EDGE DISTANCE, SPACING, AND BEARING IN BOLTED CONNECTIONS

By

Brian E. Lewis
and
Farrel J. Zwerneman

Prepared as part of an investigation
conducted by the
School of Civil and Environmental Engineering
Oklahoma State University
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EXECUTIVE SUMMARY

Tests were conducted to determine the effect of edge distance on bearing capacity in a bolted connection. More specifically, these tests were conducted to determine whether or not a discontinuous increase in bearing capacity occurs when end distance reaches one and one-half times the diameter of the bolt in the connection. Such a discontinuity exists in design specifications published by the American Institute of Steel Construction and the Research Council on Structural Connections.

All specimens used in these tests were fabricated from hot rolled flat bars of ASTM A36 steel. Bar thicknesses tested were 1/4 in., 1/2 in., and 3/4 in. Bolts used in the tests were either ASTM A325 or A490. Bolt diameters tested were 5/8 in., 3/4 in., and 1 in. Specimens were built as lap splices with untensioned bolts loaded in double shear. Both one- and two-bolt connections were tested.

Research results demonstrate that a discontinuous increase in bearing capacity does not occur when end distance reaches one and one-half times the diameter of the bolt in the connection. Bearing strength for the end bolt in a connection is shown to be conservatively predicted using a method recently proposed by K. H. Frank and J. A. Yura.

Although bolt spacing was not the focus of this research, results of the two-bolt tests indicate that a spacing of three times the diameter of the bolt in the connection is not adequate to develop full bearing strength in bolts away from the end. Further work is needed to define the conditions causing this reduction in bearing strength, and to determine if changes in the specifications are necessary.

ACKNOWLEDGMENTS

The investigation reported here was conducted as a project of Engineering Research at Oklahoma State University in the School of Civil and Environmental Engineering under partial sponsorship by the American Institute of Steel Construction. The authors wish to thank Mr. Nestor Iwankiw of the American Institute of Steel Construction for his assistance in obtaining financial support and for his suggestions regarding the test variables. The authors also wish to thank W&W Steel of Oklahoma City for donation of materials used in fabricating test specimens.

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NOMENCLATURE

A_b = nominal cross-sectional area of a bolt, in.^{2}

d_b = diameter of a bolt, in.

F_b = bearing strength of the connected plate, ksi

F_u = ultimate strength of the connected plate, ksi

F_y = yield strength on the connected plate, ksi

L_c = clear distance between the edge of the hole and edge of the adjacent hole or t connected part parallel to the applied force, in.

L_e = distance from the end of the connected part to the center of the hole, in.

P_s = force that a single connector exerts on the connected part, kips

$P_{1/4}$ = force required to elongate the bolt hole 1/4 in., kips

R_n = nominal bearing force, kips

t_p = thickness of the connected plate, in.

$2.4d_bt_pF_u$ = full bearing capacity for a single-bolt connection per AISC/LRFD, kips

INTRODUCTION

In the current *Load and Resistance Factor Design Specifications for Structural Steel Buildings* [American Institute of Steel Construction, 1994] (subsequently referred to as AISC/LRFD) there is a discontinuity in the bearing strength limit state when end distance equals 1.5 times the bolt diameter. The AISC/LRFD states that, for connections with two or more bolts in the line of force, once the distance from the end of the connected part to the center of a standard hole (L_e) reaches 1.5 times the bolt diameter (d_b) and the spacing (s) is $3.0d_b$, the designer may use the full bearing strength ($2.4d_bt_pF_u$) of the plate for all holes; otherwise, the nominal bearing strength of the hole nearest the end is $L_et_pF_u$. Therefore, as L_e approaches $1.5d_b$ from below, bearing strength approaches $1.5d_bt_pF_u$; when L_e reaches $1.5d_b$, bearing strength instantly increases to $2.4d_bt_pF_u$.

A proposed change to the *Specification for Structural Joints Using ASTM A325 or A490 Bolts* [Research Council on Structural Connections, 1988; Minutes, 1994] removes the discontinuity at $1.5d_b$. According to the proposed method, the bearing strength (R_n) is $1.2L_ct_pF_u$, but must be less than $2.4d_bt_pF_u$. Thus, the equation for bearing strength is $R_n = 1.2L_ct_pF_u \leq 2.4d_bt_pF_u$.

This report details the results of a test program which investigates the strength of single- and two-bolt bearing connections and compares the results to published equations. The program has the following objectives:

1. determine the strength of single-bolt connections with various end distances, bolt diameters, and plate thicknesses;
2. determine the strength of two-bolt connections with various end distances, bolt spacings, bolt diameters, and plate thicknesses; and,
3. compare the strength of connections which undergo gross deformations with those that elongate the bolt hole 1/4 in.

LITERATURE SEARCH

Several independent research programs have been conducted to establish design criteria for end distance and spacing. Sinclair [1968] investigated the capacity of single-angle, single-bolt connections used in tower and power substation structures. Only 5/8-in. bolts with 11/16-in. diameter holes were tested. As variables in his tests, Sinclair included end distance (parallel to the direction of the load), edge distance (transverse to the direction of the load), thickness, yield strength of the material, and ultimate strength of the material. Sinclair's report states that bearing capacity conforms to the equation:

$$R_n = d_b t_p F_y (2.011x + 0.279)$$

where x is the distance from the centerline of the hole to the end of the material. (In later comparisons to experimental data, the preceding equation is modified by substituting $F_u/1.5$ for F_y. This is approximately the relationship observed in Sinclair's tests, and allows Sinclair's equation to be plotted on the same nondimensional scale as the experimental data and other equations discussed.)

In *Guide to Design Criteria for Bolted and Riveted Joints,* Kulak et al. [1987] consolidate data from other investigators, and identify a lower bound L_e/d_b ratio that prevents a single fastener from tearing out of the plate material. This lower bound is defined as $L_e/d_b \geq 0.5 + 0.715F_b/F_u$. The authors also propose an alternate relationship of $L_e/d_b \geq F_b/F_u$ to determine the required end distance. The authors suggest a limit of $L_e/d_b = 1.5$ as an absolute lower limit, similar to the limits included as Table 1 in this report. There is no suggestion of a minimum required end distance to achieve full bearing capacity.

Additional information related to bearing strength is available in Frank and Yura [1981]. This work included an investigation of bearing strength of outer splice plates in double shear connections. Tests considered the effect of bolt preload, type of hole (round or slotted), and a deformation limit of 1/4 in. for 1-in. diameter bolts (numerous tests indicated that the hole must elongate 100% to 300% more than 1/4 in. to gain just 20% more bearing capacity). Only two test specimens were designed to fail by end tearout while all others maintained sufficient end distance. End tearout was computed by assuming that the plate fails along two shear planes which start at the edge of the bolt hole and continue to the end of the plate. Fully torqued bolts were reported to produce approximately 10% increase in capacity over snug tight bolts. The report also indicates that the bearing ratio has an effect on the strength of the connection. Bearing ratio *(BR)* is defined as the ratio of bearing stress to net section stress in the plate. Recommendations for bearing strength (F_b) are as follows:

$$2.0 < BR \leq 4.0 \qquad F_b = 2.4F_u\,(0.5 + 0.125\,BR)$$

$$4.0 < BR \qquad F_b = 2.4F_u$$

Current AISC Specifications draw on the work of Kulak et al., Frank and Yura, and past practice. The work of Kulak et al. is used to describe the increase in bearing capacity with increasing end distance, the work of Frank and Yura is used to define the bearing capacity limit, and the discontinuous increase in bearing capacity at an end distance of $1.5d_b$ is based on past practice.

HISTORICAL PROGRESSION OF SPECIFICATIONS

This research program was undertaken to assess the accuracy of current AISC design provisions related to bearing capacity. To begin this assessment, it is helpful to review provisions from earlier specifications which led to current practice. The sixth edition of the *Specification for the Design, Fabrication, and Erection of Structural Steel Buildings* [American Institute of Steel Construction, 1963] (subsequently referred to as AISC/ASD) lists the following requirements with regard to spacing, end distance, and bearing:

1. the minimum spacing of rivets or bolts shall be greater than $2.67d_b$;
2. the minimum end distance (L_e) shall be the greater of $1.5A_b/t_p$ or the value from Table 1 shown below; and,
3. the allowable bearing stress on bolts in bearing type connections shall not exceed $1.35F_y$.

A commentary is provided in the sixth edition, but it does not include a discussion of the provisions listed above. The same basic provisions are listed in earlier specifications, and appear to be based on accepted practice.

Table 1. Minimum Edge Distance for Punched, Reamed, or Drilled Holes

Bolt Diameter	At Sheared Edges	At Rolled Edges
1/2	7/8	3/4
5/8	1-1/8	7/8
3/4	1-1/4	1
7/8	1-1/2	1-1/8
1	1-3/4	1-1/4
1-1/8	2	1-1/2
1-1/4	2-1/4	1-5/8
Over 1-1/4	1-3/4 x Diameter	1-1/4 x Diameter

The seventh edition of the AISC/ASD [American Institute of Steel Construction, 1970] maintained the same requirements as the sixth edition.

The eighth edition of the AISC/ASD [American Institute of Steel Construction, 1978] specified an allowable bearing strength of $1.5F_u$. This is a significant increase from $1.35F_y$ in the 1963 and 1970 AISC/ASD. End distance requirements also changed. The minimum end distance became the larger of the value in Table 1 or $2P_s/F_ut_p$ where P_s is the force that a single bolt transmits to the connected material. This equation is based on the relationship $F_b/F_u = L_e/d_b$ proposed by Kulak et al. [1987], with a safety factor of 2.0 applied.

The ninth edition of the AISC/ASD [American Institute of Steel Construction, 1989] required the allowable bearing stresses, minimum end distances, and minimum spacings listed below:

1. when $L_e \geq 1.5d_b$ and $s \geq 3.0d_b$ and there are two or more bolts in the line of the force, then $F_b = 1.2F_u$; and,
2. *in all single-bolt connections and in multi-bolt connections when* $L_e < 1.5d_b$ or $s < 3.0d_b$, then $L_e \geq 2P_s/F_ut_p$, $s \geq 2P_s/F_ut_p + d_b/2$, and $F_b = L_eF_u/2d_b \leq 1.2F_u$.

Substituting the full bearing force, $1.2F_ud_bt_p$, for P_s to calculate L_e, $L_e \geq (2)(1.2F_ud_bt_p)/F_ut_p = 2.4d_b$. It is apparent that the end distance required to develop full bearing capacity surpasses $1.5d_b$ for single bolt connections.

To support the different treatment of single- and multi-bolt connections, AISC/ASD refers to an article authored by Jones [1940]. In the article, Jones criticizes the 1936 AISC/ASD for restricting the enclosed bearing strength of steels to 40,000 psi. Tests at the time had shown that bearing stresses of 165,000 psi were reached before yielding of the joint occurred. Jones also mentioned these tests seemed to indicate, for static loading, bearing on structural rivets might be overlooked without reduction of the safety factor. It was found that the true danger was not the rivet failing in bearing, but punching out the end of the plate. Jones noted that the "time honored" end distance of 1-1/2 in. was quite inadequate except when end tear-out was prevented by other elements. The tests which Jones referenced did not vary rivet shear or plate tension; only bearing stress was varied by changing plate thickness. Test results showed an increase in breaking load due to increased end distance. The paper indicated the 1936 AISC/ASD required there be at least the same shearing area in the plate behind the rivet as in the rivet. Since the rivets were generally lower strength than the connected material, this ensured that the rivet would fail before end punching occurred. The article provides no quantitative support for treating single- and multi-bolt connections differently with regard to end distance.

In 1986, the American Institute of Steel Construction introduced the first edition of the AISC/LRFD. Except for safety factors, the provisions in the AISC/LRFD are the same as those in the 1989 AISC/ASD discussed above. Regarding end distance, spacing, and bearing, the requirements in the second edition of the AISC/LRFD [1993] are identical to the first edition. Requirements from the first two editions are given below:

1. when $L_e \geq 1.5d_b$ and $s \geq 3.0d_b$ and there are two or more bolts in the line of the force and deformation is a design consideration, then $R_n = 2.4d_bF_u$;
2. if deformation is not a design consideration, then $R_n = L_et_pF_u \leq 3.0d_bt_pF_u$; and
3. when $L_e < 1.5d_b$ or $s < 3.0d_b$ or there is only a single bolt in the direction of the force, then for the bolt nearest the end $R_n = L_et_pF_u \leq 2.4d_bt_pF_u$ and for the remaining bolt holes $R_n = (s-d_b/2)t_pF_u \leq 2.4d_bt_pF_u$.

A discontinuity in the limit state is present at an end distance of $1.5d_b$ for multi-bolt connections.

TEST PROGRAM

A test program was developed primarily to determine if the discontinuity in bearing strength at $1.5d_b$ which is present in design specifications is justified. Test variables included in the program are clear end distance (L_c), plate thickness (t_p), bolt spacing (s), and bolt diameter (d_b).

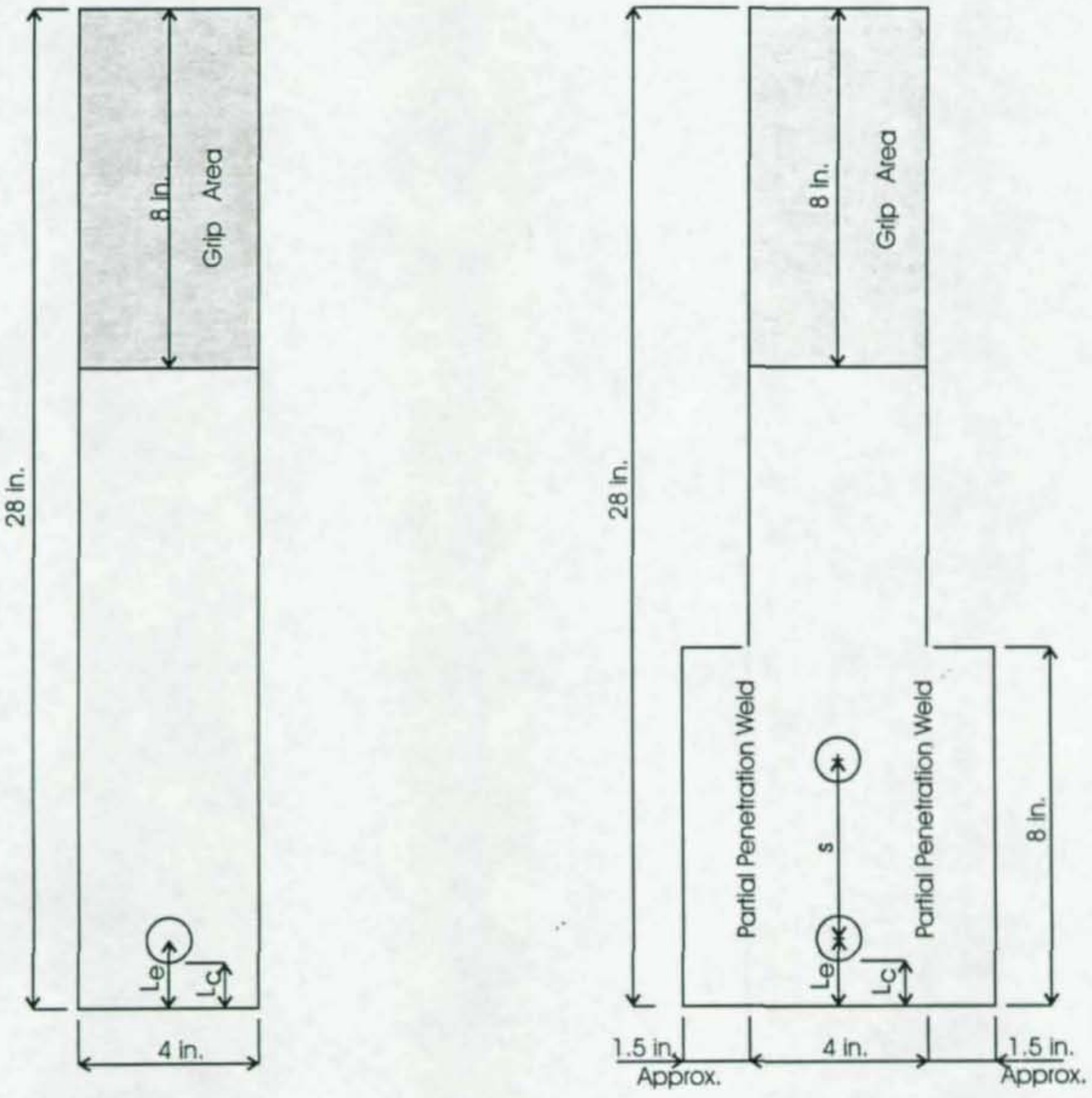
Tensile Tests. An ASTM standard tensile test was used to determine the yield strength (F_y) and the ultimate strength (F_u) of the steel used to fabricate the test specimens. The tensile specimens were cut from ten 20-ft lengths of bar. The 1/4- and 1/2-in. bars were 4 in. wide while the 3/4-in. bar was initially 5 in. wide. An acetylene torch was used to trim the 5-in. bar to a width compatible with the testing machine. Each plate's strength was determined by removing and testing one ASTM standard tensile specimen. In addition, a second specimen was taken from the 5-in. wide bar after it was trimmed to a 4-in. width to check for any strength changes due to the cutting process (i.e. ten tests from untorched bars and one test from a trimmed bar). The results of the tensile tests are given in Table 2. The 3/4-in. bar had slightly lower strength than the 1/4- and 1/2-in. bars. There were only slight differences between the measured strengths of the trimmed and untrimmed bar tests. Subsequent plots in this report use the measured ultimate tensile strengths to normalize data.

Table 2. Tensile Tests

Mark	Thickness (inches)	Width (inches)	Yield Stress (ksi)	Ult. Stress (ksi)	Percent Reduction in Area
1	0.253	1.585	50.9	70.9	52
2	0.254	1.586	50.6	70.9	47
3	0.253	1.585	51.2	70.7	46
4	0.253	1.588	50.7	72.7	50
5	0.498	1.588	44.1	66.3	57
6	0.498	1.590	48.6	70.5	54
7	0.744	1.607	43.9	63.7	59
7B	0.740	1.619	43.1	63.6	NA
8	0.747	1.596	43.6	62.7	63
9	0.742	1.634	45.7	63.7	56
10	0.748	1.628	43.6	62.4	57

Specimens. Single-bolt test specimens were fabricated from 4-in. wide ASTM A36 steel bars with thicknesses of 1/4 in., 1/2 in., or 3/4 in. Bolt diameters used were 5/8-, 3/4-, and 1-in. Hole diameters are standard for each bolt size. Clear end distances vary between 0.125 in. and 2.75 in. A drawing of the single-bolt specimen is provided in Figure 1(a). Forty-eight single-bolt tests were conducted; specimens and test results are listed in Table 3.

Two-bolt specimens had the same plate thicknesses and widths as single-bolt specimens, but were fabricated with two standard holes in the line of force. Again, specimens had varying end distances and bolt diameters. To study the effects of bolt spacing, the testing program incorporated three spacings for 5/8- and 3/4-in. diameter bolts, and two spacings for 1-in. diameter bolts. The center-to-center spacing of three bolt diameters ($3d_b$), which matches the current AISC/LRFD requirement, was included as a test spacing for all three bolt diameters. To eliminate net section failures in the two-bolt tests, an extension was welded on each side of the specimens in the vicinity of the holes. A drawing of the two-bolt specimen is provided in Figure 1(b). Fifty-three two-bolt specimens were tested; specimens and test results are listed in Table 4.



(a) Single-Bolt Specimen

(b) Two-Bolt Specimen

Figure 1. Test Specimens

Table 3. Single-Bolt Tests

Specimen	Mark*	Edge Distance (in.)	Thickness (in.)	Bolt Diameter (in.)	Load (lbs)	Tear Out	1/4" Disp.
1	1	0.272	0.260	0.750	11,300	x	
2	4	0.266	0.253	0.750	11,220	x	
3	4	0.769	0.253	0.750	22,220	x	
4	4	1.232	0.254	0.750	29,800	x	
5	4	1.478	0.252	0.750	33,450	x	
6	7	0.300	0.741	0.750	32,950	x	
7	7	0.482	0.746	0.750	44,700	x	
8	7	0.714	0.753	0.750	57,300	x	
1	7	1.130	0.746	0.750	71,250	x	
10	4	0.204	0.252	1.000	11,150	x	
11	4	0.750	0.250	1.000	23,050	x	
12	4	1.245	0.252	1.000	32,120	x	
13	4	2.269	0.251	1.000	40,790	x	
14	7	0.247	0.740	1.000	32,820	x	
15	7	0.754	0.744	1.000	63,400	x	
16	7	1.254	0.742	1.000	88,500	x	
17	10	0.283	0.743	1.000	36,250	x	
18	10	0.765	0.744	1.000	65,500	x	
19	10	1.236	0.743	1.000	90,000	x	
20	2	0.256	0.252	1.000	13,250	x	
21	2	0.766	0.250	1.000	23,800	x	
22	2	1.229	0.250	1.000	32,800	x	
23	3	2.264	0.252	1.000	42,250	x	
24	2	0.258	0.250	0.750	11,400	x	
25	2	0.786	0.250	0.750	22,750	x	
26	2	1.256	0.252	0.750	30,750	x	
27	2	1.498	0.252	0.750	33,950	x	
28	10	0.189	0.742	0.750	26,650	x	
29	10	0.467	0.744	0.750	44,900	x	
30	10	0.801	0.742	0.750	62,750	x	
31	10	1.011	0.742	0.750	74,100	x	
32	10	0.073	0.745	0.750	12,100	x	
33	1	0.302	0.251	0.625	11,300		x
33B	1	0.302	0.251	0.625	11,300	x	
34	3	1.036	0.251	0.625	23,900		x
34B	3	1.036	0.251	0.625	25,220	x	
35	3	1.751	0.251	0.625	28,000		x
35B	3	1.751	0.251	0.625	31,550	x	
36	1	2.650	0.249	0.625	30,500		x
36B	1	2.650	0.249	0.625	31,720	x	
37	3	2.496	0.250	0.750	32,000		x
38	5	2.500	0.498	0.750	70,000		x
39	6	2.540	0.500	0.750	69,500		x
40	8	0.488	0.748	0.750	44,200		x
41	8	0.718	0.742	0.750	56,000		x
42	8	1.570	0.748	0.750	81,500		x
43	8	1.917	0.740	0.750	90,000		x
44	9	0.532	0.740	1.000	50,200		x
45	9	0.742	0.745	1.000	60,200		x
46	8	1.501	0.751	1.000	86,200		x
47	9	2.538	0.745	1.000	103,000		x
48	8	2.530	0.746	1.000	106,500		x

*Indicates which 20-ft bar was used to make specimen.

Table 4. Two-Bolt Tests

Specimen	Mark*	Edge Dist. (in.)	Thickness (in.)	Bolt Diam. (in.)	Spacing (in.)	Load (lbs)	Tear Out	1/4" Disp.
1	5	0.488	0.496	1.000	1.835	97,200	x	
2	6	1.788	0.496	1.000	1.830	103,800	NET SECTION	
3	5	1.972	0.496	1.000	1.830	NA	NET SECTION	
4	5	1.248	0.496	1.000	1.833	NA	NET SECTION	
5	1	0.303	0.745	0.750	2.685	115,500	BOLT SHEAR	x
6	7	0.348	0.741	0.750	1.470	104,000		x
6B	7	0.348	0.741	0.750	1.470	106,750	x	
7	7	0.243	0.741	0.750	1.109	88,500		x
7B	7	0.243	0.741	0.750	1.109	90,200	x	
8	9	0.129	0.745	0.750	2.705	99,100	x	NA
9	7	0.086	0.743	0.750	2.644	93,600	x	NA
10	9	0.527	0.746	0.750	1.438	103,000		x
10B	9	0.527	0.746	0.750	1.438	111,250	x	
11	10	0.287	0.742	0.750	1.429	95,000		x
11B	10	0.287	0.742	0.750	1.429	99,800	x	
12	6	2.508	0.495	0.625	1.541	NA	BOLT SHEAR	
13	1	2.516	0.249	0.625	1.623	51,100		x
13B	1	2.516	0.249	0.625	1.623	51,200	x	
14	1	0.779	0.249	0.625	1.560	44,300		x
14B	1	0.779	0.249	0.625	1.560	46,250	x	
15	3	0.506	0.250	0.625	1.610	40,100		x
15B	3	0.506	0.250	0.625	1.610	40,200	x	
16	1	1.538	0.249	0.625	1.549	50,250		x
17	1	1.577	0.249	0.625	2.829	51,400		x
18	1	2.362	0.250	0.625	2.838	51,600		x
19	3	2.516	0.250	0.625	2.856	51,500		x
20	2	0.769	0.250	0.625	2.820	51,100	x	
21	3	1.217	0.250	0.625	2.887	NA	NET SECTION	
22	3	0.540	0.250	0.625	2.819	45,000		x
22B	3	0.540	0.250	0.625	2.819	47,500	x	
23	3	0.277	0.249	0.625	2.815	40,200		x
23B	3	0.277	0.249	0.625	2.815	40,900	x	
24	6	2.461	0.496	0.750	2.695	127,800		x
25	5	1.458	0.497	0.750	2.720	NA	WELD BROKE	
26	6	0.736	0.496	0.750	2.674	105,250		x
26B	6	0.736	0.496	0.750	2.674	115,800	x	
27	5	1.456	0.502	0.750	1.100	115,500	x	
28	5	2.168	0.502	0.750	1.073	130,600	GROSS SECT.	
29	1	1.494	0.255	0.625	1.238	55,000		x
30	3	2.556	0.256	0.625	1.170	59,500	WELD BROKE	
31	6	1.481	0.507	0.750	1.446	126,700	WELD BROKE	
32	5	1.467	0.506	0.750	1.465	109,000		x
33	5	0.272	0.497	0.750	1.453	69,700		x
33B	5	0.272	0.497	0.750	1.453	70,600	x	
34	4	0.25	0.250	0.750	1.447	38,200		x
35	6	0.775	0.498	0.750	1.443	99,400		x
36	6	0.707	0.500	0.750	1.425	97,000		x
37	6	0.519	0.495	0.750	1.457	89,000		x
38	5	2.525	0.502	0.750	1.476	116,000		x
39	4	0.734	0.250	0.750	1.446	37,200	X VERY LOW	
40	2	2.521	0.251	0.625	2.820	60,600		x
41	6	0.670	0.500	0.750	1.050	90,000		x
42	1	0.517	0.250	0.625	1.148	36,500	x	x
43	2	1.487	0.252	0.625	2.803	58,000		x
44	2	2.512	0.250	0.625	2.800	60,230		x
45	9	0.745	0.740	1.000	1.996	146,800		x
46	9	0.498	0.750	1.000	1.890	135,600		x
47	9	0.991	0.742	1.000	1.883	155,000		x
48	8	1.483	0.740	1.000	1.860	NA	WELD BROKE	
49	8	2.465	0.742	1.000	1.906	NA	WELD BROKE	
50	9	0.540	0.748	1.000	2.880	146,000		x
51	8	0.760	0.742	1.000	2.991	151,000		x
52	9	1.009	0.745	1.000	2.925	160,000		x
53	8	1.525	0.752	1.000	2.825	NA	WELD BROKE	

*Indicates which 20-ft bar was used to make specimens.

In Tables 3 and 4, it can be seen that several of the specimen numbers are followed by the letter "B", such as specimen 33B in Table 3. Specimens 33 and 33B are actually the same specimen, with loads measured at different levels of bearing deformation in the hole.

A number of the specimens listed in Table 4 were not included in the data analysis because the failure mode did not involve either end tearout or bearing deformation. Specimens labeled "net section" failed in tension through a bolt hole; specimens labeled "bolt shear" failed by shearing through one or both bolts; and specimens labeled "weld broke" failed in the longitudinal weld used to attach the extension plates.

Test Fixture. The test fixture consisted of three 4-in. wide, 1-in. thick ASTM A572 grade 50 steel plates (one pull plate and two splice plates) bolted together to form a double shear connection with the specimen. The design of the specimen allowed for a gap between the test specimen and the fixture to ensure freedom of movement out of plane. See Figure 2 for a drawing of the test fixture.

Measurements. A plot of displacement versus force was generated for every test using an X-Y recorder. A direct current differential transformer (DCDT) was used to measure the full displacement of the specimens including elastic stretching of the plate (which was very small compared to the hole elongation). A dial gauge was also used to monitor displacements. To determine the force corresponding to 1/4 in. of deformation, the test was stopped at a point where the elongation of the hole was more than 1/4 in., and the overall hole elongation was recorded. It was then necessary to move back through the recorded data to find the load corresponding to 1/4 in. deformation ($P_{1/4}$). If the gross section (above the bolts in Figure 1) yielded before the elongation was 1/4 in. in the two-bolt specimens, the hole was measured as yielding began, then iteratively reloaded and remeasured until the elongation of the hole was greater than 1/4 in. The proper load was found by interpolation between the last two readings.

TEST RESULTS

Test results are plotted in terms of bearing capacity versus clear end distance. The ratio F_b/F_u is used to normalize the data to 2.4 when full bearing strength is achieved according to the design provisions of the AISC/LRFD.

Single-Bolt Tests. Forty-eight single-bolt tests were conducted, of which thirty-six were loaded through bearing deformations far in excess of 1/4 in. The remaining tests

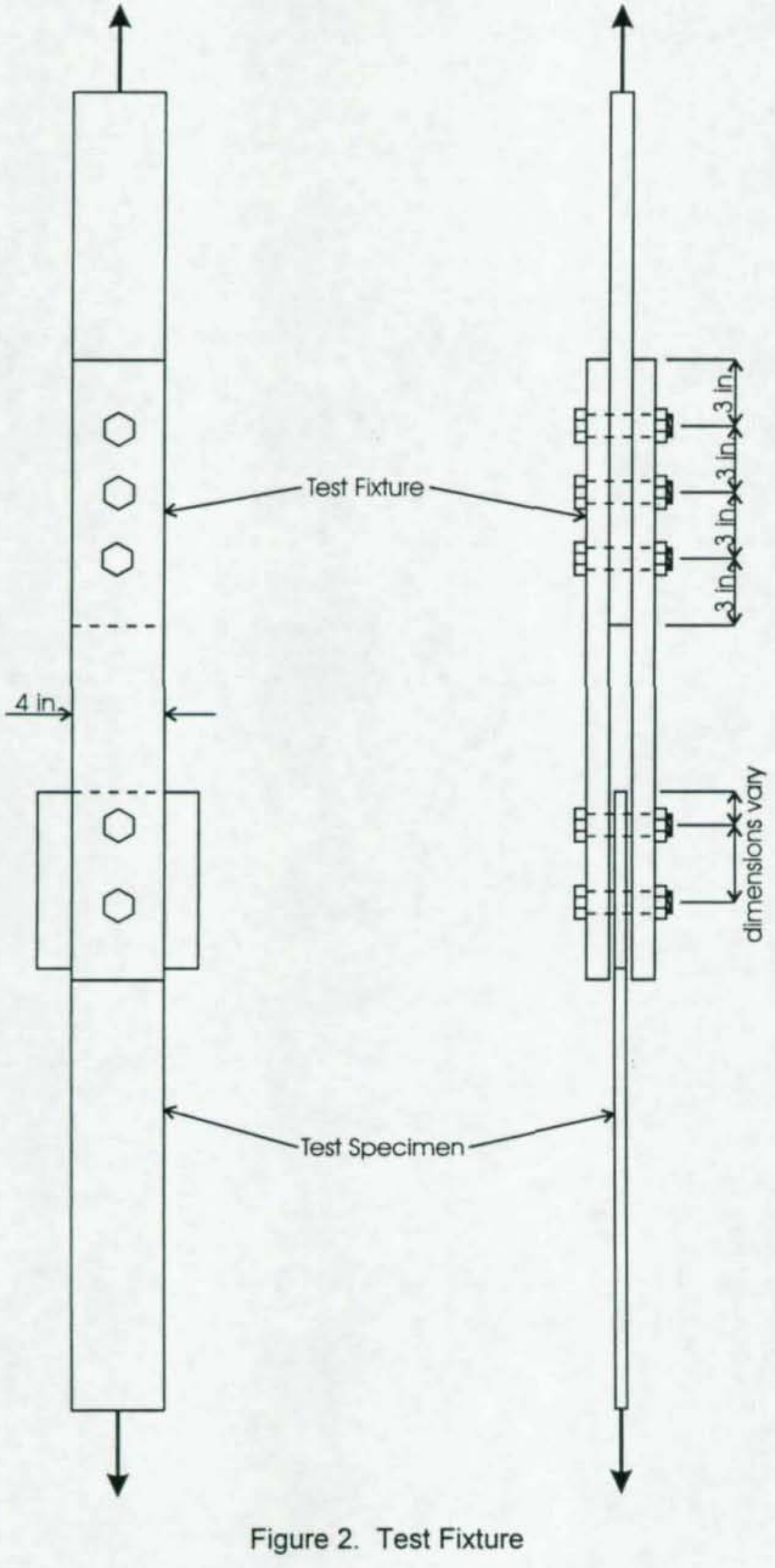


Figure 2. Test Fixture

were performed to find the load corresponding to 1/4 in. of deformation in the bolt holes. Two basic failure modes were observed: end tearout and bearing failure. When using 1/4-in. deformation as a failure criterion, end tearout failures did not occur. The ASTM A-36 steel was very ductile and thus required extreme deformations to fail as an end tearout.

In Figures 3, 4, and 5, it can be seen that normalized bearing strength increases linearly with clear end distance (L_c) until L_c reaches approximately 1.6 in. Beyond $L_c = 1.6$ in., bearing strength does not significantly increase with larger end distances. It can also be seen that when $L_c > 1.6$ in., the normalized bearing strength based on 1/4-in. deformation decreases as bolt diameter increases.

Figure 6 is a plot of F_b/F_u versus hole deformation normalized by the bolt diameter. As bolt diameter increases, deformation of the bolt hole increases in order to achieve the full bearing strength specified in AISC/LRFD. The apparent low bearing strength seen in Figure 5 for 1-in. diameter bolts is a result of stopping the test at 1/4-in. deformation, which is inadequate deformation to develop full bearing strength for these large diameter bolts.

Alternatively, the 5/8-in. diameter bolts indicate a bearing strength greater than the AISC/LRFD limit. For these smaller bolts, 1/4-in. deformation was more than adequate to develop full bearing strength. All four of the specimens built with 5/8-in. diameter bolts were tested to both a deformation of 1/4 in. and tearout. The additional bearing stress required to move from 1/4-in. deformation to tearout ranged from 0 to 12.5 percent.

In Figures 3, 4, and 5, the various equations for bearing strength are plotted with the data. The AISC/LRFD limit state accurately describes the relationship between L_c and F_b/F_u for all three bolt diameters that were tested. The full bearing limit of $2.4d_bt_pF_u$ is slightly low for 5/8-in. and 3/4-in. diameter bolts and slightly high for 1-in. diameter bolts. The proposed equation from Frank and Yura [Minutes, 1994] plots below the test data. The slope of the Frank/Yura curve is slightly steeper than indicated by the data. This curve assumes the same bearing limit of $2.4d_bt_pF_u$ as has been used in the past. Sinclair's equation, which was developed from single angle tests, accurately predicts the bearing strength for 5/8-in. and 3/4-in. diameter bolts; however, the curve overpredicts the capacity of the 1-in. diameter bolts. The curve identified as Kulak et al. has a larger

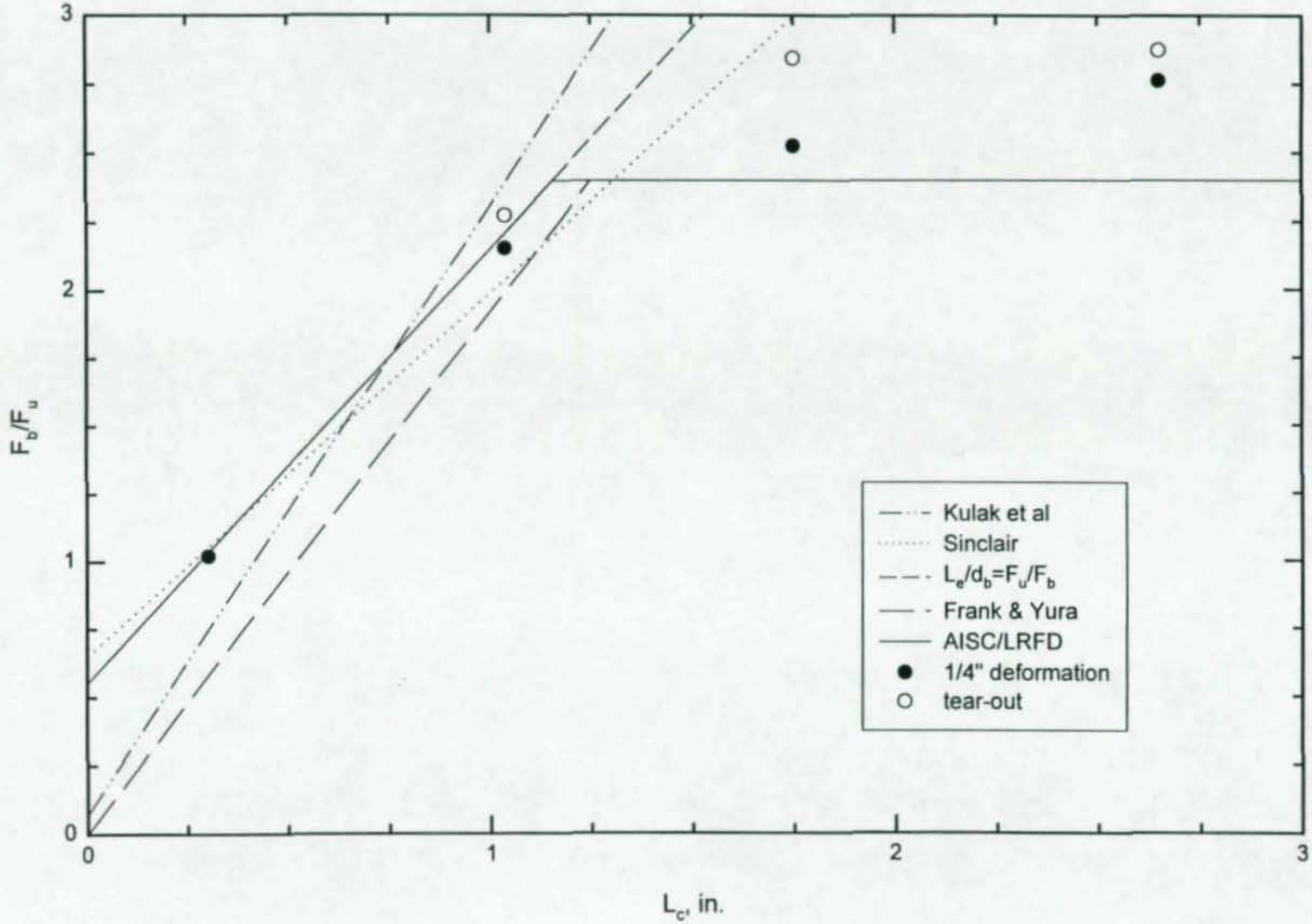


Figure 3. Comparison of 5/8 in. Single-Bolt Test Data to Various Design Equations

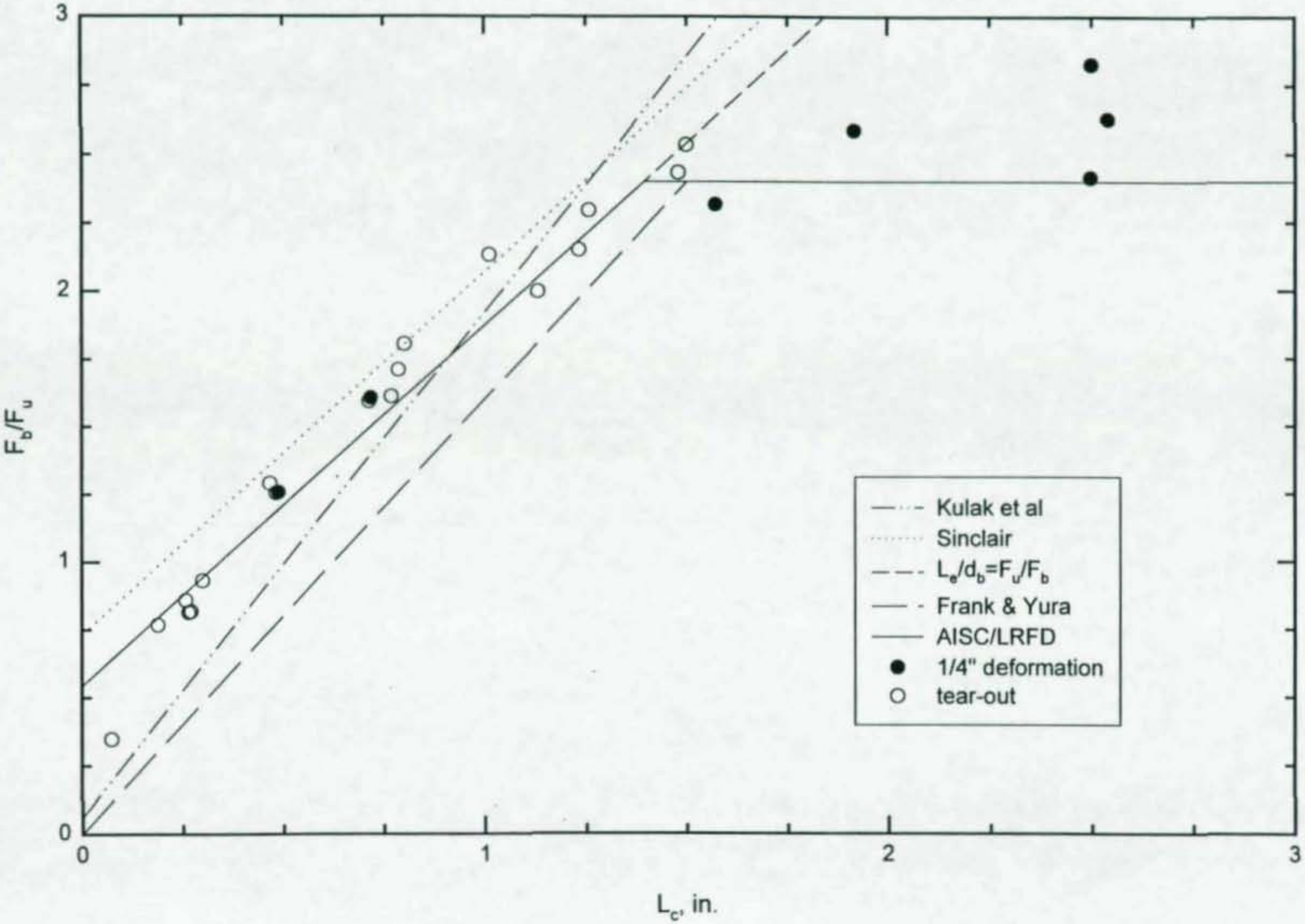


Figure 4. Comparison of 3/4 in. Single-Bolt Test Data to Various Design Equations

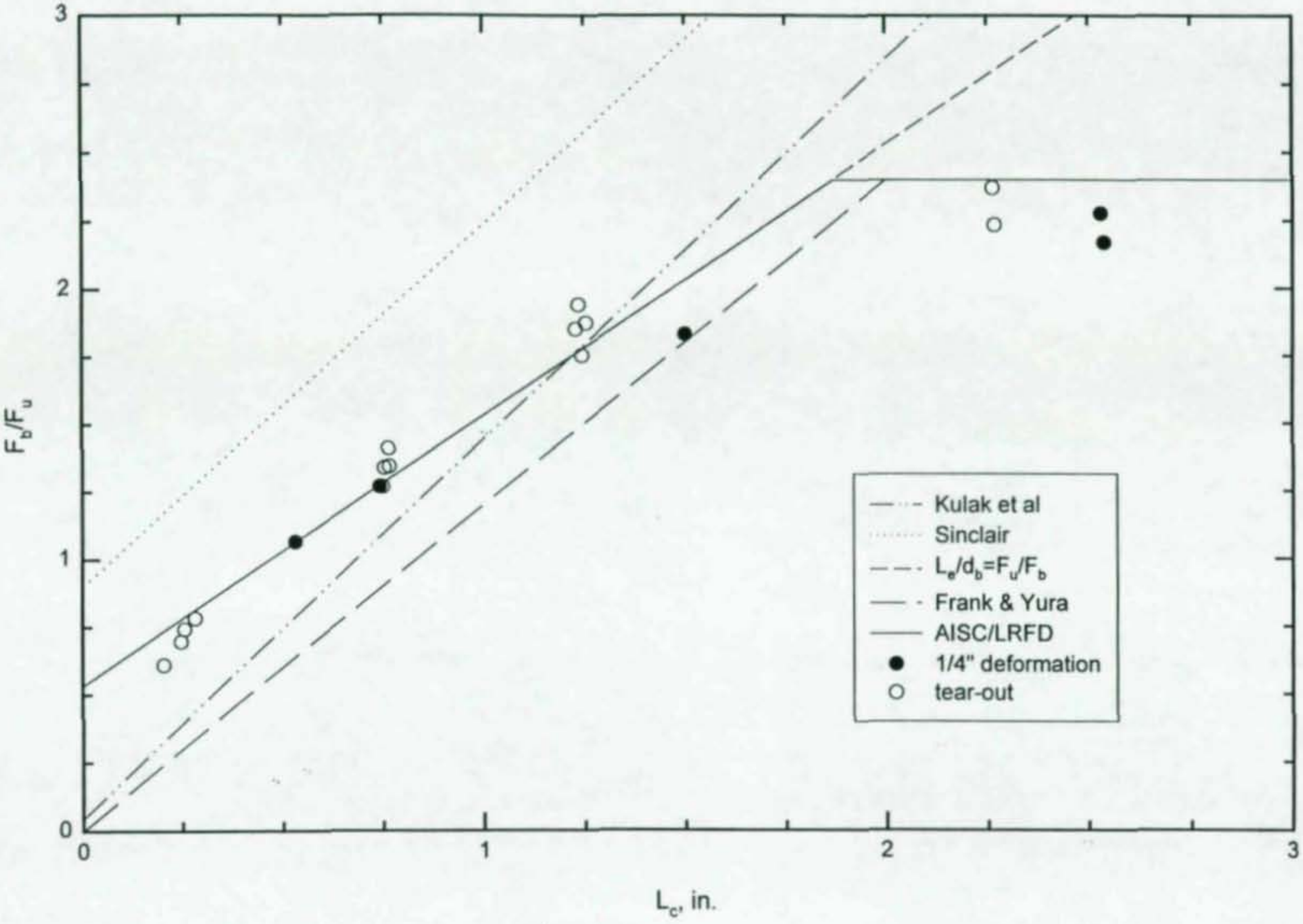


Figure 5. Comparison of 1 in. Single-Bolt Test Data to Various Design Equations

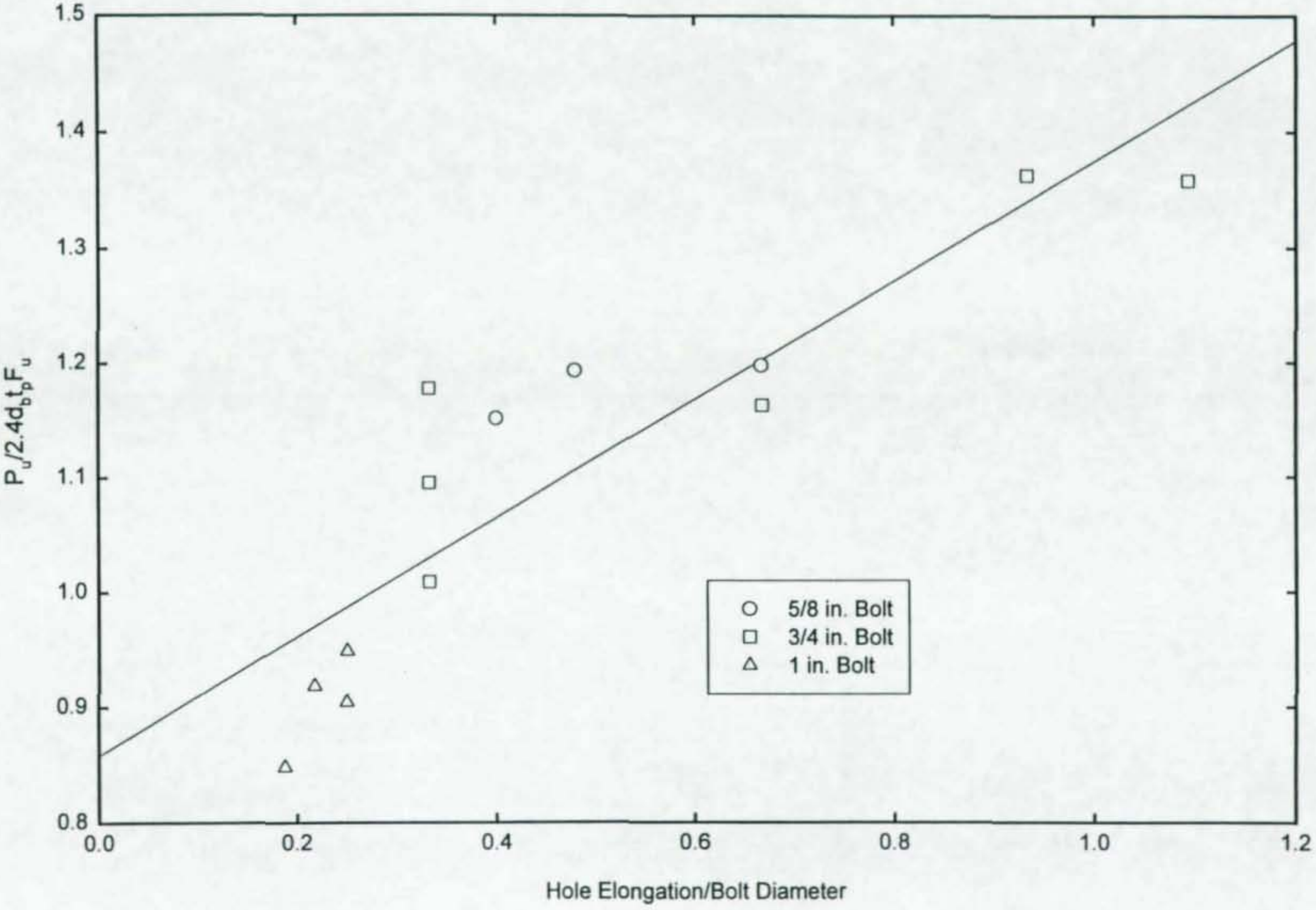


Figure 6. Effect of Bolt Diameter on Limiting Hole Elongation

slope than that of the other equations. This curve underpredicts capacity for small end distances and overpredicts for large end distances.

Although the last curve discussed above is identified as "Kulak et al." in the figures, it should be recalled that the linearly increasing portion of the curve identified as AISC/LRFD is the same as $L_e/d_b = F_u/F_b$. This relationship was also first proposed by Kulak, Fisher, and Struik [1987] as an alternative to the line identified as Kulak et al.

Two-Bolt Tests. Fifty-three two-bolt tests were conducted. Only results for specimens limited by tearout and 1/4-in. deformation are included in graphs.

Data for 5/8-in. diameter bolts are plotted in Figure 7. The data show a linear increase in capacity with increasing end distance. The AISC specified jump in capacity at $L_e = 1.5d_b$ overpredicts the capacity of the connection. The Frank/Yura equation predicts a linear increase in capacity up to full bearing, but the predicted capacity is significantly less than measured.

Data for 3/4 in. bolts are plotted in Figure 8. The data tend to follow the Frank/Yura equation and fall below the AISC/LRFD equation. The only data which plot significantly below the Frank/Yura curve correspond to bearing failures in specimens with spacing $3.0d_b$ or less.

Only six two-bolt tests were performed with 1-in. diameter bolts; data are plotted in Figure 9. The data plot very close to the proposed Frank/Yura equation, but are well below equations in AISC/LRFD. Only 1/4-in. deformations were allowed for the 1-in. bolt tests. Net section fracture prevented performing 1-in. bolt tests to full bearing capacity.

ANALYSIS OF RESULTS

Single-Bolt Tests. Test results show that for clear end distances starting at zero, bearing capacity is greater than zero. Even when L_c is zero the bolt is, for all practical purposes, completely surrounded by the connected plate and capable of carrying load. As L_c increases above zero, the bearing capacity of the connection increases, up to a limiting value. This limiting value is dependent on the ratio of the hole deformation to the bolt diameter.

When using 1/4 in. of deformation as a failure criterion, the 5/8-in. diameter bolts produce the largest bearing stresses at failure. The 1-in. diameter bolts generate the least stress using the deformation failure criteria. Since 1/4 in. is a larger percentage of

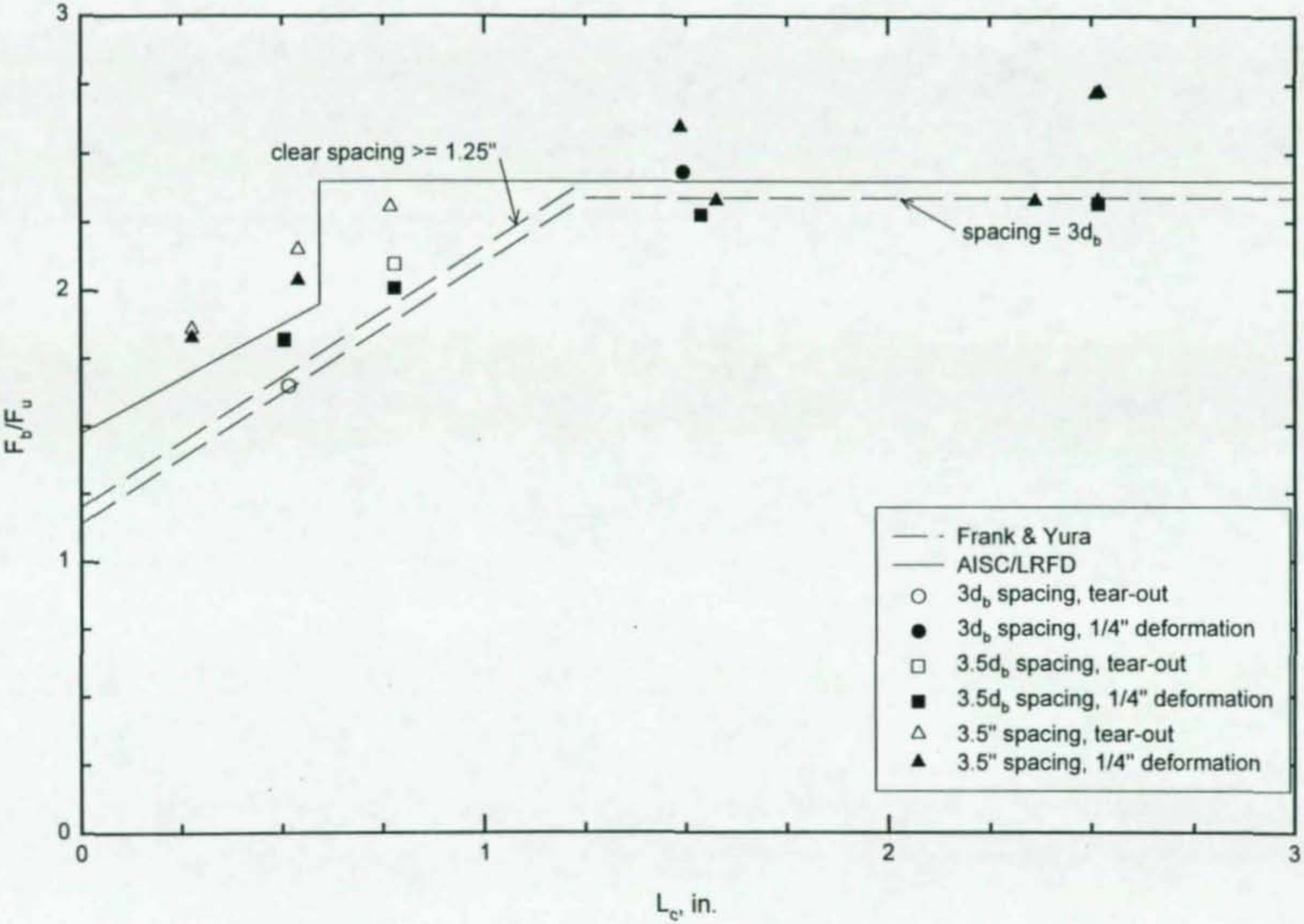


Figure 7. Comparison of 5/8 in. Two-Bolt Test Data to Selected Design Equations

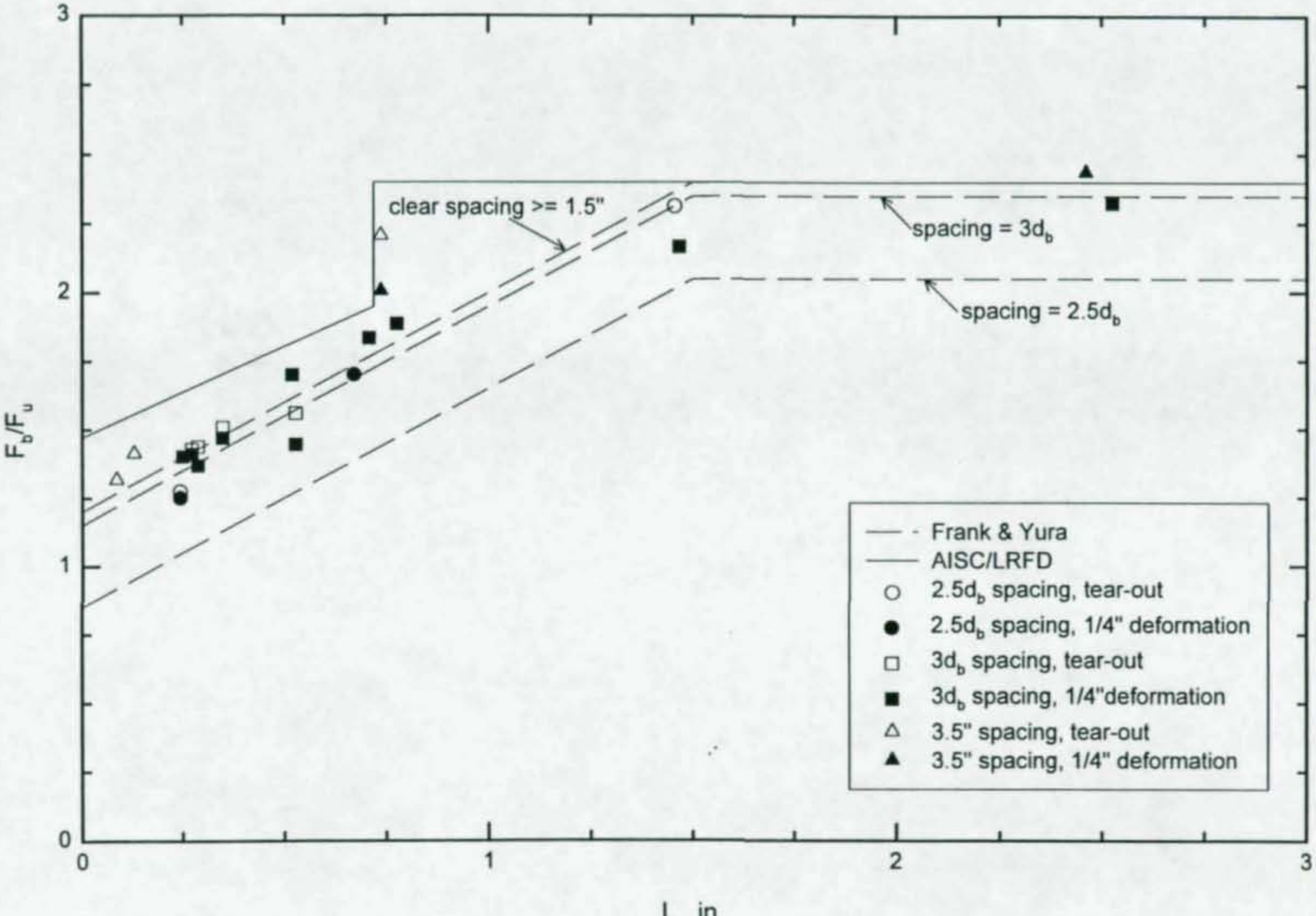


Figure 8. Comparison of 3/4 in. Two-Bolt Test Data to Selected Design Equations

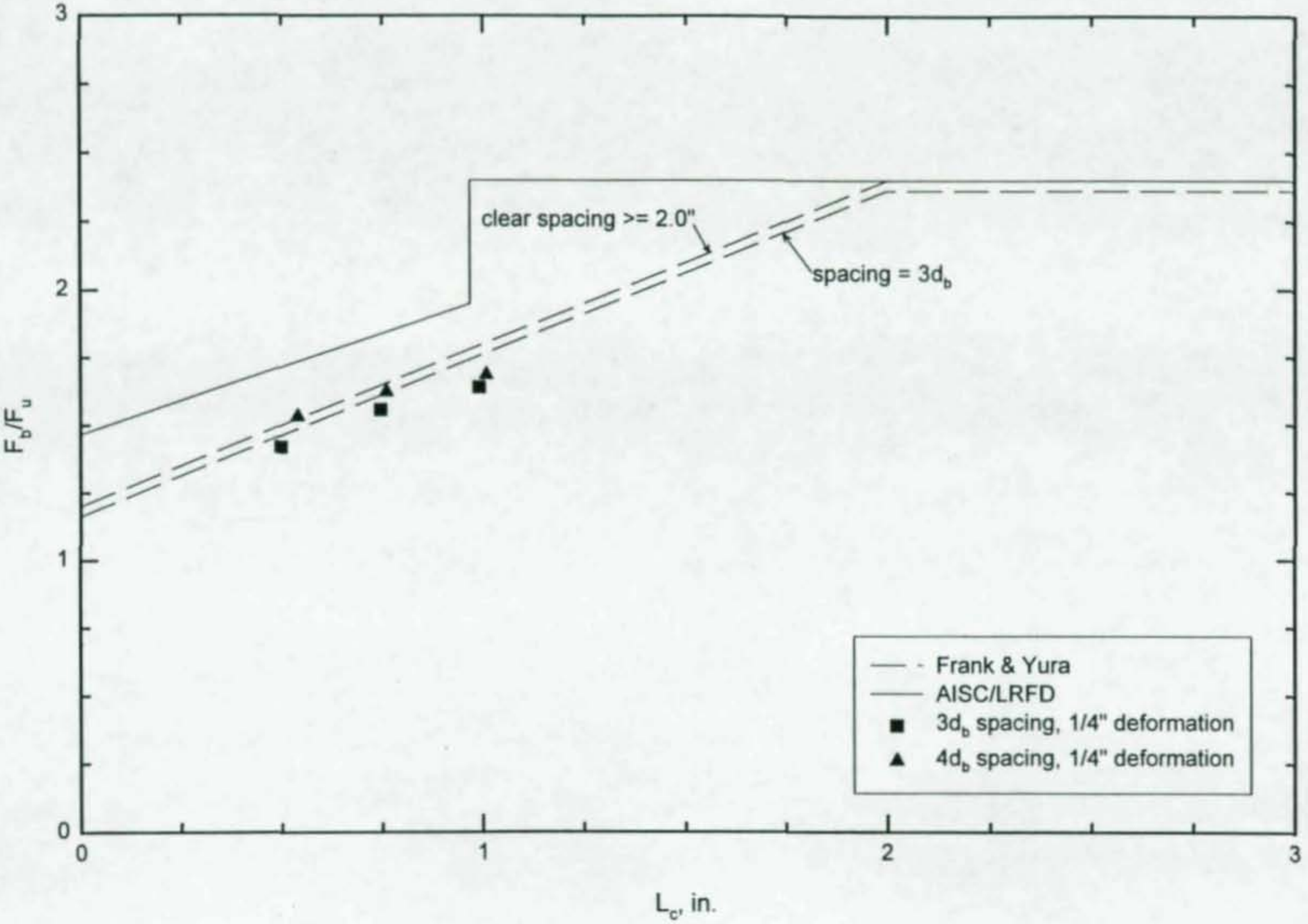


Figure 9. Comparison of 1 in. Two-Bolt Test Data to Selected Design Equations

the diameter of smaller bolts, more relative distortion must occur ahead of the bolt in order to reach failure.

The AISC/LRFD design curve is the most accurate for the single-bolt tests. The data fit along the initial curve for all bolt diameters. This indicates that the relationship, $L_e/d_b = F_b/F_u$, holds for single-bolt connections which incorporate ASTM A36 steel.

The Frank/Yura equation is conservative for the single-bolt connections as shown by the test results. The equation uses clear distance between the edge of the hole and the end of the plate to compute strength; the small amount of additional material back from the edge of the hole to the center of the hole is neglected. The result is a slight conservatism in the equation for normal end distance, with conservatism increasing as clear end distance approaches zero.

The equation which Sinclair used to determine the capacity of single angle-single bolt connections accurately depicts the maximum bearing stresses for the 5/8-in. and 3/4-in. diameter bolts. However, the 1-in. diameter single-bolt tests indicate strength values well below those predicted. Sinclair's tests incorporated only 5/8-in. diameter bolts which were commonly used in tower structures at the time. Therefore, the equation may not be accurate for other bolt diameters.

The lower bound equation proposed by Kulak, Fisher, and Struik has a slope which does not correspond to results from the single-bolt tests.

Two-Bolt Tests. The capacity of two-bolt connections is dependent on bolt spacing as well as end distance. Connections with smaller bolt spacings have less capacity than those with larger bolt spacings. The AISC/LRFD recommended end distance of $1.5d_b$ and bolt spacing of $3.0d_b$ are not sufficient to develop a full bearing force of $2.4d_bt_pF_u$ in both bolts. This is the case even though the bearing ratios (BR) always exceed 4.0 in the two-bolt tests. Frank and Yura [1981] have demonstrated that a BR of 4.0 is adequate to develop full bearing.

All of the two-bolt test data suggest that the discontinuity in the bearing strength limit state when the end distance is $1.5d_b$ is unconservative. The AISC/ASD (1989) justifies the discontinuity by suggesting that single-bolt connections are more dependent on end distance than two-bolt connections and references an article by Jones [1940]. Jones did say in his article that the real danger was end punching rather than bearing on the rivets and that other elements could prevent end punching of the edge bolt, but did not comment on the available strength of the end hole in multi-fastener connections.

Test results suggest that the bearing capacity of a connection is not necessarily the additive bearing strengths of the individual holes. Using a spacing of 2.25 in. $(3d_b)$ for the 3/4-in. diameter bolts does not allow two full bearing failures in the bolts $(P_{1/4} \neq 4.8d_bt_pF_u)$. The clear distance between the holes for this case is 1-7/16 in., which judging from the single-bolt data should be adequate to resist a full bearing load before deforming 1/4 in. The main difference between the single- and two-bolt tests is the higher tension in the bars at the net section of the interior hole as compared to the hole closest to the end. There is also tension in the bars between the holes in the multi-fastener connections which is not present in the one-bolt configurations. When a spacing of 3.5 in. (L_c = 2-11/16 in.) was used for 3/4-in. diameter bolts, the connection did resist the required force per AISC/LRFD before failure; however, the failure load $(P_{1/4})$ was less than the additive results from two equivalent single-bolt tests. A comparison of the deformations of the two-bolt tests using different spacings is shown in the Appendix.

The results of the 1-in. diameter bolt tests indicate approximately the same strength for both the 3.0-in. (L_c = 1.875 in.) and 4.0-in. (L_c = 2.875 in.) bolt spacings. When 1/4-in. deformation is the failure criterion, the larger bolts seem to induce less bearing stress on the connected part since less material build-up occurs ahead of the bolt. The 1/4-in. deformation is a smaller percentage of the bolt diameter for the larger bolts.

CONCLUSIONS AND RECOMMENDATIONS

The current AISC/LRFD Specification accurately predicts the bearing strength of single fastener connections. For ASTM A36 steel the bearing strength for single-bolt connections increases with end distance until it reaches a maximum level. The rate of increase is described by the relationship $L_e/d_b = F_b/F_u$. The maximum level is dependent on the ratio of hole elongation to bolt diameter.

A maximum bearing stress of $2.4F_u$ is adequate for use in design equations, even though this value overpredicts the capacity of 1-in. diameter single-bolt connections when 1/4-in. deformation is used as the failure criterion. As justification for this recommendation, it should be remembered that the test plates were unconfined during load application. In most connections, confinement is supplied by a bolt which has been tightened to snug as a minimum. This confinement will increase the bearing capacity of the connection. A bearing strength of $3.0F_u$ was not reached in any test even when excessive deformations were allowed to occur.

Regarding two-bolt connections, the discontinuity in the bearing limit state at $1.5d_b$ causes the AISC/LRFD to significantly overestimate connection capacity. Furthermore, the AISC/LRFD recommended spacing of $3.0d_b$ is not large enough to develop the required bearing stress for 3/4-in. and 1-in. diameter bolts before the connection reaches the 1/4-in. deformation limit. The equation suggested by Frank and Yura is conservative for both the 5/8-in. and 3/4-in. diameter bolts if enough spacing is provided. However, the bearing strength of the 1-in. diameter bolts is somewhat less than the value which Frank and Yura predict for 1/4-in. deformations. Neither the AISC/LRFD nor the Frank/Yura equations incorporate the effect of tensile stresses acting simultaneously with bearing stresses in the connection. In order to accurately predict the bearing strength of a multi-fastener connection, a better analysis which includes the interaction of tension and bearing should be performed.

Judging from the results of this test program, a change in the existing AISC Specification is warranted for multi-fastener connections. The Frank/Yura equation is based on simple principles which are easy to remember and use. This approach is conservative for all single-bolt connections and those two-bolt connections with adequate spacing.

Additional 1-in. diameter two-bolt tests along with three-bolt tests should be performed to obtain more data for studying the limit state of bearing.

REFERENCES

1. American Institute of Steel Construction. *Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings.* Sixth Edition, New York, Apr. 1963.
2. American Institute of Steel Construction. *Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings.* Seventh Edition, New York, Feb. 1969.
3. American Institute of Steel Construction. *Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings.* Eighth Edition, Chicago, Nov. 1978.
4. American Institute of Steel Construction. *Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings.* Ninth Edition, Chicago, Jun. 1989.
5. American Institute of Steel Construction. *Load and Resistance Factor Design Specification for Structural Steel Buildings.* First Edition, Chicago, Sep. 1986.
6. American Institute of Steel Construction. *Load and Resistance Factor Design Specification for Structural Steel Buildings.* Second Edition, Chicago, Dec. 1993.
7. Frank, K. H., and J. A. Yura. *An Experimental Study of Bolted Shear Connections.* FHWA/RD-81/148, Dec. 1981.
8. Jones, J. "Static Tests of Riveted Joints." *Civil Engineering*, No. 10, No. 5, May 1940, pp. 285-287.
9. Kulak, G. L., J. W. Fisher, and J. H. A. Struik. *Guide to Design Criteria for Bolted and Riveted Joints.* Second Edition, 1987, John Wiley & Sons.
10. Minutes of the June 3, 1994, Meeting of the Research Council on Structural Connections, Proposal by J. A. Yura and K. H. Frank.
11. Sinclair, G. R. "The Ultimate Load Carrying Capacity of Single Angle, Single Bolted Connections." M.S. Thesis, University of Windsor, May 1968.

APPENDIX

PHOTOGRAPHS OF TEST SPECIMENS

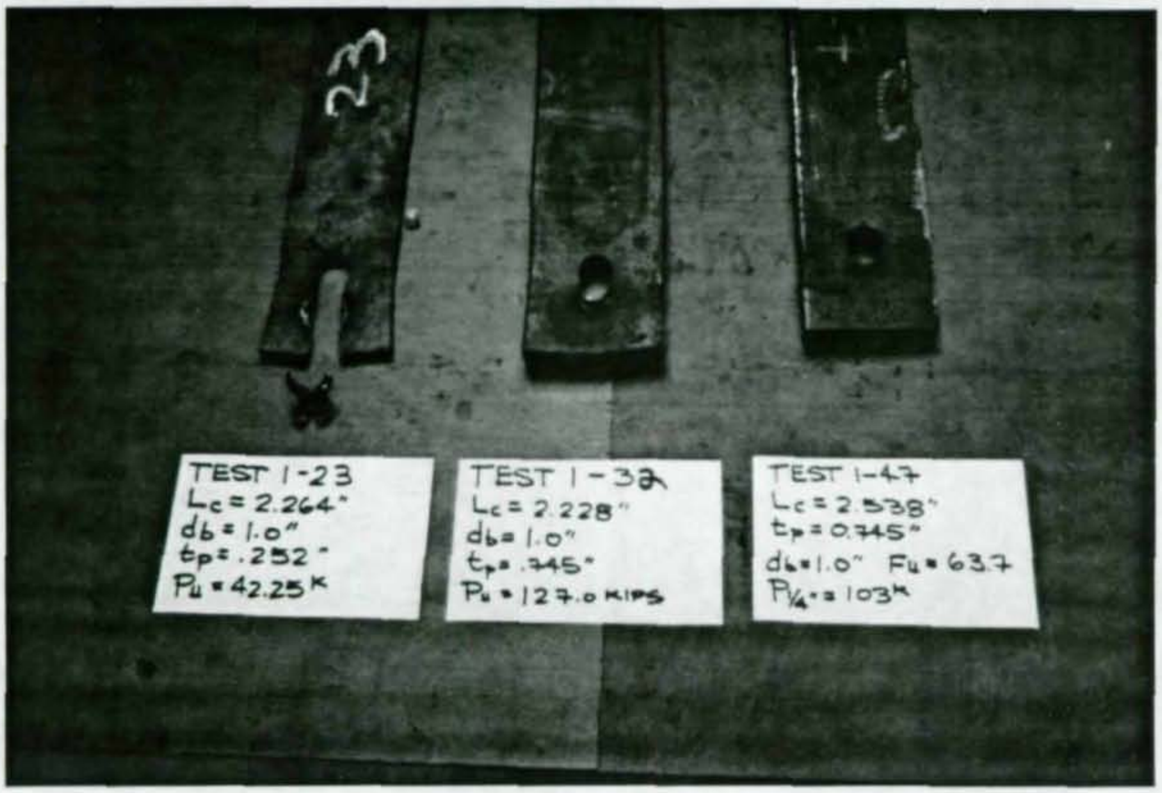


Figure 10. Comparison of Different Failure Criteria for Large End Distances. The specimen at left is an example of end tearout, the specimen in the middle is an example of excessive deformation, and the specimen at right is an example of 1/4 in. deformation.

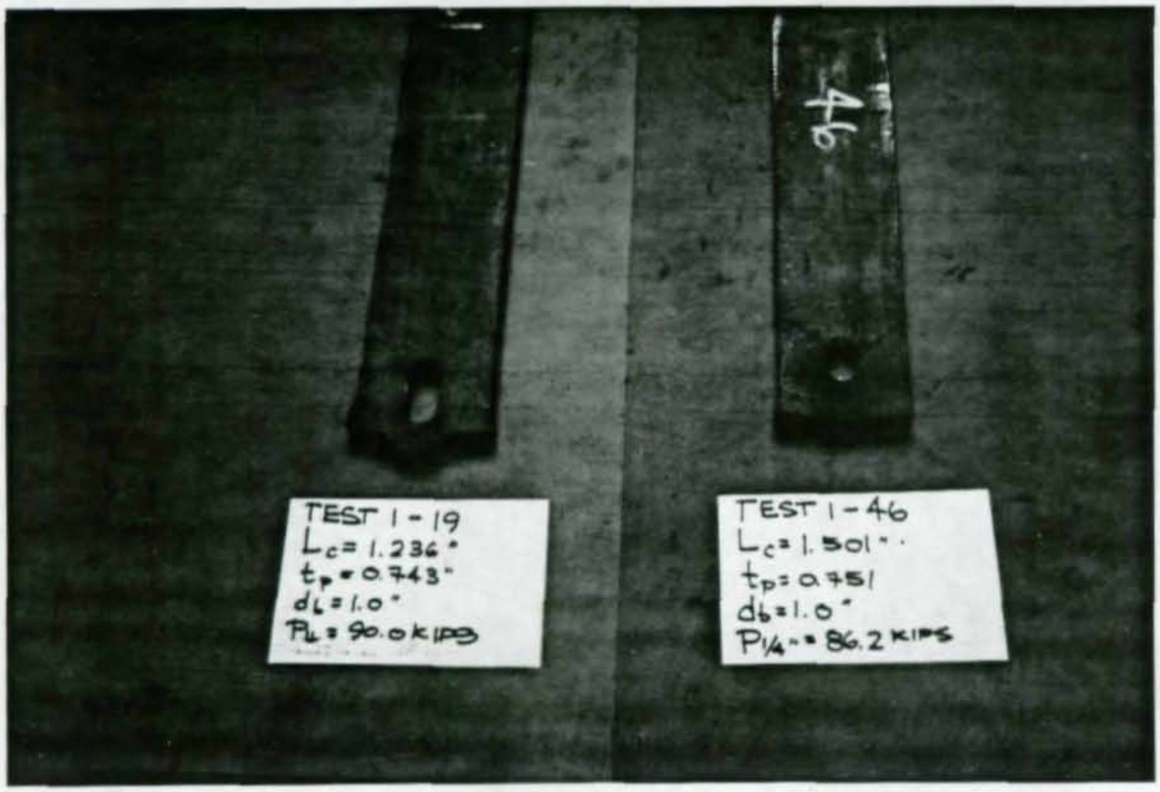


Figure 11. Comparison of Excessive Deformation and 1/4 in. Deformation. The two specimens are of approximately the same configuration. The one on the left was allowed to undergo excessive deformation while the one on the right was stopped at 1/4 in. deformation in the bolt hole.

Figure 12. Specimens of Different Thickness with the Same End Distance. For the specimen on the left, t_p = 0.25 in. and F_b/F_u = 1.34; for the specimen on the right, t_p = 0.744 in. and F_b/F_u = 1.41.

Figure 13. Comparison of End Tear-Out Failures. The specimen on the left with the large end distance experienced a large build-up of material ahead of the bolt prior to tearout. The specimen on the right with the small end distance failed before any large deformations occurred.

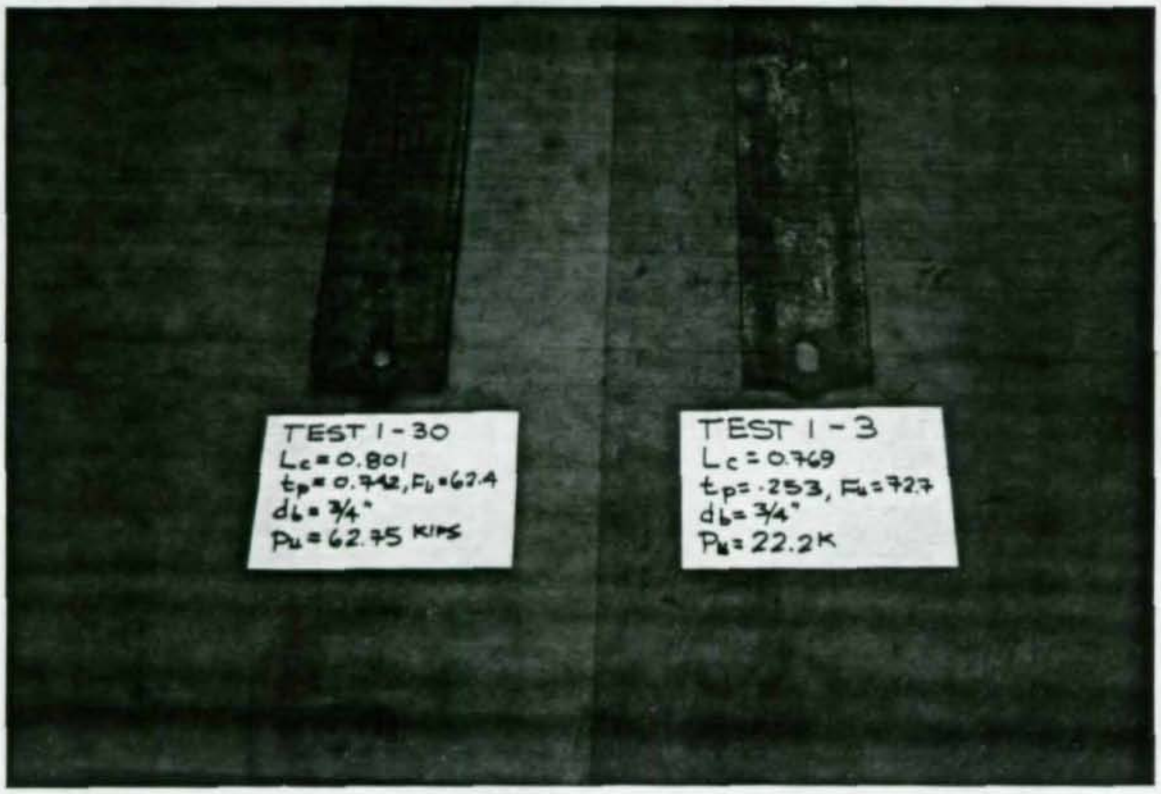


Figure 14. Large Deformations in 3/4 in. Diameter Single-Bolt Specimens with Different Plate Thicknesses.

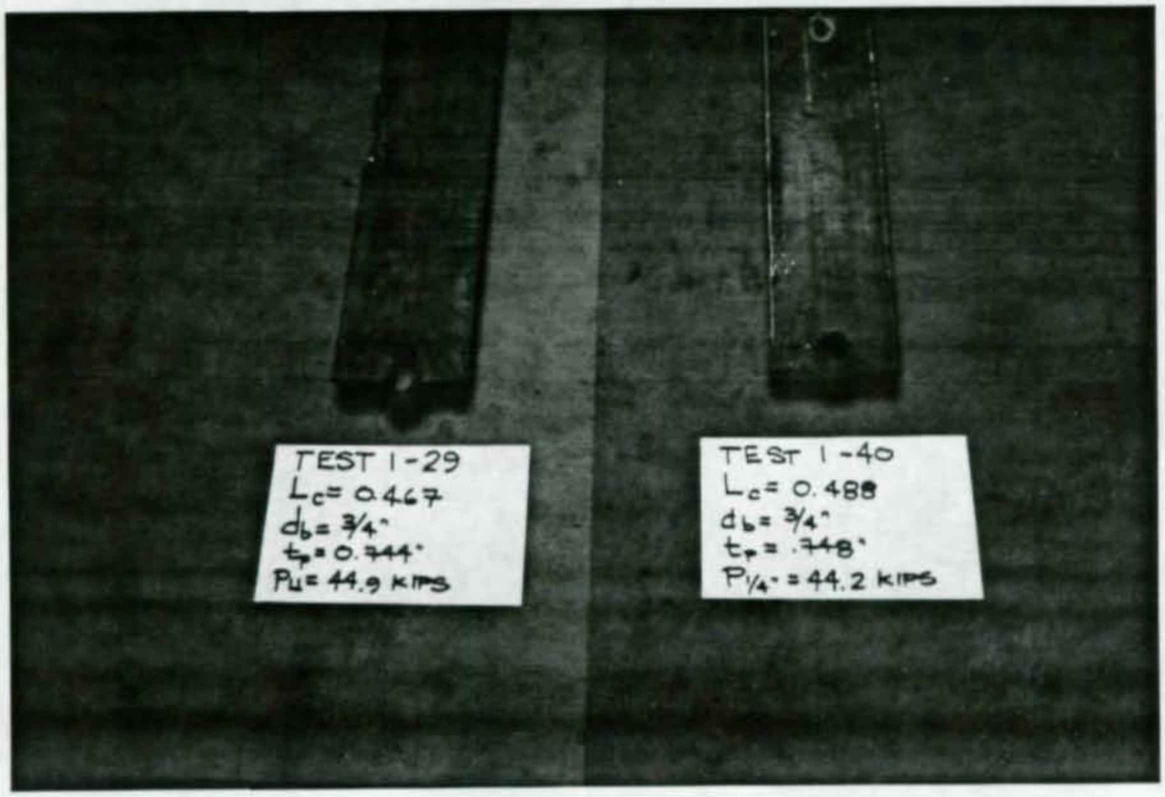


Figure 15. Two Failures for 3/4 in. Diameter Single-Bolt Specimens with Small End Distances. The specimen on the left was tested to end tearout while the specimen on the right was tested to 1/4 in. deformation. Approximately the same load was present in both specimens at the end of the tests. For small end distances, there is only a slight increase in capacity when large deformations are allowed.

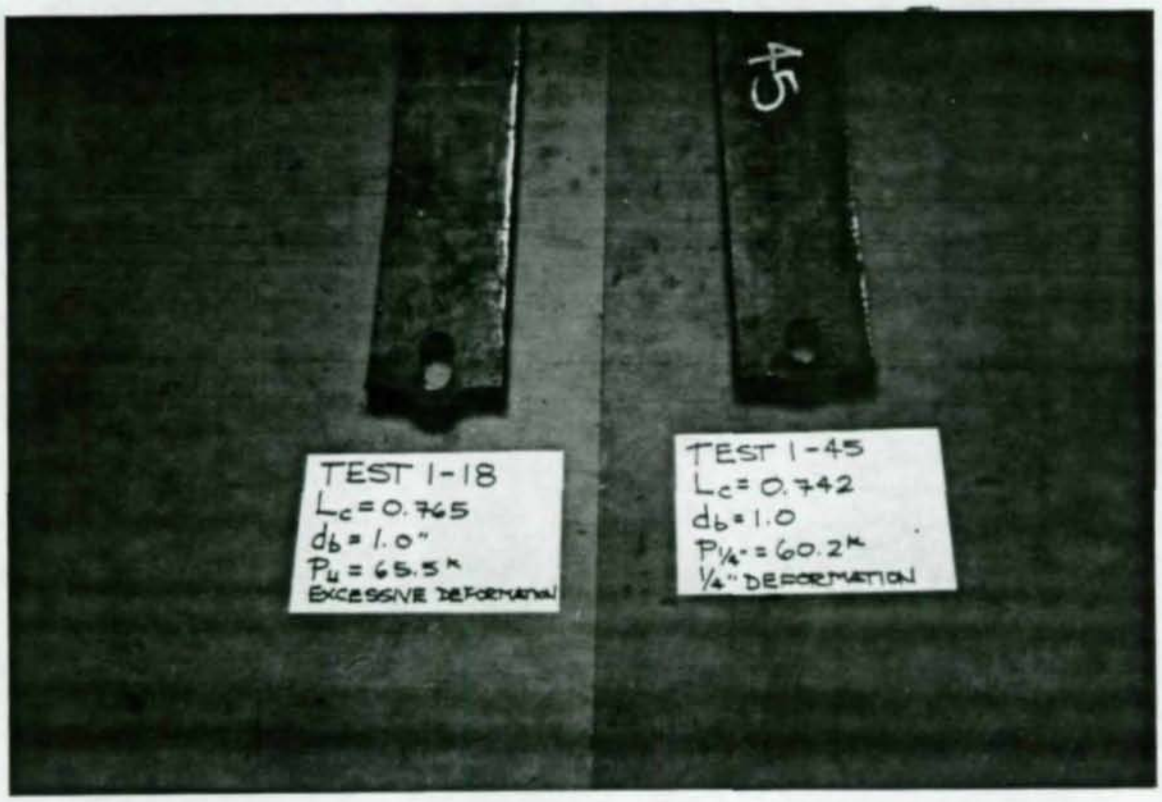


Figure 16. Two Failures for 1 in. Diameter Single-Bolt Specimens with Medium End Distances. The specimen on the left was tested to end tearout, while the specimen on the right was tested to 1/4 in. deformation. The maximum load for the specimen on the left was nine percent higher than for the specimen on the right.

Figure 17. Two Failures for 1 in. Diameter Single-Bolt Specimens with Large End Distances. The specimen on the left was loaded through a large deformation, while the one on the right was stopped at 1/4 in. deformation. The maximum load for the specimen on the left is twenty-three percent higher than for the specimen on the right. There was a bolt failure during the test on the left; therefore, the result is not plotted.

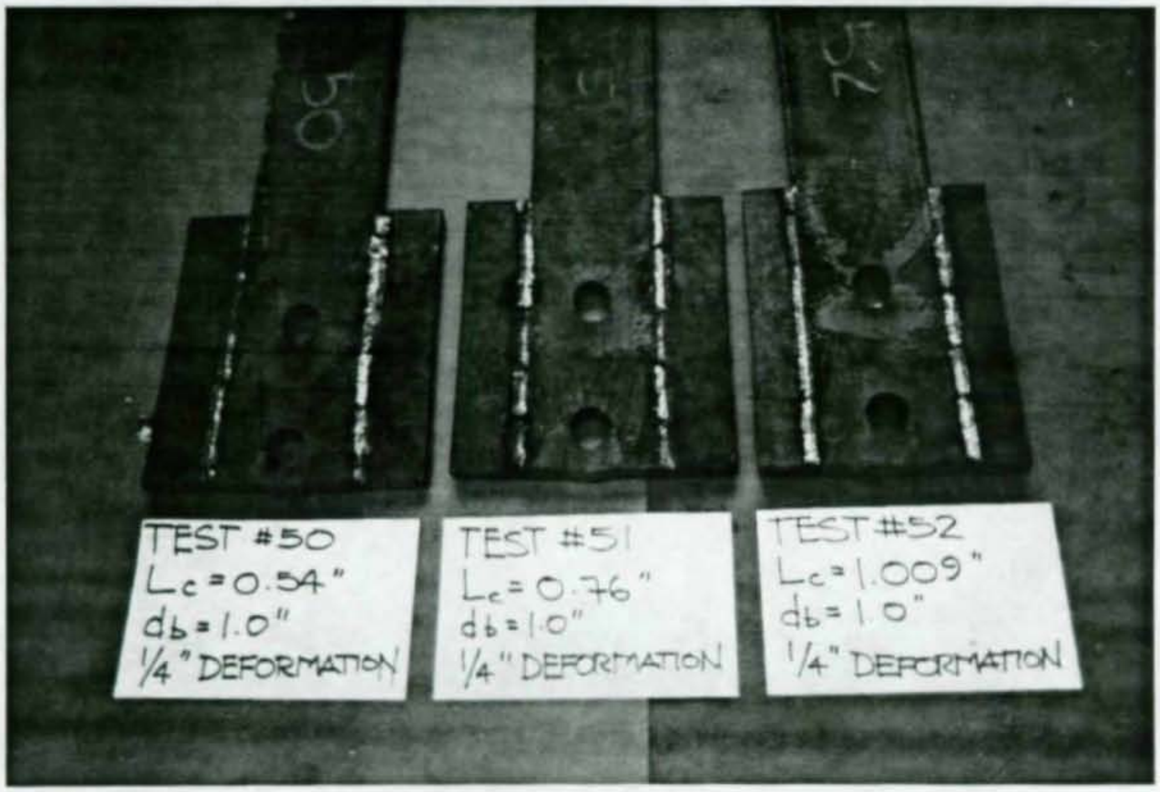


Figure 18. Comparison of 1/4 in. Deformations on Two-Bolt Specimens with 1 in. Diameter Bolts. The failure load for the specimen in the middle is 151 kips. This is less than the additive results from the specimens in Figures 16 and 17 (60.2 kips + 103 kips = 163.2 kips). The clear end distances for the specimens in Figures 16 and 17 are approximately equal to the clear end distance and clear spacing for the specimen in this figure.

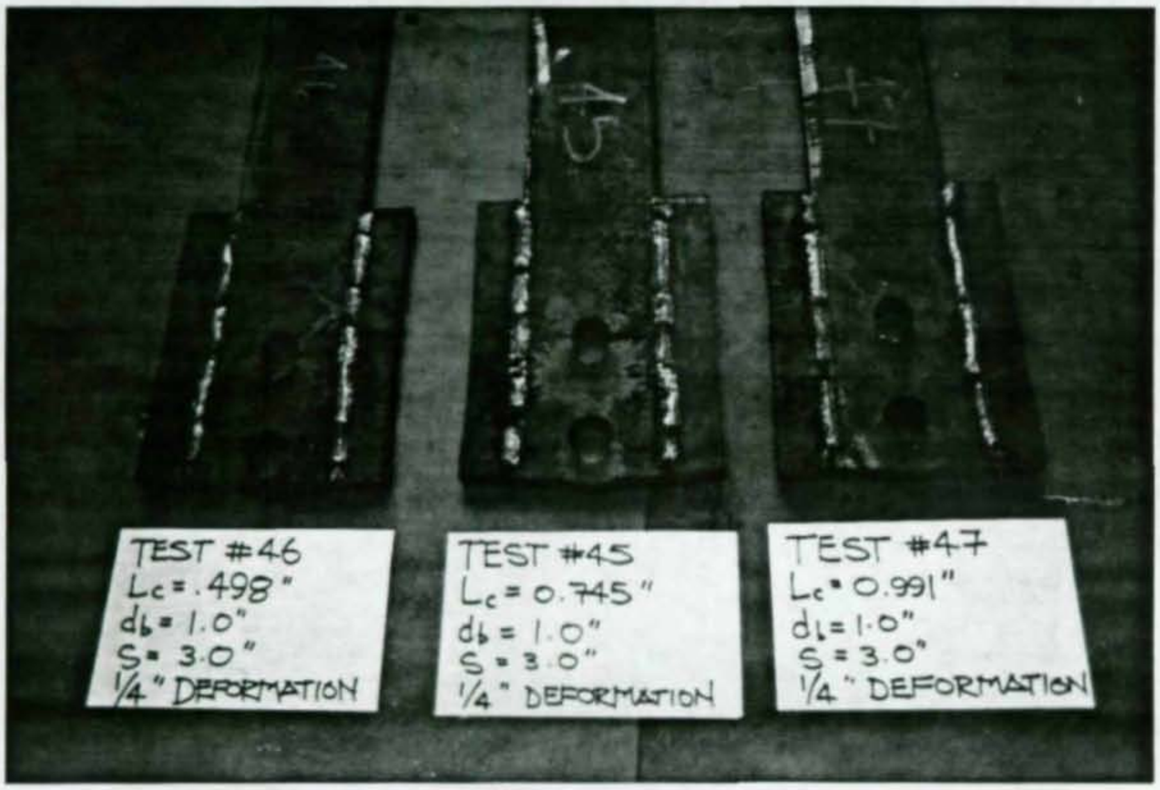


Figure 19. Comparison of 1/4 in. Deformations on Two-Bolt Specimens with 1 in. Diameter Bolts and 3 in. Bolt Spacing. The failure load for the specimen in the middle is 146.8 kips. This is less than the additive results from the specimens in Figures 16 and 17 (60.2 kips + 103 kips = 163.2 kips). The clear end distance for the bar in Figure 16 is approximately the same as for the bar in this figure, and the clear end distance for the bar in Figure 17 is approximately the same as the clear spacing for the bar in this figure.

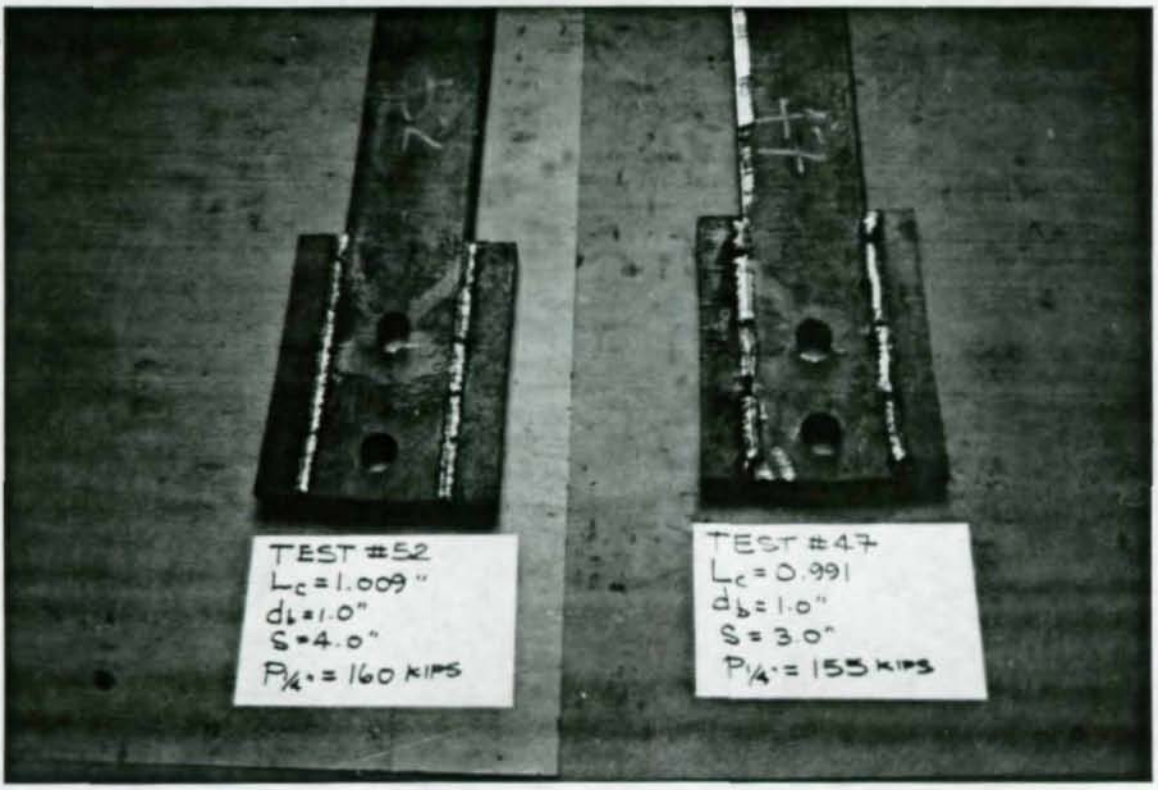


Figure 20. Specimens Showing the Effect of Bolt Spacing on Failure Loads. The spacing on the right is equal to $3d_b$, which is the recommended spacing to achieve a bearing stress of $2.4F_u$.

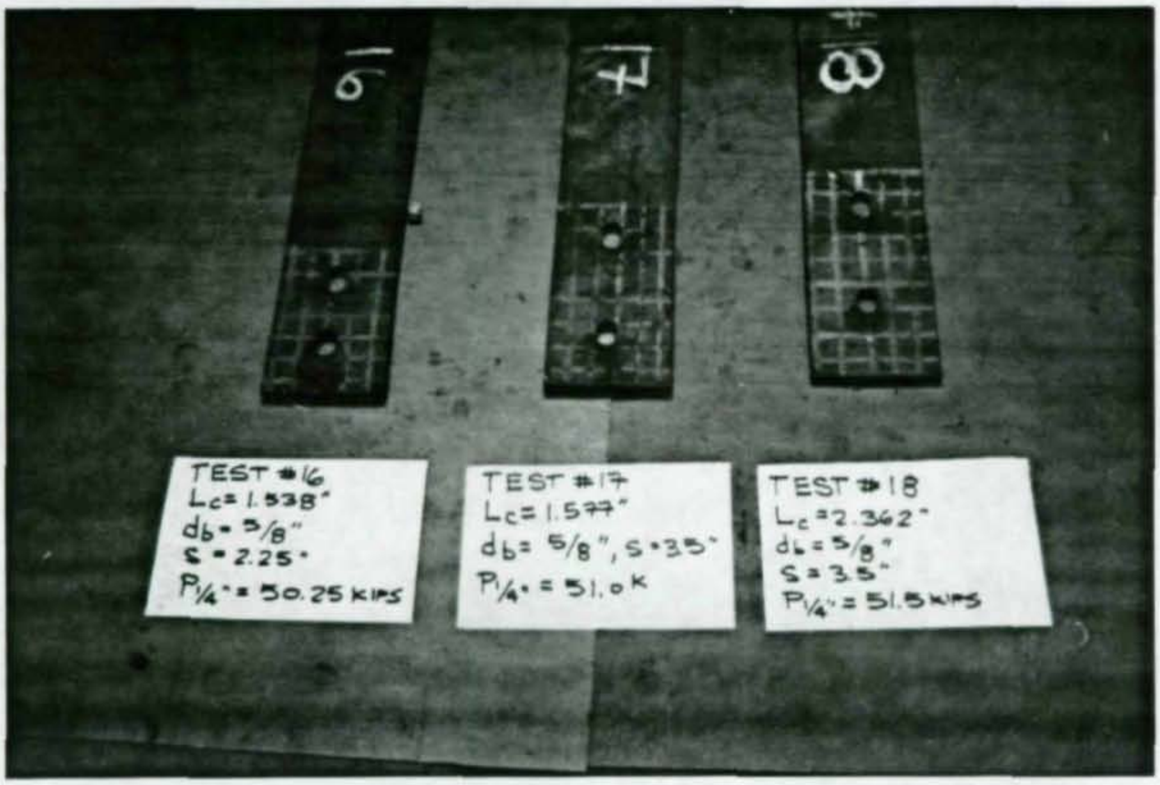


Figure 21. Comparison of Failure Loads for Two-Bolt Specimens with 5/8 in. Bolts. All spacings are greater than $3d_b$.

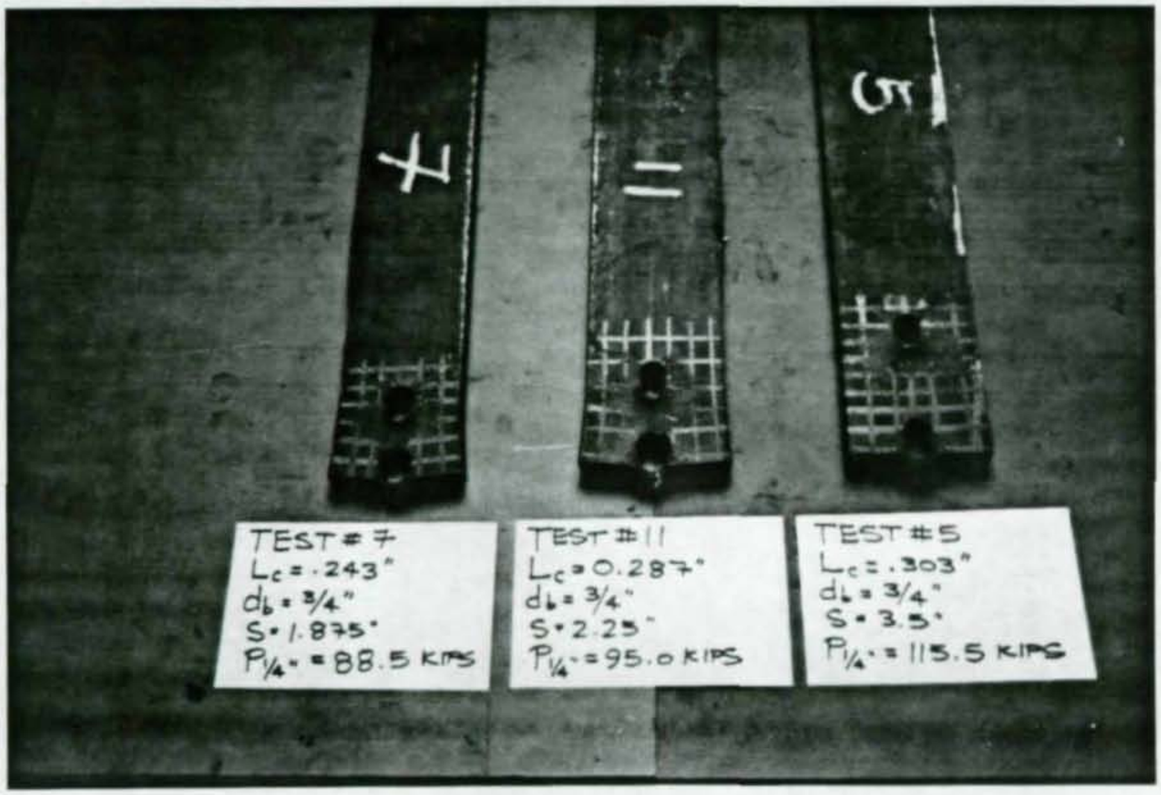


Figure 22. Specimens Illustrating the Effect of Bolt Spacing on Failure Load When End Distances are Small and 1/4 in. Deformation is Used as the Failure Criteria. Maximum load increases as bolt spacing increases.

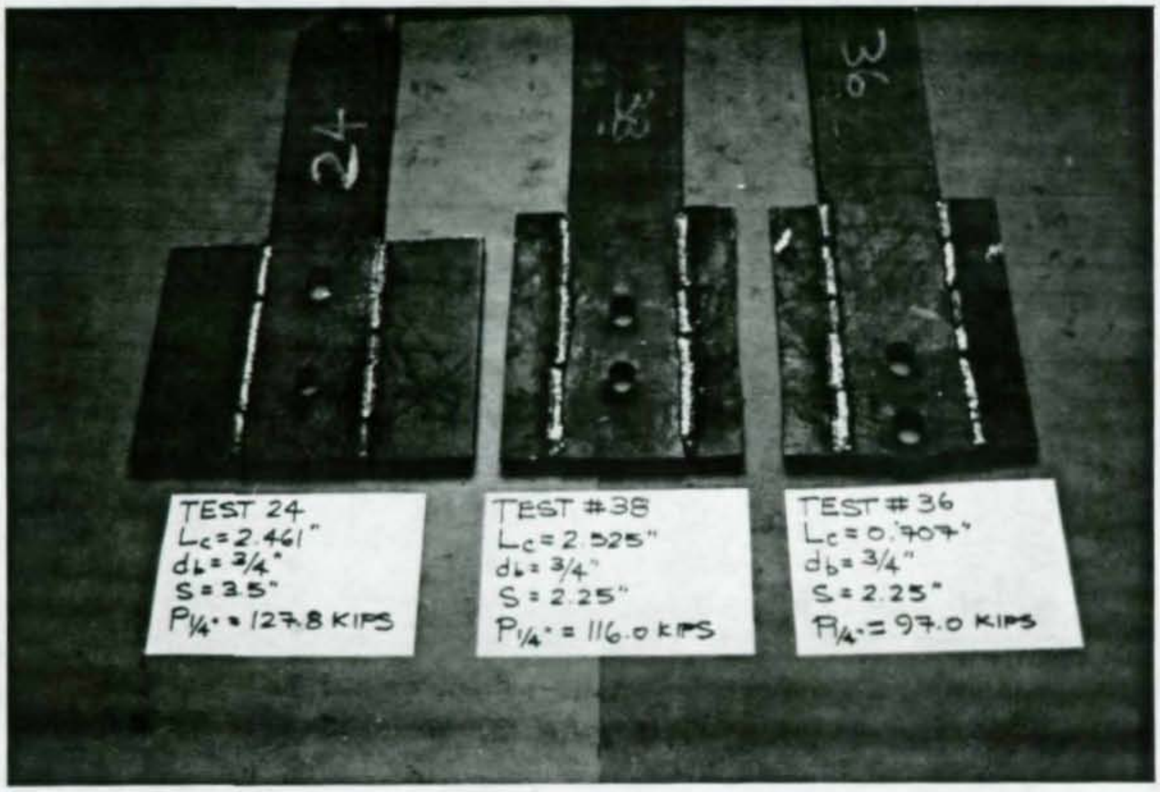


Figure 23. Specimens Built with 3/4 in. Diameter Bolts and Capable of Resisting a Bearing Stress of $2.4F_u$ According to the AISC/LRFD. Only the specimen with 3.5 in. bolt spacing and 2.461 clear end distance is capable of resisting $2.4F_u$ at 1/4 in. deformation.

Figure 24. Specimens Built with 5/8 in. Diameter Bolts and Capable of Resisting a Bearing Stress of *2.4F_u* According to the AISC/LRFD. Only the specimen with 3.5 in. spacing and 2.512 in. clear end distance is capable of resisting $2.4F_u$.

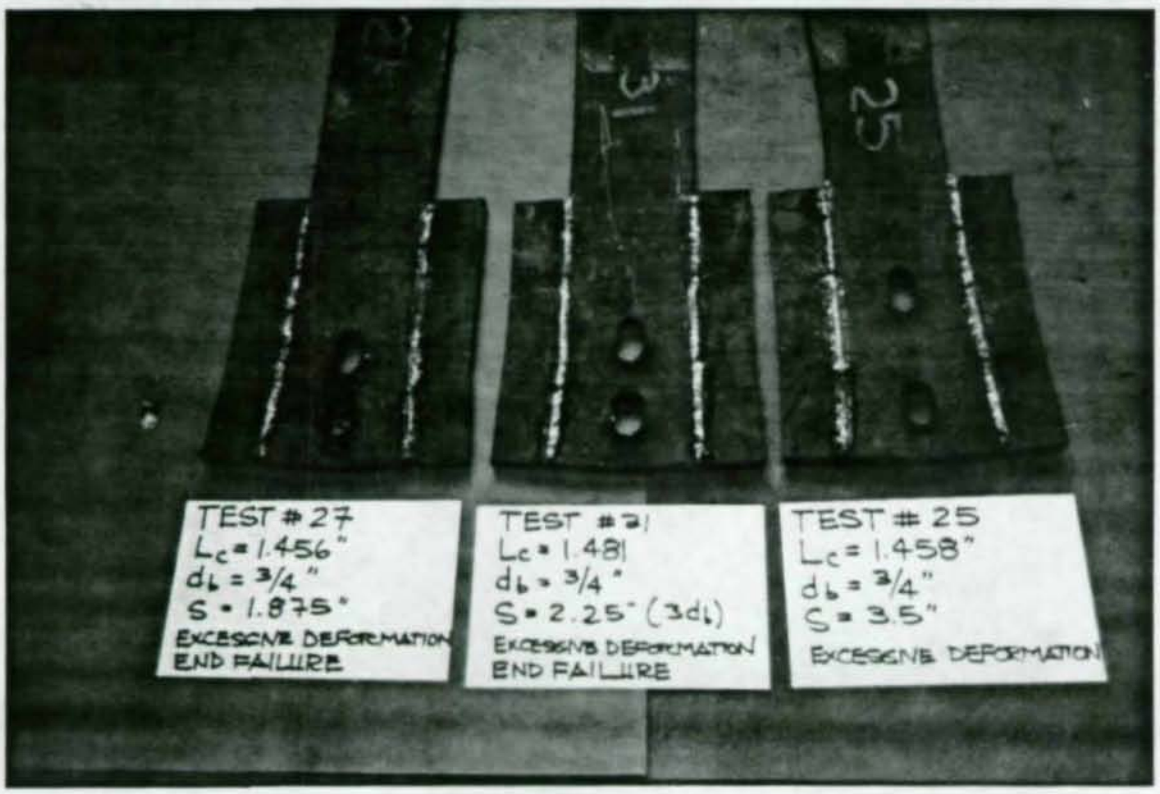


Figure 25. Comparison of Deformation Patterns on Specimens with 3/4 in. Bolts and Different Bolt Spacings. The top of the end hole in the specimen on the left is flattened due to the force from the bolt above.

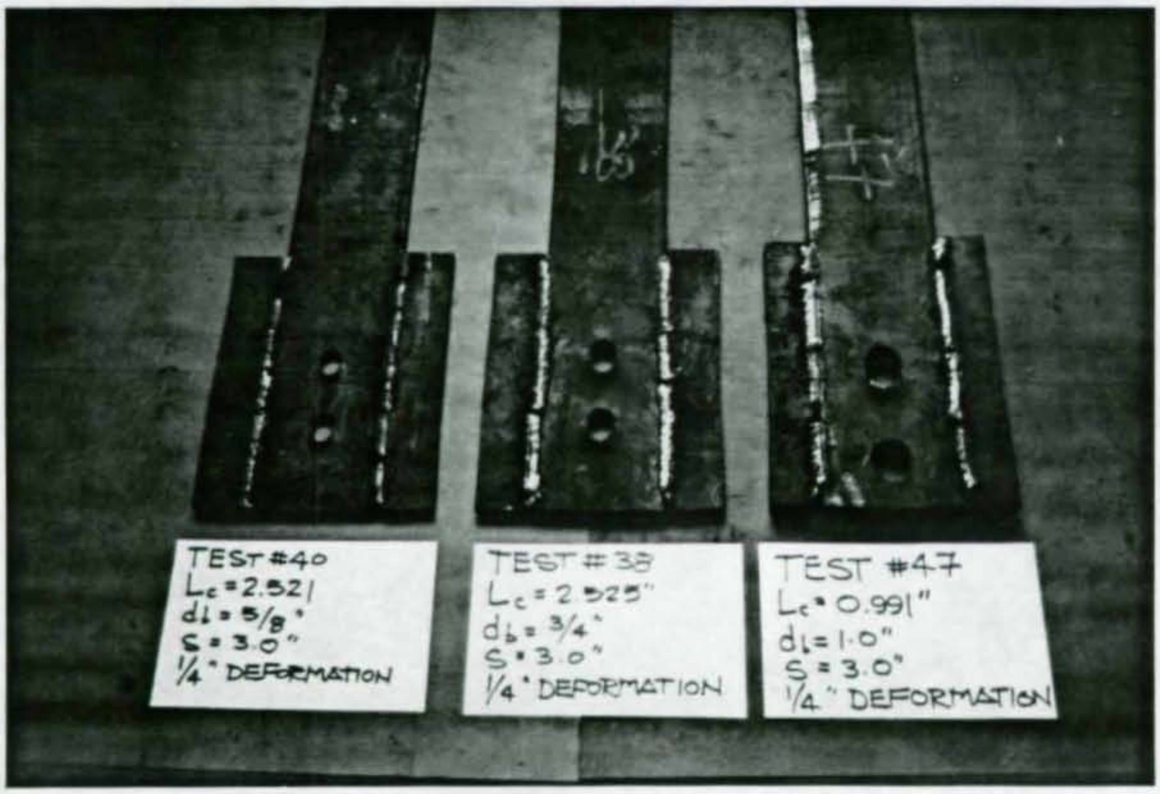


Figure 26. Comparison of Two-Bolt Specimens with 1/4 in. Deformation and Different Bolt Diameters. The 1/4 in. limit is a larger percentage of the 5/8 in. diameter; therefore, the bearing stress required to reach this limit is higher for the 5/8 in. diameter bolt.