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Large Bolted Connections

A440 STEEL JOINTS CONNECTED BY A490 BOLTS

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This work was carried out as part of the Large Bolted Connections Project sponsored by the Pennsylvania Department of Highways, the Department of Commerce - Bureau of Public Roads, the American Institute of Steel Construction, and 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 report presents data from eight static tension tests of full-sized bolted butt joints fabricated from 1-in. plies of A440 steel plate and connected by 7/8-in. ASTM A490 high-strength bolts. In addition, this report includes the results of a theoretical analysis of A440 steel joints fastened with either A490 bolts or A502-Grade 2 high-strength rivets. Both the theoretical and experimental studies were designed to show the effects of specific variables on the ultimate joint strength, including variations in pitch, joint length, and changes in the ratio of net plate area (A_n) to the total fastener shear area (A_s).

The theoretical studies show that the average shear strength decreases with increasing joint length. Fastener pitch had a minor effect on the shear strength. Total joint length had the most important effect on the average shear strength at ultimate joint load for a given A_n/A_s ratio. Variations in the A_n/A_s ratio produced major changes in average shear strength. The maximum deviation between the theoretical solution and test results was 7%.

Experimental data show that the present slip coefficient of 0.35 used in the RCRBSJ specification is reasonable.

INTRODUCTION

The recent development of the ASTM A490 high-strength bolt was necessitated by the increased use of high-strength steels. So that connections could have reasonable proportions, fasteners of higher strength than the A325 bolt had to be developed. However, efficient use of A490 bolts is dependent on a more thorough knowledge of the behavior of structural connections fabricated with them.

Several experimental studies of the behavior of butt joints of A7 or A440 steel connected by the widely-used A325 bolts have been made.[(1)(2)(3)] Also, a general solution for the ultimate strength and the load distribution within a mechanically-fastened butt joint has been developed.[(4)] This solution has led to theoretical studies of the effect on the ultimate load behavior of butt joints of such variables as joint length, pitch, relative proportions of plate tensile area and fastener shear area, type of connected steel, and variations in fastener diameter.[(4)(5)(6)]

The purpose of the present study was to determine the basic behavior of the A490 bolt in butt joints of A440 steel. Both theoretical and experimental studies were made which included the effects of pitch, joint length, and variations in the A_n/A_s ratio. These variables were also included in similar analytical studies of A440 joints fastened by the A502-Grade 2 high-strength rivet made for comparison with the bolted joints. The experimental work also included taking data related to the slip behavior of bolted joints.

The study was limited to butt joints fabricated from 1-in. plies of A440 steel, as shown in Fig. 1. Since the material properties of A440 steel vary with thickness, it was necessary to choose a specific thickness in the theoretical studies. One was chosen because this material was on hand. It had been used in previous tests[(3)] and would allow useful comparisons to be made.

The theoretical work, like the test program, considered only joints connected with 7/8-in. fasteners. Previous work[(5)] has shown that, for a given A_n/A_s ratio and joint length, variations in fastener diameter have a very minor effect on the average shear stress at ultimate joint load. For this reason, the effect of variations in fastener diameter was not included.

DESCRIPTION OF TEST SPECIMENS

PILOT TESTS

Four compact joints were tested to determine the shear strength of the bolts and the effect of variations in the A_n/A_s ratio on short joints. These four joints, K42a, K42b, K42c, and K42d, had two lines of four A490 bolts placed at a pitch of 3½-in. as shown in Fig. 1. The A_n/A_s ratio was varied from 1.22 for K42a up to 1.37 for K42d by varying joint width as indicated in Table 1. The joints were fastened with 7/8-in. x 5½-in. lot KK A490 bolts.

LONG JOINTS

Previous work(5) has shown that the three important variables in joint behavior were pitch, joint length, and the A_n/A_s ratio. These four long joints were designed to get the maximum number of cross-comparisons to verify the effect of these variables. The geometries of joint length when the A_n/A_s ratio is kept constant while pitch is varied are found by comparing joints K131 and K132. A comparison of joints K132 and K133 shows the effect of variations in A_n/A_s when pitch and joint length are kept the same. The effect of pitch for a given joint length and A_n/A_s ratio, is shown by comparing joints K132 and K191. Thus, each long joint tested helped to verify specific points of interest and provided information for the theoretical predictions. The long bolts used in these joints were 7/8-in. x 9½-in. lot AB bolts.

MATERIAL PROPERTIES

The ASTM A440 plate for these joints was cut from strips 26-in. by 1-in. by 36-ft. Steel from the same heat was used in both the pilot and long joints.

Several standard plate coupons were tested, giving an average static yield stress of 43 ksi and an ultimate strength of 76 ksi. Thus, this plate material was about 13% stronger than the specified minimum.

Coupons cut from the rivet stock, designated as Lot HR, gave an average tensile strength of 83.6 ksi for undriven specimens and 87 ksi for driven specimens. The A502-Grade 2 specification requires that the tensile strength of this rivet steel be greater than 68 ksi, but less than 83 ksi. Thus, maximum strength rivet material was used.

The load-deformation characteristics of single A490 bolts and A502-Grade 2 rivets sheared in A440 steel jigs had to be determined so that theoretical prediction of joint load could be made. The double shear strength of the KK lot and AB lot A490 bolts was 103.5 and 101.1 ksi, respectively. Calibration tests of these bolts are reported in Ref. 8. Both lots were ordered to the minimum strength requirements of ASTM A490.

So that the clamping force exerted on the faying surfaces could be measured, the load-deformation characteristics of the A490 bolts installed by torquing were determined. The procedures for establishing a "mean" load-deformation curve for bolts under torqued tension have been explained elsewhere.[8] Having established a "mean" load-deformation curve, the clamping force per bolt could be easily determined by measuring the installed bolt extension.

FABRICATION AND ASSEMBLY OF TEST JOINTS

All shop work for the fabrication of the test joints was done by a local fabricator. Plates were flame cut to rough size and then milled to final dimensions. Oil and grease were wiped with solvent from the plates to prepare clean faying surfaces.

The plates for each joint were assembled and then clamped. Alignment of holes was assured by drilling through the entire clamped assembly. All holes were drilled 15/16-in. to allow 1/16-in. clearance for the 7/8-in. bolts.

The bolting up was done by Fritz Engineering Laboratory technicians under supervision of the engineers on the project. All the bolts of a particular joint were first "snugged" using the pneumatic impact wrench. The KK lot bolts used in joints K42a through K42d were then installed by turning the nut ½ turn. The AB lot bolts used in K131, K132, K133, and K191 were installed at 2/3 turn beyond snug.

Complete records of bolt elongations were kept for each bolt in every joint of the test series. These data were related to the previously determined load-deformation curves of the particular bolt lots so that the clamping force on each joint could be readily determined.[8]

INSTRUMENTATION

The instrumentation was similar to that described in previous work.[2][3] SR4 electric resistance strain gages were attached to the edge of each plate to detect eccentricity of loading caused by uneven gripping or curvature in the joint. Dial gages accurate to 0.001-in. were used to measure joint elongation. More sensitive gages accurate to 0.0001-in. were used to measure the slip between lap and main plates.

TEST PROCEDURES

After the specimen had been mounted in the testing machine and fitted with instrumentation, a low gripping load of 20 to 50 kips was applied. After all initial readings had been taken, load was applied in increments of 50 kips up to about 80% of the expected slip load. At each load increment, strain gage and joint slip dial data were recorded. The load was then removed in increments back to the initial gripping load. This type of cyclic loading was repeated with the maximum load increased on each load cycle until major slip occurred. Beyond the 80% load, joint elongation and slip dials were read at intervals of 10 kips. This method gave a continuous load-deformation curve up to major slip.

After the major slip load had been passed, the elastic and inelastic plate deformations were recorded at specific load increments through the strain gage readings, the slip and joint elongation dials, and visual observations. Joints K42a through K42d were tested to failure in one day. For the four long joints, two testing days were required. In these cases the load attained on the first day had caused yielding of the net plate section. The load was reduced at the end of the day and on the second day the joint was reloaded to its previous high and then tested to failure as usual.

ANALYTICAL STUDIES OF ULTIMATE STRENGTH

EFFECT OF JOINT LENGTH

Theoretical[(4)(5)(6)] and experimental[(1)(2)(3)] results of previous investigations had shown that joint length has an important effect on the ultimate strength of a joint. It is the purpose of this section to show quantitatively the expected behavior of typical A440 steel butt joints connected by A490 bolts or A502-Grade 2 rivets. The reported numerical values are for joints whose component parts have the material properties of the test joints.

The three variables of major concern in the behavior of mechanically fastened joints are the A_n/A_s ratio, joint length, and pitch length. Thus, in order to study the effect of variations in joint length, the A_n/A_s ratio and pitch length must be kept constant. In this study a pitch of 3½-in., or four fastener diameters, was chosen. This common value represents a typical field situation. A_n/A_s ratios of 1.16 for bolted and 0.727 for riveted joints were selected. These particular ratios correspond to gemoetries which result from current allowable stress values.[(9)(10)] Of course, any constant A_n/A_s ratio and any specific pitch length could have been chosen. The above values were selected because they are consistent with current practice.

All joints analyzed in this section were considered to be connected with fasteners having the shear properties of the AB lot bolts or the HR lot rivets. The following geometrical properties were also assumed so that joints of reasonable dimensions would be analyzed: for joints having up to twelve fasteners in a line, the thickness of the gripped material was taken as 4-in. Joints having more than twelve fasteners in line were assumed to have 8-in. of gripped material.. Only joints which were symmetrical in every respect were considered. Only one gage width was considered because previous studies had indicated that this would be satisfactory.[4]

The results of this theoretical work are plotted in Fig. 2. This figure shows the shear strength plotted as a function of joint length. Only the case of fastener shear is shown in this plot, although plate failure could occur in short joints. The ordinate indicates the average shear stress in all the fasteners when the end fastener has reached its maximum load. This study shows that joint length has about the same influence on shear strength regardless of the type of fastener.

Figure 2 shows that the shear strength of short joints (10-in. or less) approaches the strength of the single fastener. As the joints become longer, however, the shear strength decreases. This is because the interior fasteners of a long joint take much less of the load than the interior fasteners of a short joint. Figure 3 shows the stress in each fastener when the end fastener has reached its ultimate load in joints with thirteen fasteners in line. This figure shows very clearly that the interior fasteners carry considerably less load than the end ones.

This decrease in fastener load at the joint interior is well understood and is simply a function of the differential movement of the lap and main plates.[2][3][4] Near the joint center the strains in the main and lap plates are relatively small, since these portions are usually still elastic. Near the ends greater differential strains occur because either the lap plates or main plates are inelastic. Thus, greater loads are induced for the end fasteners.

EFFECT OF PITCH

Pitch is the distance along the line of principal stress between centers of adjacent fasteners. This distance plays an important role in the distribution of load among the fasteners. In order to study the effect of pitch, a constant A_n/A_s ratio must be maintained so that for any given joint length, the effect of pitch on shear strength can be shown.

Analytical studies were made of the variations in shear strength for joints with fastener pitches of three, four, and six fastener diameters. Figure 4 shows the plot of shear strength against joint length for each pitch studied. Again, only failure by fastener shearing is considered. This shows that joints with longer pitches give a higher shear strength at a given joint length. This figure also shows that the important variable is not pitch length per se, but joint length. Joint length is, of course, controlled by pitch for a given number of fasteners, but Fig. 4 shows that for a given joint length the shear strength does not change significantly with changes in pitch. As the joints become longer, the shear strength curves tend to converge, indicating that shear strength is even less affected by pitch in long joints. This study shows that pitch length per se is not an important variable. For a given A_n/A_s the shear strength is controlled not by pitch length but by total joint length.

The load distribution within joints of the same length, but with different pitches, is shown in Fig. 5. This joint with thirteen bolts in line at a pitch of 2-5/8-in. had a predicted shear strength of 82.5 ksi. The one with seven bolts at a pitch of 5¼-in. had a predicted shear strength of 84.7 ksi. The joint with the greater number of fasteners will, of course, carry the greater load.

EFFECT OF THE A_n/A_s RATIO

The ratio of the net plate area to the total shear area is a measure of the relative rigidity of the plate material with respect to the fastener material. For example, consider a joint with an 8-in. grip connected by 13-7/8-in. fasteners. If this joint has an A_n/A_s ratio of 1.50 it will be 6.82-in. wide per gage strip, but only 4.86-in. wide when A_n/A_s is 1.00. One would intuitively expect that the inner fasteners of the wider joint would carry more load. This effect is shown graphically in Fig. 6. This plot shows that the inner fasteners take less of the joint load as the A_n/A_s ratio is decreased. The lower the A_n/A_s ratio, the sooner the yielding of the net section occurs. Thus, the differential strains at the joint ends build up under much lower load than is required for wider joints. The ultimate load of the end fastener, therefore, is reached long before differential strains in the joint interior have caused any substantial loads in the inner fasteners.

The variations of shear strength at a given joint length for various A_n/A_s ratios are shown in Figs. 7 and 8. A constant pitch of 3½-in. was used throughout this section. The dotted lines in these figures show that joint failure will occur by tearing of the plate at specific joint lengths for a particular A_n/A_s ratio. For A_n/A_s ratios above certain values (above approximately 1.16 for bolted joints), failure will always be precipitated by shearing of one or more fasteners.

Figures 7 and 8 verify the intuitive reasoning mentioned above. As the A_n/A_s ratio is decreased, the shear strength decreases rapidly for a given joint length. It is interesting to note that A_n/A_s ratios of 1.90 and 1.30 approach the "rigid plate" condition for the bolted and riveted assemblies respectively. (If the plate material were completely "rigid" each fastener would take the same load.) This study has shown that variations in the A_n/A_s ratio have a major effect on the shear strength of bolted or riveted joints.

TEST RESULTS AND ANALYSIS

LOAD-DEFORMATION BEHAVIOR

Complete load-deformation data were taken for each joint tested. Typical plots for a short and long joint are shown in Figs. 9 and 10. Figure 9 shows the initial behavior up to and including major slip. In these cases, the joint deformation was almost linear up to major slip. The load-unload cycle had little effect on the joint deformation; negligible deformation occurred before major slip. At a well-defined load, the main plate suddenly moved about 1/16-in. with respect to the lap plate. This was always very sudden, and was usually accompanied by a loud "bang" as the movement was arrested by several fasteners coming into bearing. As in other [illegible], tests,[1][2][3] the slip load has been taken as the load at which this sudden major movement occurred. In two tests this movement was less than the 1/16-in. hole clearance, but the point of sudden movement (usually more than 1/32-in.) was always clearly defined.

Beyond major slip, inelastic plate and bolt deformations began to occur as shown in Fig. 10. The short joints all failed by sudden, simultaneous shearing of all fasteners. In the longer joints, failure occurred when an end fastener sheared.

SLIP BEHAVIOR

The term "slip coefficient (K_s)" is defined as

$$K_s = \frac{P_s}{m\ n\ T_i}$$

where P_s is the slip load, m is the number of faying surfaces, T_i is the average clamping force in the bolts, and n is the number of bolts. The average clamping force per bolt in each joint is given in Table 1 along with the slip load determined by actual test. With these values known, the slip coefficient K_s is easily determined. The individual values of K_s for the various joints are shown in Table 1. The average value for the slip coefficient was 0.35, with variations from 0.32 to 0.40. There seemed to be no difference in the slip coefficient caused by variations in joint length or width.

The Research Council specification gives an allowable shear stress of 20 ksi for A490 bolts used in friction-type bridge joints and 22.5 ksi for those used in buildings.(9) The average shear stress at slip for these eight tests was 36 ksi, with variations from 32.7 ksi up to 39.8 ksi as shown in Fig. 11 and Table 1. Hence, the average factor of safety against slip was 1.80 for friction-type bridge joints and 1.59 for building joints. These tests have shown that bolts installed by the turn-of-nut method have clamping forces in excess of the proof load. Also, the use of the slip coefficient of 0.35 was confirmed by these tests.

Previous tests of A440 steel joints fastened with A325 bolts had shown slightly lower slip coefficients.(3) The A440 plate used in those tests was from the heat used in the tests reported here so that a direct comparison is valid. The average slip coefficient of the joints connected with A325 bolts was 0.30, whereas these tests gave a value of 0.35. This would indicate that the higher clamping force of the A490 bolts may have a beneficial influence on the slip coefficient.

ULTIMATE LOAD BEHAVIOR

The theoretical solution indicated that variations in the A_n/A_s ratio would have a negligible effect on the ultimate strength of the short joints (see Table 1). The test data shown in Table 1 verified this prediction. The maximum variation between the theoretical and experimental data was 1.8% for the short joints.

As was mentioned previously, the long joints were designed to get the maximum number of cross-comparisons. The results are tabulated in Table 2. This table shows that greater bolt strength was developed in joint K131 than in the longer joint K132 when the A_n/A_s ratio and number of bolts were kept the same. Comparison of K132 and K133 gives an excellent view of the effect of varying the A_n/A_s ratio. K132, with an A_n/A_s ratio of 1.30, failed at 1312 kips, whereas K133, with an A_n/A_s of 1.90, carried a load of 1660 kips before failure. The effect of pitch is shown by comparing joints K132 and K191. In this case, K191, having more bolts, carried a higher load but the average shear strength was nearly the same for both joints.

Table 1 shows that the theoretical predictions were lower than the test data for all joints fastened with the longer bolts. It had been noted in earlier tests(4) that joints fastened with long bolts usually gave higher ultimate test loads than had been predicted. A qualitative explanation for this can be given by considering the sheared bolts in Fig. 12. In the calibration jig the bolt is actually sheared at almost 90 degrees to its centerline. In joints fastened with long bolts, however, the individual plates move separately by slipping over each other as is shown in Fig. 13. This causes the bolt to bend and results in an increased shearing area and thus produces an increase in ultimate load and ultimate deformation.

This "bending" action influences the bolt behavior by causing an increase in the load required to shear the bolt and an increase in the ultimate bolt deformation. This means that the end fastener in a joint with more than four plies deforms more than predicted by the standard calibration process and thus forces the interior bolts to carry more load.

The amount which a bolt bends is controlled by the slippage of the plates with respect to each other. For joints with high A_n/A_s ratios the bending action is more pronounced in more bolts. This is illustrated by Fig. 13. Joints K132 and K133 were the same in every respect except that K132 had an A_n/A_s ratio of 1.30, while this ratio in K133 was 1.90. It is apparent from the photographs in Fig. 13 that greater bolt bending had occurred at the interior bolts in the higher A_n/A_s assembly.

In summary, it is apparent that the "bolt bending" phenomenon is not of major consequence. The ultimate load data are summarized in Table 1, and they confirm the analytical studies. For joints connected with short fasteners the analytical solution is nearly exact and for those connected with longer fasteners the predicted results are usually lower than the test values.

COMPARISON TO PRESENT DESIGN CODES

Currently, A440 joints are proportioned to produce A_n/A_s ratios of 0.727 for A502-Grade 2 riveted joints and 1.16 for A490 bolted bearing-type joints. These ratios correspond to allowable shear stresses of 20 and 32 ksi respectively, when the allowable plate tensile stress is 27.5 ksi. Figures 7 and 8 show the variations in shear strength with joint length for different A_n/A_s ratios. These A_n/A_s ratios can be expressed in terms of allowable shear stress: for example, an A_n/A_s ratio of 1.60 is equivalent to designing a joint for an allowable shear stress of 1.60 x 27.5 = 44 ksi. Each A_n/A_s ratio in these figures is accompanied by an equivalent allowable shear stress.

It is apparent from Figs. 7 and 8 that a higher allowable shear stress gives a more stable shear strength at joint failure. It is interesting to note that short joints (less than 12-in.) designed according to present specifications may fail by tearing of the plate. This behavior is, of course, dependent on the specific material properties of the component parts.

Variations in the factor of safety of A490 bolts are shown in Fig. 14. In this context, factor of safety is defined as the average shear stress at joint failure divided by the equivalent allowable shear stress. The point where plate failure occurs, about 12-in., is considered the cut-off point.

For bolted joints an allowable stress of 44 ksi results in a variation in factor of safety from 2.3 for a single bolt down to 1.95 for a joint 84-in. long. If the allowable stress is increased to 52 ksi, the variation is from 1.90 to 1.85. For the present allowable stress of 32 ksi, the factor of safety against plate failure for joints less than 12-in. is about 2.95, as determined from Fig. 7. The factor against shear then decreases to 2.15 for 84-in. joints.

In a recent paper[6] a more rational approach for the choosing of allowable stresses is suggested. It is suggested that a consistent factor of safety of about 2.0 or 2.1 should be used to set allowable stresses. This would ensure that the connection would not fail before plate yielding occurred. When this concept is applied to the bolted joints, we see immediately that the allowable stress for short joints can be raised. If the stress were raised to 40 ksi, for example, the factor of safety would vary only from 2.30 for a single fastener to 2.1 for a joint 40-in. long. The allowable stress for joints from 40-in. to 84-in. could be set at 32 ksi, which would result in a variation in the factor of safety from 2.5 to 2.1. This method gives a much more constant factor of safety, although variations must still occur.

From this study it is apparent that the currently specified shear stress of 32 ksi is too conservative for short joints. It appears that the allowable shear stress could be raised to at least 40 ksi for joints less than 40-in. long. Because the rivet material was so much stronger than the minimum ASTM value, no conclusions regarding the behavior of rivets are made.

SUMMARY

As a result of the theoretical and experimental studies conducted under this program, the following conclusions and recommendations have been made:

(1) The theoretical solution developed in Ref. 4 for the load distribution within a joint and the ultimate load of a joint is sufficiently accurate for all practical cases.

(2) The average fastener shear strength is greatly influenced by increases in joint length. The fastener pitch influences the average shear strength mainly through its effect on joint length.

(3) Variations in the A_n/A_s ratio have a major effect on the average fastener shear stress at ultimate joint load. An increase in this ratio causes an increase in the average shear stress.

(4) In order to make more efficient use of the A490 bolts, a higher allowable shear stress should be specified for short joints. Suggested values are 40 to 45 ksi in joints less than 40-in. long. The present specification of 32 ksi for all A490 bearing-type bolted joints is unduly conservative for short joints.

(5) Test results have shown that the average shear stress at major slip varied from 32.7 to 39.8 ksi for A440 steel fastened with A490 bolts. These values substantiate the use of a slip coefficient of 0.35 for the design of friction-type joints. Also, these tests indicate that many joints designed to carry load in bearing and shear will actually be carrying the load by friction at working loads.

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

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This study has been carried out as a part of the research project on "Large Bolted Connections" being conducted at Fritz Engineering Laboratory, Department of Civil Engineering, Lehigh University. Professor W. J. Eney is Head of the Department, and Professor L. S. Beedle is Director of the Laboratory.

The project is sponsored financially by the Pennsylvania Department of Highways, the U. S. 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 through an advisory committee under the chairmanship of Mr. T. W. Spilman.

Table 1 Nominal Dimensions and Test Results

ITEM	UNITS	K42a	K42b	K42c	K42d	K131	K132	K133	K191
Bolts Lot		KK	KK	KK	KK	AB	AB	AB	AB
Number in Line		4	4	4	4	13	13	13	19
Nominal Shear Area	in^2	9.62	9.62	9.62	9.62	15.62	15.62	15.62	22.84
Plates									
Mean Width	in.	7.64	7.89	8.12	8.36	6.01	6.01	8.35	8.37
Mean Thickness	in.	2.03	2.03	2.02	2.03	4.02	4.01	4.05	3.99
Mean Gross Area	in^2	15.51	16.02	16.40	16.97	24.16	24.10	33.82	33.40
Mean Net Area	in^2	11.70	12.21	12.59	13.16	20.40	20.34	30.02	29.65
Grip (excl. wahser)	in.	4.06	4.06	4.04	4.06	8.04	8.02	8.10	7.98
Pitch	in.	3.50	3.50	3.50	3.50	2.63	5.25	5.25	3.50
A_n/A_s	-	1.22	1.27	1.31	1.37	1.30	1.30	1.92	1.30
Slip Load (Test)	kips	350	314	334	383	542	580	548	846
Bolt Shear Stress	ksi	36.4	32.7	34.7	39.8	34.6	37.0	35.0	37.0
Avg. Ext. of Bolts	in.	0.027	0.032	0.041	0.026	0.057	0.050	0.045	0.054
Clamping Force per Bolt	kips	60.0	59.5	57.5	59.6	65.2	65.2	65.1	65.5
Slip Coefficient	-	0.36	0.33	0.36	0.40	0.32	0.34	0.33	0.34
Type of Failure		All Bolts Sheared	All Bolts Sheared	All Bolts Sheared	All Bolts Sheared	One Bolt Sheared	One bolt Sheared	One Bolt Sheared	One Bolt Sheared
Load at Failure	kips	980	980	996	1004	1425	1312	1660	1794
Predicted Failure Load	kips	982	984	985	986	1381	1254	1548	1788
Avg. Bolt Shear Stress (test)	ksi	101.9	101.9	103.5	104.3	91.1	84.0	106.0	78.8

Table 2 Influence of Test Variables on Joint Strength

Joints	Variables	Constant	Ultimate Loads (Test) kips	Shear Strength ksi
K131	Length; Pitch	A_n/A_s; No. of bolts	1425	91.1
K132			1312	84.0
K132	A_n/A_s	No. of bolts; length; pitch	1312	84.0
K133			1660	106.0
K132	Pitch; No. of bolts	Length; A_n/A_s	1312	84.0
K191			1794	78.8

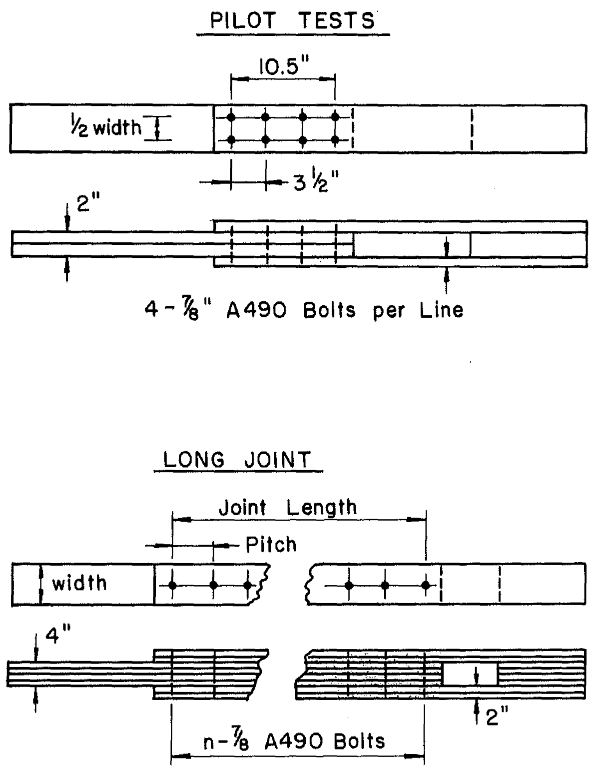

Fig. 1 Geometry of Test Joints

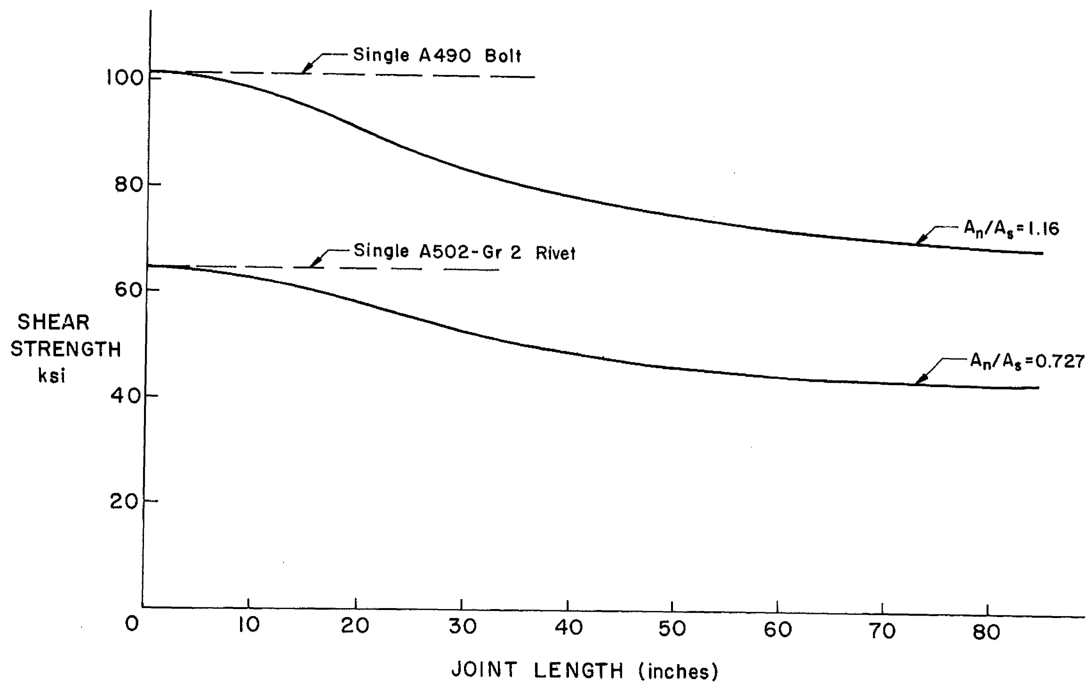

Fig. 2 Effect of Joint Length on Shear Strength

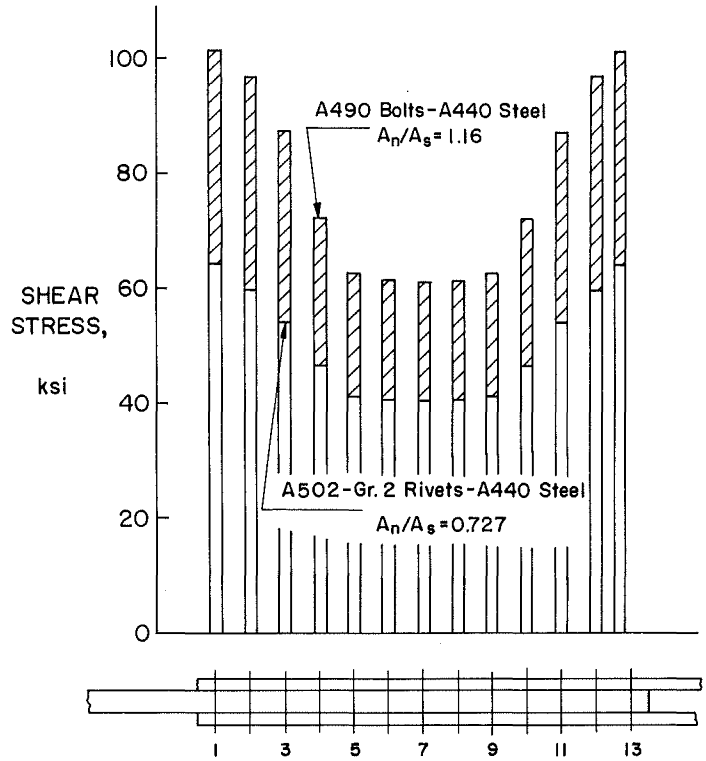

Fig. 3 Load Partition in Joints with Thirteen Fasteners in Line

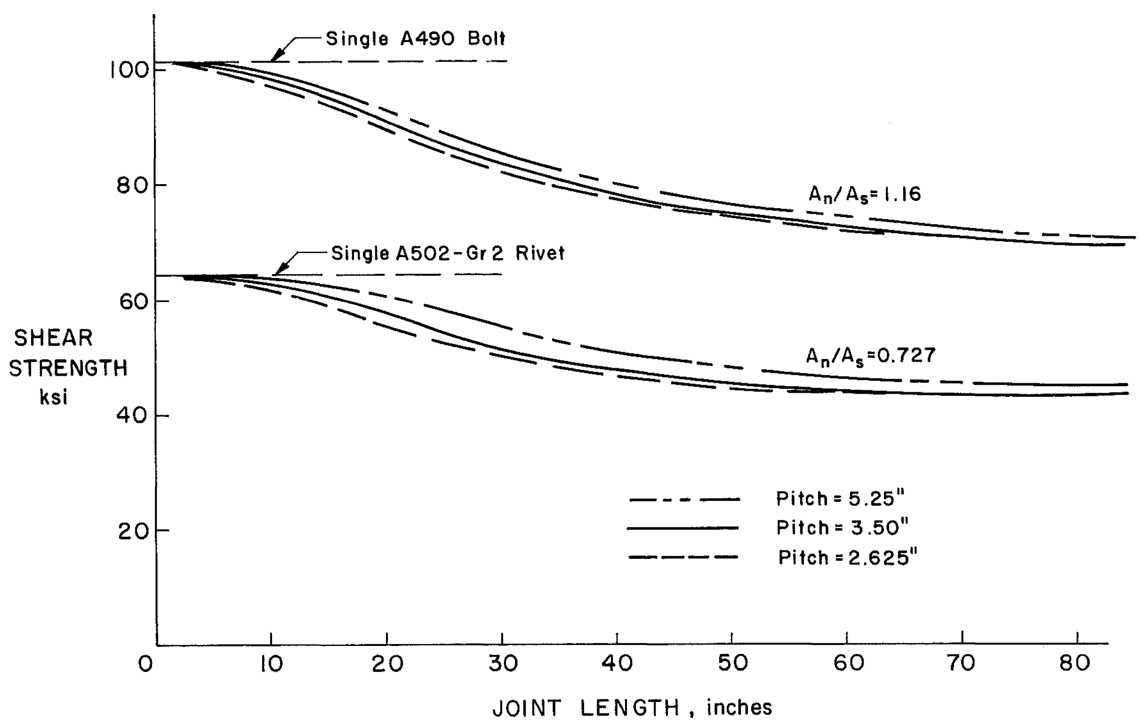

Fig. 4 Effect of Pitch on the Shear Strength

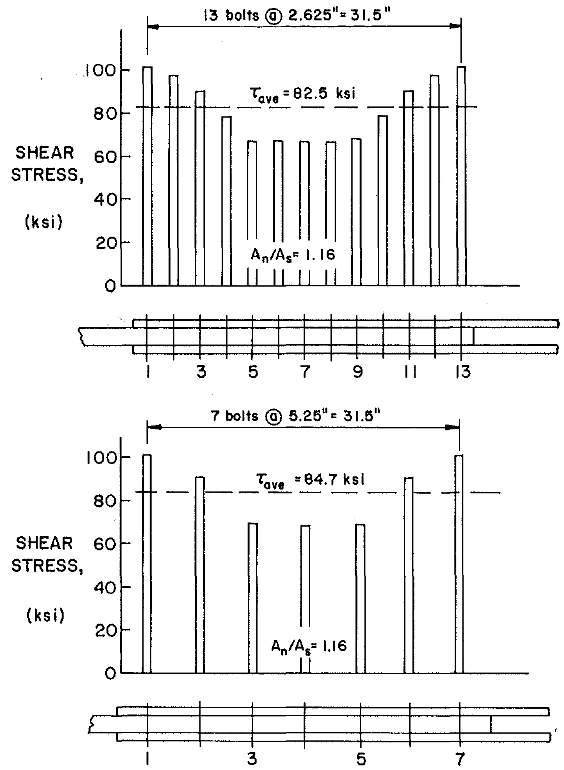

Fig. 5 Load Partition in Joints of the Same Length but Different Pitch

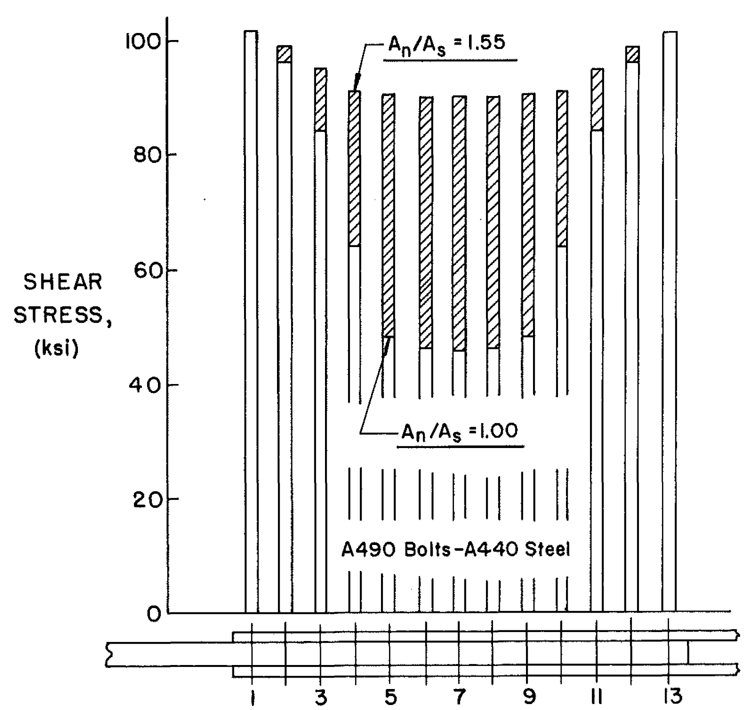

Fig. 6 Effect of Variations of A_n/A_s on Load Partition

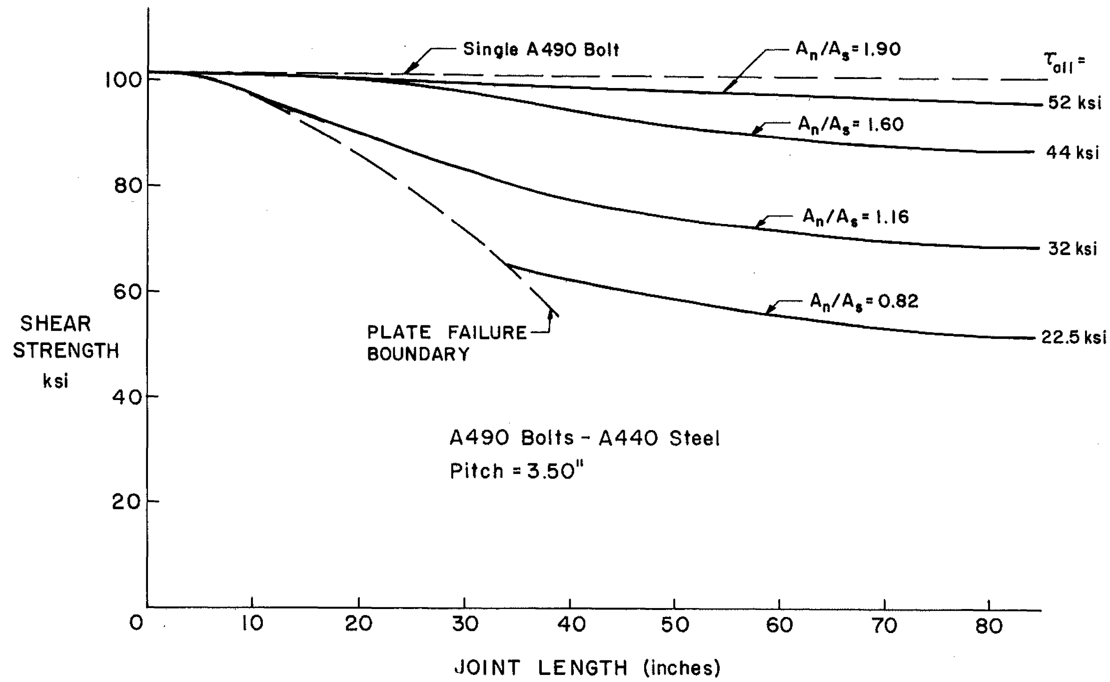

Fig. 7 Effect of Variations of A_n/A_s on the Shear Strength of Bolted Joints

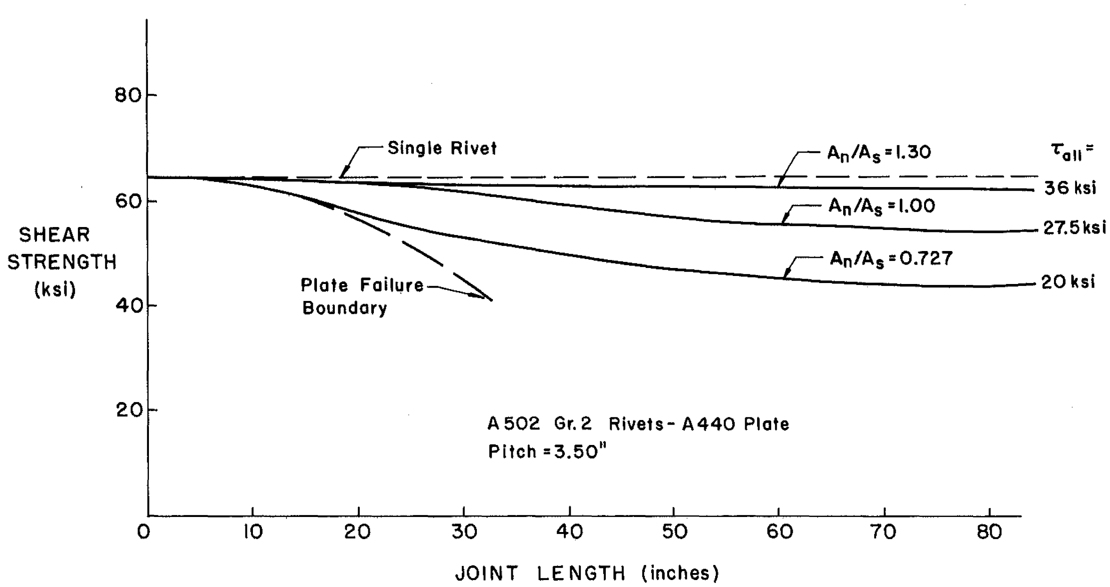

Fig. 8 Effect of Variations of A_n/A_s on the Shear Strength of Riveted Joints

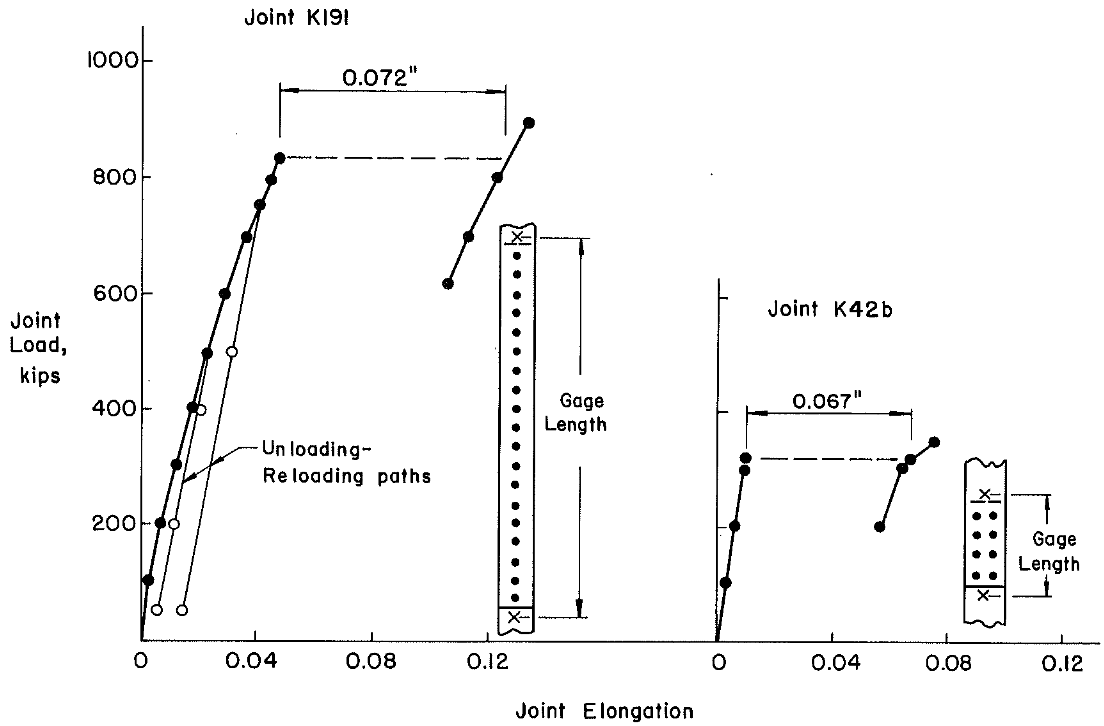

Fig. 9 Load-Deformation Characteristics of Bolted Joints up to Major Slip

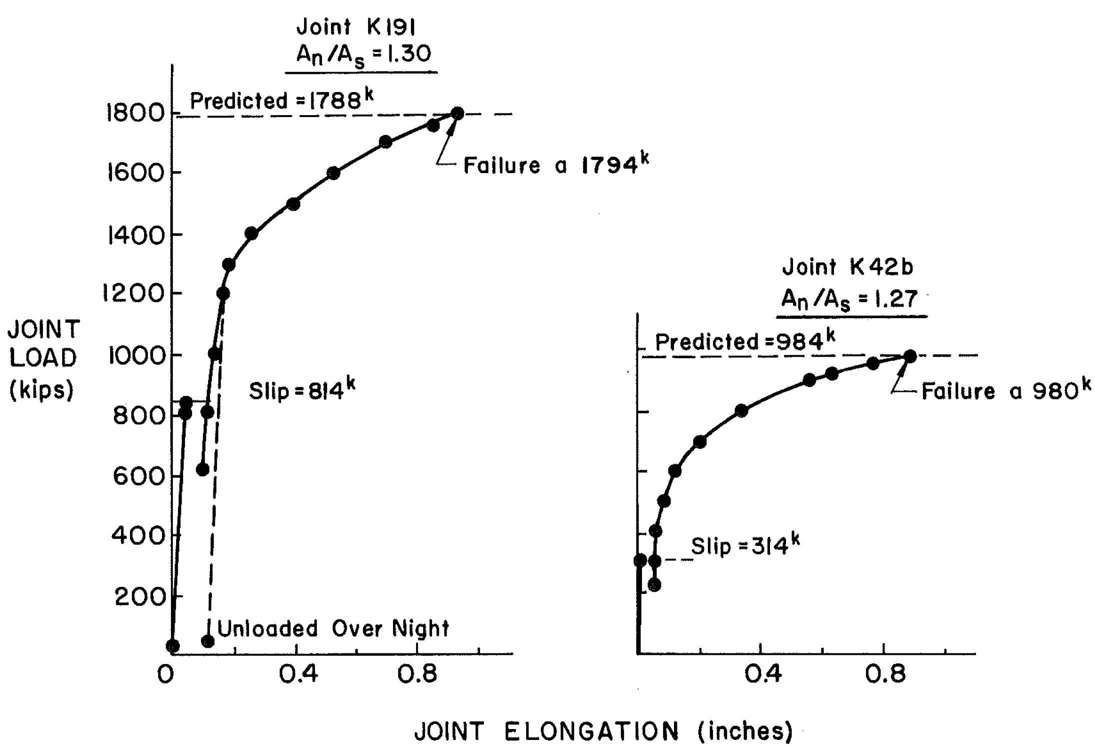

Fig. 10 Load-Deformation Characteristics of Bolted Joints up to Failure

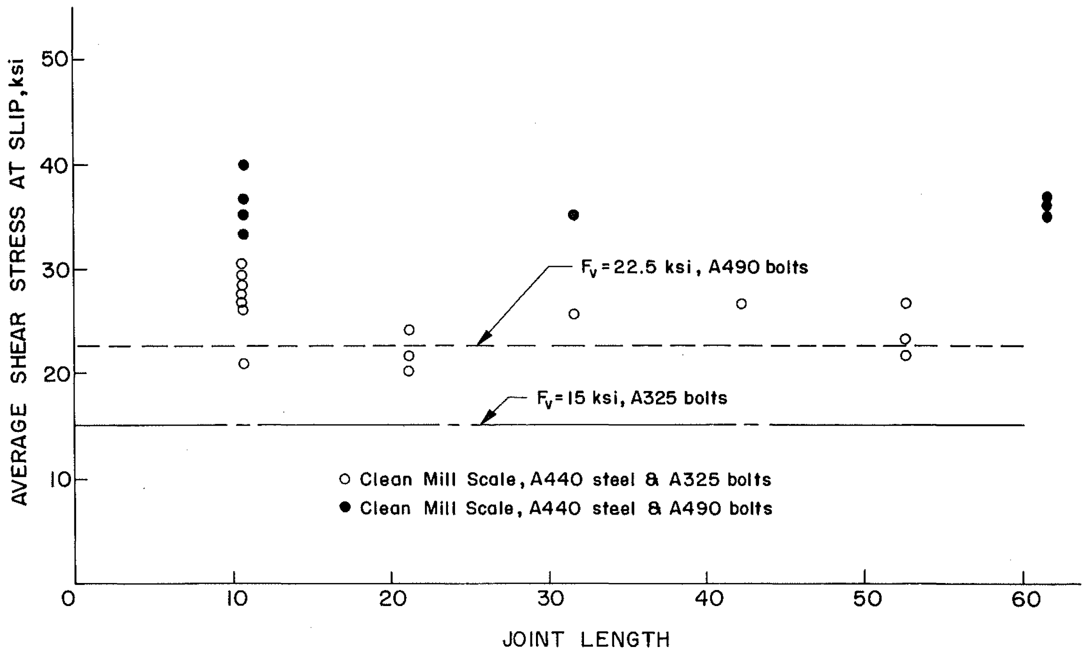

Fig. 11 Slip Resistance of Bolted Joints

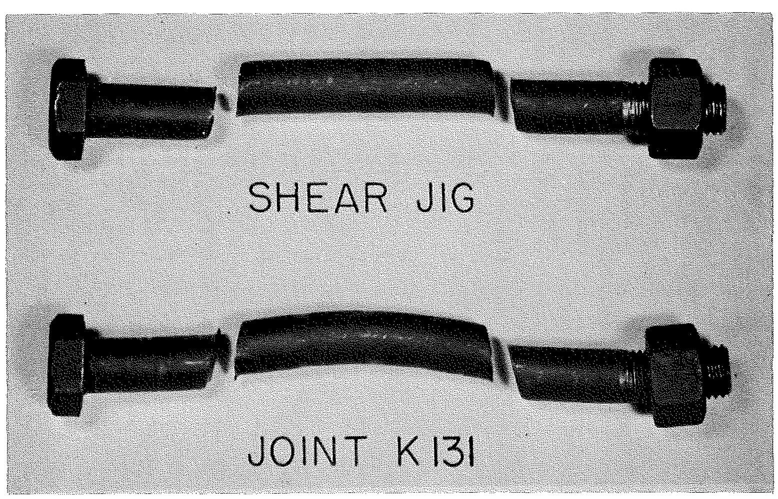

Fig. 12 Comparison of Sheared Bolts

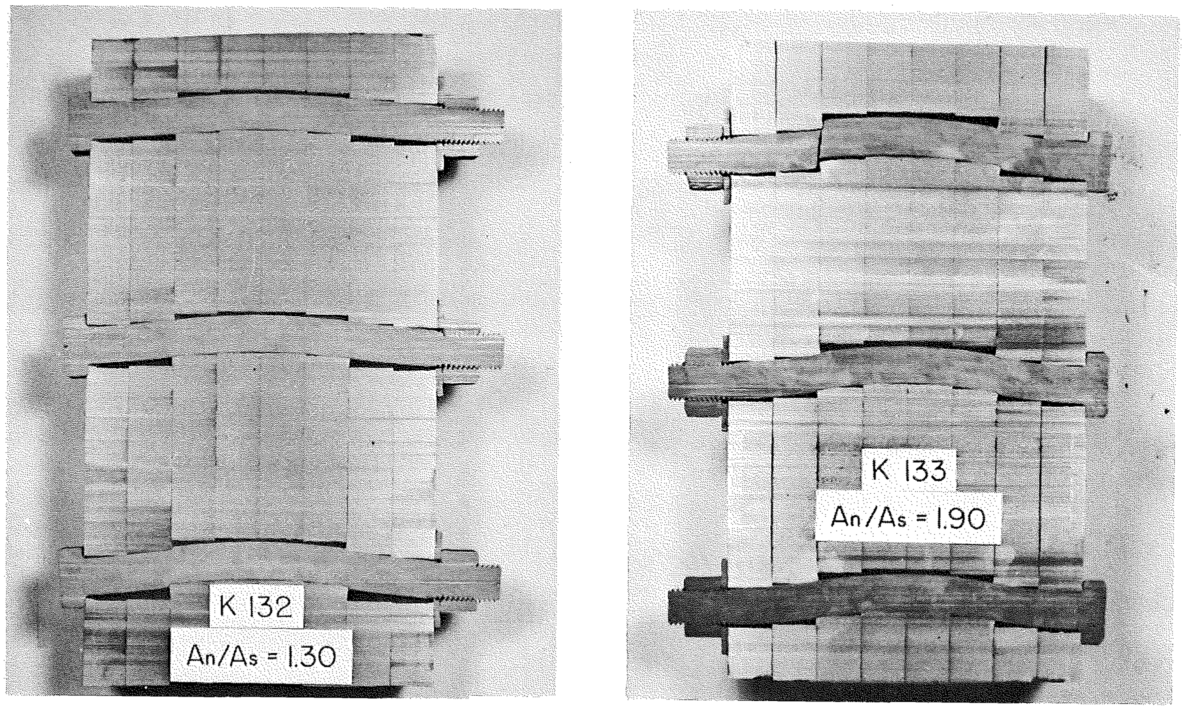

Fig. 13 Sawed Sections of Joints K132 and K133 Showing Bolt Bending

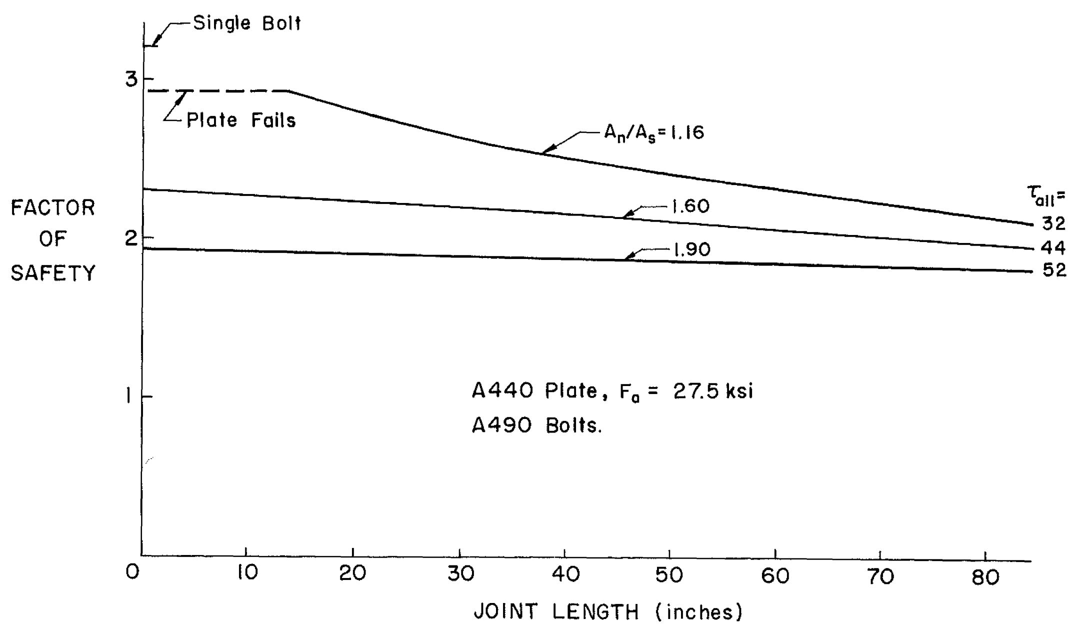

Fig. 14 Variation in Factor of Safety for Different Allowable Shear Stresses

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The results of tests conducted to determine the behavior of joints fabricated of A440 steel plate and fastened with 7/8-in. diameter ASTM A490 bolts are covered in this report. The experimental results of four compact joints, conducted to determine the bolt shear strength and the effect of variation in A_n/A_s ratio, and four long joints are presented. The variables covered in this investigation include pitch, joint length, and changes in the A_n/A_s ratio. Theoretical studies were carried out and the conclusions reached concerning the experimental variables are included. The present specification for all A490 bearing-type bolted short joints, and the slip coefficient used for the design of friction-type joints are discussed in relation to the test results.

KEY WORDS: bolted joints; high-strength bolts; joint length; pitch; slip coefficient.