FURTHER STATIC TENSION TESTS
OF LONG BOLTED JOINTS

by

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This report is supplemental to Fritz Laboratory Report No. 271.8, "Static Tension Tests of Long Bolted Joints". The work included is a continuation of the original study of the effect of joint length on bolt performance. Results of tests of four additional long butt joints fabricated of A7 steel plate and 7/8" A325 bolts are presented. The data covers slip and ultimate strength behavior of the connections.
1. INTRODUCTION

1.1 Background

The usual design assumption that all bolts in a bearing type connection carry equal shear stress at ultimate load has been shown to be erroneous for long joints. The original study of long bolted joints conducted at Lehigh University(1) determined the variation of average ultimate shear stress in joints having from three to ten A325 bolts in line. The original twelve test joints were arranged in two series as follows:

(1) D-Series - Part a; 3 to 10 bolts in line at 3 1/2" pitch, 4" grip, variable width;

(2) D-Series, Part b; 7 to 10 bolts in line at 3 1/2" pitch, constant width, variable grip

Data on the slip behavior of these joints was recorded also.

When the original work was reviewed there appeared to be four outstanding questions concerning the scope of the tests. First, the slip resistance of the Part a joints appeared to be affected adversely by the polished condition of the faying surfaces. Second, maintaining pitch at 3 1/2", 4 bolt diameters, resulting in joints that were longer than need be since the specified minimum pitch is 3 diameters. Third, the larger of the variable width joints had unrealistically high g/d values. Fourth, it was not assured that the tests encompassed the longest joints one might expect to find in practice.
1.2 **Scope**

A third series of long joints, designated D Series-Part c was designed to answer some of these questions. This series consisted of four joints having from ten to sixteen bolts in each of two lines. Two of the specimens had 13 bolts in line and were identical except for the pitch distances. The plate thicknesses were increased to permit higher loads without going to very wide plates and the consequent unrealistic g/d values, and careful attention was paid to the preservation of the mill scale faying surfaces.

2. **DESCRIPTION OF TEST JOINTS**

In the D-Series - Part c tests, the number of bolts in line, the pitch and the joint width were the chief variables. Similar to previous tests, the specimens were half of a double shear butt joint with two one-inch plates combined to make up each of the two lap plates and four one-inch plates combined to form the main plate. The bolts were A325 bolts, 7/8" in diameter, and 9 1/2" long under head. The bolts had regular hexagon heads and 2 1/4" of rolled threads thus excluding the thread from the shearing planes. Heavy semi-finished nuts and two washers per bolt were used.
The specimens were D10, D13, D13A, and D16, where the number designates the number of bolts in each of the two lines. All the bolts were spaced at a pitch of $3\frac{1}{2}''$ except D13A which had a $2-5/8''$ pitch (3 diameters). The grip of 8" was the same in all cases. Further information may be found in Fig. 1.

3. MATERIAL PROPERTIES

3.1 Plates

The plate material used for the D-Series - Part c was from the same rolling as that of the D-Series - Part a. Varying lengths of ASTM A-7 structural steel universal mill plates 24" x 1" were burned to a rough width and machined to the finished dimensions of the test joints.

The method of cutting coupons and a typical stress strain curve for this material have been shown previously in Ref. 1. The results of applicable coupon tests are tabulated in Table 1.

3.2 Bolts

The bolts used were made to the physical specification of ASTM A-325. All were of the same heat treatment and were designated as C-Lot.

Three bolts, chosen at random, were pulled in direct tension. They satisfied the proof load requirements of the specification (3) and developed an average ultimate load of $53.5^k$ (100.3% of the specified minimum).
Three bolts were tensioned by turning the nut against the resistance of the Skidmore-Wilhelm Calibrator. The average ultimate load developed was 45.8 k.

The calibration procedures used above are described in Ref. 4, in Ref. 4.

Six C-Lot bolts were tested individually in double shear jigs. The average ultimate shear stress was 91 ksi. Procedures for shear testing of single bolts are described in Ref. 15, in Ref. 5.

4. FABRICATION OF TEST JOINTS

4.1 Shop Procedure

The shop fabrication procedure was similar to that for the previous D-Series joints (1).

Surface preparation consisted of hand wire brushing to remove loose mill scale and wiping with solvent to remove oil or grease.

4.2 Bolting-Up Procedure

The bolting-up operation was carried out at the Fritz Laboratory by a Bethlehem Steel Company erection crew. This provided duplication of current field procedure but still allowed research personnel to record bolt tension data during the tightening operation. The tightening procedure chosen was the turn-of-nut method (6) in which nuts are "shugged"
with the impact wrench and then turned through a prescribed rotation. Since the grip length was greater than five inches, all nuts were tightened 3/4 of a turn beyond "snug". Bolts tightened in the original fitting-up pattern were "touched-up"—tightened a little more in order to compensate for relaxation caused by tightening of the other bolts.

All tightening was done with the joints resting on edge. Bolt measurements had to be made with the bolts vertical so the joints were laid flat between steps in the tightening operation. The general procedure and description of measurements is given in Ref. 1. Final bolt elongations are shown graphically in Fig. 2. The bolt tensions can be read from the load-elongation curves plotted above the elongation histogram.

5. INSTRUMENTATION

The following equipment was used to measure deformations of test specimens:

(1) electric strain gages (SR-4) for measuring strains in the inner and outer plates;

(2) slide bar extensometer for measuring plate elongations between each transverse row of bolts;

(3) dial gages (0.01") for measuring slip between the inner and outer plates as well as total elongation of the joint;
(4) dial gages (0.001") for measuring relative displacement between the plies of material making up the outer and inner layers of each member.

This is identical to the instrumentation for the D-Series-Part b and further descriptions may be found in Ref. 1.

6. TEST PROCEDURE

The test procedure used for the D-Series - Part c followed the precedent set in the previous D-Series tests. A few minor changes were made in the method outlined in Ref. 1.

Since the specimens were substantially larger than any tested before, testing operations required more than one day. On the first day of testing a joint would be loaded up to and beyond slip and yield regions. The load would then be reduced to the initial gripping load and held there overnight. On the second day of testing the load would be increased rather rapidly to the highest load of the previous day and then the load would be increased in increments until failure of the joint occurred.

The ultimate joint load was always taken to be the load at which the first bolt sheared. No further loads were applied and the specimens were preserved intact after failure of the first bolts.
7. TEST RESULTS

A complete summary of the test results is given in Table 2. All specimens failed by shearing one or two end bolts and the load at which this occurred was considered the ultimate load for the joint. Figure 3 is a sketch of the failure patterns of these joints. A brief discussion of each test is given below.

Joint D16, the longest joint tested, experienced major slip at a load of 1,242 k or an average bolt shear stress of 32.3 ksi. The total amount of slip was approximately 0.064". The first bolt sheared at a load of 2,085 k or an average bolt shear stress of 54.2 ksi.

Joint D13 experienced first major slip at a total load of 960 k corresponding to an average bolt shear stress of 30.7 ksi. Several small slips occurred thereafter, the last being at a load of 1100 k. However, it was apparent that the initial slip load was the one of consequence since the amount of slip at that point was about 0.075". The joint reached a maximum load of 1854 k (average bolt shear stress of 59.3 ksi) at which time a loud noise was heard, the load began to drop, and at 1820 k a second loud noise was heard and one bolt flew out of the joint.

The first major slip for joint D13A was at a load of 792 k or an average bolt shear stress of 25.3 ksi. There
was some evidence that slip might have been hastened by misalignment of the joint in the testing machine. The failure occurred by shearing one end bolt at a load of 1988\(k\). This corresponds to a nominal shear stress of 63.6 ksi in the bolts.

The smallest joint, D10, went through several minor slips before the major slip occurred at a load of 900\(k\), (bolt shear stress of 37.4 ksi). Failure occurred at a load of 1544\(k\) for an average bolt shear stress of 64.2 ksi. The actual failure probably took place in two stages. At the ultimate load it is believed that one bolt failed but it could not be removed from the joint even though 40\(k\) of load fell off at that time. Upon reloading, the adjacent bolt failed at 1544\(k\) also, and the test was discontinued. It was not until all load had been removed that the first fractured bolt was found to be loose.

8. ANALYSIS OF RESULTS

8.1 Joint Slip

An important result of these tests is the verification of previous conclusions on the slip behavior of joints having dry mill scale faying surfaces. Previous tests in Part a of the D-Series\(^1\) had shown slip coefficients of .212 to .335. These joints had contact surfaces from which the mill scale had been removed by use of a power grinder. This method resulted in considerable polishing of the
surfaces and it was felt that the slip coefficient was not indicative of that which could be expected with undisturbed tight mill scale surfaces.

Later tests in Part b of the program, where surface preparation consisted of hand wire brushing only, corroborated this opinion by producing slip coefficients from .375 to .541. However, since the plate material was thinner and of a different rolling, the effect of plate roughness caused by the different rolling equipment still had to be considered as an influencing factor.

In the joints described in this report, the plate material was the same as that used in Part a but the surface preparation removed loose mill scale only. The resulting slip coefficients ranged from .312 to .455 thus verifying previous opinions that .30 is a reasonable lower limit for contact surfaces of tight mill scale.

All joints (with T/S = 1/1.10) of the Large Bolted Joints Project are compared in Fig. 4, and it is evident that, so far as experience at Lehigh University is concerned, the working shear stress of 15 ksi provides an adequate factor of safety against slip even for semi-polished contact surfaces and a working stress of 22 ksi will provide a similar margin for mill scale surfaces. However, the 1960 Specifications of The Research Council for Riveted and Bolted Structural Joints restricts the design of all friction type joints to the lower value of 15 k.
8.2 Unbuttoning Factor

In previous work\(^1\) the effect of joint length on the ultimate strength of a bolted joint has been portrayed by use of the non-dimensional unbuttoning factor, \(U\). This factor is a measure of efficiency and is defined by the following relation:

\[ U = \frac{\tau_{avg}}{\tau_1} \]

Where \(\tau_{avg}\) equals the average shear stress on the bolts when the first bolt fails, and \(\tau_1\) is the shear strength of a single bolt of the same lot.

Fig. 5 shows the unbuttoning factor, \(U\), plotted against the joint length in terms of \(N\), the number of \(3\frac{1}{2}''\) pitch distances. The four joints described in this report are plotted as triangles. They continue the trend indicated by the other Lehigh University tests showing that as the length of the joint increases, the average shear stress decreases. With 16 bolts in line the average shear stress at failure is only 60% of the shear strength of a single bolt.

Joints D10 and D13A illustrate that unbuttoning of end bolts in long joints is not so much a question of the number of bolts but rather of the total length between the end bolts. In those joints, with 10 and 13 bolts in line, the distance between the end bolts was the same because of
the use of $3 \frac{1}{2}''$ and $2 \frac{5}{8}''$ pitches respectively. The tests produced almost identical unbuttoning factors of 0.708 and 0.701. One must be careful not to construe this to mean that the carrying capacity of the 10-bolt in line connection is equal to that of the 13-bolt in line connection. Because of the greater number of fasteners the latter is capable of carrying 1.3 times the load of the smaller joint, as evidenced by the failure loads of $1988k$ and $1544k$.

Comparing joints D13A and D13 illustrates further the effect of total joint length as opposed to the number of fasteners in line. Though both connections had 13 bolts in line, D13A had an overall length of $(13 - 1) 2 \frac{5}{8}'' = 31 \frac{1}{2}''$ whereas D13 had $(13 - 1) 3 \frac{1}{2}'' = 42''$ between the end bolts. This greater length resulted in failure of the end bolt in D13 at a lower load and a lower average shear stress. The unbuttoning factors are 0.701 and 0.654 for D13A and D13 respectively. Thus a 7% increase in load carrying capacity was achieved by decreasing the pitch from $3 \frac{1}{2}''$ (4 diameters) in D13 to $2 \frac{5}{8}''$ (3 diameters) in D13A.
9. CONCLUSIONS

The following conclusions have been drawn from the results of the D-Series - Part c tests and a comparison of these results with previous tests of bolted joints conducted at Lehigh University.

(1) The average shear stress on all the bolts of a connection at the time the first bolt fails decreases linearly as the length of the joint increases. The ratio of this average shear stress to the ultimate shear strength of a single bolt is called the unbuttoning factor and it varies from approximately 0.9 with 3 bolts in line to 0.6 with 16 bolts in line. (Figure 5). Thus a bearing type connection designed at a working shear stress of 22 ksi and requiring 16 7/8" A325 bolts in line could have a factor of safety against bolt failure of as little as 2.2 if the bolts are at the lower limit of specified strength.(3).

(2) Friction behavior is dependent on the clamping force of the bolts and the condition of the contact surfaces. In these connections, because of the 8" grip, the nuts were tightened 3/4 of a turn from the snug position. This method produced uniform bolt tensions of about 1.3 times the minimum specified bolt tension - the proof load.
The dry, tight mill scale contact surfaces produce slip coefficients varying from .312 to .455. This verified opinions based on the previous Lehigh University work that .30 is a reasonable lower limit of slip coefficient for these surface conditions.

The joint with the lowest slip resistance slipped at an average shear stress of 25.3 ksi, well above the specified design stress of 15 ksi for friction type joints. (2)

(3) Pitch has a significant effect on connection efficiency. Results of limited tests related to this variable indicate that joints of equal length (center to center of end-most fasteners) but with different numbers of fasteners will have similar unbuttoning factors. Also, in joints of the type tested here, spacing of a given number of bolts at the minimum allowable pitch will result in the better joint.

(4) The long 8" grip through 8 plies of material seemed to introduce no detrimental effect on bolt performance attributable to bending.
10. ACKNOWLEDGEMENTS

The work described in this report is part of a larger investigation of large bolted joints being conducted at the Fritz Engineering Laboratory of the Civil Engineering Department of Lehigh University under the direction of Dr. Lynn S. Beedle. This project is sponsored financially by the Pennsylvania Department of Highways, the Bureau of Public Roads and the American Institute of Steel Construction. Technical guidance is provided by a committee of the Research Council on Riveted and Bolted Structural Joints.

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Table 2  
Results of Joint Tests  

D-Series – Part c

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PATTERN

All Holes Drilled 15/16"
Pitch 3 1/2" except 2 5/8"
for D13A
Gage = 1/2 Width
All Grips = 8"

BOLTS

No. in Line 10 13 13 16
No. of 7/8" A325 Bolts 20 26 26 32
Nom. Shear Area 24.04 31.25 31.25 38.46

PLATES

Nom. Width in. 8.47 10.47 10.47 12.43
Nom. Thickness in. 4.00 4.00 4.00 4.00
Nom. Gross Area Sq. in. 33.88 41.88 41.88 49.72
Nom. Net Area Sq. in. 26.24 34.20 34.22 41.93
Actual Net Area Sq. in. 26.38 34.38 34.38 42.22
% Dev. in Net Area % -.53 -.52 -.47 -.69

T/S RATIO $A_s / A_{net}$

Nominal 1:1.10 1:1.10 1:1.10 1:1.10
Actual   1:1.09 1:1.09 1:1.10 1:1.09

WORKING LOAD (T=20,000) (S=22,000) Kips 529 688 688 846

SLIP LOAD (First Major) Kips 900 792 960 1242

Nom. Bolt Shear ksi 37.4 25.3 30.7 32.3
Nom. Tension-Net Section ksi 34.1 23.0 27.9 29.4
Avg. Elong. of Bolts in. 0.0762 0.0702 0.0767 0.0671
Clamping Force per Bolt Kips 49.5 49.0 49.5 48.6
Slip Coefficient 0.455 0.312 0.373 0.399

TYPE OF FAILURE

Load at Failure Kips 15.44 19.88 18.54 20.85
Nom. Bolt Shear ksi 64.2 63.6 59.3 54.2
Nom. Tens. - Net Section ksi 58.5 57.8 53.9 49.4
Act. Tens. - Net Section ksi 58.8 58.1 54.2 49.7

* As measured from the direct tension calibration curve
Fig. 1 Dimensions of Joints, D-Series - Part c
Fig. 2 Histogram of Bolt Elongations, D-Series – Part c
Note: 
Bolts Unbuttoned By Shearing At Head Ends In Joint D10 
And D13A. Others Failed At Nut Ends.

Fig. 3 Sequence of Bolt Failures, D-Series - Part c
Fig. 4 Slip of Large Bolted Joints
Fig. 5 Unbuttoning Factor