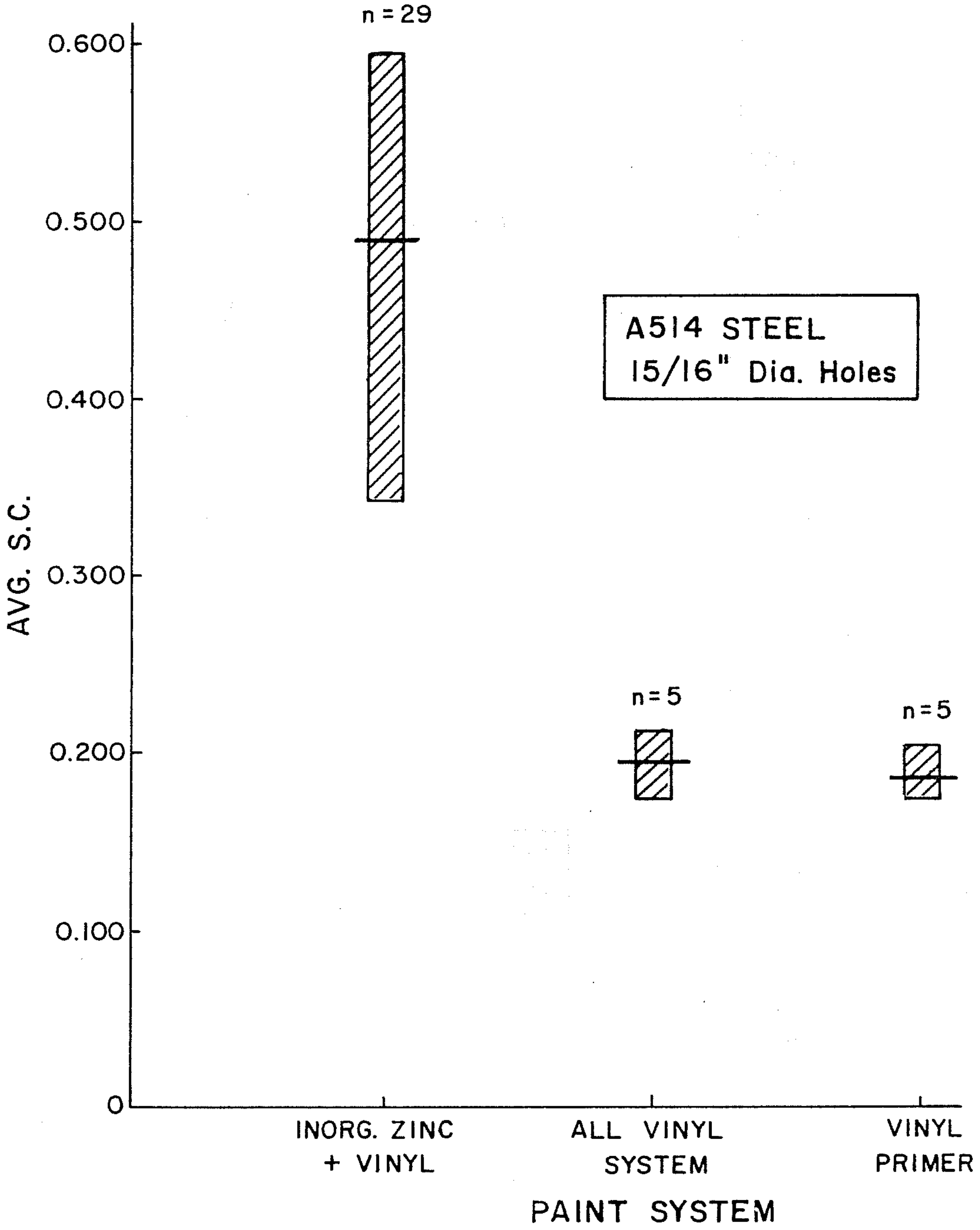


Fig. 8.4 Comparison of average slip coefficient for different vinyl systems

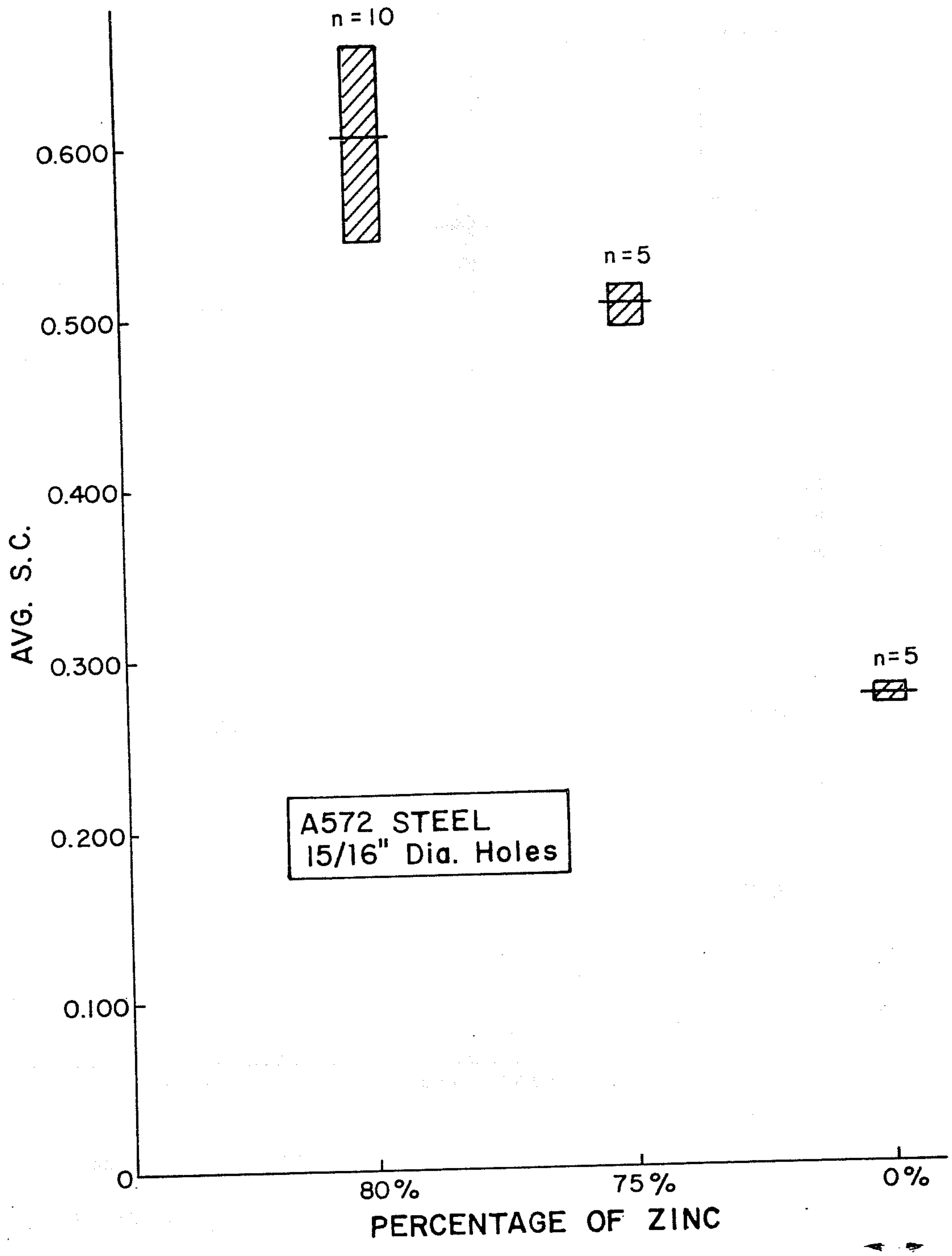


Fig. 8.5 Effect of the percent of zinc in inorganic zinc rich primer on the average slip coefficient

in order to establish a direct mathematical relationship between the percentage of zinc and the ASC. Such a relationship may be included in a design specification to provide the ASC for any specified percentage of zinc in the paint.

In summary, the following Table 8.1 lists the overall ASC, standard deviation, and the number of tests for each of the coating systems. Figure 8.6 shows the overall ASC as well as the range for each of the coating systems. Figure 8.7 shows typical load-slip curves.

TABLE 8.1 OVERALL AVERAGE SLIP COEFFICIENTS

Surface Treatment	Average Slip Coeff. (ASC)	Standard Deviation	Total No. of Tests
Sandblasted	0.521	0.077	103
Organic zinc primer	0.464	0.061	106
Organic zinc primer with epoxy top coat	0.276	0.031	88
Inorganic zinc primer with vinyl top coat	0.510	0.057	94
Inorganic zinc primer 80% zinc	0.618	0.030	20
75% zinc	0.507	0.010	5
0% zinc	0.276	0.003	5
Vinyl primer	0.193	0.016	15
All vinyl system	0.195	0.014	5
Powder epoxy	0.079	0.010	10

From the above table it is evident that coated surfaces have lower standard deviations than blast-cleaned uncoated surfaces.

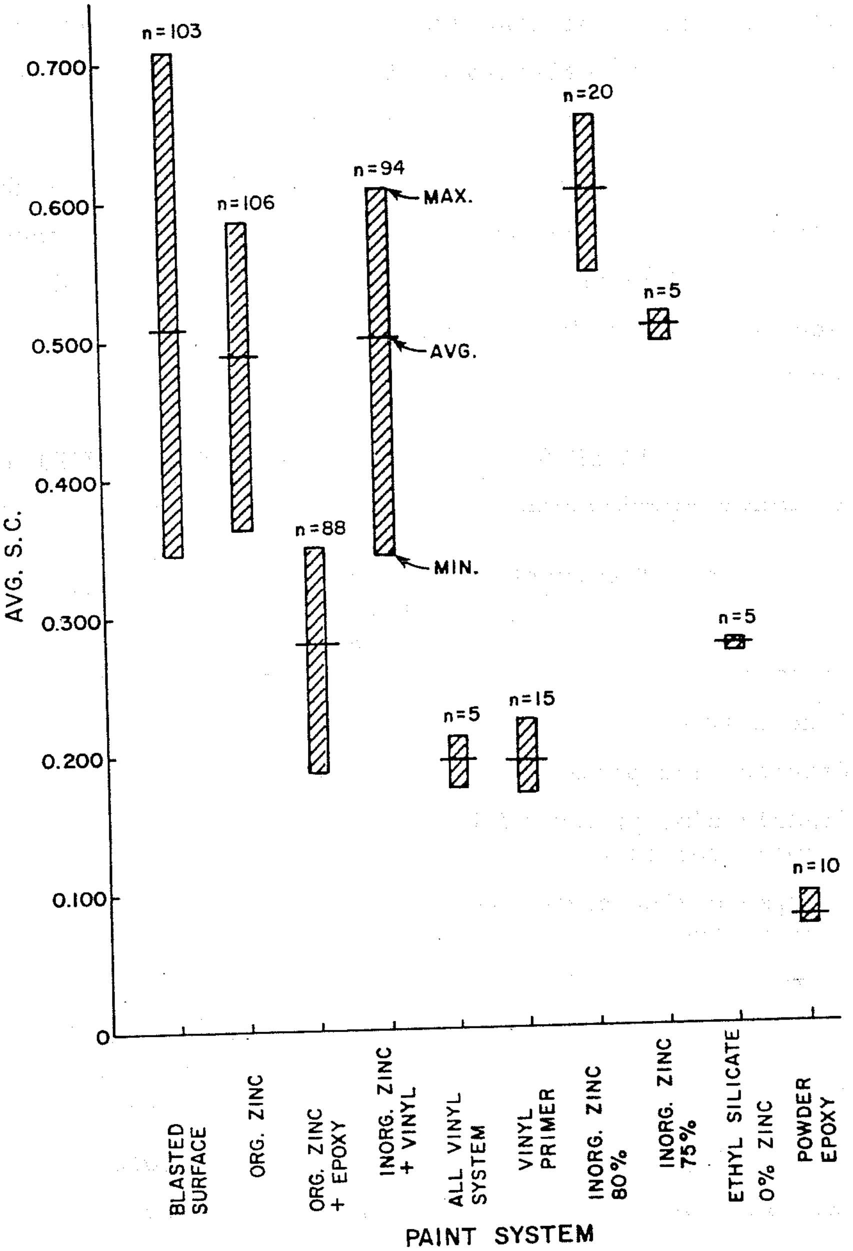


Fig. 8.6 Comparison of overall average slip coefficient for sandblasted and painted surfaces (blasted and painted surfaces: A36, A572, and A514 steel; hole sizes: 15/16, 1, and 1-1/8 in. dia.; clamping force: 39 and 49 kips; paint thickness: 3 to 15 mils) [n = total number of tests]

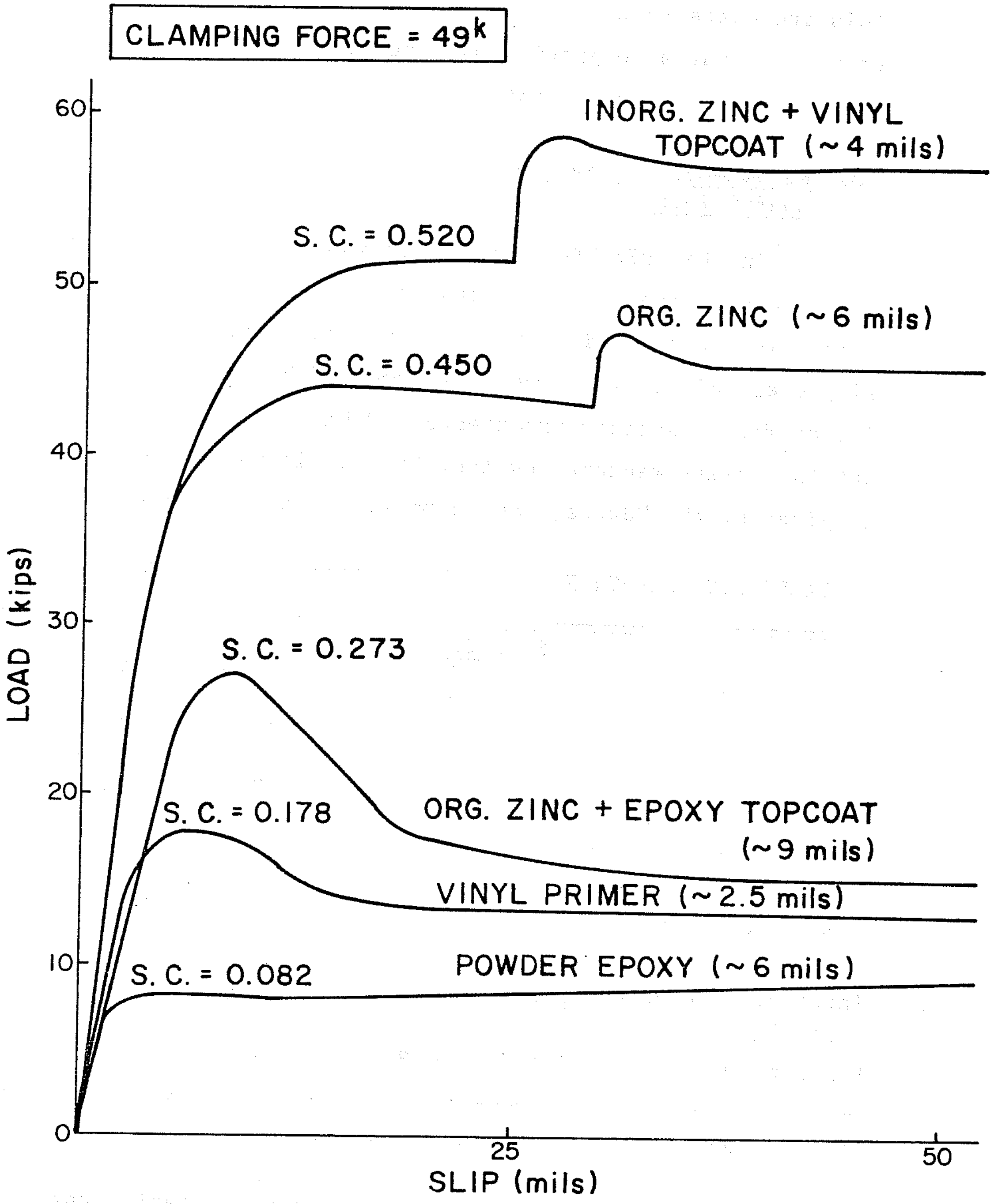


Fig. 8.7 Typical load-slip curves

This indicates that coatings not only protect the surfaces against corrosion, but also provide more reliable surfaces with respect to their friction characteristics.

8.4 Recommended Allowable Slip Coefficients

In the 1976 "Bolt Specification" [5], allowable shear stresses are given as a function of the surface treatment. These values were based mainly on the frequency distribution and mean slip coefficients which were recommended by Fisher and Struik [6] for different surface treatments. Table 8.2 is an attempt to find out the safety factors involved in the allowable shear stresses, as given by the "Specs," and comment on their adequacy.

TABLE 8.2 SAFETY FACTOR FOR DIFFERENT SURFACE TREATMENTS

Surface Treatment (1)	Slip Coeff.* Avg. (2)	Slip Coeff.* Std. Dev. (3)	Specs Allowable Shear Stress (A325) ksi (4)	Calc. Shear Stress (A325) ksi (5)	F.O.S. (6)
Blast-cleaned	0.493	0.074	27.5	36	1.31
Organic zinc-rich paint	0.350	0.035	21.0	26	1.22
Inorganic zinc-rich paint	0.500	0.050	29.5	37	1.24
Vinyl primer	0.270	0.023	16.5	20	1.20

*Values recommended by Fisher and Struik.

Columns 2 and 3 list the average slip coefficients and standard deviations. The A325 allowable shear stresses [5] shown in Column 4 were based on the values given in Columns 2 and 3 [6]. These allowable stresses were based on a clamping force provided by the calibrated wrench installation, which is assumed to be 1.13

times the minimum required clamping force [6]. Column 5 is the calculated shear stress based on the given slip coefficient of Column 2 and on a clamping force provided by the calibrated wrench installation (A325 bolts) for comparison purposes. Column 6 is the factor of safety (F.O.S.) which is obtained by dividing Column 5 by Column 4.

The "Specs" state in its commentary that the values of the allowable shear stresses should provide connections that have a probability that slip may occur at full design load, which is at most 10 percent. However, by looking at the considerably low factors of safety involved (Column 6), it appears that the "Specs" did not consider cases of overloads or special loads when suggesting their allowable stresses. Also, the commentary of the "Specs" states that the safety index of friction-type connections has always been less than that required for other types of connections, because slip resistance is a serviceability criterion. However, in an indeterminate structure slip can affect the stress distribution as well as the structural performance (serviceability). In structures with large gravity loads such as multistory frames, slip can significantly increase the P-Δ moments, thus reducing the ultimate strength of the frame.

Usually friction-type connections when specified are intended for important structures (e.g., bridges) where slip is objectionable. Thus, it is felt that the 10 percent slip probability value adopted by the Specification is somewhat high. Table 8.3 lists allowable slip coefficients for the different surface treatments considered in this research. These values are calculated using the frequency distribution and the mean value for each surface treatment. The table gives the allowable slip coefficients for different probabilities of slip as well as for a mean factor of safety of 1.5. Table 8.4 gives the recommended allowable slip coefficients (approximated from Table 8.3) and shear stresses (for A325 and A490 bolts). These

TABLE 8.3 ALLOWABLE SLIP COEFFICIENTS

Surface Treatment	Overall* Average Slip Coeff.	Allowable Slip Coeff. based on a probability of slip			Allowable Slip Coeff. FOS=1.5
		10%	5%	1%	
Sandblasted	0.521	0.421	0.392	0.339	0.347
Organic zinc-rich primer	0.464	0.385	0.362	0.319	0.309
Organic zinc-rich primer with epoxy top coat	0.276	0.236	0.224	0.202	0.184
Inorganic zinc-rich primer with vinyl top coat	0.510	0.436	0.415	0.374	0.340
Inorganic zinc-rich primer--80% zinc	0.618	0.577	0.563	0.533	0.412
--75% zinc	0.507	0.492	0.486	0.470	0.338
-- 0% zinc	0.276	0.271	0.270	0.265	0.184
Vinyl primer	0.193	0.171	0.165	0.151	0.129
All vinyl system	0.195	0.174	0.165	0.143	0.130
Powder epoxy	0.079	0.065	0.061	0.051	0.053

*See Table 8.1.

TABLE 8.4 RECOMMENDED ALLOWABLE SLIP COEFFICIENTS

Surface Treatment	Allowable Slip Coefficient	Allowable Shear Stress (ksi)	
		A325	A490
Sandblasted	0.34*	22.0	28.0
Organic zinc-rich primer	0.31**	20.0	25.0
Organic zinc-rich primer with epoxy top coat	0.18**	11.5	14.5
Inorganic zinc-rich primer with vinyl top coat	0.34**	22.0	28.0
Inorganic zinc primer			
80% zinc	0.41**	27.0	33.0
75% zinc	0.34**	22.0	28.0
0% zinc	0.18**	11.5	14.5
Vinyl primer	0.13**	8.5	10.5
All vinyl system	0.13**	8.5	10.5
Powder epoxy	0.05*	3.0	4.0

*Based on 1% slip probability.

**Based on FOS = 1.5.

values are based on a mean factor of safety of 1.5 or a 1 percent slip probability, whichever governs. The allowable shear stresses are calculated for A325 bolts and A490 bolts based on minimum specified clamping force [5]. However, the allowable shear stresses may be increased by 13 percent when using the calibrated wrench, and 35 percent when using the turn of the nut method of installation.

It may appear to the reader from first sight that the allowable shear stresses given in the table for organic and inorganic zinc-rich paints are comparable with those of the Specifications for the same coatings. However, this is not quite true. The factors of safety (FOS) used by the Specification for organic and inorganic zinc-rich paints were about 1.22 and 1.24, respectively (see Table 8.2). But the FOS used in Table 8.4 was at least 1.5. However, the reason for these seemingly comparable values is that the Specification allowable stresses were based on conservative slip coefficients due to the inadequacy of the test data. The suggested allowable (design) slip coefficients of Table 8.4 are based on large numbers of tests and provide connections that have a probability that slip may occur at full service load, which is at most 1 percent.

CHAPTER 9

SUMMARY AND RECOMMENDATIONS

9.1 Summary

About 600 friction-type bolted joints were tested to evaluate the slip characteristics of five different coating systems on the contact surfaces and to study the influence of several variables on their slip behavior. Curing time tests were also conducted to determine the time required by each coating system to guarantee its reasonable curing. The recommended curing time for each coating system is given in Chapter 5. Blast-cleaned uncoated control surfaces were tested and the effect of the variables on their slip behavior was investigated. Based on the test results and the discussions in the preceding chapter, significant conclusions have been reached and can be itemized as follows:

(A) Blasted Surfaces

1. The slip behavior and slip coefficient of joints with oversize holes (1 or 1-1/8 in. diameter holes) were identical to those of joints with 15/16 in. diameter holes (standard holes for 7/8 in. diameter bolts).

2. The slip coefficient was not affected by the level of force at which the joint was clamped.

3. Joints of A572 Grade 50 steel showed about 12.5 increase in slip resistance when compared to A36 or A514 steel joints. The slip coefficients for A36 and A514 steel joints were about the same.

4. The surface roughness as measured by the Keane Tator surface comparator did not affect the slip coefficient.

5. Different sandblastings did not affect the average slip coefficient significantly.

(B) Coated Surfaces

1. For any of the coating systems considered in this study, there was no decrease in the slip coefficient for oversize holes with up to 1/4 in. hole clearance (7/8 in. diameter bolts).

2. The clamping force level did not greatly affect the slip coefficient. Usually, the lower clamping force (39 kips) gave a slightly higher average slip coefficient. Most of the time, the differences did not exceed 5 percent and are mainly attributed to the scatter in test results.

3. Coated joints of A36 steel showed an increase in slip resistance when compared to joints of A572 or A514 steels. The percentage increases in slip resistance were: 15 percent for organic zinc-rich primer, 12 percent for organic zinc-rich primer with an epoxy top coat, 11 percent for vinyl primer. In the case of inorganic zinc-rich primer with a vinyl top coat, the slip resistances for the three steel types were about the same. Always, joints of A572 and A514 steels developed about the same slip resistances.

4. Paint film thickness did not appear to have any significant effect on the average slip coefficient for any of the coating systems considered. However, this conclusion may not apply to very small thicknesses (less than 3 mils) or very large thicknesses (greater than 15 mils), since such thicknesses were not considered in the scope of this study.

5. For painting systems with top coats, not only does the top coat affect the friction characteristics of the joint, but also the primer. In other words, coating systems that have the same top coat but different primers are expected to provide different slip resistances.

6. The percentage of zinc in inorganic zinc-rich primers greatly affects the slip resistance. Primers with 80 percent and 75 percent zinc (by dry weight) offered high slip resistances as compared to the base (0% zinc). Compared to the 80 percent zinc primer, the zincless paint (ethyl silicate base) provided an average slip coefficient which was less by about 55 percent.

7. The average slip coefficients for the different surface treatments are summarized in the previous chapter (Table 8.1 and Fig. 8.6). The organic zinc-rich primer, inorganic zinc-rich primer, and the inorganic zinc-rich primer with vinyl top coat systems had slip coefficients comparable to a blast-cleaned surface. The other coatings had slip resistances less than a mill scale surface.

9.2 Design Recommendations

1. Based on this research study, it is suggested that the effect of the following variables may be considered insignificant with respect to the static slip behavior of friction-type joints with coated or uncoated contact surfaces:

(i) Hole size up to 1/4 in. clearance (7/8 in. diameter bolts)
(ii) Type of steel (A36, A572, and A514)
(iii) Clamping force (corresponding to A325 and A490 bolts)
(iv) Paint thickness on each plate in contact (3 mils to 14 mils)

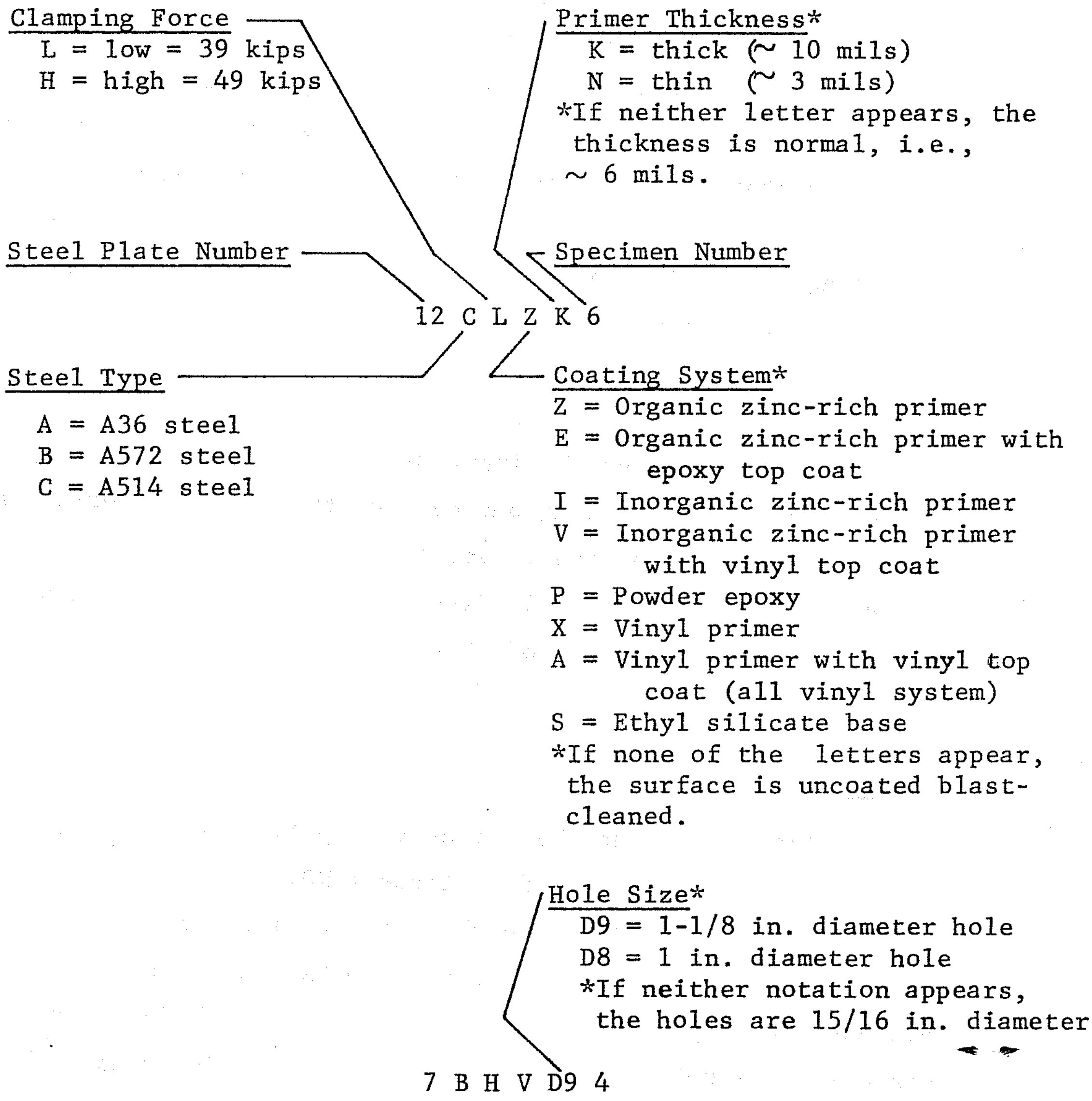
2. Allowable static slip coefficients as well as shear stresses developed from the average slip coefficients available for the different surface treatments considered in this study are summarized in Table 8.4 of the previous chapter. A safety factor based on a 1 percent probability of slip or at least 1.5 was used.

3. The powder epoxy coating is not recommended for friction-type joints. It provides an extremely low resistance to slip, which would lead to uneconomical design.

APPENDIX A

SPECIMEN INDEX

The following example is an attempt to explain the specimen indexes given in Chapters 6 and 7.



Clamping Force
- L = low = 39 kips
- H = high = 49 kips

Primer Thickness*
- K = thick (~ 10 mils)
- N = thin (~ 3 mils)

*If neither letter appears, the thickness is normal, i.e., ~ 6 mils.

Steel Plate Number

Specimen Number

12 C L Z K 6

Steel Type
- A = A36 steel
- B = A572 steel
- C = A514 steel

Coating System*
- Z = Organic zinc-rich primer
- E = Organic zinc-rich primer with epoxy top coat
- I = Inorganic zinc-rich primer
- V = Inorganic zinc-rich primer with vinyl top coat
- P = Powder epoxy
- X = Vinyl primer
- A = Vinyl primer with vinyl top coat (all vinyl system)
- S = Ethyl silicate base

*If none of the letters appear, the surface is uncoated blast-cleaned.

Hole Size*
- D9 = 1-1/8 in. diameter hole
- D8 = 1 in. diameter hole

*If neither notation appears, the holes are 15/16 in. diameter

7 B H V D9 4

APPENDIX B

SAMPLE EXAMPLE OF THE STATISTICAL ANALYSIS

Subroutine AOVRNC was used for the analysis of all the experiments. A simple program was written for mobilizing the subroutine. This example illustrates the method of analysis for the steel type (and clamping force) effect experiment for organic zinc-rich primer with an epoxy top coat paint system. The experiment is a 3 x 2 factorial experiment with steel at three levels (A36, A572, and A514) and clamping force at twl levels (39 and 49 kips). The following is a brief description of the input data and the computer output for this experiment.

Input Data

Table B1 gives the input data. There are six groups of numbers, each representing one cell of the 3 x 2 factorial table. Column A is the steel type. The figures 1.360, 2.500, and 3.100 stand for A36, A572, and A514 steel, respectively. Column B represents the clamping forces of 39 kips and 49 kips. Column C lists the slip coefficients.

Output

Table B2 gives the computer output. The first table is a 3 x 2 factorial analysis of variance (ANOVA). The sources of the variation are: the "ROW" which is the clamping force level, the "COL" which is the steel type, and the RXC which is the interaction between the steel and the clamping force. The "ROW W" and "COL W" stand for the weighted "ROW" and "COL". Because of the number of replications per cell are equal in this experiment, the "ROW W"

TABLE B1 INPUT DATA

ORGANIC ZINC+EPOXY-NORMAL. THICK.- -STANDARD HOLES-EFFECT OF STEEL GR.

A	B	C
1.360	39.000	.326
1.360	39.000	.306
1.360	39.000	.256
1.360	39.000	.350
1.360	39.000	.346
2.500	39.000	.288
2.500	39.000	.300
2.500	39.000	.265
2.500	39.000	.289
2.500	39.000	.281
3.100	39.000	.299
3.100	39.000	.287
3.100	39.000	.247
3.100	39.000	.265
3.100	39.000	.282
1.360	49.000	.269
1.360	49.000	.265
1.360	49.000	.298
1.360	49.000	.303
1.360	49.000	.329
2.500	49.000	.249
2.500	49.000	.270
2.500	49.000	.282
2.500	49.000	.265
2.500	49.000	.219
3.100	49.000	.333
3.100	49.000	.273
3.100	49.000	.218
3.100	49.000	.273
3.100	49.000	.273

Col. A - Steel Type

Col. B - Clamping Force

Col. C - Slip Coefficient

TABLE B2 COMPUTER OUTPUT

```
SOURCE OF VARIATION          DF      SS       MSQ        F       PROB.

 ROW                          1    .0024    .0024    2.8826    .1025
 COL                          2    .0069    .0034    4.1373    .0286*
 RXC                          2    .0010    .0005     .5781    .5686
 ROWW                         1    .0024    .0024    2.8826    .1025
 COLW                         2    .0069    .0034    4.1373    .0286
 GR.36 VS. GR.50              1    .0058    .0058    6.9594    .0144*
 GR.36 VS. GR.100             1    .0044    .0044    5.3462    .0297*
 GR.50 VS. GR.100             1    .0001    .0001     .1062    .7473
           WITHIN            24    .0199    .0008

CELL SUMMARY

  CELL NAME                 MEANS    STD.DEV.    N
GROUP NO.        1          .3168     .0342      5
GROUP NO.        2          .2846     .0115      5
GROUP NO.        3          .2760     .0182      5
GROUP NO.        4          .2928     .0236      5
GROUP NO.        5          .2570     .0218      5
GROUP NO.        6          .2740     .0364      5
```

and "COL W" give the same values in the table as for the "ROW" and "COL", respectively. Also, the hypotheses comparing each two types of steel separately are given (GR 36 = Grade 36 steel [A36], GR 50 = Grade 50 steel [A572], and GR 100 = Grade 100 steel [A514]). The table lists the DF, SS, MSQ, F, and PROB. for each source of variation. The DF is the degrees of freedom; SS is the sum of squares; MSQ is the mean square; F is the F-statistic, and PROB. is the probability of rejecting the hypothesis that all the means are equal when it is, in fact, correct. For testing the significance of the different sources of variation, a 5 percent level of significance was used. Therefore, if the PROB is less than .05, the hypothesis is rejected, indicating the significance of this source of variation. An asterisk marks the hypotheses which are rejected. The table indicates that steel type (ROW) is significant (PROB = .0286 < .050) and that the mean of A36 steel is significantly different from that of A572 and A514 steels. These statistical inferences have been used in the discussion in Chapter 8.

The second table of the computer output (CELL SUMMARY) gives the mean and standard deviation for each cell. This table is identical to the summary table given in Chapter 7 for the same experiment (Table 7.8). Slight differences may be observed in the standard deviations when comparing the two tables. The standard deviations in Table 7.8 are calculated using a divisor of (N - 1) (where N = the number of replications per cell) to provide a better estimate. Standard deviations in the computer output table are calculated using a divisor of N only.

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