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a Division of the PORTLAND CEMENT ASSOCIATION

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FLUOR POWER SERVICES, INC.
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TENNESSEE VALLEY AUTHORITY
Knoxville, Tennessee

DUKE POWER COMPANY
Charlotte, N. C.

TESTS TO EVALUATE COEFFICIENT OF STATIC FRICTION BETWEEN STEEL AND CONCRETE

by

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HIGHLIGHTS

An experimental investigation was conducted to determine the coefficient of static friction between cast-in-place concrete or grout and rolled steel plate. Push-off tests were performed under conditions that represent the interior and exterior bearing surfaces of a containment vessel.

Test Program

Five sets of three similar push-off tests were conducted. Specimens consisted of either concrete cast on top of, or grout cast under a flat steel plate. Three sets of concrete specimens were tested with a wet interface at normal stress levels of 20, 60, and 100 psi. One set of concrete specimens was tested with a dry interface at a normal stress of 60 psi. One set of grout specimens was tested with wet interface at a normal stress of 60 psi. For each specimen, nominal bond stress and coefficient of static friction at interface were measured.

Conclusions

Results of this investigation have shown the following:

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1. Bond strength for concrete specimens varied between 25 and 89 psi. For grout specimens, bond strength was negligible.
2. For wet concrete interface specimens average effective* coefficients of static friction were 0.67, 0.65, and 0.64, at normal stresses of 20, 60, and 100 psi, respectively. The corresponding average peak* coefficients of static friction were 0.70, 0.68 and 0.64, respectively.
3. For dry concrete interface specimens with a normal stress of 60 psi, the average effective and average peak coefficients of static friction were 0.57 and 0.69, respectively.
4. For wet grout interface and normal stress of 60 psi, both average effective and average peak coefficients of static friction were 0.68.

INTRODUCTION

The purpose of this investigation was to determine experimentally the coefficient of static friction between cast-in-place concrete or grout and rolled steel plate. For concrete specimens, wet and dry interface conditions were tested. For grout specimens, wet interface condition only was tested. The work described in this report complies with Fluor Power Services Inc. Purchase Order No. B-1394 dated January 31, 1978.

*Definitions of effective and peak coefficients of static friction are given under heading "Shear Stress - Slip Relationship".

EXPERIMENTAL PROGRAM

This section describes the test specimens, test variables, manufacturing procedure, test setup, instrumentation, and testing procedure.

Test Specimens

Test specimens represented conditions at either steel-concrete or steel-grout interface in the lower support region of a containment vessel. To simplify testing, the friction surface was simulated as a flat plate.

A test specimen is shown in Fig. 1. The test surface was 13.5 in. wide and 24 in. long. These dimensions give a test area of 324 sq.in.

Test Variables

Fifteen specimens were tested in this investigation. All specimens were tested in sets of three. Test variables included

1. Concrete blocks with wet and dry interface
2. Grout blocks with wet interface
3. Level of normal compressive stress

Experimental program as summarized in Table 1 comprised the following three series.

Series I - Wet Concrete-to-Steel Interface

Series I consisted of nine tests. Three tests were performed at each of three levels of normal compressive stress. After breaking the bond, the concrete-to-steel interface was intentionally saturated with water for the friction tests.

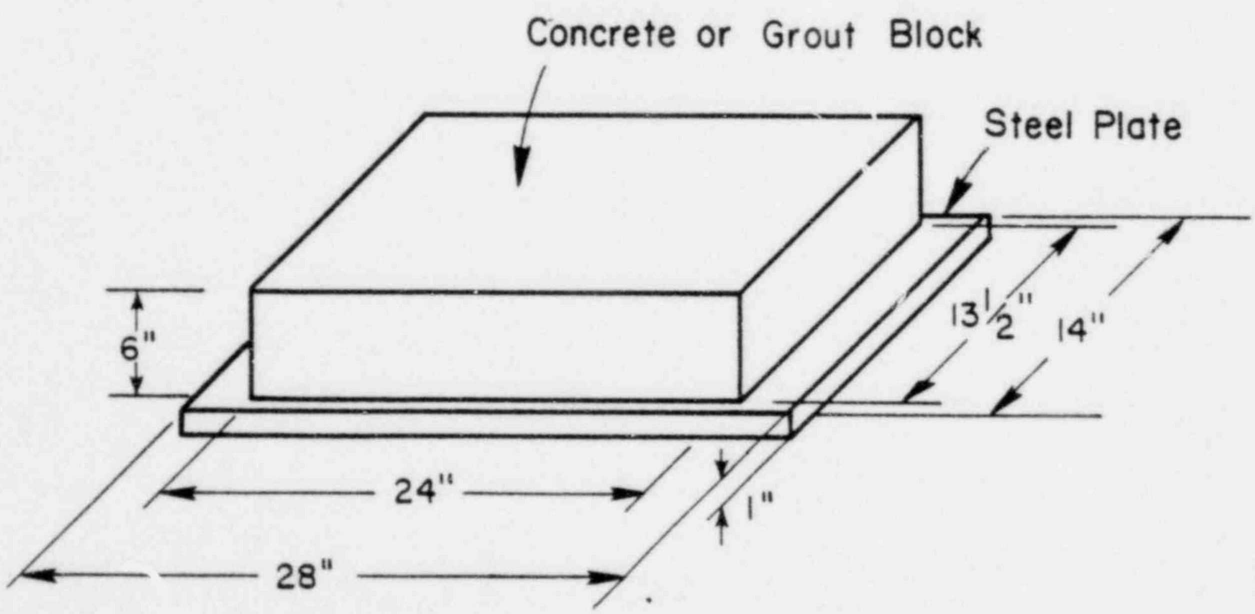

Fig. 1 Test Specimen

TABLE 1 - EXPERIMENTAL PROGRAM

Test Number	Series	Specimen*	Normal Compressive Stress (psi)	Interface Condition
1	I	CWB-1	60	Concrete to Steel (wet)
2		CWA-1	100	
3		CWC-1	20	
4		CWB-2	60	
5		CWA-2	100	
6		CWC-2	20	
7		CWB-3	60	
8		CWA-3	100	
9		CWC-3	20	
10	II	CDB-1	60	Concrete To Steel (dry)
11		CDB-2	60	
12		CDB-3	60	
13	III	GWB-1	60	Grout to Steel (wet)
14		GWB-2	60	
15		GWB-3	60	

*Specimen Identification is as follows:

First Letter: C is for Concrete, G is for Grout
Second letter: W is for Wet, D is for Dry
Third letter is the Load Level: A = 100 psi, B = 60 psi, C = 20 psi
Last digit is for first, second or third test of each set.

Series II - Dry Concrete-to-Steel Interface

Three tests were performed in Series II. Normal compressive stress was held constant at an intermediate level. The concrete-to-steel interface was not wetted after breaking the bond.

Series III - Wet Grout-to-Steel Interface

Series III consisted of three tests at the same level of compressive stress as in Series II. However, after breaking the bond the grout-to-steel interface was completely wetted.

Manufacture of Specimens

Concrete and grout specimens were manufactured according to different procedures discussed below. In all specimens, the steel plate was as rolled SA 516 Grade 70 steel, one inch thick and 14x28 in. in size.

Steel Plate Cleaning

The steel plate was cleaned in accordance with the Steel Structures Council Specifications SSPC-SP2-63, Hand Tool Cleaning[(1)*]. Oil and grease were removed using acetone solvent. Rust scale was removed by hand hammering. Loose mill scale was removed by hand wire brushing.

Concrete-to-Steel Specimens

After cleaning the steel plate, wood formwork was clamped to the top of the steel plate. The concrete mix was designed to yield a compressive strength between 3000 and 5000 psi at 28

*Number in parenthesis denote references listed at the end of the report.

days. The mix was made using Type I Portland Cement, Elgin Sand and Elgin Gravel with a maximum aggregate size of 1-1/2 in.

Concrete was compacted using an internal vibrator. From each batch, six 6x12 in. standard concrete cylinders were taken. These cylinders were used to determine the concrete compressive strength.

Concrete was cured for 7 days under plastic sheeting. Formwork was then stripped and specimens kept in the laboratory at a temperature of 73 F and a relative humidity of 50% until test time at 28 to 30 days.

Grout-to-Steel Specimens

Grout-to-steel specimens were prepared in a setup as shown in Fig. 2. The setup was designed to simulate field conditions of placing grout at the exterior bearing surface of a containment vessel. Formwork was clamped to the underside of the steel plate. The specimen was inclined during grouting. The difference in height between the bottom horizontal edges of the grout block was 4 in.

The grout mix specifications called for

Cement: Type 2, ASTM C-150, no admixtures

Fine Aggregate: Natural Elgin Sand, ASTM C33

Cement to Sand Ratio: 1 to 2 by Volume

Water to Cement Ratio: 0.5 by weight

Flow of this mix was measured after five drops in three seconds on a flow table.

Grout was placed through a funnel secured to the top of the right-hand side pipe shown in Fig. 2. This pipe had a 2 in.

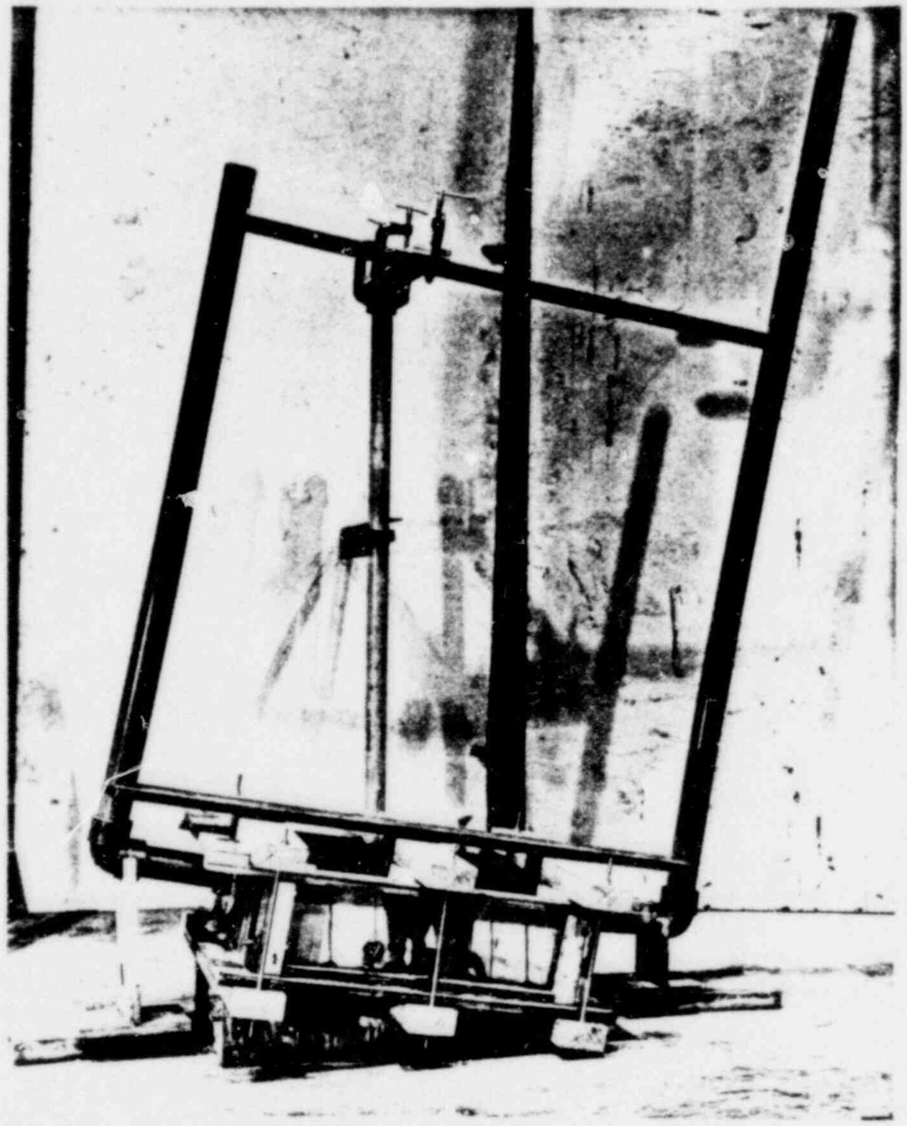

Fig. 2 Setup for Preparation of Grout Specimens

diameter. Because of its consistency, the grout filled the form and flowed upward in the left-hand pipe. The height of the left-hand side pipe corresponded to 5-ft head measured from the center of the grout block.

To permit bleeding of air trapped under the plate, holes were provided around the top perimeter of the form. These holes were sealed as soon as air bleeding was completed.

The tubing was sawed off after 7 days. The specimens were then stripped and turned upside down. They were kept in the laboratory at a temperature of 73 F and a relative humidity of 50% until test time. Grout compressive strength was measured using six 2-in. cubes.

Test Setup

The test setup is shown in the photograph of Fig. 3 and schematically in Fig. 4. This setup is capable of applying vertical loads normal to the shear plane and horizontal loads parallel to the shear plane. The main components of the setup are shown in Fig. 5. They were assembled as follows:

Test specimen was grouted to the lower block shown in Fig. 5. Brackets clamped to the lower block served as guides to position the steel plate. During testing, the brackets prevented slip of the test specimen with respect to the lower block.

The upper block shown in Fig. 5 was grouted on top of the test specimen. Brackets embedded in the upper block served as guides to place it. During testing, the brackets also helped prevent slip of the specimen with respect to the upper block.

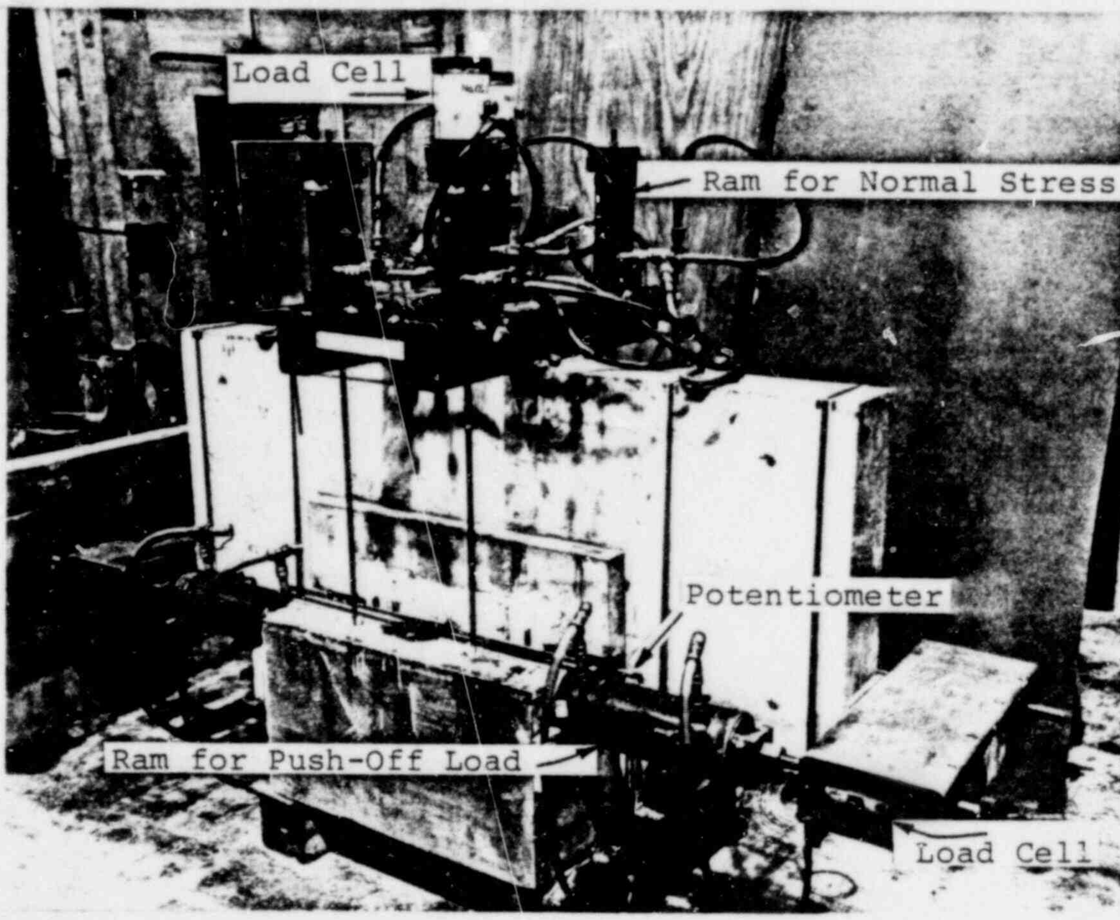

Fig. 3 Test Setup

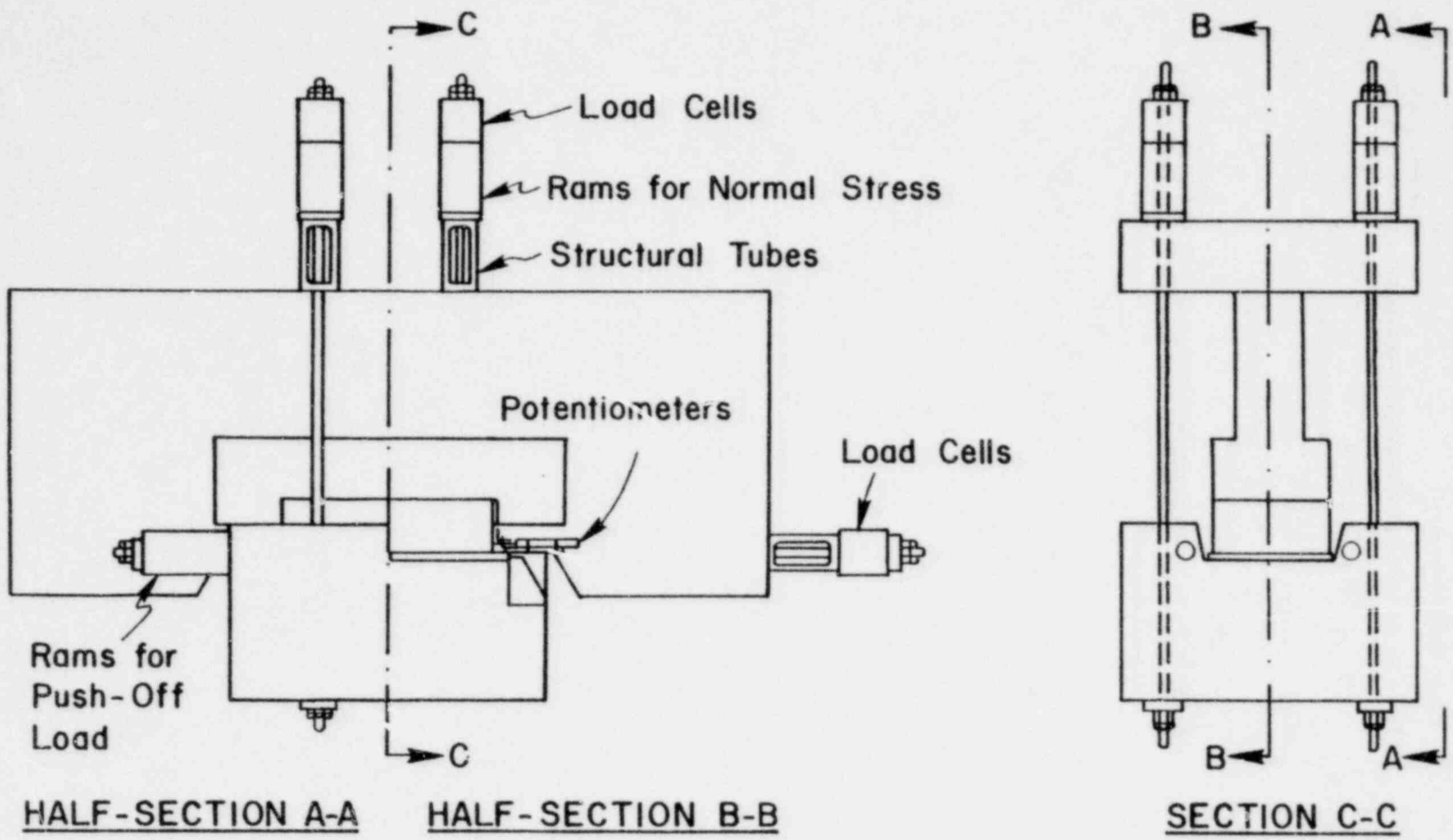

Fig. 4 Schematic of Test Setup

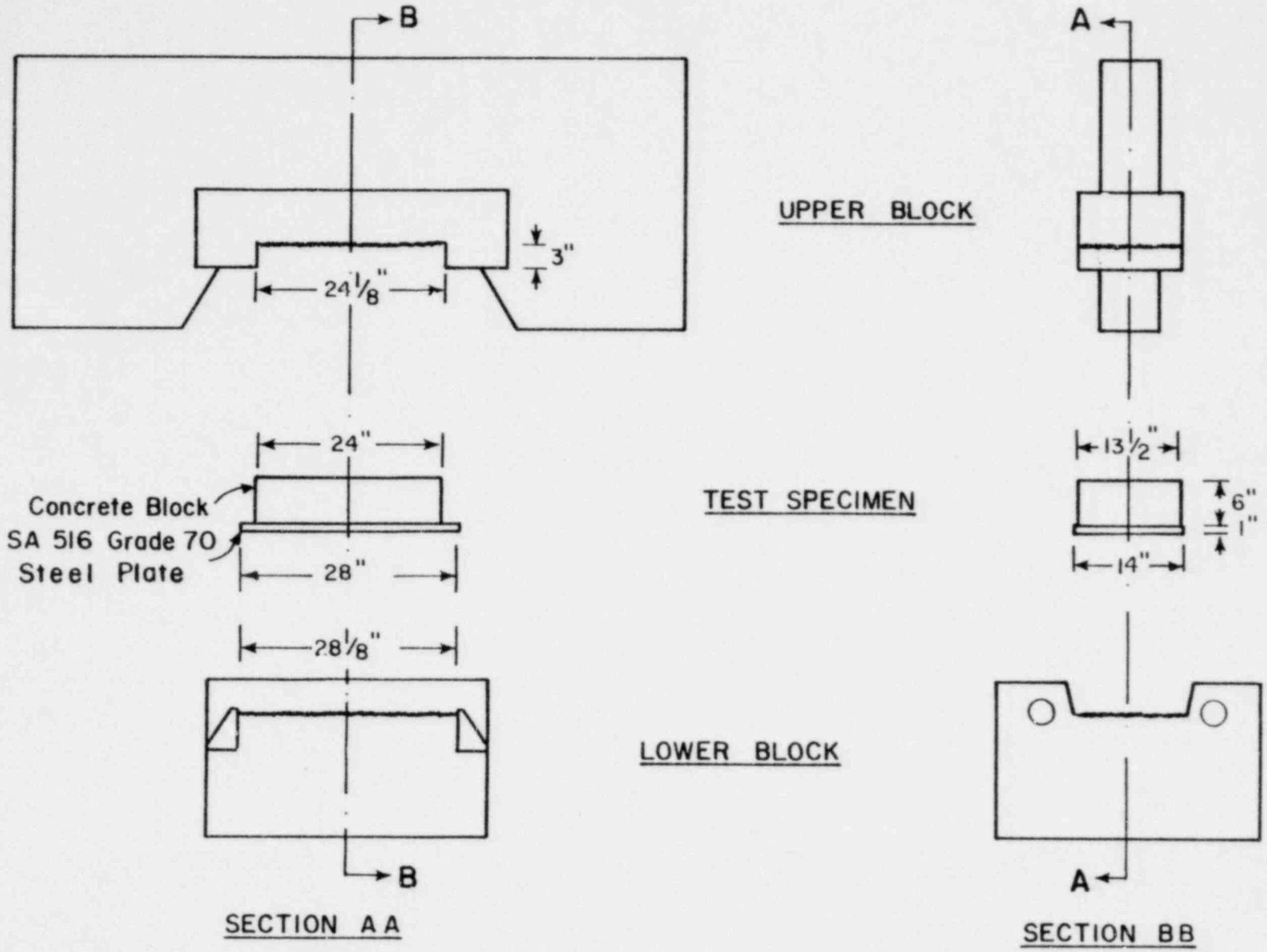

Fig. 5 Test Setup Components

Horizontal rams were used to apply in-plane shear loads. Vertical rams were used to apply normal stresses. All rams were loaded using hydraulic oil pressure.

Instrumentation

All loads were measured using calibrated load cells(2) acting in series with the hydraulic rams.

Slip of the concrete test block relative to the steel plate was measured with two potentiometers as shown in Fig. 6. Each potentiometer was attached to a bracket secured to the steel plate. The potentiometer's plunger was attached to a bracket on the concrete test block.

An X-Y plotter was used to obtain a continuous record of the in-plane shear versus slip at the friction interface. The Y-axis of the plotter was calibrated to indicate the in-plane shear stress. This consisted of the sum of loads from two load cells divided by the interface area. The X-axis indicated the average slip measured by two potentiometers.

Test Procedure

Bond between concrete and steel was broken by application of an in-plane shear force applied at the shear-friction interface. No normal compressive stress other than the weight of the upper block was applied at this stage. This weight was equivalent to a nominal stress of 8.18 psi. The shear stress required to cause first slip was noted. The concrete block was then moved back to its original position on the steel plate.

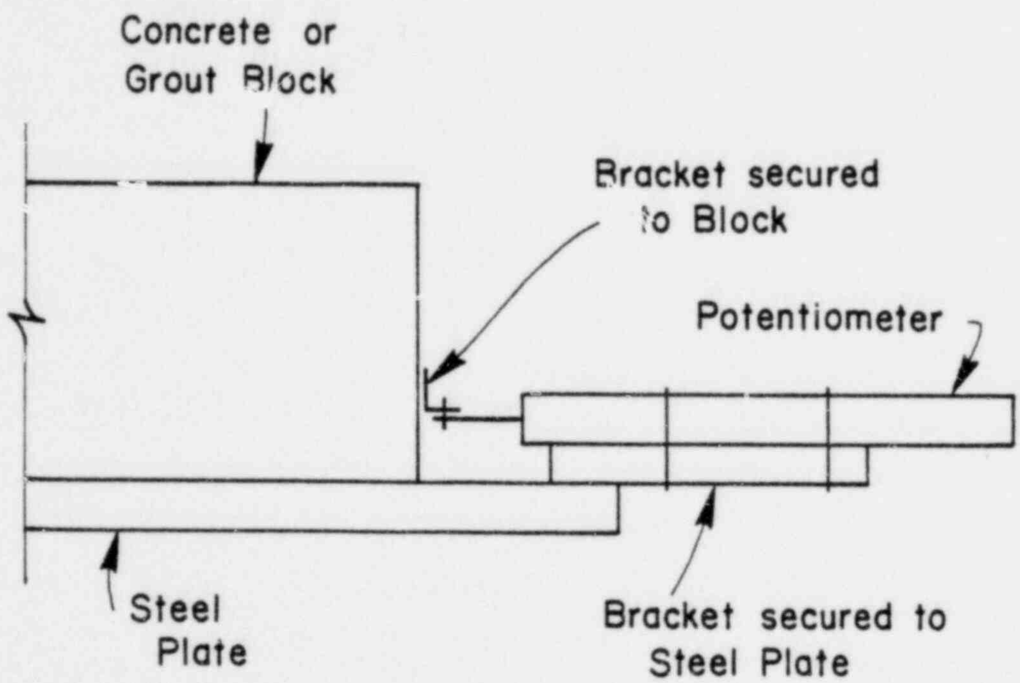

Fig. 6 Attachments to Measure Slip

For tests requiring a wet friction surface, the interfaces were separated after bond was broken. The interfaces were then saturated with water to ensure a wet surface during testing. Interfaces remained saturated during subsequent testing. During each test, normal stress was held constant.

After application of normal compressive force, the shear load was applied slowly. A continuous record of the horizontal load versus slip at the shear-friction interface was obtained. A representative shear stress versus slip curve is shown in Fig. 7. It can bee seen that slip occurred in increments. Each slip increment occurred within a fraction of a second and was accompanied by a drop in shear stress. The drop was a result of the stiffness of the loading system. To eliminate the effect of stiffness of the loading system, the shear stress versus slip curves reported under test results were idealized by a curve joining the peaks of the saw teeth of Fig. 7. Note that the testing rate was adjusted to obtain 0.1 in. slip within three to five minutes. The test was stopped when 0.5 in. slip was reached.

TEST RESULTS

Results presented in this section include material properties, bond strengths at interface, shear stress versus slip relationships, and coefficients of static friction. The effects of normal stresses, wet interface, grout versus concrete, and concrete strength on the coefficient of static friction are discussed.

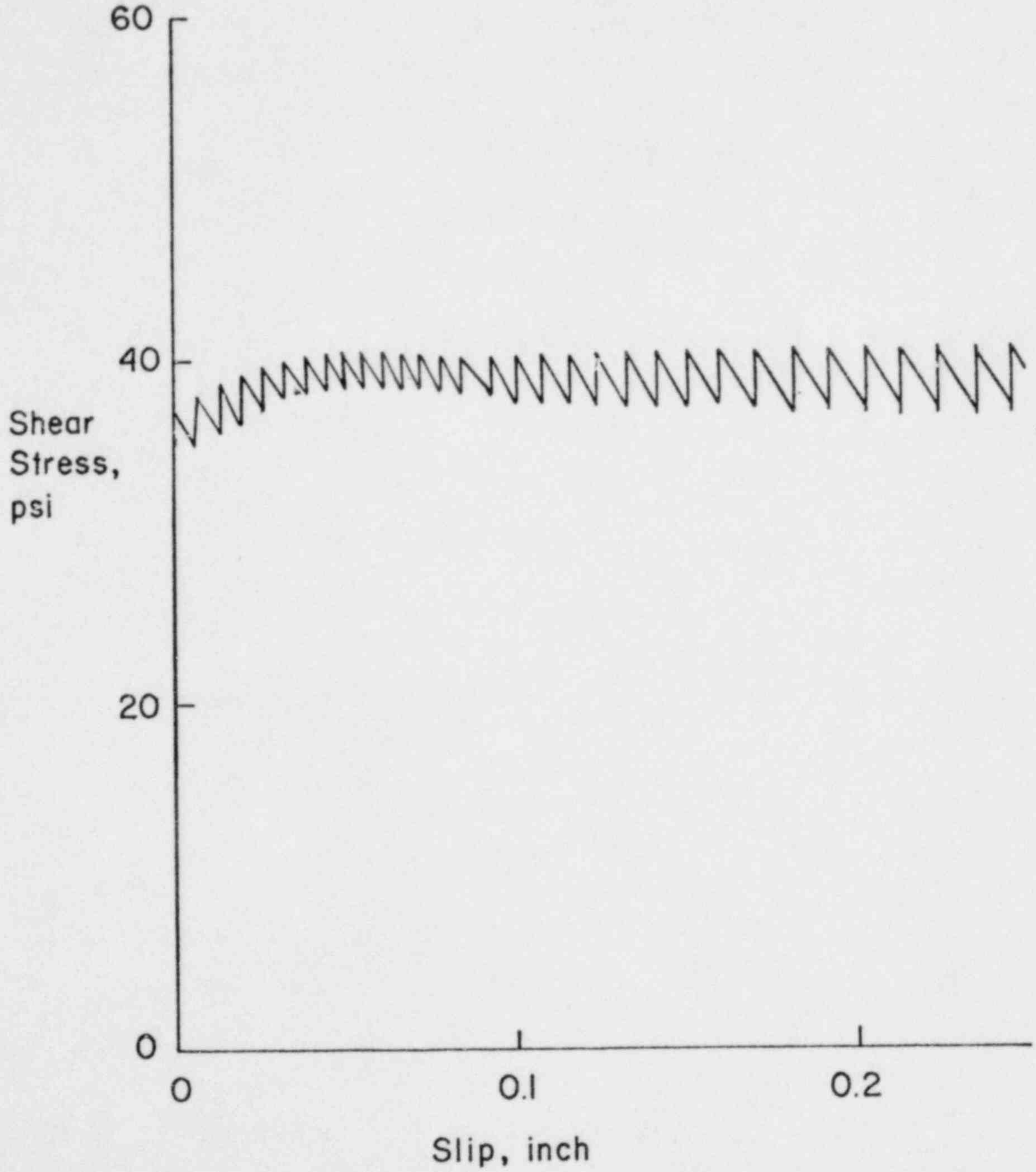

Fig. 7 Representative Continuous Record of Shear Stress versus Slip

Concrete Strength

At test age, six concrete cylinders were loaded to determine concrete compressive strength. The average concrete strength is listed in Table 2. Age of concrete at time of testing is also listed.

Grout Properties

Grout strength was measured using 2 in. cubes. The average cube strength is listed in Table 3. The flow measured on the flow table after five drops in three seconds is also listed.

Bond Strength at Interface

Bond strength is the nominal shear stress required to break the bond between the concrete or grout block and the steel plate. It is equal to the in-plane shear force that broke the bond divided by the area of the interface (324 sq. in.).

Measured bond strengths are listed in Table 4 where the specimens have been grouped in sets of three similar tests. For concrete specimens, the bond strength varied between 25 and 89 psi.

For grout specimens, bond strength was negligible. Inspection of the interface after testing indicated that after placing the grout, bleeding occurred inside the formwork. Sand particles settled and water laitance moved up, with a larger accumulation at the highest point of the formwork. As cement hydrated, water was absorbed. As a result, air gaps formed between the steel plate and grout block. Moreover, air bubbles

TABLE 2 - CONCRETE STRENGTH

Test Number	Specimen	Test Age (days)	Average Concrete Strength (psi)
1	CWB-1	28	3770
2	CWA-1	29	3510
3	CWC-1	28	3275
4	CWB-2	28	3510
5	CWA-2	28	3780
6	CWC-2	28	3525
7	CWB-3	28	3030
8	CWA-3	28	3800
9	CWC-3	28	3270
10	CDB-1	28	3620
11	CDB-2	28	3720
12	CDB-3	28	3710

TABLE 3 - GROUT PROPERTIES

Test Number	Specimen (days)	Test Age Days	Average Cube Strength (psi)	Flow*
13	GWB-1	28	7680	142
14	GWB-2	30	7655	121
15	GWB-3	28	8390	120

*ASTM C230[3]

TABLE 4 - BOND STRENGTH AND COEFFICIENT OF FRICTION

Specimen	Bond Strength (psi)	Shear Stress (psi)		Coefficient of Friction			
		Peak	Effective	Peak		Effective	
CWA-1	52.8	62.0	62.0	0.62		0.62	
CWA-2	48.6	63.5	63.5	0.63	0.64*	0.63	0.64
CWA-3	51.4	68.0	67.8	0.68		0.68	
CWB-1	55.0	42.0	40.7	0.70		0.68	
CWB-2	25.0	40.4	39.6	0.67	0.68	0.66	0.65
CWB-3	89.0	40.5	36.1	0.68		0.60	
CWC-1	61.2	13.8	12.8	0.69		0.64	
CWC-2	83.6	14.2	14.0	0.71	0.70	0.70	0.67
CWC-3	78.4	13.9	13.5	0.69		0.67	
CDB-1	67.3	40.5	33.7	0.68		0.56	
CDB-2	53.0	46.2	35.0	0.77	0.69	0.58	0.57
CDB-3	58.2	36.9	34.0	0.62		0.57	
GWB-1	8.0	41.2	41.2	0.69		0.69	
GWB-2	-	40.9	40.9	0.68	0.68	0.68	0.68
GWB-3	-	40.0	40.0	0.67		0.67	

*Average of each set

had formed at the interface as shown in Fig. 8. The left hand side was the highest point as cast. In Specimens GWB-2 and GWB-3, the bond had broken during handling of the specimens before testing.

Shear Stress - Slip Relationship

Shear stress versus slip curves for Series I, II, and III are plotted in Figs. 9, 10, and 11, respectively.

Peak and effective shear stresses are listed in Table 4. Peak shear stress is defined as the highest shear recorded on shear stress versus slip curve. Where the peak shear stress occurred at a slip less than 0.5 in., an effective shear stress was determined. Effective shear stress is defined as the lowest shear stress occurring after the peak shear stress. Where the peak shear stress occurred at 0.5-in. slip, the effective shear stress was considered equal to the peak shear stress.

Coefficient of Friction

Coefficient of friction is defined as the shear stress divided by the normal stress. Coefficients of friction corresponding to each of the peak and effective shear stresses are listed in Table 4. An average coefficient of friction for each set is given in the same table.

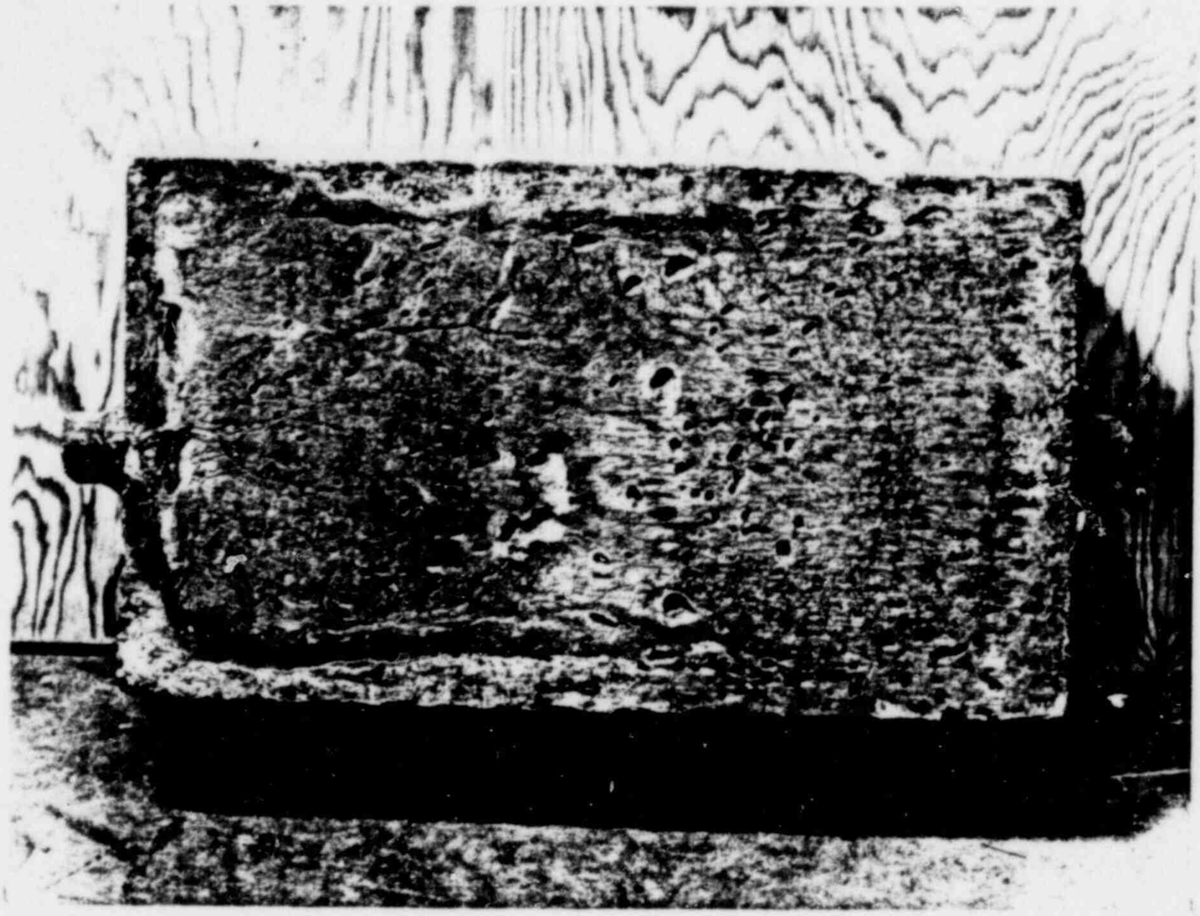

Fig. 8 Friction interface of Specimen GWB-1 after Testing

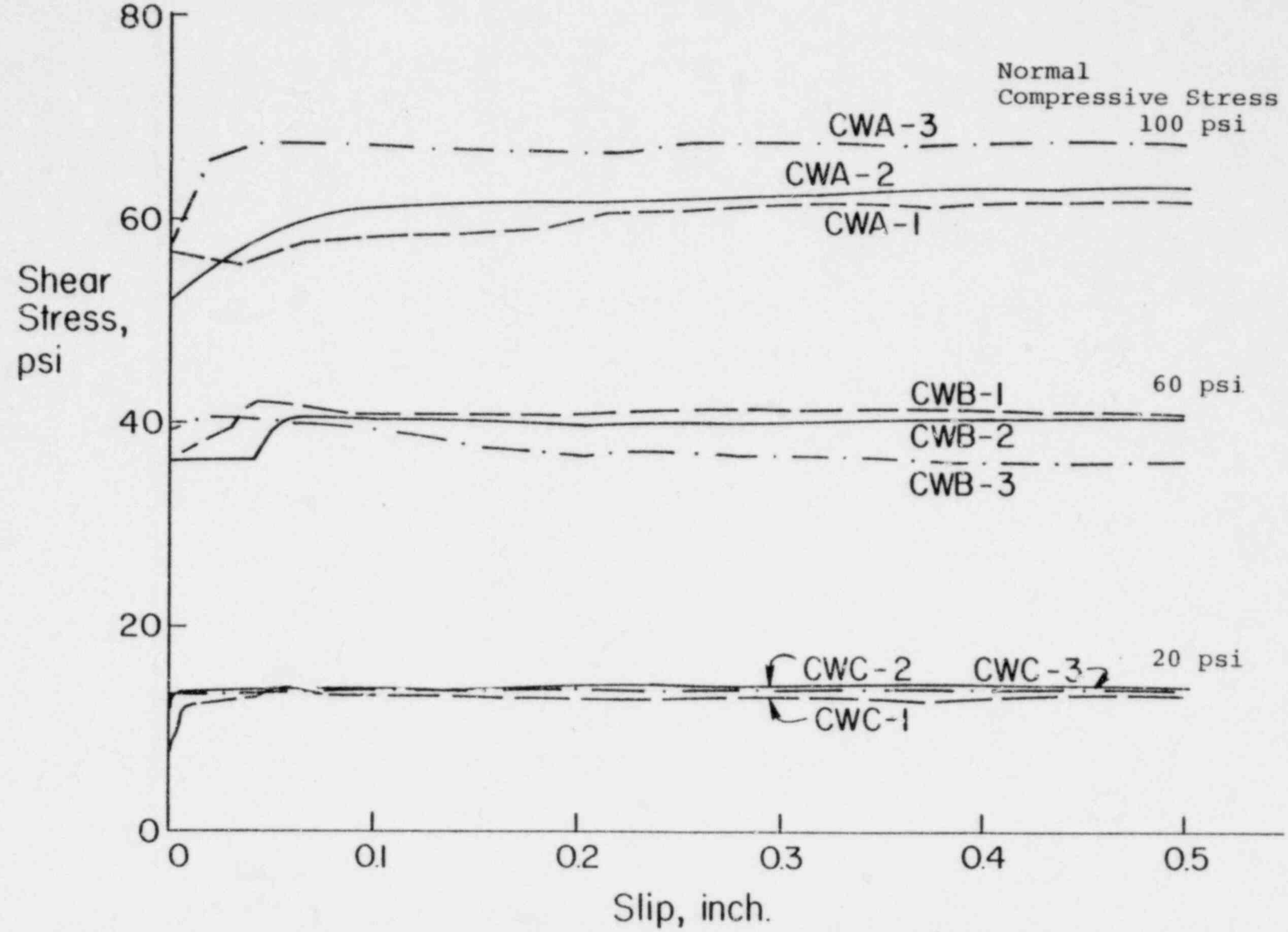

Fig. 9 Shear-Stress versus Slip of Series I

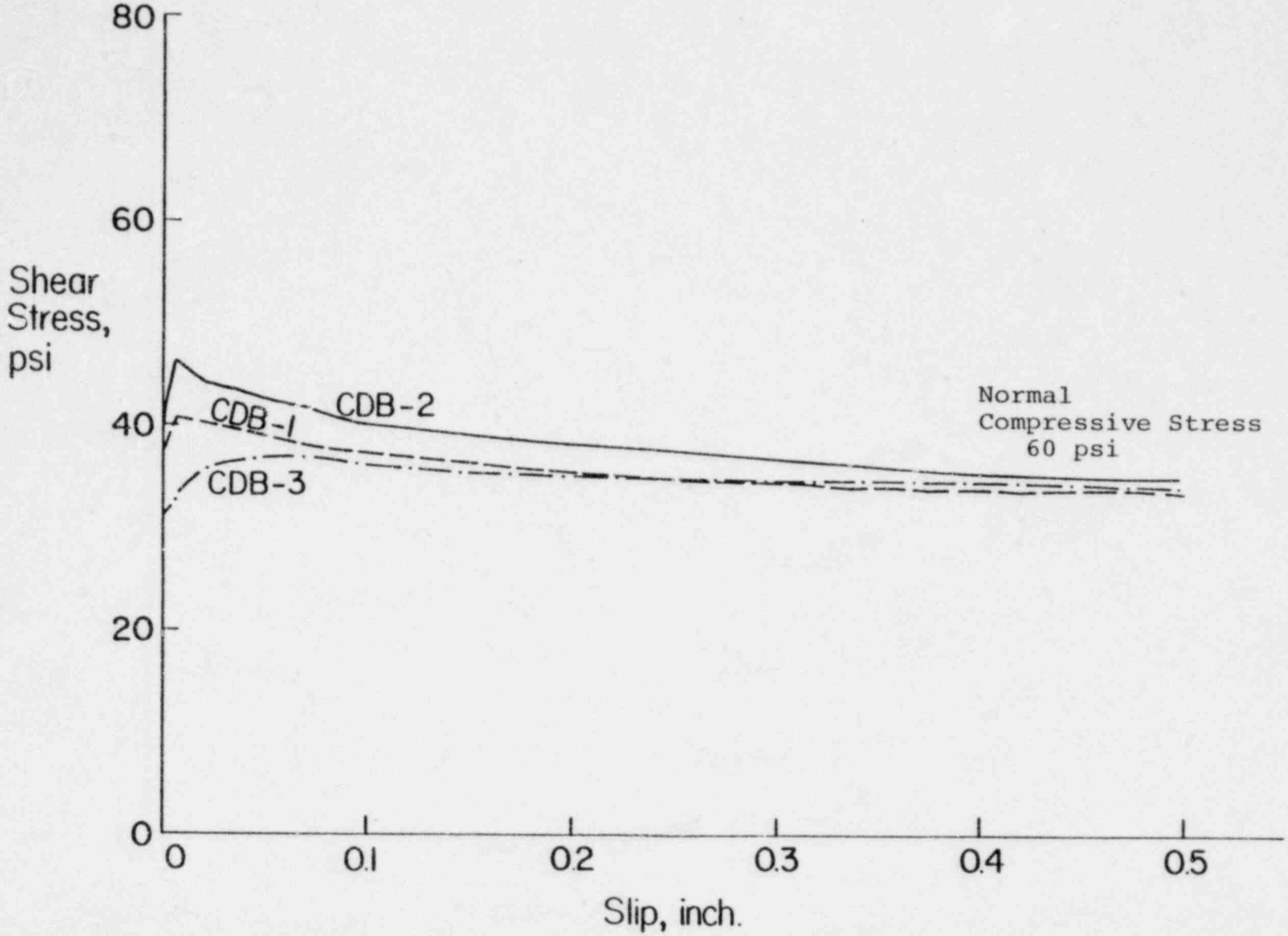

Fig. 10 Shear-Stress versus Slip of Series II

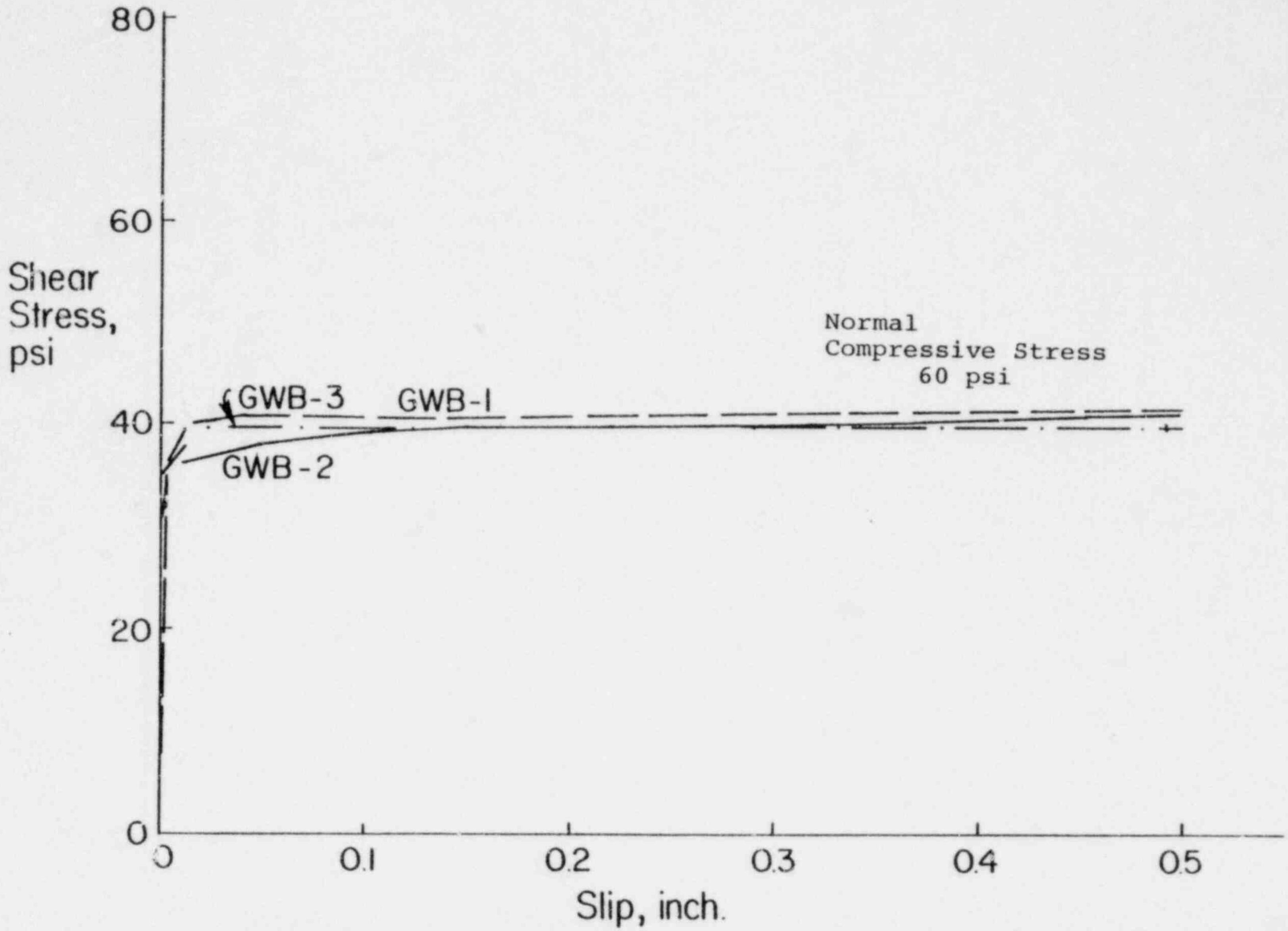

Fig. 11 Shear-Stress versus Slip of Series III

Effect of Normal Stresses

The effect of normal stress on coefficient of friction is shown in the results of Series I, concrete-to-concrete specimens with wet interface. At normal stresses of 20, 60, and 100 psi, the average peak coefficients of static friction were 0.70, 0.68 and 0.64, respectively. The corresponding average effective shear stresses were 0.67, 0.65, and 0.64, respectively. These average coefficients of static friction tended to decrease as normal compressive stress increased.

Effect of Wetting Interface

The effect of wet interface on coefficient of static friction can be seen when comparing average results of CWB and CDB tests in Table 4. Corresponding to peak shear stress, the average coefficients of static friction are 0.68 and 0.69 for wet and dry interfaces, respectively. These coefficients are fairly close. However, the average coefficients corresponding to effective shear stress, are 0.65 and 0.57 for wet and dry interfaces, respectively. Therefore, it appears that the average coefficient of friction corresponding to effective shear stress is about 12% lower for the case of dry interface.

Grout Versus Concrete Interface

Comparisons between coefficient of static friction for grout or concrete against rolled steel is obtained from the GWB and CWB sets of specimens. The average peak coefficient of static friction was the same in both cases although in the grout series not all of the interface area was in contact with the steel plate. This interface condition with air gaps and bubbles can be expected in the field. However, variation of the grout surface condition did not appear to affect the measured coefficient of friction.

The average effective coefficient of static friction for concrete and grout specimens were 0.65 and 0.68, respectively. The observed coefficient for the grout specimens was about 5% higher than for the concrete specimens.

Effect of Concrete Strength

Concrete strengths are listed in Table 2, and coefficients of static friction are listed in Table 4. Based on the test results of Series I, the coefficient of static friction apparently increased with increased concrete strength. However, the range of concrete strengths is too small to state positively what the effect of concrete strength is on the coefficient of static friction.

Concluding Remarks

Fifteen specimens were tested to determine the coefficient of static friction between cast-in-place concrete or grouted mortar and rolled steel plate. The specimens simulated the condition that could exist at the interior and exterior bearing surfaces of a containment vessel. A detailed summary of the test program, and conclusions appear under "HIGHLIGHTS" at the beginning of this report.

ACKNOWLEDGMENTS

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CAVEAT

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