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Large Bolted Connections

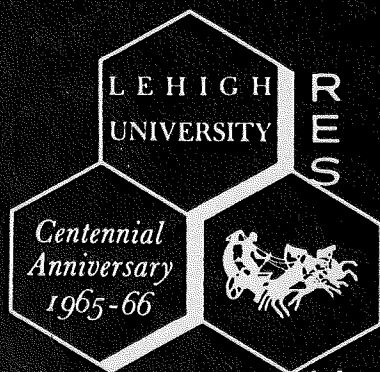
BEHAVIOR OF LARGE BOLTED JOINTS

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by

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TO THE UNIVERSITY OF PENNSYLVANIA



Fritz Engineering Laboratory Report No. 288.31

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This work was carried out as part of the Large Bolted Connections Project, sponsored financially by the Pennsylvania Department of Highways, the Department of Commerce - Bureau of Public Roads, and the American Institute of Steel Construction. Technical guidance is provided 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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S Y N O P S I S

This paper summarizes the results of tension tests of long structural splices of A7 or A440 steel connected by high-strength bolts (A325 or A490) which have provided background for parts of the specification of the Research Council on Riveted and Bolted Structural Joints. The influence of the joint length, pitch, relative proportions of the net tensile area of the plate to the bolt shear area on the ultimate strength of bearing-type connections is determined by theoretical studies and confirming tests. Data on the slip resistance is also presented for use in designing friction-type connections.

1. I N T R O D U C T I O N

When the A325 high-strength bolt was first used, it was as a one-for-one replacement for the A141 steel rivet. It was soon 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 to help establish allowable stresses which recognized the superior strength of the bolt. Tests were conducted on compact joints to determine the proper ratio of shear area and net tension area to achieve a so-called balanced design.⁽¹⁾ It was shown in these studies that the proper tension-shear ratio was 1 to 1.10 for A325 bolts in A7 steel joints. Thus, for bridge specifications, if the allowable tensile stress in the plate were 18 ksi, then the allowable shear stress in the bolts would be 20 ksi. These stresses imply a factor of safety of 3.3 against the ultimate strength of bolts and plate in a compact joint.

Subsequently, tests were conducted on long bolted joints which were proportioned using the tension-shear relationship that had been established for the compact joints.⁽²⁾ These tests showed that the longer joints were not able to effect a complete re-distribution of the load because the end fasteners failed prematurely. This failure was not due to any deficiency of the fastener but was the result of the accumulated differential strains between the main and the lap plates. Since the end fasteners did not have the ability to deform sufficiently

to accommodate these differential strains, equalization of load among all bolts could not take place.

The balanced design criterion was also used in recent tests to determine the relative proportions of shear area and net tensile area when A325 bolts were used to connect A440 steel plates.⁽³⁾ This work showed that the balanced design concept would yield a tension-shear ratio of 1 to 1.0 for material in the thickness range of 3/4-in. to 1½-in. Subsequent analytical studies⁽⁴⁾⁽⁵⁾ and tests⁽⁶⁾ indicated that the ultimate load was greatly affected by the relationship between the net tensile area of the plate (A_n) and the shear area of the bolts (A_s).

More recently, analytical studies and tests have been conducted on A440 steel joints connected by A490 bolts.⁽⁷⁾

This paper summarizes the results of these studies on large bolted connections and discusses the design criteria for bearing-type connections.

2. DESCRIPTION OF TEST SPECIMENS

The research program summarized in this report consisted of static tension tests of large bolted joints. Twenty-four double shear, bolted, A7 steel butt joints with from three to sixteen 7/8-in., 1-in., or 1-1/8-in. A325 bolts in line were tested. Four double shear, riveted A7 steel butt joints with from five to thirteen 7/8-in. A141 steel rivets

were tested for comparative purposes. Also, four bolted, A7 steel lap joints with from two to ten 7/8-in. A325 bolts in a line were tested to verify single shear behavior. Additional details of these tests are given in Refs. 1 and 2.

Eighteen double shear, bolted, A440 steel butt joints with from four to sixteen 7/8-in. A325 bolts in line were tested to determine what effect grade of steel had on joint behavior. Details of these tests are given in Refs. 3 and 6.

Eight double shear, bolted A440 steel butt joints with from four to nineteen 7/8-in. A490 bolts in line were tested to investigate the behavior of the new, higher strength A490 bolt. Results of these tests were first reported in Ref. 7.

3. F A B R I C A T I O N A N D A S S E M B L Y

The joints were assembled by a local fabricator. Plates were first cut by torch and then machined to final dimensions. Loose mill scale was removed by hand brushing with a wire brush. Oil and grease were wiped from the plates with solvent in order to establish a faying surface condition which would be comparable to that likely in the field. Eight A7 steel butt joints had all mill scale removed with a power tool. This resulted in a semi-polished surface. The plates were assembled into the required configuration, clamped together, and the four end holes sub-

drilled and reamed. Fitted pins were inserted to maintain alignment while the remainder of the holes were drilled through all plies of the assembly.

The bolting-up operation was carried out by a field erection crew of the fabricator. Bolts with grips less than five inches had the nuts tightened one-half turn from "snug". The nuts of A325 bolts were torqued through a three-fourths turn and those of A490 bolts a two-thirds turn from snug for bolts with grips of five inches or more. In all cases, bolt threads did not intercept the shearing planes.

4. T E S T I N G

The joints were loaded in static tension using a 5000 kip universal testing machine with wedge grips. The progress of a test is well illustrated by load-deformation curves. Typical behavior is shown in Fig. 1 for an A440 steel joint with ten A325 bolts in line. As load was first applied, the load transfer mechanism was one of friction and linear response was observed up to the time of major slip. Usually the joint slipped into bearing instantaneously. After major slip, the principal load transfer mechanism was that of shear and bearing. As load was applied, inelastic deformations occurred in the bolts and plate until one of the end bolts failed, at which time 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. This sequential failure of bolts, starting from the ends, is termed "unbuttoning".

5. EFFECT OF JOINT LENGTH AND
VARIATIONS IN PLATE AREA

In many of the early tests of mild steel joints, the plate area at the net section was about 75% of the shear area of the bolts.⁽¹⁾⁽⁸⁾ In these cases, failure usually occurred by tearing and fracture of the plate. The exception was one joint which had 13 fasteners in line. This failed by unbuttoning.⁽⁸⁾

In the shorter joints, failure occurred in the plate even when the plate area and the shear area were equal. Figure 2 is a photograph of a large mild steel splice connected by A325 bolts. The plate area is equal to 96% of the bolt shear area.

Figure 3 shows the influence of joint length on the strength of double-lap, A7 steel butt joints.⁽¹⁾⁽²⁾ A plotted point is the reported average shear stress at failure for the given length. Bolts in a particular joint were from the same lot; however, several lots with differing strengths were used in the joint tests. The scatter in the experimental results is caused primarily by these variations. All bolts had strengths which exceeded the ASTM minimum and the tensile strength of the plate material was up to 9% greater than that specified by ASTM.

Also shown in Fig. 3 is the theoretical strength curve for failure of the bolts as found using the procedure developed in Ref. 5. The permissible shear stress of 20 ksi according to recent specifications is shown on the graph.⁽⁹⁾⁽¹⁰⁾ The theoretical calculations have been based on minimum strength A325 bolts and A7 steel plates. It is clear that the short, compact joints are substantially stronger than the longer joints.

The four A7 steel joints connected by A141 steel rivets tested for comparative purposes showed the same general behavior as the bolted joints. The results, illustrated in Fig. 4, show good agreement between predicted⁽⁵⁾ and test⁽²⁾ values.

Initial tests on A440 steel joints connected by A325 bolts were performed on compact joints with two lines of four bolts each. These tests were designed to determine the shear strength of the bolts. In addition, it was desirable to know what influence variations in the net plate area had on the shear strength.

These tests showed that the shear strength of the bolts was about 70 ksi. The minimum ultimate strength of 1-in. A440 steel plate is 67 ksi. Previous investigations of riveted 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 portions of the load carried by the plate and by the fasteners were equal, the A_n/A_s ratio was nearly unity for this combination of bolt and plate material. Subsequent test specimens having from 7 to 16 bolts in a line

were proportioned using ratios of either 0.8, 1.0, or 1.2. All bolts were installed in drilled and aligned holes and were tightened by the turn-of-nut method.

The results of these tests are summarized in Fig. 5. (3)(6) The dashed horizontal line represents the shear strength of a single bolt. If the plate were perfectly rigid, complete redistribution would occur at all lengths. In the short joints, simultaneous shearing of all the bolts did occur. In the longer joints however, one or more bolts in the lap plate end sheared due to their larger deformation before the full strength of all of the bolts could be achieved. The results are plotted in this figure with the average shear stress at failure as a function of joint length.

As the net tensile area of the plate is increased relative to the bolt shear area, as would result from higher allowable bolt shear stresses, the average shear strength of the bolts in the longer joints increased.

When the net plate area of A440 steel joints was only 80% of the bolt shear area ($A_n/A_s = 0.80$), short and medium length joints invariably failed by tearing of the plate. The predicted plate failure boundary is also indicated in Fig. 5. In the longer joints, the accumulated differential strains between the main and lap plates caused a bolt failure before the plate failed.

Two sawed sections of joints with seven A325 bolts in line, shown in Fig. 6, show the influence of the accumulated differential

strains between the main plate and the lap plate. It is evident that the accumulated strains were much higher for joint E721 with an A_n/A_s ratio of 0.8 than for joint E71 in which A_n/A_s was 1.0. As judged by the deformations in the joints, the distribution of load among the fasteners is more nearly uniform in joint E71. 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. This indicates that complete, or almost complete, redistribution of load had taken place.

Recent tests of joints using A490 bolts installed in A440 steel plate are summarized in Fig. 7. (7) The behavior of these joints parallels those previously discussed.

6. E F F E C T O F J O I N T W I D T H

The effect of internal lateral forces caused by plate necking near the ultimate tensile strength of a wide joint was investigated with tests of eight A7 steel joints and three A440 steel joints fastened with A325 bolts. (1)(3) These joints had from four to six lines of bolts with from four to seven bolts in each line.

Generally, the behavior of these joints was directly comparable to joints with only two lines of fasteners and the same number of bolts in each line. For example, an A440 steel joint with six lines of four bolts failed at exactly three times the ultimate load of a joint with two lines of four bolts. Similarly, the ultimate load of a joint with four

lines of seven bolts failed at twice the ultimate load of a joint with two lines of seven bolts.

Approximately the same behavior was observed in A7 steel joints, although in some cases plate necking was found to contribute to premature failure of corner bolts. In general, joint width did not significantly affect the joint behavior.

7. E F F E C T O F N U M B E R O F S H E A R P L A N E S

Although specifications have traditionally assigned to rivets a single shear value equal to one-half that for double shear, it seemed advisable to investigate this relationship experimentally for high strength bolts. Four lap joints of A7 steel fastened with two lines of from two to ten A325 bolts each were tested. An external bracing system was used to eliminate the effects of the inherent eccentricity of the joints. Because of different tension-shear ratios, only one of these joints could be compared to a corresponding butt joint. In this case, the lap joint failed at almost exactly half the failure load of the butt joint.

8. D E S I G N C R I T E R I A F O R B E A R I N G - T Y P E C O N N E C T I O N S

The theory developed in Ref. 5 was used to compare the relative behavior of A7 and A440 steel joints fastened with A325 bolts for the

"balanced design" condition. Such a comparison is made in Fig. 8 where the theoretical curve for A7 steel joints with $A_n/A_s = 1.1$ is compared to the theoretical curve for A440 steel joints with $A_n/A_s = 1.0$. This comparison shows that the A325 bolts perform better in A440 steel ($A_n/A_s = 1.0$) than in A7 steel ($A_n/A_s = 1.1$) for these proportions. It should be noted again that balanced design was achieved only for very short joints. In the longer joints, the end bolts failed before the tensile strength of the plate was developed.

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 (using the above ratios) that the allowable shear stress would be 20 ksi for A325 bolts in A7 steel and 25 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. The corresponding factor of safety would be 2.7 for compact A440 steel joints. In both cases, an increase in joint length results in a decrease in the factor of safety. For long joints, the factor of safety is about 2.2 and is nearly independent of the grade of steel in the joints.

It is not reasonable to vary the 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.⁽⁹⁾ As shown in Fig. 9, the behavior of the bolt for a given allowable stress (20 ksi) is nearly the same in the two different steels. Here the factor of safety is plotted as a function of joint length for the current allowable shear

stress of 20 ksi for A325 bolts installed in A7, A440, and A514 steel plate. (9)(10) The curves show the factor of safety against shear failure in the bolt, whereas the horizontal lines show the cut-off that would occur as a result of plate failure for the three types of steel.

For short joints, the factor of safety against shear in the bolt is the same regardless of the type of connected steel, namely, 3.7. For long joints, neglecting plate failure, the factor of safety is seen to vary depending upon the joint length.

It can be noted that higher strength steel joints develop less strength for the given allowable bolt stress (Fig. 9) than the A7 steel joints. This is contrary to the results shown in Fig. 8 which described the "balanced design" condition. The same situation holds at other stress levels. If, for example, the allowable shear stress in the bolt were 30 ksi, the corresponding A_n/A_s ratio for A7 steel is 1.50 and for A440 steel it is 1.09. Figure 10 shows that the strength of A440 steel joints is slightly less than A7 steel joints for this stress level in the bolts. The factor of safety for the A325 bolt, in this instance, varies from about 2.45 to 2.0 for both types of 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 show a decrease in the bolt shear strength.

This examination has shown that the concept of balanced design leads to inconsistent allowable bolt stresses for different steels and

the same bolt. For a given allowable stress (20 ksi), the resulting geometric configurations for different steels provide ultimate joint strengths which decrease slightly with an increase in steel strength. A more logical criterion for design results if the factor of safety is fixed against the shear strength of the fastener. It is apparent that increasing the allowable stress in bearing-type joints would have no adverse effect on the minimum factor of safety. It would simply mean that the material would be used more efficiently. Additional discussion of this design criterion is given in Ref, 11.

9. S L I P R E S I S T A N C E

Although the primary objective of these studies of high-strength bolts in bearing-type connection was to evaluate the ultimate strength of the joints, information was also obtained on their slip resistance. The factors which determine the load at joint slip are the bolt clamping force and the slip coefficient. The clamping force was determined from measurements of the bolt elongations taken during fabrication.

The slip coefficient, K_s , has been computed as

$$K_s = \frac{P_s}{mn T_i} \quad (1)$$

in which P_s is the major slip load; m is the number of bolt shear planes; n is the number of bolts; T_i is the average initial bolt tension (or

clamping force) as obtained from a torqued tension calibration curve using the average elongation of all bolts in a joint. The resulting values of K_s are shown in Fig. 11.

The A7 steel joints with clean mill scale had slip coefficients which ranged from 0.33 to 0.57 with an average value of 0.46. The A440 steel joints with clean mill scale had an average slip coefficient of 0.32. The average value generally used for steel joints is 0.35.⁽⁹⁾ The eight A7 steel joints which had the mill scale removed with a power tool had slip coefficients which ranged from 0.22 to 0.36, with a mean value of 0.29. This emphasizes the importance of ensuring that mill scale remains intact on faying surfaces in friction-type connections.

In addition to the A440 steel joints connected by A325 bolts, eight A440 steel joints connected by A490 bolts were tested. The number of bolts in a line varied from four to nineteen. The steel plate for both series of tests was from the same heat. The slip coefficient ranged from 0.33 to 0.40, with an average value of 0.35. This was only slightly higher than that obtained for the A440 steel joints connected by A325 bolts. Hence, the type bolt did not significantly affect the slip coefficient.

The slip resistance of bolted joints was not affected by joint width or length. Figure 11 shows the variation in slip coefficient was random and that joint geometry was not a significant variable.

Although the bolts are not actually acting in shear, it has been convenient to regulate the design of friction-type connections by

an allowable bolt shear stress.⁽⁹⁾ The average shear stress at time of major slip is plotted as a function of joint length in Fig. 12. The horizontal line extending across the graph at 13.5 ksi represents the working stress level for A325 bolts. The horizontal line at 20 ksi is for A490 bolts. It is readily apparent that all joints with clean mill scale faying surfaces had factors of safety against slip which exceeded the value of 1.55 described in Ref. 9. This was true for A325 and A490 bolts.

10. FURTHER RESEARCH

A number of studies are now underway at Lehigh University to explore factors not yet covered up to the present time. Among these are:

1. Studies of constructional alloy steel (A514) joints fastened with A325 or A490 bolts.
2. Studies of joints in which two or more different grades of steel are joined.
3. Studies to determine the influence of joint flexibility on the installation of A490 bolts.
4. Studies of the influence of slotted and oversize holes on slip resistance of joints and installation of bolts.

It is hoped that the results of this work will contribute to a better understanding of bolted joints and to further improvements in their use.

11. S U M M A R Y A N D C O N C L U S I O N S

The following conclusions are based on the results of theoretical studies and of 54 confirming tests of large bolted joints conducted at Lehigh University and summarized herein. The principal items under investigation were the effect of joint length on the ultimate strength, the effect of variations in the net tensile area, the type of connected steel, and the type of fastener. Information was also obtained on the applicability of the turn-of-nut method, the effect of surface condition on slip resistance, the effect of pitch, the effect of joint width, the effect of number of shear planes, and long grip bolts.

1. Joints of A440 steel with up to four A325 fasteners in line were capable of developing about 96% of the shear strength of a single bolt. Similar joints of A7 steel fastened with A325 bolts behaved in substantially the same manner.
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.

The fastener pitch influences the shear strength mainly through its effect on joint length. This unbuttoning-type of failure was observed for all types of fasteners including rivets. It emphasizes the fact that joints should be kept as short as possible.

3. The decrease in strength with increasing joint length was slightly more for A440 steel joints than for A7 steel joints when the fasteners are proportioned to the same allowable shear stress.
4. Controlled variation in the plate area at the net section affected the bolt shear strength, as would be expected. As the plate area increased, greater rigidity was achieved and a correspondingly higher shear strength of the bolt groups resulted. This emphasizes the value of keeping the number of fasteners to a minimum.
5. An increase in joint width had no appreciable effect on the ultimate strength of A440 steel joints and only slightly affected the strength of A7 steel joints.
6. Good agreement was obtained between the test results and the theoretical analysis developed for determining the ultimate strength of bolted joints. The variation between the computed strength and the test result seldom exceeded 5%.

7. A more logical criterion for design results if the factor of safety is fixed against the shear strength of the fastener. The balanced design concept is shown to have no meaning as inconsistent allowable bolt stresses would result.
8. Bolts used in single shear have one-half the load carrying capacity of comparable bolts in double shear, provided the shear planes act through the bolt shank.
9. The tests confirmed that no special provision need be made for high-strength bolts in long grips.
10. These tests indicated that a reasonable mean value of the slip coefficient for tight mill scale faying surfaces of A7 or A440 steel is about 0.35. Neither joint length nor width had any appreciable effect on the slip coefficient.
11. All bolts in these tests were tightened by the turn-of-nut method. The A325 bolts had preloads about 1.3 times their specified proof load. The A490 bolts had preloads about 1.1 times their specified proof load.

12. A C K N O W L E D G E M E N T S

The work described in this paper is part of an investigation of large bolted joints being conducted at the Fritz Engineering Laboratory, Department of Civil Engineering, Lehigh University. Professor William J. Eney is head of the Department and the Laboratory. The project is sponsored 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. Committee 10 of the Research Council on Riveted and Bolted Structural Joints has provided technical guidance.

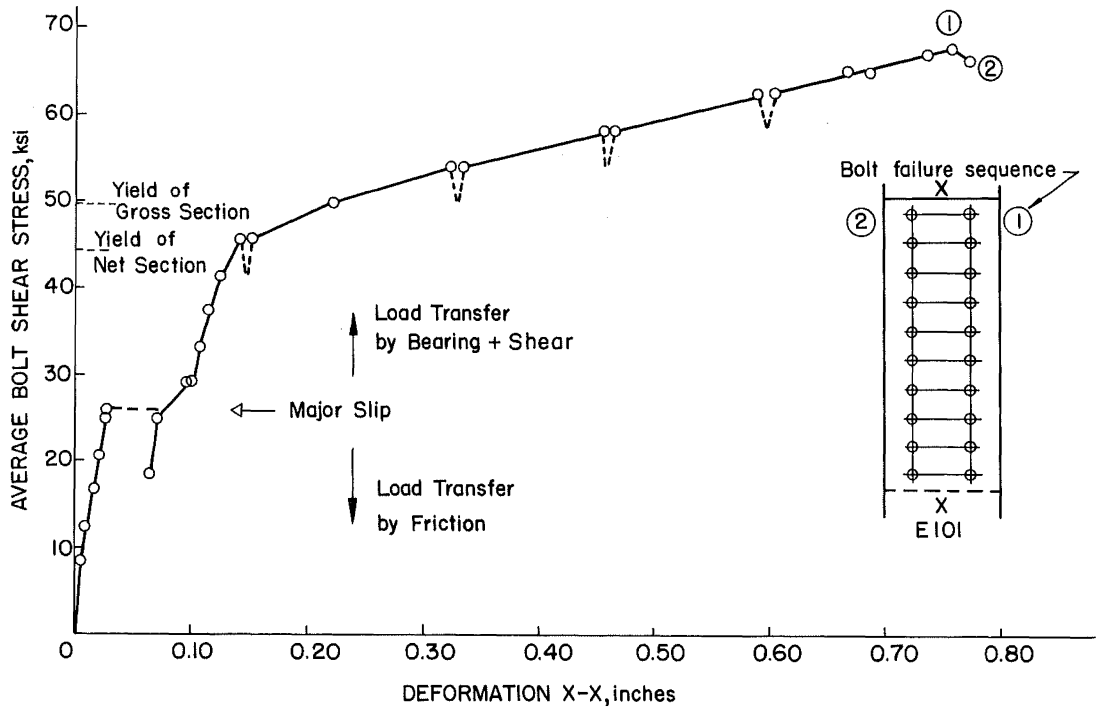


Fig. 1 Typical Load-Deformation Curve

(A440 Steel Joint Connected by A325 Bolts)

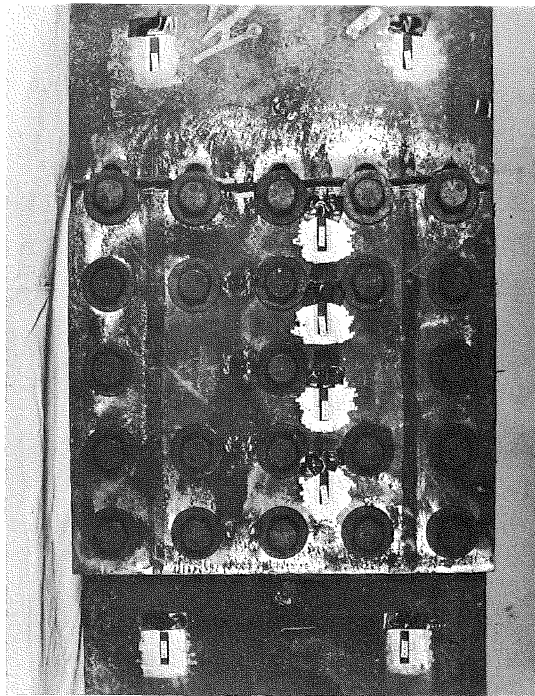


Fig. 2 Tensile Failure of Large Bolted Joint

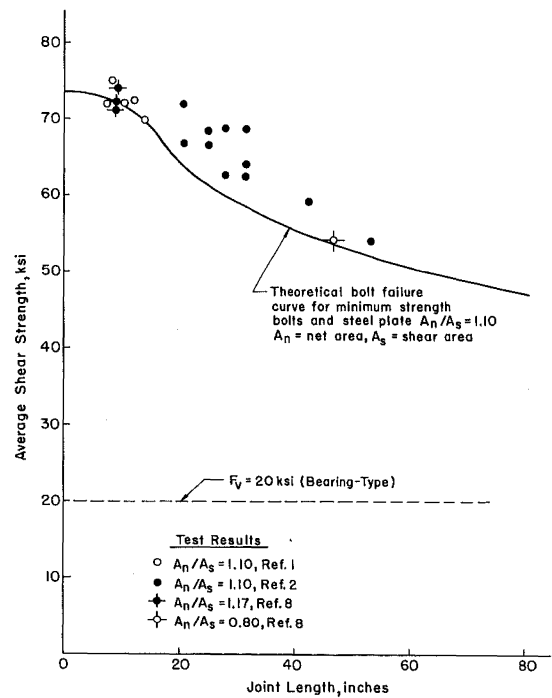


Fig. 3 Comparison of Computed Failure Curve with Test Results of A7 Steel Joints Connected by A325 Bolts

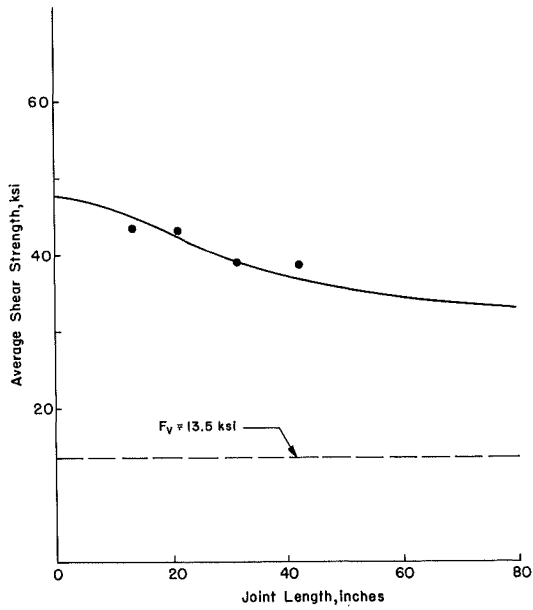


Fig. 4 Comparison of Computed Failure Curve with Test Results of A7 Steel Joints Connected by A141 Steel Rivets

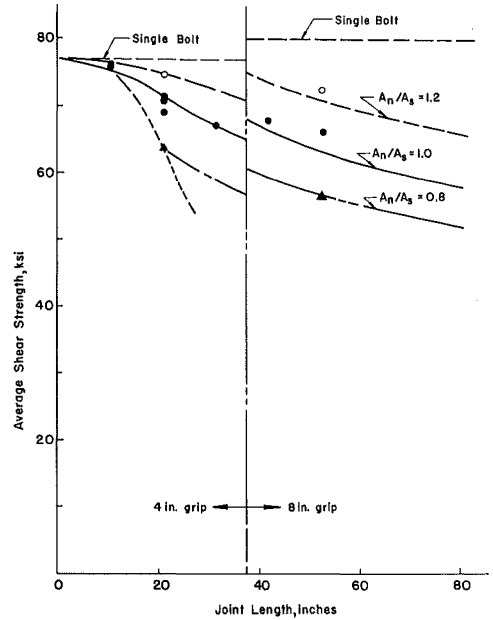


Fig. 5 Comparison of Computed Failure Curves with Test Results of A440 Steel Joints Connected by A325 Bolts

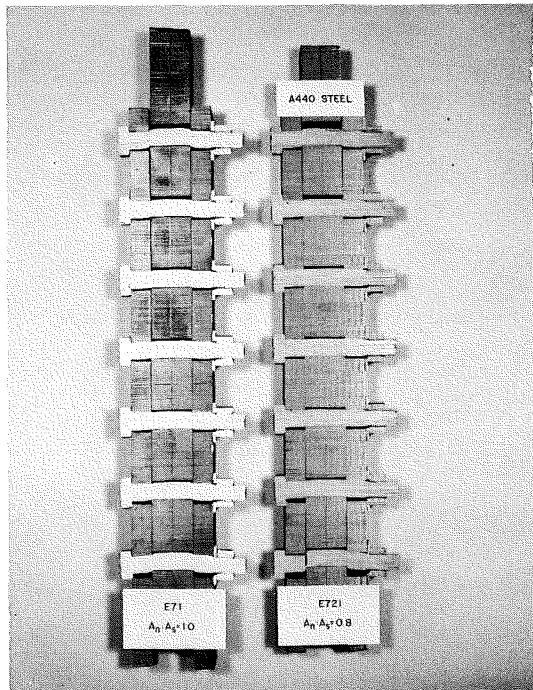


Fig. 6 Sawed Sections of Test Joints After Failure

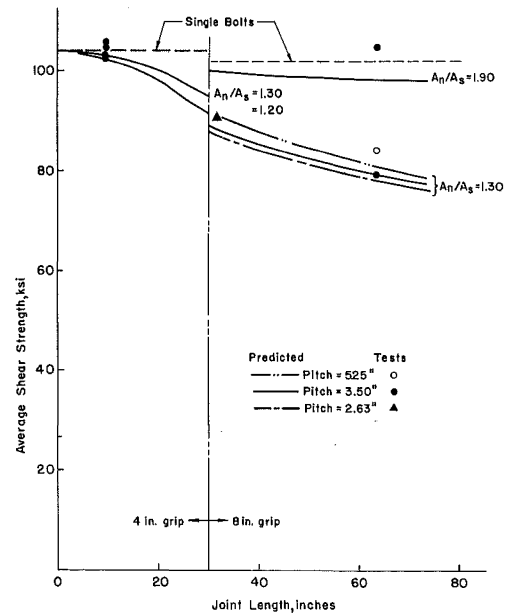


Fig. 7 Comparison of Computed Failure Curves with Test Results of A440 Steel Joints Connected by A490 Bolts

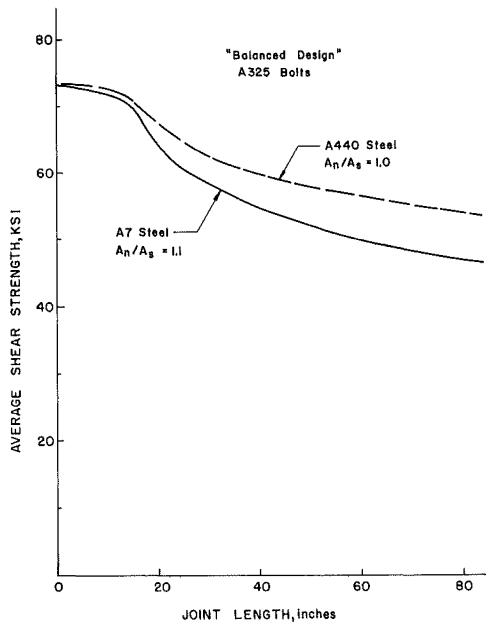


Fig. 8 Effect of Length on Ultimate Strength for Balanced Design

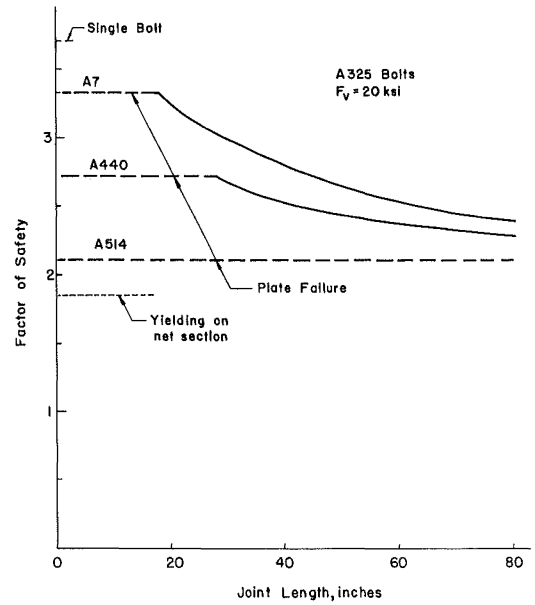


Fig. 9 Current Factor of Safety for A325 Bolts in Various Steels

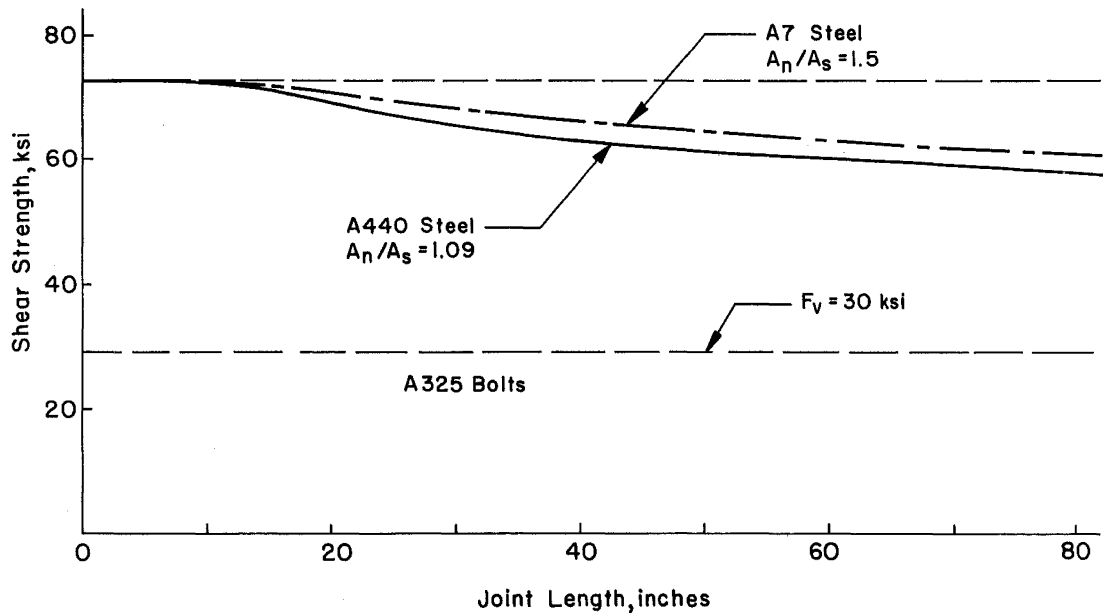


Fig. 10 Predicted Behavior of A325 Bolts Designed for 30 ksi in Bearing-Type Joints

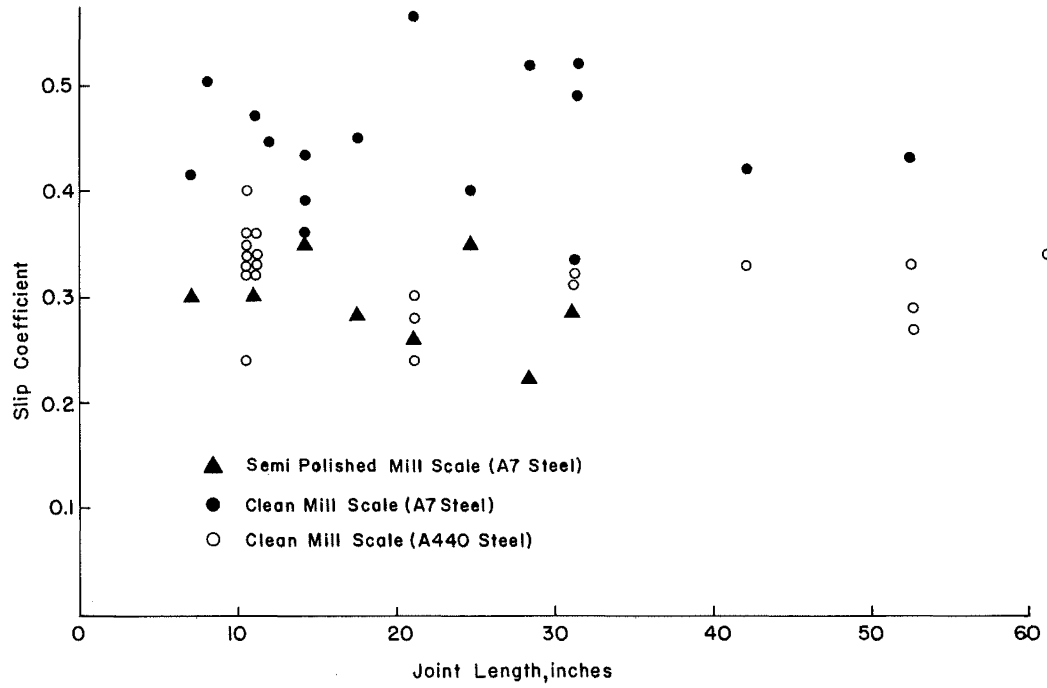


Fig. 11 Slip Coefficient for Bolted Joints

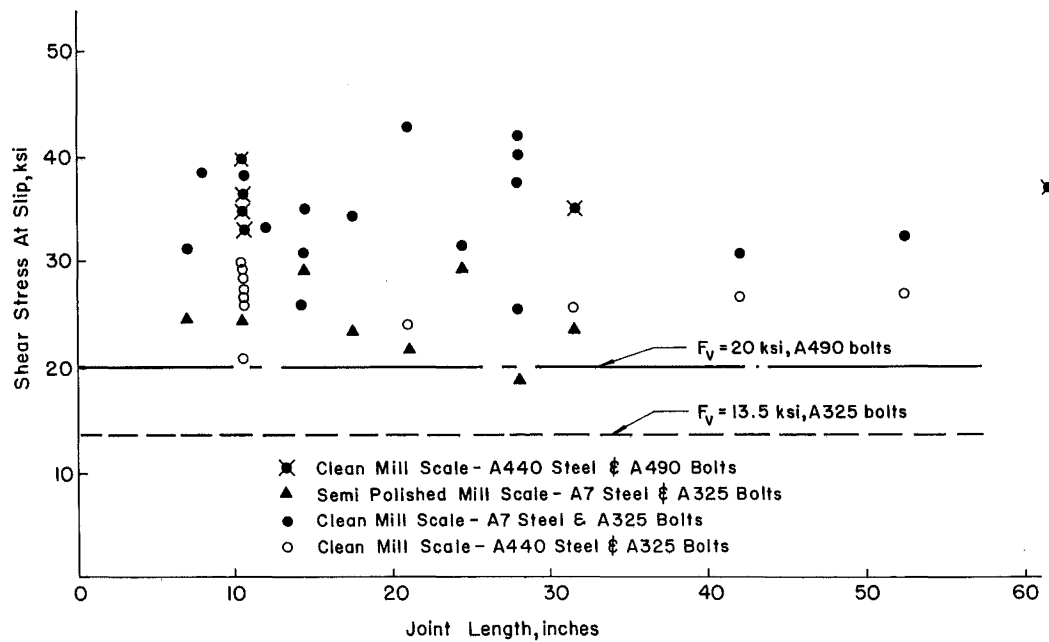


Fig. 12 Slip Resistance of Bolted Joints when Bolts are Tightened by Turn-of-Nut Method

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This paper summarizes the results of tension tests of long structural splices of A7 or A440 steel connected by high-strength bolts (A325 or A490) which have provided background for parts of the specification of the Research Council on Riveted and Bolted Structural Joints. The influence of the joint length, pitch, and relative proportions of the net tensile area of the plate to the bolt shear area on the ultimate strength of bearing-type connections is determined by theoretical studies and confirming tests. Data on the slip resistance is also presented for use in designing friction-type connections.

KEY WORDS: bolts; friction; joints; shear; slip; steel; structural engineering; testing.