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LARGE BOLTED JOINTS

STATIC TENSION TESTS OF LONG BOLTED JOINTS

by

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FEBRUARY 1960

FRITZ LABORATORY REPORT No. 271.8
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John L. Rumpf

This work has been done in conjunction with the Large Bolted Joints Project at Lehigh University which is sponsored financially by the Pennsylvania Department of Highways, the Bureau of Public Roads, and the American Institute of Steel Construction, and in an advisory capacity by the Research Council on Riveted and Bolted Structural Joints.

Fritz Engineering Laboratory
Department of Civil Engineering
Lehigh University
Bethlehem, Pennsylvania

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SYNOPSIS

This paper is a detailed report of tests of twelve long butt joints fabricated with A7 steel and fastened with 7/8" A325 bolts. Bolt shear areas were proportioned using a tension-shear ratio of 1/1.10. The major variable of the test series was joint length so that this report presents the first systematic study of the effect of joint length on bolt performance. Additional data were collected to provide information on joint slip characteristics. Possible ultimate strength design procedures based on these test results are offered.
1. INTRODUCTION

1.1 Background

Consider a structural joint with several fasteners in line with the load. The usual design assumption is that each fastener carries an equal share of the working load. However, it can be shown theoretically and verified experimentally that the end fasteners carry a higher percentage of the working load, the joint still behaving elastically. As the load is increased, the more highly stressed end fasteners deform and thereby effect a redistribution of load among the other fasteners. The amount of redistribution is a function of the fasteners' ability to deform without fracture. It has been found experimentally that ordinary low carbon rivets are ductile enough to permit redistribution to the point that at ultimate load each rivet is carrying approximately an equal share of the load providing the joint is not exceptionally long.

If this complete redistribution takes place it is possible to predict the ultimate fastener load ($P_{uf}$) for a joint by simply multiplying the number of fasteners ($n$) by the resistance value of a single fastener ($R_1$). $R_1$ can be determined by experiment with single fastener connections. Thus,

$$P_{uf} = nR_1$$
If complete redistribution of load cannot take place among the fasteners because of inflexibility, the actual ultimate load of the connection can be expected to fall short of that predicted as above. Saying this in another way, if the observed ultimate fastener load \( (P) \) is divided by the number of fasteners \( (n) \), the value of \( R \) determined will be an average one and less than \( R_1 \).

\[
\frac{P}{n} = R_{avg} < R_1
\]

Although \( R_{avg} \) is less than \( R_1 \), at least one end fastener must be loaded to a value of \( R_1 \) in order for the failure load to be reached.

The manner of load distribution among the fasteners is demonstrated during testing by the mode of failure. Some joints will fail completely by apparent simultaneous shearing of all the fasteners indicating a fairly complete redistribution; others will fail by shearing of one or more end fasteners while the rest of the joint remains intact. As joints become longer the fasteners must be more and more ductile to accomplish this redistribution of load. If the end fasteners lack this ductility, they will shear at lower and lower values of \( R_{avg} \) and the joint experiences "premature" failure. This "premature" failure has been termed "unbuttoning" since failures begin at the ends and
proceed toward the center of the joint as one would unbutton a shirt.

Unbuttoning has been noticed in long riveted joints. Current specifications do not require the use of a reduced \( R_{avg} \) for the design of a long riveted joint. Because the A325 bolt is made of higher strength material than the rivet, one might suspect that ductility has been sacrificed and therefore unbuttoning might be a more serious problem in bolted joints.

Tests of large bolted joints having increasing numbers of bolts in line have been made in order to determine how the value of \( R_{avg} \) is affected. In order to be able to visualize this variation in \( R_{avg} \) as the joint length increases, the quotient \( R_{avg} \) divided by \( R_1 \), termed the unbuttoning factor \( U \), will be plotted against joint length. This plot will indicate the relationship which exists between the shear resistance of high strength bolts and joint length.

1.2 Scope

These tests represent the second phase of the testing program on "Large Bolted Joints" being conducted at Fritz Laboratory, Lehigh University. The first phase consisted of full scale tests of compact butt type joints\(^{(1)}\) to determine proper working stresses for high strength bolts.
since the "one bolt for one rivet" rule of the 1954 specifications(2) did not result in a balanced design. These tests have been completed and show that the allowable shear stress may be safely increased from 15,000 psi to 22,000 psi (T/S ratio = 1.00 : 1.10) based on an ultimate design concept as long as shearing occurs through the full shank. However, there were no joints with this T/S ratio which were longer than 14" between the end rows of bolts.

In order to obtain test data concerning the performance of long joints designed at a T/S ratio of 1.00 : 1.10, the "unbuttoning" tests were formulated with the main variable being the number of bolts in line. These tests were designated "D-Series" and subdivided into two categories:

(1) Part a - variable width
(2) Part b - variable grip

This notation arises in the following way. If the T/S ratio is to be held constant when the number of bolt shearing areas is increased there must be a corresponding increase in the area of the net section. There are two alternatives: (1) hold the thickness or grip constant and vary the width or (2) hold the width constant and vary the grip.

All test joints were completely instrumented to pro-
vide slip, plate strain, overall elongation and load partition data. This report will deal primarily with observations based on ultimate joint strength and eliminate most of the plate strain data which will be included later in a report on the load partition throughout bolted joints.

1.3 Survey of Literature

Evidence of the unbuttoning problem is not common in the literature on bolted connections since few full scale tests of large bolted joints have been conducted. In 1959, a report(3) of a test on a long joint conducted at the University of Washington recorded the unbuttoning phenomenon in a bolted connection having thirteen rows of bolts in a pattern 48" long. The configuration of the pattern was three bolts per row alternated with one bolt per row, and the grip was 6".

In previous full scale tests conducted at Lehigh(1) the tendency for end fasteners to fail in such a manner that the remainder of the joint remains intact was noted in most joints which experienced bolt failure. In only two instances did an apparently simultaneous shear failure take place. However, since these tests were conducted with compact joints (none longer than 14") the average shear stress at first bolt failure was not greatly affected by
In 1940, R.E. Davis, G.B. Woodruff and H.E. Davis(4) reported instances in which premature fastener failure had occurred in joints using 7/8" rivets. They pointed out that since at ultimate load each rivet was carrying approximately an equal share of the load, excessive strain rather than excessive stress causes end fasteners to fail.

Summarizing, in tests of large bolted and riveted joints premature failure of end fasteners has been experienced. In long bolted joints a similar effect might be observed.
2. DESCRIPTION OF TEST JOINTS

2.1 D-Series - Part a

In the D-Series - Part a tests, joint length and width were the chief variables. Eight test joints ranging from two lines of three bolts to two lines of ten bolts, each having a pitch distance of 3 1/2" and a grip of 4" were included in this series (Fig. 1). The specimens were actually half of a double shear butt joint having two one-inch plates combined to make up the inner main plates and having outer lap plates of one-inch thickness. The fasteners in each case were 7/8" A325 bolts of standard length under head and having the minimum length of thread.(2)

The design of the test specimens proceeded as follows:

For balanced design the ultimate load of the net section of the plates must be equal to the ultimate load of the bolts.

\[
P_{\text{un}} = P_{\text{ub}}
\]

\[
A_n \sigma_n = A_b \tau
\]

\[
\frac{\sigma_n}{\tau} = \frac{A_b}{A_n} = \frac{T}{S}
\]

\[
\frac{T}{S} \times A_n = A_b
\]

For two lines of 7/8" bolts, 15/16" holes, gage equal to one-half plate width and T/S = 1/1.10 for balanced design(1)

\[
\frac{1}{1.10} \left[ \left( \frac{g}{2} + g + \frac{g}{2} \right) - 2 \times \frac{15}{16} \right] 2 \times 1 = 2n (2 \times 0.601)
\]
\[ g = 0.661n + 0.938 \]

and

\[ w = 2g = 2(0.661n + 0.938) \quad \ldots \quad (2.1) \]

As \( n \), the number of bolts in line, is varied from 3 to 10 the width \( (w) \) varies from 5.84" to 15.10". All plates were cut and milled to the proper width from 24" U.M. plates. Figure 1 outlines the nominal dimensions for each specimen.

The specimen numbering system was as follows: the joint with three bolts in line was designated D31. The D indicates D-Series of tests while the first number 3 designates the number of bolts in line. Since there were fabricated two identical joints of each configuration, the number 1 indicates the first of these. To the present time none of the second specimens have been tested.

2.2 D-Series - Part b

In the D-Series - Part b, joint length and thickness were the chief variables. In order to keep the width constant and the T/S ratio constant at 1/1.10 it became necessary to vary the thickness as the number of bolts in line was increased. Preliminary computations showed a width of 9 7/8" to be good. Then, following a procedure similar to that used to derive Eq. 2.1, it follows that

\[ \frac{T}{S} = \frac{2.40n}{16} = \frac{0.15n}{t} \quad \ldots \quad (2.2) \]
Using $T/S$ to be $1/1.10$, the thickness required for balanced design can be found. For practical reasons this thickness must sometimes be increased or decreased slightly to the nearest $1/16"$. The tension-shear ratio is then also increased or decreased accordingly so that the final ratios are only approximately $1/1.10$. With $n = 6$ the resulting design is equivalent to the 6 bolt joint of Part a. Since long joints are under study no joints with less than 6 bolts in line were proposed for this part.

Ordinarily thick grips will occur, in practice, in built up types of members. In order to insure better properties of the steel the thicknesses of single plates was restricted to less than one-inch. For this reason the thick plates of these joints were built up of a number of plies of thinner material. Figure 2 is a general detail of the four joints included in Part b. In cases where two different thicknesses of material were needed the thinner of the two ($t_o$) was always placed on the outside.

Again, the numbering system for these specimens was patterned after that of Part a. The series began with a joint having seven bolts in line; thus it was called D701. The number 7 designates seven bolts in line while the number 1 indicates the first of two identical joints having seven bolts in line. The number 0 was chosen to indicate a variable grip joint as opposed to the joint D71 of the variable width series. As before, none of the second joints have been tested.
3. **MATERIAL PROPERTIES**

3.1 **Plates**

The plate material used for the D-Series - Part a, was ASTM A7 structural steel cut from universal mill strips 24" x 1" and approximately 72'-0" long. With this size plate material it was possible to cut plate for four test specimens from one 72'-0" strip while still allowing extra plate stock for coupon testing and fill material. Figure 3 is a schematic diagram of the cutting scheme used for test specimens and coupon material. Plates were burned to a rough width and then machined to the finished dimension.

Two plate coupons were cut from the material of each joint tested. These coupons were 1" in thickness and milled to 1 1/2" in width so that the stress area was 1.5 square inches. The coupons were tested in a 120k testing machine with an autographic strain recording device measuring strains over an 8" gage length. The recorder was used throughout the elastic and plastic ranges while the strain rate was 0.05 inches per minute. Then the strain rate was increased to 0.2 inches per minute to speed testing through the strain hardening range while strain readings were taken with a dividers and steel scale. The material exhibited a continuously rising yield zone. Figure 4 is a typical stress-strain curve for plate material of the D-Series - Part a.
Table 1 shows a complete listing of all coupon properties. Both the static yield stress level at 0.5% strain and the 0.2% offset yield stress have been recorded. According to the Lehigh University tests the average static yield level stress at 0.5% strain and the average yield stress at 0.2% offset were both lower than the ASTM minimum yield stress of 33 ksi while the mill test yield stress was 37.5 ksi. Average ultimate tensile stress was 60 ksi, identically the ASTM minimum ultimate strength while, according to the mill test, ultimate tensile strength was 61.7 ksi. This variation between laboratory test results and mill test results has been attributed primarily to the difference in strain rate used in the laboratory and in the mill. (5) All coupons exhibited ductile type failures. This plate would be called minimum strength A7 steel plate.

In Part b, the cutting scheme was somewhat similar to that of Part a although it was complicated a little by having eight plates of two different thicknesses going into the make-up of one joint. Joints were cut from A7 universal mill strips 10 1/4" wide and of thicknesses varying from 9/16" to 7/8". All strips were rolled from the same heat, and the 66'-6" lengths were sufficiently large to provide one thickness of material for two joints plus coupon material. The 10 1/4" universal mill strips were milled along both edges to give the final desired width of 9 7/8".
Plate coupons similar to those used in Part a were cut from each plate used. The general testing procedures used were also similar to those described previously. Figure 5 is a schematic diagram of the cutting scheme used for plates and coupon material while Fig. 6 is a typical stress-strain curve.

Two coupons were cut from each plate thickness used to fabricate the test joints. As before, both static yield level stress at .5% strain and .2% offset yield stress were recorded and can be found with other plate properties in Table 2. Both static yield level stress at .5% strain (33.6 ksi) and the yield stress at .2% offset (35.0 ksi) were lower than mill test yield strength (37.3 ksi). The ultimate tensile strength of 64.3 ksi was also slightly lower than the reported mill test ultimate. Again, this can be attributed to the slower strain rate used in the coupon tests at Lehigh. Failures were of the ductile type.

Plate thicknesses varied from 9/16" to 7/8" and yet the greatest variation in yield at 0.2% offset was ± 6.6% from the average while the greatest variation in ultimate strength was ± 3.4%. The variations in any one joint would be less than the figures quoted above; therefore, fairly uniform plate strains could be expected from similarly stressed plates.
3.2 Bolts

The bolts used in D-Series - Part a, were 7/8" A325, 5 1/2" under head. The thread was the standard rolled thread two inches in length. All bolts were from the same lot which was designated the D-lot. Five bolts were chosen at random and tested in direct tension. A proof load check was made on each bolt to insure that after loading and unloading no permanent elongation existed in the bolt. After completing the proof load check, testing was resumed to failure.

A tension-elongation relationship was chosen to calibrate the bolts of the D-lot. Elongation readings were taken with a C-frame extensometer equipped with a .0001" dial gage. The average ultimate load for the D-lot was 56.7 k.

In addition, a torqued calibration curve was established in the Skidmore-Wilhelm calibrator for each of 6 D-lot bolts chosen at random. In this case average ultimate load was 51.8 k. The ultimate tension induced in a bolt by turning the nut against the resistance of the Skidmore-Wilhelm calibrator was 8.6% less than the direct tension ultimate strength. A more complete explanation of this phenomenon and the bolt calibration procedure\(^{(6)}\) has been offered previously.
Based on the direct tension calibration relationship the bolts of the D-lot were very nearly minimum strength bolts (106.7% of specification minimum ultimate strength).

Bolts for Part b of the D-Series were all 7/8" A325 bolts from the same heat although the length under head necessarily varied with each joint. For this reason, lot numbers were assigned according to the length under head. The threads on all these bolts were cut and of standard length (2 1/4"). A brief summary of the results of calibration of five bolts from each of the four lots is given below.

<table>
<thead>
<tr>
<th>Lot</th>
<th>Length U.H.</th>
<th>Direct Tension</th>
<th>Torqued</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>6 1/2&quot;</td>
<td>54.8(^k)</td>
<td>52.0(^k)</td>
</tr>
<tr>
<td>U</td>
<td>7 &quot;</td>
<td>55.2</td>
<td>51.5</td>
</tr>
<tr>
<td>V</td>
<td>7 1/2&quot;</td>
<td>53.6</td>
<td>50.0</td>
</tr>
<tr>
<td>W</td>
<td>8 1/2&quot;</td>
<td>55.1</td>
<td>51.5</td>
</tr>
</tbody>
</table>

Since the bolts of the T, U, V and W lots were from the same heat, any variation in reported ultimate loads must be considered as being normal test variation and amounts to no greater variation from the average than 1.1\(^k\) or approximately 2%. For all further work all bolts of the D-Series - Part b can be said to have an average ultimate load of 54.7\(^k\).
4. FABRICATION OF TEST JOINTS

4.1 Shop Procedure

All shop work necessary for the fabrication of the test specimens was done at the Bethlehem Steel Company fabricating shops in Bethlehem, Pennsylvania.

The shop procedure was the same for all joints except for the preparation of the faying surfaces. Through a misunderstanding in the detail drawings, the plates of the D-Series - Part a were gone over with a mechanical grinder to remove all mill scale. Surface irregularities were still present, but the faying surfaces were completely devoid of mill scale and quite shiny and reflective (see Fig. 12). In the preparation of joints of Part b, only loose mill scale was removed by hand wire brushing.

Plates for the various joints were assembled according to the detail drawings and clamped together securely. The four corner holes were subdrilled and reamed for alignment. Pins machined to fit the reamed holes were inserted to hold the joint in alignment while the remainder of the holes were drilled to size through all the plies of the solid material. All holes were 15/16" diameter to allow 1/16" clearance for the 7/8" bolts.

Since the joints were actually one-half of a butt joint,
fill plates were welded between the outer plates in the grip area while the inner plates were also welded together in the gripping area to insure uniform load distribution during test and to facilitate handling of the joints after testing was completed. Shipping bolts were installed after the welding operation to expedite handling.

4.2 Bolting-Up Procedure

The bolting-up operation was done at Fritz Laboratory by a Bethlehem Steel Company Erection Department field crew. This arrangement was chosen so that the Fritz Laboratory staff crew could gather information concerning bolt tension and elongation in a connection tightened by a practicing field crew according to their present field procedure, the turn-of-nut method. According to this method, all bolts are snugged with the impact wrench and then given a prescribed amount of rotation. The rotation beyond snug required to produce adequate bolt tensions is dependent upon the diameter of the bolt and the grip thickness. All bolts in joints of the D-Series - Part a, and in joint D701 of Part b, received 1/2 turn from snug. The bolts used in D801, D901 and D1001 each received 3/4-turn beyond snug since their grip was greater than 5".

During the actual tightening operation, the joints were
placed on edge and the bolts approximately centered in the holes. In certain of the joints when intermediate elongation readings were taken, the joints were placed horizontally to accommodate the C-frame extensometer. When the tightening operation was resumed, the joint was again placed on edge. The general tightening procedure was as follows:

(1) A logical fitting-up pattern was chosen. (See Figs. 16 and 22).

(2) Drift pins were inserted for alignment and fitting-up bolts were snugged and given the required amount of rotation.

(3) The remainder of the bolts were snugged and tightened.

(4) The fitting-up bolts were then checked for tightness and touched-up according to the feel of the operator.

4.3 Bolt Tension Measurement

Complete records of bolt elongation were kept for each bolt in every joint of the series. This step afforded an opportunity to check the bolting-up operation as well as gather information on: (1) bolt tension at the snug position, (2) loss in tension of fitting-up bolts as neighboring bolts are tensioned, (3) final bolt tensions. The final measurement of bolt tensions terminated the primary fabrication and control steps in the test program.
5. **INSTRUMENTATION**

5.1 **General**

The following equipment was used to instrument the test specimens:

1. Electric strain gages (SR-4) for measuring strains in the inner and outer plates;
2. Slide bar extensometer for measuring elongations between each transverse row of bolts;
3. Dial gages (0.001") for measuring slip between the inner and outer plates as well as total elongation of the joint;
4. Dial gages (0.0001") for measuring relative displacement between the plies of material making up the outer and inner plates in D-Series - Part b.

In the D-Series - Part a, the instrumentation of every joint was identical with the exception of DI01. The joints of Part b of the D-Series were also instrumented alike. Figure 7 shows the instrumentation layout for DI01, the remainder of the D-Series - Part a, and also Part b of the D-Series.

5.2 **Electric Strain Gages**

In joint DI01 plate strains were measured with SR-4 type Al gages. The gages were located on the edges of all
four plates between the bolt rows and within the bolt pattern on the face of the outer plates. This scheme was modified for the remainder of the D-Series -- Part a, to merely eight gages, four on the edge of the inner plates on the gross material and four similarly located on the outer plates. For the variable grip tests, the same gage locations were used, but since there were eight plies of material per joint rather than four as in the variable width joints, sixteen gages were used for each joint. In both cases, the purpose of these strain gages was to give an indication of the general alignment of the joint in the grips by means of the stress distribution on the gross section.

5.3 Slide Bar Extensometer

The slide bar extensometer is a hand-held instrument of the Whittemore type fitted with a .0001" dial gage to record the elongation of the plate material between rows. Small holes were drilled on the edge of each plate at the pitch line to accommodate the tips of the extensometer which were set to span a 3 1/2" pitch. Gage point center-drills for the slide bar extensometer were numbered as follows: the gage point location one pitch distance above the top row of bolts was called row 0 while the gage point
location one pitch distance below the bottom row of bolts was called Row X. Intermediate gage point locations were numbered 1 through n respectively from the top of the joint. (See Fig. 7). These readings can be quickly converted to average strains within a given pitch and therefore provide some indication as to the plate stresses present at any particular section. By summing the elongations in every pitch of the main plate along a joint and adding the amount of rigid body motion between the inner and outer plates, these slide bar readings can be used to check the readings of the overall elongation dials (0.001"). Since this report deals primarily with ultimate strength consideration, most of the slide-bar extensometer data has been omitted. The readings have been checked, however, and will appear in a later report dealing with load partition throughout a bolted joint.

5.4 Slip Gages

One dial gage (0.001") was mounted on small metal brackets welded to each edge of a joint at the bottom row of bolts on the inner plate. A second bracket was welded between the lap plates one pitch distance beyond the last row of bolts to provide a pedestal for the dial gage plunger. Figure 8 is a photo of the dial gage instrumentation of D701, a variable grip joint. The slip dials are the lower dials in the photo and measured the rigid body motion of the
inner and outer plates plus the elongation in the lap plates between the last row of bolts and a point one pitch distance below the last bolt row. They were used on all joints of the D-Series.

5.5 Joint Elongation Dials

Joint elongation was measured from a point one pitch distance above the first row of bolts to a point one pitch distance below the last row of bolts (Row 0 to Row X). A .001" dial gage was used on both faces to record this elongation. The gage was mounted on a stud at the upper limit, and its plunger contacted a pedestal connected to a similar stud at the lower limit of the joint (Fig. 8). The joint elongation dial in this photo is the center dial at the top of the joint.

By combining pitch elongation readings with slip gage readings, the total elongation as recorded on the elongation dials can be checked according to the following combination of slip dial and slide bar extensometer readings:

\[ e_{\text{total}} = \text{Slip} + \sum e_{\text{main}} \]
5.6 Plate Displacement Dials

Plate displacement dials (.0001") were necessary for the variable grip joints in which main and lap plates were built up from plies of material rather than from solid plates of the thickness required. They were used to detect any relative movement between the two plies of the lap plates or the four plies of the main plate. The lap plate displacement dials can be seen in Fig. 8 but the main plate dials are hidden due to their location between the lap plates at the bottom of the joint. The displacements observed from these gages were of such a slight magnitude and random behavior that one may assume that the inner \( t_i \) and the outer \( t_o \) laminations of the variable grip joints acted as a single plate.
6. **TEST PROCEDURE**

The procedure used in the testing of joints of the D-Series was standardized so that each joint was tested under identical conditions. Joint D101, the first to be tested, was the only exception although the procedure for testing D101 was quite similar to the general test procedure. The primary difference between D101 and the remainder of the D-Series joints was that for D101, the gage were removed at 1200\(k\) while failure did not occur until approximately 1500\(k\). In all the other tests the gages were left on the joint through failure so that a complete history of all gage readings was available for the entire test.

The first step in the general test procedure was to mount the specimen in the testing machine and attach all gages and dials required in the instrumentation layout. Zero readings were then taken on all instruments. The specimen was gripped, and testing proceeded in even load increments until major slip was experienced at which point joint elongation readings were taken the instant the joint slipped. At major slip, the testing machine would drop load due to the sudden displacement and stabilize at some lower load level; all gages were read at this lower load point. Load was again applied in increments to slip load and beyond. Beyond plate yield, test procedure was modified
slightly in that only joint elongation readings were taken as the desired load increment was attained. At this point the loading valve of the testing machine was closed to allow time for the load to stabilize at a constant strain value. When all evidence of straining had stopped, and a period of at least ten minutes had elapsed complete readings were taken. This modified procedure was followed until failure of the joint occurred. Since the amount of straining which occurred during the stabilization time was quite small, it was neglected; therefore, the dial gage readings taken at the lower load level were said to be the same as the actual readings at first attainment of the desired load increment.

When a bolt "unbuttoned" from the test specimen, the unloading valve of the testing machine was opened to arrest the failure at that point. After the load was dropped to a safe level, the joint was inspected visually and gages were read. Load was again applied to the joint until a second bolt unbuttoned or complete shearing of all remaining bolts occurred.
7. TEST RESULTS

7.1 D-Series - Part a

A complete summary of the results of the variable width series of tests is given in Table 3. The specimens failed either by tearing of the plates or by first shearing one or more end fasteners while the joint remained intact. The load at which the first bolt sheared has been considered the failure load even though complete rupture had not occurred and though in some instances higher loads were attained. In most cases in which unbuttoning was experienced, (D101, D81, D71), load was reapplied to the joint to see how far the joint could be unbuttoned before complete failure would occur. Joint D91 was the only variable width joint which was kept intact after unbuttoning occurred. Figure 9 is a sketch of the unbuttoned patterns of these joints. Test specimens D61 and D51 failed by tearing of the plate material but joints D41 and D31 were not tested to complete failure although a maximum load had been reached prior to stopping the test. A brief discussion of each test is given below.

Joint D101, the largest of the variable width joints, having a total of twenty bolts in its pattern, experienced first major slip at a load of 568\(^k\) or a nominal bolt shear of 23.6 ksi. Two other major slips occurred later, one at
604 k and the second at 670 k. At this point the total amount of slip was approximately 0.065". The first bolt unbuttoned at a load of 1506 k or an average bolt shear of 62.6 ksi. Figure 10 is a close-up of D101 after the first three bolts unbuttoned. The total unbuttoning sequence can be seen in Figure 9. At the time of first bolt failure (1506 k) the actual tension on the net section was 57.8 ksi, but the maximum load carried by the joint was 1532 k at a corresponding tension on the net section of 58.8 ksi.

First major slip for joint D91 was experienced at a load of 405 k (nominal bolt shear 18.8 ksi). Three other major slips were noted before the joint came into full bearing. The joint experienced first bolt failure at an applied load of 1358 k and a corresponding net section tension of 57.3 ksi. The complete load-elongation curve for the test of joint D91 is shown in Fig. 11. A total of six bolts unbuttoned, the joint still remaining intact. This joint also carried more load after several bolts had unbuttoned than it did with a full pattern (Fig. 9). Testing was discontinued after six of the original eighteen bolts had unbuttoned. Figure 12 is a photo of D91 showing the unbuttoned pattern after testing.

Joint D81 experienced first major slip at a load of 560 k which corresponds to a nominal bolt shear of 29.1 ksi. Several other major slips followed until the specimen was
pulled into complete bearing at a load of approximately 650 ksi. First bolt failure occurred at a load of 1282 ksi, the highest load of the test. A total of six bolts unbuttoned before complete shearing of all remaining bolts occurred. The maximum nominal bolt shear was 66.7 ksi while the maximum net section tension was 61.0 ksi. After complete failure of D81 occurred, one line of bolts was arranged and photographed to present a visual record of bolt deformations throughout the length of the joint (Fig. 13).

First major slip occurred in joint D71 at a nominal bolt shear of 21.3 ksi or a net section tension of 19.4 ksi. Further slippage was recorded until the joint came into full bearing at a load of approximately 560 ksi. First bolt failure occurred at a nominal bolt shear of 66.9 ksi (1126 ksi). Actual tension developed by the net section was 61.9 ksi. Two bolts unbuttoned from this particular joint before complete shear failure occurred at a load of 1112 ksi.

Joint D61 slipped at a load of 338 ksi which corresponds to a nominal bolt shear of 23.4 ksi and a net section tension of 21.3 ksi. In this specimen plate failure occurred at a load of 994 ksi or a nominal bolt shear of 68.9 ksi. The actual net section tension was 64.0 ksi which resulted in an actual net efficiency of 108.0%. Values of efficiency shown in Table 3 are based on nominal dimensions. Figure 14 is an edge view of D61 after one of the inner plates tore at the first
row of bolts. The separation of the scribe lines along the edge of the joint is approximately 0.5 inches at the first row of bolts.

First major slip occurred in the test of joint D51 at a load of $348^k$. This load produced a nominal bolt shear of 29.0 ksi and a net section tension of 26.3 ksi. Again this joint failed by complete tearing of the main plates (Fig. 15). Note the necking of the main plates in both directions. The failure load of $850^k$ produced a nominal bolt shear stress of 70.7 ksi and an actual net section tension of 64.6 ksi. Net efficiency in joint D51 was 107.7%.

Joint D41 experienced first major slip at a load of $234^k$. Nominal bolt shear was 24.3 ksi while the net section tension was 22.1 ksi. The maximum load applied to D41 was $690^k$ and when the load began to fall off the test was stopped before either plate or bolts failed. Inspection of the joint shows that a plate failure was imminent. This was the first case in the Lehigh test program that a plate rupture load was not equal to the maximum load. The nominal bolt shear at maximum load was 71.7 ksi while the tension on the net section was 65.3 ksi giving a net efficiency of 107.8%.

Joint D31 slipped at a load of $176^k$. As in the case
of D41, testing was halted shortly beyond a maximum load of $514^k$, before either a plate or a bolt failure occurred. At that point the net efficiency of the plate material was 110.1%.

In summarizing the test results of the variable width series of tests it is evident that two of the specimens (D91 and D71) experienced first major slip at loads less than the working load computed on the basis of an allowable shear stress of 22 ksi in double shear. The average slip coefficient for this series of joints was approximately 0.28 when clamping force was computed on the basis of results of a direct tension bolt calibration procedure. It is important to bear in mind that the faying surfaces of these joints were free of all mill scale and quite smooth (Section 4.1) and therefore this value of slip coefficient is not representative of the slip behavior of joints with tight, dry mill scale surfaces.

Calculation of the clamping force was made by means of Fig. 16 which is a histogram used to record the individual bolt elongations. The heavy squares represent fitting-up bolts which correspond to the heavy circles in the joint pattern while the open squares represent the other bolts in the pattern. The elongation of each bolt was plotted to the same abscissa as the calibration curves above. Therefore, by entering the graph with a particular bolt elongation one
can read up to a curve and pick off the corresponding tension. However, since the region of the curve involved at one-half turn-of-nut from snug is relatively flat, an average elongation for all bolts in a joint was found and, from it, average bolt tension. The clamping force of the joint depends on whether one reads the tension from the direct tension or the torqued calibration curve.

Nominal bolt shear at maximum load ranged from 62.6 ksi for D101 to a maximum of 71.7 ksi for joint D41.

7.2 D-Series - Part b

Table 4 is a summary of the results of the variable grip series of tests. Each of the variable grip joints experience bolt failures. Figure 17 is a sketch showing the unbuttoned patterns and the corresponding failure loads. In all cases, testing was discontinued before complete failure occurred, it being felt that a partially unbuttoned joint would be more useful and educational than a completely ruptured one.

Joint D1001 experienced first major slip at a load of 1010k or a nominal bolt shear of 42.01 ksi. Testing was continued through the slip zone and then discontinued for the day. The following day testing was resumed until two bolts, one from each of the end rows, unbuttoned at a load
of 1667 ksi. At this load, the nominal bolt shear was 69.3 ksi while the net section tension was 62.2 ksi. It is of interest to note that some slip occurred at a load of 1482 ksi during this test. The slip dials advanced rapidly and a resounding thump was heard.

First major slip occurred during the testing of D901 at a load of 865 ksi or a nominal bolt shear of 40.0 ksi. The first bolt unbuttoned at a load of 1497 ksi at a nominal bolt shear of 69.2 ksi. Actual net section tension at this point was 61.6 ksi. Two other bolts were unbuttoned before testing was discontinued. Figure 16 is a complete test curve for this particular test, and Fig. 19 is a photo of the unbuttoned pattern after test.

Specimen D801 experienced first major slip at a load of 610 ksi. This load resulted in a nominal bolt shear stress of 31.7 ksi, the lowest of the variable grip joints. At a load of 1313 ksi, the first bolt unbuttoned; load was reapplied to the joint until a second bolt unbuttoned at a lower value of 1244 ksi. Maximum nominal bolt shear was 68.3 ksi while actual net section tension was 62.3 ksi. Figure 20 is a photo of the edge of D801 at the bottom of the joint showing the separation of the scribe lines as well the bending of bolts in the adjacent rows. This photo was taken after two bolts had unbuttoned and testing was discontinued; the head of the bolt in the last row is missing since this was one of the
bolts that unbuttoned.

First major slip occurred in joint D701 at a load of $720^k$ or a nominal bolt shear of 42.8 ksi. Actual tension on the net section was 37.4 ksi. At a load of $1213^k$ or a nominal bolt shear of 72.1 ksi two bolts unbuttoned at the top row of the joint. This joint (D701) was the only one in which the head end of the bolts sheared off. Figure 21 is a close-up of the top of joint D701 where the two bolts unbuttoned. Note the relative movement of the main and lap plates necessary to produce bolt failures.

In summary, it is evident that none of the variable grip joints, all of which had tight mill scale faying surfaces experienced slip below the working load computed on the basis of a 22 ksi allowable average shear stress. A bolt tension histogram was again utilized to compute joint clamping force (Fig. 22). The tension-elongation curves shown are average curves of three bolts from each of the lots used (T,U,V,W), or a total of twelve bolts each for the direct tension and the torqued calibration curve.

This average curve is permissable because the tension elongation curves are flat in the region being used and depend primarily upon the amount of thread within the grip which is almost constant for all these joints. The average slip coefficient for this series of joints was
approximately 0.48 when the clamping force was computed on
the basis of the direct tension calibration curve.

Figure 23 is a history of bolt tensions produced by
the turn-of-nut tightening method during the bolting up of
a typical test joint. The bar graph corresponding to any
particular bolt is plotted adjacent to the bolt in the
pattern, the dark bolts representing fitting-up bolts.
The tensions shown were read from a direct tension cali-
bration curve. It is of particular importance to realize
that despite a wide variation in tension at snug (19 k), the
final bolt tensions do not vary by more than approximately
2.5 k. Also, it can be seen that the touching-up operation
more than restores original tension.
8. **ANALYSIS OF RESULTS**

8.1 **Tension-Shear Ratio**

The term "balanced design" as pertains to bolted joints can be defined as the proportioning of tension and shearing areas such that, at ultimate load, either plate failure or bolt failure could occur. When balance is attained in a design, all materials are used efficiently. Previous tests of large, compact, bolted joints have been conducted\(^1\) and resulted in the conclusion that a tension-shear ratio of 1.00/1.10 will result in a balanced design. This, in effect, says that if an allowable tensile stress of 20 ksi is used to proportion the connected material, an allowable shear stress of 22 ksi (1.10 x 20 ksi) should be used to proportion the A325 bolts. In the tests mentioned in Ref. 1 all joints tested at the 1.00/1.10 tension shear ratio experienced bolt failure. The net section tension at bolt failure almost equaled the ultimate coupon strength and did exceed the ASTM minimum ultimate strength. The bolts were minimum strength while the plate was medium strength A7 steel.

As noted previously, both the variable width and the variable grip joints of the D-Series were proportioned on the basis of a 1.00/1.10 tension-shear ratio. A brief analysis of their failure modes reveals that, while eight
of the specimens failed by shearing of the bolts, four experienced plate failure. The four joints which experienced plate failure (D31 - D61 inclusive) were essentially short, compact joints. In these connections where the bolts and plate were minimum strength the bolts were able to hold the joint together at the 1/1.10 ratio until the plates tore at an average stress on the net section exceeding the coupon stress by 7%. This fact reinforces the conclusion drawn previously that a 1/1.10 tension-shear ratio does result in a balanced ultimate design for compact joints.

8.2 Joint Slip

The slip characteristics of test specimens of the D-Series can best be analyzed by comparing Part a, the variable width joints, with Part b, the variable grip joints. All bolts were tightened according to the recommendations of the one-half turn-of-nut method. (7) According to this tightening procedure, all 7/8" diameter bolts having grip lengths greater than 5 inches should receive 3/4 turn-of-nut from the snug position rather than the customary one-half turn. Consequently, the bolts used to assemble joints D801, D901 and D1001 each received 3/4 turn from snug.
Despite these differences in material strength and bolting-up procedure, the final average bolt tensions did not exhibit any marked variations (Figs. 16, 22). Average bolt tensions ranged from a low of 47.5k in joint D701 to a high of 53.1k in joint D101 (Table 3,4).

The factor which affects joint slip most is the slip coefficient or apparent coefficient of friction. This slip coefficient necessarily depends on the condition of the faying surfaces; a smooth, shiny surface would have a lower slip coefficient than a rough surface. Similarly, a surface completely devoid of mill scale would be expected to have a lower slip coefficient than one having a tight mill scale surface. The faying surfaces of the variable width joints were ground with a mechanical grinder until a mirror-like finish was evident in many places. This was an extremely unnatural surface condition; consequently, the average slip coefficients noted in the testing of these joints was 0.28. On the other hand, joints of the variable grip test series had tight mill scale surfaces; in these tests the average slip coefficient was 0.48, considerably higher than that of the variable width joints. A certain amount of variation was present among the joints of each group (Table 3,4), but it is felt that the average figures are sufficiently accurate to indicate the trend and emphasize the effect of surface preparation on the slip
characteristics of the D-Series test specimens.

Figure 24 is a bar graph used to indicate the slip performance of all large bolted joints with $T/S = 1/1.10$ tested at Lehigh University. The horizontal line extending across the graph from 22 ksi is the working stress level while the height of the bar is governed by the bolt shear stress at slip. Two joints (D91, D71) slipped below working stress while others in Part a slipped at shear stress values greater than the working stress. The slip loads for this group were low because of the semi-polished faying surfaces. Shiny faying surfaces such as these would hardly be encountered under ordinary conditions of practice. None of the compact or variable grip joints slipped below the working stress level. In fact, each of these joints exhibited considerable factor of safety against slip.

In order to present a fair picture of the range of slip coefficients one can reasonably expect in a bolted joint, a complete resume of the slip data for the large compact bolted joints tested at Lehigh is submitted in Table 5 to supplement the bar graph (Fig. 24) and Tables 3 and 4. The average slip coefficient for all joints having tight mill scale faying surfaces (Compact Joints and D-Series - Part b) was 0.45. On the other hand the average slip coefficient for the D-Series - Part a joints, which had the semi-polished faying surfaces, was 0.28.
8.3 The Unbuttoning Factor

Figure 25 is shown to present a picture of the effect of joint length on the average shear strength of the fasteners. The ordinate is a non-dimensional quantity called the unbuttoning factor \( U \) which is computed by dividing the average ultimate shear strength of the bolts in a joint \( (R_{\text{avg}}) \) by the shear strength of a single bolt of the same lot \( (R_1) \).

\[
U = \frac{R_{\text{avg}}}{R_1} = \frac{\tau}{\tau_1} \quad (8.2)
\]

Thus, the factor \( U \) is an efficiency factor measuring how well the configuration of the joint can develop the full capacity of the bolts. The basic shear stress of the bolts has been established by testing single bolts in a double shear jig made of A7 steel with the same grip as the large joints.

Bolts used in the D-Series - Part a joints (D-Lot), when tested in double shear, failed at a shear stress of approximately 85.3 ksi while bolts used in the compact joints, the B-Lot, A-Lot and G-Lot, failed at shear stress values of 81.4 ksi, 83.2 ksi and 84.0 ksi respectively. Similarly, the ultimate shear stress of bolts used in the D-Series - Part b joints was approximately 93.3 ksi. These values would correspond to the value \( \tau_1 \) in Equation (8.2).
The abscissa indicates the length of the joint in terms of the number of 3 1/2" pitches since almost all joints tested used 7/8" bolts at this pitch. Two exceptions, A3 and G1, used a 4" pitch for 1" and 1 1/8" bolts respectively.

The four joints which failed by tearing of the plates do not give true unbuttoning factors since the average ultimate shear stress used is that occurring at plate failure, not bolt failure. However, these points do delineate a lower limit for $U$ and confirm the previous finding(1) that in short compact joints the average shear stress is about 90% of the single bolt shear stress.

This graph also shows a definite decrease in values of $R_{avg}$ as joint length increases. The average shear stress of bolts in a joint having ten bolts in line is 75% of the shear stress of a single bolt rather than the 90% experienced with the compact joints.

8.4 Discussion of Possible Design Procedures

The following possible design procedures are offered as an aid for interpreting the unbuttoning curve (Fig. 25). This curve is based strictly on test results of the D-Series joints plus those compact joints(1) designed at
a tension-shear ratio of 1.00/1.10. It does not include test results from any source other than Lehigh University.

a) **Ultimate Strength Design**

In certain types of bolted connections where slip into bearing can be tolerated or where joints are initially fabricated in bearing and no reversal of load will occur, an ultimate strength design is possible. Riveted joints have been designed this way for years. The problem is to arrive at a reasonable value for the working stress. In order to do this the graph of Fig. 26 was plotted. The points on this graph were plotted by multiplying the unbuttoning factors by the shear strength of a minimum strength A325 bolt of the same size. This shear strength of a minimum strength bolt was taken as 0.68 times the minimum tensile strength (0.68 x 115 ksi for 7/8" and 1" bolts and 0.68 x 105 ksi for 1 1/8" bolts). Numerous tensile and shear tests of single bolts conducted at Lehigh University have shown this value to be reasonable. When a straight line is fitted through these points by the method of least squares, the resulting equation is

\[ \tau_u = 72.07 - 1.71N. \]

This curve suggests two design concepts, constant factor of safety or constant allowable stress.

Consideration of the joint length effect shown in
Figure 26 will reveal that to achieve a constant factor of safety for joints of all lengths, the allowable shear stress must necessarily decrease with the length of the joint. To establish the location of this line a factor of safety of three was chosen because the present minimum factor of safety for design of A7 steel is \( \frac{\sigma_u}{\sigma_w} = \frac{60}{20} = 3 \). This factor produces a working stress of \( \tau_w = 24.02 - 0.57N \). At \( N = 3.5 \), the working stress is 22 ksi. If working stresses are increased one-third for the combination of static load plus wind, the same relationship will apply with a constant factor of safety of 2.25.

The second ultimate strength design concept is to maintain a constant allowable stress regardless of joint length. To set the location of this allowable stress level it seems reasonable to set \( \tau_w = 22 \) ksi. By so doing joints shorter than 3 1/2 pitches would have factors of safety greater than 3; conversely, joints longer than 3 1/2 pitches would have factors of safety lower than 3 reaching 2.58 at \( N = 9 \). With static load combined with wind the lowest factor of safety for the same joint length would be 1.93. If both minimum safety factors are considered adequate for the respective loading conditions cited, this approach would be the simpler. It should be noted that since 1 1/8" bolts are made of slightly weaker material, the factor of safety for that size bolt may be
lower than above.

8.5 Long Grips

Current rivet specifications carry special provisions for the proportioning of long grip rivets. For example, the AISC Specification states that "Rivets which carry calculated stress, and the grip of which exceeds five diameters, shall have their number increased 1 percent for each additional 1/16 inch in the rivet grip". This stipulation presumably arises because of the increased bending stresses in long rivets.

The bolts of the D-Series - Part b which would fall into this grip classification were proportioned without any regard to this provision because at working load the bolts are transferring load by friction and not by shear, bearing and bending. Even at ultimate load where the bolt is in bearing and subject to bending this effect is of no importance for the grips studied.
9. **CONCLUSIONS**

The following conclusions are based primarily on test results of the D-Series or Unbuttoning Series of tests conducted at Lehigh University. Certain of these observations are reinforced by previous tests of large, compact, bolted joints, the complete results of which can be found in Ref. 1. The design recommendations presented herein express the authors' concept of an improved design procedure suggested by the test results of full scale A325 bolted connections tested at Lehigh University.

1. The average shear resistance of high strength bolts in a connection decreases as the connection becomes longer. In joints with up to 5 rows of bolts (4 pitches at 3 1/2") the average shear resistance of the bolts is about 90% of the shear resistance of a single bolt but for 10 rows of bolts (9 pitches at 3 1/2") it has decreased to 75% (Fig. 25).

This same trend has been noticed in test of riveted connections but because of the different configurations of those connections it is difficult to assign a numerical value for the percent reduction that will be comparable to the above work.

2. A tension shear ratio of 1.00/1.10 will provide a reasonably balanced ultimate design for joints of
A7 steel whose length does not exceed approximately 32 inches (Section 8.1). The factor of safety against failure will range from approximately 3.1 to 2.6 when an allowable shear stress of 22 ksi is used for design of minimum strength bolts (Fig. 26).

3. The load at which a bolted joint slips into bearing has no relation to the ultimate strength of the joint. The slip load depends upon the faying surface condition and clamping force of the bolts (Section 8.4). The slip coefficient determined experimentally from these tests with dry mill scale surfaces was 0.45. The clamping force obtained by the turn-of-nut method was approximately 1.3 times proof load as measured by a direct tension calibration procedure.

4. Within the thicknesses studied there is no need to increase the number of bolts to compensate for the bending of the bolts due to long grips (Section 8.5).
10. ACKNOWLEDGEMENTS

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11.APPENDIX

11.1 Definition of Terms

Unbuttoning - the term used to define the "premature" type failures experienced in long bolted joints.

Unbuttoning Factor - $U = \frac{R_{avg}}{R_1}$, where $R_{avg}$ is found by dividing the joint failure load by the number of bolts and $R_1$ is the shear resistance of a single bolt.

$T/S$ - the ratio of net tensile stress to shear stress on the nominal area of the fasteners in a structural joint.

Direct Tension Calibration - the relating of internal bolt tension to bolt elongation by pulling a single bolt in static tension at a prescribed grip.

Torqued Calibration - the relating of internal bolt tension to bolt elongation when the internal tensions are induced by impact torquing the nut of the bolt against the resistance of a prescribed thickness of grip material.

Major Slip - sudden, large relative displacement of inner and outer plates of the test joint.

Compact Joint - the term given to joints having not more than six (6) rows of bolts arranged in a full pattern with values of $p/d$ and $g/d$ approximately 4.

Slip Coefficient - $\mu = \frac{P_s}{mnT_1}$, where $P_s$ is the load required to produce major slip, $m$ is the number of slip planes, $n$ is the total number of bolts and $T_1$ is the average clamping force per bolt as determined from the Direct Tension Calibration Curve.

$p/d$ - expresses the ratio of pitch (vertical spacing of bolt rows) to the actual diameter of the hole in the plate.

$g/d$ - expresses the ratio of gage (transverse spacing of bolt lines) to the actual diameter of the hole in the plate.
11.2 List of References

1. R.T. Foreman, J.L. Rumpf,
   STATIC TENSION TESTS OF COMPACT BOLTED JOINTS,
   Lehigh University, Fritz Laboratory Report
   No. 271.6, July 1959

2. Research Council on Riveted and Bolted Structural
   Joints of the Engineering Foundation,
   SPECIFICATIONS FOR THE ASSEMBLY OF STRUCTURAL
   JOINTS USING HIGH STRENGTH BOLTS, 1954

3. D.D. Vasarhely, S.Y. Beano, R.B. Madison,
   Zung-An Lu, V.C. Wasishth,
   EFFECTS OF FABRICATION TECHNIQUES ON BOLTED
   JOINTS, Proceedings of ASCE, Vol. 85, ST3,
   March 1959

4. R.E. Davis, G.B. Woodruff, H.E. Davis,
   TENSION TESTS OF LARGE RIVETED JOINTS,
   Transactions of ASCE, Vol. 105, p.1193, 1940

5. A.W. Huber, L.S. Beedle,
   RESIDUAL STRESS AND THE COMPRESSION STRENGTH

6. R.A. Bendigo, J.L. Rumpf,
   CALIBRATION AND INSTALLATION OF HIGH STRENGTH
   BOLTS, Lehigh University, Fritz Laboratory
   Report No. 271.7, September 1959

7. E.F. Ball, J.J. Higgins,
   INSTALLATION AND TIGHTENING OF HIGH STRENGTH
   BOLTS, Proceedings of ASCE, Vol. 85, ST3,
   p.117, March 1959
# TABLE 1 Results of Coupon Tests, D-Series - Part a

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<td>Average Static Yield Level</td>
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<td>Ultimate Tensile Stress</td>
<td>Average Ultimate Tensile Stress</td>
<td>% Elongation in 8&quot;</td>
<td>Average % Elongation in 8&quot;</td>
<td>% Reduction in Area</td>
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<td>37,300</td>
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<td>64,500</td>
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<td>22.8</td>
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<td>64,500</td>
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<td>28.0</td>
<td>58.6</td>
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<td>64,300</td>
<td>64,300</td>
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<td>27.3</td>
<td>59.1</td>
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<td>59.1</td>
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<td>UNITS</td>
<td>D101</td>
<td>D91</td>
<td>D81</td>
<td>D71</td>
<td>D61</td>
<td>D51</td>
<td>D41</td>
<td>D31</td>
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</tr>
<tr>
<td>PATTERN</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| All holes drilled &
| All pitches $\frac{3}{4}$
| Gage = $\frac{1}{3}$ width | | | | | | | | |
| BOLTS | | | | | | | | | |
| No. in line | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | |
| No. of $\frac{1}{4}$ A325 bolts | 20 | 18 | 16 | 14 | 12 | 10 | 8 | 6 | |
| PLATES | | | | | | | | | |
| Nom. width | in | 15.10 | 13.78 | 12.46 | 11.12 | 9.80 | 8.48 | 7.16 | 5.84 |
| Nom. thickness | in | 2.02 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Nom. gross area | sq in | 30.20 | 27.56 | 24.92 | 22.24 | 19.60 | 16.96 | 14.32 | 11.68 |
| Nom. net area | sq in | 26.45 | 23.81 | 21.17 | 18.49 | 15.85 | 13.21 | 10.57 | 7.93 |
| % dev. in net area | % | -1.51 | -0.38 | -0.80 | -1.68 | -1.96 | -0.38 | 0.0 | -1.13 |
| T/S RATIO | ($A_s/A_{net}$) | | | | | | | | |
| Nominal | | | | | | | | | |
| Actual | | | | | | | | | |
| WORKING LOAD ($T=20,000$) | kips | 529 | 476 | 423 | 370 | 317 | 264 | 212 | 159 |
| SLIP LOAD (First Major) | kips | 568 | 405 | 560 | 358 | 338 | 348 | 234 | 176 |
| Nom. bolt shear | ksi | 23.6 | 18.8 | 29.1 | 21.3 | 23.4 | 29.0 | 24.3 | 24.4 |
| Nom. tens.-net sect. | ksi | 21.5 | 17.0 | 26.5 | 19.4 | 21.3 | 26.0 | 21.3 | 22.1 |
| Avg. elongation of bolts | in | 0.0381 | 0.0368 | 0.0329 | 0.0310 | 0.0313 | 0.0324 | 0.0267 | 0.0249 |
| Clamping force per bolt | kips | 53.1 | 53.0 | 52.3 | 52.0 | 52.0 | 52.0 | 52.1 | 51.0 |
| Slip coefficient | &l;67 | 0.212 | 0.335 | 0.246 | 0.271 | 0.334 | 0.287 | 0.289 | |
| TYPE OF FAILURE | | | | | | | | | |
| Load of failure | kips | 1506 | 1358 | 1282 | 1126 | 994 | 850 | 690 | 514 |
| Nom. bolt shear | ksi | 62.6 | 62.8 | 66.7 | 66.9 | 68.9 | 70.7 | 71.7 | 71.3 |
| Nom. tens.-net sect. | ksi | 57.0 | 57.1 | 60.6 | 60.8 | 62.6 | 64.3 | 65.3 | 64.6 |
| Act. tens.-net sect. | ksi | 57.8 | 57.3 | 61.0 | 61.9 | 64.0 | 64.6 | 65.3 | 65.5 |
| EFFICIENCY % | g/d | | | | | | | | |
| Theoretical | | | | | | | | | |
| Test | | | | | | | | | |
| Net | | | | | | | | | |

*As measured from the direct tension calibration curve
TABLE 4 Results of Joint Tests, D-Series - Part b

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<th>ITEM</th>
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<th>D90I</th>
<th>D80I</th>
<th>D70I</th>
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<td></td>
<td></td>
</tr>
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<td>All holes drilled</td>
<td>15/16&quot;</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>All pitches</td>
<td>3 1/2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gage</td>
<td>1/2 width</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>BOLTS</td>
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</tr>
<tr>
<td>No. in line</td>
<td></td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>7</td>
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<td>No. of 7/8 A325 bolts</td>
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<td>20</td>
<td>18</td>
<td>16</td>
<td>14</td>
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<td>Nom. shear area (=actual)</td>
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<td>16.83</td>
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<td>PLATES</td>
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<td></td>
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<td>Nom. thickness</td>
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<td>in</td>
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<td>3.00</td>
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<td>29.62</td>
<td>25.92</td>
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<tr>
<td>Nom. net area</td>
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<td>sq in</td>
<td>27.00</td>
<td>24.00</td>
<td>21.00</td>
</tr>
<tr>
<td>% dev. in net area</td>
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<td>%</td>
<td>-.70</td>
<td>+1.33</td>
<td>+.30</td>
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<td>1:1.09</td>
<td>1:1.13</td>
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<td>1:1.12</td>
<td>1:1.10</td>
<td>1:1.14</td>
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<td>423</td>
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<td>SLIP LOAD (First Major)</td>
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<td>865</td>
<td>610</td>
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<td>.0473</td>
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*As measured from the direct tension calibration curve
TABLE 5 Results of Tests, Compact Joints with T/S = 1.00/1.10

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<th>B6</th>
<th>A3</th>
<th>G1</th>
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<td>20</td>
<td>18</td>
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<td>36.0</td>
<td>36.0</td>
<td>36.0</td>
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<td>26.6</td>
<td>24.8</td>
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<td>609</td>
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<td>Shear of bolts</td>
<td>Shear of bolts</td>
<td>Shear of bolts</td>
<td>Shear of bolts</td>
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FIG. 1 Dimensions of Joints, D-Series - Part a
FIG. 2 Dimensions of Joints, D-Series - Part b

<table>
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<th>MARK</th>
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<th>$t_0$ in.</th>
<th>$t_i$ in.</th>
<th>GRIP in</th>
<th>g/d</th>
<th>SHEAR AREA sq.in.</th>
<th>NET AREA sq.in.</th>
<th>T/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1001</td>
<td>10</td>
<td>13/16</td>
<td>7/8</td>
<td>6 3/4</td>
<td>5.27</td>
<td>24.04</td>
<td>27.00</td>
<td>1:1.13</td>
</tr>
<tr>
<td>D901</td>
<td>9</td>
<td>3/4</td>
<td>3/4</td>
<td>6</td>
<td>5.27</td>
<td>21.64</td>
<td>24.00</td>
<td>1:1.11</td>
</tr>
<tr>
<td>D801</td>
<td>8</td>
<td>5/8</td>
<td>11/16</td>
<td>5 1/4</td>
<td>5.27</td>
<td>19.23</td>
<td>21.00</td>
<td>1:1.09</td>
</tr>
<tr>
<td>D701</td>
<td>7</td>
<td>9/16</td>
<td>5/8</td>
<td>4 3/4</td>
<td>5.27</td>
<td>16.83</td>
<td>19.00</td>
<td>1:1.13</td>
</tr>
</tbody>
</table>
FIG. 3 Location of Coupons, D-Series - Part a

FIG. 4 Stress-Strain Diagram for Plate Material, D-Series - Part a
FIG. 5 Location of Coupons, D-Series - Part b

FIG. 6 Stress-Strain Diagram for Plate Material, D-Series - Part b
Key

S — location of slip gage

• — location of SR4, Type "A" gage

— gage point for slide bar extensometer

⊗ — gage point for joint elongation gage

D — location of displacement gage

Fig. 7 Instrumentation Layout
FIG. 8 Instrumentation on Test Joint
Note:
Bolts Unbuttoned By Shearing At Head End

FIG. 9 Unbuttoning Sequence, D-Series - Part a
FIG. 10 Joint D101 Partially Unbuttoned

FIG. 12 Joint D91 with Six Bolts Sheared

FIG. 11 Load-Elongation Curve for Joint D901
FIG. 13 Sheared Bolts from Joint D81

FIG. 14 Edge View of Joint D61 After Plate Failure

FIG. 15 Plate Failure of Joint D51
FIG. 16 Bolt Tension Distribution, D-Series - Part a

- • FITTING-UP BOLTS
- O OTHER BOLTS

AVG. e - 0.381"  AVG. T- 53.1 k
0.368"  53.0 k
0.329"  52.3 k
0.310"  52.0 k
0.313"  52.0 k
0.324"  52.1 k
0.267"  51.0 k
0.249"  50.6 k

D1O-1
D9-1
D8-1
D7-1
D6-1
D5-1
D4-1
D3-1
Test Discontinued
Before Other Bolts Sheared

Joint D1001

Joint D901

Joint D801

Joint D701

Note:
All Bolts Unbuttoned By Shearing At Head Ends Except In Joint D701 Where Both Unbuttoned Bolts Sheared At The Nut End.

FIG. 17 Unbuttoning Sequence, D-Series - Part b
FIG. 18 Load-Elongation Curve for Joint D91

FIG. 19 Joint D901 with Three Bolts Sheared
FIG. 20 Edge View of Joint D801 After Two Bolts Unbuttoned

FIG. 21 Joint D701. Close-up of Sheared Bolts
FIG. 22 Bolt Tension Distribution, D-Series - Part b
1. Snuggling Tension
2. $\frac{3}{4}$ Turn from snug
3. Relaxation (occurs as adjacent bolts are tightened)
4. Touch up
5. Snug+$\frac{3}{4}$ turn

FIG. 23 Bolt Tension During Tightening, Joint D1001
TIGHT MILL SCALE

SEMI-POLISHED

BOLT SHEAR STRESS, ksi

COMPACT JOINTS (Ref. 1)  D-SERIES - PART b  D-SERIES - PART a
FIG. 25 Unbuttoning Factor

FIG. 26 Relation of Working Stress to Ultimate Stress