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DOUBLE SHEAR TESTS OF HIGH STRENGTH BOLTS

by

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ABSTRACT

A series of tests was conducted on sixty single bolt, double shear test joints to determine the basic double shear strength of a high strength bolt. Both 7/8 inch and 1 inch bolts were used. The bolts were tightened to various degrees of initial tension.

It was found that the ultimate shear strength is not influenced by the amount of initial tension, and that the ultimate shear strength of a single bolt subjected to double shear is approximately 70% of the ultimate tensile strength as determined by a static tension test.
I. INTRODUCTION

1.1 Affiliation with Project 271

As part of Project 271, "Large Bolted Joints", a research program was conducted to determine the basic "double shear" strength of a single ASTM-A325 high strength bolt with various amounts of initial tension. This information could then be applied to the study of the behavior of large bolted joints.

1.2 Originally Proposed Program

The original proposal called for sixty tests to be conducted, thirty tests on 7/8 inch bolts and thirty tests on 1 inch bolts. For each of the two bolt sizes, five tests were to be conducted at each of six different values of initial tension: zero tension, 90% of proof load, 1/2 turn-of-the-nut, 1 turn-of-the-nut, 1 1/2 turns-of-the-nut, and 2 turns-of-the-nut. Each bolt was to be tested in a new, double shear test joint that had its faying surfaces coated with molycote to minimize the friction between the plates. Because of the existing friction in the test joint, the results obtained are actually bolt resistance values. This is composed of two parts, the shear strength of the bolt and the friction resistance. By minimizing the friction resistance, the bolt resistance value might better approximate the
true shear strength of the bolt. The load was applied at a slow rate by a commercial testing machine, the ultimate load was recorded, and load-deformation readings were recorded. The bolt was in the "slipped" position at the onset of each test.

1.3 **Explanation of the Method of Presentation of this Report**

Modifications were made to the original proposal because of results obtained during the initial tests. As the manner of modification was continuously predicated by preceding observations and occurrences, the most logical way of presenting the program completely, and also justifying the necessity of the various deviations, is to give a chronologically based account of the test program and the test results.

1.4 **Outline of the Test Program**

The actual test program as followed not including preparation and instrumentation, was as follows:

a) Thirty-six tests on lubricated joints

b) Investigation of friction coefficients of lubricated and non-lubricated faying surfaces

c) Eight tests on non-lubricated joints to evaluate loss of clamping force
d) Eight tests on new non-lubricated joints and four tests on used non-lubricated joints to determine the history of the loss of clamping force.

e) Eight tests on non-lubricated joints to investigate the behavior of the joint between the ultimate load and the rupture load.

f) Five tests on 7/8 inch rivets

1.5 Materials

The high strength bolts used in this study were of the type furnished under ASTM Designation A325. The bolt lengths were 5 1/2 inches under head, and quenched and tempered washers and heavy duty nuts were used. Table 1 gives the average ultimate tensile strength of the bolts and a comparison with ASTM specifications. Both the 7/8 inch bolts and the 1 inch bolts exceeded the minimum requirements, and the 7/8 inch bolts had an average ultimate tensile stress approximately 9% greater than that of the 1 inch bolts.

The 7/8 inch bolts were designated as the "Z" lot and the 1 inch bolts were designated as the "Y" lot.

The plate used in this study was ASTM A7 structural steel. Coupon tests were conducted to determine the structural properties. Table 2 gives the properties of the steel in the 7/8 inch bolted joints (designated as J1), the 1 inch
bolt joints (designated as J2) and the riveted joints (designated as J3). The mill test results of the steel in J1, J2 and J3 are shown in Table 3.

II. PREPARATION AND INSTRUMENTATION

2.1 Load-Elongation Characteristics of Bolts

The values of initial tension of the bolts was determined by measuring the elongation of the bolts and then reading the corresponding tension from a predetermined load-elongation curve. These curves were obtained by direct tension loading of bolts of the same lot. Figure 1 shows the testing machine fixtures used to pull the bolts. The grip used was four inches, the same grip as used in the test joints. Five bolts each of both the 7/8 inch and 1 inch diameters were tested, with readings of elongation taken until the ultimate load was reached. An average curve was computed for both size bolts. It is of interest to note that all five tests on 1 inch bolts yielded consistent load-elongation curves, but that the 7/8 inch bolts, when tested, displayed a lack of uniformity of load vs. elongation at loads above the yield stress. Three later tests on 7/8 inch bolts showed more consistency, but not comparable to the 1 inch bolts. Figures 2 and 3 show the extreme load-elongation readings that were obtained. The curve enclosed
between the extremum is the average load-elongation curve, and was used as a Calibration Curve to determine the initial tension of the bolts used in the shear tests.

The results of the tests on the 7/8 inch bolts suggest that a lack of uniformity may exist in the material or physical properties of the 7/8 inch bolts that contribute to the development of a greater scatter in the results of the shear tests on the 7/8 inch bolt.

2.2 Calibration of the Torque Wrench

As a matter of general interest, the maximum torque reading for each bolt was recorded during the bolting-up of the joints. The torques are given in Tables 4, 5, 6 and 7. This necessitated a calibration of the torque measuring dial on the wrench. A BLACKHAWK 1000 ft. lb. torque indicator and torque wrench were used. Controlled values of torque were applied by suspending known weights at a measured lever distance. The dial indicator was found to give accurate readings within approximately ±10 foot-pounds, for a range of 0 to 600 foot-pounds.

2.3 Description of Test Joints

A double shear test joint is shown in Fig. 4. The two outside shear plates are 4" x 1" x 3 1/2", and the center
shear plate is made of two 4" x 1" x 3 1/2" plates tack welded together. The four inch width was used to conform with good design practice of using a $\frac{g}{d}$ (gage length divided by the diameter of the hole) ratio of approximately four. The hole diameters were drilled 1/16 inch larger than the corresponding bolt diameters. The bearing edges of the plates were milled to insure simultaneous bearing of the bolt on both outside plates.

Figure 5 shows the condition of the faying surfaces before being lubricated. The mill scale was wire brushed, and all burrs were removed.

2.4 Preparation of Test Joints

The joints were delivered by the fabricator in "bolt-to-ship" form, held together by temporary machine bolts. They were disassembled and cleaned with an ordinary machine shop solvent, and then faying surfaces were sprayed with Moly-Spray-Kote, a commercial lubricant. Elsewhere in this report the lubricant will be referred to as molycote.

The test joints were then assembled using bolts of the (Y and Z lots). The same letter-number identification appearing on each bolt was punched on all three plates of each corresponding joint, with two exceptions. The bolt identified as Z was tested in a joint identified as Z55,
and bolt Z7 was tested in a joint identified as Z27.

2.5 Design of Bolting-Up Apparatus and Bolting of Joints

It was necessary to design an apparatus that would grip the test joint during the bolting-up of the joints. The apparatus had to serve two basic functions: to maintain the joint in bearing or the "slipped position" upon the bolt, and to maintain all milled bearing surfaces parallel to one another. To accomplish this, the assembly shown in Figs. 6 and 7 was devised.

The main plate, 10" x 1/2" x 10", was milled to the same specifications as the bearing edges of the test joint. Two 1/2" x 1/4" x 3" bars were welded normal to the main plate to aid in positioning the joint as well as to support the joint when it is not subjected to clamping action. Two 1 inch diameter high strength bolts are welded to the main plates. Riding on the bolts is a 2 1/2" x 1" x 10" bar. This bar is forced against the joint by tightening the nuts on the two bolts. The 2 1/2" x 1" x 10" bar is milled to the same specifications as the bearing edge of the joint.

It was difficult to hold the milled bearing edges of the outer and inner plates exactly parallel, but any slight discrepancy was compensated somewhat by the spherical block head of the testing machine. As shown in paragraph 2.6, the
extremely small rotation that did occur was quantitatively observed from data taken during the tests.

The manner of control of the various tension loadings on the bolts was a slight deviation from that prescribed by the original proposal. The original proposal called for a small, nominal torque to be the zero value of loading on the bolt. After several attempts at this procedure it was found more feasible to use a nominal, low value of bolt elongation as the "zero condition". In other words, the three plies of the test joint were considered "drawn up" with the faying surfaces in good contact when the bolt began to elongate. Figure 6 shows a test joint being held by the bolting up assembly while a measurement of the bolt elongation is being made. The use of an open end wrench supplemented with an additional leverage bar permitted the application of torque with the bolt extensometer positioned on the bolt in the test joint. In a few cases, when the bolt extensometer reached approximately .0005 inches the "drawing-up" of the bolt reoccurred, that is, the nut turned but the bolt did not elongate. In these instances, the nut was loosened and the torque was reapplied.

The criterion for initial tension loading of the bolt, the turn-of-the-nut method, does not allow the same accuracy as is obtained with the bolt extensometer, i.e., it is
virtually impossible to apply precisely the prescribed turn-of-the-nut. Therefore, the extreme readings of the bolt extensometer, for any one loading condition, deviated from the average by as much as ± 3%. The resultant variation in the clamping forces, however, is negligible because the slope of the load-elongation curves for the statically pulled bolts is relatively small at loads corresponding to 1/2 turn-of-the-nut and higher. Tables 4 and 5, columns 4 and 5, give the measured elongations and corresponding bolt tensions. The bolt tensions were read from a direct tension vs. elongation curve using the elongation produced by the turn-of-the-nut as an argument.

2.6 Design and Operation of Displacement Measuring Instrumentation

The proper way to measure the deformation of the bolt is to measure the relative vertical movement of the plates of the test joint at the horizontal centerline of the bolt.

A simpler, but not quite exact way is to measure the relative vertical movement of the center plate with respect to the bed of the testing machine. This method is in error because it not only measures the shear and bending deformation of the bolt, but also includes the compressive shortening of the side plates.
The latter method was adopted and the effect of the compressive shortening was computed to be negligible.

Two desired characteristics of the relative displacement measuring apparatus were that it should function until the rupture of the bolt without the possibility of its being damaged, and, that the time required in preparation for each test be minimized because of the many tests that were to be conducted. The apparatus devised is shown in Figs. 8, 9 and 10. The 1" x 1/4" x 12" bar is held snugly against the center shearing plate of the joint by the tension in the two springs. As the center shear plate is displaced downward by the direct load from the testing machine, the 1" x 1/4" x 12" bar also moves downward, allowing the depressed plungers on the Ames dials to measure the displacement. The two 1" x 1" x 4" bars that are welded to the 5" x 1" x 11" main plate are spaced at such a distance as to permit a clearance for the center plate of the joint in the event it may displace below the level of the 1" x 1" x 4" bars. A 1" x 1 1/2" x 4" milled block is centered on top of the center shear plate of the joint in the event it may displace below the level of the top of the outside shear plates. The small bar seen between the 1" x 1/4" x 12" bar and the center plate of the test joint serves as a filler to replace two studs that were previously attached to the 1" x 1/4" x 12" bar for the
purpose of obtaining a two-point support. It was thought that a two-point support would create a better controlled direct contact with the center shear plate. However, it was observed that, not being able to get a true alignment among the Ames dial plungers, the springs in tension, and the studs on the bar, an overturning was occurring about the studs. The studs were therefore removed and replaced by the bar. No shortcomings of this arrangement were observed.

The Ames dials, which are positioned symmetrically with respect to the test joint, should show equal increments of displacement as the center plate of the test joint undergoes vertical displacement. In the event a flush alignment could not be attained while bolting-up the joint, as explained in paragraph 2.5, the center plate would undergo both rotation about the bolt and vertical translation. The average increment, obtained algebraically, of the two Ames dials is the value of the vertical translation, regardless of any rotation.
III. FIRST STAGE OF TESTING, IN ACCORDANCE WITH ORIGINALLY PROPOSED PROGRAM

3.1 General Procedure of Tests

A total of thirty-six tests were made, eighteen on 7/8 inch diameter bolts, and eighteen on 1 inch diameter bolts. Three tests were made on each size bolt at each of six different initial tensions in the bolts. The originally proposed tensions were used; zero tension, 90% of proof load, 1/2 turn-of-the-nut, 1 turn-of-the-nut, 1 1/2 turns-of-the-nut, and 2 turns-of-the-nut.

No specific manner of strain rate control was maintained during the various tests, although a general uniformity prevailed. Qualitatively, it can be stated that a slow rate of strain application was used, as was specified in the proposal for the research. The time rate of strain application was increased slightly as the slope of the load-displacement curve decreased. The load application was stopped to take displacement readings at each increment. A negligible amount of creep occurred at loads near the ultimate load. Approximate times for the tests were twenty minutes for the 7/8 inch diameter bolts and twenty-five minutes for the 1 inch diameter bolts.
3.2 Results of the Tests, and Interpretation

The results of these tests are summarized in Tables 4 and 5, and in Figs. 11 and 12, where the use of molycote has been indicated.

As can be seen from the results, no apparent trend exists in the relationship between the initial tension in the bolt and the value called $P_{ult}$, the ultimate double shear load imposed upon the bolt. Two possible explanations for this behavior were considered.

The first possibility was that the consideration of the friction force in the joint, when subtracted from $P_{ult}$, would reveal variation in the ultimate shearing strengths of the bolts subjected to various tensions; i.e.,

\[ P_{ult} = (\tau_{av.})(2A) + 2 \mu_f \]  

Eq. (1)

where:

- $P_{ult}$ = ultimate load delivered to the joint
- $\tau_{av.}$ = average shearing strength of the bolt
- $A$ = cross sectional area of the bolt
- $T$ = tension force in the bolt
- $\mu_f$ = friction coefficient of lubricated faying surface
The determination of the friction coefficient, and its subsequent use in Eq. 1 might show that the shear strength did vary with different bolt tensions.

The second possibility was that a considerable loss of the initial bolt tension was occurring prior to the attaining of $P_{ult}$. In this event, all bolts would have been subjected to comparable external loadings at ultimate load and at rupture load.

If, upon investigation, it is observed that the second possibility does exist, that is, the initial tension is relaxed, then the first possibility need not be considered.

If it is observed that the second possibility does not exist, then the first possibility must be considered.

To investigate the second possibility from at least a qualitative and possibly a quantitative point of view, tests could be conducted on test joints that did not have their faying surfaces lubricated. The existing clamping force when $P_{ult}$ occurs can be determined from the following:

$$\Delta P_{ult} = 2T (\mu_{ult} - \mu_e)$$  \hspace{1cm} \text{Eq. (2)}
where: \( \Delta P_{\text{ult}} \) = increase in \( P_{\text{ult}} \) that occurs when non-lubricated joints are used rather than lubricated joints

\( T \) = tension force in the bolt

\( \mu_{\text{l}} \) = friction coefficient of lubricated faying surface

\( \mu_{\text{n}} \) = friction coefficient of non-lubricated faying surface

It was decided to attempt an evaluation of the friction coefficients to investigate the above considerations.

Figure 13 shows the condition of the joint following a test. The flaky appearing material is both the molybdenum that has been changed into a leaf-like substance, and previously tight mill scale that has flaked from either local yielding or the shearing forces caused by the transmitting of friction. Considerable permanent deformation can be observed where the bolt was in bearing against the plate. The threads of the bolt caused permanent deformation to the circumferential area about the hole in the lap plate.

Figure 14 shows typical Load vs. Relative Displacement curves that were obtained. Readings of Relative Displacement were not taken after the ultimate load during the first 36 tests.
3.3 Performance and Evaluation of Instrumentation

Using a comparison of the increments on the two Ames dials as a criterion, it is felt that the apparatus used to measure the relative displacements performed very effectively during the tests. After the center shear plate had been slightly rotated until the bearing surface was flush, both dials showed the same increments repeatedly, even at very large increments.

IV. EVALUATION OF FRICTION COEFFICIENTS FOR LUBRICATED AND NON-LUBRICATED JOINTS

4.1 Method of Evaluation

A clamping device, which would simulate the clamping force of a torqued high strength bolt, was devised. It is shown in Fig. 15 where it is applying a clamping force to a test joint. By torquing the nuts of the 8 inch long, 1 inch diameter high strength bolts, clamping forces were attained that were of the same order of magnitude as existed in the previously tested joints.

To maintain control of the valve of the applied clamping force, the load-elongation characteristic of the 8 inch long
bolts was first determined. This was done in the same manner as was previously discussed in Paragraph 2.1. See Fig. 1. Three bolts were pulled. The maximum applied load in each case was 40 kips, which is well below the elastic limit of the bolts. All three bolts displayed the same slope of their load-elongation curves. The bolt extensometer was used to measure the elongations of the bolts as the clamping force was applied.

New joints were used for the tests. These joints were later used for further shear tests of bolts.

Four variables were considered in this series of tests: condition of surface (lubricated or non-lubricated), amount of clamping force, the rate of application of the applied load, and the effect of repeated stopping and restarting of the load application.

4.2 Results of Friction Tests

Many of the friction tests run were not part of a planned program, but were done as an afterthought to fully utilize clamped joints on which a planned or series of planned tests had been performed. Consequently, a complete
resume will not be attempted. It was observed, in general, that the latter three variables mentioned in Paragraph 4.1 did not affect the friction coefficients, although a slight scatter of results was observed.

The following summary of results was obtained:

<table>
<thead>
<tr>
<th>Surface Condition</th>
<th>Static Coefficient</th>
<th>Kinetic Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>molycoted</td>
<td>.11</td>
<td>.10</td>
</tr>
<tr>
<td>not molycoted</td>
<td>.40</td>
<td>.38</td>
</tr>
</tbody>
</table>

It may be mentioned that information obtained in correspondence with the Alpha Molykote Corporation, the manufacturer of the lubricant that was employed, was that the expected coefficient of static friction under the conditions existing in the joint was between 0.10 and 0.13. The conducted tests yielded a corresponding value of 0.11.
V. SECOND STAGE OF TESTING, INCLUDING EFFORTS TO EVALUATE THE POSSIBLE LOSS OF CLAMPING FORCE

5.1 Measurement of the Existing Bolt Tension at Shearing Loads Below the Ultimate Shear Load

Two independent methods, both of which could be utilized during the conducting of one test, were used to investigate the possible loss of clamping force. One method, based on the difference of the friction forces in lubricated and non-lubricated joints was discussed in Paragraph 3.2 and utilizes (1) of that paragraph. However, because of the scatter obtained for $P_{ult}$, in previous tests, quantitative values that can be computed are to be interpreted only as a general indication of the loss of initial tension.

The second method yielded results which are not confused by a scatter of values, but which depend on the validity of certain measurements. The method consisted of the following steps: stopping of the shear test immediately following the attainment of $P_{ult}$ by immediately releasing the hydraulic pressure in the testing machine so that the shearing load reduces to zero; measurement of the length of the bolt, as it remains clamping the joint, by use of the bolt extensometer; complete releasing of the existing tension in the bolt by the loosening of the nut; and, finally, the
measurement of the bolt with no tensile force acting on it. Between the initial application of shearing force and the attaining of \( P_{ult} \), the relative axial movement of the ends of the bolt, that is, the change in length of the bolt, is a result of several factors, but primarily the result of the large inelastic bending deformation. The other contributors, if any at all, can be associated with the loss of initial tension. When the ultimate shear load is removed, another slight change in length occurs from the elastic recovery of the bending strains, similar to the previous mentioned inelastic deformation and much smaller. (This is mentioned again later in this section.) At present, these deformations are not under consideration and are of no interest. The shortening that will occur when the nut will now be loosened is what is being considered.

The assumptions made were as follows:

(a) the load-elongation characteristics of the bolt, as the nut is being removed, is a linear relationship of the same slope as the linear segment of the load-elongation curve of the bolt when pulled in tension (see Figs. 2 and 3)
(b) the method of measuring the bolt lengths is not affected by the slight rotation of the bolt ends, i.e., the bolt extensometer seats in the same manner on the deformed bolt as on the non-deformed bolt.

(c) the change in length of the bolt, due to the elastic recovery of the flexure strains when the shear load is released, is negligible.

The first assumption is based on general knowledge of material behavior. The second assumption cannot be validated but appears reasonable when it is considered that the rotation that occurs during the elastic recovery is very small. The third assumption is verified by an approximate solution of the change in length of the bolt. This change is a higher order function of the vertical displacement for small vertical displacement for small vertical displacements, i.e., in the figure below of a cantilever deflection, $\Delta V$ is the small vertical deflection and $\Delta H$ is the higher order horizontal deflection:

![Diagram of cantilever deflection with $\Delta V$ and $\Delta H$ labels]
The approximation made was a conservative idealization of the complicated lateral load distribution and end couples acting on the bolt. The value found was .000417 inches for a 7/8 inch diameter bolt. This corresponds to an elastic shortening caused by the removal of 1.7 kips tension force.

As the test results have indicated that the ultimate shear strength does not vary with the initial tension, and as a new consideration, the loss of initial tension, has been introduced, it was decided that it was unnecessary to continue using the six criterions of initial tension. It was thought that more usable information could be obtained by conducting three tests at each of the four intermediate tensions, 90% of proof load, 1/2 turn-of-the-nut, 1 turn-of-the-nut, and 1 1/2 turns-of-the-nut and with non-lubricated mill scale faying surfaces. This was justified by considering that the two tension criterions eliminated represent less practical ranges of tension of high strength bolts. However, it may be pointed out that this consideration as applied to the criterion of 2 turns-of-the-nut initial tension, will, in the later recommendations of paragraph 12.3, be shown to be unjustified.

Initially, two tests were conducted on both the 7/8 inch and 1 inch bolts at each of the four different initial
bolt tensions. The tests were immediately stopped when $P_{ult}$ was reached. The values of $P_{ult}$ found displayed little variation with the values found using the lubricated joints. The variation did show a slightly higher trend over the eight tests, although in one case the value of $P_{ult}$ was found to be lower than the average of three tests on bolts of the same initial tension and using lubricated joints.

If no loss of initial tension would have occurred, the extreme increases would have been as follows: a minimum of approximately 20 kips for a 7/8 inch bolt at 90\% of proof load, and a maximum of approximately 42 kips for a 1 inch bolt subjected 1 1/2 turns-of-the-nut.

In the second phase of this test series, which was the measurement of the elastic recovery upon removal of the nut, the first noteworthy observation was the striking ease with which the nuts were removed from the bolts, indicative of a considerable loss of tension in the bolts.

Table 8 shows the value of the initial tension in the bolt, the elastic strain recovery in the bolt upon removal of the nut, and the corresponding tension in the bolt at $P_{ult}$. The latter value was obtained by multiplying the elastic recovery by the slope of the straight line segment
of the applicable load vs. elongation calibration curve. (See Figs. 2 and 3.) From the values of tension occurring in the bolt at $P_{ult}$, the value $P_{ult}$ should be approximately 5 kips higher for the non-lubricated joints. This value is obtained from Eq. (2) of paragraph 3.2. The value of 5 kips also approximates the general magnitude of the differences as actually found by test. However, the significance is questionable when consideration is given to the prevailing scatter. The actual values of $P_{ult}$ can be observed for comparison in Tables 5 and 7, and Figs. 11 and 12 along with the results of tests that will be discussed in Chapter 6, but are applicable to this discussion with no limitations or adjustments necessary.

5.2 Measurement of the Existing Bolt Tension at Shearing Loads Below the Ultimate Shear Load

It was thought that the accuracy of the evident large losses of clamping force could be confirmed by investigating the progressing loss of the initial bolt tension caused by progressively increasing shear loads below $P_{ult}$. In other words, show that at increasing shear loads below $P_{ult}$, the loss of clamping force approaches that obtained at $P_{ult}$ in a rational manner. Also it was thought that the information might be of general interest and later use.
Four of the remaining joints for both the 7/8 inch bolts and the 1 inch bolts were allocated for this further investigation of the loss of initial tension. As the bolts had been already torqued to the four values of initial tension that were mentioned before, some further torquing was done such that for both the 7/8 inch and 1 inch bolts, three joints were clamped by 1 turn-of-the-nut, and one joint by 1 1/2 turns-of-the-nut. The criterion for the percentages of \( P_{ult} \), to which the joints were to be subjected was prescribed in the following manner: conduct one test at a percentage of \( P_{ult} \) equivalent to the value at which the load-displacement curves of previous shear tests first displays a marked tendency toward non-linearity (approximately 80 kips for the 7/8 inch bolts and 100 kips for the 1 inch bolts); conduct a second test at a load equal to one-half the first mentioned; and conduct the third test at approximately halfway between the first mentioned and the average \( P_{ult} \) (100 kips for the 7/8 inch bolts and 115 kips for the one inch bolts). As will be shown later in this section, this was a judicious choice.

Upon observing the results of these tests, it was desired to obtain additional information to confirm an apparent trend of the loss of clamping force at various values of \( P_{ult} \). It was decided to attempt further tests with joints
that were used previously, that is, plates that had permanent bearing deformation. Five such tests were made on 7/8 inch bolts at 1 turn-of-the-nut initial tension. Two of the previous values of percentage of \( P_{ult} \) were repeated in an attempt to evaluate the possibility of the previously deformed joint as a variable.

The results obtained are shown graphically in Figs. 16, 17, and 18.

Figure 18 has the same information as in Fig. 16, but the manner of presentation is slightly different. This is for purposes of comparison with Ref. 1, page 1343, Fig. 6 which is based on research at the University of Washington. The research work at Washington included a series of tests on primarily four 7/8" bolt joints pulled in tension. Information regarding the manner of determining the "Residual bolt tension in percentage", the ordinate of the graph in Fig. 6, is not given.

The curve of Ref. 1 differs slightly from Fig. 18 of this report, at the extremities. The difference in the vicinity of small values of the abscissa can possibly be attributed to the tests at Washington being performed on joints that were not in an initially slipped position. Inspection of Table 3 of Ref. 1 reveals the average stress
on the net section of test specimens, which is the abscissa in the graph of Ref. 1, is in neighborhood of 20 ksi. At approximately this same value of abscissa, the straight line portion of the curve in Ref. 1 begins.

At the other extreme of the curve in Ref. 1 remains relatively straight, primarily because of extrapolation from earlier points. Actually, the authors of Ref. 1 could well have discontinued the straight line in favor of a concave upward curve. This then would correspond favorably with Fig. 8.

In paragraph 8.1, an attempt is made to explain the cause of the loss of initial tension.

Figures 19 and 20 show the bolts that were used for these tests as well as a typical ruptured bolt and a typical bolt tested to ultimate. These qualitatively show the relative deformation of bolts subjected to various degrees of double shear. The loadings on the bolts shown in Fig. 19 were, from top to bottom, 40 kips, 80 kips, 100 kips, ultimate, and ultimate. The loadings on the bolts shown in Fig. 20 were, from top to bottom, 50 kips, 100 kips, 118 kips, ultimate, and ultimate.
It is of interest to note that the slope of the curves of Figs. 16 and 17 become non-linear at approximately the same shearing force at which the load vs. displacement curves (see typical curves in Fig. 14) undergo large decreases in slope. This is a strong indication that the relaxation of the initial tension is closely linked with the shearing deformation of the bolt.

VI. INVESTIGATION OF THE LOAD-DISPLACEMENT RELATIONSHIP BETWEEN THE ULTIMATE LOAD AND RUPTURE

6.1 Reason for the Investigation

The final eight tests conducted, four tests each on both 7/8 inch bolts and 1 inch bolts, were tests to rupture. The prime objective was to determine the load-displacement characteristics between the ultimate load and the rupture load. The information is to be used in the investigation of large bolted joints. In previous tests, as an oversight, this data was not taken.

The values of $P_{ult}$ obtained also serve to statistically abet the scatter of results concerning the basic shear strength of a high strength bolt.
6.2 Description of the Results

A summary of the results is shown graphically in Fig. 21. As can be seen, the load drops off rapidly when compared to the rate of increase as \( P_{ult} \) is approached. Also, the slopes are generally the same although the rupture load varies. The drop of load for the \( 7/8 \) inch bolt was approximately twice that displayed by the 1 inch bolt.

VII. CONTROL OF THE RATE OF MOVEMENT OF THE CROSSHEAD

7.1 Method of Control Used

During the last eight tests, discussed in Chapter 6, it was decided to exercise a strict control of the rate of displacement application. A constant strain rate was not possible because of the general mechanics and functioning of the hydraulic pressure system. The criterion adopted was a constant value setting, which originally was hoped to lead to a constant rate of the movement of the crosshead. The setting chosen was one that approximated the initial settings of the earlier tests. Loading was not stopped to take readings.
7.2 Results

A marked decrease occurred in the rate of application of displacement at higher loads. The time required to run the individual tests was approximately doubled. When the results of these eight tests are compared to the results of the earlier tests, no change in the value of $P_{ult}$ was observed, nor was any variation of the load-displacement relationship observed.

VIII. DISCUSSION OF THE LOSS OF CLAMPING FORCE

The relaxation of the initial bolt tension is probably a very complex problem. Little success was achieved in finding a rational explanation of this behavior during the course of this investigation. However, two reasons for linking the relaxation very closely to the shearing deformation were observed.

As explained in paragraph 5.3, it appeared that the bolts used in tests at the University of Washington showed a negligible relaxation of initial tension until slip had occurred such that the bolts were in bearing. Also pointed out in paragraph 5.3, the slope of Fig. 18 which is the rate of relaxation with respect to the shearing force, becomes non-linear and rapidly decreases at approximately the same
shearing load at which the load displacement curves behave similarly. Thus the amount of relaxation is a function of the amount of bolt deformation, which is composed of bending and detrusion.

IX. COMPARISON OF RESULTS WITH OTHER RESEARCH

9.1 Tests Conducted at the University of Illinois

The only available published information concerning the shear strength of a single high strength bolt emanated from the University of Illinois. It is observed that neither the surface preparation of the faying surface, nor the initial bolt tension, has any apparent affect on the ultimate shear strength of the high strength bolt. However not enough tests were made to give conclusive results. Four tests were conducted on \( \frac{7}{8} \) inch bolts, two with 0 kips initial tension and two with 35 kips initial tension. The faying surfaces used were lacquered and dry mill scale.

It is interesting to note that the nominal shear stress found in the two-bolt butt joints at Illinois corresponds to a value of \( P_{ult} \) of approximately 10% less than the bolts tested during this program. However tension tests of four bolts at the University of Illinois from the same lot as those used in the shear tests, showed approximately a 10% higher ultimate tensile strength than those tested at Lehigh
for this program. A possible explanation for this may be that both bolts in the two-bolt butt joints were not subjected to the same shear loadings, but perhaps one bolt was subjected to a slightly larger shearing deformation and hence a slightly larger shearing stress. This is quite possible in the Illinois joints as the joints were not assembled in a slipped position. Therefore the bolt deformations would be the same in both joints only if the centerlines of both bolts were exactly similarly located with respect to the perimeter of the hole.

9.2 Tests Conducted at the University of Washington

Reference 1, dealing with high strength bolt studies at the University of Washington, although not concerned with the basic shear strength of a single high strength bolt, offers some information concerning bolt relaxation that is relative to the work of this program.

It is discussed in paragraph 5.3 and briefly mentioned in Chapter 8. Nothing further is to be added.
X. TESTS ON COMPARABLE RIVETED JOINTS

10.1 Description of Test Joints

Current design procedure allows the substitution of one high strength bolt for one rivet of the same diameter. For purposes of comparing the behavior of a single rivet in double shear with the behavior of a high strength bolt under similar loading conditions, five tests were conducted on riveted joints, 7/8 inch rivets were used, and the plates of the riveted joints were of the same dimensions as those of the bolted joints. The faying surfaces of the riveted joints were mill scale. The joints were riveted according to ordinary shop riveting practice and were riveted at the same time as large joint BR2 using the same rivet stock and same procedure.

10.2 Structural Properties of Rivets

Table 9 gives the structural properties of the rivets as determined from laboratory tests on .505 inch diameter coupons cut from the formed rivet prior to driving.
10.3 Results

The average ultimate load of the five tests was 59.9 kips, which corresponds to an ultimate shearing stress of 49.8 ksi. The average ultimate load of the 7/8 inch bolts tested was slightly in excess of 100 kips.

The shearing deformation of the rivet at ultimate load was approximately the same as that observed in the bolts, approximately 1/4 inch.

XI. SUMMARY AND CONCLUSIONS

11.1 General Summary of Shear Tests

Tables 4, 5, 6 and 7 and Figs. 11 and 12 completely present the results of the shear tests that were conducted. Two prominent observations are that the double shear ultimate resistance appears to be independent of initial bolt tension, and that the double shear ultimate resistance is slightly higher when the mill scale faying surfaces are not lubricated.
11.2 Basis for the Evaluation of the Basic Shear Strength of a Single High Strength Bolt Subjected to Double Shear, and its Application

As shown in Table 1 the average ultimate tensile strength of the 7/8 inch bolts is 13.6% above the minimum requirements of the ASTM, and the 1 inch bolts are 4.9% above this same requirement. These values are based on static pulling tests conducted on five 7/8 inch bolts and five 1 inch bolts. Furthermore, from Table 10, inspection of the column called "\( \tau_{\text{eff}} \), Eff. Shear Stress", \( (\tau_{\text{eff}} = \frac{P_{\text{ult}}}{2A}) \) which is composed of averages of the indicated groupings, it is observed that the 7/8 inch bolts have approximately 10% greater strength than the 1 inch bolts. (A more exact percentage is not being considered because of the two different surface conditions involved.)

Now it is necessary that a common basis be established whereby the results from this research can be applied to determining the basic shear strength of a single high strength bolt in general. It seems logical from the above information, and somewhat necessary in the abscissa of further information, to think in terms of an effective ultimate shear stress \( (\tau_{\text{eff}} = \frac{P_{\text{ult}}}{2A}) \) as a percentage of the ultimate tensile strength. This has been done in Table 10. Included in this table is information concerning tests on 1 1/8 inch bolts.
for the 1 1/8 inch bolts is the average of three shear tests made on non-lubricated joints and subjected to an initial tension of 1/2 turn-of-the-nut. √ is based on five static tension tests, similar to those discussed in paragraph 2.1.

From the last column of Table 10 it is observed that for non-lubricated joints, the effective shear stress is 70% of the ultimate tensile stress. Applying this to the existing ASTM requirements of ultimate tensile strength gives values for a single bolt subjected to double shear:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7/8&quot;</td>
<td>115</td>
<td>80.05</td>
<td>96.85</td>
</tr>
<tr>
<td>1&quot;</td>
<td>115</td>
<td>80.05</td>
<td>126.5</td>
</tr>
<tr>
<td>1 1/8&quot;</td>
<td>115</td>
<td>80.05</td>
<td>160.1</td>
</tr>
</tbody>
</table>
XII. RECOMMENDATIONS

12.1 General

The recommendations made will not be primarily concerned with design. This is because of the complex behavior of a joint when more than one bolt is used, a problem that is being investigated in a different phase of Project 271.

12.2 Design Application

Strength considerations of a high strength bolt subjected to double shear should be considered independent of the initial tension used. The ultimate shear strength for minimum strength bolts (as determined by the ultimate tensile strength) should be 80 ksi. See paragraph 11.2.

12.3 Changes in Current Field Practice

From the standpoint of strength of the bolt and slip of the connection, it might be advisable to increase the turn-of-the-nut from the current standards, such that the applied number of turns induces approximately the maximum tension as found in load-elongation tests for various size bolts and various size grips. This would not lessen the ultimate strength of the joint, and would provide a maximum of clamping force at the working load.
12.4 Further Research

Research should be conducted to determine the cause of bolt relaxation in the anticipation of the possible elimination of bolt relaxation. If bolt relaxation could be eliminated or considerably reduced, it would increase the ultimate shear resistance of a high strength bolt substantially. For example, consider a 7/8 inch bolt that has an initial tension of 50 kips, slightly less than the specification minimum ultimate of 53.15$k$, and a joint that has a coefficient of friction of $0.40$ between its plates. Assume that normally the initial tension relaxes to 10 kips. If the relaxation is eliminated, the increase in ultimate bolt shear resistance is $40^k \times 2 \times 0.40 = 32^k$. This represents approximately a 30% increase.

12.5 Application to Other Bolt Research

Studies of the stress distribution in double shear bolted connections might possibly be investigated using the criterion of the loss of initial tension to determine the shear stresses in the bolts. This could be done only after further research to establish consistency in the relationship between the loss of initial tension and the percentage of the ultimate shearing stress applied to the bolt.
XIII. APPENDIX

13.1 References

1. Hechtman, R. A.
   Young, D. R.
   Chin, A. G.
   Savikko, E. R.

2. Munse, D. H.
   Wright, D. T.
   Newmark, N. M.
13.2 TABLES
### TABLE 1 - PROPERTIES OF BOLTS

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
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</tr>
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<tbody>
<tr>
<td>Shear Jigs J1</td>
<td>Z</td>
<td>7/8</td>
<td>60.4</td>
<td>53.15</td>
<td>113.6</td>
<td>130.7</td>
<td>115.0</td>
</tr>
<tr>
<td>Shear Jigs J2</td>
<td>Y</td>
<td>1</td>
<td>73.1</td>
<td>69.70</td>
<td>104.9</td>
<td>120.6</td>
<td>115.0</td>
</tr>
</tbody>
</table>

Note: All bolts satisfied minimum proof load requirement of specification
* Area calculated from the mean root and pitch diameter of class 3 external threads
  \[ A = \pi \left( \frac{1}{2} \text{Pitch Dia.} - \frac{3}{16} \text{Height of V Thread} \right)^2 \]

### TABLE 2 - RESULTS OF COUPON TESTS OF SHEAR TEST POINT PLATE MATERIAL

<table>
<thead>
<tr>
<th>Coupon Number</th>
<th>Static Yield Level psi</th>
<th>Yield Stress 0.2% Offset psi</th>
<th>Ultimate Tensile Strength psi</th>
<th>Per Cent Elongation in &quot;8&quot;</th>
<th>Per Cent Reduction in Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1 (7/8&quot; Bolts)</td>
<td>37 800</td>
<td>39 900</td>
<td>67 200</td>
<td>32.5</td>
<td>57.4</td>
</tr>
<tr>
<td>J2 (1&quot; Bolts)</td>
<td>38 000</td>
<td>40 100</td>
<td>66 800</td>
<td>28.5</td>
<td>56.7</td>
</tr>
<tr>
<td>J3 (7/8&quot; Rivets)</td>
<td>38 600</td>
<td>41 200</td>
<td>67 700</td>
<td>28.0</td>
<td>56.3</td>
</tr>
</tbody>
</table>
### TABLE 3 - AVERAGE MILL TEST RESULTS
OF TEST JOINT MATERIAL

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<th>Property</th>
<th>Value</th>
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<tr>
<td>Yield Point</td>
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<td>Ult. Tens. Stress</td>
<td>68,970 psi</td>
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<td>Elongation in 8&quot;</td>
<td>26.5%</td>
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<td>Bolt No.</td>
<td>Loading Criterion On Bolt</td>
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<td>---------</td>
<td>---------------------------</td>
</tr>
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<td>Z 26</td>
<td>0</td>
</tr>
<tr>
<td>Z 28</td>
<td>0</td>
</tr>
<tr>
<td>Z 31</td>
<td>90% Proof</td>
</tr>
<tr>
<td>Z 32</td>
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<td>90% Proof</td>
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<td>Z 36</td>
<td>1/2 Turn</td>
</tr>
<tr>
<td>Z 37</td>
<td>1/2 Turn</td>
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<tr>
<td>Z 38</td>
<td>1/2 Turn</td>
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<tr>
<td>Z 41</td>
<td>1 Turn</td>
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<tr>
<td>Z 42</td>
<td>1 Turn</td>
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<tr>
<td>Z 44</td>
<td>1 Turn</td>
</tr>
<tr>
<td>Z 43</td>
<td>1-1/2 Turns</td>
</tr>
<tr>
<td>Z 46</td>
<td>1-1/2 Turns</td>
</tr>
<tr>
<td>Z 47</td>
<td>1-1/2 Turns</td>
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<td>Z 51</td>
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</tr>
<tr>
<td>Z 52</td>
<td>2 Turns</td>
</tr>
<tr>
<td>Z 53</td>
<td>2 Turns</td>
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</table>

* Ultimate tensile strain exceeded
<table>
<thead>
<tr>
<th>Bolt No.</th>
<th>Loading Criterion on Bolt</th>
<th>Torque (ft-lb.)</th>
<th>Total Elongation of Bolt (inches)</th>
<th>Tension in Bolt (kips)</th>
<th>Pull of Bolt (kips)</th>
<th>Nominal Shear Stress of Bolts (ksi)</th>
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<tr>
<td>Y 60</td>
<td>0</td>
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<td>0</td>
<td>0</td>
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<td>76.4</td>
</tr>
<tr>
<td>Y 61</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>128.0</td>
<td>81.5</td>
</tr>
<tr>
<td>Y 62</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>124.5</td>
<td>79.3</td>
</tr>
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<td>Y 65</td>
<td>90% Proof</td>
<td>620</td>
<td>0.0105</td>
<td>42.9</td>
<td>128.5</td>
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<td>Y 66</td>
<td>90% Proof</td>
<td>730</td>
<td>0.0103</td>
<td>42.1</td>
<td>123.0</td>
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<td>Y 67</td>
<td>90% Proof</td>
<td>650</td>
<td>0.0102</td>
<td>41.7</td>
<td>128.0</td>
<td>81.5</td>
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<tr>
<td>Y 70</td>
<td>1/2 Turn</td>
<td>780</td>
<td>0.0377</td>
<td>59.2</td>
<td>126.5</td>
<td>80.5</td>
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<tr>
<td>Y 71</td>
<td>1/2 Turn</td>
<td>800</td>
<td>0.0315</td>
<td>57.6</td>
<td>126.5</td>
<td>80.5</td>
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<tr>
<td>Y 72</td>
<td>1/2 Turn</td>
<td>820</td>
<td>0.0350</td>
<td>58.6</td>
<td>125.0</td>
<td>79.6</td>
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<td>Y 75</td>
<td>1 Turn</td>
<td>890</td>
<td>0.0897</td>
<td>66.8</td>
<td>124.5</td>
<td>79.3</td>
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<td>1180</td>
<td>0.0869</td>
<td>66.4</td>
<td>124.5</td>
<td>79.3</td>
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<td>Y 77</td>
<td>1 Turn</td>
<td>1090</td>
<td>0.0825</td>
<td>66.1</td>
<td>120.5</td>
<td>76.7</td>
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<td>1-1/2 Turns</td>
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<td>126.5</td>
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<td>1-1/2 Turns</td>
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<td>0.1292</td>
<td>69.5</td>
<td>123.5</td>
<td>78.7</td>
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<td>Y 82</td>
<td>1-1/2 Turns</td>
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<td>69.9</td>
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<tr>
<td>Y 85</td>
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<td>0.1876</td>
<td>72.2</td>
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<td>81.8</td>
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<tr>
<td>Y 86</td>
<td>2 Turns</td>
<td>1110</td>
<td>0.1929</td>
<td>72.3</td>
<td>124.0</td>
<td>79.0</td>
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<tr>
<td>Y 87</td>
<td>2 Turns</td>
<td>1180</td>
<td>0.1956</td>
<td>72.4</td>
<td>119.5</td>
<td>76.1</td>
</tr>
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</table>
### Table 6 - Shear Tests on 7/8" Bolts, Non-Lubricated Test Joints

<table>
<thead>
<tr>
<th>Bolt No.</th>
<th>Loading Criterion on Bolt</th>
<th>Torque (ft-lb)</th>
<th>Total Elongation of Bolt (inches)</th>
<th>Tension in Bolt (kips)</th>
<th>Pult' of Bolt (kips)</th>
<th>Nominal Shear Stress of Bolts (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z 29</td>
<td>90% Proof</td>
<td>470</td>
<td>0.0098</td>
<td>32.8</td>
<td>114.0</td>
<td>94.8</td>
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<tr>
<td>Z 34</td>
<td>90% Proof</td>
<td>380</td>
<td>0.0097</td>
<td>32.5</td>
<td>112.5</td>
<td>93.5</td>
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<tr>
<td>Z 35</td>
<td>1/2 Turn</td>
<td>660</td>
<td>0.0224</td>
<td>54.0</td>
<td>114.0</td>
<td>94.8</td>
</tr>
<tr>
<td>Z 39</td>
<td>1/2 Turn</td>
<td>720</td>
<td>0.0243</td>
<td>54.5</td>
<td>111.0</td>
<td>92.4</td>
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<tr>
<td>Z 45</td>
<td>1 Turn</td>
<td>560</td>
<td>0.0602</td>
<td>60.9</td>
<td>107.0</td>
<td>89.0</td>
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<tr>
<td>Z 49</td>
<td>1 Turn</td>
<td>740</td>
<td>0.0638</td>
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<td>96.5</td>
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<td>Z 50</td>
<td>1-1/2 Turns</td>
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<td>0.1162</td>
<td>61.6</td>
<td>111.0</td>
<td>92.4</td>
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<td>0.1191</td>
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<td>1-1/2 Turns</td>
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<td>113.5</td>
<td>94.5</td>
</tr>
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<td>Bolt No.</td>
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<td>Torque (ft-lb)</td>
<td>Total Elongation of Bolt (inches)</td>
<td>Tension in Bolt (kips)</td>
<td>Purlt of Bolt (kips)</td>
<td>Nominal Shear Stress of Bolts (ksi)</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------</td>
<td>---------------</td>
<td>----------------------------------</td>
<td>------------------------</td>
<td>---------------------</td>
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</tr>
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<td>Y 63</td>
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<td>79.6</td>
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<td>122.24</td>
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<td>0.0352</td>
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<td>125,5</td>
<td>80.0</td>
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<td>Y 79</td>
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<td>65.8</td>
<td>130.25</td>
<td>83.0</td>
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<td>Y 84</td>
<td>1-1/2 Turns</td>
<td>1070</td>
<td>0.0830</td>
<td>66.2</td>
<td>135.25</td>
<td>86.2</td>
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<td>Y 88</td>
<td>2 Turns</td>
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<td>0.1336</td>
<td>69.8</td>
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<td>0.1356</td>
<td>70.0</td>
<td>130.25</td>
<td>83.0</td>
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<td>Y 234</td>
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<td>0.1386</td>
<td>70.1</td>
<td>127.75</td>
<td>81.3</td>
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<td>Bolt Diameter</td>
<td>Loading Criterion on Bolt</td>
<td>Initial Tension</td>
<td>Elastic Strain Recovery</td>
<td>Tension in Bolt at Pult</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>---------------------------</td>
<td>-----------------</td>
<td>------------------------</td>
<td>------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/8 inches</td>
<td>90% Proof</td>
<td>32.5 kips</td>
<td>0.0029 inches</td>
<td>9.70 kips</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/8 inches</td>
<td>1/2 Turn</td>
<td>53.8 kips</td>
<td>0.0025 inches</td>
<td>8.36 kips</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/8 inches</td>
<td>1 Turn</td>
<td>60.7 kips</td>
<td>0.0029 inches</td>
<td>9.70 kips</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/8 inches</td>
<td>1-1/2 Turns</td>
<td>61.5 kips</td>
<td>0.0030 inches</td>
<td>10.05 kips</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 inches</td>
<td>90% Proof</td>
<td>42.5 kips</td>
<td>0.0015 inches</td>
<td>6.12 kips</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 inches</td>
<td>1/2 Turn</td>
<td>58.2 kips</td>
<td>0.0023 inches</td>
<td>9.39 kips</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 inches</td>
<td>1 Turn</td>
<td>66.4 kips</td>
<td>0.0020 inches</td>
<td>8.17 kips</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 inches</td>
<td>1-1/2 Turns</td>
<td>69.5 kips</td>
<td>0.0019 inches</td>
<td>7.76 kips</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## TABLE 9 - COUPON TESTS ON RIVET MATERIAL

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Static Yield Level ksi</th>
<th>0.2% Offset Yield Stress ksi</th>
<th>Ultimate Stress ksi</th>
<th>Per Cent Elongation in 2&quot;</th>
<th>Per Cent Reduction in Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47.25</td>
<td>48.1</td>
<td>55.35</td>
<td>34.0</td>
<td>69.3</td>
</tr>
<tr>
<td>2</td>
<td>46.00</td>
<td>47.0</td>
<td>53.50</td>
<td>35.5</td>
<td>68.8</td>
</tr>
<tr>
<td>3</td>
<td>46.75</td>
<td>48.0</td>
<td>54.90</td>
<td>35.0</td>
<td>69.8</td>
</tr>
<tr>
<td>Avg.</td>
<td>46.70</td>
<td>47.7</td>
<td>54.60</td>
<td>34.8</td>
<td>69.3</td>
</tr>
<tr>
<td>Mill</td>
<td>41.4</td>
<td>57.00</td>
<td>33.5 in 8&quot;</td>
<td>68.1</td>
<td></td>
</tr>
<tr>
<td>ASTM</td>
<td>28.0 min.</td>
<td>52.00</td>
<td>24.0 in 8&quot;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 10 - COMPARISON OF ULTIMATE SHEAR STRESS WITH ULTIMATE TENSILE STRENGTH

<table>
<thead>
<tr>
<th>Bolts</th>
<th>Faying Surface</th>
<th>$\tau$, Eff. Shear Stress ksi</th>
<th>$\sigma$, Tensile Stress on Stress Area ksi</th>
<th>$\frac{\tau}{\sigma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/8&quot; Lot Z</td>
<td>Mill Scale</td>
<td>93.2</td>
<td>130.7</td>
<td>0.714</td>
</tr>
<tr>
<td>7/8&quot; Lot Z</td>
<td>With Moly</td>
<td>88.2</td>
<td>130.7</td>
<td>0.675</td>
</tr>
<tr>
<td>1&quot; Lot Y</td>
<td>Mill Scale</td>
<td>81.6</td>
<td>120.6</td>
<td>0.676</td>
</tr>
<tr>
<td>1&quot; Lot Y</td>
<td>With Moly</td>
<td>79.4</td>
<td>120.6</td>
<td>0.659</td>
</tr>
<tr>
<td>1-1/8&quot; Lot G</td>
<td>Mill Scale</td>
<td>84.0</td>
<td>119.5</td>
<td>0.703</td>
</tr>
</tbody>
</table>
13.3 FIGURES
Figure 1 - BOLT CALIBRATION SETUP
Bolt Calibration
Z-Series (7/6" ϕ)

Average of Five Tests
Extreme Tests

Load (Kips)

Total Elongation (Inches)

FIGURE 2
Bolt Calibration  
Y-Series (1" φ)  

Average of Five Tests  
--- Extreme Tests

Load (Kips)  
0  20  40  60  80

Total Elongation (Inches)  
0  0.10  0.50  1.00  1.50  2.00  2.50  3.00  3.50  4.00

FIGURE 3
Figure 4 - TEST JOINT

Figure 5 - FAYING SURFACE BEFORE TEST
Figure 6 - BOLTING-UP APPARATUS AND BOLT EXTENSOMETER
FIGURE 7 - Bolting-Up Apparatus
Figure 8 - SHEAR TEST INSTRUMENTATION

Figure 9 - SHEAR TEST INSTRUMENTATION
FIGURE 10 - Shear Test Instrumentation

Bracket Typical for all Posts
Double Shear Resistance (Kips)

Elongation of Bolt (Inches/4 inch grip)

**Ultimate Double Shear Resistance, \( \frac{3}{16} \)" H.S. Bolt**

- Mill Scale
  - Faying Surface \( (d_t = 0.01) \)
  - With Molykote \( (d_t = 0.07) \)

- Avg. Mill Scale: \( 111.9 \) k
- Avg. Molykote: \( 105.8 \) k

**FIGURE 11**
Figure 13 - LUBRICATED PAYING SURFACE AFTER TEST
Shear Load vs. Shearing Deformation

FIGURE 14
Figure 15 - CLAMPING ARRANGEMENT FOR FRICTION TESTS
**Shear Force on Joint (Kips)**

**Loss of Clamping Force (Kips)**

---

**Relaxation of Clamping Force, 3/8 Inch Bolts**

- Used Joint
- New Joint

---

FIGURE 16
Relaxation of Clamping Force, 1 Inch Bolts

FIGURE 17
Fig. 19 - 7/8-INCH BOLTS SUBJECTED TO VARYING SHEAR LOADINGS
Figure 20 - 1-INCH BOLTS SUBJECTED TO VARYING SHEAR LOADINGS
Shear Load vs. Shear Deformation Between Ultimate and Rupture

FIGURE 21