1960

Tests of large bolted joints, June 1960

R. T. Foreman

J. L. Rumpf

L. S. Beedle

Recommended Citation

Foreman, R. T.; Rumpf, J. L.; and Beedle, L. S., "Tests of large bolted joints, June 1960" (1960). *Fritz Laboratory Reports.* Paper 1728.
http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports/1728

J. L. Rumpf

TESTS OF LARGE BOLTED JOINTS

Authors: R. T. Foreman, J. L. Rumpf, L. S. Beedle
Oral presentation by J. L. Rumpf

Acknowledgements:

The work about to be described to you was done at the Fritz Engineering Laboratory, Lehigh University. It is part of an investigation of bolted connections that began in 1957 and is still continuing. Financial sponsorship is by the Pennsylvania Department of Highways and the Bureau of Public Roads. AISC A committee of the Research Council on Riveted and Bolted Structuran Joints serves in an advisory capacity.

Note: If not covered in Chairman's introduction, insert the following-

The co-authors of this paper are R. T. Foreman, Research Engineer, Bethlehem Steel Co., formerly Research Assistant at the Fritz Laboratory and Dr. L. S. Beedle, Chairman of the Structural Metals Division of the Fritz Laboratory.

Most of the material in this talk appears in the paper, "Static Tension Tests of Compact Bolted Joints" which appeared in the Journal of the Structural Division of 1960.

Introduction:

The items to be discussed will be those parts of the Lehigh work which bear particular relation to the new 1960 Specification of the Research Council for structural joints using

ASTM - A325 bolts - the widely used high-strength bolt.

Background:

If one compares the ultimate tensile strength of an A141 rivet with that of the heat treated A325 bolt material one sees SLIDE 1 that the bolt is quite a bit stronger. SLIDE 271-90

Also it is quite obvious from this that the bolt possesses more shear strength. Early investigat~~ions~~ors in the bolt field recognized this and tests of a few small connections showed the greater ultimate strength of the bolted connection. However, in those early days the main problem was to justify the high strength bolt as a replacement for the rivet. Many engineers were worried about slip.

Gradually the high strength bolt became accepted as a 1 for 1 substitute for the rivet and engineers became confident of the good performance of a properly installed bolt. At this time it became possible to take another look at the additional shear strength of the bolt. In doing this one must recognize that there are two types of connections to be encountered:

1. that in which "slip" is considered as failure, and,
2. That in which shearing of the bolts constitutes failure.

There are many structural joints, erected in bearing and not subject to stress reversal which fall in the latter class. It is here that we can take advantage of the shear strength of the high strength bolt.

The philosophy of the design of riveted connections has been to put in enough rivets to "develop" the member. This results in a so-called balanced design in which, if overloaded, the average shear stress on the rivets and the stress on the net section of the member reach their ultimate values simultaneously. The designer achieves this by using properly chosen allowable stresses. <u>SLIDE 2</u> For example, AISC specifications prescribe SLIDE 271-91

$\sigma = 20$ ksi F.S = 3 $\frac{60}{20} = 3$

$\tau = 15$ ksi $\frac{45}{15} = 3$

We find it convenient to speak of the Tension-Shear Ratio and in this case $\frac{T}{S} = \frac{20}{15} = \frac{1}{.75}$

In terms of joint geometry $\frac{T}{S} = \frac{A \text{ shear}}{A\, \underset{t}{\boxed{\text{net}}}}$

Obviously, when the stronger bolt is substituted for a rivet on a 1 for 1 basis the above $\frac{T}{S}$ ratio does not result in a balanced design. Too many bolts are provided and they are understressed. To make economical use of the high strength bolt a new $\frac{T}{S}$ ratio must be determined.

<u>Object of Lehigh Work:</u>

The object of the first phase of the program at Lehigh wat to determine the balanced design tension shear ratio for A325 bolts in A7 steel members. Because of lack of data on slip of large compact joints, information on slip behavior was obtained also.

General Description of Test Joints

If one takes the ultimate shear strength of a single high strength bolt and figures the T/S ratio for balanced design, ~~he~~ one computes it to be about 1/1.3. 60/78 However, each bolt (or rivet) does not take an equal share of the load as we assume in design, so this is incorrect. Tests are needed to determine the proper ratio.

The test specimens used to "zero-in" on the T/S ratio were double shear plate splices subjected to a static tension load. SLIDE 3 The plate was 18" wide, universal mill, A7 steel plate with an ultimate tensile strength of 66 ksi. The inner or main member consisted of two 1" plates and each of the outer or lap plates was a 1" plate. SLIDE 271-92

The bolts used were 7/8", 1", and 1- 1/8" diameter and were purposely made close to the minimum strength of the A325 specification. Bolts were arranged in compact patterns, with full bolting on the end rows. All holes were drilled 1/16" larger than the bolt size through the 4 plies of material. This provided perfect hole alignment. $\frac{g}{d}$ (gage over hole diameter) and $\frac{P}{d}$ (pitch over hole diameter) were in the neighborhood of 3.75. This is in the range of practice and also provides good net section efficiencies.

The contact surfaces were not painted. The only preparation was the removal of loose mill scale with a hand wire brush and the removal of oil and grease with ordinary solvent.

The number of joints in this series was:

6 with 7/8" bolts

1 with 7/8" rivets for comparison

1 with 1" bolts

1 with 1-1/8" bolts

We will discuss these in more detail shortly.

Bolting Up

The joints were assembled with an impact wrench at the Fritz Laboratory by a Bethlehem Steel Co. erection crew. Bethlehem's standard field procedure, which is an adaptation of the turn-of-nut method, was followed. A simplified description of the method would say that the nut is rotated 1/2 turn from a "snug" position. Snug is indicated when the wrench first begins to impact.

In order to evaluate the tightening procedure and to evaluate slip behavior later on, accurate measurements were made of the amount of bolt elongation caused by tightening the nut. SLIDE 4 This slide shows a histogram of the elongations of the SLIDE - 271 - 990 7/8" bolts in six joints B1 to B6. The black blocks indicate the fitting up bolts which were tightened first and which drew the plies of material into firm contact.

Above the histogram are two tension-elongation curves. The upper one, marked DIRECT TENSION, was obtained by pulling a bolt in a testing machine. In the lower one, marked TORQUE, the tension in the bolt was induced by tightening the bolt in a

Skidmore-Wilhelm Calibrator. Notice on the complete curve, in the right handccorner, that the maximum tensile strength that can be developed by tightening the nut is about 11% less, on an average, than that which is developed in direct tension.

Since the histogram is plotted to the same scale as the abscissa of the curves it is possible to read upward from a particular block to either curve and then over to determine the bolt tension. Notice that the "1/2-turn-from-snug" procedure tightens bolts up into the plastic region. Although there appears to be a large spread in elongations the curves are relatively flat in this region so there is not much variation in bolt tensions. The bolt tensions are about 125% of the proof load. $\frac{45}{36.05}$ -- from torqued curve.

Lest any one worry about tightening into the plastic range let us take a look at the following slide. <u>SLIDE 5</u> Slide 271-25 This non-dimensional plot shows the effectiveness of the turn-of-the-nut method. It shows for example that when a bolt is tightened "1/2 turn from snug" 90% of the maximum available tension has been developed. Yet at the same time only 20% of the fracture elongation has been utilized. In other words, the factor of safety against breaking a bolt during tightening is 5.

Preliminary Joint Tests

Now let us return to the test joints. Keep in mind that the purpose of these tests was to determine the balanced design T/S ratio. First let us examine joints B1, B2, and B3 with 7/8" bolts. <u>SLIDE 6</u> B1 had30 bolts - 6 rows of 5 - and Slide 271-93 a T/S ratio of 1/.74 Thus it was a connection designed according to the "1 bolt for 1 rivet" specification. In B2, one row of bolts was eliminated changing the T/S ratio to 1/.89 and in B3 another row was taken out making T/S equal to 1/1.11 Tests of these joints gave the following results: SLIDE 7 SLIDE 271-3

B1 failed by tearing of the main plate at a net section stress of 73 ksi while the nominal shear stress on the bolts was only 54 ksi.

SLIDE 8 In joint B2 failure also occured by tearing SLIDE 271-4 of a plate even though there were five less bolts. The net section stress was 73 ksi and the nominal bolt shear was up to 65 ksi.

SLIDE 9 Finally, in joint B3, with only 20 bolts a SLIDE 271-6 fastener failure occurred. This happened at a nominal shear stress of 73 ksi. SLIDE 9' - Notice the amount of deformation the A325 bolt undergoes before failure ~~and~~ also note that in these tests the shearing planes went thru full shank and not thru threads. At this point one might say, "Well, Joints B2 and B3 have bracketed the balanced design T/S ratio. It must be somewhere between 1/.89 and 1/1.11". SLIDE 271-7 However if we observe that the net section stress at the time of bolt failure was 66 ksi - and equal to the coupon stress, we conclude that we are very close to the balance point.

Further Joint Tests

To substantiate the findings of these tests five more joints were fabricated and tested using plate from the same rolling. SLIDE 10 B4, 5, and 6 used 7/8" bolts of the same lot as used SLIDE 271-94 previously while A3 had 1" bolts and G1 had 1-1/8" bolts. In B4 and B5 it was necessary to go to patterns which omitted bolts in order to achieve the desired T/S ratios.

B4 at a T/S ratio of 1/.96 produced a plate failure while all the others were bolt failures. However, the plate stress in all cases was at least 97% of the corresponding coupon stress and was always greater than the minimum ultimate stress of 60 ksi specified by ASTM-A7.

Summary of Results

The best way to see the results of the tests is on the following slide. SLIDE 11 This bar graph shows the efficiency of these compact connections. SLIDE 271-95 Efficiency in this case is defined as the tensile stress on the net section at the maximum joint load divided by the ultimate tensile strength of standard ASTM coupon cut from the same plate. It is a measure of the ability of the fasteners to "develop" the member. When a bar reaches to the 1.00 level it indicates that the bolts have developed the coupon strength. When a bar reaches to the level of the short tick mark it indicates that the bolts have developed at least the minimum tensile strength of A7 steel - 60 ksi.

The white bars, representing plate failures, illustrate the well-known fact that the stress developed on the net section of a joint exceeds the coupon stress if g/d is less than 8.

The black bars, represent bolt failures. These joints had T/S ratios of 1/1.10 or less. Of the 5 joints, 3 developed the coupon strength and all developed at least 60 ksi in the plate. We may explain the low position of B6 by its T/S ratio of 1/1.15. The low position of B5 may stem from its open pattern which appeared to affect the behavior of B5 in other respects as well.

It is fair to conclude from these results that a reasonably balanced design is achieved with a T/S ratio of 1/1.10 provided bolt threads are excluded from the shearing planes. If the working tensile stress is set at 20 ksi then the working shear stress is 22ksi and the factor of safety against rupture is 3 or more.

Bolt vs. Rivet

While we are looking at this bar graph it is interesting to compare joints B2 and BR2 which were identical except for the fasteners. B2 had 25 - 7/8" bolts and BR2 had 25 - 7/8" A141 hot driven rivets at a T/S = 1/.89 The bolts forced a plate failure at 73 ksi while the rivets sheared when only 49 ksi had been developed on the net section. The behavior of the two joints may be compared by means of the load-elongation curves for the two. SLIDE 12 Notice the different loads that each joint supported. Slide 271-96 Also notice that the riveted joint slipped despite the commonly made statement that rivets fill the hole. This is seen more clearly on the next slide, SLIDE 13 ,which enlarges the slip Slide 271-97 region. Here we see that the slip of the riveted joint amounts to about .02" while the bolted joint slip is slightly more than the 1/16" hole clearance.

In the usual working range the bolted joint is stiffer than the riveted one - being stiffer than the gross section of the main material.

Efficiency of Bolts - (Unbuttoning)

Another way of measuring the performance of joints is to see how close the average bolt shear stress in a connection approaches the shear strength of a single bolt. SLIDE 14 The ordinate here is the average shear stress at failure divided by the shear strength of a single bolt. The latter value is obtained by shearing a single bolt of the same lot in a shear jig of the same grip and A7 material. We see that in compact joints the bolts operate on the average at about 85% to 90% of the single bolt strength. This is because each bolt does not take an equal share of the load.

SLIDE 271-98

The bars have been arranged in order of the length of the joint - longer joints to the right. We notice a trend here which has been the subject of further research at the Fritz Laboratory.

Slip of Connections

Up to this point we have been concentrating on the rupture characteristics of the joints. As noted earlier, however, there are cases in which slip constitutes failure. Accordingly, information was collected on this phase of the joints' loading history. In all cases the slip was a sudden one accompanied by a resounding noise. SLIDE 15

SLIDE 271-99

Designing against slip is really a friction problem. According to the classical theory of static friction, the coefficient of friction, μ, is equal to the force that initiates sliding, F, divided by the normal force, N, which presses the surfaces together. In the case of the bolted joint we can determine a comparable quantity which we prefer to call "slip coefficient" because it is not a true coefficient of friction. Thus:

$$K \text{ slip} = \frac{P \text{ slip}}{mn\, T_i}$$

Where P_{slip} = the load on the joint which causes it to slip

m = the number of slip planes. In this case 2 for a double shear joint

n = the number of bolts

$\overline{T}_i$ = the mean initial clamping force of the bolts which is obtained from the histogram and curves shown to you previously. For example, if we enter the plot with the average elongation of the bolts in a joint we can read upward to either curve and then across to the value of T_i. Although the TORQUED curve is the correct one to use we have report coefficients of slip on the basis of the upper DIRECT TENSION curve. This gives values of slip coefficient which are on the low side and therefore conservative.

Values of slip coefficient for the joints we've been discussing are shown on the following bar graph. <u>SLIDE 16</u> The lowest value was .32 for B5, the next .39 and the highest .49. The average value was .42 . It should be recalled that B5 had an open pattern.

SLIDE 271-100

In designing a joint against slip many engineers would prefer to stick to shear stress concepts. This can be done by choosing the working stress properly and safely. Let us examine the results of these tests in the light of nominal shear stress at the time of slip. <u>SLIDE 17</u> When we do this we see that the SLIDE 271-101 worst joint slipped at 25 ksi but all the others slipped at better than 30 ksi. Thus, if we set the working shear stress at 15 ksi for a joint where slip must be prevented the minimum factor for the joints illustrated is $\overset{1.67}{\text{(1.7)}}$. If the allowable stress is increased 1/3 for wind to 20 ksi there is still a factor of safety of 1.25. A working shear stress of 15 ksi is a T/S = $\frac{20}{15} = \frac{1}{.75}$ or the T/S that we have been using when we substitute a bolt for a rivet/

Summary

Let us summarize the important findings of this test program:

1. For compact joints that may be permitted to slip into bearing and do not undergo stress reversal a balanced design can be obtained by use of a T/S ratio of 1/1.10 provided threads are excluded from the shearing plane. If a factor of safety against failure of 3 is desired this corresponds to a tensile stress of 20 ksi and bolt shear stress of 22ksi.

2. For joints where slip cannot be tolerated, a T/S ratio or 1/.75 with an allowable bolt stress of 15 ksi should provide an adequate factor of safety. However, it must be borne in mind that design against slip is really a friction problem and success

depends on surface condition and bolt tension. In this regard-

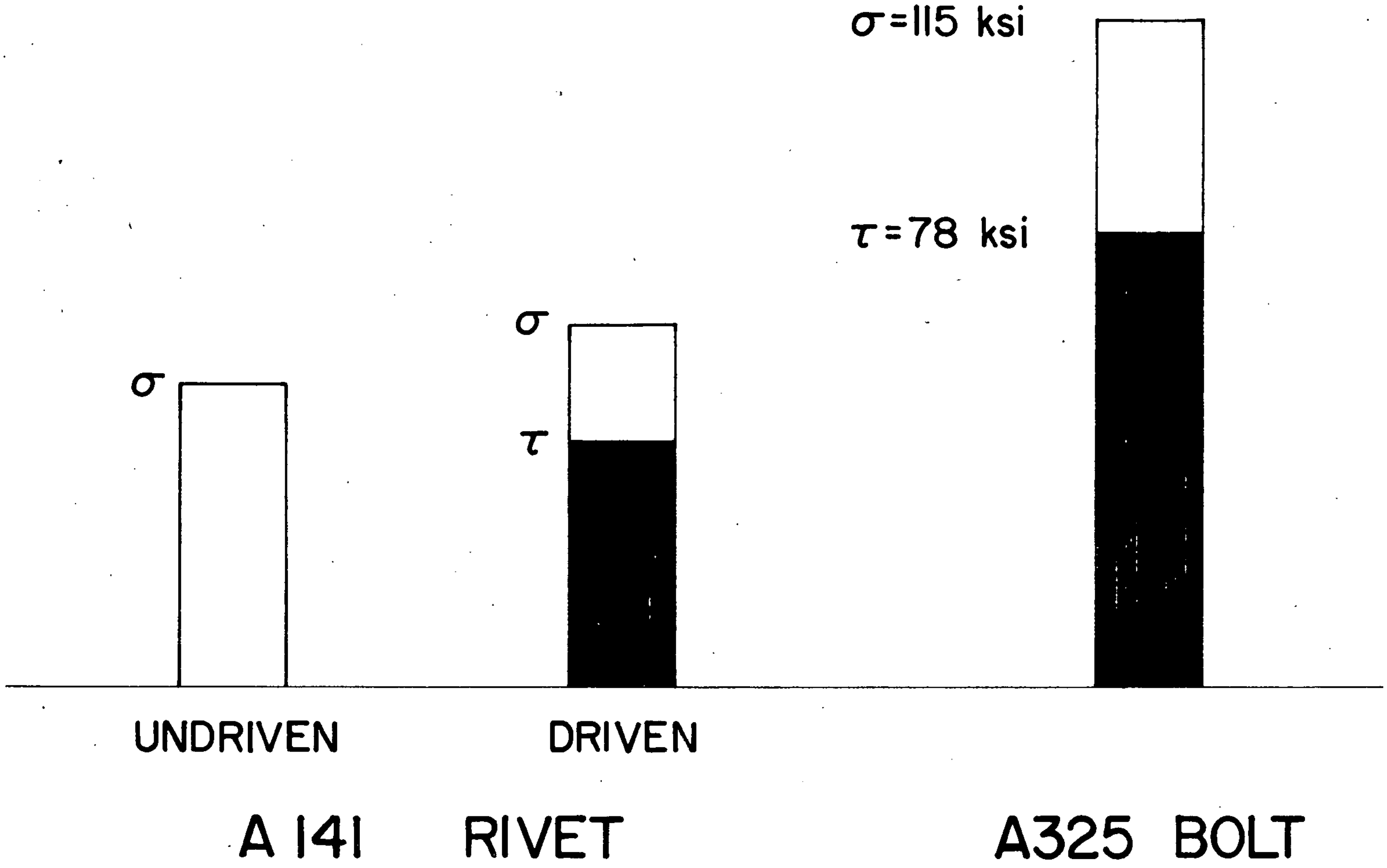
3. These tests show that for a compact, multi-bolted joint with dry, tight mill scale a slip coefficient of .35 is not unreasonable.

4. The "1/2 turn from snug" method of tightening high strength bolts produces bolt tensions which are about 125%- 130% of the proof load of the bolt. Such clamping forces are desirable from the standpoint of slip resistance and are in no way detrimental to the performance of the bolts in a shearing capacity.

5. The "1/2 turn from snug" method utilizes about 90% of the potential bolt tension but there is still a factor of safety of 5 against rupturing the bolt during tightening.

LIST OF SLIDES NOT SHOWN IN THE FOLLOWING

	~~[illegible]~~	F. L. REPORT	
Slide 4	Bolt Tension Histogram	271.1	Fig. 7
5	Efficiency of Turn-Of-Nut	271.7	Fig. 25
7	Photo Failure of B1	271.1	Fig. 14
8	" " " B2	271.1	Fig. 15
9	" " " B3	271.1	Fig. 16
9'	" Broken Bolts from B3	271.1	Fig. 17



SLIDE 1   271.90

AISC Specs

$\sigma_{net} = 20$ ksi

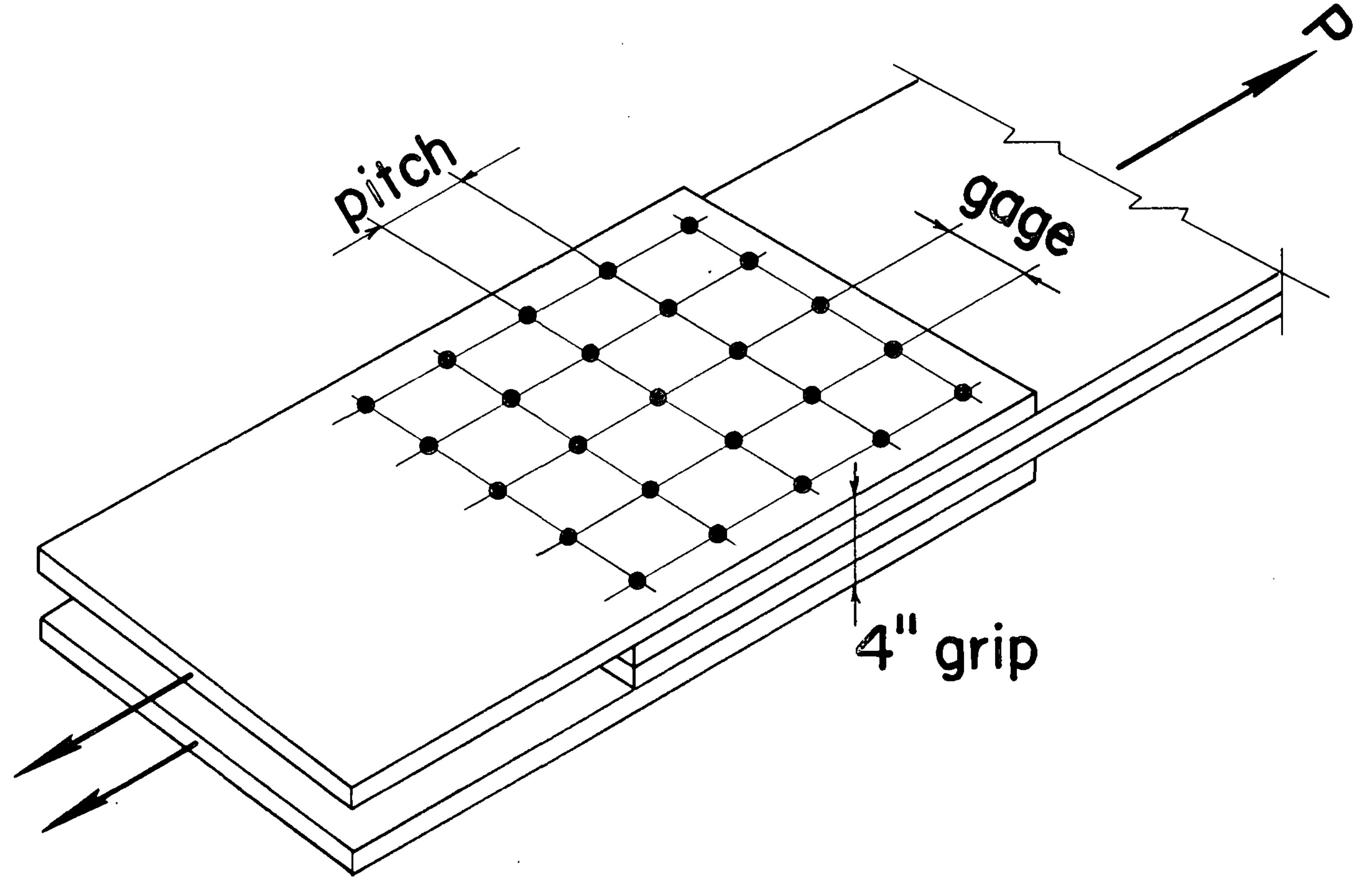
$\tau_{rivet} = 15$ ksi

Factor of Safety = 3

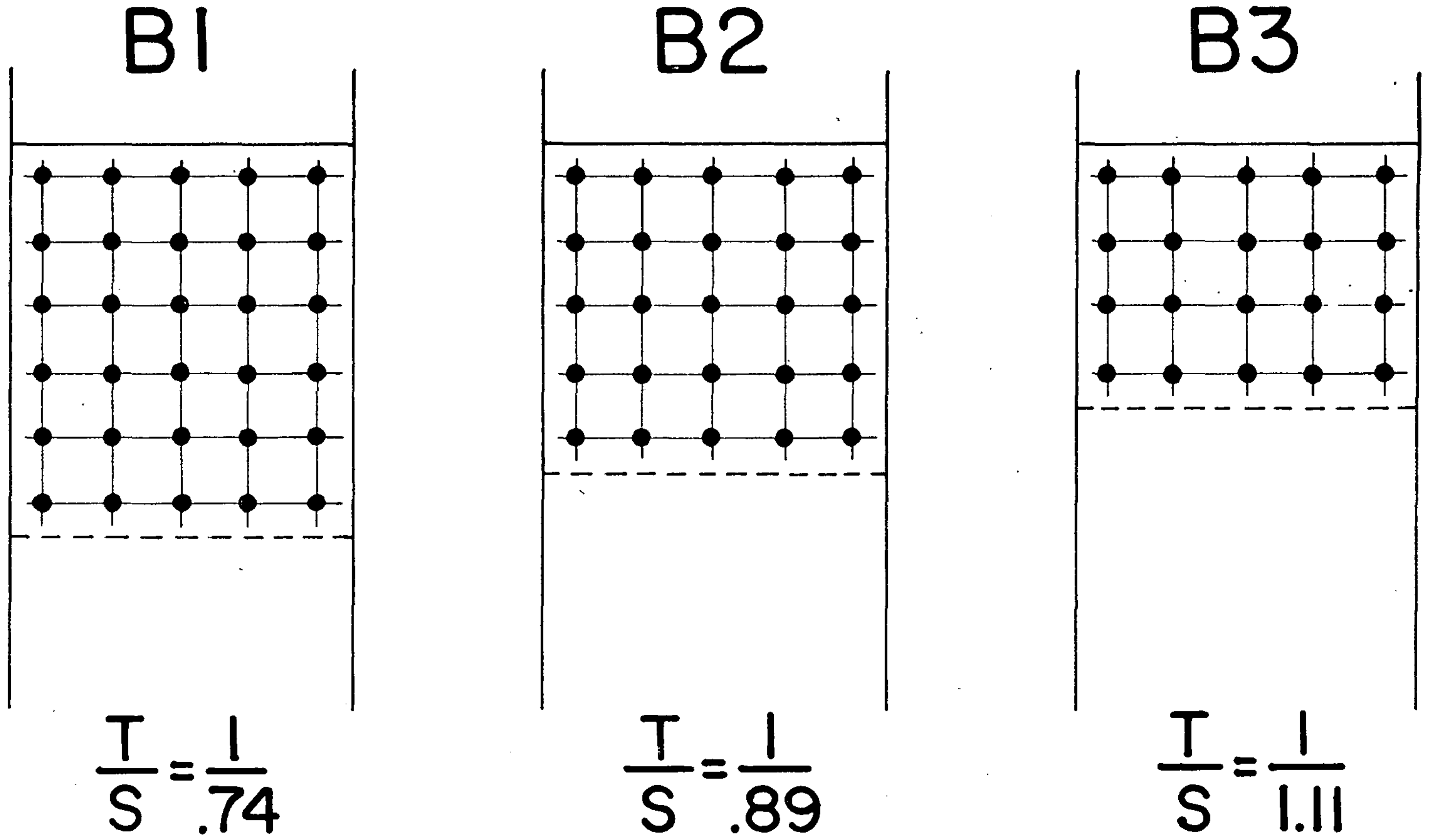
$$\frac{T}{S} = \frac{20}{15} = \frac{1}{.75}$$

$$\frac{T}{S} = \frac{A_s}{A_t}$$

SLIDE 2 271.91



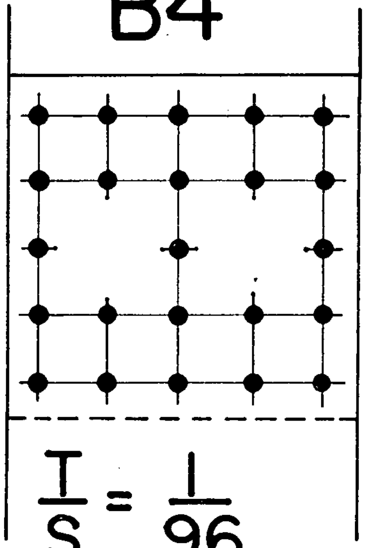
SLIDE 3 271.92



$\frac{T}{S} = \frac{1}{.74}$ $\frac{T}{S} = \frac{1}{.89}$ $\frac{T}{S} = \frac{1}{1.11}$

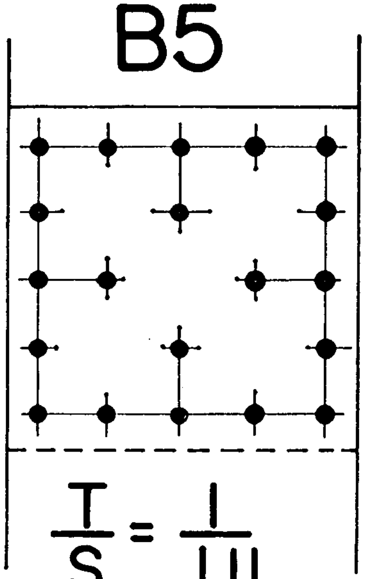
SLIDE 6 271. 93

B4



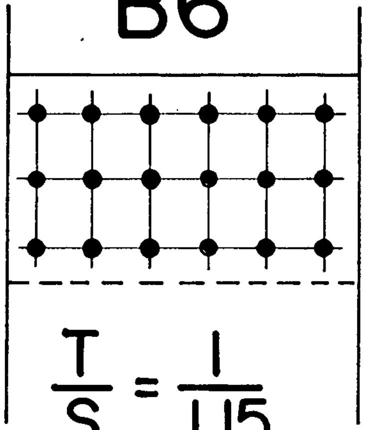
$\frac{T}{S} = \frac{1}{.96}$

B5

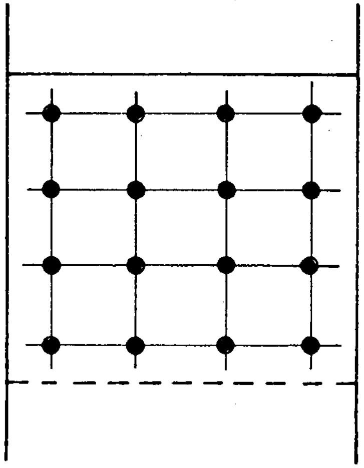


$\frac{T}{S} = \frac{1}{1.11}$

B6

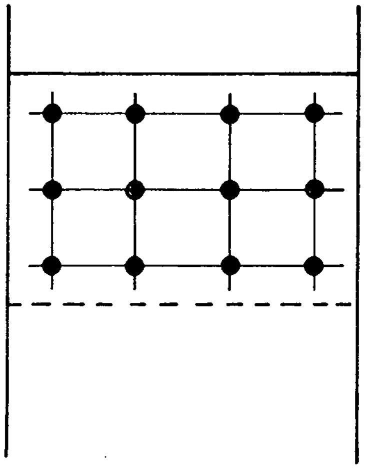


$\frac{T}{S} = \frac{1}{1.15}$



A3

$\frac{T}{S} = \frac{1}{1.10}$



G1

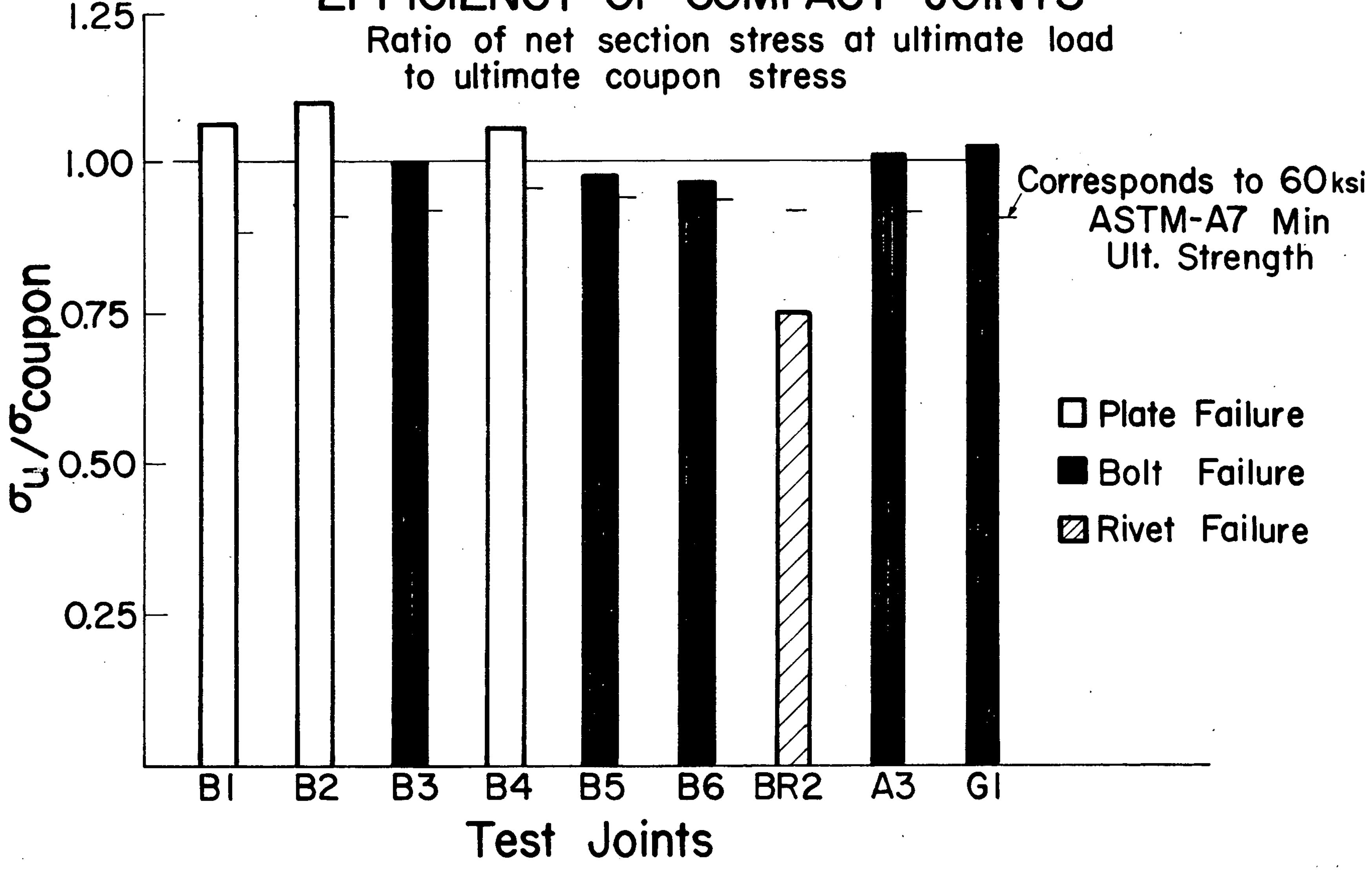
$\frac{T}{S} = \frac{1}{1.11}$

[redacted]

SLIDE 10 271.94

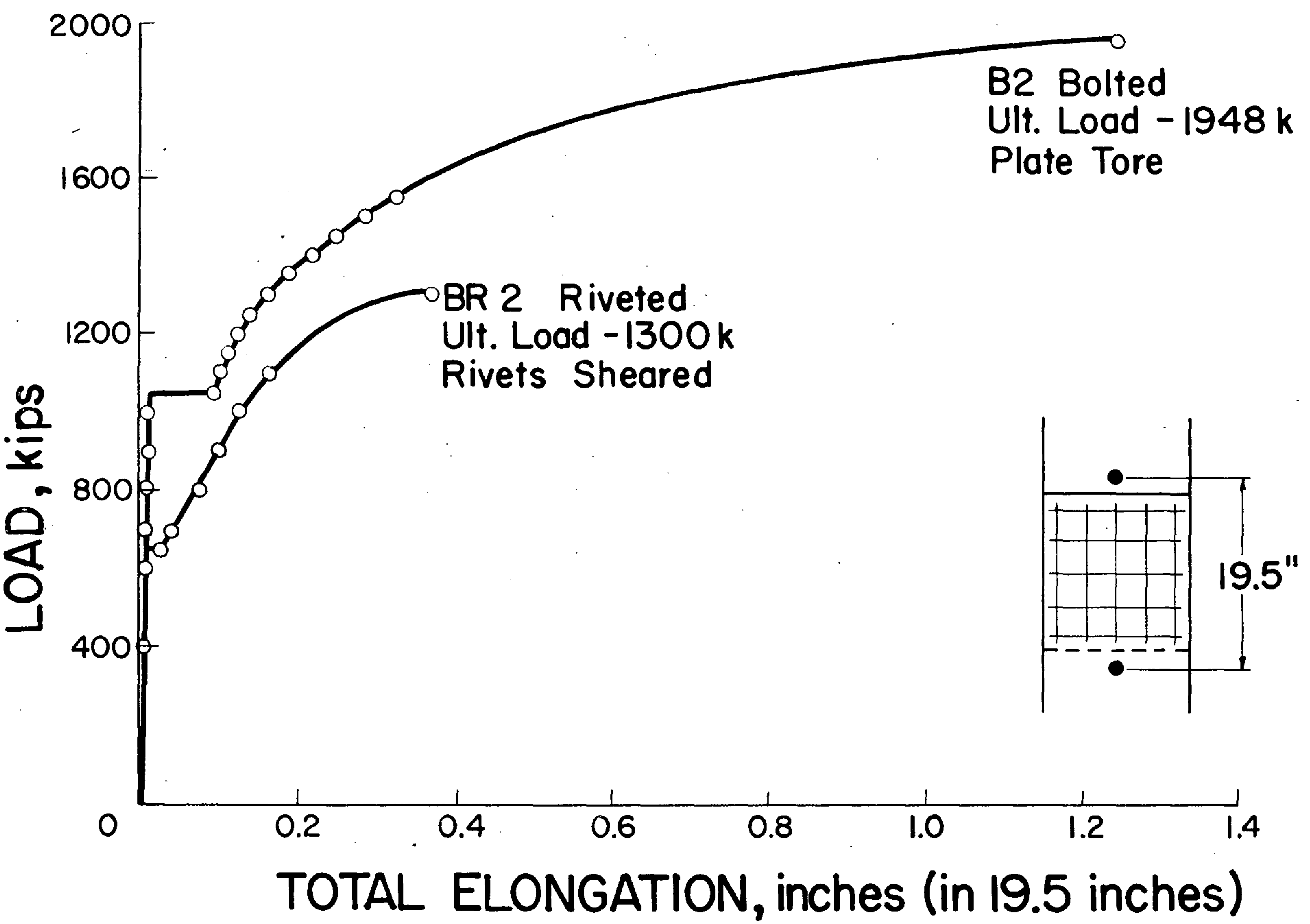
"EFFICIENCY" OF COMPACT JOINTS

Ratio of net section stress at ultimate load to ultimate coupon stress

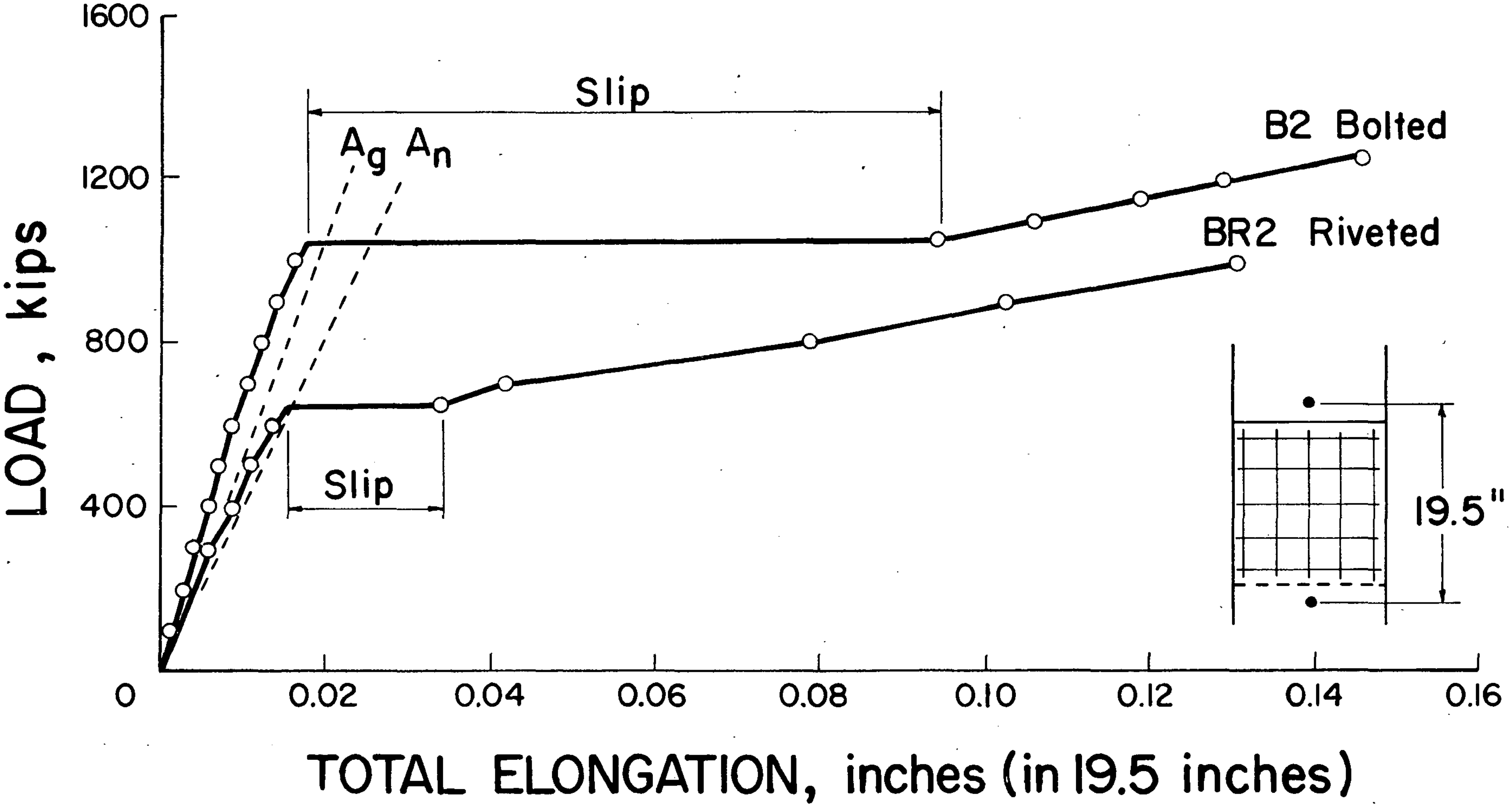


Corresponds to 60ksi ASTM-A7 Min Ult. Strength

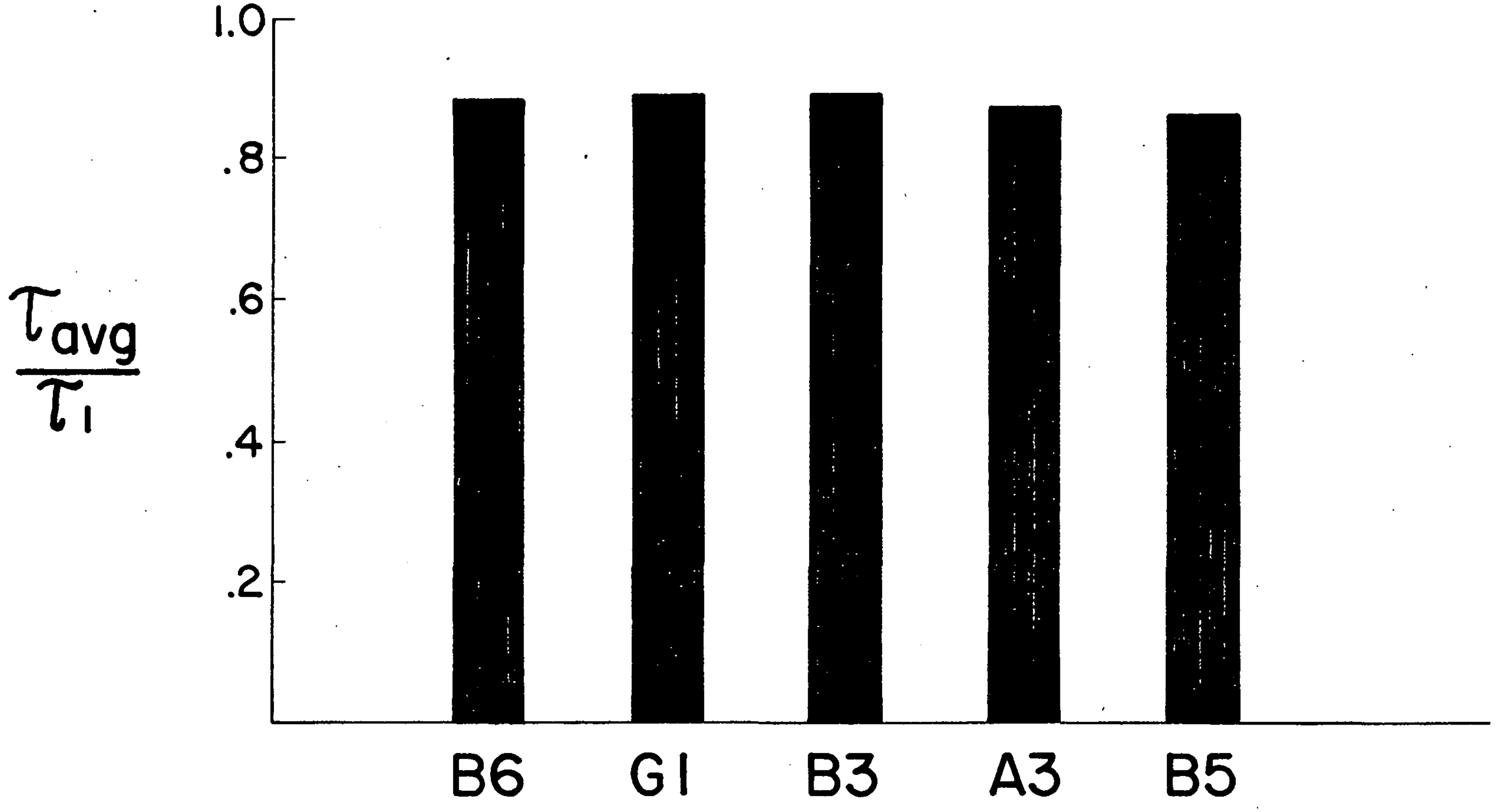
SLIDE 11 271.95



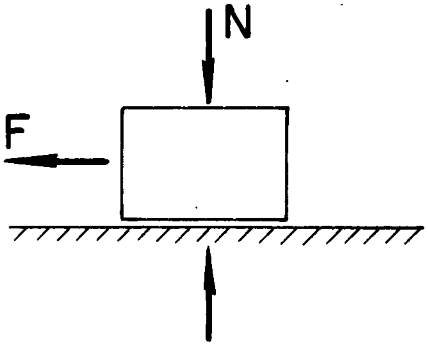
SLIDE 12 271.96



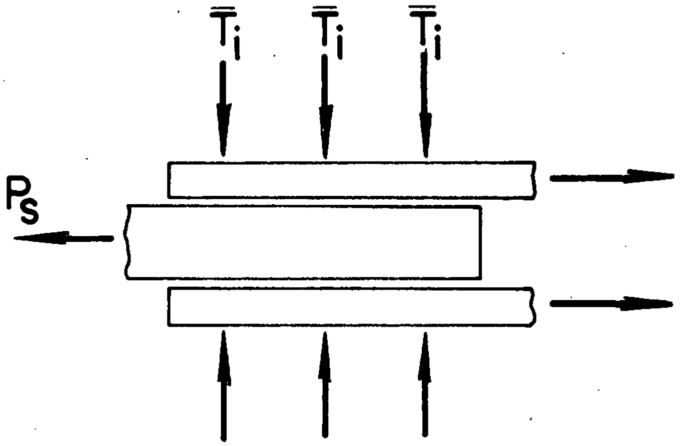
SLIDE 13 271.97



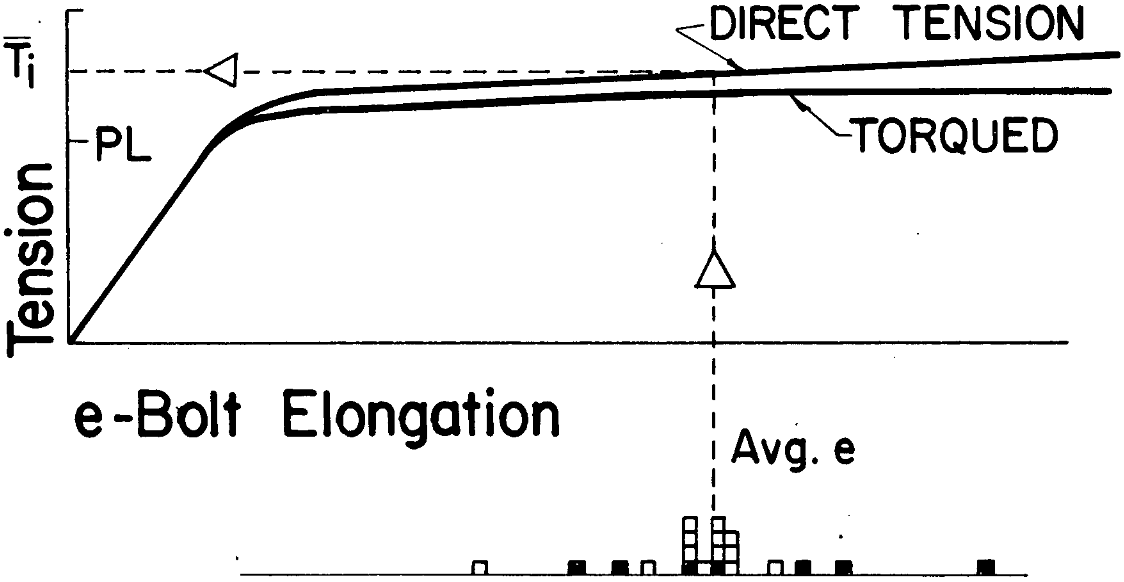
SLIDE 14 271.98



$$\mu = \frac{F}{N}$$

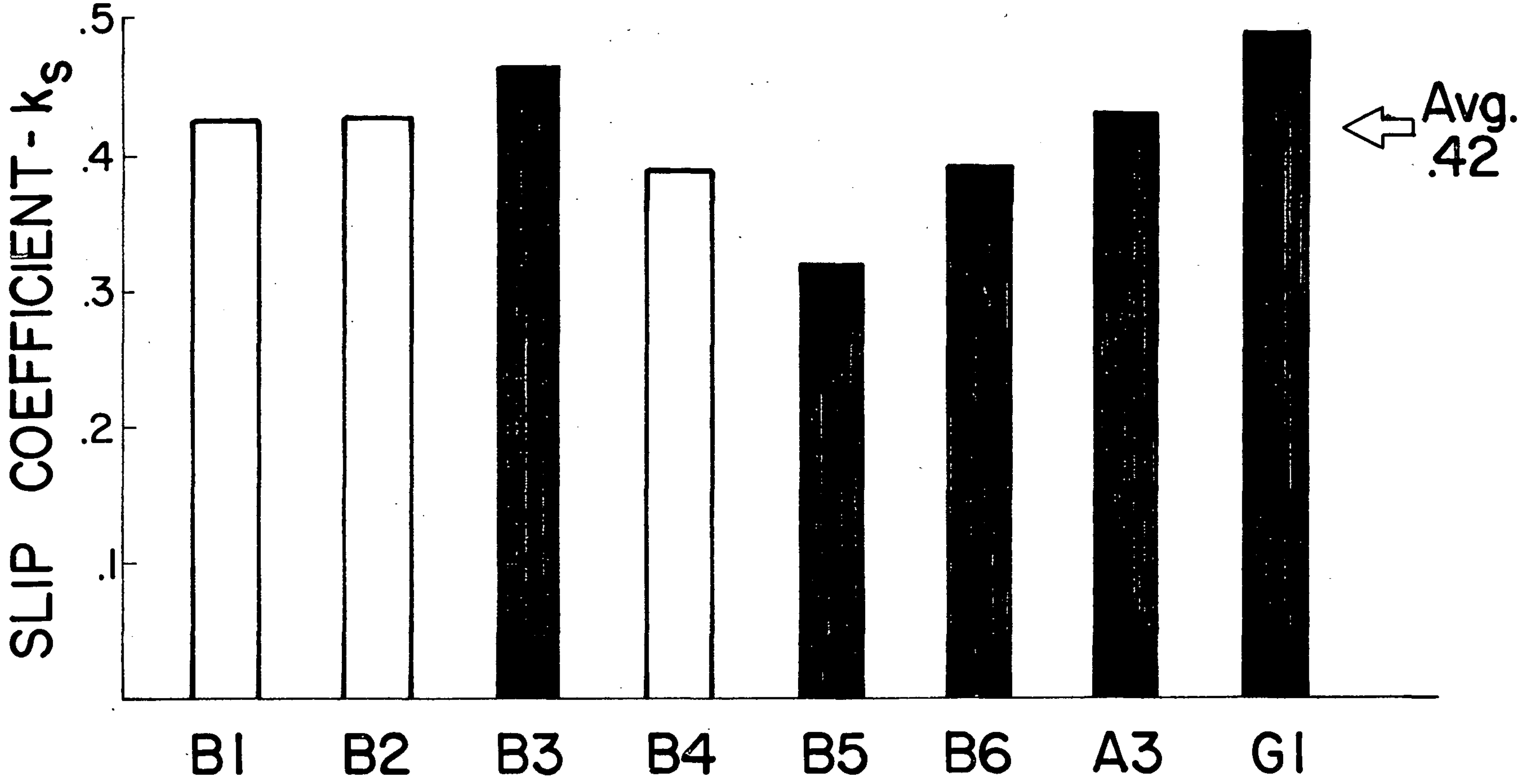


$$k_s = \frac{P_s}{mn\bar{\bar{T}}_i}$$

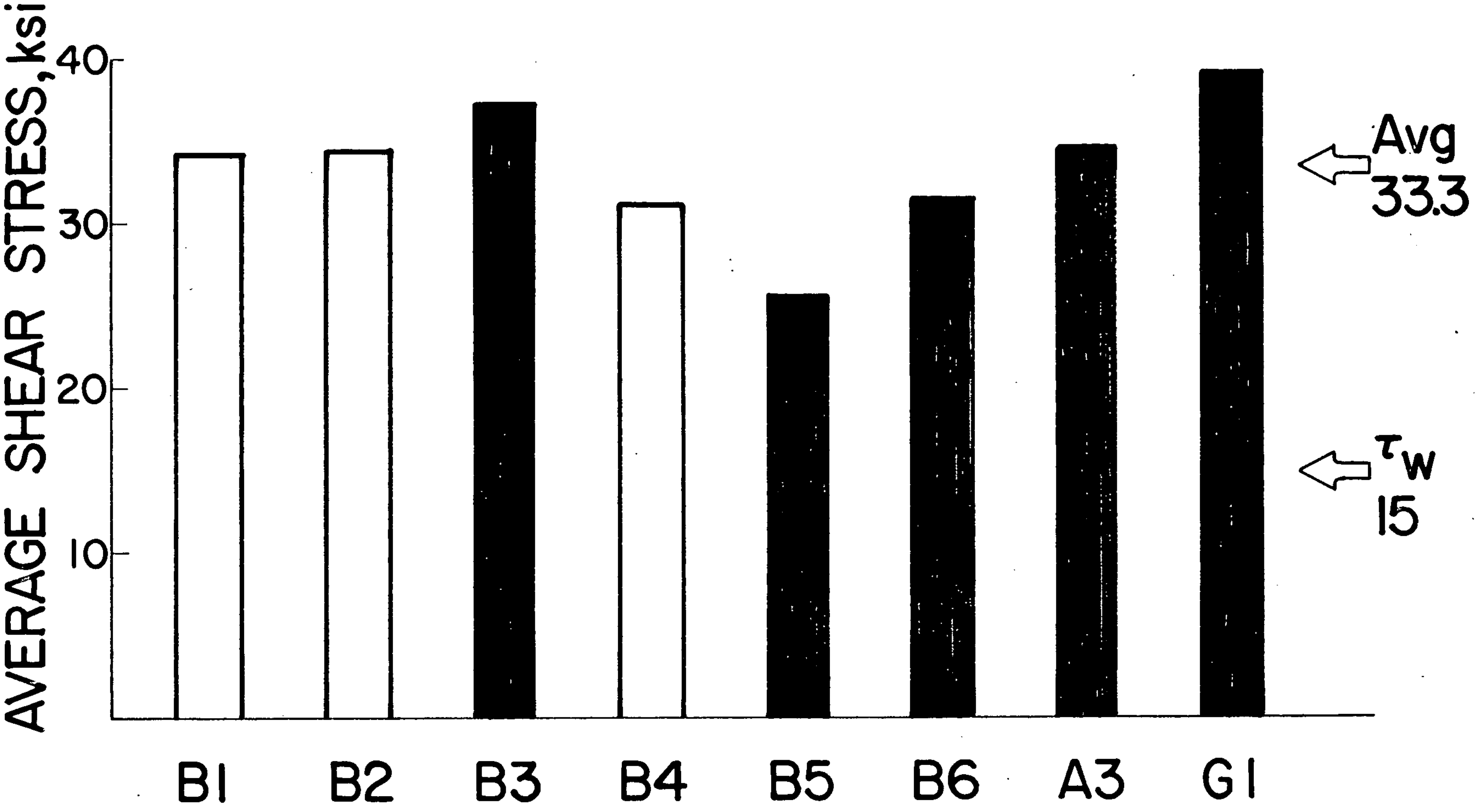


SLIDE 15 271.99

DRY MILL SCALE



SLIDE 16   271.100



SLIDE 17 271.101