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Large Bolted Joints

CRITERIA FOR DESIGNING BOLTED JOINTS (BEARING-TYPE)

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Fritz Engineering Laboratory Report No. 288.7

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Fritz Engineering Laboratory
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Introduction

Early work with riveted joints showed that rivets had an ultimate shear strength which was about 75% of their tensile strength[1]. Since the tensile strength of A141 steel rivets (58 to 62 ksi) was about equal to the ultimate strength of A7 steel plates, it was reasonable that the allowable shear stress should be set at approximately 75% of the allowable tensile stress. This led to a so-called "tension-shear ratio" of 1 to 0.75. The concept of balanced design meant that the ultimate strength of the fasteners in shear should equal the tensile capacity of the net section of the main material.

When the A325 high strength bolt was introduced as a replacement for the A141 steel rivet, direct substitution was made on the basis of one bolt for one rivet[2]. Since the shear strength of the bolt was greater than the rivet, such a bolted joint was no longer in "balance". Therefore, tests were conducted on compact joints to determine the proper ratio of shear area and net tension area for balanced design[3]. It was shown in these studies that the proper tension-shear ratio was

1 to 1.10 for A325 bolts in A7 steel joints. Thus for building specifications, a design to 20 ksi tensile stress in the plate would permit 22 ksi shear stress in the bolts. It implies a factor of safety of 3.0 against ultimate strength of bolts and plate in a compact joint.

Subsequently, tests were conducted on long bolted joints[(4)] which were proportioned using the tension-shear relationship that had been established for the compact joints. These tests showed that the longer joints were not able to effect a complete redistribution of the load because the end fasteners failed prematurely. This failure was not due to any deficiency in the fastener but was due to the accumulated differential strains between the main plate and the lap plates. Since the end fasteners did not have the ability to deform sufficiently to accomodate these differential strains, equalization of load among all bolts could not take place. As would be expected, the average shear stress at the time the first bolt failed decreased with increasing joint length. Figure 1 shows diagrammatically the observed behavior. Clearly a uniform allowable stress of 22 ksi for all such joints does not provide a uniform factor of safety.

Other investigators[5] have tested compact bolted joints of A7 steel, but only in a few cases was the shearing area of the bolts critical. In general, the plate area at the net section was 75% of the shear area of the bolts. In these cases, failure generally occurred by tearing and fracture of the plate. The exception was one joint which had 13 fasteners in line, and in this joint an "unbuttoning" failure was experienced.

The balanced design criterion was also used in recent tests to determine the relative proportions of shear and net areas when A325 bolts connected A440 steel[6]. The tests of long joints of A440 steel showed that the higher yield stress material allowed a better redistribution of load among the fasteners. This resulted because the higher yield stress level of the A440 steel enables the bolts to be reasonably uniformly loaded at the onset of major yielding in the plate. The "balanced design" shear stress for the bolt would be higher than before, so that redistribution commences while the A440 plate material is still elastic and at a relatively lower stress than in the case of A7 steel. As a result, the effect of joint length was not as marked as in the case of A7 steel.

Since balanced design means that the same factor of safety against ultimate is applied both to the bolt and to the plate, it is of interest to examine what happens when the plate strength varies. A summary of this condition is given in the upper portion of the table below for three steels: A7, A440, and constructional alloy steel. Using specification values for both ultimate strength and allowable stress, the factor of safety against ultimate can be determined. It varies considerably because allowable stresses have been based on yield, not on ultimate.

Plate Material	A7	A440 (3/4 to 1-1/2")	Constructional Alloy
Ultimate strength, ksi	60	67	115
Working stress, ksi	20	27.5	60+
F. S. Ultimate	3	2.4	1.9
A325 Bolts			
Ultimate shear strength, ksi	66	66	66
F. S. Ultimate (Plates)	3	2.4	1.9
Hypothetical allowable stress in bolts, ksi	22	27.5	36

Referring to the lower part of the table, if these same factors of safety for the steel plates are applied

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+ Ref. 7 has suggested an allowable basic tensile stress for constructional alloy steel of 54 ksi when used in bridges. The working stress for buildings has been taken as $54 \times \frac{20}{18} = 60$ ksi.

to the ultimate shear strength of A325 bolts, then the resulting "balanced design" working stresses would be obtained. When the A325 bolt is installed in A7 steel, an allowable design stress of 22 ksi is obtained. However, when the bolt is installed in A440 steel, balanced design would yield an allowable shear stress of 27.5 ksi. For constructional alloy steel, it is 36 ksi.

How can one justify a different allowable shear stress in a fastener simply because it is used in a different steel? It is clearly apparent that a different design criteria is needed.

The purpose of this report is to review all pertinent test results and to suggest an alternate design criteria.

Analysis of Tests of Bolted Joints

The tests reported in Refs. 3 to 6 in which bolt failures occurred are summarized in Tables 1 to 6. Further details of the test specimens can be found in the appropriate reference.

Figure 2 shows the influence of joint length on the strength of double lap A7 steel butt joints. A plotted point is the average shear stress at failure for the given length.

Because bolts of several lots and strengths were used, it is convenient to obtain a modified shear strength based on bolts which just meet the minimum strength requirements of the ASTM A325 specification. This was obtained by determining, where possible, the average ratio of the ultimate shear strength of a single fastener to its ultimate tensile strength. For the ten lots of bolts for which these properties were known, this ratio was approximately 0.70. Hence, for minimum strength bolts, the modified shear strength was assumed to be

$$\tau_u = 0.70\ \sigma_{min} \quad \frac{\tau_{av}}{\tau_c}$$

where τ_{av} was taken as the nominal bolt shear stress at failure in the test joints (Tables 1 - 6), the τ_c was the shear strength of a single fastener from the same lot. The minimum tensile strength σ_{min} was taken as 115 ksi for 7/8 and 1-inch bolts and 105 ksi for 1-1/8-inch bolts. The modified shear strength τ_u has been tabulated in Tables 1 - 6. It is the value used in the figures.

The shear strength of a single fastener was not available for the tests reported in Ref. 5. Hence, it was assumed that the bolts used in the joints were minimum strength and τ_u was taken equal to τ_{av}.

Also shown in Fig. 2 is the "average" line representing the observed behavior of A7 butt joints and also the theoretical predictions according to Refs. 6 and 8. The permitted stress of 22 ksi according to the 1962 specification[9] is also shown.

The long A440 steel joints were able to effect a better redistribution of load among the fasteners. This is shown in Figure 3 where the test points are plotted on the same basis as before. The "Test Average" for the A7 joints is shown for comparison. As noted earlier the reason for this improved performance is that the joint fabricated of the stronger steel has a greater "stiffness" when compared with the A325 fastener. Theoretical calculations have borne this out as shown in Figure 3.

An examination of the material properties of constructional alloy steel indicates that the behavior of such joints fastened with A325 bolts would be similar to that of A440 steel joints. Conceivably there could be even better redistribution of shear stress in the fasteners.

The results of tests of A7 steel lap joints are shown in Fig. 4 in comparison with similar butt joints. Where the tension-shear ratio was the same (joint L10), the performance was the same. An explanation for the improved performance of L7 is the fact that there was more plate area than required for balanced design (T:S = 1:1.57). This resulted in better redistribution among the fasteners because of the increased rigidity in the plate at the time the bolts were starting to yield. Increasing allowable stresses in the fasteners tends to do just this. It also tends to make the joint shorter, and thus stronger. Since joint L2 had only two fasteners in line, no redistribution was involved, and the joint attained the average strength associated with the shear failure of a single fastener.

This same increase in the average shear strength at failure was noted in the tests of A440 steel joints. As the plate area increased from 95 to 110% of the bolt shear area, the bolt shear stress increased from 78.4 to 81.3 ksi (Table 5).

Joints which are unbalanced in the opposite sense invariably fail by tearing of the plate. As a result, there is no way to determine the actual shear strength of the fasteners except for the longer joints where the unbuttoning phenomenon is also experienced as was the case with joint 153X[5]. The accumulated differential strains between the main plate and lap plate caused a bolt failure before the plate could tear.

Design Criteria

The examination up to this point has shown that

(1) the concept of balanced design (simultaneous attainment of shear and tensile ultimate) leads to inconsistent allowable bolt stresses for different plate materials,

(2) the A325 bolt behaves similarly under shear in a compact joint regardless of the type of connected material, and

(3) the balanced design concept has no meaning in long joints (especially A7 steel joints) because the bolts unbutton before the plate material can attain its full strength.

Thus a new approach is needed, one that will provide a consistent method of determining allowable stresses and will provide a rational factor of safety.

It appears that a more logical criterion would be to establish working stresses for the A325 bolt based on a uniform factor of safety against shear failure of the bolt in the joint. In long A7 steel joints, the working stress would be reduced to conform to this uniform factor of safety. For compact joints, the working stress in the bolt would not be affected by the mere fact that a different steel was being used.

This criterion is currently used in assigning allowable tensile stresses for plate material(10). As can be seen in the following table, the factor of safety against yielding is maintained constant; consequently, the factor of safety against ultimate failure changes. Whether or not the ultimate strength of the plate material is developed is not relevant, because tension members are generally considered to "fail" when they reach the yield point and unrestricted plastic flow occurs. This, indeed, is the limit of usefulness - not the fracture strength.

Plate Material	A7	A440 (3/4 to 1-1/2")	Constructional Alloy
Ultimate strength, ksi	60	67	115
Yield point, ksi	33	46	100
Allowable stress, ksi	20	27.5	60
F. S. (yield)	1.67	1.67	1.67
F. S. (ultimate)	3	2.4	1.9

If a similar philosophy were adopted for the factor of safety against shear failure in the A325 bolt, a more ordered criterion would be established.

The first question is the selection of the proper factor of safety. If one looks at past practice for both riveted and bolted joints, the factor of safety is found to vary from approximately 3.3 for compact joints to about 2.1 for joints 50 inches long [1][4]. The lower factor of safety for the longer joints has apparently been adequate in the past. In fact, according to past practice, the largest and most important joints probably have been designed with the lowest factor of safety. Even so, this factor of safety has given a considerably larger margin against failure in the bolt as compared to yielding in the connected material, and this is desirable.

The second question relates to the "law" or "rule" that theoretically would provide a uniform factor of safety. Such an allowable shear stress line is shown in Fig. 5 as line ABC. The equation of this line is:

$$F_v = 34 - 0.23L$$

where F_v is the allowable shear stress and L is the length of the joint. It provides a factor of safety of 2.2 throughout, with

22 ksi permitted for joints 50 inches long and 33 ksi permitted for the shortest joints (2 bolts in a line). For A440 steel joints more than about 26 inches in length, the "rule" would be 28 ksi (line BE) to give a factor of 2.2

Now in order to simplify design practice, it would probably be advantageous to use a constant stress for a range of joint length. A suggestion is illustrated in Fig. 5 by the dashed lines (DBE and FC):

(a) For A7 joints up to 26 inches in length and for all A440 joints use F_v = 28 ksi. (line DBE).

(b) For long A7 joints (length greater than 26 inches) use F_v = 22 ksi. (line FC).

The option should remain to permit use of line ABC whenever desirable. Naturally, there are other possibilities for approximating line ABC for short joints (such as using 30 ksi for joints up to 18 inches in length). But this is left for later discussion and adjustment.

Summary

The philosophy of balanced design of joints used in the past leads to inconsistent allowable bolt stresses for different plate materials. This criterion requires the bolts to "develop" the ultimate strength of the net section of the member. Since the ratio of the yield point to ultimate strength changes for different steels, this criterion would result in different factors of safety for the same bolt.

The average shear stress at failure for A325 bolts is similar when installed in compact joints of A7 or A440 steel. With increasing joint length, A7 steel joints were adversely affected and showed a greater decrease in the bolt shear strength than the A440 steel joints. For long joints, the concept of balanced design has no meaning.

A more logical criterion for design would result if the factor of safety was fixed against the shear strength of the fastener. This would result in a safe and economical procedure for joints connected with A325 high strength bolts.

Because connections are the most important links in structures, the factor of safety against shear failure should be larger than the factor of safety against unrestricted plastic flow in the main members. It is suggested that a factor of safety of 2.2 against shear failure in the bolt be used. For compact A7 and A440 steel joints, the resulting allowable shear stress for the A325 bolt would be 28 ksi (see Fig. 5). Because the effect of joint length is particularly important in A7 steel joints, the allowable shear stress would be reduced to 22 ksi when the joint length exceeded 26 inches.

More precise approximations to a uniform factor of safety may be used when the conditions warrant.

There are certain limitations, some of which have already been implied. Tests have not been made on the constructional alloy steel joints nor on joints fastened with A354 BD bolts; however, such tests will be made shortly. Tests have not been performed on compact A7 joints designed for the higher stresses, but it seems clear that actual joint strength under test would be better because the joints would be shorter.

Also, no data is available for joints longer than

52.5 inches (16 fasteners in line). A325 bolts in A440 steel appear to "level off" at about 62 ksi, but this is not true for A7 steel. Perhaps an allowable stress less than 22 ksi is needed for such joints.

These suggestions are based on studies of A7 and A440 steel plates joined with A325 high strength bolts in bearing-type connections. Although there will be different numbers for other materials, (constructional alloy and A440 steels connected with A354 BD bolts), it seems clear that the same philosophy is applicable. Eventually then, the terms "balanced design" and "tension-shear ratio" would disappear from use. Fasteners would be proportioned on the basis of allowable shear stresses based on a rational factor of safety that is uniform for the particular application.

TABLE 1: RESULTS OF TESTS REPORTED IN REF. 3.

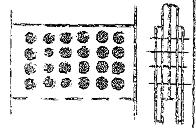
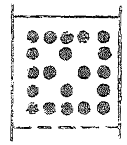
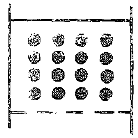
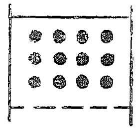
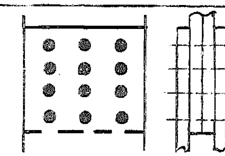
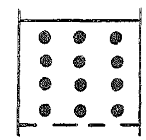
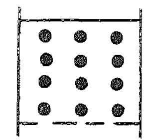
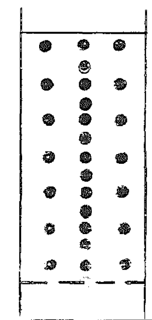
JOINT	BOLTS			PLATE		T:S	Type of Failure	Ultimate load, kips	Avg. Ult. Shear Stress τ_{av}, ksi	Modified Shear Strength τ_u, ksi	Description
	No. in Line	Size in.	Shear Area in.^{2}	Gross Area in.^{2}	Net Area in.^{2}						
B3	4	7/8	24.0	36.0	26.6	1:1.11	All bolts sheared	1750	72.9	72.4	
B5	5	7/8	24.0	36.0	26.6	1:1.11	One bolt sheared	1680	70.0	69.2	
B6	3	7/8	21.6	36.0	24.8	1:1.15	One bolt sheared	1550	71.8	70.8	
A3	4	1	25.1	36.0	27.5	1:1.10	All bolts sheared	1820	72.5	65.2	
G1	3	1-1/8	23.9	36.0	26.5	1:1.11	All bolts sheared	1798	75.2	66.2	

TABLE 2: RESULTS OF TESTS REPORTED IN REF. 5.

JOINT	BOLTS			PLATE		T:S	Type of Failure	Ultimate load, kips	Avg. Ult. Shear Stress τ_{av}, ksi	Modified Shear Strength τ_u, ksi	Description
	No. in Line	Size in.	Shear Area in.^{2}	Gross Area in.^{2}	Net Area in.^{2}						
P19	4	3/4	9.0*	12.4	10.6	1:1.17	All bolts sheared	664	73.9	73.9	
P20	4	3/4	9.0*	12.4	10.6	1:1.17	All bolts sheared	648	72.1	72.1	
P30	4	3/4	9.0*	12.4	10.6	1:1.17	All bolts sheared	640	71.2	71.2	
153X	13+	1	42.4	43.5	33.9	1:0.80	One bolt sheared	2260	53.3	53.3	

* Bolts had threads in one shear plane.

+ Center line only, outside lines contained 7 bolts.

TABLE 3: RESULTS OF TESTS REPORTED IN REF. 4.

JOINT	BOLTS			PLATE		T:S	Type of Failure	Ultimate load, kips	Avg. Ult. Shear Stress τ_{av}, ksi	Modified Shear Strength τ_u, ksi	Description
	No. in Line	Size in.	Shear Area in.^{2}	Gross Area in.^{2}	Net Area in.^{2}						
D71	7	7/8	16.8	21.86	18.18	1:1.10	All bolts sheared	1126	66.9	61.2	
D81	8	7/8	19.2	24.74	21.00	1:1.10	One bolt sheared	1286	66.7	60.4	
D91	9	7/8	21.6	27.46	23.72	1:1.10	One bolt sheared	1358	62.8	57.2	
D101	10	7/8	24.0	29.77	26.05	1:1.10	One bolt sheared	1506	62.6	57.2	
D701	7	7/8	16.8	23.77	19.25	1:1.13	Two bolts sheared	1213	72.1	62.0	
D801	8	7/8	19.2	26.00	21.06	1:1.09	One bolt sheared	1313	68.3	58.8	
D901	9	7/8	21.6	30.02	24.32	1:1.11	One bolt sheared	1497	69.2	59.6	
D1001	10	7/8	24.0	33.10	26.81	1:1.12	Two bolts sheared	1667	69.3	59.6	
D10	10	7/8	24.0	33.71	26.24	1:1.10	One bolt sheared	1544	64.2	57.2	
D13A	13	7/8	31.3	41.67	34.20	1:1.10	One bolt sheared	1988	63.6	56.4	
D13	13	7/8	31.3	41.68	34.21	1:1.10	One bolt sheared	1854	59.3	52.3	
D16	16	7/8	38.5	49.40	41.93	1:1.10	One bolt sheared	2085	54.2	48.3	

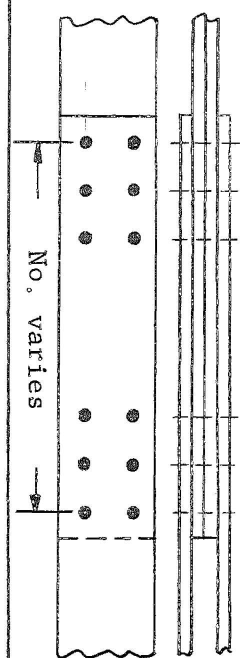


TABLE 4: RESULTS OF TESTS REPORTED IN REF. 4.

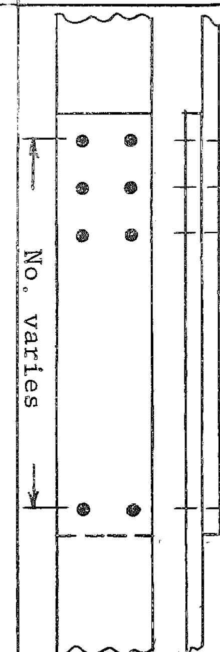
JOINT	BOLTS			PLATE		T:S	Type of Failure	Ultimate load, kips	Avg. Ult. Shear Stress τ_{av}, ksi	Modified Shear Strength τ_u, ksi	Description
	No. in Line	Size in.	Shear Area in.^{2}	Gross Area in.^{2}	Net Area in.^{2}						
L2	2	7/8	2.40	5.76	3.88	1:1.65	All bolts sheared	197	82.1	78.9	
L5	5	7/8	6.01	9.63	7.75	1:1.32	One bolt sheared	446	74.2	71.6	
L7	7	7/8	8.41	14.92	13.04	1:1.57	All bolts sheared	640	76.1	73.3	
L10	10	7/8	12.02	14.90	13.02	1:1.10	One bolt sheared	748	62.2	60.4	

TABLE 5: RESULTS OF TESTS REPORTED IN REF. 6.

JOINT	BOLTS No. in Line	BOLTS Size in.	BOLTS Shear Area in.^{2}	PLATE Gross Area in.^{2}	PLATE Net Area in.^{2}	T:S	Type of Failure	Ultimate load, kips	Avg. Ult. Shear Stress τ_{av}, ksi	Modified Shear Strength τ_u, ksi	Description
E41b	4	7/8	9.62	12.87	9.11	1:0.95	All bolts sheared	754	78.4	70.8	
E41c	4	7/8	9.62	13.25	9.49	1:1.00	All bolts sheared	770	80.1	72.5	
E41e	4	7/8	9.62	14.43	10.65	1:1.10	All bolts sheared	782	81.3	74.1	
E41f	4	7/8	9.62	13.34	9.58	1:1.00	All bolts sheared	727	75.6	70.8	
E41g	4	7/8	9.62	13.43	9.66	1:1.00	All bolts sheared	767	79.8	75.7	
E41	4	7/8	9.62	13.49	9.70	1:1.00	All bolts sheared	728	75.7	70.8	
E71	7	7/8	16.83	20.56	16.81	1:1.00	One bolt sheared	1188	70.6	66.0	
E101	10	7/8	24.04	27.79	24.04	1:1.00	One bolt sheared	1610	67.0	62.8	
E131	13	7/8	31.25	38.53	31.06	1:1.00	One bolt sheared	2125	68.0	63.6	
E161	16	7/8	38.46	45.70	38.23	1:1.00	One bolt sheared	2545	66.2	62.0	

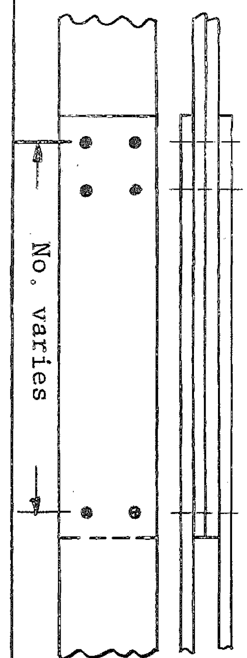
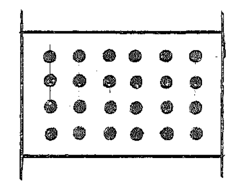
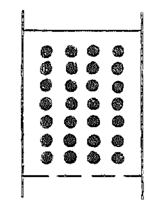


TABLE 6: RESULTS OF TESTS REPORTED IN REF. 6.

JOINT	BOLTS			PLATE		T:S	Type of Failure	Ultimate load, kips	Avg. Ult. Shear Stress τ_{av}, ksi	Modified Shear Strength τ_u, ksi	Description
	No. in Line	Size in.	Shear Area in.^{2}	Gross Area in.^{2}	Net Area in.^{2}						
E46	4	7/8	28.9	40.6	29.2	1:1.00	All bolts sheared	2180	75.6	70.8	
E74	7	7/8	33.7	41.0	33.5	1:1.00	One bolt sheared	2410	71.6	66.8	
E741	7	7/8	33.7	41.2	33.7	1:1.00	One bolt sheared	2250	66.9	62.8	

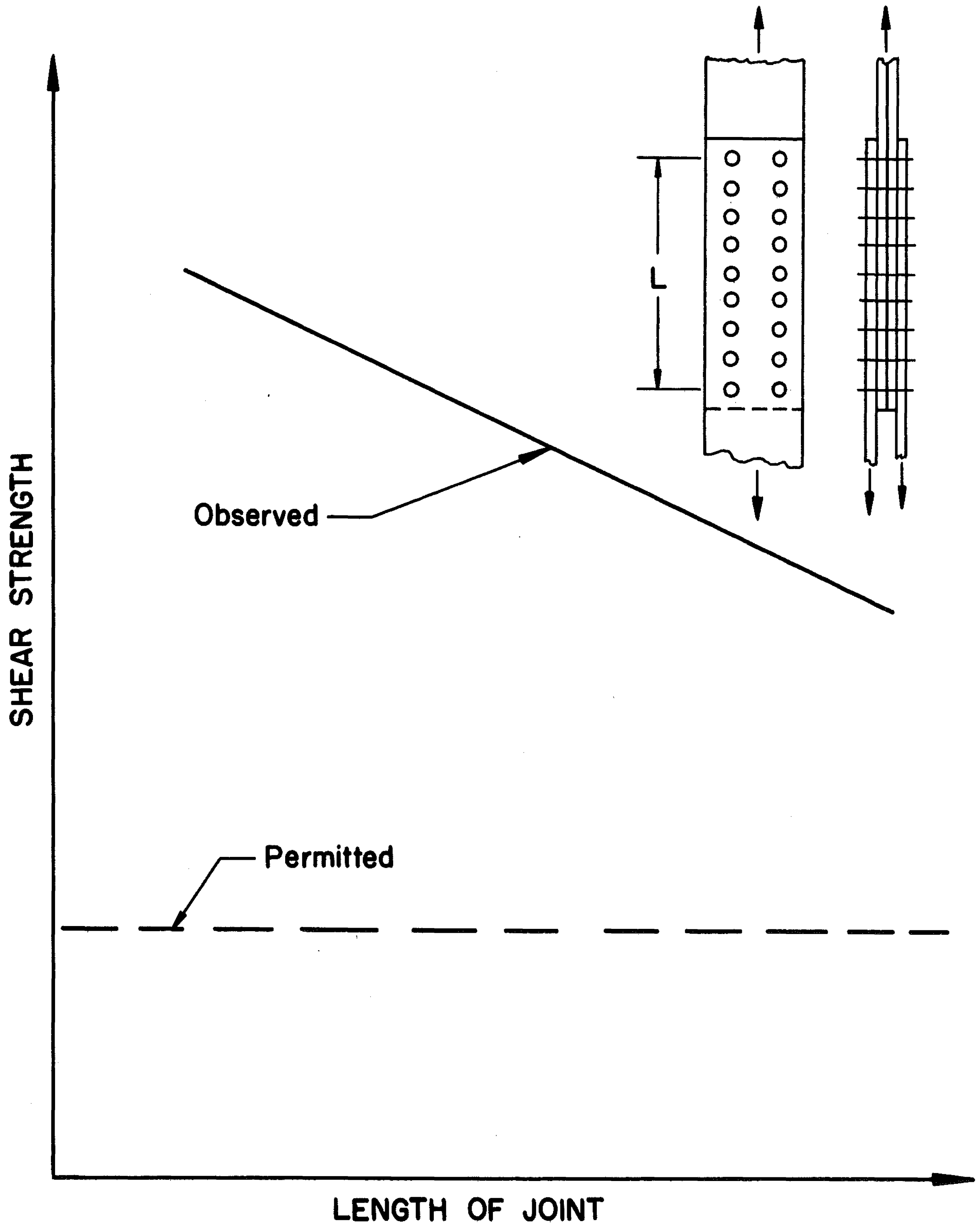


FIG. I EFFECT OF LENGTH ON BOLT SHEAR STRENGTH

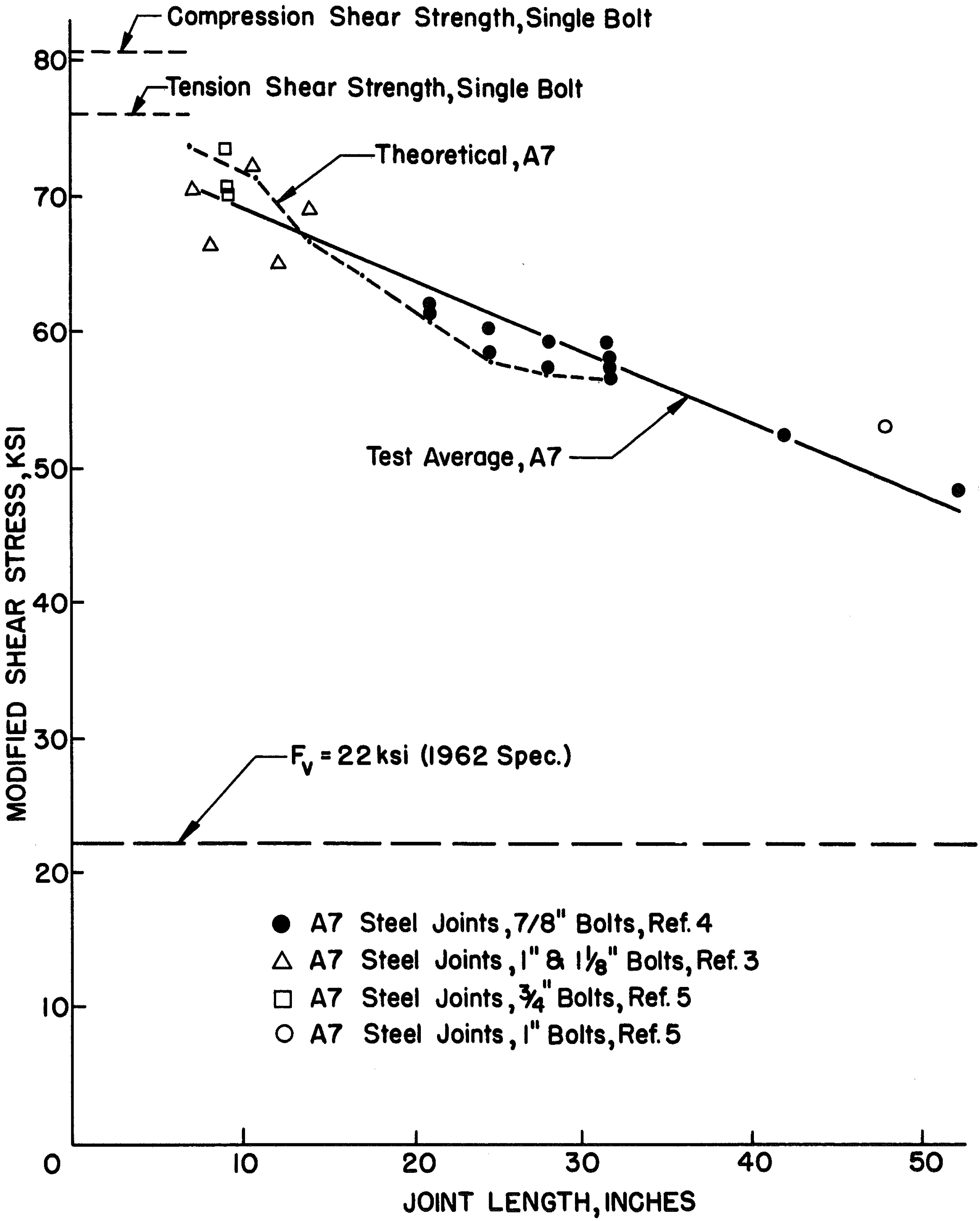


FIG. 2 TESTS OF A7 STEEL BUTT JOINTS

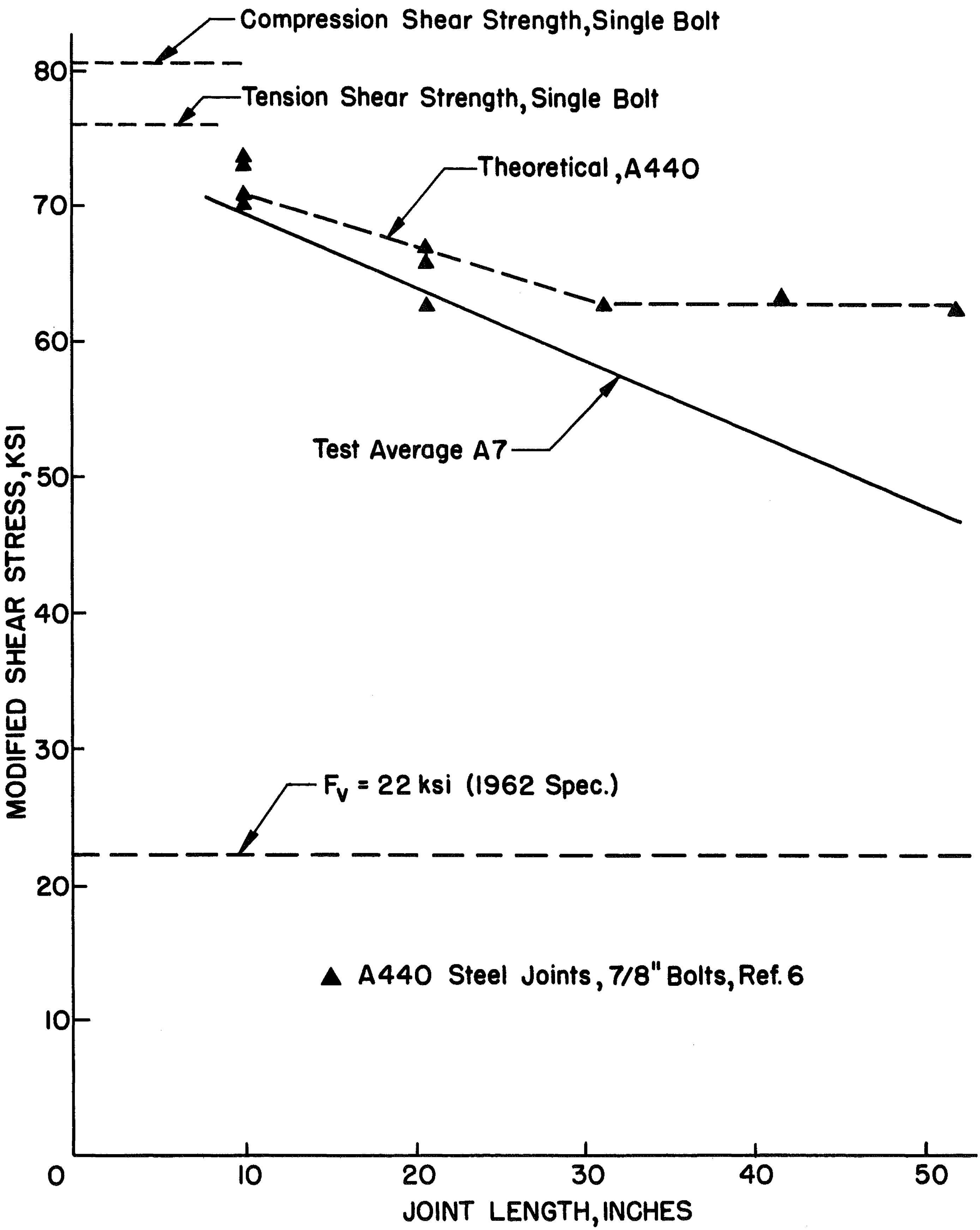


FIG. 3 TESTS OF A440 STEEL BUTT JOINTS

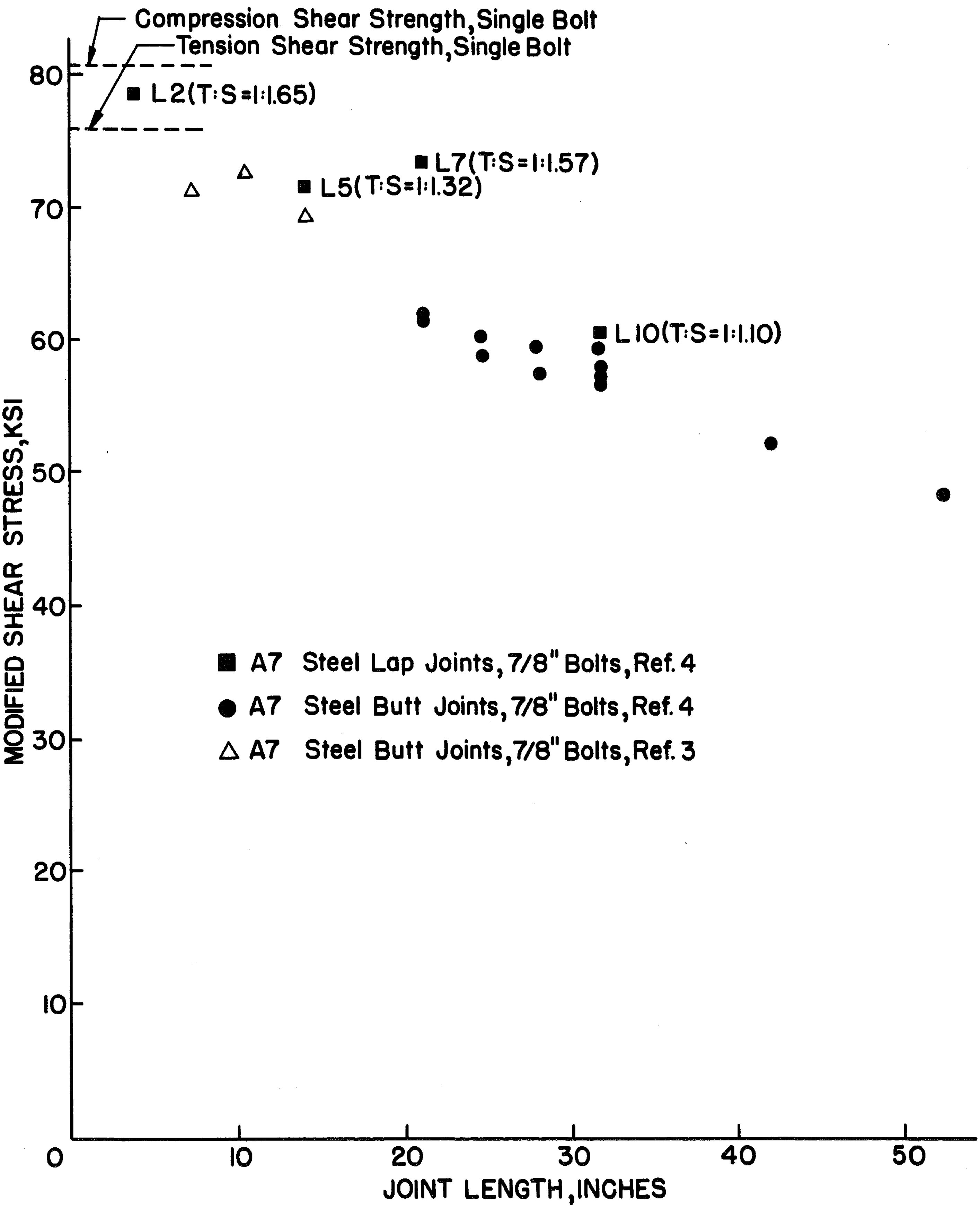


FIG. 4 PERFORMANCE OF BOLTED LAP JOINTS

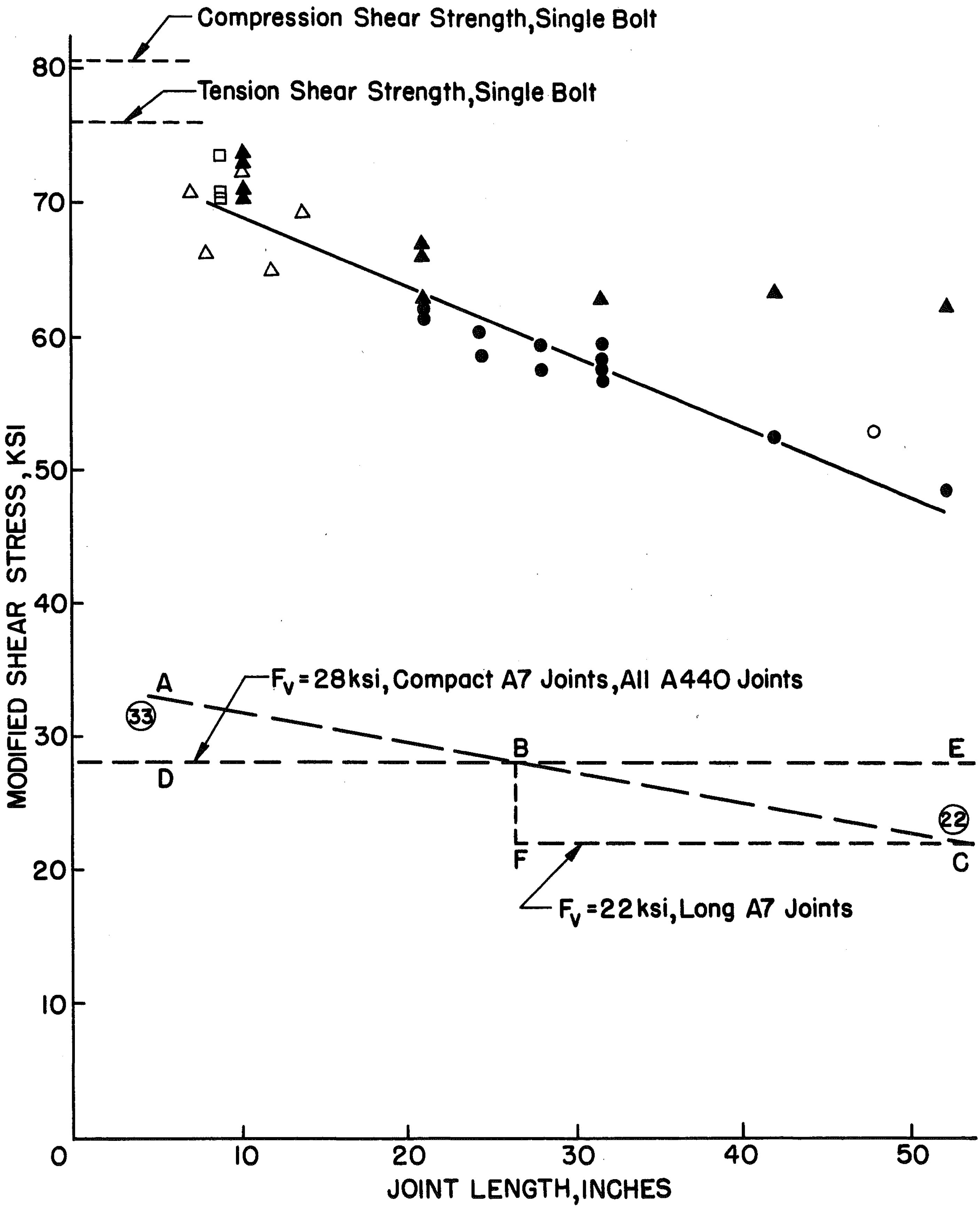


FIG. 5 COMPARISON OF ULTIMATE AND SUGGESTED WORKING STRESSES

[illegible]

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