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A514 STEEL JOINTS FASTENED BY

A490 BOLTS

by

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ABSTRACT

The results of both analytical and experimental studies of the behavior of constructional alloy (A514) butt splices which use A490 fasteners are reported.

Based on the results of previous theoretical work, the parameters that might be expected to affect the behavior of this type of joint were examined. This examination showed that the ultimate strength of these joints is a function of joint length and relative plate - fastener proportions. It is shown to be independent of fastener diameter or pitch, per se.

The validity of the previously developed theoretical work and the analytical studies reported herein have been verified by means of an extensive testing program. A comparison shows that the theoretical predictions are reliable, both for the ultimate load of the joint and for obtaining the distribution of load among the fasteners at loads less than ultimate. The experimental work also showed that blast-cleaned A514 steel has a slip coefficient of about 0.33.

The study further showed that constructional alloy steel joints using A490 bolts do not produce desirable behavior in their adjoining members if the elements of the joint are proportioned according to currently used stress levels.

1. INTRODUCTION

The use and importance of the constructional alloy steels have increased steadily since the first introduction of a proprietary product by United States Steel Corporation in 1952.[1] These steels, namely United States Steel Corporation's "T-1", Great Lakes Steel Corporation's "N-A-XTRA", and many others, had their first uses mainly in the fabrication of pressure vessels and as components in heavy construction equipment. The favorable strength to cost ratio has also made them attractive for structural applications and they are now commonly used where large loads must be carried. Their increasing importance is evidenced by the fact that these proprietary products are now covered by an ASTM specification, A514.[2]

Although steel meeting ASTM A514 is weldable, in common with other grades of structural steel mechanical fastening by means of rivets or high strength bolts is one of the primary methods of forming connections. An examination of the basic behavior of constructional alloy, bolted butt joints is the basis of this report. The results of theoretical and experimental studies are reported. Information has been obtained on both the slip behavior and the ultimate strength of such joints. Included are the effects of fastener size, joint length, variations in plate - fastener geometry and fastener pitch.

2. CHARACTERISTICS OF CONSTRUCTIONAL ALLOY STEEL

The high yield strength alloy steels were developed to meet the need for a constructional steel, primarily in plate form, which had a yield strength in order of 90,000 psi., good low temperature toughness, and good weldability. The attainment of these qualities is largely a reflection of two factors; a microstructure of tempered martensite and a low carbon content.[1] The mechanical properties of A514 steel are summarized in Table 1.

Tempered martensite is characteristically tough and this toughness is most pronounced at low levels of carbon. Furthermore, this microstructure permits the attainment of the very high strength desired at this low carbon level. The principal alloying elements employed are manganese, molybdenum, boron, chromium, nickel, and vanadium, titanium or zirconium. The latter is included in order to maintain the high yield strength characteristic of the material in the face of tempering at high temperature.

The fundamental difference in behavior between A514 and other grades of structural steel can be seen by examining Fig. 1. Constructional alloy steel is characterized by its very low ultimate vs. yield stress ratio. This can be as low as about 1.07 while the ratio for A440 and A36 steels is about 1.46 and 1.67, respec-

tively. In addition, A514, like most other alloy steels, does not exhibit a well-defined yield point.

3. ANALYTICAL STUDIES OF ULTIMATE STRENGTH

3.1 Basis of the Examination

The analytical studies reported herein have been based on the theory first reported in Ref. 3 and since extended to A514 steel.[4] In examining the application of this theory to hypothetical joints, it is appropriate to base the study on plate and fasteners of minimum strength. A lower bound to the behavior of constructional alloy steel joints fastened by A490 bolts will thus result.

Studies on the shear strength of high strength bolts[5] have shown that the minimum shear strength can be approximated by

$$\tau_{min} = \frac{\sigma_{min}}{\sigma_{ult}} \tau_{ult} \qquad (1)$$

where τ_{ult} is the double shear strength of a single fastener tested in plates subjected to a tensile load, σ_{min} is the minimum specified tensile strength of the bolt material and τ_{ult} its actual tensile strength. This same study also showed that the use of Eq. 1 does not depend upon the grade of steel used in the test apparatus.

The theoretical minimum ultimate shear strength of A490 bolts obtained by these investigators was 91.9 ksi. The three lots of A490 bolts used in the experimental portion of the present study

yielded a minimum ultimate shear strength of 91.5 ksi. Although only
7/8 in., 1 in., and 1-1/8 in. diameter bolts were tested, all A490
bolts of diameters 1/2 in. through 2-1/2 in. have the same specified
strength properties.[6] The results then are considered applicable to
all bolt sizes within this range. The value chosen for use in this
study was 91.5 ksi. The ultimate deformation of the 7/8 in. fasteners
has been assumed to be 0.125 in.[4]

The plate elements making up the joint were all assumed to
be 1 in. plies of ASTM A514 steel. The parameters needed here for
the analysis of hypothetical joints are the tensile strength and pro-
portional limit of a plate - with - holes coupon made of construction-
al alloy steel of minimum strength. The studies reported in Ref. 4
showed that, within a practical range, these parameters are indepen-
dent of geometry. The tensile strength of the plate - with - holes
was 7% greater than the value given by standard bar coupons. The
proportional limit was observed to be 93% of the yield strength of
the standard bar coupon.

3.2 Location of Failure Mode Boundary

The first step in any examination of the ultimate strength
of a bolted joint must be to determine the mode of failure. The es-
tablishing of the plate failure - fastener failure boundary line is
most conveniently done by an iterative process. At a given joint

length, the ultimate strengths of joints with decreasing values of

the ratio A_n/A_s are computed. (A_n is the net plate area of either

the main or lap plates and A_s is the total associated fastener shear

area). The process must start in the fastener failure region, that

is at a value of A_n/A_s high enough to ensure this failure mode.

With each calculation, the ultimate load so computed is compared to

the ultimate load of the plates, as represented by A_n x σ_{ult} at that

step. If the two values of load are equal, or within an acceptable

limit, a point on the boundary has been obtained. This process is

repeated for other joint lengths until the complete curve has been

obtained for the desired range.

This searching process was used to obtain the plate failure -

fastener failure boundary shown in Fig. 2. Plotted here as the

average shear stress in the fasteners vs. joint length, the computa-

tions have been based on the use of 7/8 in. diameter A490 bolts of

minimum strength connecting minimum strength A514 plate. The fas-

tener pitch used was 3.5 in. (The effects of different pitches and

bolt diameters are examined later in this chapter). Calculations

show that differences in grip length have only a very small influence

on the location of the boundary or on joint ultimate strength.

The dashed horizontal line extending across at a shear

stress level of 91.5 ksi represents the "ideal" joint, that is, one

in which all the fasteners carry an equal load. This occurs, of course,

only at $A_n/A_s = \infty$. Shown between this limiting line and the other limit, the plate failure boundary, are joint strength curves for selected values of A_n/A_s. The same failure mode boundary is plotted in Fig. 3 as A_n/A_s vs. joint length.

If A514 steel joints fastened by A490 bolts are designed according to current practice, it is unlikely that proportions will be such that failure will occur in the fasteners. For example, using an allowable stress value of 60 ksi for A514 plate[7] in combination with the current allowable shear stress value for A490 bolts used in buildings,[8] an A_n/A_s ratio of 0.53 results. As seen in Fig. 3, this A_n/A_s value intersects the plate failure - fastener failure boundary at a joint length of about 85 in. In other words, at these stress levels joints would have to be longer than about seven feet before the fasteners would be the critical element.

Recently, an allowable stress of 40 ksi has been suggested for A490 bolts used in bearing type connections.[9] Again using an allowable stress of 60 ksi in the plate material, the A_n/A_s ratio for this case is 0.67. From Fig. 3 it can be seen that plate failure would now control up to a joint length of 60 in.

3.3 Effect of Joint Length

Part of the effect of joint length upon joint behavior is implicit in the discussion of the location of the plate failure -

fastener failure boundary. That is, the type of failure mode at a given A_n/A_s ratio is a function of joint length. It was shown earlier that the plate failure mode is of considerable importance in the examination of the behavior of constructional alloy steel joints. The behavior of this type of joint when failing in the fasteners is also of importance, however. This will be particularly true if higher bolt stresses are adopted.[9] Fastener type failure would then be the governing failure mode for joints longer than about 60 in. In practice, many joints can be expected to exceed this value.

The importance of joint length in the determination of ultimate joint strength has been shown by previous investigators.[10-13] These studies showed that the end fasteners carried the highest load and in many of the experimental studies the amount of this inequality of fastener loads was enough that when an end fastener failed, the load on the joint could be redistributed to other fasteners. As the joints were reloaded following the first failure, other bolts failed in a sequential manner at equal or less joint load. This phenomenon was expected to occur in A514 steel joints to a lesser degree. Because of the much higher yield strength of this material as compared to those grades previously investigated, a more uniform distribution of fastener load should occur.

For a given number of fasteners, joint length is a function of fastener spacing (pitch). In this article, a constant pitch, taken

as 3.5 in., is used. This represents what would often be used in prac-
tice for fasteners in the range of 3/4 in. to 1-1/8 in. diameter. The
separate effect of fastener pitch upon joint behavior is examined in
Art. 3.5.

The strength curves plotted for selected A_n/A_s values in
Fig. 2 show that the effect of joint length upon strength is not pro-
nounced. They show that for a given A_n/A_s ratio the average shear
stress in the fasteners undergoes a gradual, almost linear, decrease
with joint length. For example, the decrease in average shear stress
in A490 bolts over the joint length range from 70 in. to 84 in. is
only 1.1 ksi for A_n/A_s = 0.60. Considering a greater length range, a
joint with A_n/A_s equal to 0.70 has an average shear strength of 84.2
ksi at a joint length of 56 in. If the length is increased to 84 in.,
the same A_n/A_s proportion gives an average shear stress of 81.4 ksi in
the bolts.

The effect of joint length upon the behavior of individual
fasteners within a joint can be seen in Fig. 4. Here, the shear
stresses in the fasteners of a 25 - bolt joint are shown. The A_n/A_s
ratio chosen is 0.60. This joint represents an extreme case — the
joint length is long (84 in.) and the A_n/A_s value chosen puts the speci-
men only slightly above the failure mode boundary. In such a joint,
the degree of load inequality among the fasteners could be expected to
be relatively large. This is borne out by the values shown in Fig. 4.

The shear stress in the end fasteners of this joint is 91.5 ksi while that in the centerline bolt is only 59.8 ksi.

3.4   Effect of A_n/A_s Ratio

The A_n/A_s ratio of a mechanically fastened joint can be thought of as a "modulus of rigidity". At a given joint length, an increasing A_n/A_s ratio means an increasingly more uniform distribution of load among the fasteners. As has already been pointed out, the ideal case of equal load distribution among fasteners occurs only at the value of $A_n/A_s = \infty$. This represents, then, a perfectly rigid joint. For any lesser value of A_n/A_s, the fasteners carry unequal loads.

The joint strength curves shown in Fig. 2 form the basis for this examination of the effect of the A_n/A_s ratio upon joint strength. It should be remembered that this examination is appropriate only to those joints with proportions such that they are in the fastener failure range.

The spacing of the A_n/A_s curves in Fig. 2 is significant. For example, at a joint length of 70 in. the limiting A_n/A_s values of 0.62 and ∞ cover a range of shear stress values of only 75.8 ksi to 91.5 ksi. This means that the load carried by a joint with $A_n/A_s = 0.62$ will not be greatly less than a joint of the same length with, say, $A_n/A_s = 1.00$. For this illustration, the theoretical values of joint

load for one line of fasteners are 1915 kips and 2258 kips, respectively. In other words, although the plate area was increased 61%, the load that could be carried increased only 18%. The effect of adding more plate area (by using a lower allowable plate stress) in order to make the fasteners work at a higher stress level is one of decidedly decreasing benefit.

It should be kept in mind however, that an increase in the A_n/A_s ratio at a given joint length can be obtained in several ways. One way is to decrease the allowable plate stress while maintaining a given allowable shear stress in the fasteners. This results in an increased cost and, as already shown, the resulting load increase is markedly disproportionate.

A second way of producing an increase in A_n/A_s is to make the fasteners work at a higher stress level. This produces no increase in material cost and so the benefits in increased load carrying capability, however small, can be accepted without question of economics. What must be examined now is the resulting factor of safety at any suggested higher fastener shear stress. Naturally, the amount of any increased fastener shear stress must satisfy a desired minimum factor of safety.

Another possibility would be to use a combination of these two approaches. In addition, since the increased plate area is needed only in the joint and not throughout the member, it may be feasible

in some cases to provide this by means of an upset end. These approaches have been examined in detail elsewhere.[4]

3.5 Effect of Fastener Pitch

Previous studies of bolted and riveted joints of A7, A36 and A440 steels have shown that pitch, or distance center to center of fasteners measured parallel to the line of principal stress, is not an important variable in these grades.[10,12,14] These studies showed that the important variable was, rather, joint length as determined by pitch. It is of interest to check the validity of this conclusion when dealing with A514 steel joints.

Since the location of the failure mode boundary has been found to be an important parameter in the investigation, it was decided first to compute its location for various pitches. (In effect, this establishes one point on each of an infinite number of joint strength curves). This was done for 7/8 in. diameter A490 bolts at pitches of 2.625, 3.50, 4.375, and 5.25 in. These correspond to 3, 4, 5, and 6 times the fastener diameter.

The effect of the various pitches chosen upon the location of the failure mode boundary is shown in Fig. 5. There is virtually no effect upon its location for joints whose length is less than about 40 in. For joints greater than this length, pitch apparently has an effect upon the location of the failure mode boundary and this effect is greater with increasing joint length.

The magnitude of the effect should be viewed in light of the comments made in Art. 3.4, namely, that the loads carried by joints of the same length but with appreciably different A_n/A_s values do not differ greatly. This was shown to be particularly true in the region near the failure mode boundary. Since the plate failure - fastener failure boundary line is nothing more than a "strength curve" with continuously varying A_n/A_s, the same conclusion should hold.

To investigate this further, the ultimate strengths of two A514 joints fastened with A490 bolts and having different pitches were investigated. The two extremes of those pitches investigated were chosen - 2.625 in. and 5.25 in. - and a joint length of 63 in. was used. This means that there would be 25 fasteners in the joint using the 2.625 in. pitch and 13 fasteners in the other. The same A_n/A_s ratio was used in each case. The results of this study are illustrated in Fig. 6 where the shear stresses in the fasteners of these hypothetical joints are shown. Also shown is the average shear stress in the fasteners in each case. Based on the joint with the smaller fastener pitch, it is seen that a large increase in pitch (2.625 in. up to 5.25 in.) produced only a minor increase in average fastener shear stress (82.4 ksi to 85.2 ksi).

The strength curves for the given A_n/A_s value and the two pitches investigated are shown in Fig. 7. The difference in average shear stress at any given length is substantially constant and is in

the order of 3 — 4%. Thus, the results of computations made using a pitch of 3.5 in., the value generally used in this study, can be accepted as representative of results which would be obtained using other pitches.

3.6 Effect of Fastener Diameter

The effect of different fastener diameters upon the location of the failure mode boundary and upon the magnitude of the average shear stress in the fasteners of hypothetical joints has been investigated. Three different bolt diameters were considered.

The bolt diameters chosen were 3/4, 7/8, and 1 in. The failure mode boundary was computed for each fastener diameter with pitch being held constant at 3.5 in. Within the limits of the accuracy of the solution, the boundaries computed for these three cases were identical and the results are therefore not shown graphically. To serve as a further illustration, the average shear stress in the fasteners of a 21 - bolt joint with A_n/A_s = 0.70 was computed for the same three diameters. For 3/4, 7/8, and 1 in. diameter bolts, the average shear stresses were 82.5, 82.7, and 82.6 ksi, respectively.

On the basis of these theoretical studies, it is concluded that the ultimate strength behavior of constructional alloy steel joints is independent of fastener diameter.

3.7 Behavior of Constructional Alloy Steel Joints Using A490 Bolts

These analytical studies of the ultimate strength of A514 steel joints which use A490 bolts have shown that a large proportion of these joints will have a factor of safety which is against plate failure. Using the suggested allowable stress of 60 ksi for the plate material and the current allowable shear stress of 32 ksi for the bolts, the plate failure mode governs for joints up to 85 in. long. If the suggested higher fastener shear stress of 40 ksi is used, this length is reduced to 60 in.

It is generally accepted that metallic tension members should reach or exceed the yield stress through their gross cross - section before failure occurs in the connection.[15,16] For the large class of joints described above, and using minimum specified yield and tensile strengths for A514 steel, this means that the net area of the member (A_n) should be equal to or greater than 87% of the gross area (A_g). The implications of this requirement may be seen by con- sidering a simplified member made up of plate elements of constant thickness and containing a joint using drilled, non-staggered holes. To meet the requirement that $A_n/A_g \geq 0.87$, the minimum allowable hole spacing (measured perpendicular to the line of the load) will have to be slightly greater than seven fastener diameters.

It is doubtful whether such a large minimum spacing could be accepted in structural practice. Although there is evidence to support

it,[4] there is also the question as to whether or not an A514 steel member can sustain a joint efficiency of 0.87 or greater. Specifications commonly place an upper limit of 0.85 on this factor.[17]

Present fabrication procedure, in which the connection is formed by removing hole material from the gross cross-section of the main member, thus is unlikely to produce satisfactory member behavior. The low spread between the yield and tensile strengths of A514 steel means that the strength of the net section is not sufficient to force yielding of the gross section before joint failure. This problem has been examined in detail and design criteria proposed for A514 joints which use either A490 or A325 fasteners.[4]

Examination of the other class of joints, those in which the factor of safety is against fastener failure, shows that plate stresses in the gross section of the member will be above yield at the time of joint failure. (It should also be noted that whether or not yield is reached is also dependent upon the disposition of the material used. For a given net area and considering one gage width, the ratio of net to gross area will be higher for higher values of the width to thickness ratio of the section. In this report, the practical lower limit of the width to thickness ratio as applied to either the main plate or the combined lap plates is taken as unity). The factor of safety against shear failure in the bolts is also satisfactory. If the allowable bolt shear stress of 32 ksi[8] is used along with an allowable

plate stress of 60 ksi,[7] this factor of safety is 2.01 at a joint

length of 85 in. If the stress level in the bolts is raised to 40

ksi,[9] the factor of safety is 2.02 at the 60 in. joint length and

1.98 at 85 in.

4. DESCRIPTION OF TEST SPECIMENS

4.1 Pilot Test Joints

Ten compact joints of A514 steel fastened by high strength bolts were examined. All were four-bolt-in-line specimens in which a total of four inches of plate was gripped by the fasteners. The geometry of these joints is shown in Fig. 8. Four of the joints used 1 in. diameter A490 bolts and six used 1-1/8 in. diameter A325 bolts. (Although the latter are not within the general scope of this report, a discussion of their slip behavior will be included since this behavior is independent of fastener type). All plate in these joints came from the same rolling and all fasteners of a given size or type came from the same lot of bolts. The test program examined the slip behavior of constructional alloy steel joints when A325 bolts were used and when A490 bolts were used. It examined the ultimate strength characteristics of constructional alloy steel joints only when A490 bolts were used. Complete details of the joints in the pilot series are shown in Table 2.

4.2 Large Joints

Although a considerable number of tests have been performed in the past on large, bolted plate splices,[10-12] these were all made on joints of structural carbon (A7 and A36) or high-strength (A440) steels. It has been shown that joints of constructional alloy steel

behave in a significantly different manner from those grades previously investigated.[4] To verify the theoretical predictions, an extensive experimental program using full-size joints was developed. Although the pilot tests provided valuable information, particularly with regard to the slip behavior of A514 joints, it has been shown that one of the most important variables in joint behavior is joint length.[3,10-12] Thus, the test program involving large joints was set up.

A test series of eight large joints was developed. All A514 plate used in these joints came from the same rolling. All joints used A490 bolts, of various grips, to fasten the plates. Seven of these specimens used 7/8 in. diameter fasteners and one used 1-1/8 in. diameter fasteners. Two joints each of seven, 13, 17, and 25 fasteners in line were tested. The geometry of the test joints is shown schematically in Fig. 8 and complete details and test results are shown in Table 3.

Although the 25 - bolt joints are among the largest bolted or riveted joints that have ever been tested, joints of this or even greater length are encountered frequently in the construction of large bridges.[18] Fig. 9 shows the larger of these two joints prior to testing.

The first six specimens, those of seven, 13, and 17 bolts in line were paired. One of each pair was designed to fail by tearing of the plates, the other by shearing of the fasteners. The mode of

failure is governed by the relative proportions of the plate and the fasteners. This can be described by means of the A_n/A_s ratio, where A_n is the net area of either the main or lap plates and A_s is the total shear area of the fasteners. These six joints, then, bracket the plate failure - fastener failure boundary line.

The two 25 - bolt specimens were both designed to fail in the fasteners. In A514 steel joints, it is not until joints reach about this length that any significant amount of load inequality occurs among the fasteners. Since it was desirable that the analytical studies for determining this effect be verified, these long joints were chosen.

4.3 Material Properties

The 1 in. plate used for each of the pilot and large joint test specimens came from the same rollings. In each case, the material was requested to be manufactured to minimum strength properties. Standard tensile coupons from each rolling were tested. For the plate used for the pilot tests, the average values of yield (defined by 0.2% offset strain) and tensile strength were 114.0 ksi and 121.4 ksi, respectively. The plate used for the large joints had corresponding values of 101.6 ksi and 111.9 ksi. Five coupons were tested in each case. Plate - with - holes coupons, used in connection with the theoretical studies, were also tested.[4] These allow a more accurate determination of the ultimate load of plate failure specimens. The

plate for the pilot tests gave an average ultimate stress at the net section of 125.6 ksi when coupons of this type were tested. The plate used for the large joints gave a corresponding value of 118.2 ksi.

The high strength bolts used in this program came from several lots, depending upon type, diameter, and grip length. All lots were ordered to minimum strength requirements of the applicable ASTM specification.

The bolts were subjected to a number of calibration tests. These were direct tension, torqued tension and a determination of the load - deformation characteristics of single fasteners contained in A514 steel jigs which subject the bolt to a tension - induced shearing force. The direct tension test forms an acceptance test for the given bolt lot and also establishes the strength of the lot as compared to the minimum specified value. The torqued tension test establishes the load - deformation response of bolts installed by torquing. Having obtained a mean load - deformation curve for a given lot, the clamping force provided by a bolt from that lot can be established by measuring the installed bolt elongation. The load - deformation behavior of the single bolts installed in the A514 steel jigs is necessary for the theoretical prediction of total joint load. The details of testing involved in each of these calibrations have been previously described.[5,19] Results of the direct tension and the shear calibration tests are contained in Table 4.

4.4 Fabrication and Assembly of Test Joints

All shop work for the fabrication of the test joints was done by a recognized steel fabricator. The plate was blast-cleaned prior to layout and assembly, then flame cut to rough size and, finally, milled to specified dimensions. The blast cleaning was done with a Pangborne Roto-Blast using No. 50 chilled steel grit. Before bolting-up, any oil or grease on the plates was removed with solvent.

The plates for each joint were assembled and clamped. The holes were then sub-drilled through the entire assembly with a tape drill. All holes were then reamed to size. Shipping bolts were installed and the pieces sent to the laboratory.

The installation of the bolts was done at Fritz Engineering Laboratory by Project personnel. The plates were first aligned and clamped and then brought into close contact by means of a few fit-up bolts. The remaining holes were fitted with test bolts which were then "snugged" using an impact wrench. The fit-up bolts were then replaced with test bolts and these also snugged. Working from the most rigid part of the joint, the bolts were given the prescribed nut rotation as per standard procedure.[8] Complete data was taken on the change in bolt elongation as each fastener was installed. Using the previously determined load - elongation curves, the clamping force on each joint could then be established.

4.5 Instrumentation

The instrumentation used on these joints was similar to that which has been used in previous work on bolted joints.[10,11] Electric resistance strain gages were attached to each edge of each plate just as it entered the joint. These served to detect possible eccentricity of loading caused by uneven gripping or curvature of the specimen. The large joints also had electric resistance strain gages placed across the width of the lap plates at certain locations between fasteners. These made it possible to compare theoretical and experimental plate loads in these regions. Dial gages measuring to 0.0001 in. were used to measure the slip between main and lap plates. Joint elongation, the movement between points one pitch length removed from each of the extreme fasteners, was measured by means of 0.001 in. dial gages. In addition, similar dials were placed on the member as close as possible to the gripping heads. The measurements so obtained were termed "member elongations" and were taken in an attempt to relate the elongation of the joints to the elongation of the members in which they would be contained.

Most of the instrumentation described here can be seen in Fig. 10.

4.6 Test Procedure

The specimen was first placed in the upper grips of the testing machine and then the instrumentation fitted. After all initial

readings had been taken, the specimen was gripped in the lower head and the loading process commenced. The load was applied at intervals suitable to the expected slip and failure loads. In order to minimize the dynamic effects, the load was applied as slowly as possible, particularly as the test approached the expected slip load. At each load increment, all strain gages and elongation dials were read and recorded.

As the test approached the predicted failure load, the instrumentation vulnerable to damage was removed and safety equipment installed. The test then continued until the specimen failed, either by shear of a single fastener, shear of all of the fasteners, or by fracture of the plates. Each test was completed in a single day.

5.   TEST RESULTS AND ANALYSIS

5.1 Load - Deformation Behavior

Complete load - deformation data were taken for each joint tested. Typical results for a large joint are shown in Fig. 11 where the behavior of Specimen J171 is illustrated. The load - deformation response is nearly linear up to the point of major slip. At this load, which was well-defined in all of the tests except one, the main and lap plates moved relative to one another a little less than the amount of the hole clearance. This movement was always sudden and was accompanied by a loud "bang" as some or all of the fasteners came into bearing.

Following major slip, the load - deformation response was again linear for a short time until a second, minor slip took place. Inelastic deformations in both plate and bolts then began to occur. For those specimens failing by fracture of the plates, such as the one illustrated in Fig. 11, the curve became very flat as the eventual failure load was approached. Specimens designed to fail by shearing of the fasteners also became inelastic. However, because of their relatively greater plate area, the load - deformation curve approached the failure load on a much steeper slope.

The exception to this general behavior among the large joints was Specimen J251. Here, slip occurred in three almost equal increments

at greatly different loads. After bolting up, this specimen had a
large initial curvature. A horizontal jack had to be used to force
the bottom end of the joint into the lower grip. Because of this be-
havior, the results of this test were not used in analyzing the slip
behavior of these joints.

The pilot tests behaved in a fashion very similar to that
described here for the large joints. However, none showed the second,
minor slip that was observed in most of the large joint tests.

5.2 Slip Behavior

The slip behavior of bolted joints has customarily[10] been
evaluated on the basis of a "slip coefficient" (K_s). This is defined
as

$$K_s = \frac{P_s}{m \, n \, T_i} \tag{2}$$

where P_s is the slip load, m is the number of faying surfaces, n is
the number of bolts, and T_i is the average clamping force per bolt.
Slip coefficients computed on this basis are shown in Table 2 for the
pilot tests and in Table 3 for the tests of the large joints.

Variations in the value of the slip coefficient appear to
be random, that is, they are independent of joint length or width, or
magnitude of clamping force. For example, Specimens J131 and J132,

which have the same joint length and are only slightly different in width, have identical values of K_s in spite of a large difference in clamping force. Specimens F42e and J172 have approximately the same clamping force per bolt but lengths of 10-1/2 in. and 56 in. respectively. The values of K_s for these two joints also are identical.

The mean value of K_s for the 17 joints included in the study is 0.33 with a standard deviation of 0.04. The results are shown graphically in Fig. 12. The value of slip coefficient most commonly specified[8] for joints with clean mill scale is 0.35. It should be pointed out again that all of the plate used in these tests was blast-cleaned with No. 50 chilled steel grit. Although this is not an unusual shop procedure for alloy steel plate, it probably results in a conservative value of the slip coefficient.

Although the fasteners are not actually acting in shear, it has been convenient to regulate the design of friction-type connections by an allowable bolt shear stress. The average shear stresses at time of major slip and depending upon fastener type are shown in Fig. 13. Also shown are the working stress levels for the two types of bolts when used in buildings, according to current specifications.[8] Based on the mean values, the factors of safety against slip are 1.48 and 1.86 for A325 and A490 bolts, respectively. The recommended values for structures designed according to this specification are 1.52 for A325 bolts and 1.43 for A490 bolts.

5.3 Ultimate Load Behavior

(1) Pilot Tests

All of the four compact joints using A490 bolts were expected to fail by fastener shear. The theoretical studies showed that individual fastener loads in joints of this short length would be almost equal. Hence, predicted ultimate loads were taken simply as multiples of the individual fastener strengths. The maximum error on predictions so computed was only 2.3%. With one exception, the predicted loads were less than the actual loads. All predicted and actual ultimate loads are tabulated in Table 2.

(2) Large Joints

The use of the plate - with - holes coupons to predict the ultimate load of the plate failure specimens gave values virtually identical to the test values. All joints failed in the mode predicted and failure was always through an end bolt hole, either in the main plate or in the lap plates. A typical plate failure specimen is shown in Fig. 14.

The analytical method developed[4] to predict the ultimate load of A514 steel joints failing by fastener shear also gave excellent results. The maximum error in predictions of the five large joints tested was 5.6%.

Further verification of the analytical method was obtained by comparing theoretical and actual loads in the plates. The latter were computed from the strain gage readings taken continuously during each test. Two joints were chosen for the comparison, one a plate-failure type (J131) and the other a joint expected to fail by fastener shear (J172). Two locations in each joint were examined, the first pitch from the "loaded" end and a pitch near the centerline of the joint, and only loads above the slip load were considered. Table 5 summarizes the comparison and shows that the theoretical computations gave results in good agreement with the actual values. The comparison is shown graphically in Fig. 15.

Specimens J072, J132, J172, and J252 all failed by an apparent simultaneous shearing of all of the fasteners. Although the end fasteners should, and probably did, fail first, the high level of load in the remaining bolts meant that they were not able to carry the additional load from the first failed fastener. That the failure was as hypothesized can be seen in Fig. 16. Here, the sheared bolts from Specimen J132 have been reassembled. Although failure was by apparent simultaneous shear of all fasteners, it is obvious from the deformations that an end bolt did fail first.

The only joint tested in which the test could be stopped once an end fastener failed was Specimen J251. This joint had been proportioned such that it was very close to the plate failure - fas-

tener failure boundary. A sawed section taken through the end four fasteners, including the failed one, is shown in Fig. 17. The large amount of bolt bending, as shown here, is not present in the shear calibration test made on the individual fastener. In effect, then, the calibration test produces a shear failure in the bolt at approximately 90° to its axis while the bolt in the test joint is being sheared on a plane providing more area than this minimum value. For this reason, the actual loads in joints of this type may be expected to be slightly larger than those predicted.

If higher allowable shear stresses for A490 bolts are eventually adopted, bearing stresses higher than those presently encountered will result. Although no particular emphasize was placed on examining the effect of high bearing stresses in the development of the test program, all joints were visually inspected in this regard after failure.

The highest bearing stress developed in the joints of the pilot study was 77.3 ksi (Specimen J42a). In the large joint test series, the maximum average bearing stress was 69.4 ksi (Specimen J072). In no case did any of the joints show signs of distress as a result of these magnitudes of bearing stresses imposed on the plate.

6.   SUMMARY AND CONCLUSIONS

This report has included the results of both analytical and
experimental studies of the behavior of constructional alloy (A514)
butt splices which use A490 fasteners.

Based on previous theoretical work,[4] a study was made of the
parameters that might be expected to affect the behavior of these joints
The parameters investigated included fastener type, diameter, and
pitch, relative proportions of plate and fasteners, and joint length.

The validity of the previously developed theoretical study
and the analytical work reported herein have been verified by means of
an extensive testing program. A comparison shows that the theoretical
predictions are reliable, both for the ultimate load of the joint and
for obtaining the distribution of load among the fasteners at loads
less than ultimate.

The conclusions reached as a result of this study can be
itemized as follows:

1.   The slip coefficient of blast-cleaned A514 steel is
      about 0.33. Within reasonable limits, this value
      appears to be independent of joint length or width or
      magnitude of clamping force.

2. An accurate theoretical solution is available for predicting the ultimate load of bolted, butt splices of constructional alloy steel fastened by A490 bolts. The same theoretical development can be used to provide plate or individual fastener loads at levels less than ultimate.

3. The ultimate strength of these joints is a function of joint length and relative plate - fastener proportions, It is independent of fastener diameter or pitch, per se.

4. Constructional alloy steel joints using A490 bolts do not produce yielding on the gross section if the elements of the joint are designed according to currently used stress levels.

5. The use of higher allowable shear stresses in A490 bolts, in line with those suggested in other grades of steel, is suitable in A514 steel joints.

7.   ACKNOWLEDGMENTS

8. <u>TABLES AND FIGURES</u>

TABLE 1   MECHANICAL PROPERTIES OF A514 STEEL

	Plates	Structural Shapes
Yield Strength, Ext. under load, min, psi	100,000	100,000
Tensile Strength, psi	115,000/135,000	115,000/140,000
Elongation in 2 in. min, %	18	18
Reduction of Area, min, %	3/4 in. and under-40 over 3/4 in.— 50	3/4 in. and under-45 over 3/4 in.— 55

TABLE 2

JOINT DIMENSIONS AND TEST RESULTS - PILOT STUDY

Item	Units	F42a	F42b	F42c	F42d	F42e	F42g	J42a	J42b	J42c	J42d
<u>Bolts</u> Type	-	A325	A325	A325	A325	A325	A325	A490	A490	A490	A490
Diameter	in.	1-1/8	1-1/8	1-1/8	1-1/8	1-1/8	1-1/8	1	1	1	1
No. in Line (n)*	-	4	4	4	4	4	4	4	4	4	4
Shear Area (A_s)	in.^{2}	15.90	15.90	15.90	15.90	15.90	15.90	12.57	12.57	12.57	12.57
Joint Length	in.	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
<u>Plate</u> Width	in.	5.56	6.36	6.76	7.16	7.56	7.96	6.84	7.16	7.47	7.79
Thickness (t)	in.	2.03	2.04	2.04	2.04	2.04	2.05	2.04	2.05	2.04	2.05
Gross Area (A_g)	in.^{2}	11.28	12.98	13.80	14.51	15.41	16.31	13.93	14.63	15.24	15.95
Net Area (A_n)	in.^{2}	6.40	8.07	8.90	9.66	10.52	11.40	9.58	10.25	10.85	11.55
A_n/A_s	-	0.40	0.51	0.56	0.61	0.66	0.72	0.76	0.82	0.86	0.92
<u>Slip</u> Load	kips	396	332	326	342	346	398	480	506	518	448
Clamping force/bolt	kips	69.0	70.0	68.5	70.5	69.0	70.0	86.0	80.0	80.0	80.0
Slip Coefficient	-	0.36	0.30	0.30	0.30	0.31	0.36	0.35	0.40	0.40	0.35
<u>Ultimate Load</u> Predicted	kips	Not reported herein						1210	1210	1210	1210
Actual	kips							1238	1228	1206	1220
Failure Mode	-							Bolts	Bolts	Bolts	Bolts

* Pitch = 3.5 in. for all joints

TABLE 3

JOINT DIMENSIONS AND TEST RESULTS - LARGE JOINTS

Item	Units	J071	J072	J131	J132	J171	J172	J251	J252
Bolts Type	-	A490	A490	A490	A490	A490	A490	A490	A490
Diameter	in.	7/8	7/8	7/8	1-1/8	7/8	7/8	7/8	7/8
No. in Line* (n)	-	7	7	13	13	17	17	25	25
Shear Area (A_s)	in.^{2}	8.41	8.41	15.63	25.84	20.44	20.44	30.07	30.07
Joint Length	in.	21	21	42	42	56	56	84	84
Plate Width	in.	3.86	4.71	6.38	7.00	8.07	10.09	6.97	9.22
Thickness (t)	in.	2.03	2.04	2.04	4.08	2.04	2.02	4.08	4.08
Gross Area (A_g)	in.^{2}	7.82	9.58	12.99	28.55	16.48	20.40	28.35	37.55
Net Area (A_n)	in.^{2}	5.92	7.66	11.08	23.70	14.55	18.52	24.55	33.73
A_n/A_s	-	0.70	0.91	0.71	0.91	0.71	0.90	0.82	1.12
Slip Load	kips	270	364	620	974	730	700	**	938
Clamping force/bolt	kips	71.3	69.7	70.5	110.5	66.6	66.9	72.1	72.0
Slip Coefficient	-	0.27	0.37	0.34	0.34	0.32	0.31	-	0.26
Ultimate Load									
Predicted	kips	700	810	1309	2485	1720	1950	2740	2935
Actual	kips	710	850	1308	2615	1718	2015	2735	3100
Failure Mode	-	Plate	Bolts	Plate	Bolts	Plate	Bolts	Bolts	Bolts

* Pitch = 3.5 in. for all joints

** Not defined - joint was warped

TABLE 4   BASIC STRENGTH PROPERTIES OF TEST BOLTS

	LOT B	LOT C	LOT D	LOT JJ *
Bolt Grade	A490	A490	A490	A490
Bolt Dia., in.	7/8	1-1/8	7/8	1
Grip, in.	4	8	4	4
Connecting Material	A514	A514	A514	A514
Specified Min. Tensile Str., kips**	69.3	114.5	69.3	90.9
Actual Tensile Str., kips	72.2	119.5	75.4	99.1
Shear Test: R_{ult}, kips	116.6	191.8	119.8	151.7
Δ_{ult}, in.	0.127	0.165	0.131	0.155

*

From Ref. 5

** Corresponds to a tensile strength of 50 ksi

TABLE 5

COMPARISON OF THEORETICAL VS. MEASURED PLATE LOADS

Specimen	Location (bolt lines)	Total Joint load kips	Theoretical Load in Plates kips	Measured Load in Plates kips
	17-16	800	730	694
J172		1350	1250	1218
		1850	1736	1780
(Ult. load = 2015[k])	11-10	800	448	400
		1350	770	722
		1850	1080	1046
J131	13-12	700	624	616
		1050	950	996
(Ult. load = 1308[k])	7-6	700	316	312
		1050	482	456
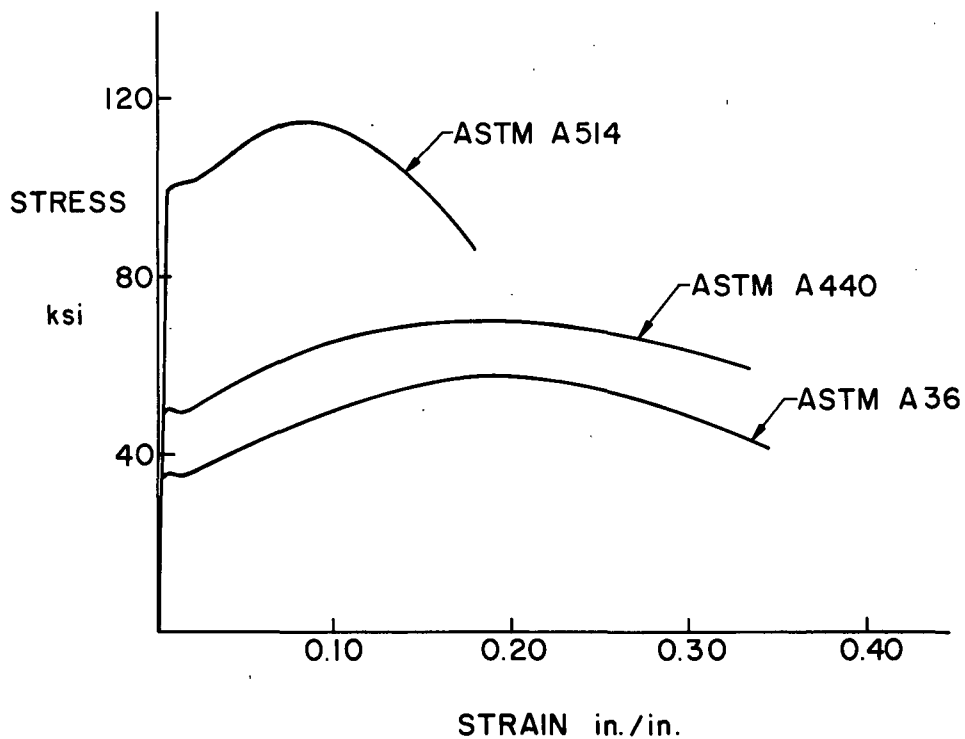
Fig. 1 Typical Stress - Strain Curves of Various Steels
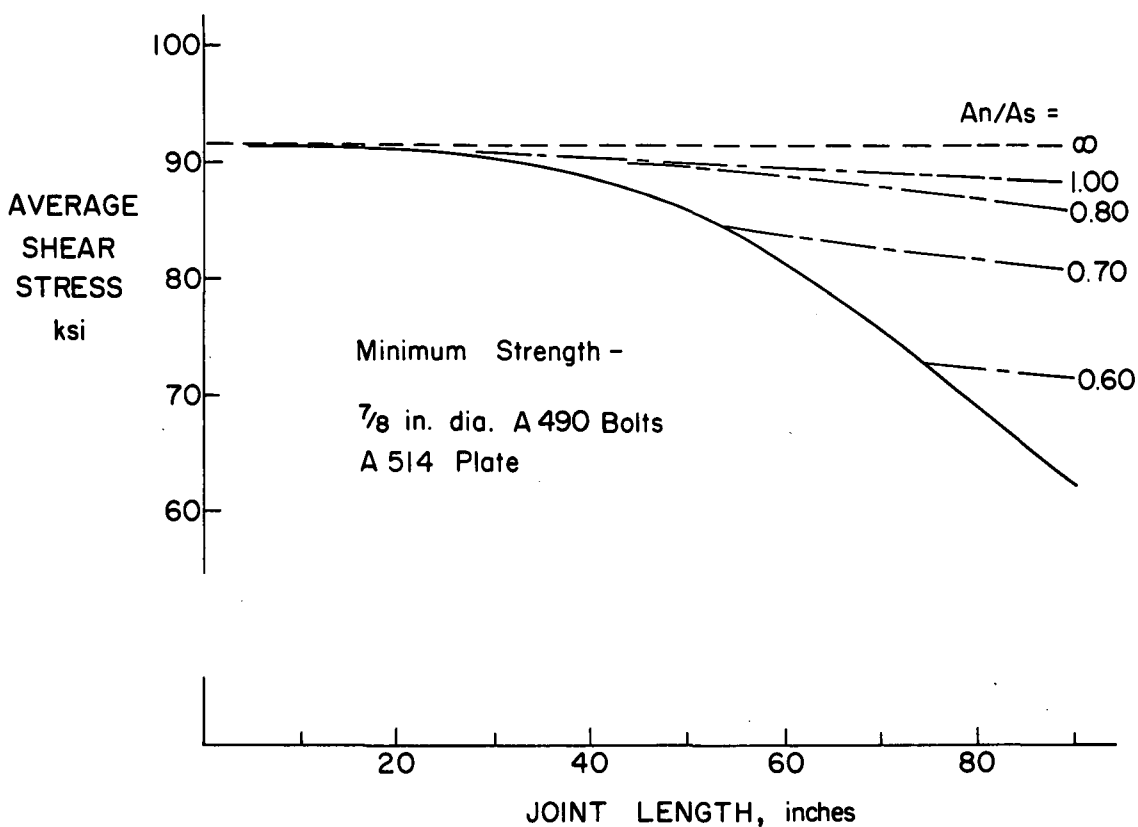
Fig. 2 Failure Mode Boundary (τ vs. L)
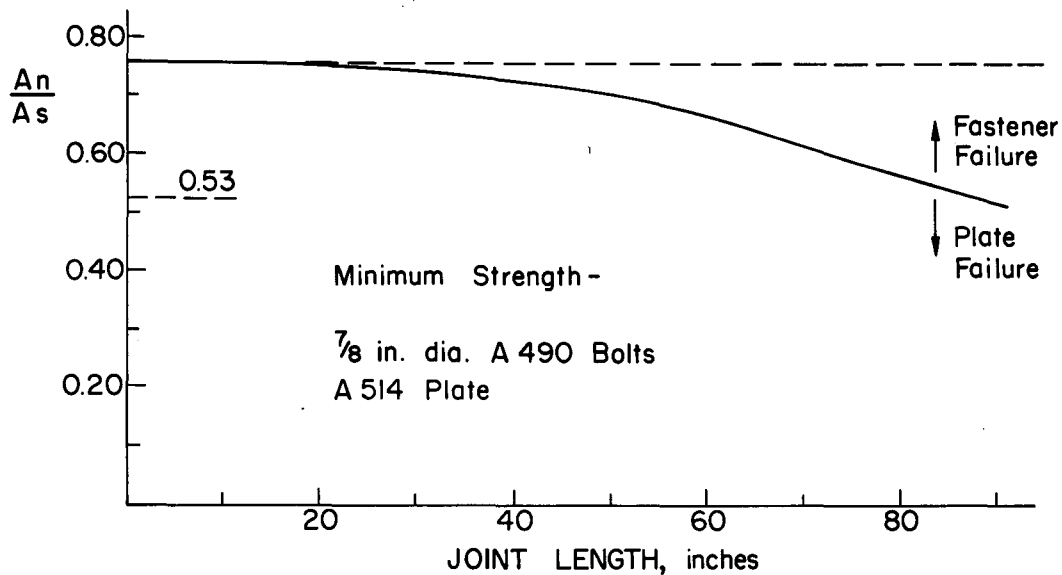
Fig. 3 Failure Mode Boundary (A_n/A_s vs. L)
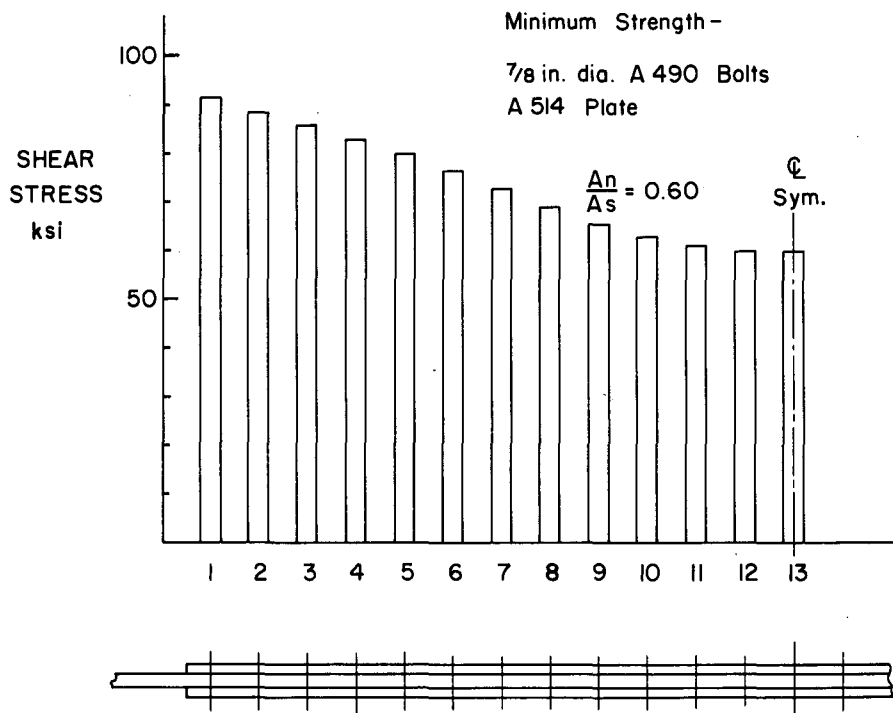
Fig. 4 Load Distribution to Fasteners of 25-Bolt Joint
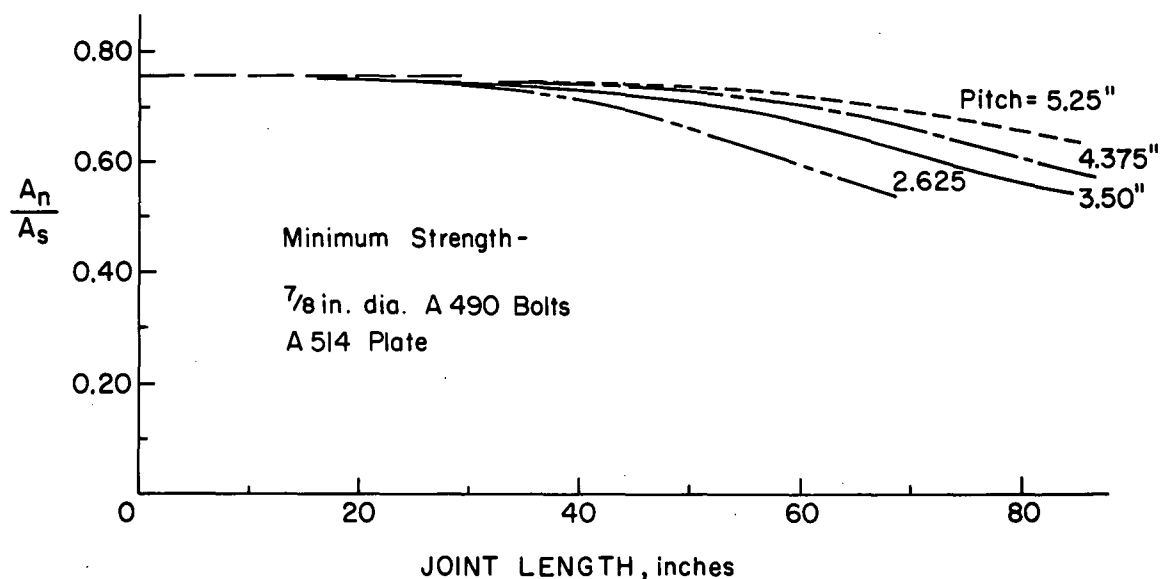
Fig. 5   Effect of Pitch on Failure Mode Boundary
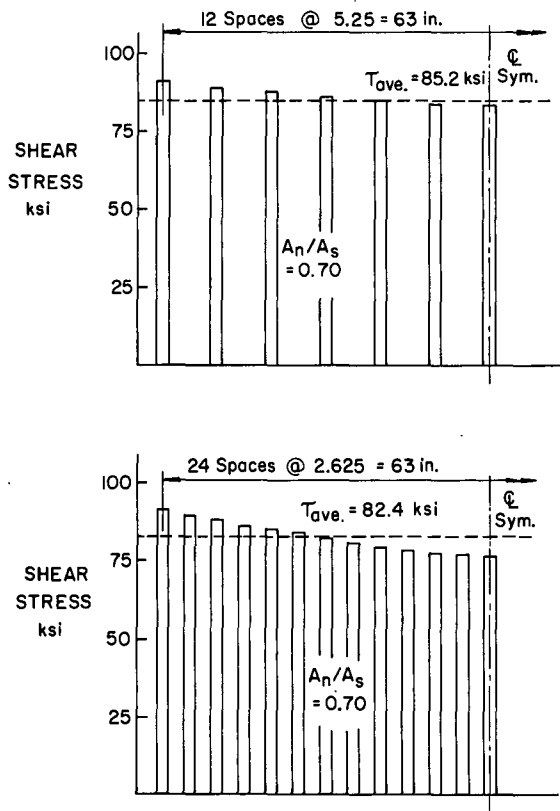
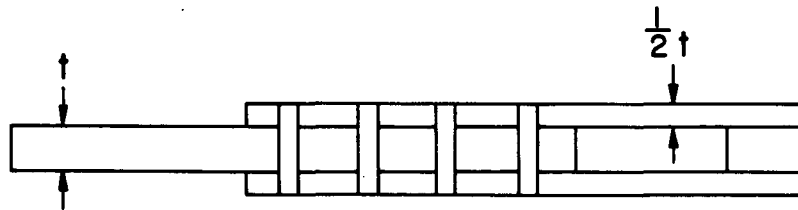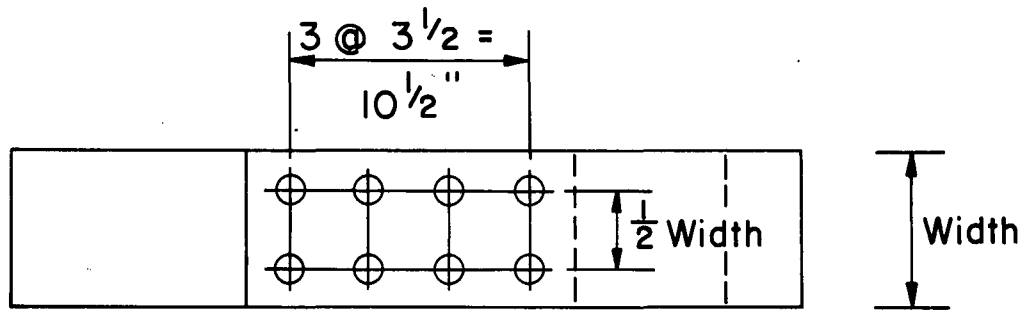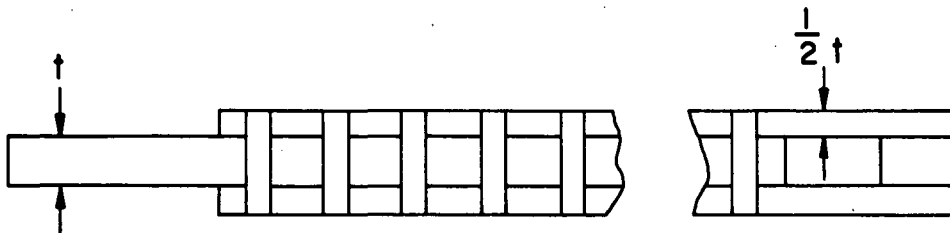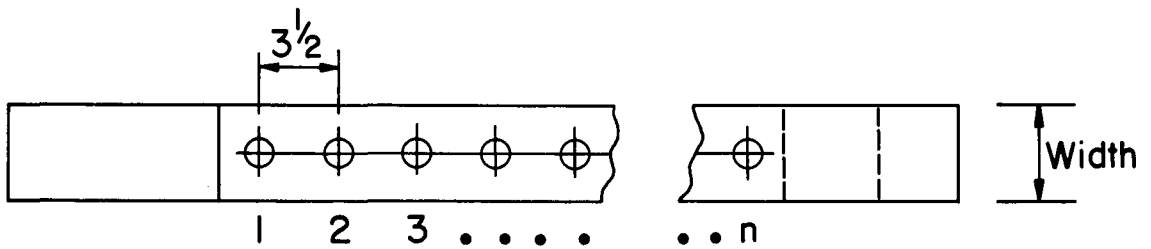Fig. 6   Load Distribution in Joints of Same Length
But of Different Pitch
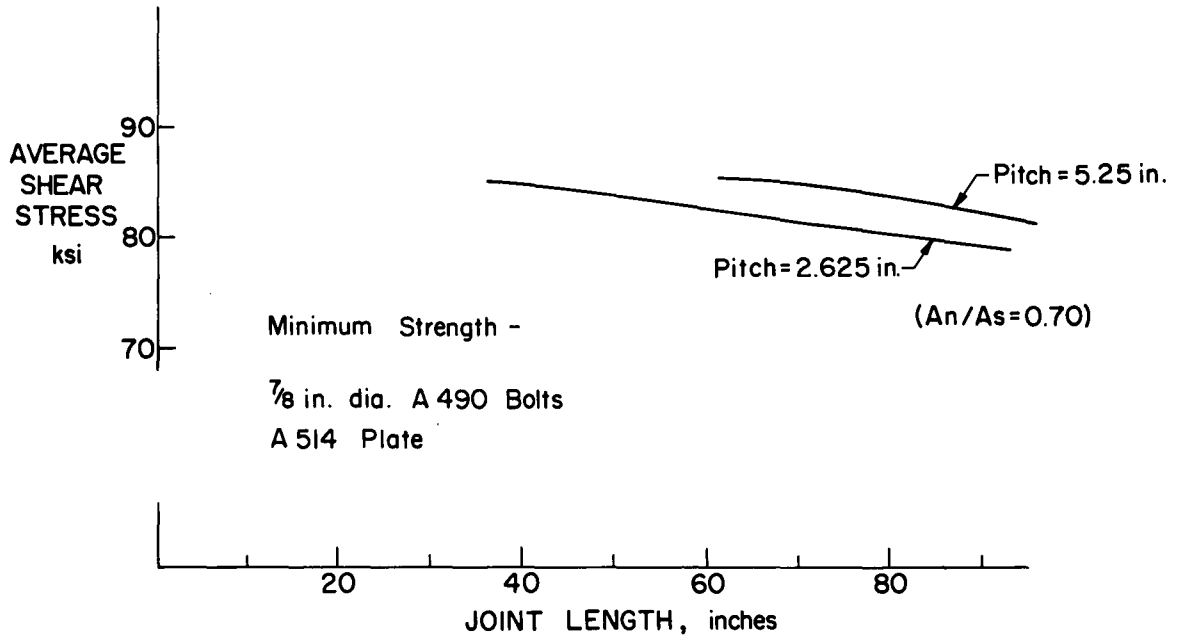
Fig. 7 Effect of Pitch on Joint Strength (τ vs. L)

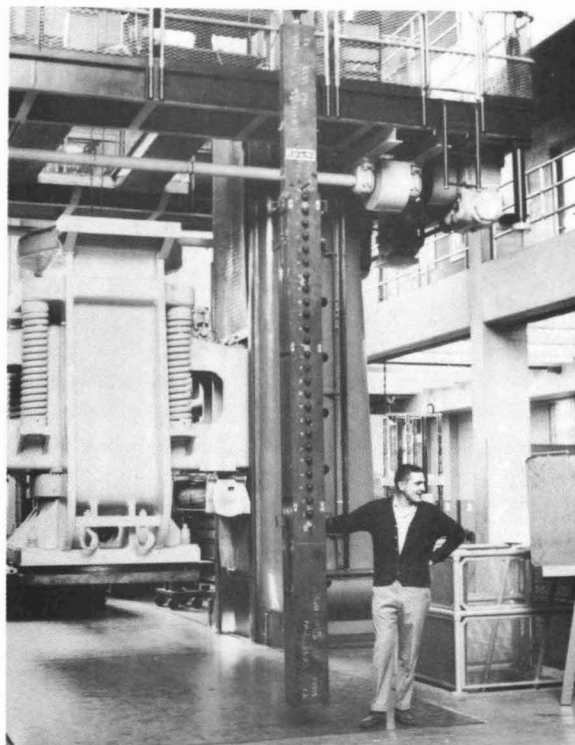(a) Pilot Study

(b) Large Joints

Fig. 8 Geometry of Test Joints

Fig. 9 Specimen J252 Prior to Testing

Fig. 10 Instrumentation of Test Specimens
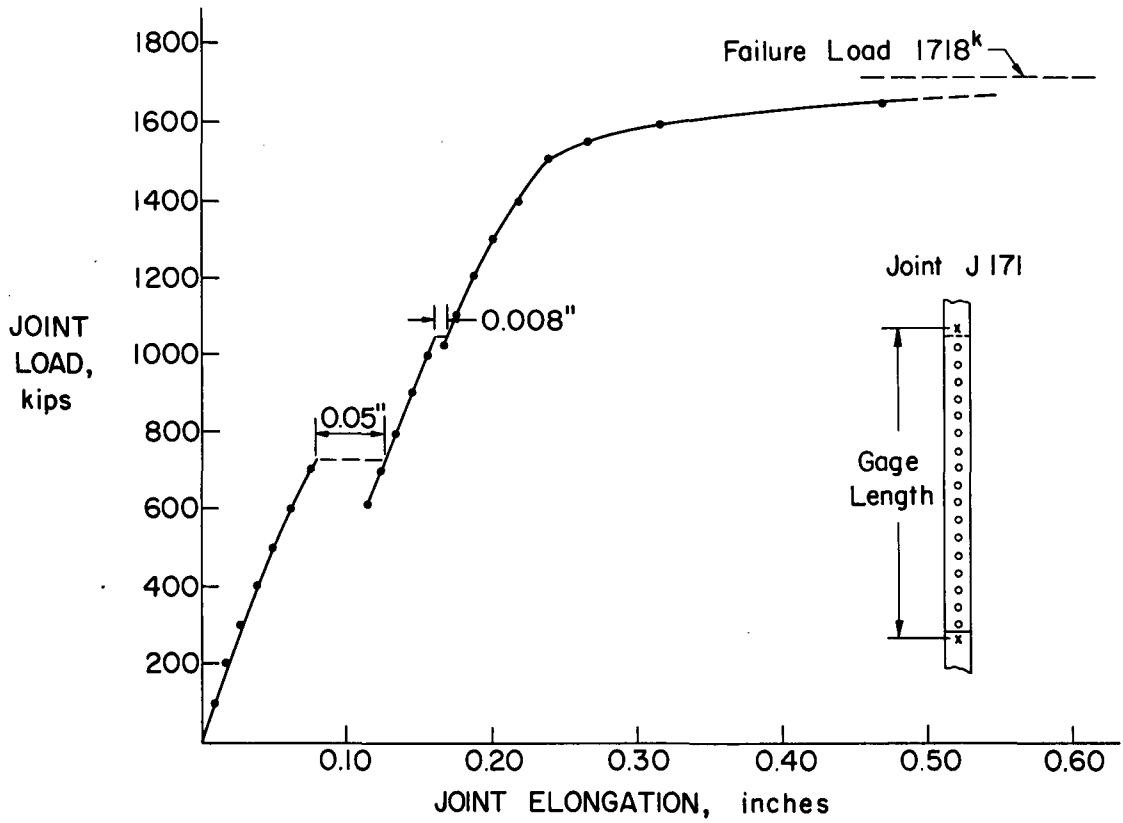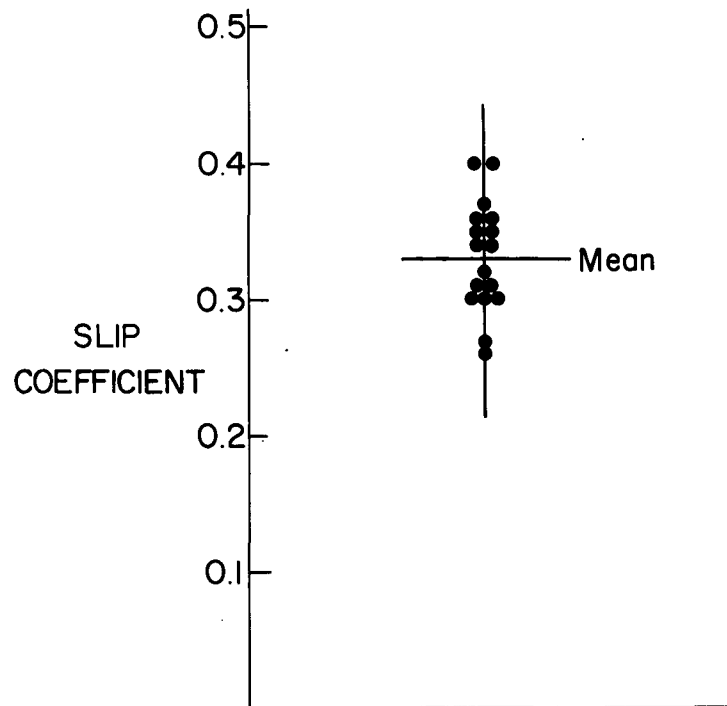
Fig. 11 Typical Load - Deformation Response
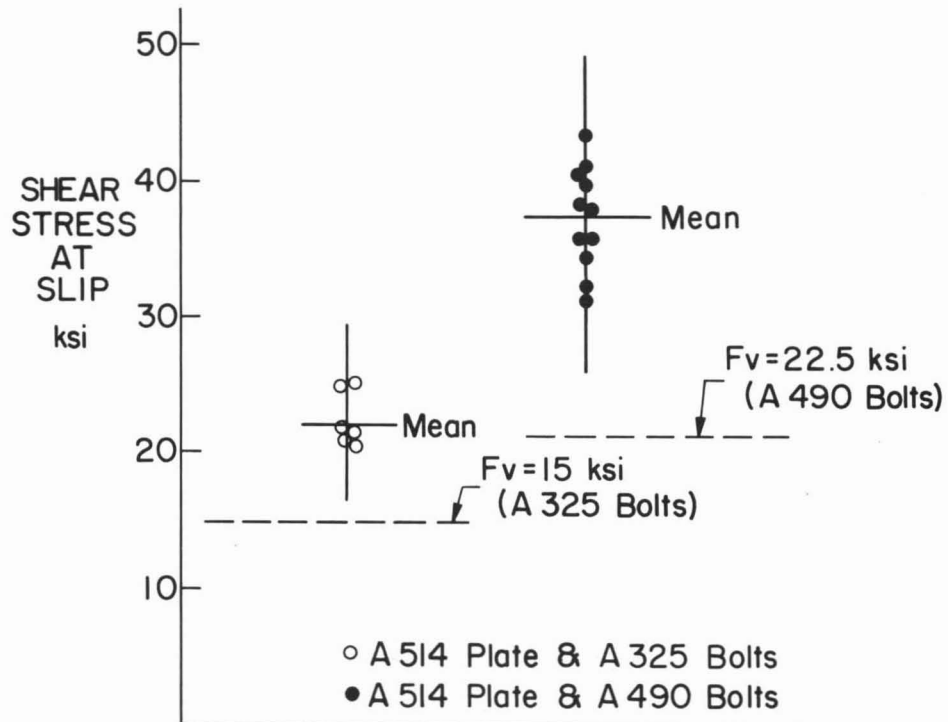

Fig. 12 Slip Coefficient

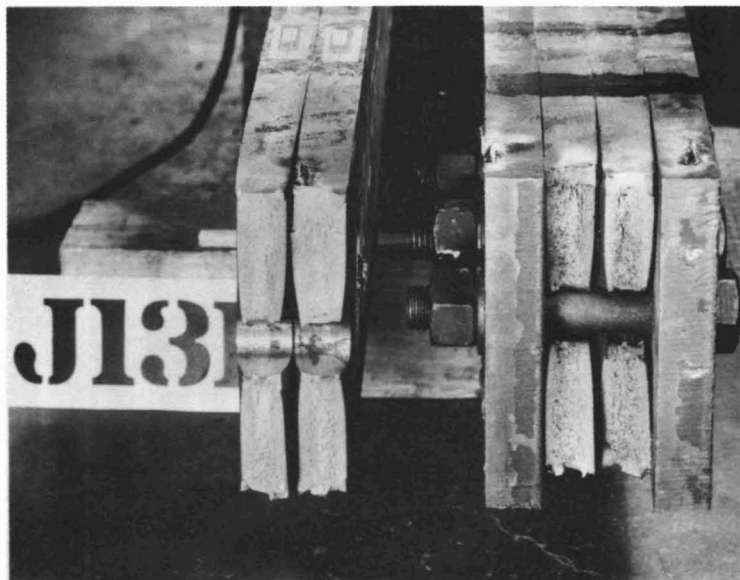Fig. 13 Average Shear Stress at Slip
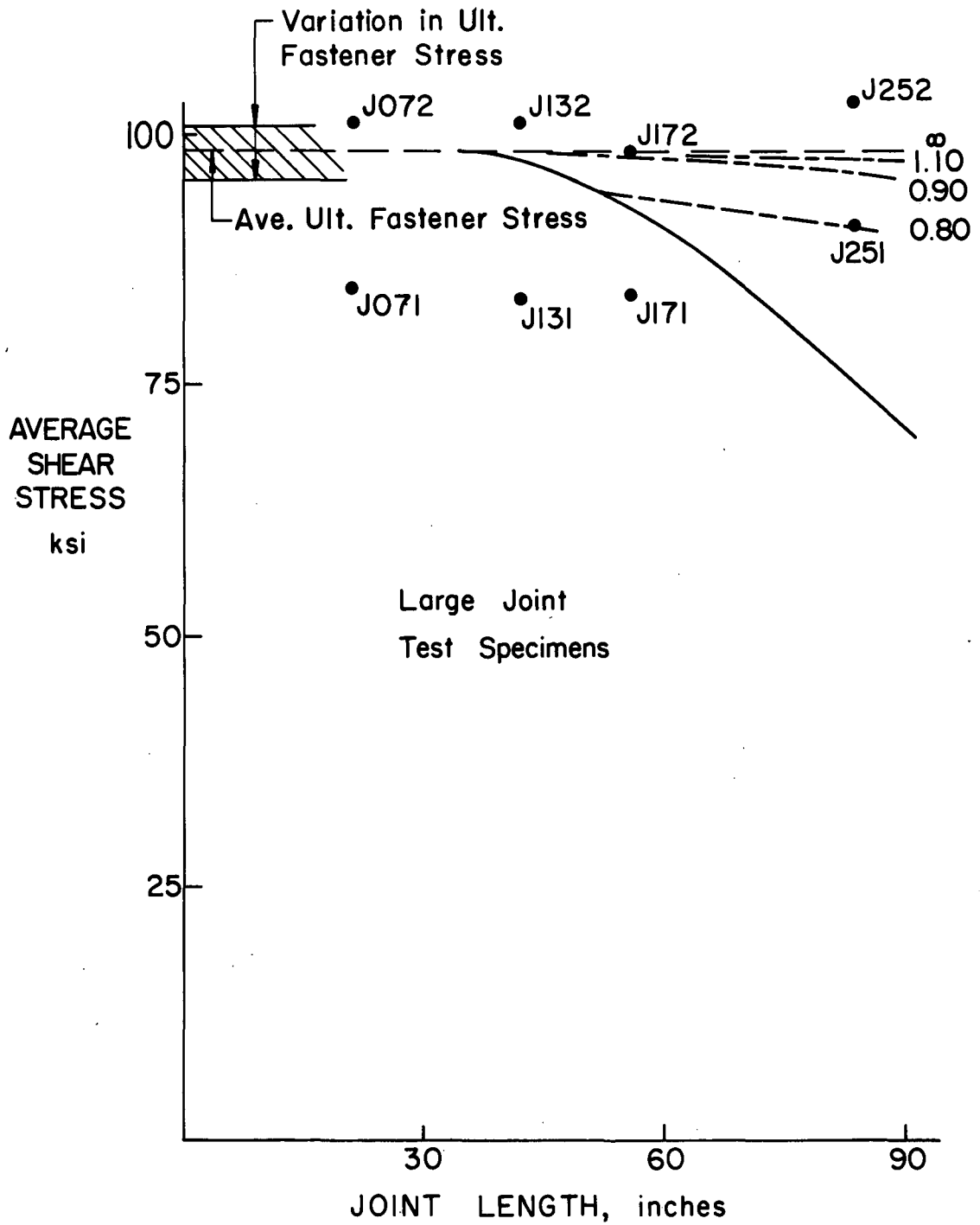

Fig. 14 Typical Plate Failure

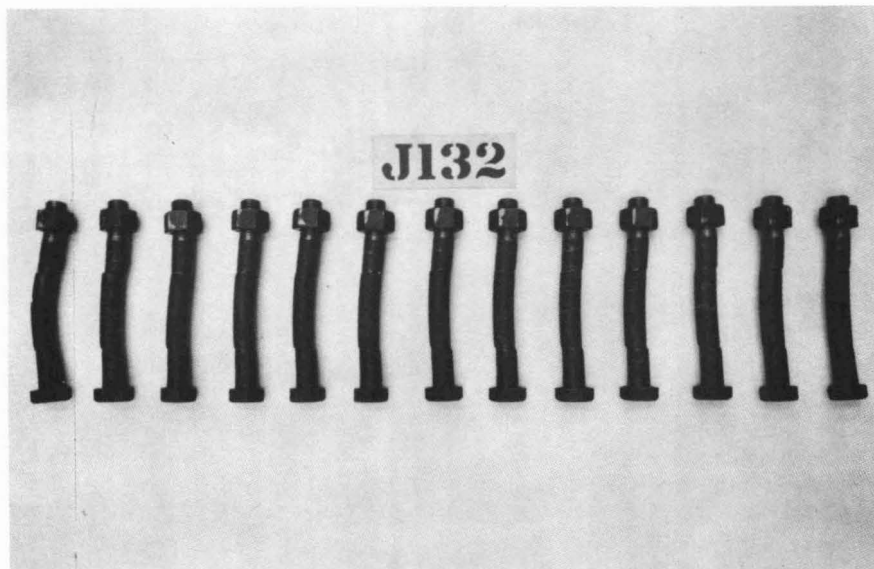Fig. 15   Predicted and Actual Results - Large Test Joints

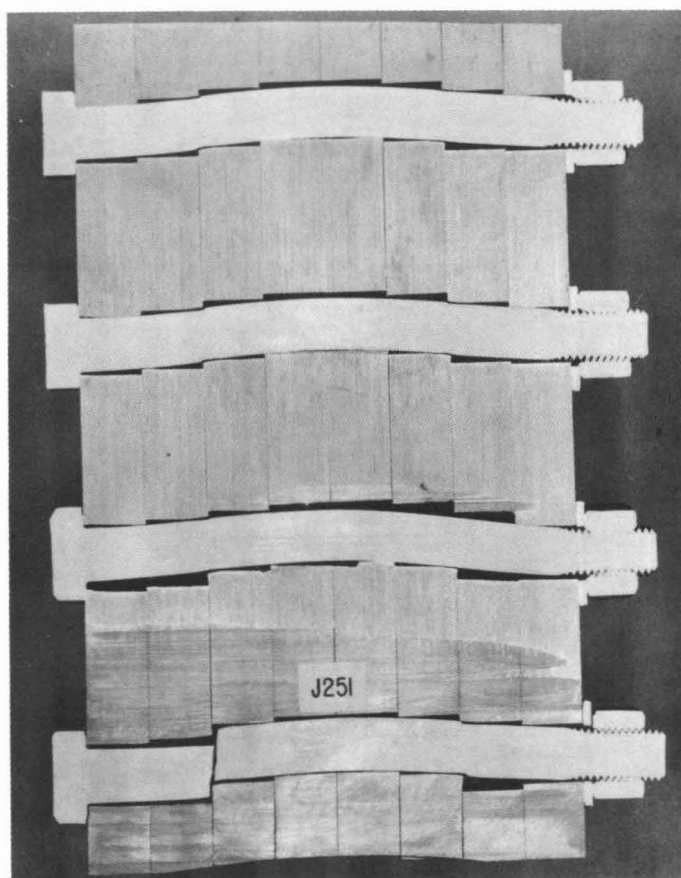Fig. 16 Sheared Bolts from Specimen J132

Fig. 17 Sawed Section from Specimen J251

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