Bolted joints of high-strength steel, October 1964

J. W. Fisher

Follow this and additional works at: http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports

Recommended Citation
http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports/165

This Technical Report is brought to you for free and open access by the Civil and Environmental Engineering at Lehigh Preserve. It has been accepted for inclusion in Fritz Laboratory Reports by an authorized administrator of Lehigh Preserve. For more information, please contact preserve@lehigh.edu.
Large Bolted Connections

BOLTED JOINTS OF HIGH-STRENGTH STEEL

by

John W. Fisher

Fritz Engineering Laboratory Report 288.24
When the A325 high-strength bolt was first used it was as a 1 for 1 replacement for the A141 steel rivet. It was early recognized that the bolt was stronger than the rivet and an extensive research program was initiated at Lehigh University in 1957 to determine the behavior of the A325 bolt in large bolted butt splices and help establish allowable stresses which recognized the superior strength of the bolt. The results of this program was reported by Dr. J. L. Rumpf at the annual meeting of ASCE in 1961. As a result of this study bearing-type connections were recognized which permitted allowable shear stresses of 22 ksi in A325 bolts. Only 2 bolts were now needed where formerly 3 were required when only friction-type joints were used.

The increased use in recent years of high-strength steel for construction created a need for information concerning the behavior of these steels when used in connections fabricated with A325 bolts. With the higher yield stress level, the connection behavior may have differed from the earlier tests of mild steel.

The earlier tests of A7 steel joints had indicated that joint length influenced the ultimate strength of bolted joints. This slide
illustrates this effect as the average shear strength is plotted as a function of joint length. A decrease in average shear strength is seen to accompany an increase in joint length.

**SLIDE 3**

The reason for this behavior is clearly seen in this sawed section of a joint with 6 bolts in a line. As judged by the deformation in the joint the redistribution of forces amongst the fasteners was not complete when the end fastener failed.

2. **Initial Concept of Tests**

**SLIDE 4**

Pilot tests were undertaken on A440 steel joints connected by A325 bolts. These were compact joints with 2 lines of four bolts as shown in this slide. The tests were designed to determine the shear strength of the bolts. Also, it was desirable to know what influence variations in the net plate area had on the shear strength.

**SLIDE 5**

These initial tests showed that the shear strength of the bolts was about 70 ksi. The minimum ultimate strength of 1 in. A440 steel is 67 ksi. Previous investigations of rivet and bolted joints had developed the concept of "balanced design". That is at ultimate load the shear strength of the fasteners was equal to the tensile capacity of the plate. The compact joint tests indicated that when the loads were balanced the $A_n/A_s$ ratio was nearly unity. Subsequent
test specimens having 4 to 16 bolts in a line were proportioned by this ratio. All bolts were installed in drilled holes that were perfectly aligned. They were tightened by the turn-of-nut method.

3. Results of Tests

SLIDE 6

All joints were tested in static tension. The progress of a test is well illustrated by load-deformation curves. Typical behavior is illustrated for a joint with 10 bolts in a line. As load is first applied, the load transfer mechanism is one of friction, and linear response is observed up to the time of major slip. Usually the joint slipped into bearing at one instant. After major slip the principal load transfer mechanism was due to shear and bearing. As load was applied, inelastic deformations occurred in the bolts and plate until one of the end bolts failed when the load was considerably above the yield load of the plate. Additional loading caused a second bolt to shear at a slightly lower load in this case.

SLIDE 7

Although the primary objective of these tests was to evaluate the ultimate strength, information was also obtained on the slip resistance. The factors which determine the load at joint slip are the slip coefficient and the bolt clamping force. Bolt elongations were measured during fabrication and the clamping force was determined from these measurements.
This slide is a bar graph which illustrates the slip resistance of the A440 steel joints. The bottom horizontal line extending across the graph at 15 ksi represents the working stress level for friction-type connections. The horizontal line at 20 ksi would apply to connections subjected to static plus wind loading. No joint slipped below an average shear stress of 20 ksi. The average slip coefficient was 0.32. The minimum value was 0.25 and the maximum value 0.36. Also, note that neither length nor width appreciably influenced the slip coefficient.

SLIDE 8

In this slide the A440 steel joints are compared with the earlier tests of A7 steel butt joints. The A440 steel joints had a lower slip coefficient. The A7 steel joints had slip coefficients which ranged from 0.33 to 0.57. The average value of 0.32 for the A440 steel joints is but slightly less than the 0.35 value that is generally obtained for A7 steel joints.

SLIDE 9

Several wide joints were tested as the earlier studies of A7 steel joints had indicated that the lateral forces caused by plate necking affected the ultimate strength. This was not the case for the A440 steel joints fastened with A325 bolts. Neither the slip resistance or the ultimate strength were apparently affected by joint width.
SLIDE 10

In the short joints simultaneous shearing of all the bolts occurred. However, in the longer joints one or more bolts in the lap plate end sheared due to their larger deformation before the full strength of all bolts could be achieved. The results are plotted in this slide with the average shear stress at failure as a function of joint length. A decrease in average shear stress can be seen between the compact and longer joints.

4. Analytical Solution

SLIDE 11

Analytical solutions have been developed to aid in more comprehensive studies of the joint behavior at ultimate load. Initially graphical solutions were developed which utilized the calibration load-deformation curves of the component parts.

The load-deformation behavior of the bolts was determined from calibration tests of single bolts. This is a sawed section of a single bolt in a test jig near its ultimate load.

SLIDE 12

Relationships were also obtained for the plates by testing special calibration coupons as shown in this slide.

SLIDE 13

Recently mathematical models have been developed to predict this behavior and the solution is accomplished on the digital computer.
The theory has been checked with the experimental data by using the actual material properties of the joints. The maximum deviation between theory and test was less than 4%, with the theoretical value usually less than the experimental value. Two different lots of bolts were used in the test series to accommodate the change in grip. This together with the change in geometry accounts for the discontinuity at a joint length of approximately 40 inches.

SLIDE 14

Additional analytical studies were made to determine what influence the joint proportions had on the ultimate strength. Minimum strength materials were used in these hypothetical studies. For equal bolt shear and net tensile areas which would result with a 27.5 ksi allowable shear stress the relationship was similar to that obtained for the test joints in the preceding slide. The dashed horizontal line represents the shear strength of a single bolt. If the plate area were perfectly rigid, complete redistribution would occur at all lengths.

SLIDE 15

As the plate net tensile area is increased relative to the shear area as would be the case with higher allowable shear stresses, the average shear strength of the bolts in the longer joints increased. This is readily apparent in this slide where the theoretical line for equal bolt shear and net tensile areas \( (A_n/A_s = 1.0) \) is compared with the theoretical line when the net plate area is 20% greater than the bolt shear area \( (A_n/A_s = 1.2) \).
When the net plate area is decreased with respect to the bolt shear area ($A_n/A_s = 0.8$) short and medium length joints invariably fail by tearing of the plate. The plate failure boundary is also indicated in this slide. In the longer joints the accumulated differential strains between the main plate and lap plate cause a bolt failure before the plate fails.

Several additional tests were undertaken after this theoretical study was made to further check on the validity of the theory. Two joints were proportioned with the net plate area 20% greater than the bolt shear area ($A_n/A_s = 1.2$). Two other joints were proportioned with the $A_n/A_s$ ratio equal to 0.8. The results of these latter tests are shown in this slide and are compared with theoretical curves as well as the previous series of tests. The agreement between the test results and theory is very good.

A comparison of two sawed sections of joints with 7 bolts in line readily shows the influence of the accumulated differential strains between the main plate and the lap plate. It is visually evident that the accumulated strains were much higher for joint E721 with an $A_n/A_s$ ratio of 0.8. As judged by the deformations in the joints the distribution of load amongst the fasteners is more nearly uniform in joint E71 with $A_n/A_s = 1.0$. Joint E722 of the same length and
number of bolts but with $A_n/A_s = 1.2$ failed by a simultaneous shearing of all the fasteners indicating that almost complete redistribution had taken place.

**SLIDE 19**

The theory was also used to compare the relative behavior of A7 and A440 steel joints for the "balanced design" condition. Such a comparison is made in this slide where the theoretical curve for A7 steel joints with $A_n/A_s = 1.0$. This comparison shows that the A325 bolt performs better in A440 steel than in A7 steel for these proportions. It should be noted that balanced design was only achieved for very short joints. In the longer joints the end bolts failed before the tensile strength of the plate was developed.

**SLIDE 20**

The reason for the improved performance of the joints fabricated from A440 steel is the more favorable redistribution of load among the fasteners for the "balanced design" proportions. The reason for the different behavior is illustrated in this slide. The calculated bolt shear stresses in each fastener of a 10 fastener joint at two different stages can be compared. The slide shows that the higher yield point steel effects a better redistribution of the bolt forces, the stresses being more uniform in the A440 steel joint than in the A7 steel joint.

All of the bolts were loaded into the inelastic region in
the A440 steel joints before any significant yielding occurred in the plate. Thus the plate was rigid, the bolts plastic, and the redistribution was good. In the A7 steel joints inelastic deformations occurred nearly simultaneously in the end fasteners and in the plate and this caused increased deformation in the end bolts. As a result these bolts picked up load at a faster rate than the interior bolts and the redistribution was not as complete.

SLIDE 21

Since balanced design means that the same factor of safety against ultimate is applied to both the bolt and to the plate this would imply that the allowable shear stress would be 22 ksi for A325 bolts in A7 steel and 27.5 ksi for A325 bolts in A440 steel. For compact A7 steel joints where balanced design is achieved, the factor of safety would be about 3.3. For compact A440 steel joints the corresponding factor of safety would be 2.45. In both cases an increase in joint length results in a decrease in the factor of safety so that for long joints the factor of safety is nearly the same or about 2.1.

SLIDE 22

It is not very reasonable to vary allowable stresses for the same bolt depending on which material is being connected. A more rational approach is to establish working stresses based on the behavior of the bolt in the various steel joints. For a given allowable stress the behavior of the bolt in the two different steels is
nearly the same as indicated in this slide. For example, if the allowable shear stress were taken as 30 ksi, the corresponding $A_n/A_s$ ratio for A7 steel is 1.50 and for A440 steel the ratio would be 1.09. This comparison shows that the strength of A440 steel joints is slightly lower than the A7 steel joints for a specified allowable stress that is common to both steels. The comparison shows that factor of safety for the A325 bolt now varies from about 2.45 down to 2.0 for both connected steels. This analysis has shown and tests have verified that the shear strength of A325 bolts installed in compact joints of A7 or A440 steel is the same. With increasing joint length both A7 and A440 steel joints showed a decrease in the bolt shear strength.

This examination has also shown that the concept of balanced design leads to inconsistent allowable bolt stresses for different steels and that for a given allowable stress the behavior of the bolt is nearly the same in different steels. A more logical criterion for design results if the factor of safety is fixed against the shear strength of the fastener.

5. Summary

The important findings of this investigation on high-strength steel joints can be summarized as follows:

1. The shear strength of A325 bolts in compact joints of A440 steel was found to be the same as in joints of A7 steel.

2. As joint length increased with an increasing number of bolts in a line, the differential deformations in the connected material...
caused the end bolts to shear before all bolts could develop their full shearing strength.

3. The decrease in shear strength with increasing joint length is influenced by the relative proportions of the bolt shear area and the plate net tensile area.

4. The decrease in strength with increasing joint length is nearly the same for A7 and A440 steel joints when the fasteners are proportioned to the same allowable shear stress.

5. An increase in joint width had no appreciable effect on the ultimate strength of the A440 steel joints.

6. Good agreement was obtained between the test results and the theoretical analysis.

7. These tests yielded a mean slip coefficient for tight mill scale faying surfaces of 0.32. Neither joint length nor width had any appreciable effect on the slip coefficient. This value is only slightly lower than the generally accepted average value of 0.35 for mild steel.

8. All bolts were tightened by the turn-of-nut method and consistently had preloads approximately 1.3 times the proof load of the bolt.

6. Work in Progress

Before concluding this talk I would like to briefly review the work that is currently in progress on bolted joints of high-strength steel.
Analytical and experimental work is underway on A440 steel joints connected by the new A490 bolt. Also, quenched and tempered steel joints connected by either A325 or A490 bolts are being investigated. The results of much of this work will be available in the near future.

7. Acknowledgements

Also, I would like to indicate that this project is sponsored financially by the Pennsylvania Department of Highways, the U.S. Department of Commerce - Bureau of Public Roads, the American Institute of Steel Construction and the Research Council on Riveted and Bolted Structural Joints.

Technical guidance is provided by an advisory committee of the Research Council.
A325 Bolts
\[ \tau_{\text{ult}} = 70 \text{ ksi} \]

A440 Steel
\[ \sigma_{\text{ult}} = 67 \text{ ksi} \]

\[ \frac{\tau}{\sigma} = \frac{A_n}{A_s} \approx 1.0 \]

"BALANCED DESIGN"
Yield of $A_g$
Yield of $A_n$
Load Transfer by Bearing + Shear
Load Transfer by Friction
Major Slip
Bolt failure sequence
DEFORMATION X-X, inches
CLEAN MILL SCALE

SHORT JOINTS
LONG JOINTS
WIDE JOINTS

SHEAR STRESS ksi
0 10 20 30

NUMBER OF BOLTS IN A LINE
A440 Steel
SLIDE 7
A440 Steel Joints - A325 Bolts

Shear Strength ksi

Joint Length, Inches

Theoretical Failure Curve

Joint Length: 4 in. grip to 8 in. grip

An/As = 1.0
A440 Steel Joints - A325 Bolts

Shear Strength (ksi)

Joint Length, Inches

$A_n/A_s = \infty$

$F_v = 27.5$
A440 Steel Joints - A325 Bolts

Shear Strength (ksi) vs Joint Length (inches)

- $A_n/A_s = \infty$
- $F_v = 33$
- $F_v = 27.5$

Slide 15
A440 Steel Joints - A325 Bolts

\[ F_v = 33 \]
\[ 27.5 \]
\[ 22 \]

Shear Strength ksi

Joint Length, Inches
SHEAR STRENGTH ksi

Single Bolt (8B Lot)

Single Bolt (H Lot)

\[ \frac{A_n}{A_s} = 1.2 \]

\[ \frac{A_n}{A_s} = 1.0 \]

\[ \frac{A_n}{A_s} = 0.8 \]

4 in. grip \quad 8 in. grip

JOINT LENGTH, INCHES
"BALANCED DESIGN"
A325 Bolts

A440 Steel
$A_n/A_s = 1.0$

A7 Steel
$A_n/A_s = 1.1$

SHEAR STRENGTH ksi

JOINT LENGTH, INCHES

SLIDE 19
BALANCED DESIGN LEADS TO

\[ F_v = 22 \text{ ksi} \quad \text{A325 Bolts in A7 Steel} \]

\[ F.S. = 2.15 \text{ to } 3.30 \]

\[ F_v = 27.5 \text{ ksi} \quad \text{A325 Bolts in A440 Steel} \]

\[ F.S. = 2.10 \text{ to } 2.45 \]

SLIDE 21
WORK UNDERWAY

A440 Steel Joints Connected by A490 Bolts

Quench and Tempered Steel Joints Connected by A325 or A490 Bolts