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An evaluation of the behaviour of slip-critical connections subjected to combined shear and tension.

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AN EVALUATION OF THE BEHAVIOUR OF SLIP-CRITICAL CONNECTIONS SUBJECTED TO COMBINED SHEAR AND TENSION

by

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ABSTRACT

For slip-critical connections, slip of the connected parts cannot be tolerated, thus they must be designed so that the applied load is carried by the frictional force developed between the connected parts which is induced by the clamping force of the pretensioned bolts. Once the slip resistance of the connection is overcome, the connected parts slip and the connection becomes a bearing-type joint.

Presently, Clause 13.12.3, *Connections in Combined Shear and Tension*, of S16.1-94 gives an expression for slip-critical connections subjected to combined shear and tension. This expression is an interaction equation that has not been confirmed by experimental results but was chosen as a matter of judgement. The objective of this research was to examine the validity of this interaction equation. In doing so, it was necessary to determine the slip coefficient of A36 steel with mill scale and to devise an accurate method to monitor the induced bolt tension, or preload.

Four tension and six compression joints were tested in order to determine the slip coefficient. Two methods were used to monitor the bolt preload. First an approximate method was used. These results were used to determine the average bolt preload. This value was used in determining the slip coefficient for the tension joints. The second method used a preload cell that allowed the actual bolt preload to be measured during testing. The preload cell was used in testing the compression specimens to determine the slip coefficient.

Once the slip coefficient was known and a method of monitoring the bolt preload was established, a connection simulating testing device was used to test connections subjected to various combinations of shear and tension. In order to verify the results of the testing device, a slip-critical connection loaded equally in shear and tension was tested.

From the compression and tension joints, the slip coefficient was found to be 0.24. All the bolts achieved preloads that exceeded the minimum bolt preload required by S16.1-94.

The results of the testing device and the slip-critical connection indicate that the interaction equation given in S16.1-94 is satisfactory. No modifications to this equation are recommended.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter I

INTRODUCTION

1.1 General

Slip-critical or friction-type connections are joints in which movement, or slip, of the parts being connected cannot be tolerated. These types of connections are often used in situations where the connection is "subjected to stress reversals, severe stress fluctuations, or in any situation wherein slippage of the structure into bearing would produce intolerable geometric changes"[1] (Kulak et al. 1987)*. "The use of slip-critical connections should be the exception rather than the rule. They are the preferred solution only where cyclic loads or frequent load reversals are present, or where the use of the structure is such that the small one-time slips that may occur cannot be tolerated"[2] (CISC 1994).

In accordance with Clause 21.12.2, *Connections Using Pretensioned High-Strength Bolts*, of the Canadian Standards Association, "Limit States Design of Steel Structures", CAN/CSA-S16.1-94 (CSA 1994), pretensioned high-strength bolts are to be used in slip-critical connections. Pretensioned bolts produce a clamping force on the connected parts. This clamping force provides the frictional resistance between the connected parts that is fundamental in slip-critical connections. The clamping force is often referred to as the initial bolt tension or bolt preload.

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* Numbers indicate the appropriate endnote as given on page 135. References are denoted using parentheses and are given in full on page 136.

Unlike bearing connections where the bolt bears against the edge of the bolt hole, bolts in slip-critical connections are not in contact with the perimeter of the bolt hole. There is a space or gap between the bolt hole and the bolt that results from the bolt hole clearance (usually the bolt hole is made 1/16 inch larger than the bolt diameter). In slip-critical connections, the external force applied to the joint is transmitted solely through the frictional forces that act on the contact area of the parts being connected. The connected parts do not bear on the bolt, thus the bolt does not transmit the applied load to the connected parts. Failure of slip-critical connections means the friction force developed between the connected parts has been overcome and as a result the connected parts have moved with respect to one another and now bear against the bolt. Upon failure, the connection becomes a bearing-type joint in which the applied load is transmitted through the bolt to the connected parts. Slip-critical connections are used to meet serviceability requirements. The connection must be designed according to the requirements for slip-critical connections (at the specified loads) and bearing-type connections (at factored loads).

1.2 Objective

In Clause 13.12.3, *Connections in Combined Shear and Tension*, of S16.1-94, it is stated that bolts in a slip-critical connection subjected to both a shear force, V, and a tensile force, T, must satisfy the following interaction equation:

[1.1] $$\frac{V}{V_s} + 1.9\frac{T}{nA_bF_u} \leq 1.0$$

where V_s is the slip resistance of the joint, n represents the number of bolts in the connection, A_b is the nominal area of the bolt, and F_u is the specified minimum tensile strength of the bolt. The term

$$[1.2] \qquad \frac{1.9}{nA_bF_u}$$

represents the reciprocal of the total initial bolt tension, or preload, T_i, for n bolts. For a single bolt, the bolt preload, T_i, is:

$$[1.3] \qquad T_i = 0.70 \times 0.75 A_bF_u = 0.53 A_bF_u$$

where A_b is the nominal bolt area and F_u is the specified minimum tensile strength for the bolt. The 0.70 multiplier is used since the preload corresponds to 70% of the specified minimum tensile strength for the bolt. The 0.75 multiplier is used to convert the nominal bolt area, A_b, into the stress area of the bolt.

The slip resistance of the joint, V_s, is given in Clause 13.12.2, *Shear Connections*, of S16.1-94 as:

$$[1.4] \qquad V_s = 0.53c_1k_smnA_bF_u$$

where c_1 is a coefficient used to relate the specified initial tension and mean slip to a 5% probability of slip for bolts installed by turn-of-nut procedures, k_s is the mean slip coefficient (given in Table 2 or as determined by tests carried out in accordance with *Testing Method to Determine the Slip Coefficient for Coatings Used in Bolted Joints* of the RCSC), m represents the number of contact surfaces, n represents the number of bolts, A_b indicates the nominal area of the bolt, and F_u is the minimum specified tensile strength for the bolt.

Although S16.1-94 governs the design of slip-critical connections subjected to combined shear and tension, their performance has not been tested. In fact, Equation 1.1 (the interaction equation given in Clause 13.12.3) was chosen "as a matter of judgement" since "there are no published test results covering this situation"[3] (Kulak et al. 1990).

Therefore the objective of this research project is to evaluate the behaviour of slip-critical connections subjected to combined shear and tension forces. In doing so, the validity of the interaction equation given in S16.1-94 (presented herein as Equation 1.1) will be examined.

1.3 Methodology

In order to study slip-critical connections, the slip coefficient, k_s, of the connected parts and the clamping force, or bolt preload (induced by pretensioning), must be known since these factors affect the slip resistance of the connection (refer to Equations 1.1 and 1.4).

As seen in Equation 1.4, the slip resistance of the connected parts is related to the slip coefficient, k_s, of the surfaces. The slip coefficient of the connected parts must be determined experimentally. It varies for different surface conditions and different types of steel. Most of the research on slip has been performed using symmetric butt splices that are loaded in tension and the slip of the specimen is monitored as the joint is loaded[4] (Kulak et al. 1987). A connection loaded in compression has also been used in determining the slip coefficient and is recommended by the Research Council on Structural Connections (RCSC) Specification for Structural Joints Using ASTM A325 or A490 Bolts (RCSC 1994). During this work, four tension and six compression joints were tested in order to determine the slip coefficient, k_s, of the steel used.

The slip coefficient is determined using the following expression:

[1.5] $$k_s = \frac{P_{SLIP}}{mnT_i}$$

where P_{SLIP} is the slip load, m represents the number of slip planes, n represents the number of bolts in the connection, and T_i is the initial bolt tension, or preload.

Since the slip coefficient varies with the induced bolt preload, the bolt preload must be determined before the slip coefficient can be evaluated. The bolt preload results from the nut being tightened against the resistance of the material that is being connected[5] (Kulak et al. 1987). Two methods of determining the induced bolt preload were applied in the course of this work. The first was an approximate method using a load cell. The second method involved a load cell that was made in-house. This "preload cell", used to monitor the bolt preload as the nut was tightened and during testing of the connection.

In order to examine the validity of the interaction equation given in S16.1-94 (presented above as Equation 1.1), a connection simulating testing device was used to test slip-critical joints subjected to combined shear and tension. Also, in order to verify the results obtained using the connection simulating testing device, a slip-critical connection was designed and tested.

1.4 Materials

The bolts used in this research project were ASTM A325 19.05-mm (¾-inch) diameter bolts. Both 69.8-mm (2 ¾-inch) and 120.6-mm (4 ¾-inch) bolt lengths were used as required by the thickness of the materials being connected. The plates used in the connections were manufactured from A36 (minimum yield 36000 psi) hot rolled bar with mill scale. Mill scale refers to the "as rolled" condition of the steel scale.

Chapter II

LITERATURE REVIEW

2.1 General

This chapter gives a brief overview of the relevant research contributions. These are outlined and then any findings that pertain to this research project are summarized and explained.

There are no published test results concerning the behaviour of slip-critical connections subjected to combined shear and tension. However, Munse and Cox (1956) examined the behaviour of rivets subjected to combined shear and tension. Chesson, Faustino, and Munse (1965) performed the same type of testing with high-strength bolts instead of rivets.

Since in slip-critical connections it is imperative to know the slip coefficient and the bolt preload, previous work on slip-critical connections loaded in tension or compression to determine the slip coefficient, k_s, was also reviewed. Hechtman, Young, Chin, and Savikko (1955) studied the slip of double-lap joints (assembled with high-strength bolts) under static loads. Brookhart, Siddiqi, and Vasarhelyi (1966) investigated the surface treatment of high-strength bolted joints. Vasarhelyi and Chiang (1967) examined joints manufactured from various steels to determine the various coefficients of friction. Lee, O'Connor, and Fisher (1969) studied the effects of surface coatings and exposure on the slip behaviour of double-lap joints. Fouad (1978) examined the slip behaviour of bolted coated friction joints. Yura, Frank, and Cayes (1981) examined bolted friction connections with weathering steel (A588), commonly used in bridge construction. Polyzois and Yura (1985) studied the effect of burrs on bolted friction connections.

2.2 Previous Work

Munse and Cox (1956) performed research on rivets subjected to combined shear and tension. At the time their research was performed, specifications only provided for rivets subjected to direct shear or tension. The test device used allowed each riveted connection to be tested in load combinations ranging from pure shear to pure tension. The testing device allowed for seven different combinations of shear and tension to be applied to the test joint. A device similar to this was used in this research to test slip-critical bolted connections subjected to combined shear and tension.

Chesson, Faustino, and Munse (1965) used a device similar to that used by Munse and Cox (1956). The authors investigated the behaviour of high-strength bolts subjected to combined shear and tension.

Hechtman, Young, Chin, and Savikko (1955) tested double-lap joints subjected to either tension, compression, or torsion loading to determine the slip characteristics of these joints and to compare the effects of different loading conditions on the slip tests. The affect of various factors on the slip characteristics of joints was also examined. These factors included different surface conditions of the faying surfaces, the total faying area, the number of rows of bolts in the joints, and the bolt tension. The majority of the test specimens were loaded in tension and consisted of mill scale surface conditions. In this study, the plates considered to have clean mill scale were wire brushed and cleaned with carbon tetrachloride to dissolve any grease and oil. The bolt tension was determined by monitoring the bolt elongation. Each bolt used was individually calibrated to obtain its load-elongation curve.

In determining the coefficient of friction at first slip, Hechtman et al. (1955) took the slip load as the load at which the first major slip occurred. This slip was often followed by further slippage of the plates until they were fully bearing on the bolt. Although the term major slip seems to imply that the amount of slip of the joint should be fairly large, often it was not. The first major slip was taken as the first significant amount of slip that occurred. The authors noted that loading the joints slowly gave a better indication of the behaviour of the joint and minimized the influence of the testing machine operator on the shape of the load vs. slip curve obtained. From this research the authors concluded that due to "the considerable scatter in the test results of bolted joints, it is reasonable to expect identical joints loaded in either tension or compression to develop approximately equal resistance to slip"[6] (Hechtman et al. 1955). Also the tests did not seem to be affected by variations in lap-plate thickness, the faying area, and the bolt pattern.

Brookhart, Siddiqi, and Vasarhelyi (1966) studied the surface treatment of high-strength bolts and the surface treatment of the faying surfaces of the tension joint. The mill scale plates tested were cleaned with acetone prior to testing to remove any grease or oil.

Manual torquing was used to induce the clamping force. The clamping force was controlled by measuring the bolt elongation.

Vasarhelyi and Chiang (1967) studied the coefficient of friction of various newly developed steels. In doing so, they set forth to provide a more complete list of the coefficients of frictions of different types of steel. Their study also examined the effect of the number of faying surfaces in the joint on the nominal coefficient of friction. The authors also researched the fundamentals of friction phenomena. They distinguished between the nominal coefficient of friction and the true coefficient of friction. The nominal coefficient of friction was obtained from a tension test joint whereas the true coefficient of friction was determined from a direct friction test of plate samples loaded in compression. However, prior to the publication of their test results, a new term was introduced to describe the slip behaviour of joints. This term is the slip coefficient of the joint. For the coefficient of friction, the slip load is taken as the load in which one of the joined elements move. Whereas for the slip coefficient, the slip load is taken as the load which corresponds to the friction force being definitely overcome and as a result the joined elements slip a relatively large amount[7] (Vasarhelyi et al. 1967).

For both the nominal and true coefficients of friction, Vasarhelyi et al. (1967) used the clamping force at the instance of slip in calculating the coefficient. The clamping force at the instance of slip was lower than the initial clamping force induced by pretensioning. The clamping force decreased with the increase in the applied load on the specimen in a nearly linearly fashion. It was found that at major slip, the initial clamping force had been reduced by about 4% of the applied load on the joint.

Vasarhelyi et al. found the average nominal and true coefficients of friction to be 0.29 and 0.32, respectively for the joints using A36 steel. Based on this research, Kulak et al. (1987) reported the slip coefficient for A36 steel was 0.27, with a standard deviation of 0.05.

From this research, it was found that the generally accepted value of the coefficient of friction for mill scale surfaces could be extended to the newly developed types of steel. Also, it was found that the number of faying surfaces did not affect the coefficient of friction.

Lee, O'Connor, and Fisher (1969) only tested coated surfaces. Their study did not include testing mill scale surface conditions, hence the findings are not significant to this research project. Their study is included in this literature review since the testing methods gave some insight on the procedure to follow in testing slip specimens.

Fouad (1978) tested bolted friction compression joints with coated faying surfaces. A constant clamping force was applied using a threaded rod and a centerhole hydraulic jack. This clamping system is termed a "hydraulic bolt". The author stated that a constant clamping force was maintained in order to eliminate the Poisson's ratio effect that may lead to an increase in the bolt force in a compression type joint. An increase in the bolt force would lead to an increase in the slip load. In using a hydraulic bolt, the compression test joint would not result in a higher slip resistance than a similar tension test joint.

Yura, Frank, and Cayes (1981) tested bolted friction connections with weathering steel. Since Hechtman et al.'s (1955) conclusion that either tension or compression joints can be used to determine the slip resistance of the joint was based on limited tests, both tension and compression joints were used in this research. The faying surfaces considered were blast cleaned (using various techniques) and clean mill scale. Clean mill scale was obtained by cleaning the faying surfaces with acetone. The compression specimens used a hydraulic bolt that ensured the clamping force remained constant during testing. It was found that the type of joint used (tension or hydraulic bolt compression joint) has no affect on the slip characteristics of the joint.

Polyzois and Yura (1985) used hydraulic bolted compression joints to study the effect of burrs on friction connections. In using a hydraulic bolted specimen, the bolt clamping force was kept constant during testing. The effect of burrs on the clamping force, or bolt preload was also studied. This study used 3/8-inch thick and ¾ in thick grade A36 and A572 steel. Most of the test specimens had clean mill scale surface conditions. A small number of the test specimens had painted surfaces. The slip load was taken as either the maximum load before the plates went into bearing, or the load at which there was a sudden increase in deflection. For the specimens with mill scale surface condition it was found that the presence of burrs increased the frictional resistance, and thus the slip coefficient, of the connection. The presence of burrs required an increase in the amount of rotation required to reach the snug tight condition and minimum specified bolt preload. The slip coefficient for plates without burrs was found to be 0.31.

2.3 Standards and Specifications

Although this research was performed to test the validity of the interaction equation given in S16.1-94 for the behaviour of slip-critical connections subjected to shear and tension, the RCSC Load and Resistance Factor Design (LRFD) "Specification for Structural Joints Using ASTM A325 or A490 Bolts" (RCSC 1994) and the American Institute of Steel Construction (AISC) Load and Resistance Factor Design (LRFD) "Specification for Structural Steel Buildings" (AISC 1994) were also reviewed.

The *Testing Method to Determine the Slip Coefficient for Coatings Used in Bolted Joints* outlined by the RCSC was followed in determining the slip coefficient for the steel used in this research project.

The AISC specifications for slip-critical connection in combined shear and tension were compared to those given by S16.1-94.

2.3.1 S16.1-94

The design and evaluation of slip-critical connections is governed by various clauses in S16.1-94. The relevant clauses are; Clause 13.12, *Bolts in Slip-Critical Connections*, Clause 21.12, *Connections Using Bolts*, Table 7, and Clause 23.5, *Turn-of-Nut Tightening.*

In Clause 13.12.2, *Shear Connections*, the slip resistance, V_s, is given as:

$$[1.4] \qquad V_s = 0.53 c_1 k_s m n A_b F_u$$

where c_1 is a coefficient used to relate the specified initial tension and mean slip to a 5% probability of slip for bolts installed by turn-of-nut procedures, k_s is the mean slip coefficient (given in Table 2 or as determined by tests carried out in accordance with *Testing Method to Determine the Slip Coefficient for Coatings Used in Bolted Joints* of the RCSC), m represents the number of contact surfaces, n represents the number of bolts, A_b indicates the nominal area of the bolt, and F_u is the minimum specified tensile strength for the bolt.

The interaction action equation which must be satisfied by slip-critical bolted joints subjected to both shear and tension is given in Clause 13.12.3, *Connections in Combined Shear and Tension*, as:

$$[1.1] \qquad \frac{V}{V_s} + 1.9 \frac{T}{n A_b F_u} \leq 1.0$$

where V is the shear component of the applied force, V_s is the slip resistance of the joint, T is the tensile component of the applied force, n represents the number of bolts, A_b is the nominal area of the bolt, and F_u is the minimum specified tensile strength for the bolt. For all clean mill scale surfaces, Table 2 gives the slip coefficient, k_s, as 0.33 and the coefficient c_l as 0.82 (for A325 bolts).

In Clause 21.12.2, *Connections Using Pretensioned High-Strength Bolts*, slip-critical connections are listed as one of the situations in which pretensioned bolts must be used.

The minimum bolt tension required for pretensioned bolts is given in Table 7. For a 19.05-mm (¾-inch) A325 bolt, the minimum bolt tension is 125 kN.

Clause 23.5, *Turn-of-Nut Tightening*, outlines the procedure to be followed in snug tightening and the subsequent rotation to be applied in pretensioning bolts.

2.3.2 RCSC LRFD Specification

The Research Council on Structural Connections Specifications for Structural Joints Using ASTM A325 or A490 Bolts; *Testing Method to Determine the Slip Coefficient for Coatings Used in Bolted Joints* provided the basis for the compression specimens used to determine the slip coefficient in this research project.

The compression joint consists of three plates connected with a threaded rod. The clamping force is to be applied using a centerhole compression ram. The clamping force is to be maintained at a constant load during testing and should be measured with an accuracy of 2.224 kN (0.5 kips). This specification suggests measuring the pressure in the calibrated ram or placing a load cell in series with the test specimen to monitor the bolt preload and ensure that it is constant. Also, the use of instrumentation to measure the slip deformation is outlined. The testing set-up and testing procedure described in this specification provided the basis for the set-up and procedure used in determining the slip coefficient using a compression specimen.

2.3.3 AISC LRFD Specification

The American Institute of Steel Construction Specification for Structural Joints Using ASTM A325 or A490 Bolts allows for slip-critical connections to be designed at both nominal and factored load levels. The use of slip-critical connections is outlined in Section 5a. This is very similar to that given in S16.1-94. The nominal slip resistance, R_s (in kips) of slip-critical joints designed at nominal (service) loads is given in Section 5(b) as:

[2.2] $$R_s = D\mu T_m N_b N_s$$

where D is the slip probability factor, μ is the mean slip coefficient, T_m is the minimum faster tension given in Table 4 as 28 kips (125 kN) for a ¾-inch nominal bolt (this corresponds to 70% of the specified minimum tensile strengths of bolts), N_b represents the number of bolts used in the joint, and N_s indicates the number of slip planes. D is given as 0.81 for μ equal to 0.33 (for clean mill scale steel surfaces).

Equation 2.2 is equivalent to that given in S16.1-94, Clause 13.12.2, *Shear Connections,* presented above as Equation 1.4. For situations where the connection is also subjected to an applied nominal tensile load, T, the slip resistance (ϕR_s) shall be multiplied by the following reduction factor:

$$[2.3] \qquad \left[1-\frac{T}{T_m N_b}\right]$$

Thus the equation for slip-critical connections subjected to combined to shear and tension at service loads is:

$$[2.4] \qquad R_s' = \phi D\mu T_m N_b N_s\left[1-\frac{T}{T_m N_b}\right]$$

where ϕ is 1.0 for standard holes. Equation 2.4 can be re-arranged as:

$$[2.5] \qquad \frac{R'_s}{R_s}+1.9\frac{T}{N_b A_b F_u}=1$$

Equation 2.5 is equivalent to the interaction equation in S16.1-94, Clause 13.12.3, *Connections in Combined Shear and Tension*, presented above as Equation 1.1.

However, Carter, Tide and Yura (1997) propose a change to both the AISC LRFD Specification for Structural Steel Buildings and the RCSC LRFD Specification for Structural Joints Using ASTM A325 or A490 Bolts. They propose that the reduction factor, given above as Equation 2.3, be changed to:

[2.6] $$\left[1-\frac{T}{0.8T_m N_b}\right]$$

The reduction in this equation introduced by the 0.8 multiplier is proposed so that the equation for slip-critical connections at service loads provides a factor of safety consistent with that provided for slip-critical connections at factored loads.

Since S16.1-94 does not allow slip-critical connections to be designed at factored loads, this proposed change does not affect Equation 1.1

Chapter III

EXPERIMENTAL PROCEDURE: DETERMINATION OF BOLT PRELOAD

3.1 General

Bolt preload, or initial bolt tension, is a factor that affects the slip resistance of a connection, thus it must be determined in order to study slip-critical connections. Bolt preload results from the nut being tightened against the resistance of the material that is being connected[8] (Kulak et al. 1987). According to Clause 21.12.2, *Connections Using Pretensioned High-Strength Bolts*, of S16.1-94, pretensioned bolts are required in slip-critical connections, according to seismic design requirements, in all elements resisting crane loads, in connections subjected to impact or cyclic loading, in connections in which the bolts are subjected to tensile loads, and in connections with oversized or slotted holes that are not specifically designed to accommodate movement of the connected parts.

Pretensioned bolts must be tightened to the minimum bolt preload as specified in Clause 23.4.1, *Bolt Tension*, of S16.1-94. For a 19.05-mm (¾-inch) A325 bolt, the minimum bolt preload is 125 kN. This corresponds to 70% of the specified minimum tensile strength of the bolt. The initial bolt tension, or preload, is given as:

[1.3] $$T_i = 0.70 \times 0.75\, A_b F_u = 0.53\, A_b F_u$$

where A_b is the nominal bolt area and F_u is the specified minimum tensile strength for the bolt. The 0.75 multiplier is used to convert the nominal bolt area, A_b, into the stress area of the bolt.

Presently, S16.1-94 identifies turn-of-nut tightening as an adequate method to pretension bolts. It also permits the use of a direct tension indicator (Clause 23.6, *Tightening by Use of a Direct Tension Indicator*), provided it can be shown that the method is accurate. If turn-of-nut tightening is employed, a rotation of one-third, one-half, two-thirds, or three-quarters of a turn past snug is required to achieve the minimum bolt preload or clamping force. The nut rotation from the snug-tight condition is governed by the length of the bolt as given in Table 8, Clause 23.5, *Turn-of-Nut Tightening*, of S16.1-94. Snug-tight is defined as "the tightness attained by a few impacts of an impact wrench or the full effort of a person using a spud wrench" in Clause 23.5, *Turn-of-Nut Tightening*, of S16.1-94. The tolerance in the amount of rotation is given as ±30°. This tolerance results since turn-of-nut tightening is a strain control method. The load vs. elongation curve for bolts is relatively flat in the inelastic region and pretensioned bolts, as a whole, enter this inelastic range[9] (CISC 1994). Due to this flat portion of the load vs. elongation curve for bolts, the tightness achieved in the snug-tight condition is not critical. Thus the amount of rotation can be slightly less or more than that specified in S16.1-94 without significantly changing the induced bolt preload.

It should be mentioned that although the name implies that the nut be the turned element, it has been shown that either the nut or bolt head can be turned without any adverse affect on the induced bolt preload or the connection. Hence, Table 8, Clause 23.5, *Turn-of-Nut Tightening*, of S16.1-94 states "nut rotation is rotation relative to a bolt regardless of whether the nut or bolt is turned".

Presently, there is no widely accepted method of monitoring the bolt preload. For the purpose of this research, an approximate method was initially used in which a series of bolts were pretensioned and their preload was measured using a load cell. The average preload obtained by these bolts was used as the bolt preload in subsequent testing where the preload was not monitored.

It became apparent that the actual bolt preload that existed in each test specimen must be known, therefore an improved method to monitor bolt preload was devised. This improved method involved the use of a homemade load cell, or "preload cell".

3.2 Approximate Method

3.2.1 Test Set-up

To determine the bolt preload, a bolt was used to connect a series of plates similar to those that would be used in a tension splice to determine the slip coefficient of the connection. A load cell was used in the place of the nut to measure the bolt preload as the bolt head was turned. The load cell was connected to a strain indicator. For convenience, the load cell was attached to the base of a hydraulic jack located in a loading frame in the laboratory. This ensured that the load cell remained stationary as the bolt was turned into the load cell. This set-up is shown in Figure 1.

3.2.2 Bolt Specimens

The bolts used were A325, 19.05-mm (¾-inch) diameter high-strength bolts. The length of bolt used was 69.8-mm (2 ¾-inch).

3.2.3 Test Procedure

Two bolts were used to connect plates similar to those used in the tension joints used to determine the slip coefficient. One bolt was used to aid in keeping the plates aligned. The other bolt was the test specimen used to determine the bolt preload. This bolt was turned into the load cell. The bolt was tightened to the snug-tight condition and then turned one-third turn past snug, as per Table 8, Clause 23.5, *Turn-of-Nut Tightening*, of S16.1-94. Readings of the strain indicator were recorded at snug-tight and at one-third turn past snug. These strain readings were converted to the corresponding load, using the load cell calibration data. This procedure was repeated with ten different bolts. Since the bolts enter the inelastic region upon pretensioning, the bolts were only used once.

The data obtained was used to estimate the average bolt preload that exists at snug-tight and at the fully tightened condition. The average bolt preload obtained at the fully tightened condition was taken as the bolt preload during subsequent testing where a nut would be used instead of the load cell. Hence the exact value of the bolt preload would not be known during the testing performed to determine the slip coefficient of the connected plates using a tension joint.

3.2.4 Load Cell

A 444.8 kN (100 kip) capacity load cell was used in determining the bolt preload. The load cell was calibrated using the universal testing machine and a strain indicator.

3.3 Preload Cell Method

It became apparent that the range in the bolt preload readings was too great to accurately predict the bolt preload. Therefore using the average bolt preload, rather than the actual preload that existed in the bolt, to determine the slip coefficient may have lead to some error. It was decided that the actual bolt preload would have to be monitored during all subsequent testing.

As a result, an improved method for determining the bolt preload was introduced. This method is much more accurate in that the preload is measured for the bolt that is being used in the test joint, as the connection to be tested is being assembled. The device used is a "preload cell". The RCSC, *Testing Method to Determine the Slip Coefficient for Coatings Used in Bolted Joints* (1994), states that the clamping force can be applied and monitored using a calibrated pressure ram or it can be controlled by placing a load cell in series with the ram. This concept of placing a load cell in series with the test specimen led to the development of the preload cell. Although washer shaped strain gauge based load cells are commonly available, this preload cell was fabricated by the Technical Support Center of the University of Windsor.

3.3.1 Preload Cell Description

The preload cell consisted of a hollow shaft 50.8-mm (2-inch) in length, 31.8-mm (1 ¼-inch) outside diameter and 19.05-mm (¾-inch) inside diameter manufactured from tool steel with a specified minimum yield strength of 1000 MPa. Four 5-mm length foil strain gauges were placed on the outside face of this shaft along its axis as shown in Figure 2.

3.3.2 Test Set-up

The preload cell was placed in series with the material being connected. The test joint sat against the head of the bolt, the preload cell rested against the test joint and the nut bore on the preload cell. The location of washers within the test specimen set-up is described in the chapters dealing with the test joints.

3.3.3 Test Procedure

As the nut was tightened, a compressive strain was induced in the preload cell that was monitored using a switch and balance unit and a strain indicator. This strain in the preload cell was used to indicate the bolt preload in the same way as a conventional load cell. Readings of the strain in the preload cell were recorded when the nut was tightened to the snug-tight condition and turned the required rotation past snug.

3.3.4 Electrical Resistance Strain Gauges

Four electric resistance strain gauges were used to measure the strain in the preload cell. These strain gauges were attached to the outside face of the preload cell. They were placed in the center of the preload cell, along its longitudinal axis, and equally spaced around shaft, refer to Figure 2. Four gauges were used to eliminate the effects of eccentric loading during tightening of the nut. Also, in using four strain gauges, any affect due to the minor misalignment of the strain gauges and/or bending effects present due to imperfections in the materials would be minimized.

The strain gauges had a 5-mm gauge length, the gauge factor was 2.11 ± 1%, and the electric resistance was 199.9Ω. The foil strain gauges and lead wires were covered with Gagekote #5, a protective coating for strain gauges.

3.3.5 Preload Cell Calibration

The preload cell was calibrated in the same was as a conventional load cell. A 300 kN capacity universal testing machine was used in this calibration.

In order to obtain a calibration curve, the average of the four strain gauge readings was used. The calibration curve obtained for this load cell was very close to a straight line. The data was fitted to a straight line using least squares linear regression. The preload cell was periodically calibrated during the course of this work to ensure that it was not strained into the inelastic range.

Chapter IV

EXPERIMENTAL PROCEDURE: DETERMINATION OF THE SLIP COEFFICIENT

4.1 General

In studying slip-critical connections, the slip coefficient of the connected materials must be known. In any test for slip resistance, the slip displacement of the connected materials is monitored as the joint is loaded. This data is used to determine the slip load, which along with the bolt preload force is used to determine the slip coefficient. The slip coefficient, k_s, is given as:

$$[1.5] \qquad k_s = \frac{P_{SLIP}}{mnT_i}$$

where P_{SLIP} is the slip load, m represents the number of slip planes, n represents the number of bolts in the connection, and T_i is the initial bolt tension, or preload.

Tension joints are usually used in the determination of the slip coefficient; however, Hechtman et al. (1955), and Yura et al. (1981) have shown that compression joints can also be used. Also, S16.1-94 identifies the method outlined by the RCSC (1994) as an adequate method to determine the slip coefficient. This research project used both types of joints to determine the slip coefficient of the clean mill scale A36 hot rolled bar.

4.2 Definition of Slip and Slip Load

The slip is the slip displacement that is observed between the connected plates which is usually measured using dial gauges.

The definition of the slip load depends on the shape of the load vs. slip curve obtained by testing the specimen. As explained by the RCSC (1994), *Testing Method to Determine the Slip Coefficient for Coatings Used in Bolted Joints*, the typical load vs. slip curve has one of three forms (refer to Figure 3). For curve (a), the slip load is taken as the maximum load, provided that this load occurs before a slip of 0.4-mm (0.02-inch) is reached. For curve (b), slip load is the load at which the slip rate increases suddenly. This type of slip is called "major slip" since the plates suddenly slip. For curve (c), slip load is the load that corresponds to a cumulative slip of 0.4-mm (0.02-inch). This applies when the load vs. slip curve shows a gradual change in slip displacement and "the slipping builds up continuously as evidenced by cumulative microslips"[10] (Kulak et al. 1987).

For the purpose of this research project, the slip load was taken as the load that corresponded to the first significant slip of the test joint. Since slip-critical connections are designed to resist movement of the connected parts, it was decided that the first significant occurrence of slip (whether it was a major or minor slip) would be called the first major slip and it would be used to indicate the slip load. This corresponds to the slip load used by Hechtman et al. (1955) and Polyzois and Yura (1985). Movement of the joint after the first major slip was classified as either further major slips or microslips.

Microslips occurred when there was very little slip displacement as the applied load increased whereas major slips showed a more significant change in the slip displacement as the applied load increased.

A loud noise and/or a drop in the applied load often accompany slippage of the connected parts, thus these indications were also used in determining the slip load.

Theoretically, the amount of slip can be twice the hole clearance, however, in laboratory tests it is usually only about one half of the hole clearance[11] (Kulak et al. 1987).

4.3 Specimen Fabrication

In manufacturing the friction specimens, every attempt was made to retain the original mill scale surface condition of the plates so the specimens could be classified as "clean" mill scale according to Clause 13.12, *Bolts in Slip-Critical Connections*, Table 2 of S16.1-94. The 19.05-mm (3/4-inch) thick plates were saw cut from the same A36 hot rolled bar. The edges of the plates were saw cut to the required dimensions and then smoothed using a disk to remove any roughness along the edges that might influence the slip coefficient. Following usual practice, the holes were made 0.06-mm (1/16-inch) larger than the bolt diameter. As per Polyzois and Yura (1985) any burrs were removed by countersinking the holes. Following the practice of Brookhart et al. (1966) and Yura et al. (1981), the specimens were washed with acetone prior to testing to remove any residual grease and oil from the manufacturing process.

4.4 Tension Tests

Four two-bolt symmetric butt splices were tested to determine the slip load and hence the slip coefficient. The tension joints used were Type A specimens (Kulak et al. 1987)[12]. The dimensions of the specimens used are standard and are a function of the bolt diameter used. For a 19.05-mm (¾-inch) diameter bolt, the center plate (or main plate) thickness was 19.05-mm (¾-inch) and the outside (or lap) plate thickness was 9.5-mm (3/8-inch). The 9.5-mm (3/8-inch) thick plate was A36 hot rolled bar manufactured by the same supplier as the 19.05-mm (¾-inch) thick steel bar. The dimensions of the tension friction specimen are shown in Figure 4. The end dimensions of the center plates were chosen to correspond with the grips used in the universal testing machine.

4.4.1 Test Set-up

The tension friction specimen was properly aligned and the bolts were placed in the holes. An effort was made align the plates so that they were in contact with the bolts in the direction opposite to which they would be pulled during loading due to the applied tensile load. This allowed the maximum slip movement to occur during testing.

The bolts were then tightened to the snug-tight condition. The bolt head was then marked and then turned one-third turn past snug. Tightening proceeded from the outermost bolt inward. The nuts were held in a vice as the bolt head was turned. Although washers were not required as per S16.1-94, Clause 23.4.2, *Hardened Washers*, a washer was placed under the bolt head to protect the plate as the bolt head was turned.

The equipment used to measure the slip displacement was attached to the specimen after the bolts were tightened. The specimen was then placed in the universal testing machine.

4.4.2 Bolt Specimens

Each test specimen required four A325, 19.05-mm (¾-inch) diameter high-strength bolts to be used. The length of bolt used was 69.8-mm (2 ¾-inch).

4.4.3 Instrumentation

During testing, two 0.001-inch dial gauges were attached to tabs mounted on the specimen to monitor the slip displacement. One dial gauge was used to measure the displacement of the upper-center plate with respect to the two lap plates and the other was used to measure the displacement of the bottom-center plate with respect to the two lap plates as shown in Figure 5.

The tabs used to hold the dial gauges and the platforms on which the plungers of the dial gauge rested were glued (using "super" glue) to the first three specimens tested. The tabs holding the dial gauges and the platforms for the fourth specimen tested were bolted to it so these results could be compared to those where the tabs and platforms were glued to the specimens.

4.4.4 Universal Testing Machine

A 600 kN capacity universal testing machine was used to test the tension friction specimens. Although the capacity of the machine far exceeded the load to be applied to the tension specimen, this machine was used since the specimens would not fit within the space available between the loading heads of the 300 kN capacity universal testing machine. Regular flat grips were used in the machine during the testing of the tension friction specimens.

4.4.5 Test Procedure

Once the dial gauges and platforms were mounted on the specimen and the specimen was placed in the universal testing machine, the load was slowly applied to the specimen. Readings of the dial gauges were recorded regularly so as to provide an accurate load vs. slip curve. Any drop in load and/or slip noise was recorded since these are indications of slip.

The first three tests were terminated when the tabs and/or platforms, fell off the specimens. This occurred as the plates slipped into full bearing on the bolts. The fourth test was terminated when excessive slip displacement was recorded.

4.5 Compression Tests

In order to verify the results of the tension tests, six compression type friction tests were performed. The compression tests followed the procedure outlined by the RCSC (1994), *Testing Method to Determine the Slip Coefficient for Coatings Used in Bolted Joints.* This procedure is recommended by S16.1-94 in Clause 13.12.2, *Shear Connections* to determine the slip coefficient of joints. A similar compression type joint was used by

Hechtman et al. (1955), Vasarhelyi and Chiang (1967), and Yura et al. (1981), in which the coefficient of clean mill scale surfaces were tested.

The compression test specimens consisted of three plates connected by a single rod. Although recommended by the RCSC, a hydraulic bolt that provides a constant clamping force was not used, rather a rod with threaded ends was used. However the clamping force was monitored during testing. The work by Vasarhelyi and Chiang (1967) used manually tightened bolts whose pretension was monitored during testing.

The plates were 101.6 x 101.6-mm (4 x 4-inch) with a 15.9-mm (5/8-inch) diameter hole drilled 38.1-mm (1 ½-inch) from the edge. This specimen is shown in Figure 6.

4.5.1 Test Set-up

In assembling the specimens, a nut was placed on one end of the rod. This end was held in a vice to keep it stationary while the preload was induced. The preload cell was then placed over the rod. The plates were aligned and then clamped. They were aligned so as to allow for the maximum slip displacement. The strain readings from the strain gauges attached to the preload cell were set to zero on the strain indicator. A second nut was tightened to the snug-tight condition. Readings of the strain gauges were recorded when the nut was snug-tight. The nut was then rotated until the desired preload was induced in the rod. The desired preload was established by reviewing the preload values obtained from the approximate method to measure the bolt preload. The bolt preload obtained using a load cell gave some indication of the actual bolt preload induced by turn-of-nut tightening for a 19.05-mm (¾-inch) diameter A325 bolt.

Although not required as per Clause 23.4.2, *Hardened Washers*, of S16.1, a washer was placed under the nut that was turned to prevent damage to the plate.

4.5.2 Bolt Specimen

For economic and efficiency reasons, a 19.05-mm (¾-inch) diameter rod with threaded ends was used instead of a bolt since the required length of bolt was not easily attainable. The rod was 165.1-mm (6.5-inch) in length. The use of a rod in no way affects the results of the compression test for the coefficient of friction since the preload force induced was comparable to that obtained from turn-of-nut tightening for bolts. In order to ensure the rod could be used a number of times without entering the inelastic range, it was quenched and tempered to a Rockwell Hardness of C-50.

4.5.3 Instrumentation

Slip is the relative displacement of the center plate with respect to the two lap plates. As specified by the RCSC (1994), the slip should be the average that occurs at the centerline of the specimen and can be obtained by taking the average of two dial gauges mounted on either side of the specimen. Hence, a 0.0001-inch dial gauge was mounted on either side of the center plate, as shown in Figures 7 and 8. The plungers of the dial gauges rested on the head of the testing machine.

4.5.4 Universal Testing Machine

A 300 kN capacity testing machine was used to test the compression specimens. As recommended by the RCSC (1994), a spherical head was used in the universal testing machine in order to ensure uniform contact along the edge of the center plate, refer to Figures 7 and 8. Thus any eccentric loading was eliminated. The compression specimen was centered between the heads of the universal testing machine.

4.5.5 Test Procedure

Following the testing procedure outlined by the RCSC (1994), the load was slowly applied to the specimen and before a load of about 4000 N was reached, the plates on which the plungers of the dial gauges rested were put into place. In allowing the specimen to sustain a load of less than 4000 N before the dial gauges were effective, the deformation caused by the initial specimen settling was removed from the slip readings.

Readings of the dial gauges were regularly taken during testing. Any drop in the applied load and/or slip noise was recorded. Also, as per Vasarhelyi and Chiang (1967), readings of the strain gauges were periodically taken so that the clamping force at the instance of slip could be determined.

The tests were terminated when excessive slip displacement was recorded.

Chapter V

EXPERIMENTAL PROCEDURE: TESTING DEVICE

5.1 General

In order to determine the behaviour of slip-critical connections subjected to combined shear and tension, a connection simulating testing device was used. This device was similar to that used by Munse and Cox (1956) to test rivets subjected to combined shear and tension and later used by Chesson et al. (1965) to perform the same type of testing with high-strength bolts.

This device allowed the bolt in the simulated connection to be loaded in a number of load combinations ranging from pure shear to pure tension. The data from these tests was used to examine the validity of the interaction equation given in Clause 13.12.3, *Connections in Combined Shear and Tension*, of S16.1-94 (presented herein as Equation 1.1). This interaction equation was chosen "as a matter of judgement" since "there are no published test results covering this situation"[13] (Kulak et al. 1990). It should be noted that no tests were performed in the seventh setting. This setting allowed the bolt in the connection to be loaded in pure tension. The use of high-strength pretensioned bolts in connections where the bolts are subjected to tensile loads was not included in the scope of work of this research.

5.2 Definition of Slip Load

The slip load of each specimen was taken as the load corresponding to the first significant slip of the test joint, as described in Chapter IV, Section 4.2.

5.3 Test Set-up

The components of the testing device are shown in Figure 9. This figure shows the assembly sequence of the components of the testing device. The testing device consisted of the two test blocks connected by a pretensioned high-strength bolt. The preload cell was placed in series with the test blocks in order to determine the initial bolt preload and monitor the preload during testing. The test blocks fit within four split loading blocks that were attached to four pull plates. The pull plates were attached to two load blocks with loading grips. These load blocks with loading grips, along with a threaded rod, allowed the device to be loaded in the universal testing machine. The device was held together by eight assembly bolts.

5.3.1 Bolt Specimens

The bolts used in this phase of the research were A325, 19.05-mm (¾-inch) diameter high-strength bolts. The length of bolt used was 120.6-mm (4 ¾-inch).

5.3.2 Instrumentation

In order to measure the slip of the test specimen, a dial gauge and its resting platform were mounted on the split loading blocks. Ideally the slip of the test blocks should have been monitored, however the configuration of the testing device did not provide adequate space to mount a dial gauge and resting platform on the test blocks. In mounting the displacement measuring equipment on the split loading blocks, the initial readings reflected the device properly aligning itself. However, once the device was properly aligned, the displacement readings only indicated the slip behaviour of the test blocks.

Due to the rotation of the testing device as the load combination progressed from pure shear to pure tension, two set-ups were required for the slip measuring equipment. The first set-up is shown in Figures 10 and 11. This was used for settings 1 and 2 (refer to Table 1 which describes the nomenclature used for the settings of the testing device). The set-up for settings 3 through 6 is shown in Figures 12 and 13. A 0.0001-inch dial gauge was used for both configurations.

5.3.3 Testing Specimens

In slip-critical connections, the condition of the faying surfaces of the connection is of prime importance. Since testing the connection alters the faying surfaces, a new set of test blocks was used for each test. In total 21 sets of test blocks were used during this phase of work.

5.3.4 Fabrication of the Test Specimens

The test blocks were made from A36 hot rolled bar with mill scale surface condition. During fabrication, every effort was made to retain the original "as rolled" mill scale surface condition of the steel bar. These specimens were saw cut from the same bar as was used to manufacture the specimens used in determining the slip coefficient, therefore the slip coefficient is valid for these test blocks.

The bar was saw cut into squares. Holes were drilled in the center of these squares. Following usual practice, the holes were made 0.06-mm (1/16-inch) larger than the bolt diameter. As per Polyzois and Yura (1985), the holes were countersunk to remove any burrs. The squares were then turned into the round test blocks using a lathe. Prior to testing, the loading blocks were lightly wire brushed to remove any loose scale and washed with acetone to remove any residue that remained from the lubricants used during the manufacturing process. The procedure of removing any loose mill scale was performed as per previous research by Hechtman et al. (1955). Little, if any, loose scale was removed by this process.

5.3.5 Universal Testing Machine

A 600 kN capacity universal testing machine was used to test the joint. Although the maximum load applied to the device did not exceed 300 kN, the 300 kN capacity testing machine could not be used since the space between the stationary and moving heads of the machine was not sufficient for the testing device. The load was applied to the test specimen via a threaded rod attached to each load block with loading grips.

5.4 Test Procedure

In assembling the test specimen, the bolt was passed through the test blocks and the preload cell and then the nut was tightened. Initially, only one washer was used under the nut, the turned element. However, in order to prevent damage to the load cell, a second washer was used under the head of the bolt for specimens S2-2 through S4-3. A washer was not used under the head of the bolts tested in settings 5 and 6 in order to prevent the bolt head from touching the top of the loading block.

Since the thickness of the material being connected, or the material in the grip length, exceeded four times the bolt diameter, one-half turn from snug was required to achieve the desired preload.

In order to achieve the maximum slip, the loading blocks were aligned so as to provide the maximum hole clearance in the direction opposite to which they would be pulled during testing. Readings of the strain gauges were recorded when the bolt was snug tight and fully tightened.

In assembling the testing device, the pull plates were aligned very carefully and an effort was made to tighten the assembly bolts so as to remove any slack in the device. In ensuring that the parts were in close contact before loading, much of the initial movement of the split loading blocks caused by the testing device properly aligning itself was removed from the slip, or displacement, readings. Unfortunately, it was often very difficult to completely remove the slack in the testing device and bring the pull plates and split loading blocks into contact, therefore the initial slip readings reflect the movement of the testing device and the split loading blocks. However, once the initial movement of the split loading blocks brought them into full contact, the displacement readings only measure the movement of the test blocks or the slip of the test specimen.

During testing, the load was applied very slowing and readings of the dial gauge were taken regularly in order to obtain a good load-displacement curve and therefore accurately predict the slip load. Since a drop in the load and/or a noise often accompanies slip, any such occurrence was recorded. Readings of the preload cell strain gauges were also taken regularly so the changes in the clamping force could be evaluated.

The slip test was terminated when there was excessive slip, indicating that the bolt was now in bearing, or when the applied load approached the theoretical failure load of a bolt loaded in shear. Although conservative, since as the tensile load component of the applied load increased the failure load increased, the failure load of a bolt loaded in shear was used to ensure that the bolt would not fail.

It should be mentioned that although the pull plates were originally rectangular in shape (as shown in Figures 9, 10, and 11), during the course of the work the corners of the plates were trimmed (refer to Figures 12 and 13). Removing the corners of the pull plates facilitated testing as the device was rotated for settings 2 through 6.

Chapter VI

EXPERIMENTAL PROCEDURE: SLIP-CRITICAL CONNECTION

6.1 General

In order to ensure that the testing device accurately simulated connections loaded in combined shear and tension, a connection was designed, built, and tested. A connection loaded equally in shear and tension was manufactured and tested. These results would be compared with the results of the fourth setting of the testing device (Setting 4, 45 degrees from pure shear). This load combination was chosen for ease of construction.

6.2 Definition of Slip Load

The slip load of the connection was taken as the load that corresponded to the first major slip of the connection, as described in Chapter IV, Section 4.2.

6.3 Test Set-up

As shown in Figures 14 and 15, the connection consisted of two plates connected by two bolts. The plates were cut from the same bar of 19.05-mm (¾-inch) thick A36 steel that was used in manufacturing the load blocks tested in the testing device and the tension and compression specimens used to determine the slip coefficient. The plates were 298.4-mm by 127.0-mm (11 ¾-inch by 5-inch) with a 20.64-mm (13/16-inch) diameter hole drilled 36.5-mm (1 7/16-inch) from either end. The location of the hole, with respect to the edge of the plates and the point of application of the load, was chosen to minimize any prying action effects. Also, for ease of handling a small connection was desirable.

Since two bolts were used to connect the plates, a second preload cell was made in the same manner as the first preload cell (described in Chapter III).

A 76.2-mm (3-inch) equal leg angle was welded to each plate and a heavy hex nut was welded to each angle. A 38.1-mm (1½-inch) threaded rod was attached to each nut and used to apply the load using the universal testing machine (refer to Figures 14 and 15).

6.3.1 Specimen Fabrication

In manufacturing the connection, every attempt was made to retain the original mill scale surface condition of the plates so the specimens could be classified as "clean" mill scale according to Clause 13.12, *Bolts in Slip-Critical Connections*, Table 2 of S16.1-94. The 19.05-mm (3/4-inch) thick plates were saw cut and the edges were smoothed using a disk to remove any roughness along the edges that might influence the slip behaviour of the joint. Following usual practice, the holes were made 0.06-mm (1/16-inch) larger than the bolt diameter. As per Polyzois and Yura (1985) any burrs were removed by countersinking the holes. The plates were lightly wire brushed, as per Hechtman et al. (1955), and following the practice of Brookhart et al. (1966), and Yura et al. (1981), the specimens were washed with acetone prior to testing to remove any residual grease and oil from the manufacturing process.

6.3.2 Bolt Specimens

The bolts used in this phase of the research were A325, 19.05-mm (¾-inch) diameter high-strength bolts. The length of bolt used was 120.6-mm (4 ¾-inch).

6.3.3 Instrumentation

As shown in Figure 16, two 0.01-mm dial gauges were used to monitor the slip of the connection. The dial gauges were affixed to the stationary head of the universal testing machine. One dial gauge was used to measure the slip of the top plate and the other was used to measure the slip of the bottom plate. The use of two dial gauges allowed the relative movement of one plate with respect to the other to be determined and thus the load-displacement, or slip, behaviour of the connection.

6.3.4 Universal Testing Machine

A 600 kN capacity testing machine was used to test the joint. The load was applied to the test joint via a threaded rod attached to the nut on the angle attached top plate and another attached to the bottom plate.

6.4 Test Procedure

In assembling the connection, the bolts were brought to the snug-tight condition and the strain gauge readings were recorded. The bolts were then turned one-half turn past snug and again the strain gauge readings were recorded.

The connection was placed in the universal testing machine. The dial gauges were put into place and the load was slowly applied. Readings of the dial gauges and strain gauges were taken regularly during testing. Any drop in the applied load and/or slip noise was recorded since these are indications of slip.

The test was terminated when the weld connecting the angle to the plate failed. Fortunately major slip occurred before the weld failed.

Chapter VII

RESULTS AND DISCUSSION

7.1 General

This chapter presents and discusses the results of this research program. The results obtained from testing to determine the bolt preload, and slip coefficient are presented herein. The slip data obtained from the testing device is also presented. The results obtained from the testing device are compared to those of an actual slip-critical connection loaded equally in shear and tension. This data is used to compare the experimental behaviour of slip-critical connections subjected to combined shear and tension forces with the theoretical prediction given by the interaction equation presented in Clause 13.12.3, *Connection in Combined Shear and Tension*, of S16.1-94.

The behaviour of the bolt preload is also examined for all tests in which the preload cell was used. Also, the damage to the mill scale surface of the specimens is explained for all test specimens.

7.2 Bolt Preload

7.2.1 Approximate Method and Tension Tests

The results of the approximate method for the determination of the bolt preload are shown in Table 2. Ten bolts were tightened and the pretensioning, or preload, force induced in each bolt was recorded. The bolt preload was recorded when the bolts were snug-tight and one-third turn past snug. According to Clause 23.4.1, *Bolt Tension*, of

S16.1-94, the minimum bolt preload for a 19.05-mm (¾-inch) A325 bolt is 125 kN. All the bolts tested exceeded the minimum preload by at least a factor of 1.4.

The average bolt preload for the ten bolts tested was found to be 187.0 kN with a standard deviation of 6.4 kN. This value of the average bolt preload was used in determining the slip coefficient of the symmetric butt joints loaded in tension. For these tension friction specimens, the actual bolt preload induced due to pretensioning was not monitored. In calculating the slip coefficient for these joints, the average bolt preload of 187.0 kN was assigned as the initial bolt tension.

Since S16.1-94 allows a tolerance of ±30° in the amount of rotation past snug, the bolt preload for three of the bolt specimens was recorded at one-third turn past snug ±30. The preload force that existed at one-third turn past snug minus 30° and one-third turn past snug plus ±30° is given in Table 2. The bolt preload at one-third turn past snug minus 30° was slightly below the preload achieved at one-third turn past snug. Each bolt achieved a preload at one-third turn past snug plus 30° that was within the range of readings obtained for the specimens tightened to one-third turn past snug.

7.2.2 Compression Tests, Testing Device, and Slip-Critical Connection

A preload cell was used to monitor the bolt preload in determining the slip coefficient using a compression specimen, all testing using the testing device, and in testing the connection used to verify the testing device results. The values of the bolt preload obtained using the preload cell are shown with the corresponding load-displacement data for each test performed. The induced bolt preload was at least 1.3 times greater than that required by S16.1-94.

7.3 Slip Coefficient

The slip coefficient, k_s, was determined from the following equation:

$$[1.5] \qquad k_s = \frac{P_{SLIP}}{mnT_i}$$

where P_{SLIP} indicates the slip load, m represents the number of faying surfaces ($m = 2$ for both the tension and compression specimens), n represents the number of bolts ($n = 2$ for the tension specimens and $n=1$ for the compression specimens), and T_i indicates the bolt preload.

7.3.1 Tension Tests

The slip coefficients as determined from the four tension specimens (described in Chapter IV) are shown in Table 3. The corresponding load-displacement data is given in Tables 4 through 7. The load-displacement curves for the tension specimens (Figures 17 and 18) indicate that during each test there were sudden significant slips of the joined elements as well as microslips. The first plateau in the load-displacement curve, as well as any drop in the applied load or slip noise (refer to Tables 4 through 7), was used to determine the slip load at major slip. Both major slips and microslips often followed the first major slip. As described in Chapter IV, the tests were terminated when the displacement measuring equipment fell off the joints (Specimens 1, 2 and 3) or when excessive slip displacement had occurred (Specimen 4).

In determining the slip coefficient, the bolt preload, T_i, was taken as 187.0 kN for all of the tension joints (as explained in Section 7.2.1). From the four tension specimens tested the average slip coefficient was given as 0.22 with a standard deviation of 0.01.

7.3.2 Compression Tests

The slip coefficients as determined from the six compression joints (described in Chapter IV) are given in Table 8. The corresponding load-displacement data is given in Tables 9 through 14. These tables indicate the load at which any slip noise was heard and the bolt preload readings. The only specimen to exhibit a slip noise was Specimen 1. The load-displacement curves obtained for the six compression joints are shown in Figure 19. The load-displacement curves obtained for Specimens 1, 3, and 6 show that a sudden significant slip occurred, hence this was taken as the first major slip and the corresponding load was taken as the slip load. This major slip can be identified by the first plateau in the load-displacement curves. For Specimens 2 and 4, the load-displacement curves show that there was a gradual slip or series of microslips. Following the RCSC specification, the slip load for these two tests was taken as the load corresponding to a cumulative slip of 0.508-mm (0.02-inch). As shown by the load-displacement curve for Specimen 5, it did not exhibit a major slip. Taking the slip load as the load corresponding to a cumulative slip of 0.5-mm (0.02-inch) leads to a slip coefficient that is inconsistent with the other tests and unreasonably high. Therefore this specimen's data was not used in determining the slip coefficient.

In determining the slip coefficient, the clamping force that existed just before slip occurred was used as the bolt preload, T_i, (refer to Table 8 and Table 9 through 14). The use of the clamping force at the instance of slip is used in accordance with Vasarhelyi and Chaing (1967). Since readings of the bolt preload (strain gauges) were not continuously recorded, the value of bolt preload recorded just before slip was used as the bolt preload at the instance of slip. This should not effect the results since there was little change in the preload prior to slip.

The five compression specimens gave the average slip coefficient as 0.28 with a standard deviation of 0.03. The average slip coefficient determined using the tension specimens is significantly smaller than that given by the compression specimens. The value given by the compression specimens is in accordance with that given by Vasarhelyi and Chiang (1967) as 0.27 with a standard deviation of 0.05 but it is below the slip coefficient of 0.31 reported by Polyzois and Yura (1985).

7.3.3 Slip Coefficient of A36 Hot Rolled Bar with Mill Scale

Due to the significant variations in the slip coefficient as determined by the four tension specimens, that determined by the five compression specimens, the slip coefficient reported by Vasarhelyi and Chiang and that reported by Polyzois and Yura, it was decided that the average slip coefficient given by the tension and compression specimens would be used as the slip coefficient, k_s. Using both the tension and compression test results, the average slip coefficient was found to be 0.24 with a standard deviation of 0.03.

It is interesting to note that the slip coefficient as determined from the pure shear setting of the testing device is 0.23 with a standard deviation of 0.01 (refer to Table 15). In calculating the slip coefficient, m and n were both taken as 1 (refer to Equation 1.5). This value agrees very well with the slip coefficient determined by taking the average of the slip coefficients as given by the tension and compression specimens.

7.4 Testing Device

Six tests were performed in Setting 1, pure shear load, since this was the first setting to be tested. As such, it was necessary to learn to properly set-up the testing device in order to minimize the initial movement associated with the device properly aligning itself (as explained in Chapter V, Sections 5.3.2 and 5.4) and become familiar with the testing sequence. Once the proper set-up procedure and testing sequence were determined, three tests were performed for each setting tested.

The nomenclature used to indicate the test settings and the angle from pure shear for each setting is given in Table 1. The first number indicates the setting and the second number indicates the test number. For example, S2-3 refers to the third test performed in the second setting. In all twenty-one tests were performed. No tests were performed in the pure tension setting since the use of pretensioned bolts loaded in tension was not included in the scope of the work.

The load-displacement curves obtained for each setting are shown in Figures 20 through 25. The corresponding data is given in Table 16 through 36. During testing the occurrence of a drop in the applied load and/or slip noise was recorded along with the load at which it occurred. These findings are given in the tables under the "comment" heading. These tables also show the preload data for the bolt specimen.

For each specimen tested, the slip load was taken as the load corresponding to the first major slip of the joint. The first plateau in the load-displacement curve, in conjunction with the occurrence of a drop in the applied load and/or slip noise, was used to identify the slip load.

As expected, as the load combination progressed from pure shear to pure tension, the shear load inducing slip decreased. The tensile component of the applied load tends to separate the connected plates, thus less shear force is required to cause slip of the connection.

The load-displacement curve (Figure 20) for each of the six specimens tested in Setting 1 show that the first major slip was followed by microslips and/or major slips. The slip load for these specimens varied from 37.0 to 49.2 kN.

The load-displacement curve (Figure 21) for each of the three specimens tested in Setting 2 show that the first major slip was followed by microslips leading to the joint bearing on the bolt. The slip load for these specimens varied from 43.5 to 47.4 kN.

The specimens tested in Settings 3 through 6 showed similar load-displacement behaviour. The load-displacement curve for each of these specimens (Figures 22 through 25) show that the first major slip was followed by microslips (curved portion) and another major slip (flat portion) that brought the joint into bearing on the bolt. The behaviour of Specimen S3-2 varies slightly in that successive major slips occurred rather than microslips. The slip load for the specimens tested in Setting 3 varied from 43.4 to 49.9 kN, for Setting 4 the slip load varied from 49.9 to 52.4 kN, for Setting 5 the slip load varied from 66.3 to 67.8 kN and that for Setting 6 varied from 80.0 to 87.8 kN.

The results from the 21 specimens tested were used in the interaction equation given for slip-critical connections in combined shear and tension. The equation is given in S16.1-94, Clause 13.12.3, *Connections in Combined Shear and Tension*, as:

[1.1] $$\frac{V}{V_s} + 1.9\frac{T}{nA_bF_u} \leq 1.0$$

where V and T are the shear and tensile component of the slip load, P_{SLIP}, V_s is the slip resistance of the joint, n represents the number of bolts in the connection, and the term

[1.2] $$\frac{1.9}{nA_bF_u}$$

represents the reciprocal of the total initial bolt tension, or preload, for *n* bolts. Thus this term can be replaced with the bolt preload for the *n* bolts, T_i.

Equation 1.1 can thus be rearranged as:

[7.1] $$\frac{P_{SLIP}\cos\theta}{0.53\,c_1 k_s mnA_b F_u} + \frac{P_{SLIP}\sin\theta}{T_i} \leq 1.0$$

where θ represents the angle of the bolt with respect to the horizontal, or the angle that the connection has been rotated from the shear setting (refer to Table 1). For Setting 1, the bolt is subjected to pure shear load since the applied load is vertical and the bolt axis is parallel with the horizontal (thus θ = 0°). As the device is rotated, the bolt axis is no longer parallel to the horizontal rather it changes by 15° for each rotation of the testing device.

By neglecting c_1, taking *m* and *n* equal to 1, and substituting the expression for the initial bolt tension (Equation 1.3) into Equation 7.1, Equation 7.1 can be further reduced to:

[7.2] $$\frac{P_{SLIP}\cos\theta}{k_s T_i} + \frac{P_{SLIP}\sin\theta}{T_i} \leq 1.0$$

The results obtained from each test performed using the testing device were substituted into this equation. The initial bolt preload, T_i, used in this equation was the bolt preload that was recorded just before slip (used in accordance with Vasarhelyi and Chaing (1967)). It was decided that since the preload usually increased slightly prior to slip, this value would be used in the interaction equation. The ratio of the applied tension to the bolt preload would be smaller and thus the results are more conservative.

The results of the specimens tested in the testing device are tabulated in Table 38 and shown in Figure 27. These results are discussed in more detail in Section 7.6, where a comparison is made between the experimental and theoretical results.

7.5 Slip-Critical Connection

One connection loaded equally in shear and tension was manufactured and tested. The load-displacement data for this connection is given in Table 37 and the corresponding curve is given in Figure 26. The occurrence of a drop in the applied load was used in conjunction with the load-displacement curve to determine the slip load. Major slip was followed by further slippage of the connection.

Unfortunately, the weld joining the angle to the upper plate failed before the connection slipped into bearing. Nonetheless, the results of this test support the results of the testing device, Setting 4, as can be seen in Figure 27 (described in Section 7.6).

The slip load for the connection was taken as 98.4 kN. The bolt preload used in evaluating the interaction equation for this connection was that recorded just before slip (used in accordance with Vasarhelyi and Chaing (1967) and described in detail in Section 7.3.2). As explained below (Section 7.7), there was little variation in the bolt preload recorded at one-half turn past snug and that just before slip.

7.6 Theoretical Results

Equation 1.1 (the interaction equation given in S16.1-94, Clause 13.12.3, *Connections in Combined Shear and Tension*) is a linear function as shown in Figure 27. Figure 27 is a plot of V/V_s vs. T/T_i (the ratio of the shear load applied to joint to the slip resistance of the joint vs. the tensile force applied to the joint to the initial bolt preload). This figure also presents the results of the specimens tested in the testing device and the results of the slip-critical connection.

As can be seen, the equation from S16.1-94 (presented as Equation 1.1) is somewhat conservative when compared to the results of the testing device and those obtained from the slip-critical connection. However, it slightly overestimates the behaviour for five of the six specimens tested in Setting 1 and two of the three specimens tested in Setting 6. This may be attributed to slight errors and variations in the slip coefficient and/or the definition of the slip load used. In taking the slip coefficient as the average of such a broad range of values, some error may have been introduced into the results. The points that are slightly below the interaction equation line are not of concern since variations in the slip coefficient effect the interaction equation results. A higher value for the slip coefficient would cause the data points to shift downward while a lower slip coefficient value would cause the data point to shift upward. If the slip coefficient was taken as 0.22 (as indicated by the tension friction joints) all but two data points would fall above the linear approximation given by Equation 1.1, as shown in Figure 28 and tabulated in Table 39.

In all, although it was chosen as matter of judgement, the interaction equation seems to be suitable for the experimental data presented. A linear equation is appropriate for the data.

As seen on Figures 27 and 28 the data obtained from the testing device and the slip-critical connection, does not exceed 0.5 units on the horizontal scale. Thus, the data does not confirm the behaviour of slip-critical connections subjected to combined shear and tension when the ratio of T/T_i (where T is tensile component of the slip load) is greater than 0.5. However, this area is not of significance since the data presented is for Setting 1, pure shear loading, through Setting 6. In Setting 6, the bolt is at a 75° angle from the horizontal and the shear-tension ratio is 0.27 to 1.00 (refer to Table 1). From a practical standpoint, an angle larger than 75° from the horizontal would probably not be used in slip-critical connections. Therefore, the data covers the practical range of loading for slip-critical connections.

7.7 Bolt Preload Trends

For the connections in which the preload cell was used, the bolt preload was monitored during testing. These results are given with the load-displacement data for each test. The changes in the bolt preload as the applied load was increased were similar for all testing. This behaviour is explained below.

7.7.1 Compression Test Specimens

The bolt preload for each of the six compression specimens tested followed a similar pattern. Initially, the bolt preload dropped slightly. As increasing load was applied to the connections, there were slight variations in the bolt preload. After major slip, the bolt preload dropped.

7.7.2 Testing Device

The general trend followed by the bolt preload for the specimens tested in the testing device included a slight increase in the preload as the testing device was assembled, followed by only slight variations in the bolt preload before major slip, and a significant drop in the bolt preload after major slip.

The small increase in bolt preload that was observed in the majority of bolts tested as the testing device was assembled can be attributed to the force of the spilt loading blocks on the loading blocks as the device was assembled and the parts were brought into close contact. For each test performed, readings of the strain gauges recorded prior to major slip indicate that there was little change in the bolt preload before major slip. After major slip, the results indicate that there is a significant drop in the bolt preload.

7.7.3 Slip-Critical Connection

The bolt preload behaviour of the bolts connecting the test connection also reinforces the results obtained using the testing device. There was little variation in the bolt preload before major slip for both bolts used in the connection. The preload dropped slightly. This slight drop in preload may be the result of bolt relaxation.

As expected, the bolt preload dropped significantly after major slip.

7.8 Surface Damage

7.8.1 Tension Test Specimens

The surface of the specimens tested in tension was damaged after testing. The mill scale flaked from much of the area surrounding the bolt holes of the specimens. This damage resulted from the slip action of the plates.

7.8.2 Compression Test Specimens

The surface of the compression specimens showed damage similar to that of the tension specimens.

7.8.3 Testing Device Specimens

After slip, the surface of the test blocks from Setting 1 was very damaged (refer to Figure 29). The mill scale flaked and peeled from much of the contact area of the load blocks (in a manner similar to the tension and compression specimens). In assembling the connection, the load blocks were positioned to allow for maximum slip. As such, the top edge of the first load block was not in contact with the second load block and the bottom edge of the second load block was not in contact with the first load block. The mill scale was completely removed, or scrapped from, the areas of the load blocks that were initially not in contact. This signifies that as the load blocks moved in opposite directions, the edge of one load block scraped against the other load block and completely scoured the mill scale from the area.

As seen in Figure 29, the load blocks used in Setting 2 were also damaged extensively from the slip tests. The damage was very similar to that of the specimens from Setting 1.

The surface of the load blocks tested in Setting 3 were damaged to about the same extent as those tested in the Settings 1 and 2. However, the area from which the mill scale was completely removed was far less extensive than in the previous settings (refer to Figure 30). The load blocks tested in Settings 4, 5, and 6 did not show any indications of scraping. The mill scale was not completely removed from either the top or bottom edges of the load blocks. A significant amount of scale did flake and peel from the surface of the blocks as seen in Figures 30 and 31.

7.8.3 Slip-Critical Connection

This surface damage of the slip-critical connection was similar to that of the tension and compressions specimens and the loading blocks. The mill scale flaked and peeled from the area around the holes.

Chapter VIII

OBSERVATIONS, CONCLUSIONS AND RECOMMENDATIONS

8.1 Observations

Through this work, it became evident that the determination of the slip coefficient is rather difficult. There are many factors that impeded the determination of the slip coefficient. These include:

a) The definition of the slip load is not precise. For load-displacement curves that showed many major slips and microslips, it was unclear if the slip load should have been taken as the load at which the connection firsts exhibited sudden slip or the load at which the connection slipped a fairly large amount.

b) The variation in the slip coefficient can be attributed to the non-uniform surface of steel bars. As a result, the slip coefficient obtained for specimens cut from the same stock of hot rolled bar varied significantly. Unfortunately, it may be unrealistic to expect, or hope for, a uniform surface condition for "as rolled" steel bars.

8.2 Conclusions

The following conclusions are based on the results and discussion of the experimental and theoretical data obtained in this research:

a) As expected, the induced bolt preload exceeded the minimum bolt preload as specified in S16.1-94 for all tests performed. The bolt preload exceeded the minimum value by at least a factor of 1.3. Thus turn-of-nut tightening provides an adequate factor of safety in pretensioning bolts.

b) The slip coefficient as obtained from the tension joints was significantly lower than that obtained using the compression joints. From the tension joints, the average slip coefficient was found to be 0.22 with a standard deviation of 0.01, while the compression joints gave an average value of 0.28 with a standard deviation of 0.03. It is unclear if this discrepancy resulted due to the scatter in the data or if the type of test affected the results. Both of these explanations seem valid.

Taking the slip coefficient as the average of the slip coefficients obtained from the tension and compression joints seemed to be the best approach. This decision was reinforced by the slip coefficient as determined from the testing device, Setting 1. The average slip coefficient as determined by the tension and compression joints was 0.24 with a standard deviation of 0.03 while that given by Setting 1 of the testing device was 0.23 with a standard deviation of 0.01.

c) The bolt preload did not change significantly prior to slip. After slip, there was a sudden drop in the preload. An explanation of this behaviour is beyond the scope of this work. However, in evaluating the behaviour of slip-critical connections, the initial bolt preload and/or the preload just before slip are required. The preload after slip is not required in calculations for slip-critical connections thus it was not imperative to explain the trend of the bolt preload after slip had occurred.

d) Despite the problems associated with the slip coefficient, the experimental results agree with the theoretical results. The results of both the testing device and the slip-critical connection indicate that the linear response predicted by the interaction equation is accurate. Although determined as a matter of judgement, the interaction equation given in S16.1-94 seems to be appropriate.

8.3 Recommendations

From this work, the following recommendations can be made:

a) It seems that the present interaction equation given in S16.1-94 is adequate for the design of slip-critical connections subjected to combined shear and tensile loads. No modifications to this equation are recommended.

b) A more precise definition of slip load should be specified. In doing so, the determination of the slip coefficient will be greatly simplified.

8.4 Future Research

The areas in which more research could be performed are:

a) The slip coefficient of various steels should be evaluated. Improved fabrication techniques may have changed the mill scale surface roughness of various steels since their coefficients last evaluated.

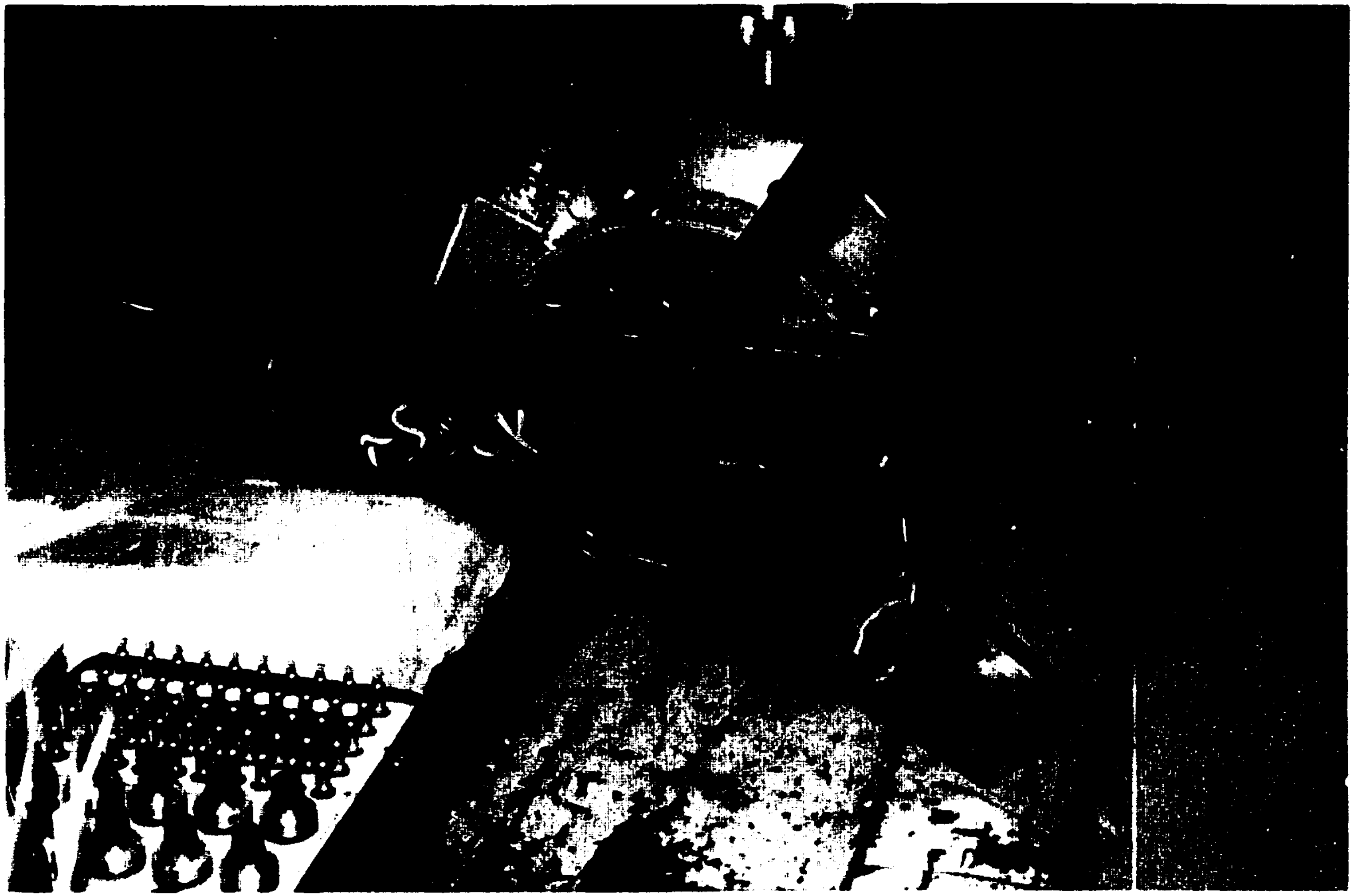
b) The effect of the type of test on the slip coefficient, if any, should be studied.

c) The trends in bolt preload can be further investigated.

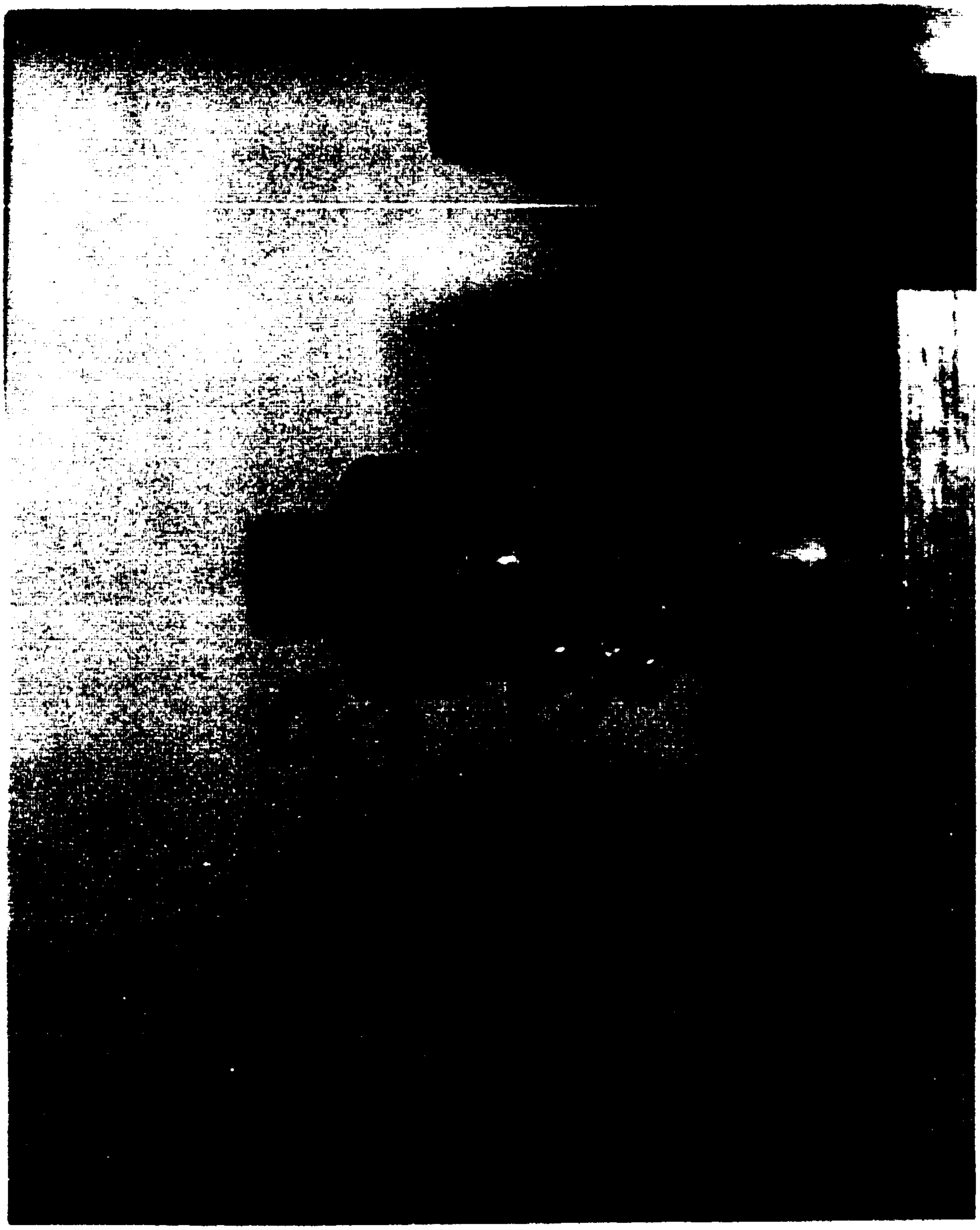
d) Research should be performed on actual slip-critical connections loaded in combined shear and tension. Thus the interaction equation of S16.1-94 can be evaluated more closely.

Appendix A

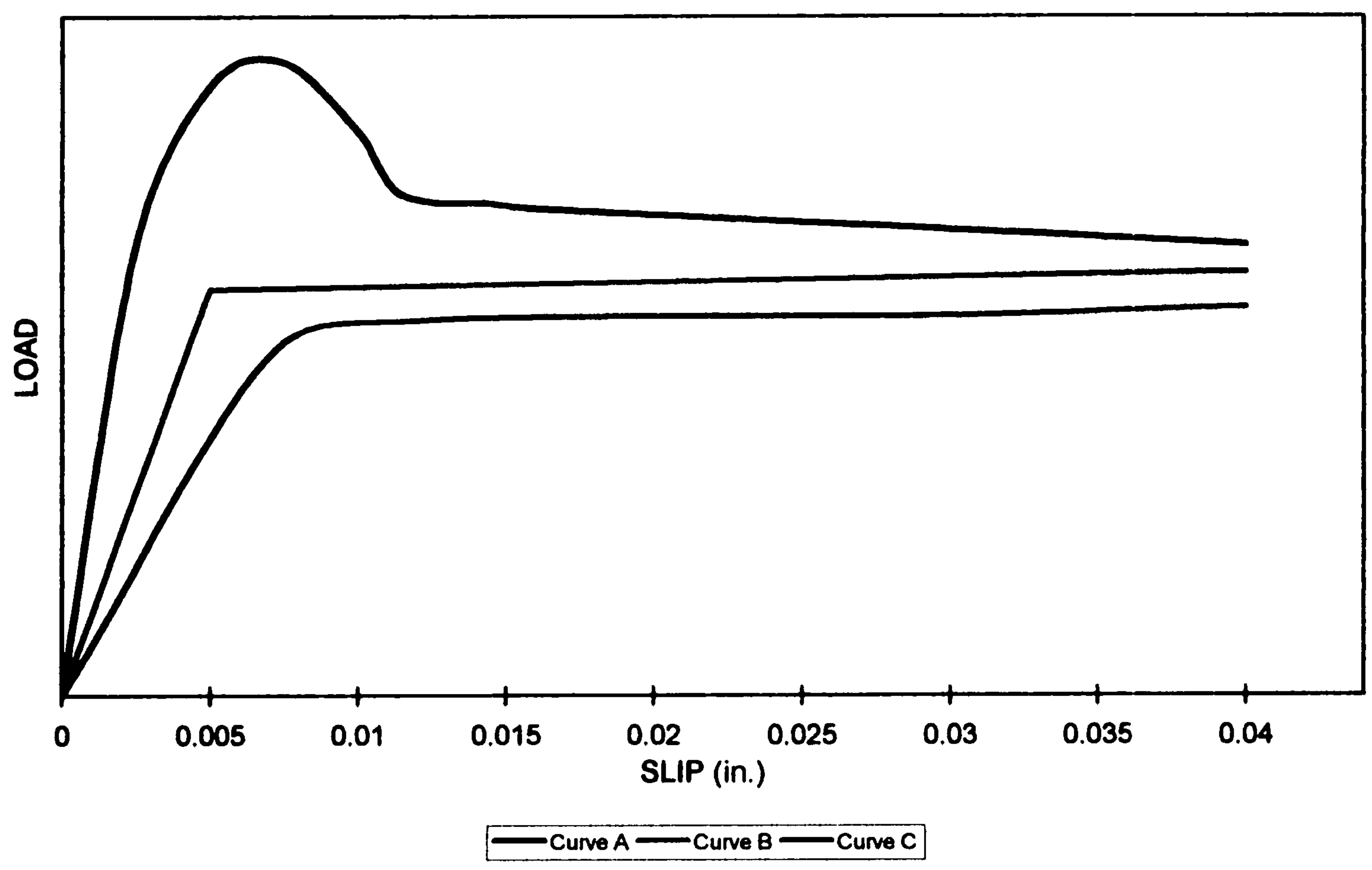
FIGURES



Approximate Determination of Preload – Set-up
Figure 1

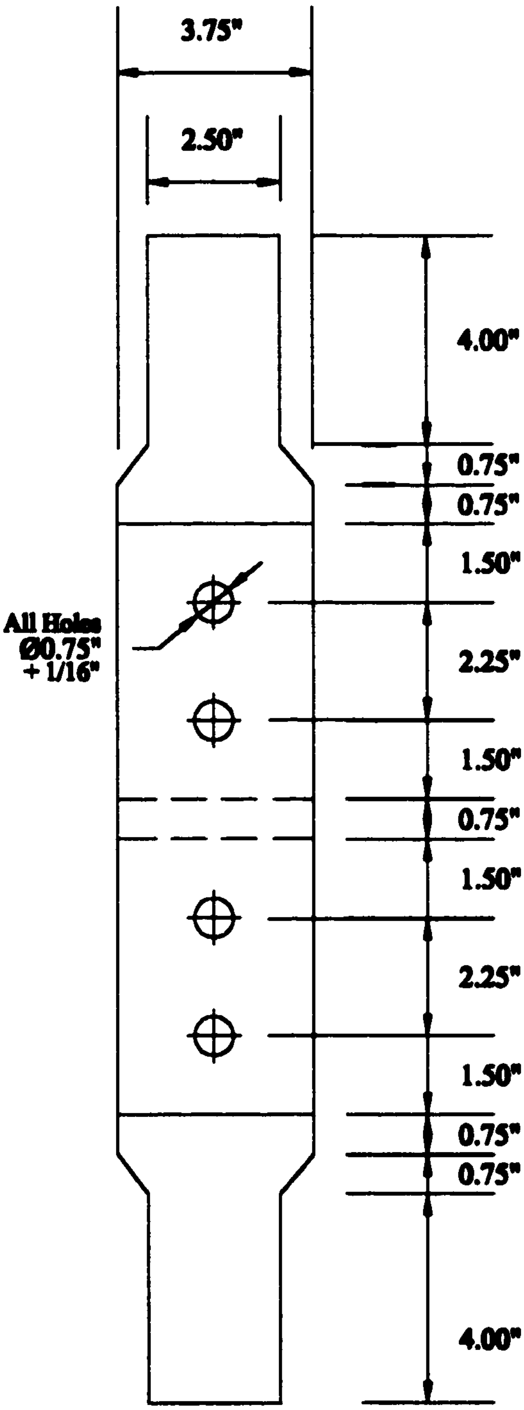


Preload Cell
Figure 2



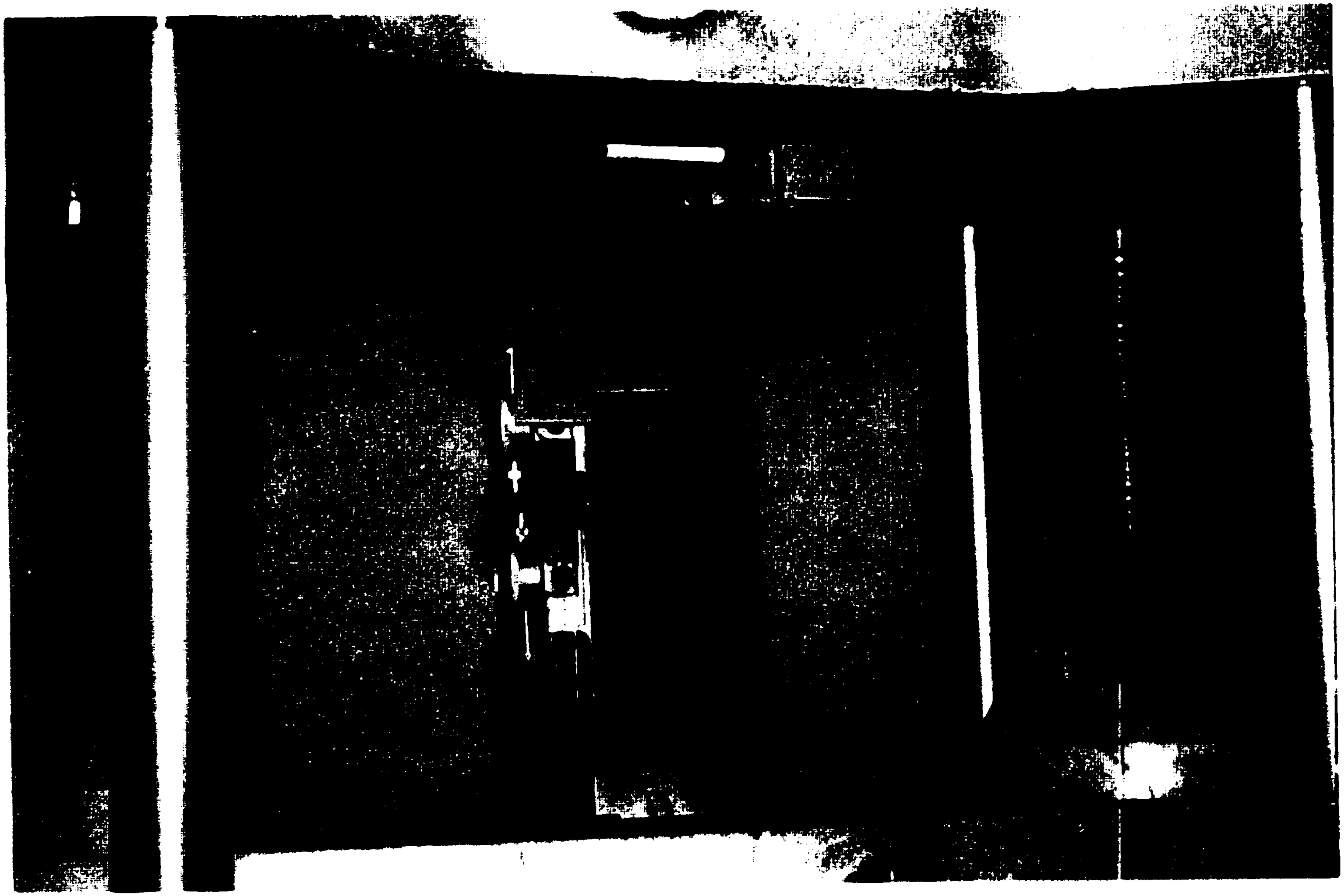
Typical Load-Displacement Curves

Figure 3

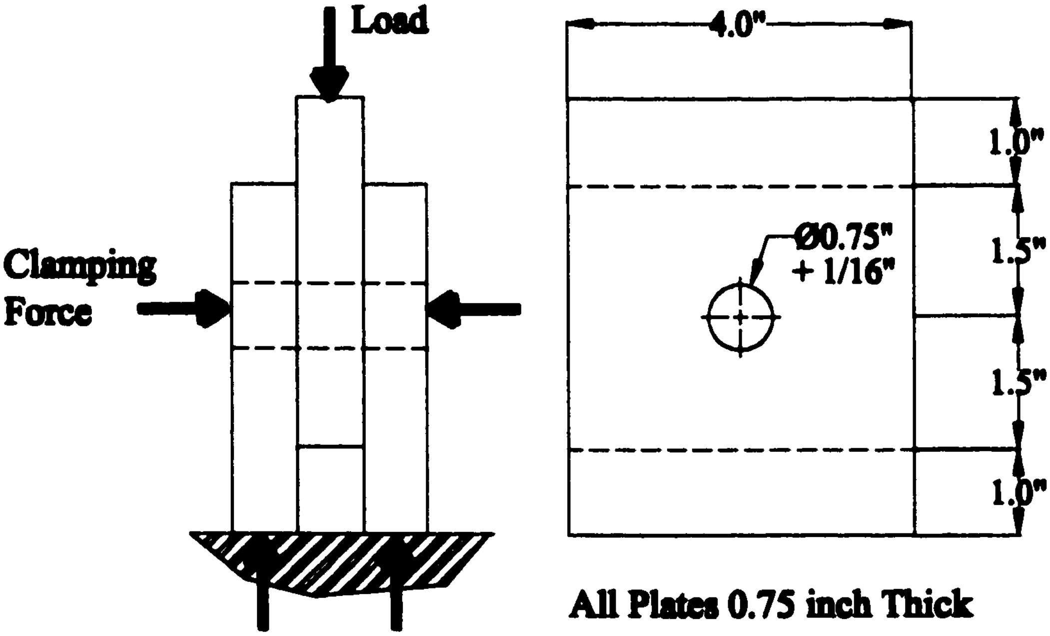


Center Plates 0.75" Thick
Lap Plates 0.375" Thick

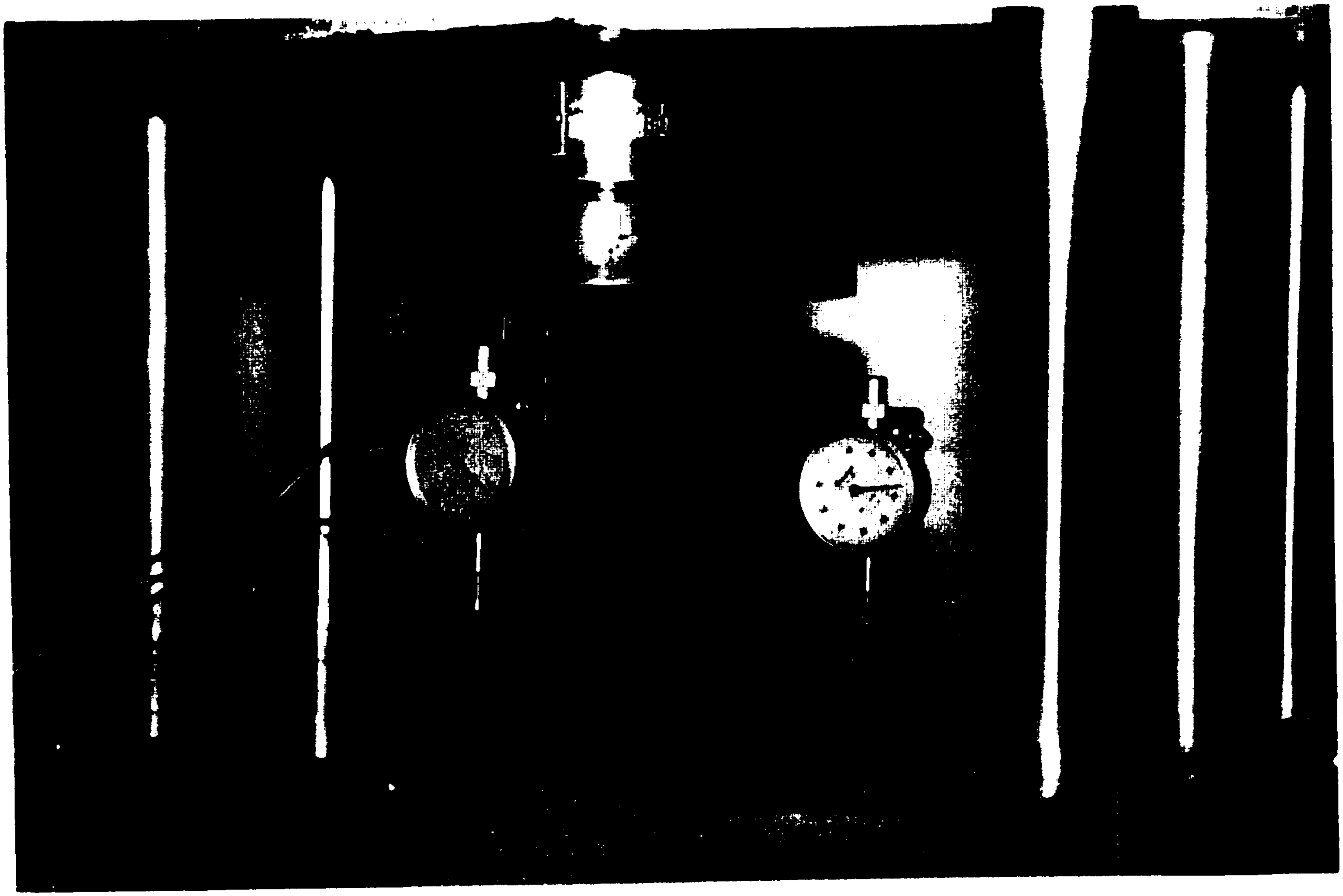
Schematic of Tension Test Specimen
Figure 4



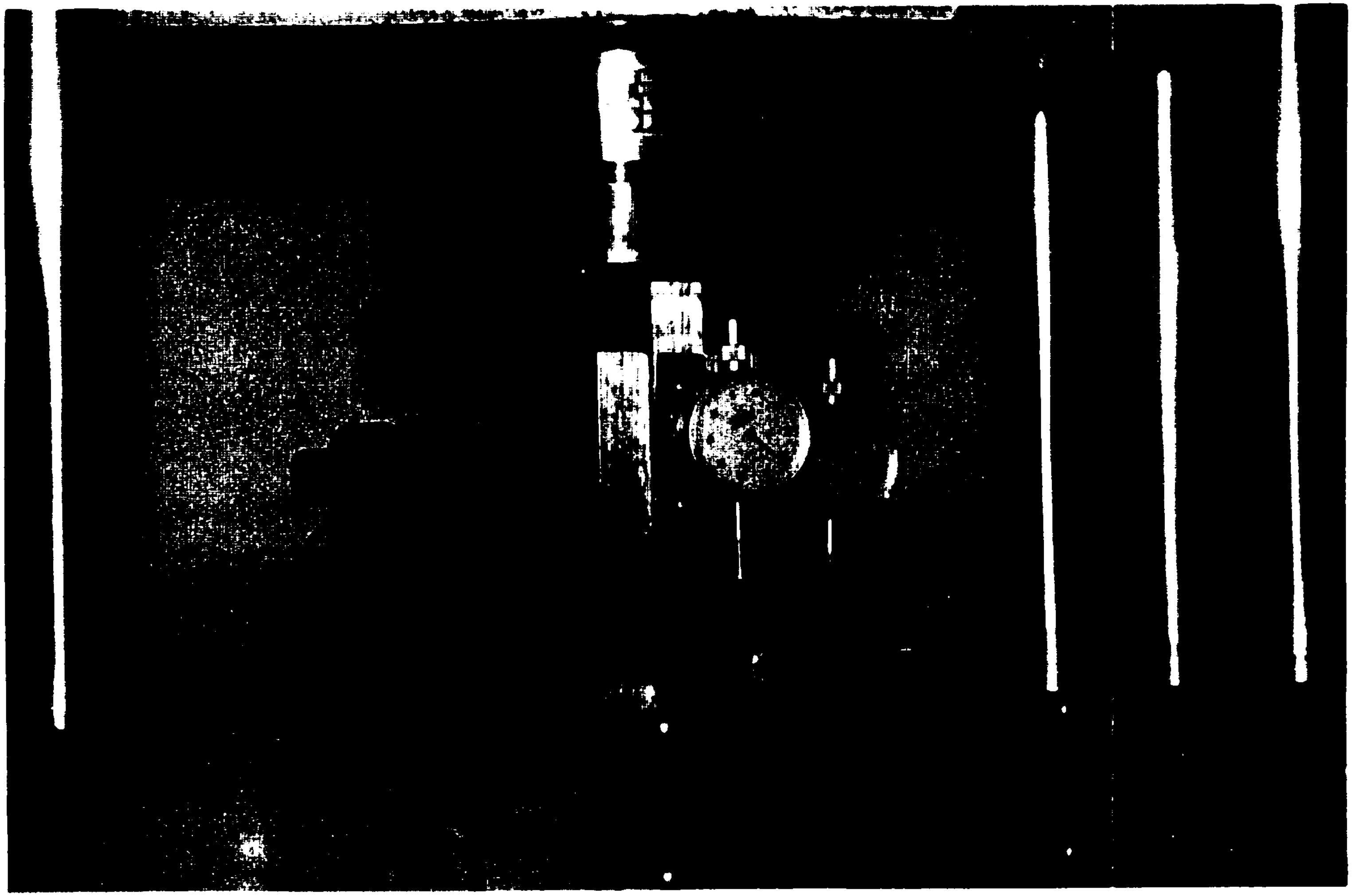
Determination of Slip Coefficient - Tension Test Specimen
Figure 5



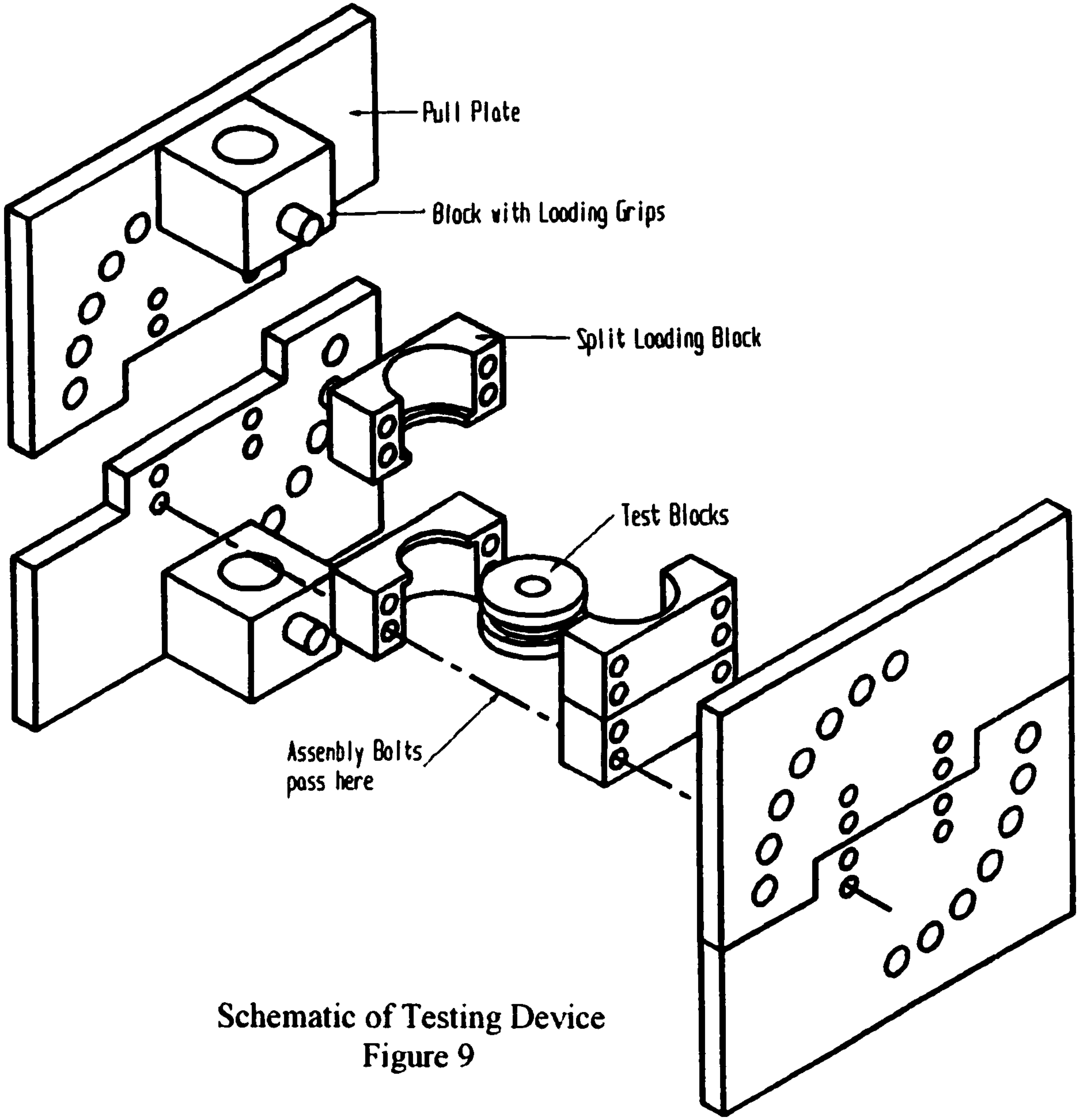
Schematic of Compression Test Specimen
Figure 6



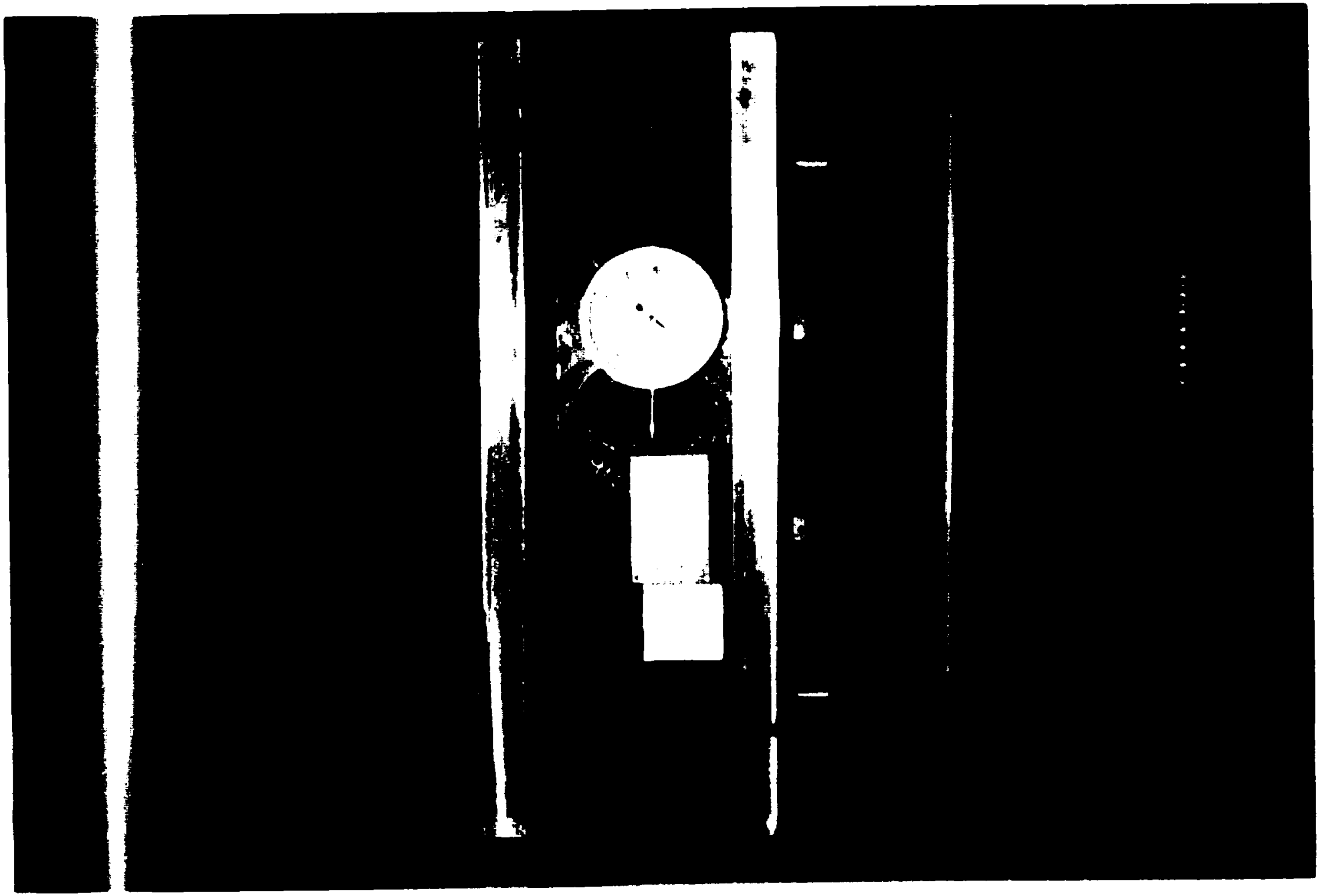
Determination of Slip Coefficient - Compression Test Specimen
Figure 7



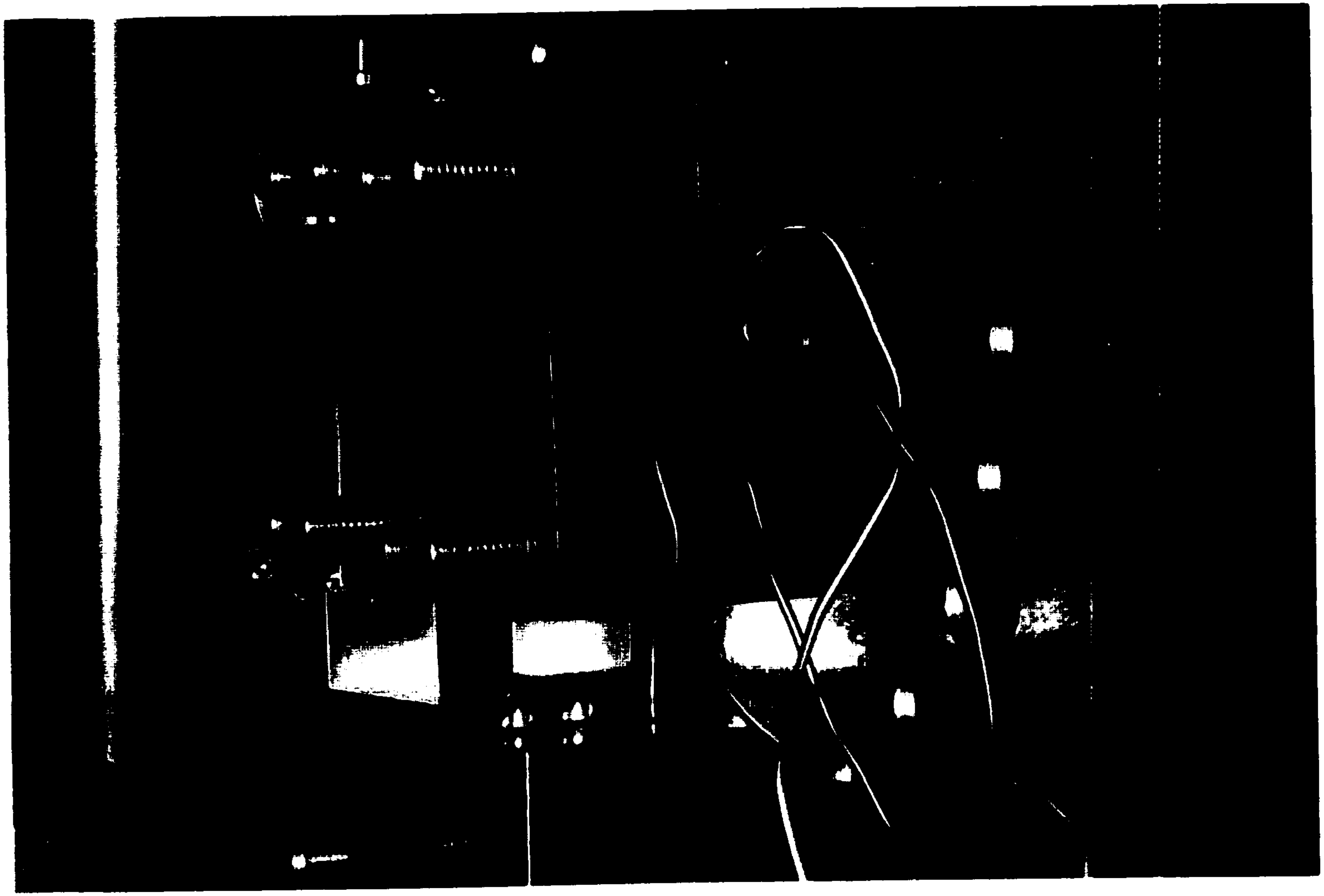
Determination of Slip Coefficient - Compression Test Specimen; View from Other Side
Figure 8



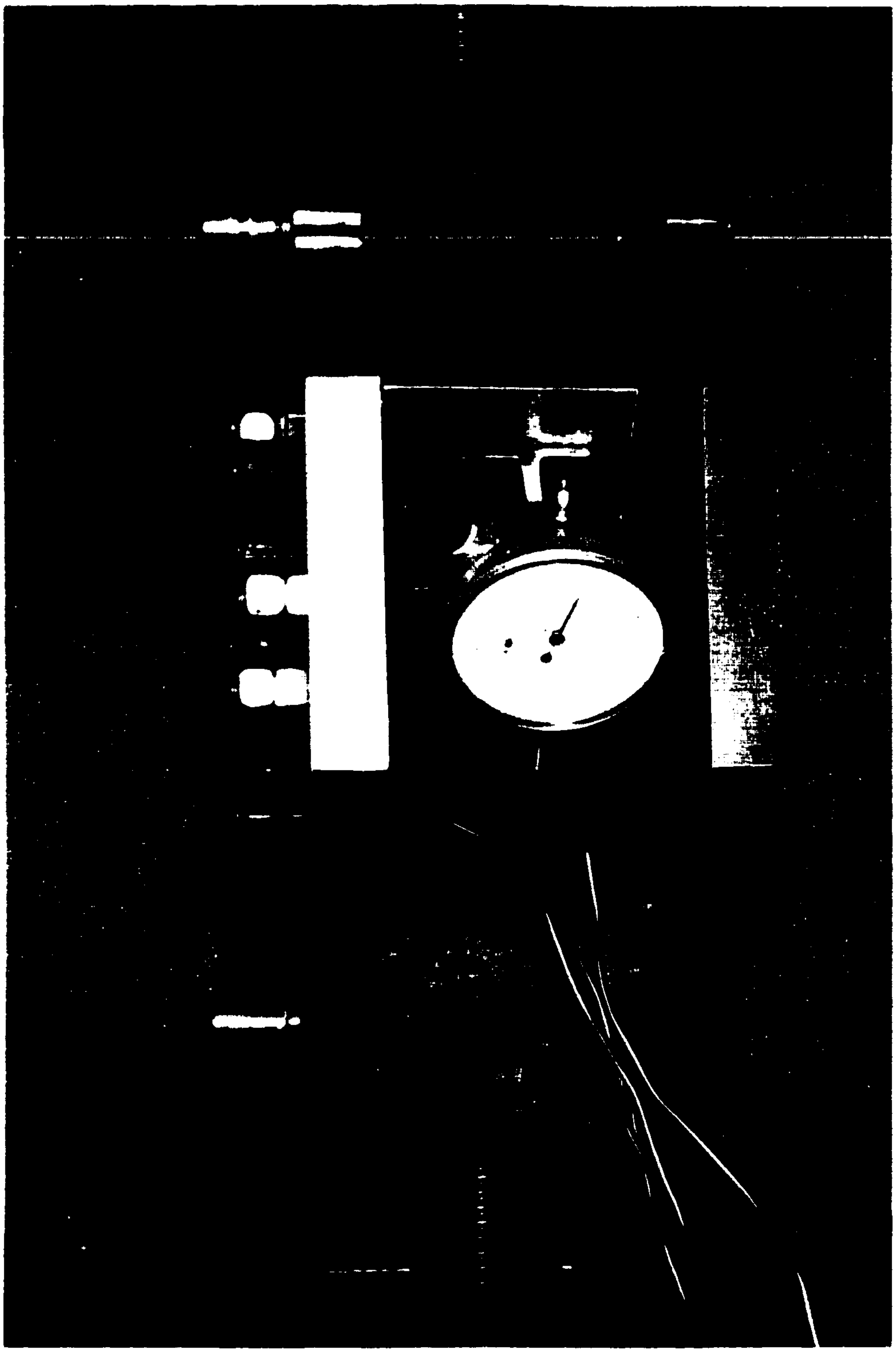
Schematic of Testing Device
Figure 9



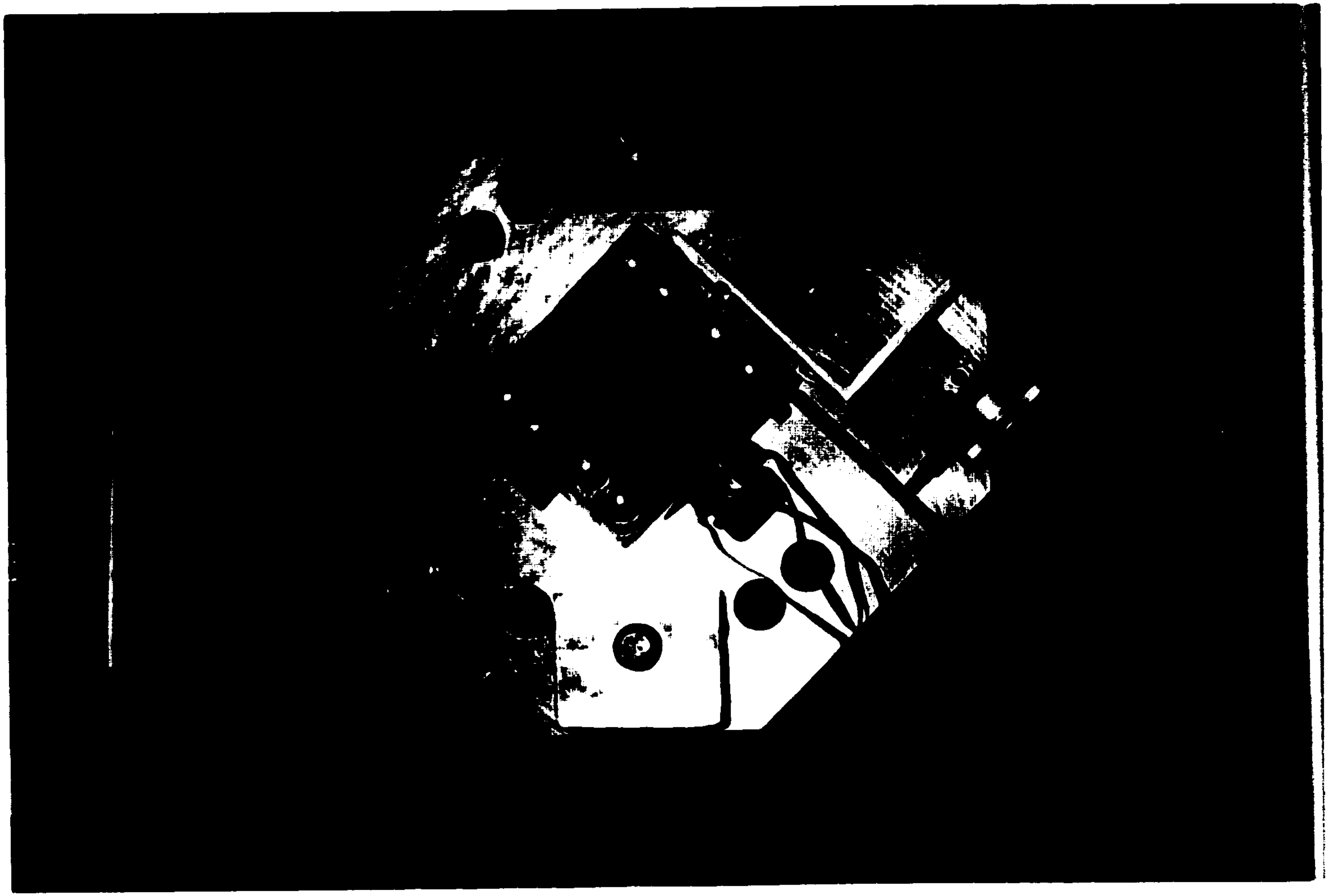
Testing Device - Location of Dial Gauge and Platform for Settings 1 and 2
Figure 10



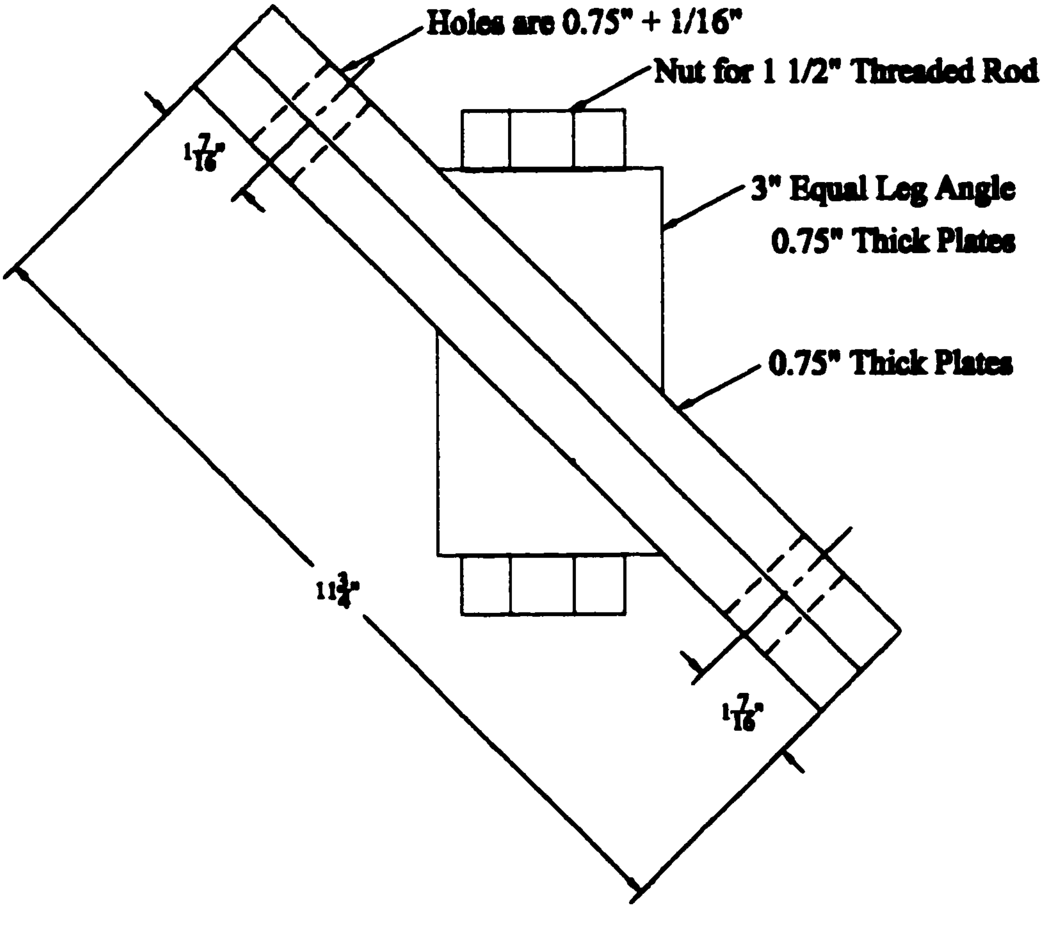
Testing Device - Dial Gauge and Platform Mounted on Split Loading Blocks for Settings 1 and 2
Figure 11



Testing Device - Location of Dial Gauge and Platform for Settings 3 through 6
Figure 12

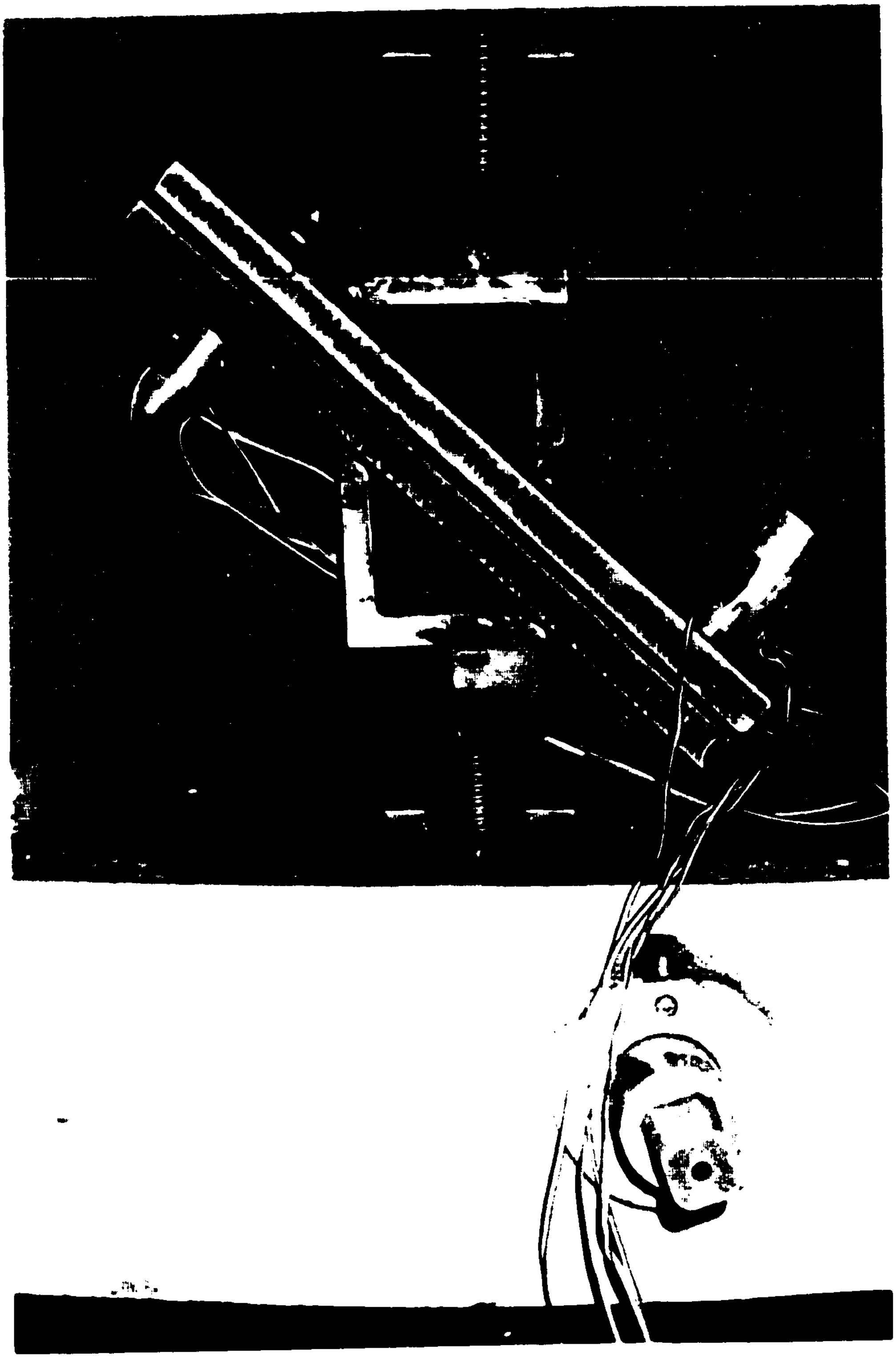


Testing Device - Dial Gauge and Platform Mounted on Split Loading Blocks for Settings 3 through 6
Figure 13

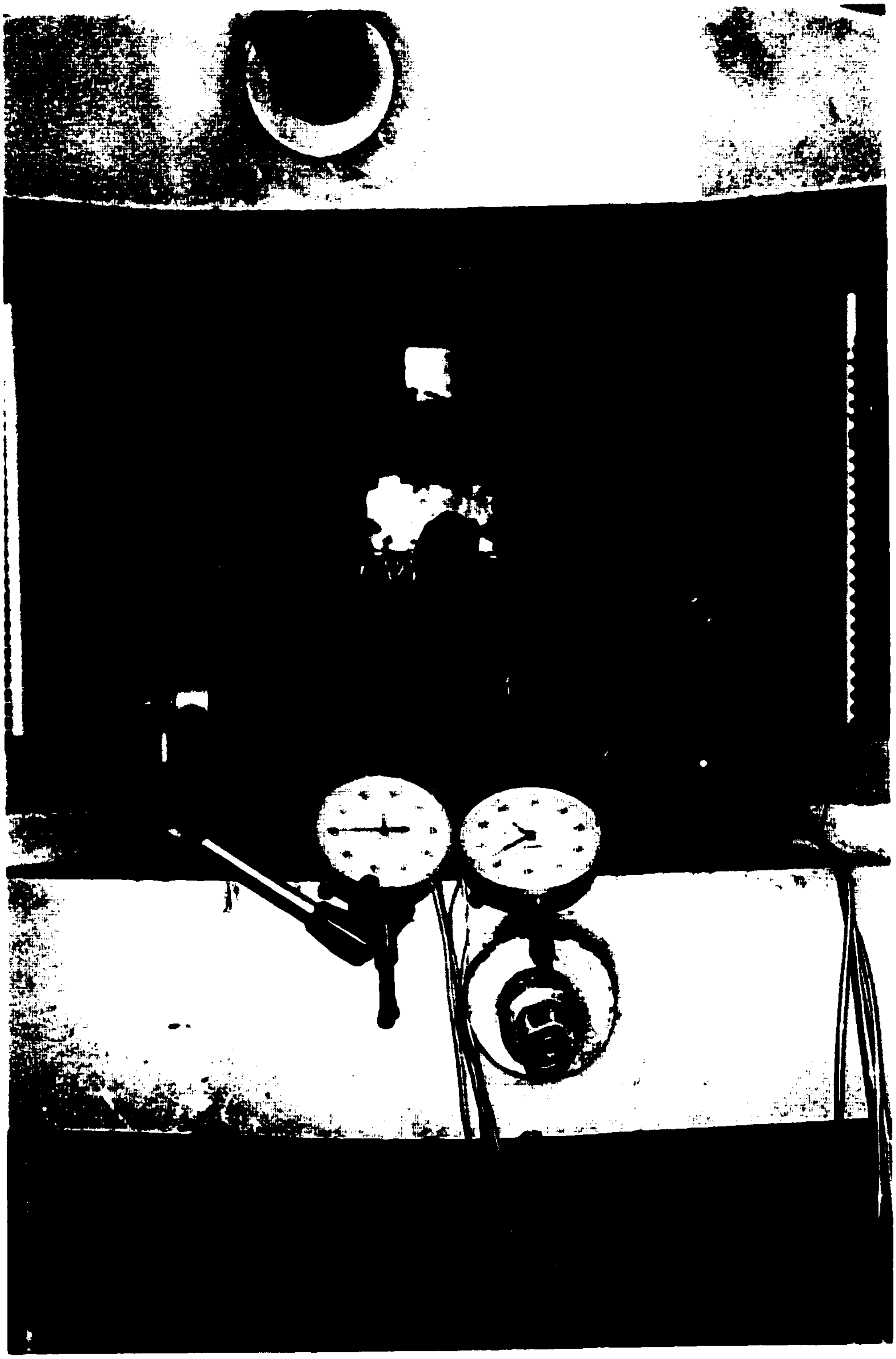


Schematic of Slip-Critical Connection

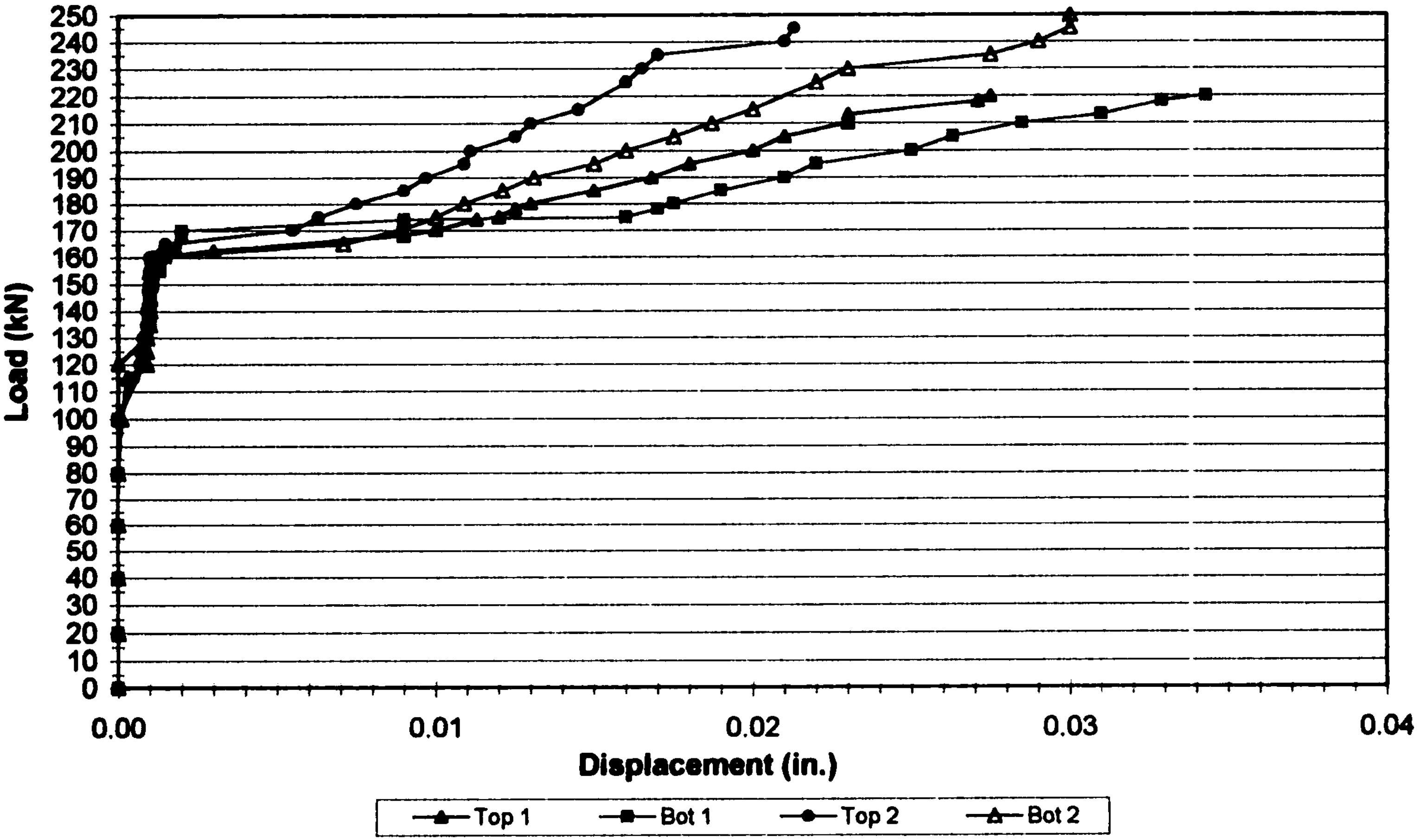
Figure 14



Slip-Critical Connection
Figure 15

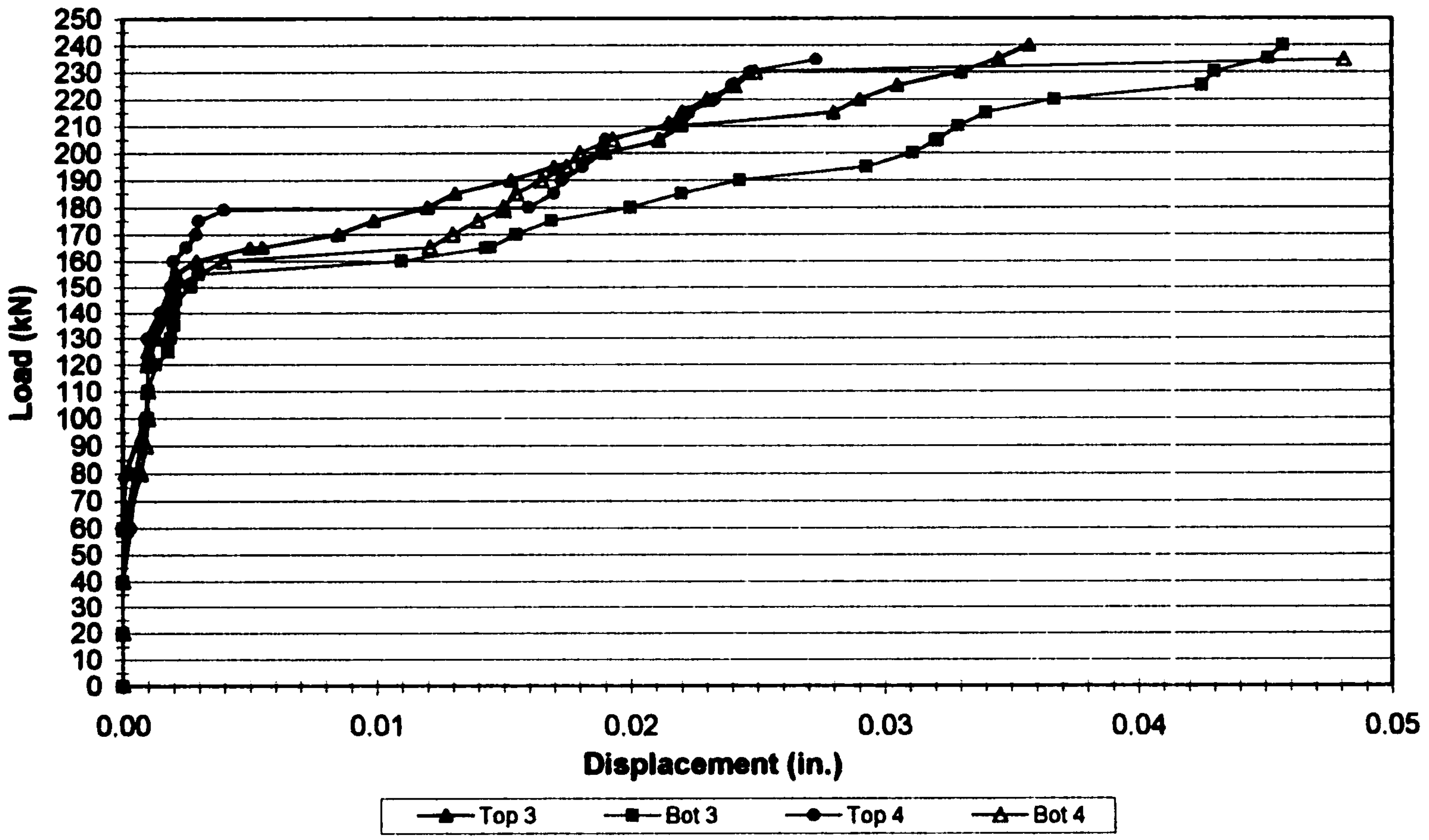


Slip-Critical Connection – Location of Dial Gauges
Figure 16



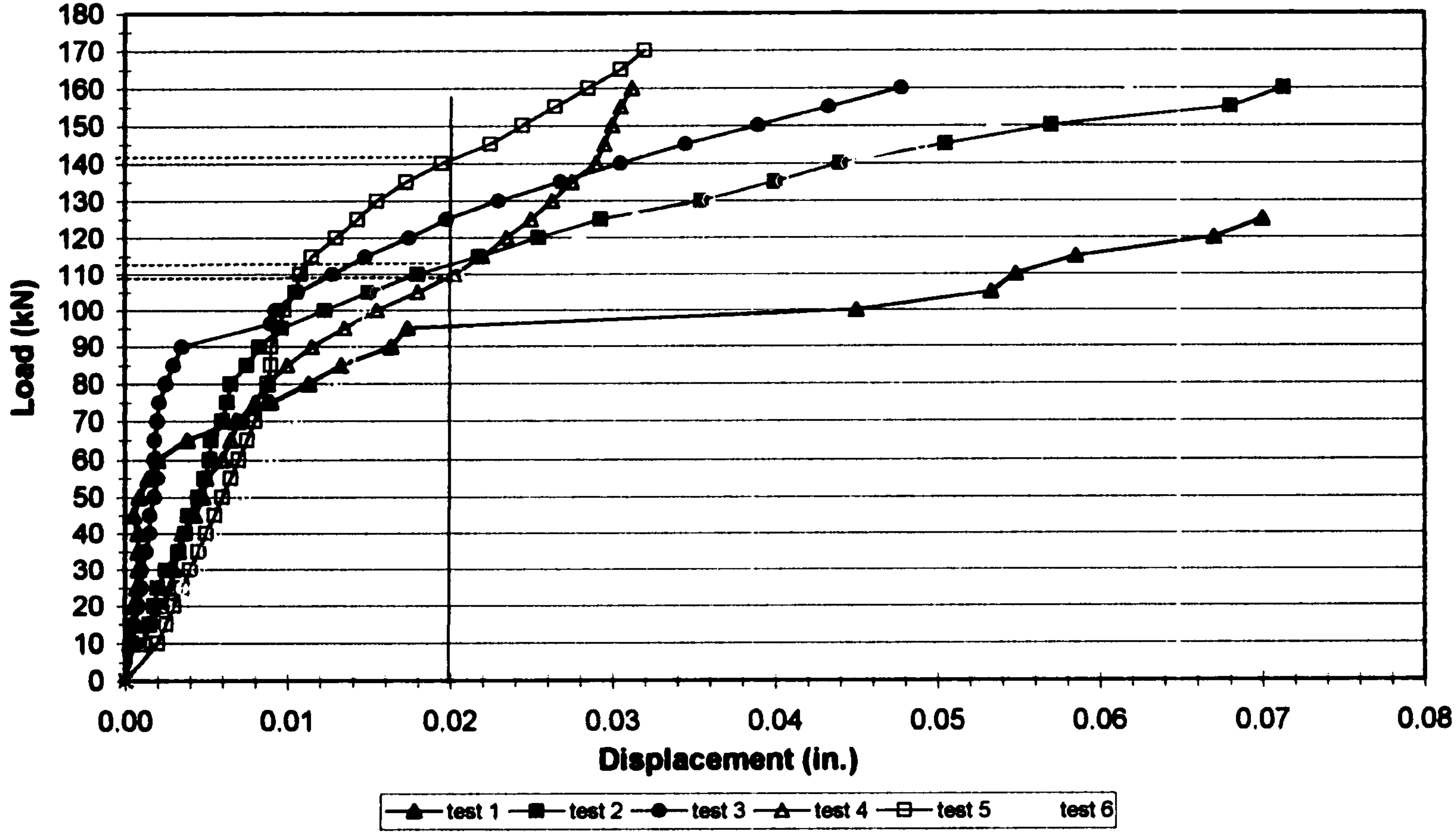
Tension Test Specimens 1 and 2
Load-Displacement Curves

Figure 17



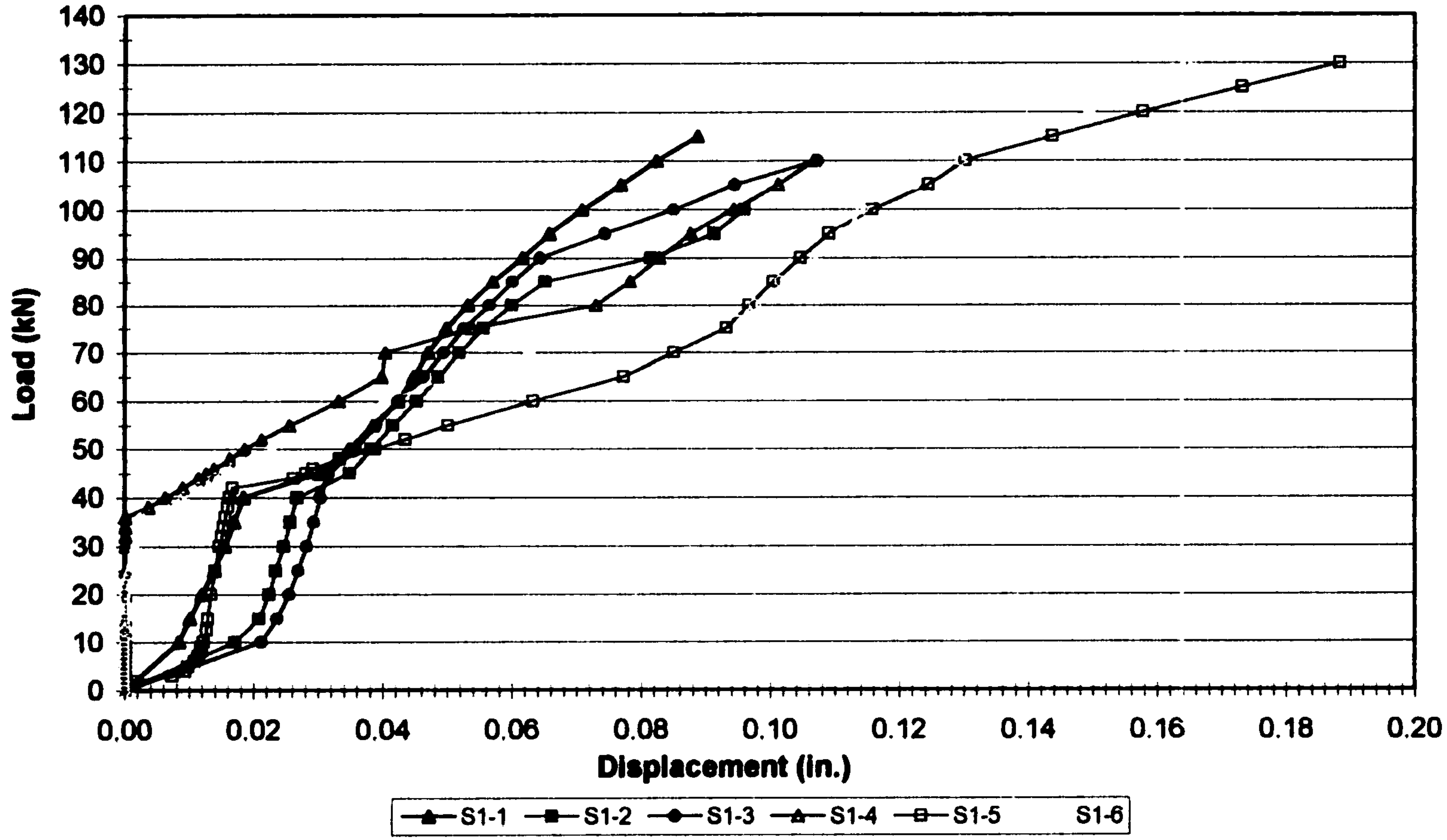
Tension Test Specimens 3 and 4
Load-Displacement Curves

Figure 18



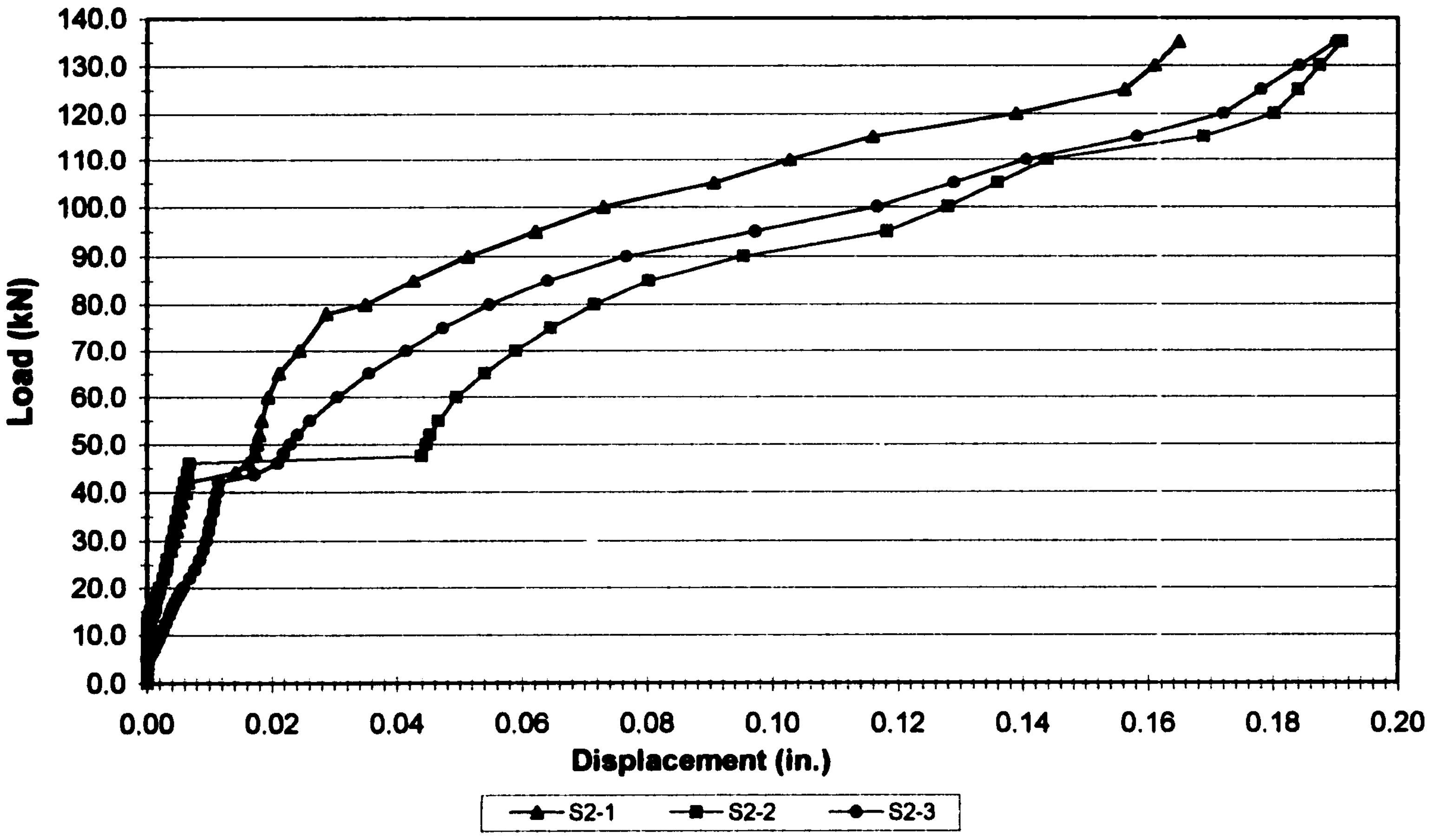
Compression Test Specimens
Load-Displacement Curves

Figure 19



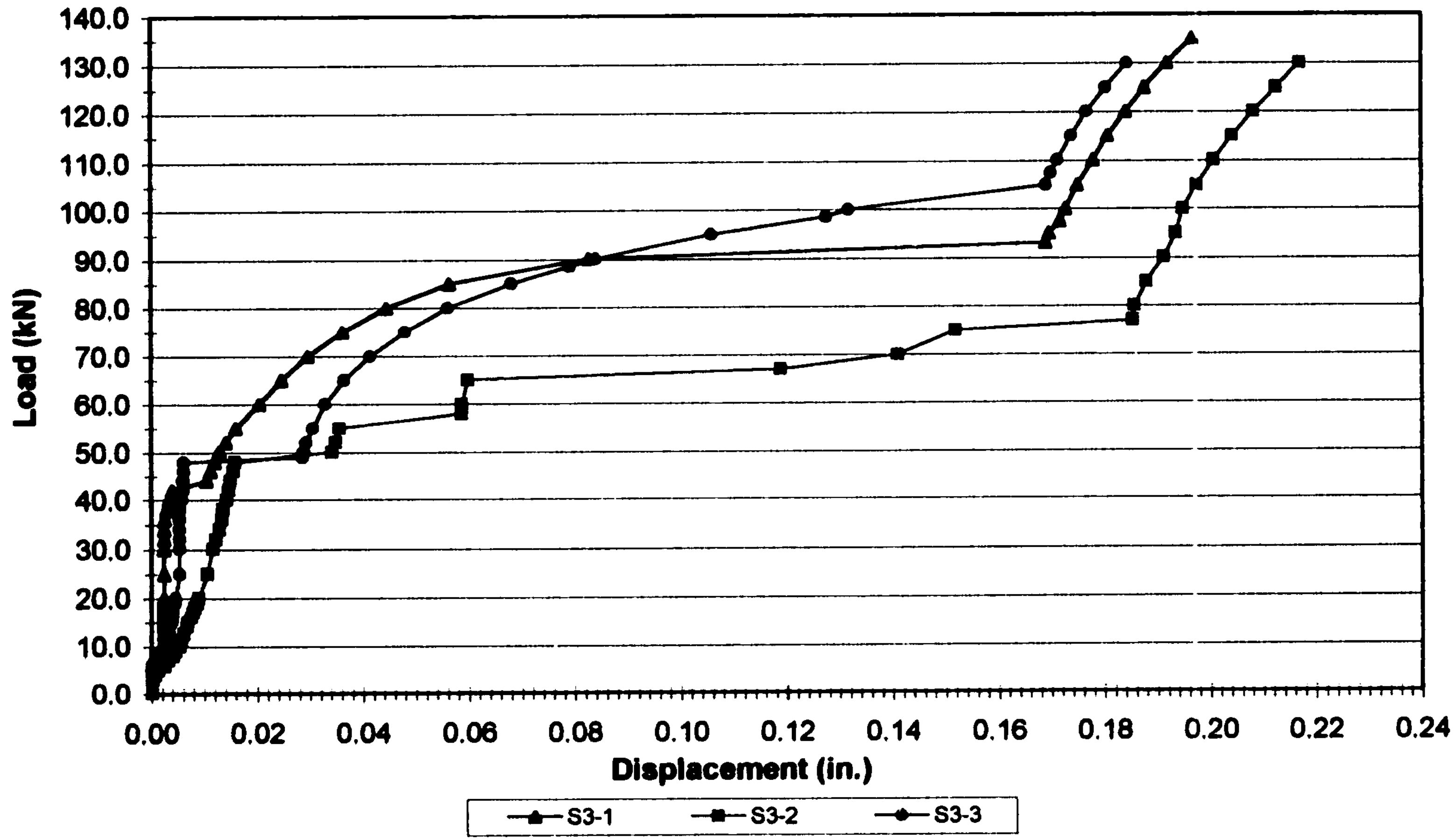
Setting 1 (Pure Shear)
Load-Displacement Curves

Figure 20



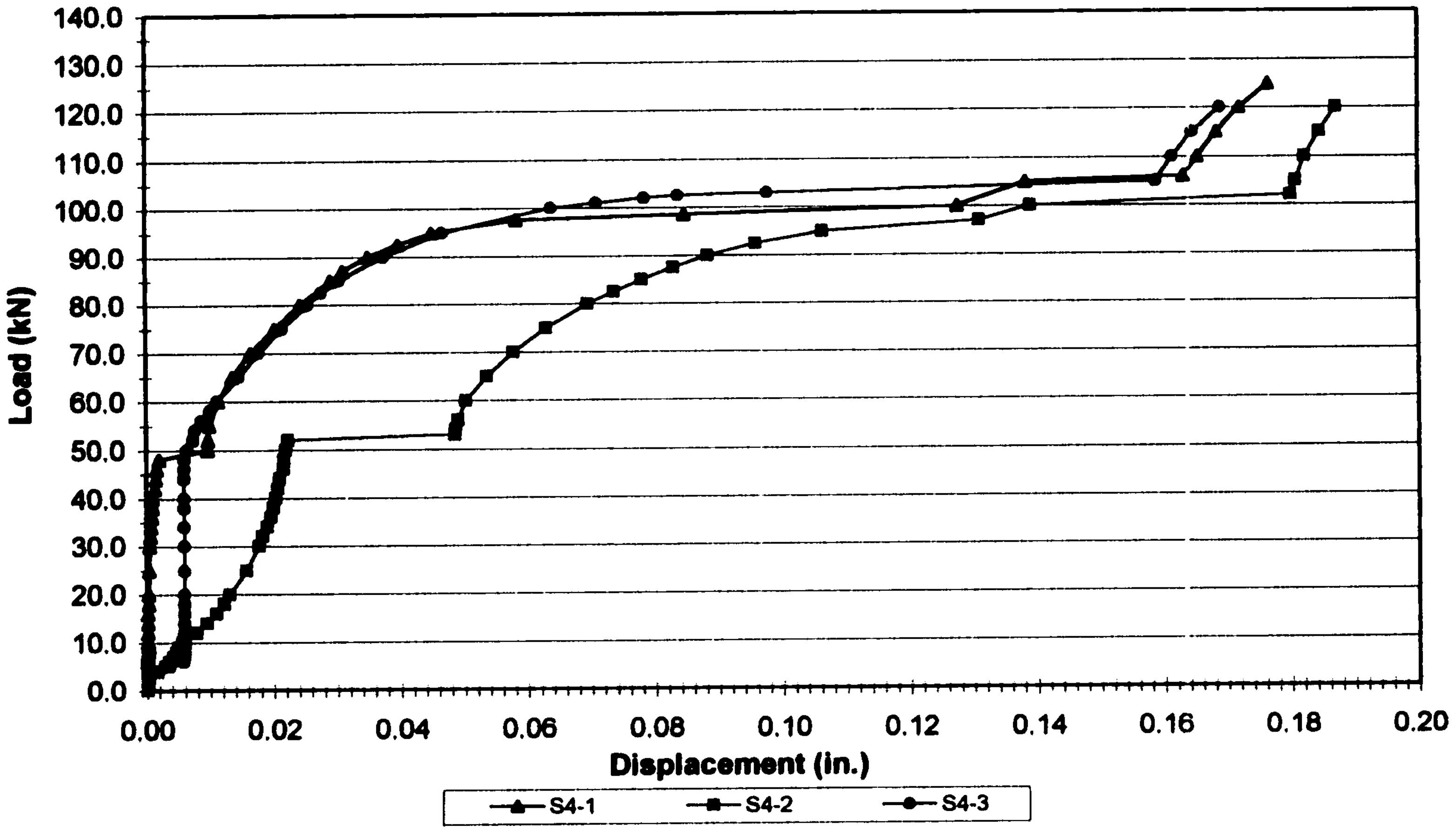
Setting 2 (15 Degrees From Pure Shear)
Load-Displacement Curves

Figure 21



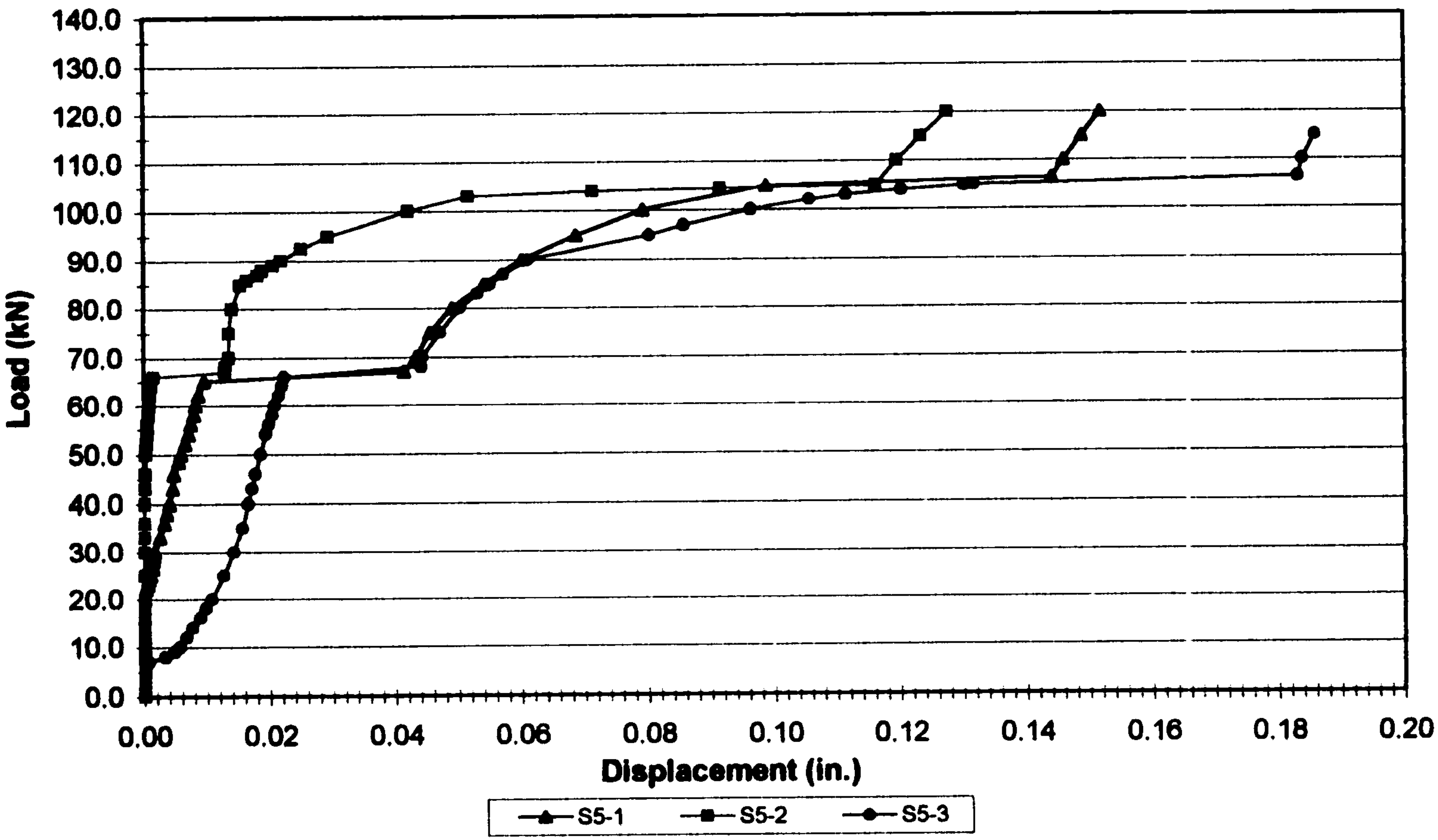
Setting 3 (30 Degree From Pure Shear)
Load-Displacement Curves

Figure 22



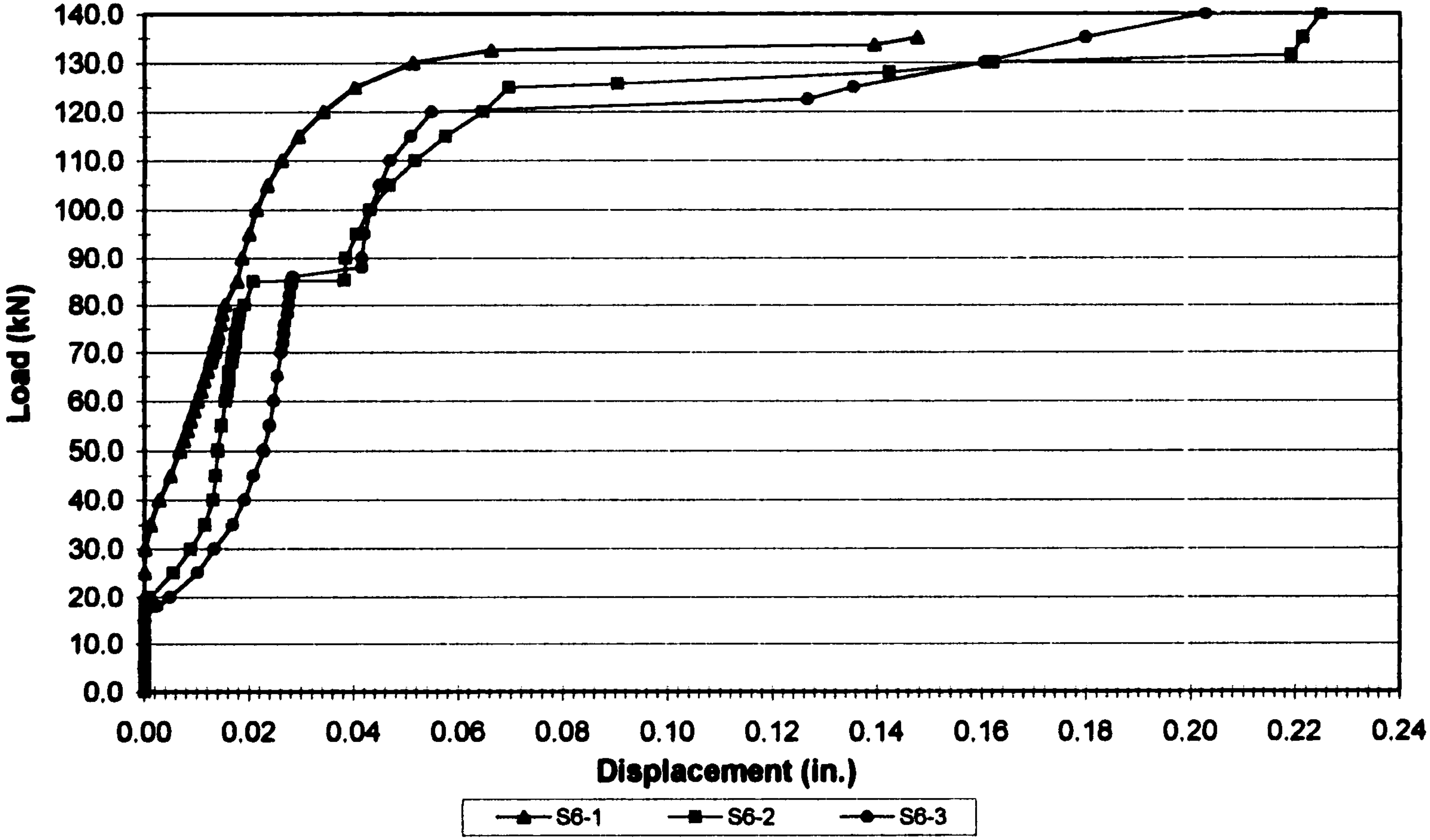
Setting 4 (45 Degree From Pure Shear)
Load-Displacement Curve

Figure 23



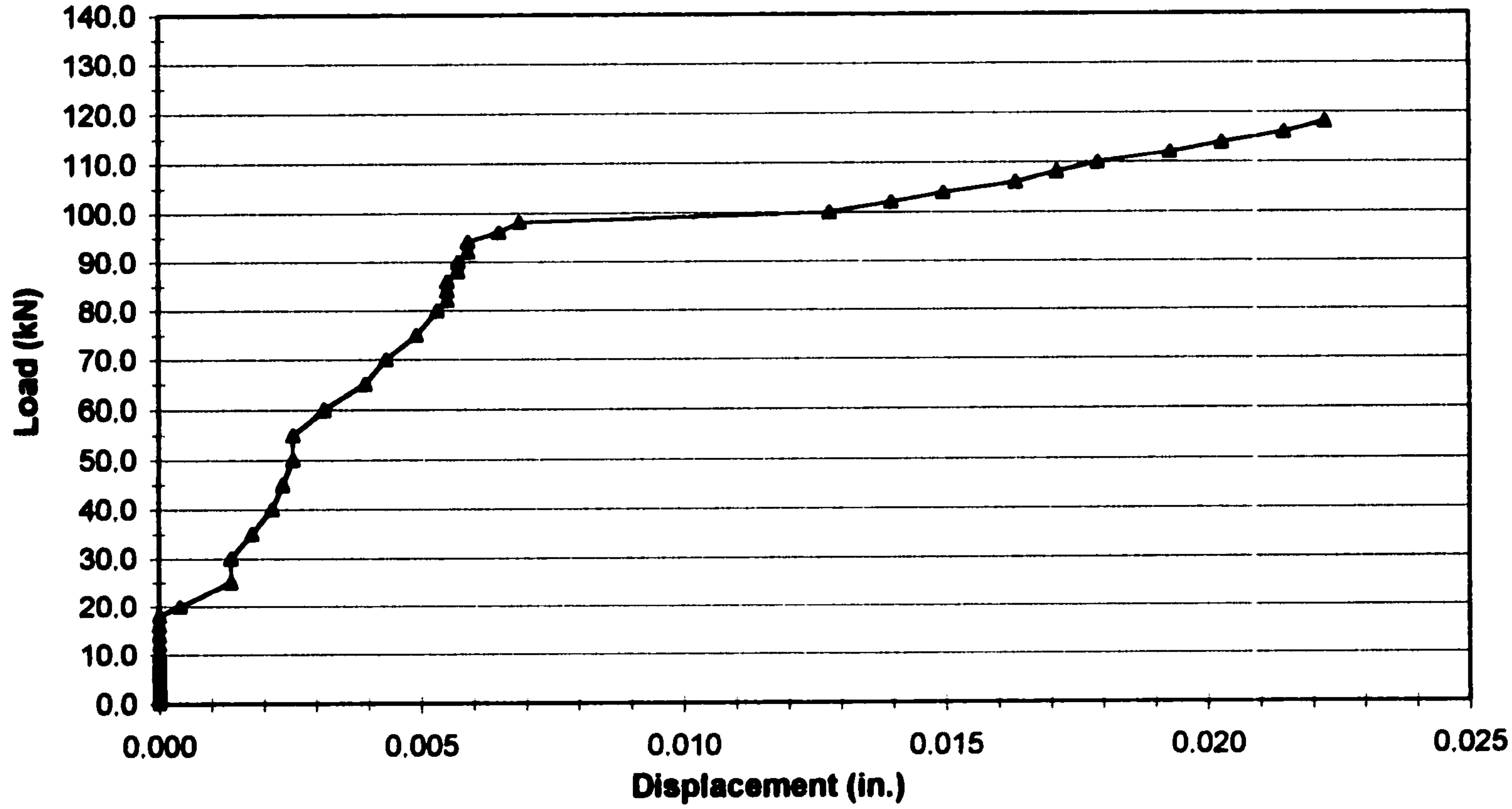
Setting 5 (60 Degrees From Pure Shear)
Load-Displacement Curves

Figure 24



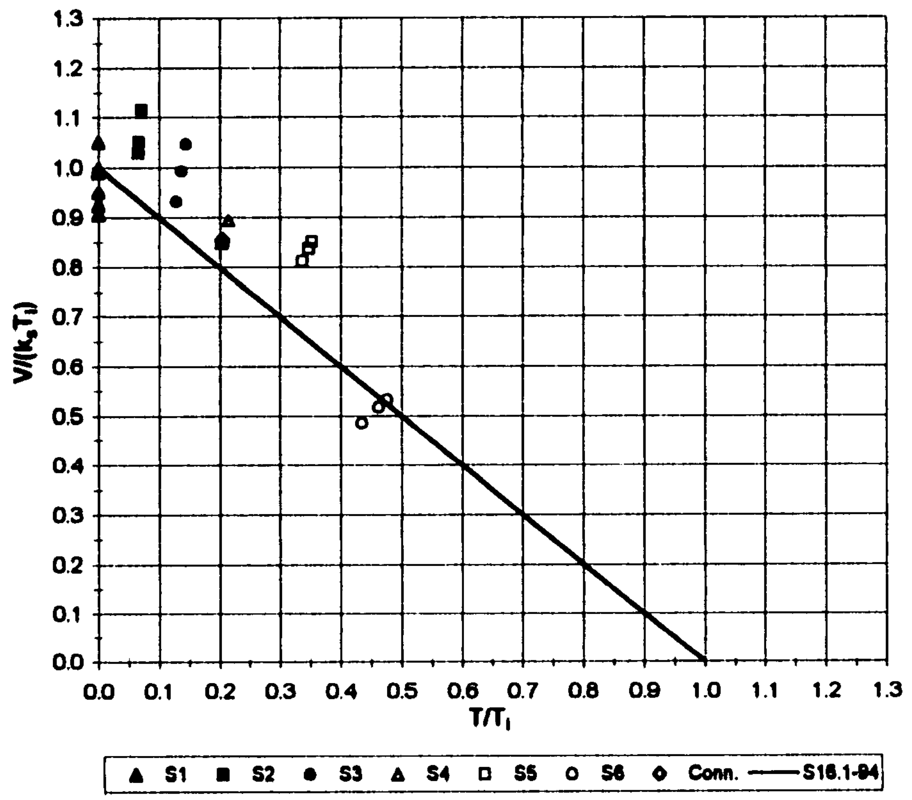
Setting 6 (75 Degrees From Pure Shear)
Load-Displacement Curves

Figure 25



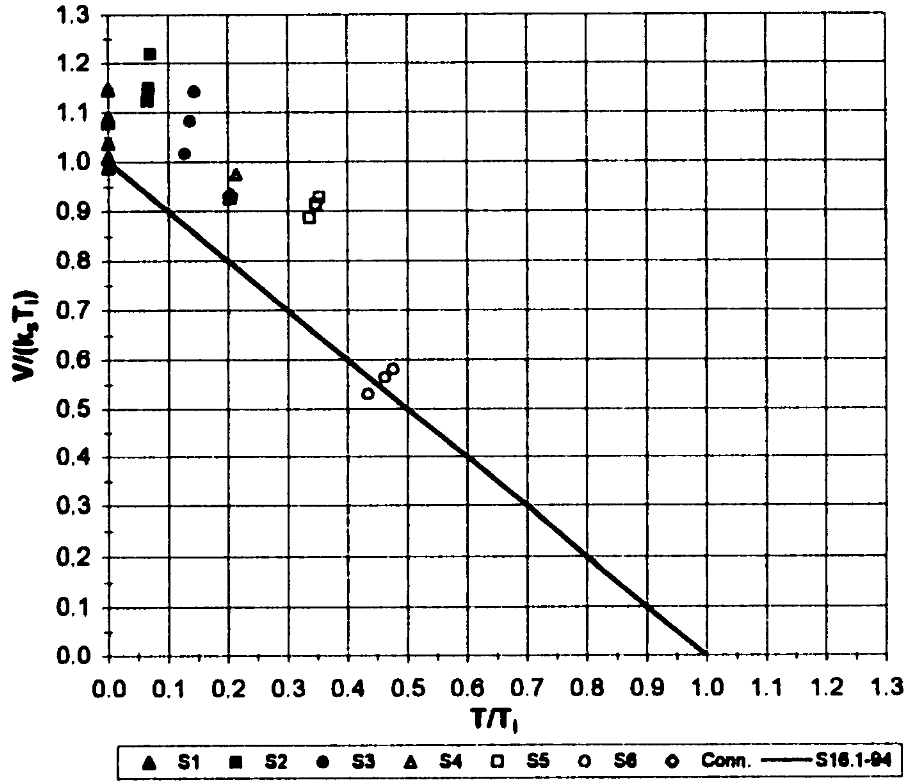
Slip-Critical Connection
Load-Displacement Curve

Figure 26



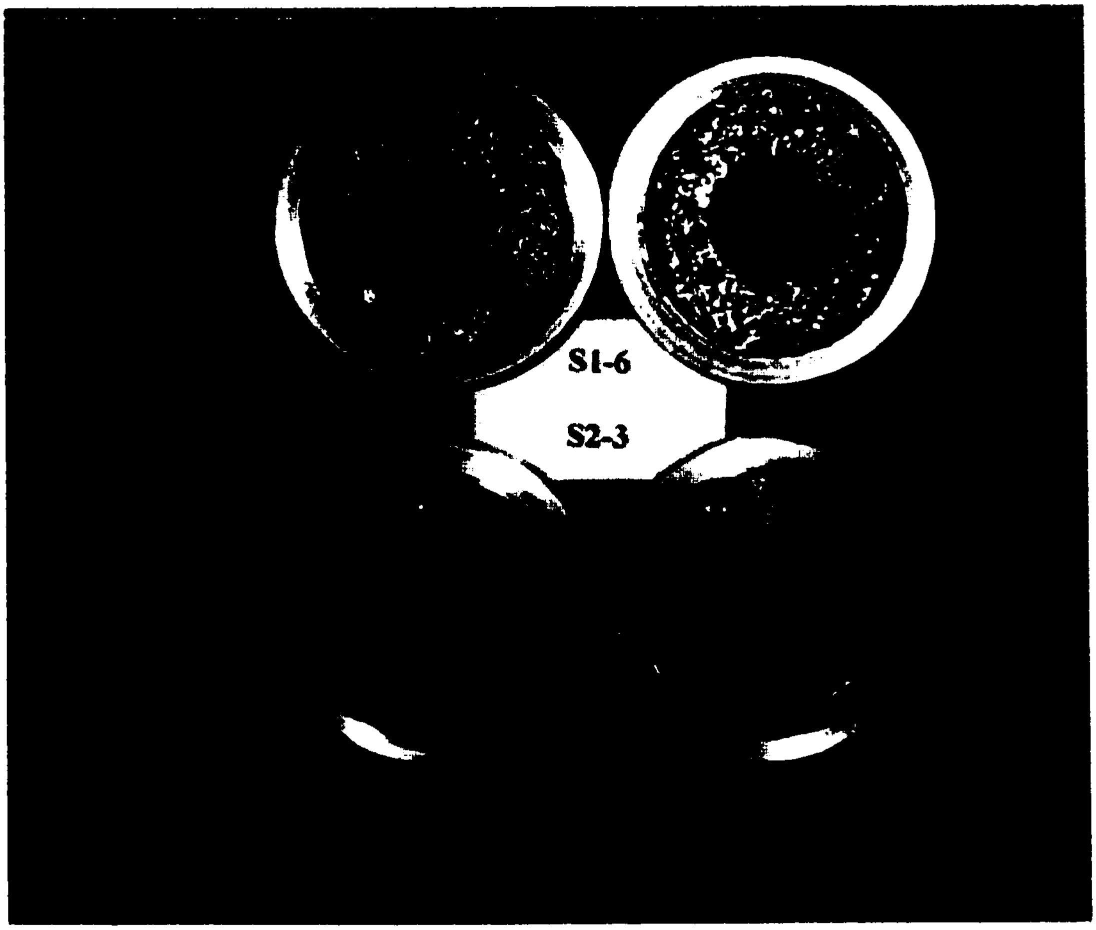
Testing Device Results, Connection Results, and S16.1-94 Interaction Equation Using $k_s = 0.24$
Graphical Representation of Interaction Equation

Figure 27

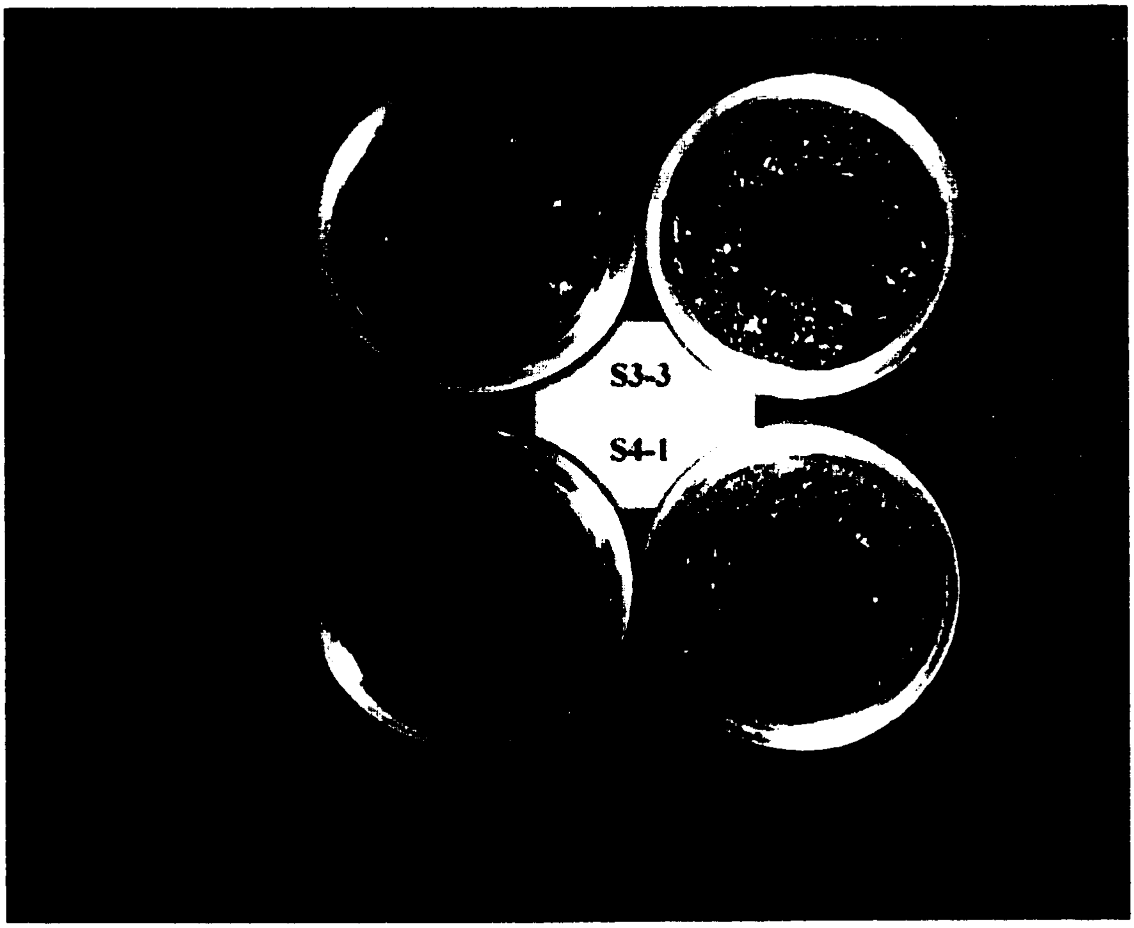


Testing Device Results, Connection Results, and S16.1-94 Interaction Equation Using $k_s = 0.22$
Graphical Representation of Interaction Equation

Figure 28



Surface Damage of Specimens S1-6 and S2-3
Figure 29



Surface Damage of Specimens S3-3 and S4-1
Figure 30

Surface Damage of Specimens S5-1 and S6-3
Figure 31

Appendix B

TABLES

Table 1

TESTING DEVICE SETTING NOMENCLATURE

Setting	Load Combination	Angle from Horizontal	Shear-Tension Ratio	Test Number
S1-1	1	0^o	1.00 to 0.00	1
S1-2	1	0^o	1.00 to 0.00	2
S1-3	1	0^o	1.00 to 0.00	3
S1-4	1	0^o	1.00 to 0.00	4
S1-5	1	0^o	1.00 to 0.00	5
S1-6	1	0^o	1.00 to 0.00	6
S2-1	2	15^o	1.00 to 0.27	1
S2-2	2	15^o	1.00 to 0.27	2
S2-3	2	15^o	1.00 to 0.27	3
S3-1	3	30^o	1.00 to 0.58	1
S3-2	3	30^o	1.00 to 0.58	2
S3-3	3	30^o	1.00 to 0.58	3
S4-1	4	45^o	1.00 to 1.00	1
S4-2	4	45^o	1.00 to 1.00	2
S4-3	4	45^o	1.00 to 1.00	3
S5-1	5	60^o	0.58 to 1.00	1
S5-2	5	60^o	0.58 to 1.00	2
S5-3	5	60^o	0.58 to 1.00	3
S6-1	6	75^o	0.27 to 1.00	1
S6-2	6	75^o	0.27 to 1.00	2
S6-3	6	75^o	0.27 to 1.00	3

Table 2

APPROXIMATE PRELOAD DATA

Bolt Number	Snug (kN)	1/3 Turn Past Snug (kN)	1/3 Turn Past Snug Minus 30° (kN)	1/3 Turn Past Snug Plus 30° (kN)
1	29.8	184.0		
2	34.8	178.8		
3	41.9	185.1		
4	41.2	197.7		
5	37.9	193.0		
6	39.1	194.4		
7	40.0	184.1		
8	39.4	178.8	161.8	183.0
9	42.1	185.0	169.5	189.2
10	42.8	188.7	166.5	194.6
Average Bolt Preload at 1/3 Turn Past Snug				**187.0 kN**

Table 3
Tension Specimens

DETERMINATION OF THE SLIP COEFFICIENT

Specimen		Slip Load (kN)	Bolt Preload (kN)	Slip Coefficient k_s
1	Top	162.6	187.0	0.22
	Bottom	174.0	187.0	0.23
2	Top	165.0	187.0	0.22
	Bottom	160.0	187.0	0.21
3	Top	160.0	187.0	0.21
	Bottom	159.3	187.0	0.21
4	Top	179.0	187.0	0.24
	Bottom	160.0	187.0	0.21
		Average Slip Coefficient		**0.22**

Table 4
Tension Specimen 1

LOAD-DISPLACEMENT DATA

Load (kN)	Displacement Top (in.)	Displacement Bottom (in.)	Comments
0.0	0.0000	0.0000	
20.0	0.0000	0.0000	
40.0	0.0000	0.0000	
60.0	0.0000	0.0000	
80.0	0.0000	0.0000	
100.0	0.0000	0.0000	
120.0	0.0000	0.0008	
130.0	0.0009	0.0009	
135.0	0.0010	0.0010	
140.0	0.0010	0.0010	
145.0	0.0010	0.0010	
150.0	0.0010	0.0011	
155.0	0.0010	0.0013	
160.0	0.0013	0.0015	
162.6	0.0030	0.0018	Load drop
168.0	0.0090	0.0020	
170.0	0.0100	0.0020	
174.0	0.0113	0.0090	Load drop
175.0	0.0120	0.0160	
178.0	0.0125	0.0170	
180.0	0.0130	0.0175	
185.0	0.0150	0.0190	
190.0	0.0168	0.0210	
195.0	0.0180	0.0220	
200.0	0.0200	0.0250	
205.0	0.0210	0.0263	
210.0	0.0230	0.0285	
213.0	0.0230	0.0310	Load drop
218.0	0.0271	0.0329	Load drop
220.0	0.0275	0.0343	

Slip Load for Top: 162.6 kN
Slip Load for Bottom: 174.0 kN

Table 5
Tension Specimen 2

LOAD-DISPLACEMENT DATA

Load (kN)	Displacement Top (in.)	Displacement Bottom (in.)	Comments
0.0	0.0000	0.0000	
20.0	0.0000	0.0000	
40.0	0.0000	0.0000	
60.0	0.0000	0.0000	
80.0	0.0000	0.0000	
100.0	0.0000	0.0001	
115.0	0.0005	0.0003	
120.0	0.0007	0.0009	
125.0	0.0007	0.0009	
130.0	0.0008	0.0009	
135.0	0.0009	0.0010	
140.0	0.0009	0.0010	
145.0	0.0010	0.0010	
150.0	0.0010	0.0010	
155.0	0.0010	0.0010	Load drop
160.0	0.0010	0.0011	Load drop
165.0	0.0015	0.0071	Load drop
170.0	0.0055	0.0089	
175.0	0.0063	0.0100	
180.0	0.0075	0.0109	
185.0	0.0090	0.0121	
190.0	0.0097	0.0131	
195.0	0.0109	0.0150	
200.0	0.0111	0.0160	
205.0	0.0125	0.0175	
210.0	0.0130	0.0187	
215.0	0.0145	0.0200	Load drop at 219.0 kN
225.0	0.0160	0.0220	
230.0	0.0165	0.0230	
235.0	0.0170	0.0275	Noise at 236.0 kN
240.0	0.0210	0.0290	
245.0	0.0213	0.0300	
250.0	N/A	0.0300	

Slip Load for Top: 165.0 kN
Slip Load for Bottom: 160.0 kN

Table 6
Tension Specimen 3

LOAD-DISPLACEMENT DATA

Load (kN)	Displacement Top (in.)	Displacement Bottom (in.)	Comments
0.0	0.0000	0.0000	
20.0	0.0000	0.0000	
40.0	0.0000	0.0000	
60.0	0.0000	0.0000	
80.0	0.0001	0.0005	
100.0	0.0009	0.0010	
110.0	0.0010	0.0010	
120.0	0.0010	0.0013	
125.0	0.0010	0.0018	
130.0	0.0011	0.0019	
135.0	0.0013	0.0020	Load drop
140.0	0.0017	0.0020	
145.0	0.0019	0.0021	
150.0	0.0020	0.0027	
155.0	0.0021	0.0030	Load drop at 159.3 kN
160.0	0.0029	0.0110	
164.9	0.0050	0.0143	
165.0	0.0055	0.0145	
170.0	0.0085	0.0155	
175.0	0.0099	0.0169	Load drop & noise
180.0	0.0120	0.0200	
185.0	0.0131	0.0220	
190.0	0.0153	0.0243	Load drop at 194.0 kN
195.0	0.0170	0.0293	
200.0	0.0190	0.0311	
204.4	0.0211	0.0320	
205.0	0.0211	0.0321	
210.0	0.0220	0.0329	
215.0	0.0280	0.0340	
220.0	0.0290	0.0367	
225.0	0.0305	0.0425	Load drop
230.0	0.0330	0.0430	
235.0	0.0345	0.0451	
240.0	0.0357	0.0457	

Slip Load for Top: 160.0 kN
Slip Load for Bottom: 159.3 kN

Table 7
Tension Specimen 4

LOAD-DISPLACEMENT DATA

Load (kN)	Displacement Top (in.)	Displacement Bottom (in.)	Comments
0.0	0.0000	0.0000	
20.0	0.0000	0.0000	
40.0	0.0000	0.0000	
60.0	0.0003	0.0001	
80.0	0.0005	0.0007	
90.0	0.0007	0.0009	
100.0	0.0009	0.0010	
110.0	0.0010	0.0010	
120.0	0.0010	0.0010	
130.0	0.0010	0.0013	
140.0	0.0015	0.0019	
150.0	0.0019	0.0020	
160.0	0.0020	0.0040	Load drop
165.0	0.0025	0.0121	
170.0	0.0029	0.0130	
175.0	0.0030	0.0140	
179.0	0.0040	0.0150	Load drop & noise
180.0	0.0160	0.0150	
185.0	0.0170	0.0155	
190.0	0.0173	0.0165	
195.0	0.0181	0.0175	
200.0	0.0189	0.0180	
205.0	0.0190	0.0193	Load drop
211.0	0.0220	0.0215	
215.0	0.0223	0.0220	
220.0	0.0233	0.0230	
225.0	0.0240	0.0241	Load drop
230.0	0.0247	0.0249	Load drop
234.6	0.0273	0.0481	

Slip Load for Top: 179.0 kN
Slip Load for Bottom: 160.0 kN

Table 8
Compression Specimens

DETERMINATION OF THE SLIP COEFFICIENT

Specimen	Slip Load (kN)	Bolt Preload (kN)	Slip Coefficient k_s
1	95.0	176.6	0.27
2	112.0	186.8	0.30
3	90.0	191.8	0.23
4	109.0	189.9	0.29
5	141.0	188.3	N/A
6	105.0	182.1	0.29
	Average Slip Coefficient		**0.28**

Table 9
Compression Specimen 1

LOAD-DISPLACEMENT DATA

Load (kN)	Avg. Disp. (in.)	Comments
0.0	0.00000	
10.0	0.00025	
15.0	0.00050	
20.0	0.00050	
25.0	0.00070	
30.0	0.00080	
35.0	0.00080	
40.0	0.00080	
45.0	0.00050	
50.0	0.00090	
55.0	0.00140	
60.0	0.00200	
65.0	0.00375	
70.0	0.00675	
75.0	0.00900	
80.0	0.01125	
85.0	0.01325	
90.0	0.01640	
95.0	0.01740	Noise just before 100 kN
100.0	0.04500	
105.0	0.05325	
110.0	0.04975	
115.0	0.05850	
120.0	0.06850	
125.0	0.07000	
		Slip Load: 95.0kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	247	24.6
Fully Tightened	1734	181.1
30.0 kN Applied Load	1700	177.5
60.0 kN Applied Load	1694	176.9
90.0 kN Applied Load	1691	176.6
115.0 kN Applied Load	1668	174.1

Table 10
Compression Specimen 2

LOAD-DISPLACEMENT DATA

Load (kN)	Avg. Disp. (in.)	Comments
0.0	0.00000	
10.0	0.00100	
15.0	0.00150	
20.0	0.00175	
25.0	0.00200	
30.0	0.00250	
35.0	0.00325	
40.0	0.00365	
45.0	0.00390	
50.0	0.00445	
55.0	0.00485	
60.0	0.00520	
65.0	0.00525	
70.0	0.00600	
75.0	0.00625	
80.0	0.00650	
85.0	0.00745	
90.0	0.00825	
95.0	0.00960	
100.0	0.01225	
105.0	0.01500	
110.0	0.01800	
115.0	0.02175	
120.0	0.02550	
125.0	0.02925	
130.0	0.03550	
135.0	0.04000	
140.0	0.04400	
145.0	0.05050	
150.0	0.05700	
155.0	0.06800	
160.0	0.07125	
		Slip Load: 112.0 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	434	44.3
Fully Tightened	1837	192.0
30.0 kN Applied Load	1803	188.4
60.0 kN Applied Load	1801	188.2
90.0 kN Applied Load	1788	186.8
120.0 kN Applied Load	1773	185.3

Table 11
Compression Specimen 3

LOAD-DISPLACEMENT DATA

Load (kN)	Avg. Disp. (in.)	Comments
0.0	0.00000	
10.0	0.00045	
15.0	0.00050	
20.0	0.00075	
25.0	0.00095	
30.0	0.00100	
35.0	0.00125	
40.0	0.00150	
45.0	0.00150	
50.0	0.00175	
55.0	0.00195	
60.0	0.00175	
65.0	0.00175	
70.0	0.00200	
75.0	0.00210	
80.0	0.00245	
85.0	0.00300	
90.0	0.00350	
96.3	0.00900	
100.0	0.00925	
105.0	0.01060	
110.0	0.01275	
115.0	0.01475	
120.0	0.01750	
125.0	0.01975	
130.0	0.02300	
135.0	0.02675	
140.0	0.03050	
145.0	0.03450	
150.0	0.03900	
155.0	0.04325	
160.0	0.04775	
Slip Load: 90.0 kN		

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	394	40.1
Fully Tightened	1875	196.0
30.0 kN Applied Load	1839	192.2
60.0 kN Applied Load	1839	192.2
90.0 kN Applied Load	1835	191.8
120.0 kN Applied Load	1823	190.5

Table 12
Compression Specimen 4

LOAD-DISPLACEMENT DATA

Load (kN)	Avg. Disp. (in.)	Comments
0.0	0.00000	
10.0	0.00100	
15.0	0.00150	
20.0	0.00225	
25.0	0.00275	
30.0	0.00300	
35.0	0.00325	
40.0	0.00350	
45.0	0.00425	
50.0	0.00475	
55.0	0.00500	
60.0	0.00600	
65.0	0.00650	
70.0	0.00700	
75.0	0.00795	
80.0	0.00875	
85.0	0.01000	
90.0	0.01150	
95.0	0.01350	
100.0	0.01550	
105.0	0.01800	
110.0	0.02025	
115.0	0.02200	
120.0	0.02350	
125.0	0.02500	
130.0	0.02625	
135.0	0.02750	
140.0	0.02900	
145.0	0.02950	
150.0	0.03000	
155.0	0.03050	
160.0	0.03120	
		Slip Load: 109.0 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	383	38.9
Fully Tightened	1828	191.0
30.0 kN Applied Load	1826	190.8
60.0 kN Applied Load	1823	190.5
90.0 kN Applied Load	1817	189.9
120.0 kN Applied Load	1805	188.6

Table 13
Compression Specimen 5

LOAD-DISPLACEMENT DATA

Load (kN)	Avg. Disp. (in.)	Comments
0.0	0.00000	
10.0	0.00200	
15.0	0.00250	
20.0	0.00300	
25.0	0.00350	
30.0	0.00400	
35.0	0.00450	
40.0	0.00500	
45.0	0.00550	
50.0	0.00600	
55.0	0.00650	
60.0	0.00700	
65.0	0.00750	
70.0	0.00800	
75.0	0.00850	
80.0	0.00875	
85.0	0.00900	
90.0	0.00900	
95.0	0.00950	
100.0	0.00975	
105.0	0.01050	
110.0	0.01075	
115.0	0.01150	
120.0	0.01300	
125.0	0.01425	
130.0	0.01550	
135.0	0.01725	
140.0	0.01950	
145.0	0.02250	
150.0	0.02450	
155.0	0.02650	
160.0	0.02850	
165.0	0.03050	
170.0	0.03200	
Slip data: 141.0 kN		

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	516	52.9
Fully Tightened	1816	189.8
30.0 kN Applied Load	1814	189.6
60.0 kN Applied Load	1812	189.4
90.0 kN Applied Load	1805	188.6
120.0 kN Applied Load	1802	188.3

Table 14
Compression Specimen 6

LOAD-DISPLACEMENT DATA

Load (kN)	Avg. Disp. (in.)	Comments
0.0	0.00000	
10.0	0.00100	
15.0	0.00200	
20.0	0.00250	
25.0	0.00350	
30.0	0.00450	
35.0	0.00500	
40.0	0.00550	
45.0	0.00650	
50.0	0.00725	
55.0	0.00800	
60.0	0.00900	
65.0	0.00950	
70.0	0.01050	
75.0	0.01175	
80.0	0.01300	
85.0	0.01400	
90.0	0.01425	
95.0	0.01450	
100.0	0.01475	
105.0	0.01550	
110.0	0.02050	
115.0	0.02500	
120.0	0.02800	
125.0	0.03150	
130.0	0.03600	
135.0	0.04050	
140.0	0.04450	
145.0	0.04900	
150.0	0.05350	
155.0	0.05775	
160.0	0.06200	
		Slip Load: 105.0 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	472	48.3
Fully Tightened	1754	183.3
30.0 kN Applied Load	1755	183.4
60.0 kN Applied Load	1753	183.1
90.0 kN Applied Load	1743	182.1
120.0 kN Applied Load	1736	181.4

Table 15
Connection Testing Device

DETERMINATION OF THE SLIP COEFFICIENT

Specimen	Slip Load (kN)	Bolt Preload (kN)	Slip Coefficient k_s
S1-1	39.7	179.3	0.22
S1-2	40.5	169.2	0.24
S1-3	49.2	195.3	0.25
S1-4	37.0	170.4	0.22
S1-5	42.2	177.8	0.24
S1-6	37.6	165.0	0.23
	Average Slip Coefficient		**0.23**

Table 16
Specimen S1-1

LOAD-DISPLACEMENT DATA

Load (kN)	Displacement (in.)	Comments
0	0.00000	
10.0	0.00840	
15.0	0.01010	
20.0	0.01200	
25.0	0.01380	
30.0	0.01550	
35.0	0.01700	
40.0	0.01845	Reaching 45.0 kN
45.0	0.03020	load drop & noise
50.0	0.03480	
55.0	0.03840	
60.0	0.04230	
65.0	0.04480	
70.0	0.04700	
75.0	0.04980	
80.0	0.05320	
85.0	0.05700	
90.0	0.06160	
95.0	0.06580	
100.0	0.07080	
105.0	0.07680	
110.0	0.08230	
115.0	0.08870	
		Slip Load: 39.7 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	370	37.5
1/2 Turn Past Snug	1713	178.9
30.0 kN Applied Load	1717	179.3
50.0 kN Applied Load	1692	176.7
90.0 kN Applied Load	1647	172.0
115.0 kN Applied Load	1549	161.7

Table 17
Specimen S1-2

LOAD-DISPLACEMENT DATA

Load (kN)	Displacement (in.)	Comments
0	0.00000	
10	0.01710	
15	0.02080	
20	0.02240	
25	0.02350	
30	0.02470	
35	0.02570	
40	0.02670	Load drop at 40.5 kN
45	0.03490	
50	0.03820	
55	0.04150	
60	0.04520	
65	0.04860	
70	0.05190	
75	0.05560	
80	0.06000	
85	0.06510	
90	0.08150	Noise at 94.8 kN
95	0.09130	
100	0.09600	
		Slip Load: 40.5 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	399	40.6
1/2 Turn Past Snug	1622	169.3
30.0 kN Applied Load	1621	169.2
45.0 kN Applied Load	1615	168.6
60.0 kN Applied Load	1568	163.7
90.0 kN Applied Load	1445	150.7

Table 18
Specimen S1-3

LOAD-DISPLACEMENT DATA

Load (kN)	Displacement (in.)	Comments
0.0	0.00000	
10.0	0.02120	
15.0	0.02360	
20.0	0.02550	
25.0	0.02690	
30.0	0.02820	
35.0	0.02930	
40.0	0.03040	
45.0	0.03160	Load drop at 49.2 kN
50.0	0.03570	
55.0	0.03890	
60.0	0.04240	
65.0	0.04630	
70.0	0.04940	
75.0	0.05260	
80.0	0.05650	
85.0	0.06010	
90.0	0.06440	
95.0	0.07440	
100.0	0.08500	
105.0	0.09450	
110.0	0.10730	
		Slip Load: 49.2 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	530	54.3
1/2 Turn Past Snug	1863	194.7
30.0 kN Applied Load	1869	195.3
50.0 kN Applied Load	1878	196.3
80.0 kN Applied Load	1775	185.4
100.0 kN Applied Load	1641	171.4

Table 19
Specimen S1-4

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00010	
5.0	0.00010	
6.0	0.00010	
7.0	0.00010	
8.0	0.00010	
9.0	0.00010	
10.0	0.00010	
11.0	0.00010	
12.5	0.00010	
15.0	0.00010	
20.0	0.00010	
25.0	0.00010	
30.0	0.00010	
32.0	0.00010	
34.0	0.00010	
36.0	0.00012	Load drop at 37.0 kN
38.0	0.00360	
40.0	0.00630	
42.0	0.00900	
44.0	0.01140	
45.0	0.01260	
46.0	0.01380	
48.0	0.01630	
50.0	0.01860	
52.0	0.02120	

Load (kN)	Disp. (in.)	Comments
55.0	0.02550	
60.0	0.03320	
65.0	0.03980	
70.0	0.04040	Load drop at 70.0 kN
75.0	0.05380	
80.0	0.07300	
85.0	0.07820	
90.0	0.08280	
95.0	0.08770	
100.0	0.09430	
105.0	0.10120	
110.0	0.10670	
		Slip Load: 37.0 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	368	37.8
1/2 Turn Past Snug	1615	170.0
30.0 kN Applied Load	1619	170.4
60.0 kN Applied Load	1551	163.2
90.0 kN Applied Load	1452	152.8

Table 20
Specimen S1-5

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00040	
2.0	0.00200	
3.0	0.00740	
4.0	0.00930	
5.0	0.00980	
6.0	0.01080	
7.0	0.01140	
8.0	0.01180	
9.0	0.01190	
10.0	0.01220	
12.5	0.01270	
15.0	0.01290	
20.0	0.01340	
25.0	0.01400	
30.0	0.01470	Load drop at 31.8 kN
32.0	0.01500	
34.0	0.01530	
36.0	0.01560	
38.0	0.01600	
40.0	0.01630	
42.0	0.01670	Load drop at 42.2 kN
44.0	0.02620	
45.0	0.02800	
46.0	0.02920	
48.0	0.03330	
50.0	0.03880	

Load (kN)	Disp. (in.)	Comments
52.0	0.04350	
55.0	0.05010	
60.0	0.06330	
65.0	0.07730	Load drop at 65.1 kN
70.0	0.08500	
75.0	0.09320	
80.0	0.09670	
85.0	0.10050	
90.0	0.10470	
95.0	0.10910	
100.0	0.11580	
105.0	0.12450	
110.0	0.13020	Load drop at 112.5 kN
115.0	0.14360	
120.0	0.15780	
125.0	0.17320	
130.0	0.18830	
		Slip Load: 42.2 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	402	41.4
1/2 Turn Past Snug	1684	177.3
30.0 kN Applied Load	1689	177.8
44.0 kN Applied Load	1674	176.3
60.0 kN Applied Load	1561	164.3
90.0 kN Applied Load	1508	158.7

Table 21
Specimen S1-6

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00000	
5.0	0.00000	
6.0	0.00000	
7.0	0.00000	
8.0	0.00000	
9.0	0.00000	
10.0	0.00000	
11.0	0.00000	
12.5	0.00000	
14.0	0.00000	
15.0	0.00000	
16.0	0.00000	
17.0	0.00000	
18.0	0.00000	
19.0	0.00000	
20.0	0.00000	
21.0	0.00010	
22.0	0.00040	
23.0	0.00055	
24.0	0.00070	
25.0	0.00090	
26.0	0.00110	
27.0	0.00130	
28.0	0.00140	
29.0	0.00160	
30.0	0.00180	

Load (kN)	Disp. (in.)	Comments
32.0	0.00200	
34.0	0.00240	
36.0	0.00265	Load drop at 37.6 kN
38.0	0.00740	
40.0	0.00920	
42.0	0.01140	
44.0	0.01390	
45.0	0.01540	
46.0	0.01680	
48.0	0.01980	
50.0	0.02270	
52.0	0.02580	
55.0	0.03040	
60.0	0.04040	
65.0	0.05040	
70.0	0.06270	Load drop at 74.7 kN
78.0	0.09680	
80.0	0.09770	
85.0	0.10160	
90.0	0.10710	
95.0	0.11120	
100.0	0.11430	
105.0	0.12230	
110.0	0.12940	
115.0	0.13870	
120.0	0.14940	
125.0	0.16100	
130.0	0.16500	
135.0	0.16840	
		Slip Load: 37.6 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	408	42.1
1/2 Turn Past Snug	1564	164.6
30.0 kN Applied Load	1567	165.0
38.0 kN Applied Load	1565	164.7
60.0 kN Applied Load	1533	161.3
90.0 kN Applied Load	1417	149.0

Table 22
Specimen S2-1

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00005	
5.0	0.00010	
6.0	0.00020	
7.0	0.00080	
8.0	0.00035	
9.0	0.00040	
10.0	0.00050	
11.0	0.00060	
12.5	0.00060	
14.0	0.00065	
15.0	0.00095	
16.0	0.00120	
17.0	0.00125	
18.0	0.00145	
19.0	0.00160	
20.0	0.00190	
22.0	0.00240	
24.0	0.00280	
25.0	0.00310	
28.0	0.00380	
30.0	0.00420	
32.0	0.00470	
34.0	0.00505	
36.0	0.00540	
38.0	0.00570	

Load (kN)	Disp. (in.)	Comments
40.0	0.00610	
42.0	0.00650	Load drop & noise
44.0	0.01410	at 43.5 kN
46.0	0.01610	
48.0	0.01730	
50.0	0.01750	
52.0	0.01790	
55.0	0.01830	
60.0	0.01940	
65.0	0.02110	
70.0	0.02440	
78.0	0.02870	
80.0	0.03490	
85.0	0.04260	
90.0	0.05130	
95.0	0.06210	
100.0	0.07300	
105.0	0.09060	
110.0	0.10270	Load drop at 113.4 kN
115.0	0.11590	
120.0	0.13880	
125.0	0.15620	
130.0	0.16100	
135.0	0.16490	
		Slip Load: 43.5 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	422	43.6
1/2 Turn Past Snug	1618	170.3
47.0 kN Applied Load	1608	169.3
60.0 kN Applied Load	1587	167.0
90.0 kN Applied Load	1495	157.2
120.0 kN Applied Load	1397	143.7

Table 23
Specimen S2-2

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00000	
5.0	0.00000	
6.0	0.00000	
7.0	0.00000	
8.0	0.00000	
9.0	0.00000	
10.0	0.00000	
11.0	0.00000	
12.5	0.00000	
14.0	0.00025	
15.0	0.00060	
16.0	0.00090	
17.0	0.00120	
18.0	0.00150	
19.0	0.00180	
20.0	0.00200	
22.0	0.00260	
24.0	0.00300	
26.0	0.00330	
28.0	0.00380	
30.0	0.00400	
32.0	0.00445	
34.0	0.00470	
36.0	0.00510	
38.0	0.00540	
40.0	0.00580	
42.0	0.00605	
44.0	0.00655	

Load (kN)	Disp. (in.)	Comments
46.0	0.00685	Load drop & noise
47.5	0.04390	at 47.4 kN
50.0	0.04470	
52.0	0.04530	
55.0	0.04660	
60.0	0.04950	
65.0	0.05400	
70.0	0.05900	
75.0	0.06450	
80.0	0.07150	
85.0	0.08020	
90.0	0.09530	
95.0	0.11820	
100.0	0.12800	
105.0	0.13600	
110.0	0.14390	Load drop at 111.4 kN
115.0	0.16880	
120.0	0.18020	
125.0	0.18400	
130.0	0.18740	
135.0	0.19100	
		Slip Load: 47.4 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	366	37.6
1/2 Turn Past Snug	1618	170.3
30.0 kN Applied Load	1623	170.9
48.0 kN Applied Load	1578	166.0
60.0 kN Applied Load	1571	165.4
90.0 kN Applied Load	1465	154.1

Table 24
Specimen S2-3

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00010	
5.0	0.00040	
6.0	0.00080	
7.0	0.00120	
8.0	0.00150	
9.0	0.00190	
10.0	0.00220	
11.0	0.00260	
12.5	0.00310	
14.0	0.00350	
15.0	0.00380	
16.0	0.00415	
17.0	0.00450	
18.0	0.00490	
19.0	0.00540	
20.0	0.00580	
22.0	0.00680	
24.0	0.00770	
26.0	0.00845	
28.0	0.00900	
30.0	0.00950	
32.0	0.00985	
34.0	0.01020	
36.0	0.01060	
38.0	0.01085	
40.0	0.01130	
42.0	0.01150	Load drop & noise
43.7	0.01720	at 43.6 kN

Load (kN)	Disp. (in.)	Comments
46.0	0.02090	
48.0	0.02190	
50.0	0.02290	
52.0	0.02410	
55.0	0.02610	
60.0	0.03050	
65.0	0.03550	
70.0	0.04140	
75.0	0.04730	
80.0	0.05470	
85.0	0.06400	
90.0	0.07660	
95.0	0.09720	
100.0	0.11670	
105.0	0.12900	
110.0	0.14060	Load drop at 113.8 kN
115.0	0.15820	
120.0	0.17200	
125.0	0.17800	
130.0	0.18420	
135.0	0.19010	
		Slip Load: 43.6 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	354	36.3
1/2 Turn Past Snug	1578	166.1
30.0 kN Applied Load	1584	166.8
44.0 kN Applied Load	1577	166.0
65.0 kN Applied Load	1555	163.6
90.0 kN Applied Load	1454	153.0

Table 25
Specimen S3-1

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00000	
5.0	0.00000	
6.0	0.00240	
7.0	0.00240	
8.0	0.00240	
9.0	0.00240	
10.0	0.00240	
11.0	0.00240	
12.5	0.00240	
14.0	0.00240	
15.0	0.00240	
16.0	0.00240	
17.0	0.00240	
18.0	0.00240	
19.0	0.00240	
20.0	0.00240	
25.0	0.00240	
30.0	0.00240	
32.0	0.00240	
34.0	0.00240	
36.0	0.00250	
38.0	0.00290	
40.0	0.00340	Load drop at 41.7 kN
42.0	0.00400	Load drop & noise
44.0	0.01050	at 43.4 kN
46.0	0.01120	
48.0	0.01200	
50.0	0.01290	
52.0	0.01410	
55.0	0.01600	
60.0	0.02040	

Load (kN)	Disp. (in.)	Comments
65.0	0.02460	
70.0	0.02950	
75.0	0.03610	
80.0	0.04440	
85.0	0.05630	
90.0	0.08260	Load drop & noise
93.0	0.16890	at 91.9 kN
95.0	0.16960	
97.5	0.17160	
100.0	0.17270	
105.0	0.17500	Repeated load drops &
110.0	0.17790	noise up to 106.5 kN
115.0	0.17790	
120.0	0.17790	
125.0	0.17790	
130.0	0.17790	
135.0	0.17790	
		Slip Load: 43.4 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	354	36.4
1/2 Turn Past Snug	1599	168.3
60.0 kN Applied Load	1582	166.5
90.0 kN Applied Load	1407	148.0

Table 26
Specimen S3-2

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00020	
4.0	0.00080	
5.0	0.00140	
6.0	0.00230	
7.0	0.00320	
8.0	0.00410	
9.0	0.00460	
10.0	0.00540	
11.0	0.00570	
12.5	0.00610	
14.0	0.00670	
15.0	0.00680	
16.0	0.00750	
17.0	0.00790	
18.0	0.00820	
19.0	0.00860	
20.0	0.00890	
25.0	0.01060	
30.0	0.01160	
32.0	0.01220	
34.0	0.01285	
36.0	0.01335	
38.0	0.01350	
40.0	0.01420	
42.0	0.01470	
44.0	0.01490	
46.0	0.01550	
48.0	0.01580	Load drop & noise
50.0	0.03420	at 49.9 kN
52.0	0.03480	
55.0	0.03550	Load drop & noise
58.0	0.05870	at 57.6 kN

Load (kN)	Disp. (in.)	Comments
60.0	0.05870	
65.0	0.05975	
67.0	0.11880	
70.0	0.14095	
75.0	0.15180	
77.0	0.18530	
80.0	0.18570	
85.0	0.18800	
90.0	0.19130	Repeated load drops &
95.0	0.19350	noise up to 93.1 kN
100.0	0.19490	
105.0	0.19750	
110.0	0.20070	
115.0	0.20420	
120.0	0.20820	
125.0	0.21260	
130.0	0.21700	
		Slip Load: 49.9 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	445	46.0
1/2 Turn Past Snug	1635	172.1
60.0 kN Applied Load	1642	172.8
90.0 kN Applied Load	1550	163.2

Table 27
Specimen S3-3

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00000	
5.0	0.00000	
6.0	0.00000	
7.0	0.00070	
8.0	0.00140	
9.0	0.00200	
10.0	0.00270	
11.0	0.00330	
12.5	0.00330	
14.0	0.00330	
15.0	0.00390	
16.0	0.00400	
17.0	0.00400	
18.0	0.00400	
19.0	0.00440	
20.0	0.00460	
25.0	0.00530	
30.0	0.00530	
32.0	0.00530	
34.0	0.00530	
36.0	0.00530	
38.0	0.00540	
40.0	0.00580	
42.0	0.00600	
44.0	0.00600	
46.0	0.00610	Load drop & noise
48.0	0.00610	at 48.2 kN
49.0	0.02860	

Load (kN)	Disp. (in.)	Comments
50.0	0.02880	
52.0	0.02930	
55.0	0.03050	
60.0	0.03280	
65.0	0.03650	
70.0	0.04140	
75.0	0.04790	
80.0	0.05600	
85.0	0.06800	
88.5	0.07900	
90.0	0.08400	
95.0	0.10580	
98.5	0.12750	
100.0	0.13170	Load drop & noise
105.0	0.16900	at 104.2 kN
107.5	0.17000	Repeated minor load
110.0	0.17120	drops
115.0	0.17380	
120.0	0.17670	
125.0	0.18030	
130.0	0.18430	
		Slip Load: 48.2 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	394	40.6
1/2 Turn Past Snug	1661	174.9
30.0 kN Applied Load	1666	175.4
49.0 kN Applied Load	1653	174.0
60.0 kN Applied Load	1646	173.3
90.0 kN Applied Load	1497	157.5

Table 28
Specimen S4-1

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00000	
5.0	0.00000	
6.0	0.00000	
7.0	0.00005	
8.0	0.00015	
9.0	0.00025	
10.0	0.00020	
12.0	0.00020	
14.0	0.00020	
16.0	0.00020	
18.0	0.00025	
20.0	0.00025	
25.0	0.00035	
30.0	0.00050	
32.0	0.00055	
34.0	0.00065	
36.0	0.00085	
38.0	0.00090	
40.0	0.00095	
42.0	0.00135	
44.0	0.00155	
46.0	0.00160	
48.0	0.00195	Load Drop & noise
50.0	0.00965	at 49.9 kN
52.0	0.00970	
55.0	0.00995	
60.0	0.01130	
65.0	0.01355	
70.0	0.01645	

Load (kN)	Disp. (in.)	Comments
75.0	0.02025	
80.0	0.02425	
85.0	0.02895	
87.0	0.03095	
90.0	0.03495	
92.5	0.03965	
95.0	0.04495	
97.5	0.05825	
98.5	0.08465	Load drop at 99.4 kN
100.0	0.12745	
105.0	0.13825	Load drop at 105.3 kN
106.0	0.16305	Repeated load drops
110.0	0.16525	
115.0	0.16825	
120.0	0.17185	
125.0	0.17635	
		Slip Load: 49.9 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	444	45.9
1/2 Turn Past Snug	1635	172.2
30.0 kN Applied Load	1638	172.5
60.0 kN Applied Load	1628	171.4
90.0 kN Applied Load	1586	166.9

Table 29
Specimen S4-2

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00020	
2.0	0.00030	
3.0	0.00030	
4.0	0.00170	
5.0	0.00290	
6.0	0.00360	
7.0	0.00420	
8.0	0.00460	
9.0	0.00500	
10.0	0.00570	
12.0	0.00780	
14.0	0.00945	
16.0	0.01100	
18.0	0.01220	
20.0	0.01300	
25.0	0.01570	
30.0	0.01770	
32.0	0.01820	
34.0	0.01900	
36.0	0.01950	
38.0	0.01990	
40.0	0.02030	
42.0	0.02070	
44.0	0.02095	
46.0	0.02150	
48.0	0.02160	
50.0	0.02190	
52.0	0.02230	Load drop & noise
53.0	0.04850	at 52.4 kN
54.0	0.04860	
56.0	0.04900	
60.0	0.05020	

Load (kN)	Disp. (in.)	Comments
65.0	0.05350	
70.0	0.05770	
75.0	0.06290	
80.0	0.06940	
82.5	0.07360	
85.0	0.07790	
87.5	0.08290	
90.0	0.08830	
92.5	0.09580	
95.0	0.10630	
97.0	0.13100	
100.0	0.13900	Load drop & noise
102.0	0.18000	at 101.3 kN
105.0	0.18070	
110.0	0.18220	
115.0	0.18450	
120.0	0.18710	
		Slip Load: 52.4 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	399	41.1
1/2 Turn Past Snug	1638	172.4
34.0 kN Applied Load	1642	172.9
60.0 kN Applied Load	1608	169.3
90.0 kN Applied Load	1519	159.9

Table 30
Specimen S4-3

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00001	
4.0	0.00001	
5.0	0.00362	
6.0	0.00572	
7.0	0.00592	
8.0	0.00592	
9.0	0.00592	
10.0	0.00592	
12.0	0.00592	
14.0	0.00592	
16.0	0.00592	
18.0	0.00592	
20.0	0.00592	
25.0	0.00592	
30.0	0.00592	
34.0	0.00592	
38.0	0.00592	
40.0	0.00592	
44.0	0.00592	
46.0	0.00592	
48.0	0.00592	
50.0	0.00632	
52.0	0.00732	
54.0	0.00767	
56.0	0.00872	
58.0	0.01002	
60.0	0.01112	
65.0	0.01457	
70.0	0.01762	
75.0	0.02132	

Load (kN)	Disp. (in.)	Comments
80.0	0.02542	
82.5	0.02762	
85.0	0.03032	
90.0	0.03742	
95.0	0.04662	
100.0	0.06372	
101.0	0.07082	
102.0	0.07842	
102.5	0.08362	
103.0	0.09762	Load drop & noise
105.0	0.15872	at 104.3 kN
110.0	0.16132	Repeated load drops
115.0	0.16452	
120.0	0.16882	
		Slip Load: 50.0 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	396	40.8
1/2 Turn Past Snug	1637	172.3
30.0 kN Applied Load	1649	173.6
60.0 kN Applied Load	1636	172.2
90.0 kN Applied Load	1586	166.9

Table 31
Specimen S5-1

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00000	
5.0	0.00000	
6.0	0.00000	
7.0	0.00000	
8.0	0.00000	
9.0	0.00000	
10.0	0.00000	
12.0	0.00000	
14.0	0.00000	
16.0	0.00000	
18.0	0.00000	
20.0	0.00000	
22.0	0.00020	
23.0	0.00050	
24.0	0.00070	
25.0	0.00095	
26.5	0.00130	
28.0	0.00135	
29.0	0.00140	
30.0	0.00160	
33.0	0.00250	
36.0	0.00310	
38.0	0.00350	
40.0	0.00400	
43.0	0.00450	
46.0	0.00470	
48.5	0.00540	
50.0	0.00580	

Load (kN)	Disp. (in.)	Comments
52.0	0.00650	
54.0	0.00710	
56.0	0.00740	
58.0	0.00790	
60.0	0.00820	
62.0	0.00870	
65.0	0.00950	Load drop & noise
67.0	0.04130	at 66.3 kN
70.0	0.04320	
75.0	0.04540	
80.0	0.04890	
85.0	0.05400	
90.0	0.06000	
95.0	0.06860	
100.0	0.07920	
105.0	0.09870	Load drop & noise
106.5	0.14400	at 106.3 kN
110.0	0.14580	
115.0	0.14870	
120.0	0.15160	
		Slip Load: 66.3 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	402	41.5
1/2 Turn Past Snug	1556	163.7
30.0 kN Applied Load	1558	164.0
60.0 kN Applied Load	1569	165.1
70.0 kN Applied Load	1467	154.4
90.0 kN Applied Load	1460	153.6

Table 32
Specimen S5-2

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00000	
5.0	0.00000	
6.0	0.00000	
7.0	0.00000	
8.0	0.00000	
9.0	0.00000	
10.0	0.00000	
12.0	0.00000	
14.0	0.00000	
16.0	0.00000	
18.0	0.00000	
20.0	0.00000	
25.0	0.00000	
30.0	0.00000	
33.0	0.00000	
36.0	0.00000	
40.0	0.00000	
43.0	0.00005	
46.0	0.00015	
50.0	0.00025	
52.0	0.00040	
54.0	0.00055	
56.0	0.00060	
58.0	0.00075	
60.0	0.00090	
62.0	0.00100	

Load (kN)	Disp. (in.)	Comments
64.0	0.00110	
66.0	0.00150	Load drop & noise
67.0	0.01290	at 66.8 kN
68.0	0.01300	Load drop & noise
70.0	0.01350	at 68.0 kN
75.0	0.01350	
80.0	0.01400	
85.0	0.01540	
86.0	0.01640	
87.0	0.01810	
88.0	0.01880	
89.0	0.02050	
90.0	0.02180	
92.5	0.02510	
95.0	0.02930	
100.0	0.04200	
103.0	0.05150	
104.0	0.07120	
104.5	0.09150	Load drop & noise
105.0	0.11610	at 104.7 kN
110.0	0.11940	
115.0	0.12320	
120.0	0.12740	
		Slip Load: 66.8 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	450	46.5
1/2 Turn Past Snug	1622	170.8
30.0 kN Applied Load	1629	171.5
56.2 kN Applied Load	1629	171.5
60.0 kN Applied Load	1629	171.5
66.2 kN Applied Load	1629	171.5
67.0 kN Applied Load	1558	164.0
90.0 kN Applied Load	1521	160.0

Table 33
Specimen S5-3

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
10.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00000	
5.0	0.00005	
6.0	0.00005	
7.0	0.00070	
8.0	0.00330	
9.0	0.00480	
10.0	0.00560	
12.0	0.00670	
14.0	0.00760	
16.0	0.00890	
18.0	0.00970	
20.0	0.01070	
25.0	0.01260	
30.0	0.01420	
35.0	0.01550	
40.0	0.01650	
43.0	0.01705	
46.0	0.01760	
50.0	0.01850	
54.0	0.01940	
56.0	0.01985	
58.0	0.02040	
60.0	0.02080	
62.0	0.02150	
64.0	0.02190	
66.0	0.02230	Load drop & noise
68.0	0.04410	at 67.8 kN
70.0	0.04420	Repeated load drops
75.0	0.04700	
80.0	0.05020	
83.0	0.05290	
85.0	0.05490	
87.0	0.05700	
90.0	0.06090	
95.0	0.08020	
97.0	0.08560	
100.0	0.09630	
102.0	0.10560	
103.0	0.11140	
104.0	0.12020	
104.8	0.13020	
105.0	0.13160	Load drop & noise
106.5	0.18310	at 106.3 kN
110.0	0.18380	
115.0	0.18580	
		Slip Load: 67.8 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	388	39.9
1/2 Turn Past Snug	1573	165.5
30.0 kN Applied Load	1581	166.4
50.0 kN Applied Load	1580	166.3
60.0 kN Applied Load	1579	166.2
66.0 kN Applied Load	1579	166.2
68.0 kN Applied Load	1515	159.4
90.0 kN Applied Load	1494	157.2

Table 34
Specimen S6-1

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00000	
5.0	0.00000	
6.0	0.00000	
7.0	0.00000	
8.0	0.00000	
9.0	0.00000	
10.0	0.00000	
12.0	0.00000	
14.0	0.00000	
16.0	0.00000	
18.0	0.00000	
20.0	0.00000	
25.0	0.00000	
30.0	0.00010	
35.0	0.00120	
40.0	0.00280	
45.0	0.00490	
50.0	0.00670	
52.0	0.00750	
54.0	0.00820	
56.0	0.00880	
58.0	0.00940	
60.0	0.01010	
62.0	0.01080	
64.0	0.01140	
66.0	0.01210	

Load (kN)	Disp. (in.)	Comments
68.0	0.01270	
69.0	0.01280	
70.0	0.01320	
70.5	0.01340	
71.0	0.01340	
72.0	0.01350	
73.0	0.01390	
74.0	0.01410	
76.0	0.01460	
78.0	0.01490	
80.0	0.01530	
85.0	0.01770	
90.0	0.01870	
95.0	0.02000	
100.0	0.02140	
105.0	0.02350	
110.0	0.02610	
115.0	0.02940	
120.0	0.03410	
125.0	0.04005	
130.0	0.05130	
132.5	0.06620	Load drop at 133.4 kN
133.5	0.13940	Load drop at 133.8 kN
135.0	0.14770	
		Slip Load: 80.0 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	440	45.4
1/2 Turn Past Snug	1710	180.0
30.0 kN Applied Load	1686	177.5
60.0 kN Applied Load	1687	177.7
66.0 kN Applied Load	1688	177.8
69.0 kN Applied Load	1687	177.7
73.0 kN Applied Load	1687	177.7
90.0 kN Applied Load	1683	177.2

Table 35
Specimen S6-2

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00000	
5.0	0.00000	
6.0	0.00000	
7.0	0.00000	
8.0	0.00000	
9.0	0.00000	
10.0	0.00000	
12.0	0.00000	
14.0	0.00000	
16.0	0.00000	
18.0	0.00000	
20.0	0.00090	
25.0	0.00550	
30.0	0.00890	
35.0	0.01150	
40.0	0.01310	
45.0	0.01355	
50.0	0.01405	
55.0	0.01470	
60.0	0.01550	
62.0	0.01590	
64.0	0.01620	
66.0	0.01630	

Load (kN)	Disp. (in.)	Comments
68.0	0.01680	
70.0	0.01705	
72.0	0.01740	
74.0	0.01750	
76.0	0.01800	
78.0	0.01820	
80.0	0.01910	
85.0	0.02090	Load drop & noise
85.2	0.03830	at 85.1 kN
90.0	0.03850	
95.0	0.04050	
100.0	0.04310	
105.0	0.04680	
110.0	0.05160	
115.0	0.05750	
120.0	0.06460	
125.0	0.06960	
125.7	0.09030	
128.0	0.14230	
130.0	0.16210	Load drop & noise
131.5	0.21910	at 131.1 kN
135.0	0.22150	
140.0	0.22490	
		Slip Load: 85.1 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	446	46.0
1/2 Turn Past Snug	1635	172.1
30.0 kN Applied Load	1638	172.4
60.0 kN Applied Load	1639	172.6
66.0 kN Applied Load	1639	172.6
70.0 kN Applied Load	1639	172.6
74.0 kN Applied Load	1639	172.5
80.0 kN Applied Load	1640	172.6
86.0 kN Applied Load	1630	171.6
90.0 kN Applied Load	1629	171.5
110.0 kN Applied Load	1613	169.8

Table 36
Specimen S6-3

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00000	
5.0	0.00000	
6.0	0.00000	
7.0	0.00000	
8.0	0.00000	
9.0	0.00000	
10.0	0.00000	
12.0	0.00000	
14.0	0.00000	
16.0	0.00000	
18.0	0.00240	
20.0	0.00480	
25.0	0.01010	
30.0	0.01340	
35.0	0.01680	
40.0	0.01910	
45.0	0.02090	
50.0	0.02280	
55.0	0.02400	
60.0	0.02480	
65.0	0.02550	
70.0	0.02610	
72.0	0.02650	

Load (kN)	Disp. (in.)	Comments
74.0	0.02670	
76.0	0.02690	
78.0	0.02740	
80.0	0.02750	
82.0	0.02780	
84.0	0.02810	
85.0	0.02815	
86.0	0.02840	Load drop & noise
88.0	0.04160	at 87.8 kN
90.0	0.04160	
95.0	0.04210	
100.0	0.04315	
105.0	0.04490	
110.0	0.04690	
115.0	0.05080	
120.0	0.05480	Load drop at 121.1 kN
122.5	0.12660	Load drop & noise
125.0	0.13540	at 122.0 kN
130.0	0.16050	
135.0	0.17990	
140.0	0.20280	
		Slip Load: 87.8 kN

PRELOAD DATA

	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	423	43.6
1/2 Turn Past Snug	1740	183.2
31.0 kN Applied Load	1741	183.3
50.0 kN Applied Load	1742	183.5
60.0 kN Applied Load	1742	183.4
70.0 kN Applied Load	1742	183.5
80.0 kN Applied Load	1741	183.4
85.0 kN Applied Load	1741	183.4
88.0 kN Applied Load	1737	182.9
90.0 kN Applied Load	1737	182.9
100.0 kN Applied Load	1736	182.8

Table 37
Slip-Critical Connection

LOAD-DISPLACEMENT DATA

Load (kN)	Disp. (in.)	Comments
0.0	0.00000	
1.0	0.00000	
2.0	0.00000	
3.0	0.00000	
4.0	0.00000	
5.0	0.00000	
6.0	0.00000	
7.0	0.00000	
8.0	0.00000	
9.0	0.00000	
10.0	0.00000	
12.0	0.00000	
14.0	0.00000	
16.0	0.00000	
18.0	0.00000	
20.0	0.00039	
25.0	0.00138	
30.0	0.00138	
35.0	0.00177	
40.0	0.00217	
45.0	0.00236	
50.0	0.00256	
55.0	0.00256	
60.0	0.00315	

Load (kN)	Disp. (in.)	Comments
65.0	0.00394	
70.0	0.00433	
75.0	0.00492	
80.0	0.00531	
82.0	0.00551	
84.0	0.00551	
86.0	0.00551	
88.0	0.00571	
90.0	0.00571	
92.0	0.00591	
94.0	0.00591	
96.0	0.00650	
98.0	0.00689	Load drop at 98.4 kN
100.0	0.01280	
102.0	0.01398	
104.0	0.01496	
106.0	0.01634	
108.0	0.01713	
110.0	0.01791	
112.0	0.01929	
114.0	0.02028	
116.0	0.02146	
118.0	0.02224	
		Slip Load: 98.4 kN

PRELOAD DATA

	Preload Cell #1		Preload Cell #2	
	Avg. Strain (x 10E -6)	Bolt Preload (kN)	Avg. Strain (x 10E -6)	Bolt Preload (kN)
Snug	544	56.5	433	45.3
1/2 Turn Past Snug	1611	169.6	1619	173.0
30.0 kN Applied Load	1609	169.3	1619	173.0
45.0 kN Applied Load	1607	169.2	1618	172.9
60.0 kN Applied Load	1605	169.0	1616	172.6
70.0 kN Applied Load	1604	168.8	1614	172.4
75.0 kN Applied Load	1603	168.7	1614	172.4
84.0 kN Applied Load	1602	168.6	1611	172.1
88.0 kN Applied Load	1600	168.5	1610	171.9
94.0 kN Applied Load	1600	168.4	1608	171.7
98.0 kN Applied Load	1599	168.3	1606	171.5
104.0 kN Applied Load	1591	167.5	1589	169.7
116.0 kN Applied Load	1593	167.7	1581	168.9

Table 38

INTERACTION EQUATION DATA AND RESULTS USING k_s = 0.24

Specimen	Angle (Degree)	T_i (kN)	Pslip (kN)	V (kN)	T (kN)	$V/(k_sT_i)$	T/T_i	$V/(k_sT_i) + T/T_i$
S1-1	0	179.3	39.7	39.7	0.0	0.923	0.000	0.923
S1-2		169.2	40.5	40.5	0.0	0.997	0.000	0.997
S1-3		195.3	49.2	49.2	0.0	1.050	0.000	1.050
S1-4		170.4	37.0	37.0	0.0	0.905	0.000	0.905
S1-5		177.8	42.2	42.2	0.0	0.989	0.000	0.989
S1-6		165.0	37.6	37.6	0.0	0.949	0.000	0.949
S2-1	15	170.3	43.5	42.0	11.3	1.028	0.066	1.094
S2-2		170.9	47.4	45.8	12.3	1.116	0.072	1.188
S2-3		166.8	43.6	42.1	11.3	1.052	0.068	1.120
S3-1	30	168.3	43.4	37.6	21.7	0.931	0.129	1.059
S3-2		172.1	49.9	43.2	25.0	1.046	0.145	1.191
S3-3		175.4	48.2	41.7	24.1	0.992	0.137	1.129
S4-1	45	172.5	49.9	35.3	35.3	0.852	0.205	1.057
S4-2		172.9	52.4	37.1	37.1	0.893	0.214	1.107
S4-3		173.6	50.0	35.4	35.4	0.849	0.204	1.052
connection		339.8	98.4	69.6	69.6	0.853	0.205	1.058
S5-1	60	165.1	66.3	33.2	57.4	0.837	0.348	1.184
S5-2		171.5	66.8	33.4	57.9	0.811	0.337	1.149
S5-3		166.2	67.8	33.9	58.7	0.850	0.353	1.203
S6-1	75	177.7	80.0	20.7	77.3	0.485	0.435	0.920
S6-2		172.6	85.1	22.0	82.2	0.532	0.476	1.008
S6-3		183.4	87.8	22.7	84.8	0.516	0.462	0.979

Where k_s was taken as: **0.24**

Table 39

INTERACTION EQUATION DATA AND RESULTS USING k_s = 0.22

Specimen	Angle (Degree)	T_i (kN)	Pslip (kN)	V (kN)	T (kN)	$V/(k_sT_i)$	T/T_i	$V/(k_sT_i) + T/T_i$
S1-1	0	179.3	39.7	39.7	0.0	1.006	0.000	1.006
S1-2		169.2	40.5	40.5	0.0	1.088	0.000	1.088
S1-3		195.3	49.2	49.2	0.0	1.145	0.000	1.145
S1-4		170.4	37.0	37.0	0.0	0.987	0.000	0.987
S1-5		177.8	42.2	42.2	0.0	1.079	0.000	1.079
S1-6		165.0	37.6	37.6	0.0	1.036	0.000	1.036
S2-1	15	170.3	43.5	42.0	11.3	1.121	0.066	1.188
S2-2		170.9	47.4	45.8	12.3	1.218	0.072	1.290
S2-3		166.8	43.6	42.1	11.3	1.148	0.068	1.215
S3-1	30	168.3	43.4	37.6	21.7	1.015	0.129	1.144
S3-2		172.1	49.9	43.2	25.0	1.141	0.145	1.286
S3-3		175.4	48.2	41.7	24.1	1.082	0.137	1.219
S4-1	45	172.5	49.9	35.3	35.3	0.930	0.205	1.134
S4-2		172.9	52.4	37.1	37.1	0.974	0.214	1.188
S4-3		173.6	50.0	35.4	35.4	0.926	0.204	1.129
connection		339.8	98.4	69.6	69.6	0.931	0.205	1.136
S5-1	60	165.1	66.3	33.2	57.4	0.913	0.348	1.260
S5-2		171.5	66.8	33.4	57.9	0.885	0.337	1.223
S5-3		166.2	67.8	33.9	58.7	0.927	0.353	1.280
S6-1	75	177.7	80.0	20.7	77.3	0.530	0.435	0.964
S6-2		172.6	85.1	22.0	82.2	0.580	0.476	1.056
S6-3		183.4	87.8	22.7	84.8	0.563	0.462	1.026

Where k_s was taken as: 0.22

ENDNOTES

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