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An Investigation of Welded Seat Angle Connections†

By INGE LYSE* and NORMAN G. SCHREINER**

Preface

The rapid advance of the process of welding in steel construction has brought forth a number of interesting research problems. One of these problems relates to the shelf-angles that are commonly used in structural practice. From an economic view-point it is desirable to know the minimum size of weld made necessary by the respective requirements of vertical shear and of bending, the bending being affected by the nature and position of the load.

This question is answered in the series of investigations conducted by the Structural Steel Welding Research Committee of the American Bureau of Welding in cooperation with the Fritz Engineering Laboratory of Lehigh University. An interesting by-product is the indication of the advantage of rolling large radius fillets on the steel shelf angles themselves.

The cooperative arrangement made between the Committee and Lehigh University illustrates the excellent work that can be done in a university laboratory under the guidance of a technical committee. Perhaps of equal importance is the familiarizing of young student engineers with the possibilities of welding and its various applications.

LEON S. MOISSEIFF, *Chairman,*
Structural Steel Welding Committee

Synopsis

THE following report presents the results of tests of twenty-nine welded seat angle test specimens and the correlative tests of four full-size beam-column connections. The test specimens consisted of two angles welded along the ends of their vertical legs to either side of a plate. The load was applied at three different positions on the outstanding leg. The full-size connections were built up of stub columns with the seat angles welded thereon in the manner described above, and a 20-in. I-beam supported on the outstanding legs. The I-beam was held in place by tack welds or bolts between the flange and the outstanding leg.

The results of the investigation show the effect of the thickness of the angle, the location of the resultant reaction of the beam, the length of the vertical leg of the angle and the strength of the weld on the strength of the seat angle connection. The high concentration of stress at the end of the beam and its effect upon the effective lever arm are pointed out. In general, the failure of this type of connection was gradual and would cause excessive deflection of the beam rather than a collapse of the structure. Since the tests were stopped slightly beyond the load required to fracture the weld at the heel of the angle, the recorded load is not the maximum that this connection can carry, but may be defined as the maximum that can be carried without excessive deflection.

The analysis of the results is the basis of the recommendations for the design of angles, welds and beams presented in the last section of this paper.

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I. Introduction

1. *Acknowledgment.*—This investigation was carried on as one of the projects of the Structural Steel Welding Committee of the American Bureau of Welding in cooperation with Lehigh University, using the facilities of the Fritz Engineering Laboratory. The steel necessary was furnished through the courtesy of the Bethlehem Steel Company and all fabrication was done in the university shop. Acknowledgment is made to all members of the Structural Steel Welding Committee for their many helpful suggestions and criticism and particularly to the Chairman, Mr. L. S. Moisseiff, Messrs. E. H. Ewertz, H. H. Moss, H. M. Priest and W. Spraragen. Acknowledgment is also due to Mr. C. H. Mercer, Consulting Engineer, McClintic-Marshall Corporation and Mr. V. E. Ellstrom, Manager of Sales Engineering, Bethlehem Steel Company, for furnishing the structural steel, to Mr. C. C. Keyser, Assistant in the Fritz Engineering Laboratory and Professor C. D. Jensen of the Department of Civil Engineering for their valuable assistance and cooperation, to Professor J. B. Reynolds of the Department of Mathematics for assistance in the theoretical analysis, and to Mr. D. M. Stewart, Research Fellow in Civil Engineering for the supplementary studies by means of photoelasticity.

2. *Purpose of the Investigation.*—The investigation of welded seat angles was made in order to obtain experimental information from which a rational theory of design could be evolved for their economic use in welded structures. In general, seat angles are used in two ways in structures:

(*a*) As an erection seat, for the purpose of supporting the end of the beam during erection and prior to the attachment of the web angles which carry the end reaction.

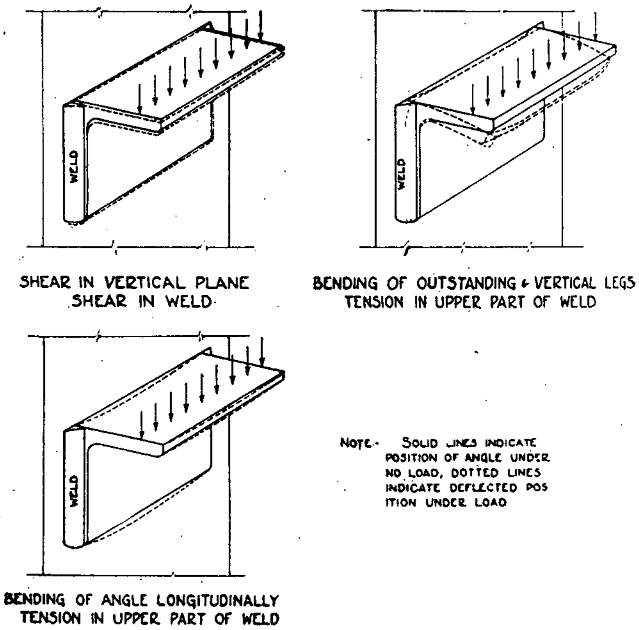


Fig. 1—Illustration of the Seat Angle Problem

Used in this way, the strength needs only be sufficient to preclude construction failure or damage in transit.

(*b*) As a load carrying member, transferring the end reaction of the beam to the column. Used thus, the beam which they support must be held against lateral as well as vertical displacement. If the beam supports a rigid flooring, such as a concrete slab, it may be considered as adequately supported laterally. However, if the beam supports a more flexible floor or is a member of an open framework, lateral support is necessary. This may be accomplished by the use of a top angle or web angles, neither of which is considered as carrying any of the vertical load.

II. General Statement of the Problem

While there are many varieties of beam seats, and structural welding engineers are designing new types whenever the opportunity presents itself, this investigation has been confined to the simplest possible type, and the one most widely used at present, namely, a simple angle seat welded to the column by means of vertical fillet welds at each end of the vertical leg. The lower flange of the supported beam may be welded or bolted to the outstanding leg of the angle. This type of beam seat is also in common use in riveted structures, and the results of this investigation apply equally well to these angles, if necessary corrections due to the different manner of attachment to the column are made.

The problem of this welded seat angle type of connection is illustrated in Fig. 1, and may be divided into three parts.

(*a*) Owing to the reaction of the load on the angle, there is a vertical shear imposed on the weld causing a downward deflection.

(*b*) Owing to the moment *Wa* (see Fig. 2), the outstanding leg bends downward and the vertical leg bends away from the column at the heel of the angle. This action of the vertical leg produces a corresponding compressive reaction toward the toe of this leg of the angle. The existence of a compression between the back of the vertical leg and the face of the column introduces an upward frictional force which offsets part of the vertical load and reduces the downward deflection due to the vertical shear strain in the weld. For a short distance from the ends of the angle, the weld restrains the vertical leg from bending outward. It follows that there is a warping of the surfaces of the angle.

(*c*) The angle acts as a short, stubby beam, elastically restrained at the ends by the weld. This action causes a greater deflection at the center than at the ends and further modifies the shape of the outstanding leg.

The beam flanges which are supported by the angle bend under the reaction and cause the reaction to be concentrated on an area under the web. The amount of this bending is determined by the relative stiffness of the flange and the outstanding leg. Since the flanges are also fastened to the outstanding leg, the two act more or less as a unit and the state of stress in the outstanding leg is thereby affected.

The stress condition in the weld itself is rather complex consisting of a combination of vertical shear and bending in two directions. The vertical shearing stress is of small importance except in certain combinations of sizes of angle and weld. Ordinarily the determining factors are the stresses set up by the bending moments.

III. Test Program

1. The test program as approved by the Committee consisted of two types of specimens designated as Series A and Series B. Series A was designed to permit the study of each variable in turn at a minimum of expense, while Series B consisted of full-size beam-column connections, permitting the correlation of the results on the

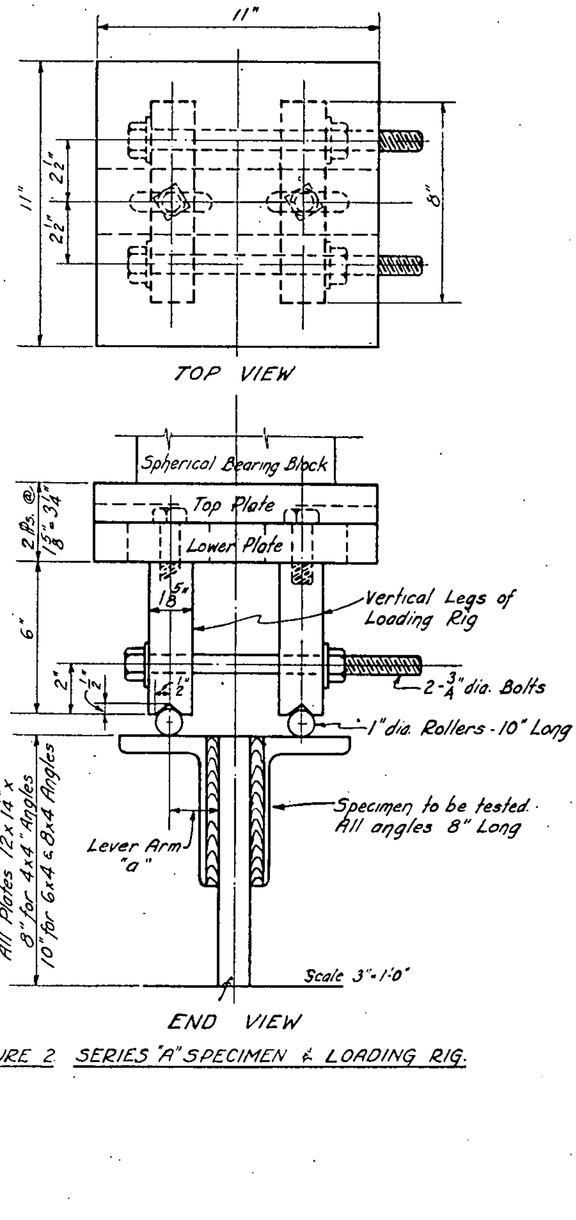


FIGURE 2 SERIES "A" SPECIMEN & LOADING RIG.

Series A specimens with those obtainable in actual practice. Series A consisted of twenty-nine specimens, Series B of four specimens.

(*a*) *Series A*—a simple, balanced test specimen was prepared as shown in Fig. 2 consisting of a central plate, on either side of which the angles were welded, care being taken to place them directly opposite each other. The load was applied through rollers symmetrically placed on each angle, thus avoiding the necessity of taking care of any eccentricity.

(*b*) *Series B* consisted of a 20-in. loading beam (I 20a, 81.4 lb.) 18 ft. 1/2 in. long, resting on seat angles 8 in. long, which in turn were welded to stub columns made up of 10-in. H-sections (B10b, 54 lb.) 12 in. long. Figure 3 shows the details of the end connections and gage points, and Fig. 4 shows a specimen ready for test. The lower flange of the beam was welded or bolted to the outstanding leg of the angle.

(*c*) *Welding.*—The welding was performed in the laboratory shop under direct supervision. The operator passed the qualification tests of the Structural Steel Welding Committee, American Bureau of Welding. The welding electrode for the major part of the investigation was a lightly coated electrode, conforming to A. W. S. Specification Class E40[1] of 5/32-in. and 3/16-in. diameter. The D.C. arc characteristics were, voltage 17 to 19, amperes 165 to 200, dependent on the electrode diameter and size of the work. The average strength of the standard 3/8-in. end-fillet welded qualification specimen was 13,250 lb. per lin. in., corrected for over-sized dimensions. The required average strength per lin. in. was 12,000 lb.

Heavily coated electrodes 3/16 in. in diameter of several commercial types were also used. D.C. arc characteristics were voltage 35, amperes 220. The average strength of the standard 3/8-in. end-fillet welded qualification specimen was 16,390 lb. per lin. in. The ductility, as determined by the free-bend test, ranged from 20 to 34 per cent.

The use of heavier bars in this type of qualification specimen seems advisable in order to produce failure in the weld directly, rather than a secondary failure due to excessive yielding of the parent metal. This is especially desirable on the specimens in which heavily coated electrodes are used.

Where multi-layer welding was specified the previous layers were carefully cleaned of scale by means of a stiff wire brush and file before adding the next layer.

The welds were carefully gaged and without exception were within the designed limits of minus 0, plus 1/8 in. A rigid specification and procedure control was laid out and followed, in consequence of which uniform results were obtained. Some difficulty was encountered in obtaining proper fusion between the heel of the angle and the plate, but failure specifically due to improper fusion at this point occurred in only three welds.

(*d*) *Angles.*—The angles were of stock size, cut on a power saw to a length of 8 in. ± 1/16 in. The outstanding leg in all cases was 4 in.; the vertical leg was 4, 6 or 8 in. The thickness varied from 1/2 in. to 1 in. The angles were clamped to the plate preparatory to welding, care being taken so that the outstanding legs were parallel to the bearing edge of the plate.

(*e*) *Specimen Nomenclature.*—In designating the specimens, a combination of letters and numbers was used as follows:

Specimens of Series A used the series letter followed by four numbers for identification, those of Series B used the series letter followed by three numbers. For example, in the symbol A 444-2:

First, letter A indicated the series to which the specimen belonged.

[1] A. W. S. Specifications for Filler Metal (Revised June 1, 1933).

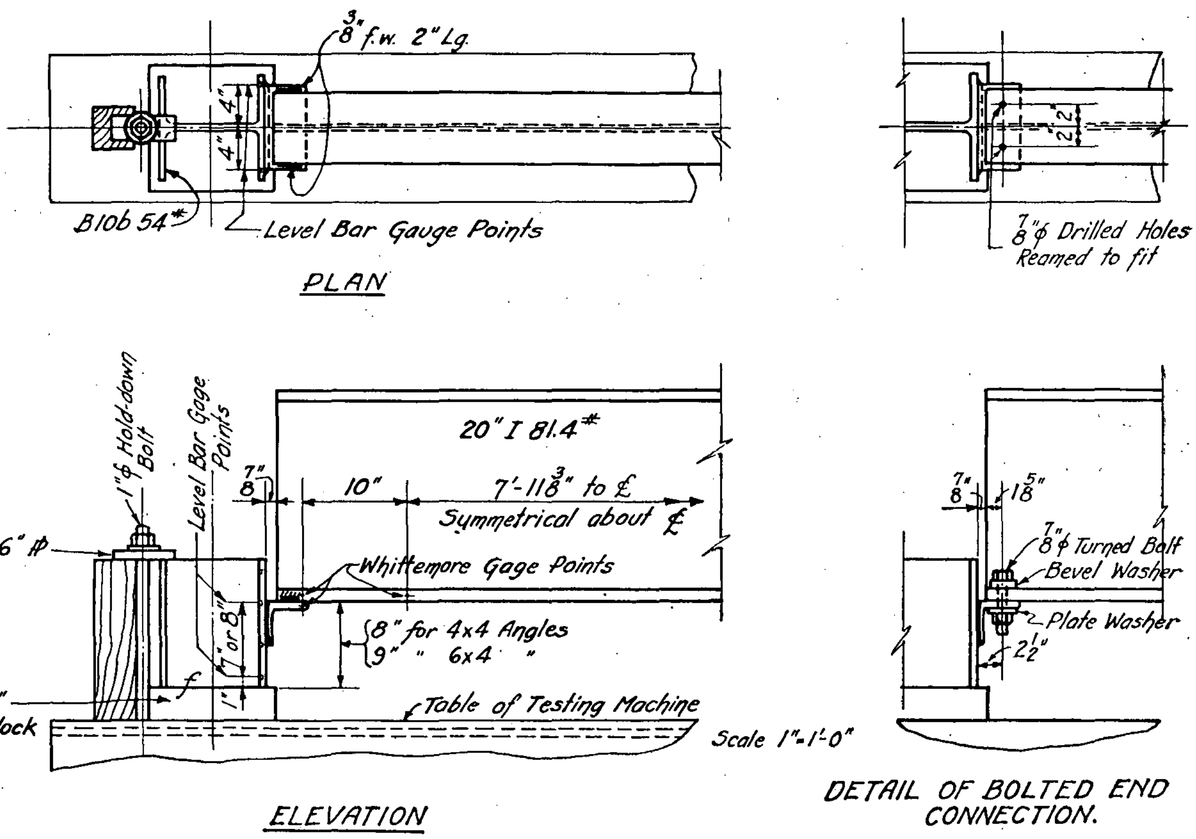


FIGURE 3. DETAILS OF END CONNECTION AND GAGE POINTS - SERIES B.

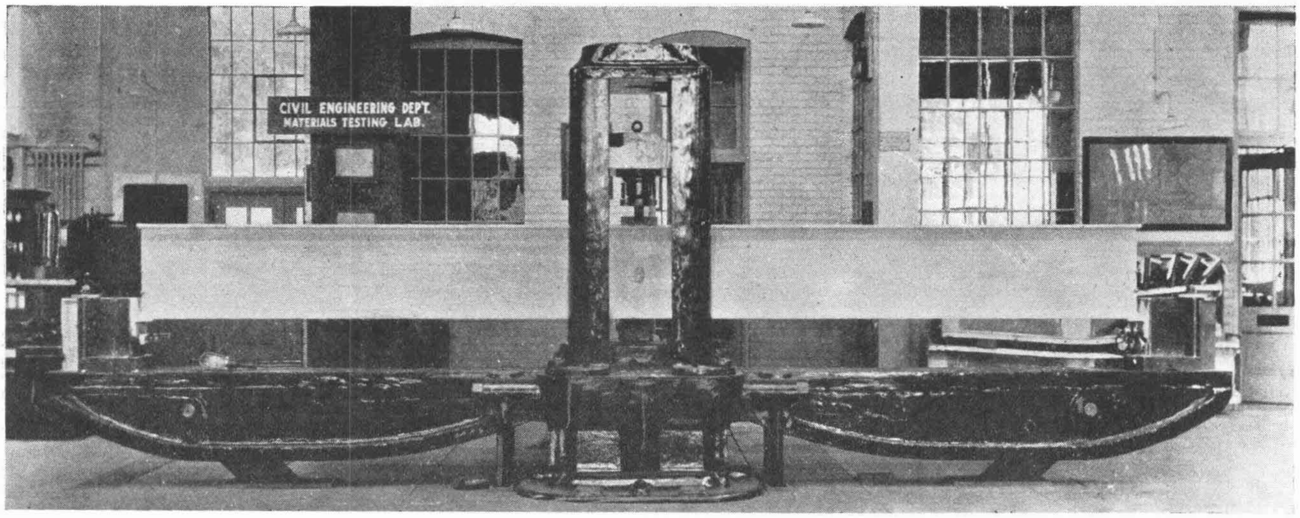


Fig. 4—Series B Specimen Ready for Testing

First numeral 4 indicated the length of the vertical leg of the angle in inches.

Second numeral 4 indicated the thickness of the angle in eighths of an inch.

Third numeral 4 indicated the size of the fillet weld in eighths of an inch.

Second letter, if used, indicated special points of difference from the general type as explained in notes accompanying the data.

Last numeral 2 indicated the lever arm at which the test was made, 1 indicating a 1.2-in. lever arm while 2 and 3 indicate 2.0-in. and 3.0-in. lever arms, respectively. This final figure was omitted in the specimens of Series B since the exact location of the resultant load was unknown. In this paper, the term lever arm will signify the distances from the back of the angle to the point of application of the load and will be designated by "*a*" (see Fig. 2).

2. *Factors Studied.*—The following factors affecting the behavior of the connection were studied:

(*a*) Effect of the lever arm of the load, in both longitudinal and lateral directions.

(*b*) Effect of the thickness of the angle.

(*c*) Effect of the length of the vertical leg of the angle.

(*d*) Effect of the size of the wled.

(*e*) Effect of the type of welding rod.

(*f*) Location of the reaction of the beam on the seat angle.

3. *Description of Loading Rig and Gaging Devices.*—(*a*) *Series A.*—The specimens of Series A were tested in the 300,000-lb. or the 800,000-lb. capacity testing machines in the Fritz Engineering Laboratory. The load was applied through an adjustable loading rig shown in Fig. 2, consisting of a top section of two steel plates, the top one of which was channeled to clear the bolt heads. The lower plate was slotted along the center line to provide easy adjustment of the vertical legs on which it rested. The vertical legs were held in any desired position by means of cap bolts passing through these slots into tapped holes in the vertical legs. The load was applied by the head of the machine through a spherical bearing block resting on the top plate.

The method of holding the 1-in. diameter rollers through which the load was applied was changed three times as requirements indicated. In the first type, Fig. 5, used only on Specimen A 443-1, the bottom of the vertical legs of the loading rig were plane and rested on the rollers, which were thus nearly free to roll, being restrained only by light spring steel fingers. Owing to the outward deflection of the angle, the secondary horizontal force pulled the vertical legs of the loading rig apart, thus increasing the lever arm. To correct this defect two $^3/_4$-in. diameter bolts were introduced, as shown in Fig. 6, to hold the vertical legs of the loading rig in position until the welds fractured. After this occurred the deflection of the outstanding legs increased materially and the bolts generally yielded slightly. The maximum increase in lever arm due to this effect averaged nine per cent at final load, with a maximum increase of sixteen per cent in the case of Specimen A 864-1. Below the load at which the weld fractured the nominal lever arm was maintained within the limits of observation. In this set-up the rollers were still nearly free to roll and the horizontal restraining force on the outstanding leg of the angles was considered negligible. This type of loading was used on Specimens A 443-2, A 443-3, A 444, A 643, A 654 and A 444a.

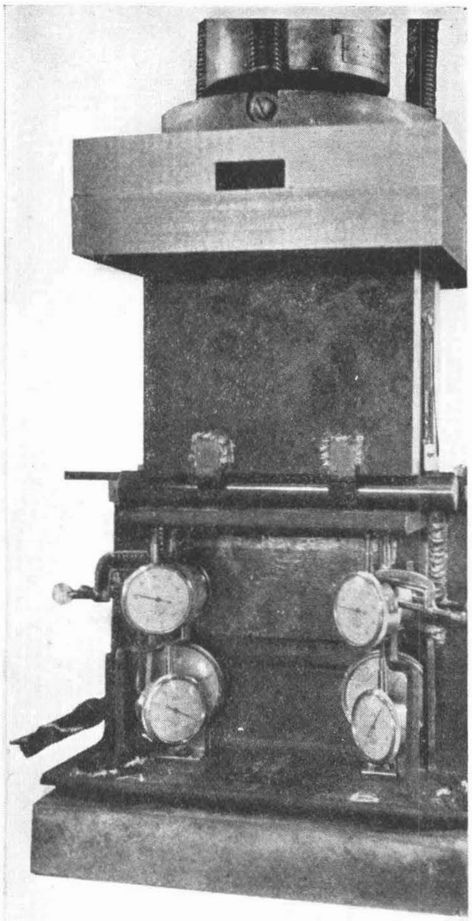
In the third set-up, the rollers were restrained in V's cut in the bottom of the vertical legs as shown in Fig. 6. This construction prevented the rollers from moving laterally and introduced a horizontal restraining force counteracting the tearing effect at the top of the weld. This type of loading rig was used on all the remaining specimens of Series A.

The load was applied over the full 8-in. length of the angle in all specimens except A 644X-1 and A 644Y-1 where the loading was through rollers 1 in. and 3 in. long, respectively. These rollers were centered longitudinally on the outstanding leg and observations were made at 3.0, 2.0 and 1.2-in. lever arms.

(*b*) *Observations.*—Measurements of the downward deflection of the outstanding leg were taken at measured intervals by two groups of four Ames dials, each group on gage lines 1 in. in from each end of the angle. The plungers of the dials were extended as necessary by means of hardened steel pins. The two dials closest to the vertical leg read to 0.0001 in. while the outer two dials of each group were graduated to only 0.001 in. Figure 5 shows the arrangement of these dials.

Tensile strains in the top end of the welds were measured with Huggenberger Tensometers using the $^1/_2$-in. gage length on Specimens A 444, A 444a, A 643, A 644 and A 654. The weld was first piled up slightly during fabrication and then filed off flush with the outstanding legs of the angle. One knife edge of the tensometer was set on the weld metal and the other on the plate, the $^1/_2$-in. gage length being divided equally between the weld and the plate.

Fig. 5—Side View of First Loading Rig and Ames Dials



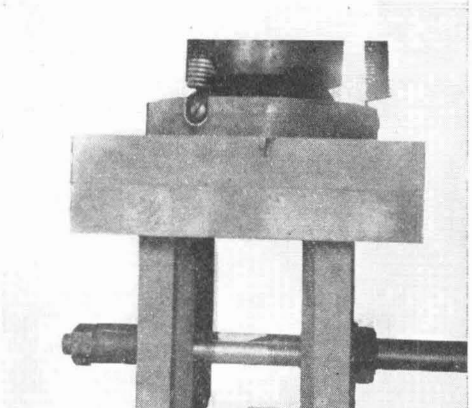
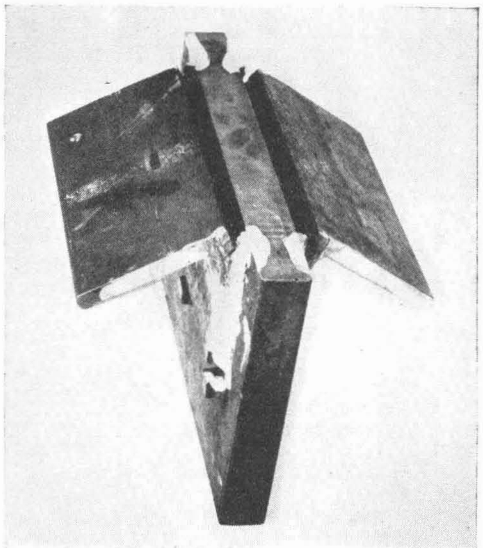


Fig. 6—End View of Final Loading Rig Showing Bolts Restraining the Vertical Legs and U-Grooves

Five tensometers equally spaced along the toe of the vertical leg of the angle measured the downward deflections of the angle with respect to the plate. Figure 6 shows a set-up ready for testing with tensometers on both angles. In most tests the groups of Ames dials were placed on one test angle and the five tensometers on the opposite angle.

Fig. 7—Typical Specimen at Completion of Test — Specimen A 443-2



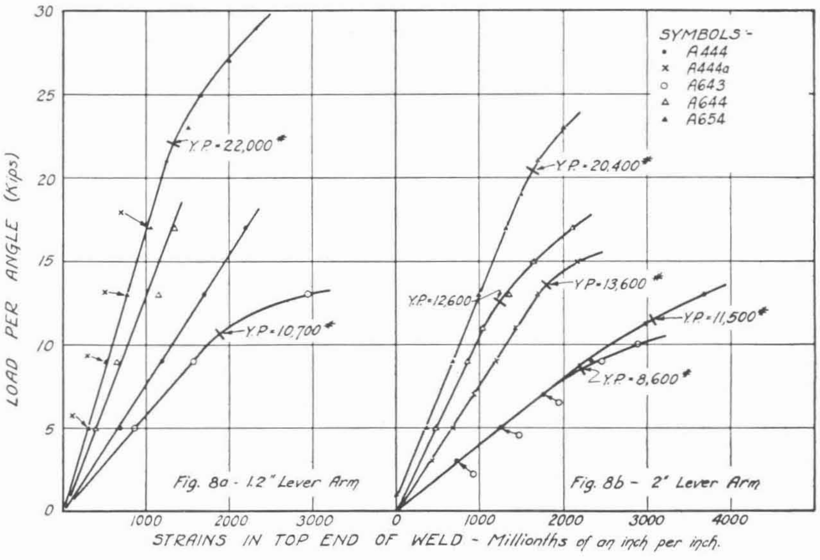


FIGURE 8. LOAD-STRAIN DIAGRAMS FOR WELDS.

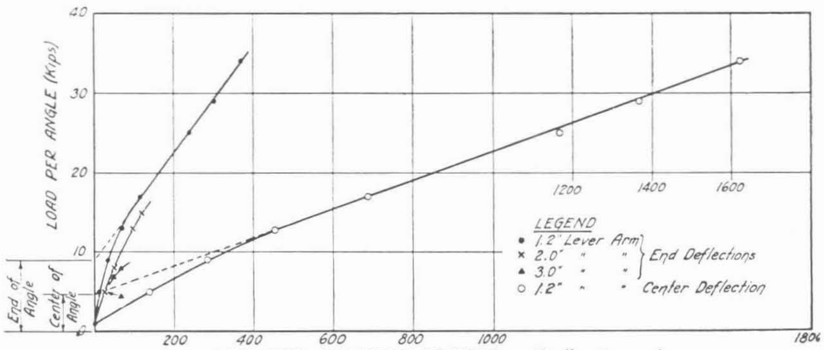


FIGURE 9 LOAD-DOWNWARD DEFLECTION CURVES TYPICAL FOR BOTH SERIES OF TESTS

(*c*) *For Series B* the 20-in. I-beam was loaded at the quarter points. A set of Ames dials measured the downward deflections of the outstanding leg of one of the test angles and five tensometers measured the total downward deflections of the other test angle. Strains in the beam flange and slip between the test angle and the beam end were measured on both sides of each end over a 10-in. gage length with a Whittemore strain gage reading to 0.0001 in. The deflection of the beam at the center was measured by the mirror, scale and wire method. The tilting of the columns was measured by means of a level bar of 3-in. base line at six-gage points on the back of the column flange.

In both series of tests the specimens were completely coated with a thin mixture of hydrated lime and water in order to better observe strain lines and cracking.

4. *Test Procedure.*—(*a*) *Series A.* Complete observations were taken at three lever arms on each specimen, namely, 3.0, 2.0 and 1.2 in. in succession, up to the yield point of the specimen as determined by disproportionate deflection and/or by cracking or scaling of the whitewash. The load was applied at a head speed of 0.05 in. per minute. The increments of load were such that approximately six points would be obtained below the yield point. In the case of the 3-in. and 2-in. lever arms, the load was slowly released after the yield point was reached and the rollers were moved in to the next shorter lever arm. In the case of the 1.2-in. lever arm the instruments were removed after the yield point was reached and the load continuously applied until the conclusion of the test. Observations were made of the scaling of the whitewash on the angle and welds and of the cracking of the welds at the top end. The test was concluded when the specimen refused to take any further load without excessive deflection, at which time the heel of the angle had generally been bent away from the plate approximately 3/8 of an inch. Final observations were made as to the location of the rollers, and the general appearance of the welds and angle.

(*b*) *Series B.* Readings on the instruments were taken from an initial load in small increments up to the final load. The speed of the head of the machine was 0.05 in. per minute. Observations were made with respect to scaling of the whitewash in any part of the specimen with particular attention paid to the behavior of the welds.

Table 1—Physical Properties of Steel in the Seat Angles

Size of Angle In.	Yield Point Lb./In.²	Ultimate Strength Lb./In.²	Per Cent Elongation in 2 In.	Per Cent Reduction of Area	Modulus of Elasticity Lb./In.²
(1)	(2)	(3)	(4)	(5)	(6)
4 × 4 × 1/2	32,400	58,510	37.0	69.3	29,650,000
Piece 2	40,260*	62,560	..	..	28,330,000
4 × 4 × 3/4	35,750	64,700	38.0	62.0	28,500,000
6 × 4 × 1/2	37,105	62,075	36.1	66.3	29,075,000
6 × 4 × 5/8	33,500	56,650	34.5	67.9	29,000,000
6 × 4 × 3/4	32,175	63,225	37.5	62.0	28,730,000
8 × 4 × 1/2	41,460	66,800	32.0	60.5	29,100,000
8 × 4 × 3/4	32,450	57,415	40.8	67.0	29,250,000
8 × 4 × 1	32,000	60,780	40.6	65.3	29,000,000

* Used for Specimens A 444C-1, B 444 and B 444B.

IV. Test Data

1. *Physical Properties of Materials.*—Two tensile specimens were cut from each angle used in the investigation, and observations made of the yield point as determined by the drop of the beam, ultimate strength, elongation in 2 in., reduction in area and modulus of elasticity in accordance with A. S. T. M. Specification A9-33. The results are presented in Table 1. Each value is the average of the two specimens mentioned above. The yield-point stress varied from 32,000 to 41,460 lb. per sq. in. and the ultimate strength from 56,650 to 66,800 lb. per sq. in.

2. *Seat Angle Tests.*—*Series A.* (*a*) The size and make-up of the test specimens are shown in Table 2, columns 2 to 5, inclusive. The test results are given in the remaining portion of the table. All these specimens

Table 2—Test Results of Series A Specimens

Specimen No.	Size of Angles In.	Weld Data: Fillet Size In.	Weld Data: Total Length In.	Lever Arm at Failure In.	Load per Angle (Lb.): Scaling of Fillet of Angle	Scaling at Top End of Weld	Crack in Top End of Weld	Final Load
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
A 443-1	4 × 4 × 1/2	3/8	8	1.2	29,950	28,550	29,325	30,430
2	4 × 4 × 1/2	3/8	8	2.0	16,800	21,000	22,225	31,250
3	4 × 4 × 1/2	3/8	8	3.0	10,400	12,350	13,470	13,470
A 444-1	4 × 4 × 1/2	1/2	8	1.2	.....	32,000	39,000	39,380
2	4 × 4 × 1/2	1/2	8	2.0	18,850	18,500	24,000	24,000
3	4 × 4 × 1/2	1/2	8	3.0	10,100	10,000	11,250	13,840
A 463-1	4 × 4 × 3/4	3/8	8	1.2	71,000	89,500	100,000	112,250
A 464-1	4 × 4 × 3/4	1/2	8	1.2	73,000	91,000	101,000	133,835
A 466-1	4 × 4 × 3/4	3/4	8	1.2	67,500	116,250	176,500	185,500
A 643-1	6 × 4 × 1/2	3/8	12	1.2	.....	33,800	38,550	41,650
A 644-1	6 × 4 × 1/2	1/2	12	1.2	37,000	40,500	46,000	67,305
X-1	6 × 4 × 1/2	1/2	12	1.2	22,250	40,500	44,150	67,500
Y-1	6 × 4 × 1/2	1/2	12	1.2	25,800	40,800	43,700	78,000
A 654-1	6 × 4 × 5/8	1/2	12	1.2	53,675	60,550	74,700	98,300
A 655-1	6 × 4 × 5/8	5/8	12	1.2	57,000	84,500	102,000	116,000
A 664-1	6 × 4 × 3/4	1/2	12	1.2	100,000	100,500	136,300	183,200
A 843-1	8 × 4 × 1/2	3/8	16	1.2	49,000	53,000	74,350	98,375
A 844-1	8 × 4 × 1/2	1/2	16	1.2	53,000	63,000	74,030	82,050
A 864-1	8 × 4 × 3/4	1/2	16	1.2	87,250	112,500	132,000	174,100
A 884-1	8 × 4 × 1	1/2	16	1.2	137,500	145,000	164,500	204,000
2	8 × 4 × 1	1/2	16	2.0	55,000	84,000	120,500	140,150
3	8 × 4 × 1	1/2	16	3.0	36,150	48,000	51,450	63,175
A 886-1	8 × 4 × 1	3/4	16	1.2	137,500	145,000	170,000	230,900
A 444a-1	4 × 4 × 1/2	1/2	4	1.2	.....	35,900	45,800	52,230
A 444C-1	4 × 4 × 1/2	1/2	8	1.2	37,000	43,500	75,000	75,000
A 644C-1	6 × 4 × 1/2	1/2	12	1.2	37,000	46,300	54,150	81,000
A 644D-1	6 × 4 × 1/2	1/2	12	1.2	35,100	38,000	52,500	69,000

were welded with a lightly coated electrode, known to welders as "bare wire" except A 444C-1, A 644C-1, A 644D-1, which were welded with a heavily coated electrode. Specimen A 444a-1 was made up with only a short length of weld on either end of the angle.

(*b*) At this point it is well to describe the general procedure of observation. As mentioned previously the instruments were removed shortly after the deformations became disproportionate to the load increments, and either the loading rig was adjusted to the next succeeding test (that is, from 3.0 to 2.0 or from 2.0 to 1.2-in. lever arm) or the loading was continued to the completion of the test. The first observation was a scaling of the whitewash on the fillet of the angles starting in the center but soon scaling over the full length. The loads at which this scaling took place are noted in column 6, Table 2. The load on the angle could then be increased approximately seventeen per cent when scaling of the whitewash on the top end of the welds would next be observed, generally on one of the welds only, but often this scaling occurred on two or more welds simultaneously. These loads are presented in column 7, Table 2. Thereafter there was a redistribution of stress and the load could be increased approximately 20 per cent, at which load (column 8, Table 2), one or more of the welds would show a visible crack at the top end extending from the root of the weld outward (in many cases at an angle of approximately 30° with the end of the angle rather than directly across the throat section). From this point on small increases in load were accompanied by large increases in deformation, the weld slowly tearing with the increase in deformation. There usually occurred several points of yield when the head of the machine could not follow the deforming angle fast enough, but these seemed to have no significance. The final load, column 9, Table 2, is that load at which the test was stopped and is significant to the extent that the specimen refused to accept any further load without excessive deformation. Generally the gap between the plate and the heel of the angle was $^3/_8$ in. at the conclusion of the test. A typical specimen at the completion of the test is shown in Fig. 7.

(*c*) The deflections of the outstanding leg, as measured by the Ames dials, were plotted using total load as ordinates and observed deflections under the load point as abscissas. In all cases the resulting load-deflection curve was a straight line up to a definite yield point when the ratio of the applied load to the deflection decreased considerably.

The point at which the slope of the curve became 50 per cent greater than the initial slope was designated as the yield point. These yield-point loads averaged 83.3 per cent of those at which the whitewash scaled on the fillet of the angle.

(*d*) The observations of the strains in the top end of the welds by means of the tensometers were not entirely satisfactory since many instruments (14.5%) failed to function because of the congestion of apparatus at this location. There was some spread between the readings of the individual tensometers on the same specimen (71% of the readings were within 20% of the average), which gives some indication of the localized nature of the strains and suggests the possibility of locked-up stresses due to the welding. No correlation between these results and the method of welding seemed possible. It was noted that, as the load increased to the yield point, the portion of the load assumed by each weld, as measured by the tensometers, became more nearly equal. It was further noted that when the four tensometer readings were averaged and plotted as abscissas against the load as ordinates, see Fig. 8, the resultant curves were again straight lines up to yield point.

(*e*) The observations of the five tensometers on the lower edge of the vertical leg of the angle were plotted against the load per angle. Figure 9 shows a typical curve of the downward deflection of the ends of the seat angle under lever arms of 1.2, 2.0 and 3.0 in., and the center deflections under a lever arm of 1.2 in. The vertical intercepts may indicate certain friction loads. It is believed that the parabolic shape of the first portion of the curve is due to the action of these frictional forces which are gradually overcome as the load increases.

3. *Full Size Tests.—Series B*. Four tests were made under this series as follows:

B 444 Test No. 1 in which the beam was loaded at the center with a concentrated load. The yield point of the the beam was reached at 85,000 lb. total load, corresponding to a maximum unit stress of 31,300 lb. per sq. in. in the beam. Since no distress was evident at the seat angles and it was not desired to harm the loading beam, the load was released and quarter-point loading was substituted. This set-up is shown in Fig. 4.

B 444 Test No. 2 was the same set-up as Test No. 1 except that the loads were applied at the quarter points and the loading was increased until the welds failed.

B 643 was a similar test with quarter-point loading, using the same loading beam but replacing the stub columns and seat angles.

Specimen B 444B was made up with the beam ends bolted to the outstanding legs of the seat angle with $^7/_8$-in. diameter, fitted bolts, whereas in the previous specimens the beam was welded to the angle.

Ames dial observations of the downward deflection of the outstanding leg were plotted against the applied load. The resulting load-deflection curves are straight lines to a load approximately equal to the load at which the whitewash on the beam web at its junction with the lower flange scaled. Table 3 presents these loads: line 5, that which may be called the proportional limit as taken from the curves; and line 6, the load at which the whitewash on the beam scaled. For greater loads the deflection increased more rapidly than the load. It is necessary here to consider the relative stiffness of the beam and the angle. In these tests the beam was very stiff in relation to the angle. At zero load, the end of the beam had full bearing on the outstanding leg of the angle; the same condition probably held for low loads, and the reaction may be considered as uniformly distributed over the full interface. Upon the application of greater loads the slope of the outstanding leg of the angle became greater than that of the end of the beam. Thus the reaction became concentrated near the end of the beam. This increased the local compressive stress in the web at the end section, which soon reached the yield point, gradually permitting adjacent web material to carry portions of the load. The line of the reaction thus moved toward the toe of the angle. The increase in the effective lever arm accounts for the disproportionate deflections after the yielding of the web.

The tensometer measurements of the downward deflection of the angle obtained at the other column when plotted against the load showed curves similar to those of Fig. 9.

The deflections of the center of the beam checked the calculated deflections within one per cent, thus showing the negligible stiffening effect on the beam of the outstanding leg of the seat angle.

The Whittemore gage readings taken to show stresses in the lower flange of the loading beam and the slip, if any, between the seat angle and the loading beam, showed much greater strains than the common beam formula leads one to expect at these points. These readings are plotted against the load in Fig. 10 and an

Table 3—Results of Tests—Series B (Bare-Wire Welds)

		B 444 Test No. 1	B 444 Test No. 2	B 643	B 444B
(1)	Specimen No.	B 444 Test No. 1	B 444 Test No. 2	B 643	B 444B
(2)	Size of Angle, In.	4 × 4 × 1/2	4 × 4 × 1/2	6 × 4 × 1/2	4 × 4 × 1/2
(3)	Weld Data: Fillet Size, In.	1/2	1/2	3/8	1/2
(4)	Weld Data: Length, In.	8	8	12	8
(5)	Proportional Limit from Inspection of Curves, Lb.	27,750	45,000	22,560	53,000
(6)	Scaling of Web of Beam at Tension Flange, Lb.	30,000	40,000	19,500	67,400
(7)	Scaling on Fillet of Angle, Lb.	45,000	51,500	28,000	30,470
(8)	Scaling at Top End of Weld, Lb.	40,000	48,500	33,500	55,000
(9)	Crack in Top End of Weld, Lb.	....	54,500	59,000	65,250
(10)	Final Load, Lb.	45,000	60,000	62,500	67,400

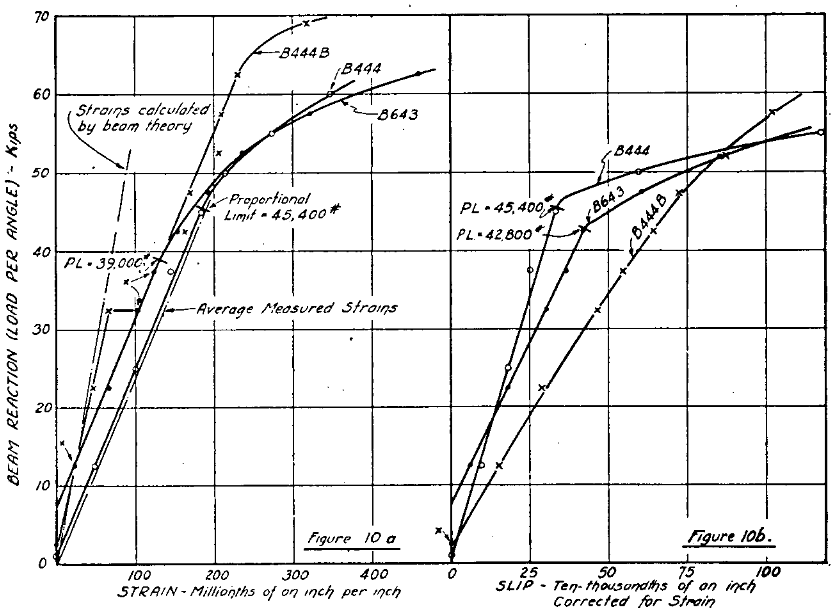


FIGURE 10 STRAINS AND SLIP OF LOADING BEAM - SERIES B.

explanation is given in the discussion to follow. The level bar indicated that the columns tilted outward due to the thrust from the lower flange of the beam. The tilting of the columns was proportional to the applied load and amounted to 0.0000645 radians per kip load per angle for B 444 Test No. 1, and to 0.000066 radians per kip load per angle for B 444 Test No. 2 and B 643.

The load at which the angle yielded is presented in line 7 of Table 3, the load at which scaling of the weld occurred in line 8, the load at cracking of the weld in line 9 and the final load at which yielding of the whole end connection became general in line 10.

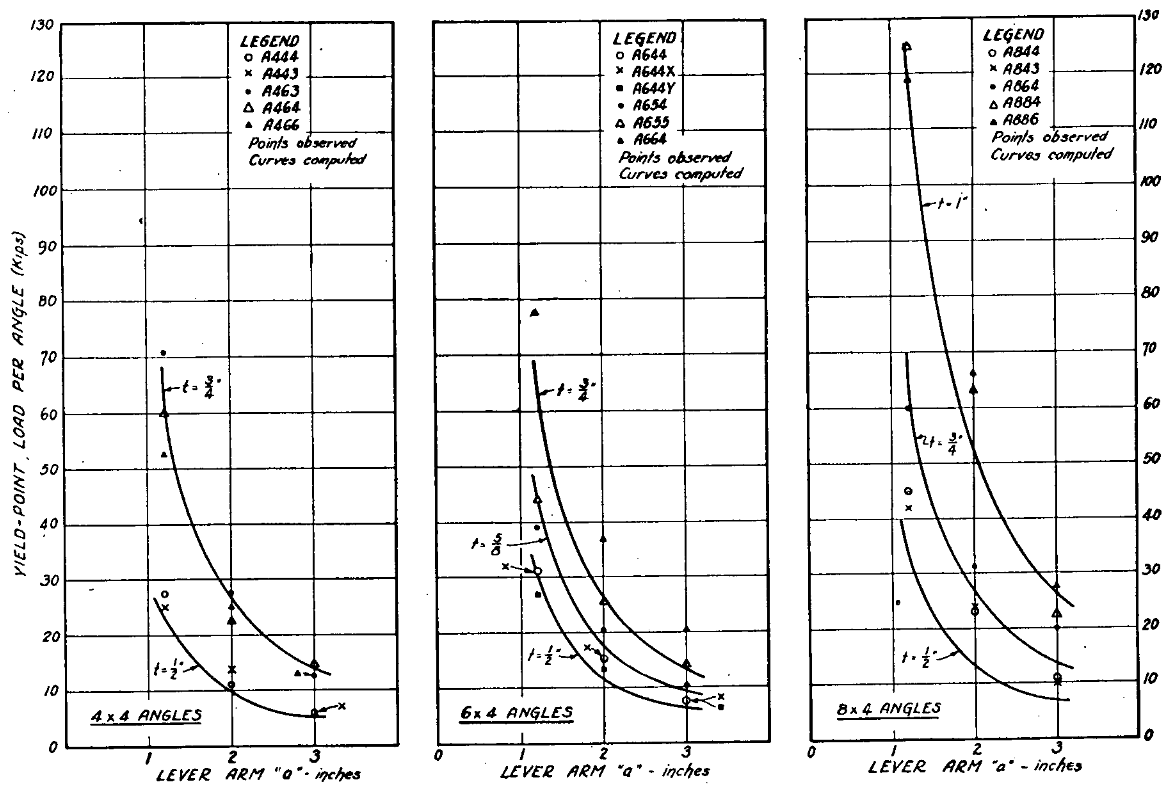


FIGURE 11. RELATION BETWEEN LEVER ARM AND STRENGTH OF ANGLES.

V. Discussion of Results

1. *Series A*.—The relation between the variables given in section III-2, and the capacity of the connection will be discussed in order.

(*a*) Figure 11 shows the relation between the lever arm and the yield-point strength of the angles, using the yield-point loads as defined in section IV-2*c*. The curves shown are those calculated by the method presented in section VI-*a*, and, except in some cases (notably Specimens A 664, A 843 and A 844), they agree very well with the observed data.

Figure 12 shows the effect of the lever arm on the strength of the weld, the ordinates being the values in column 7, Table 2. Here the product of the load times the lever arm tends to remain constant, on the assumption that the effective lever arm is the distance from the back of the angle to the center of the roller minus half the dimension of the weld fillet. The use of either the total distance from the back of angle to the center of roller or this distance minus half the thickness of the angle as the lever arm gives results almost equally satisfactory. However, from a study of the data of the deflection of the outstanding leg of the angle, and of the strength of the weld, the lever arm seems to decrease as the weld size increases; hence the first-mentioned value for the effective lever arm was chosen.

It is a matter of observation that the neutral axis of the weld was considerably above the midheight but it seemed impractical to determine the actual location. Its location apparently varied somewhat with the lever arm and with the load itself.

(*b*) A comparison of specimens A 644-1, A 644X-1 and A 644Y-1, all with lever arms of 1.2 in., but varying in that the load was applied through rollers centered on the outstanding leg of the angle over its full length, over 1 inch, and over 3-in. lengths respectively, shows negligible differences in the strength of the weld with this varying concentration of load. Neither the downward deflection of the outstanding leg nor the observed yield point of the angle was appreciably affected, but there was considerable local yielding immediately under the shorter rollers. From these tests we may assume that variations in the longitudinal distribution of the load, if symmetrically placed on the outstanding leg, introduce but small changes in the strength of the connection.

(*c*) Figure 13 shows the effect of the length of the vertical leg on the yield-point load of the angles. The observed yield-point loads were corrected for variation in the value of the yield-point stress of the material as given in Table 1. In general, the carrying capacity of the angle did not increase directly with the length of the vertical leg, and in some cases there was a decrease in the yield-point load for the longer vertical legs. The trend was not well marked and it seems that the length of the vertical leg had little, if any, effect on the yield-point load of the angle.

Figure 14 shows the effect of the length of the vertical leg on the load at which the weld scaled. Results from the $^1/_2$-in. angles with the $^3/_8$- and $^1/_2$-in. welds and $^3/_4$-in. angles with $^1/_2$-in. welds are available for comparison. In all cases the load at which the weld scaled increased noticeably with increase in the length of the vertical legs. It should be noted, however, that this increase in carrying capacity of the welds was not directly proportional to the increase in the length of the vertical leg.

(*d*) Figure 15 shows the relationship between the thickness of the angle and the load carried at its yield point. The observed data were plotted after correction was made for the variations in the yield-point stresses of the material. The loads calculated by the method given in the section on theoretical analysis are also presented. Again Specimens A 664, A 843 and A 844 fall beyond the calculated loads while the other values agree rather well. The curves show that the decrease in the radius of the fillet of the angle affects the carrying capacity of the angle. The 4 by 4-in. angles have a fillet radius of $^3/_8$ in. while the 6 by 4 in. and 8 by 4 in. have a fillet radius of $^1/_2$ in. The calculations show that the maximum unit stress in the angles having the $^1/_2$-in. fillet is only 88 per cent of that set up by the same load in an angle with a $^3/_8$-in. fillet. The test results substantiate this conclusion, giving a ratio of 89.8 per cent while the photoelastic tests[2] showed an average ratio of 84.5 per cent.

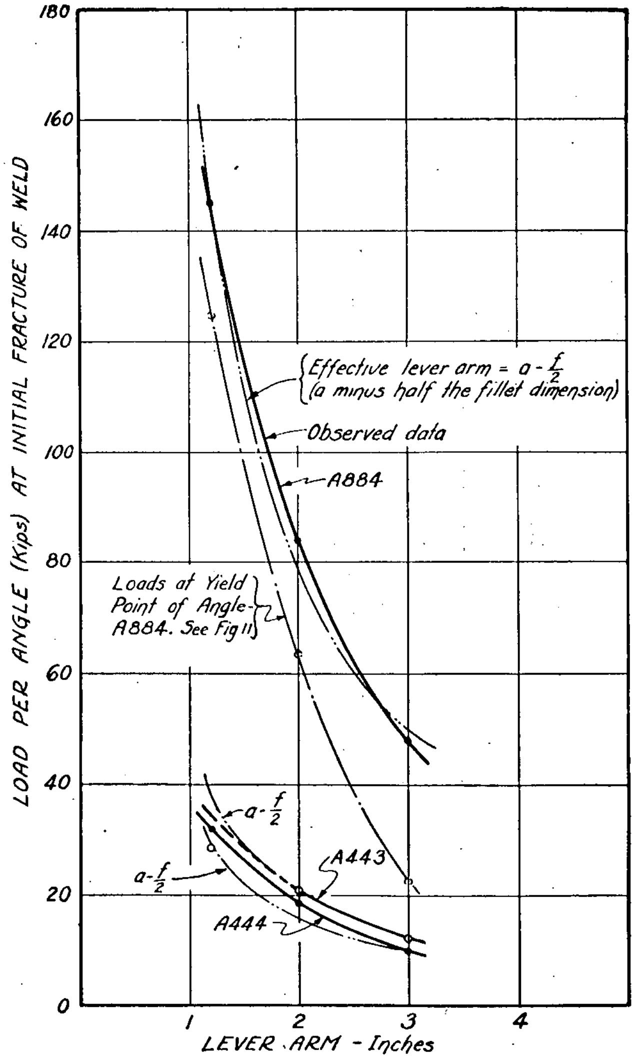


FIGURE 12. RELATION BETWEEN LEVER ARM AND STRENGTH OF WELD.

Figure 16 shows the relationship between the strength of the weld and the thickness of the angle. These curves indicate that the strength of the weld is dependent not only on its length, but to a far greater extent upon the thickness of the angle. These curves are of a higher order than second degree parabolas indicating that the strength of the weld increases slightly faster than the square of the thickness of the angle.

If these values are corrected for the variation in yield-point strength of the parent metal, the curve of the 8 by

[2] Inge Lyse and Douglas M. Stewart, "Photoelastic Study of Bending in Welded Seat Angle Connections," Journal American Welding Society, Feb. 1935.

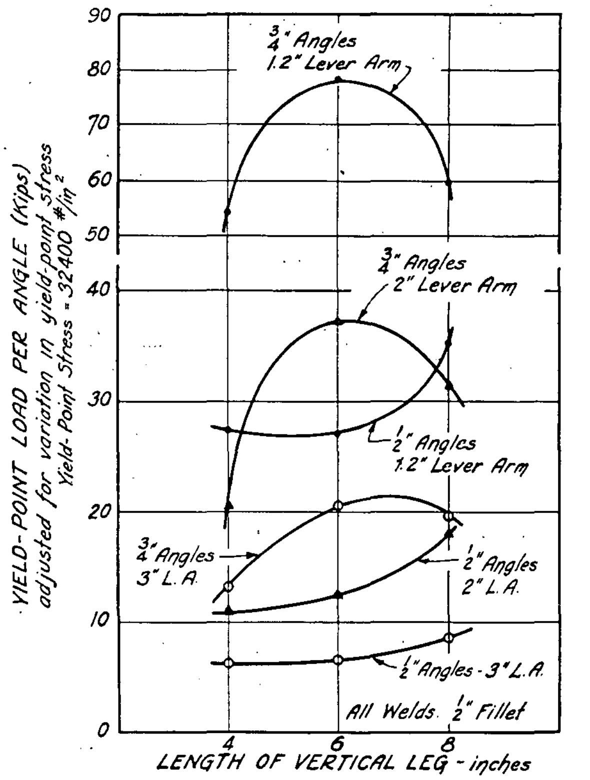


FIGURE 13. RELATION BETWEEN LENGTH OF VERTICAL LEG & STRENGTH OF ANGLES.

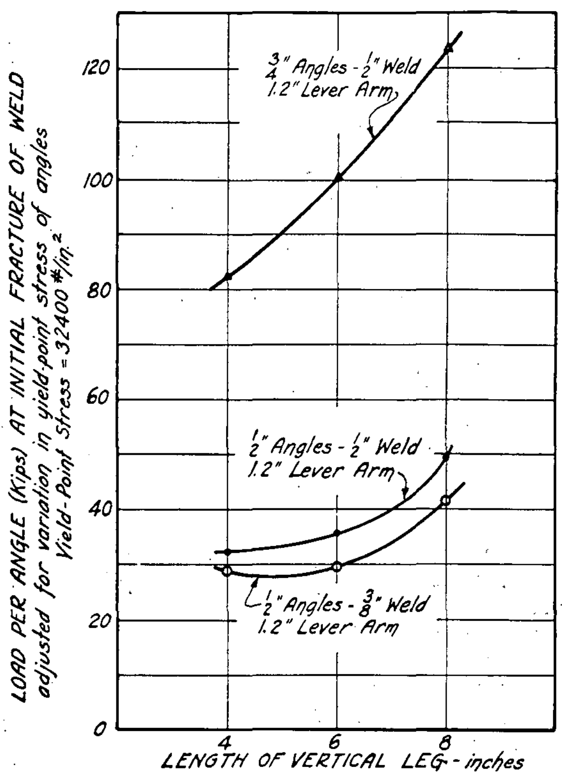


FIGURE 14. RELATION BETWEEN LENGTH OF VERTICAL LEG & STRENGTH OF WELD.

4-in. angles is a second degree parabola excepting the value of A 884-1, while those of the 4 by 4-in. and 6 by 4-in. angles correspond more nearly to higher degree parabolas, showing that the strength of the weld increased faster than the square of the thickness of the angle and was at the same time dependent on the yield-point strength of the parent metal. The value for the A 884-1 is low, most likely caused by the one-sided failure of this specimen.

Attention should be called to the effect of the thickness of the angle on the type of weld failure. The vertical leg of the angle will bend outward in the top part, thus causing a large amount of tension in the top end and subsequent fracture of the weld soon after the angle yields. However, a different kind of failure occurs when using a combination of heavy angles and light welds at the 1.2-in. lever arm. The angle will yield as before and the weld will fracture at the top end, but the additional load necessary to continue deflection of the angle is great enough to overstress the weld in shear, and the final failure will be one in shear throughout the full length of the weld. Specimens A 463-1, A 464-1, A 664-1 and A 884-1 failed in this way at shearing stresses in the weld of 14,030, 16,700, 15,270, 12,750 lb. per lin. in., respectively. Specimen A 466-1 is a border-line case, being on the point of failure in shear at a stress of 23,200 lb. per lin. in. It will be noted that in these cases the weld stress at final load, obtained by dividing the final load by the total length of weld, approached and, in some cases, exceeded the ultimate strength ordinarily assigned to such welds. Figure 17, a picture of A 884-1, shows a typical example of this type of failure.

(*e*) *Effect of Size of Weld.*—1. Specimens A 443 and A 444 may be compared under this heading. The ultimate load per inch of weld was 33 per cent greater for the $^1/_2$ in. than for the $^3/_8$-in. weld, which corresponds to the nominal increase of ultimate load with increased fillet size. The effect of size of weld on the load at which initial fracture occurred was less than on the ultimate load. At the 2.0-in. lever arm, the $^1/_2$-in. weld was only 8 per cent stronger than the $^3/_8$-in. weld; while at the 3.0-in. lever arm, the difference disappeared entirely.

2. Specimens A 463, A 464 and A 466 may likewise be compared. The specimen with the $^1/_2$-in. weld showed an increase in strength of 19 per cent (should be 33% theoretically) over that with the $^3/_8$-in. weld; the specimen with the $^3/_4$-in. weld showed an increase in strength of 39 per cent (should be 50%) over that with the $^1/_2$-in. weld. In each case the final loads were compared since the failures were of similar nature.

3. In comparing Specimens A 643 and A 644, the $^1/_2$-in. weld showed a superiority of only 19 per cent (should be 33%) over the $^3/_8$-in. weld with the 1.2-in. lever arm.

4. On the other hand, the $^5/_8$-in. weld showed a superiority of 33.3 per cent (should be 25%) over the $^1/_2$-in. weld (specimens A 654 and A 655).

5. A comparison of Specimens A 843 and A 844, showed a 19 per cent (should be 33%) increase in load at initial fracture of the $^1/_2$-in. weld over the specimens with the $^3/_8$-in. weld. For some unexplained reason both the $^3/_8$-in. and $^1/_2$-in. welds cracked at the same applied load, while the final load on the specimen with the $^1/_2$-in. weld was even less than that on the specimen with the $^3/_8$-in. weld.

6. Specimens A 884-1 and A 886-1 showed no marked difference at either initial fracture or ultimate strength, although A 886-1 should have been 50 per cent stronger than A 884-1. A 886-1 failed prematurely due to poor fusion at the top ends of the welds for a depth of approximately three-eighths of an inch.

Summing up the results of the tests concerning the effect of weld size, it seems safe to say that the weld size does affect the strength of the connection but not in direct proportion to the increase in size. The excess deformations which accompanied the yielding of the outstanding leg of the angle apparently caused the weld to fracture prematurely at the top.

It is evident from the economic standpoint that the weld size should be kept as small as possible. Comparison of the $^1/_2$ in. with the $^3/_8$ in. welds shows that while the theoretical strength should increase 33 per cent, both material and labor increase about 78 per cent for the larger weld.

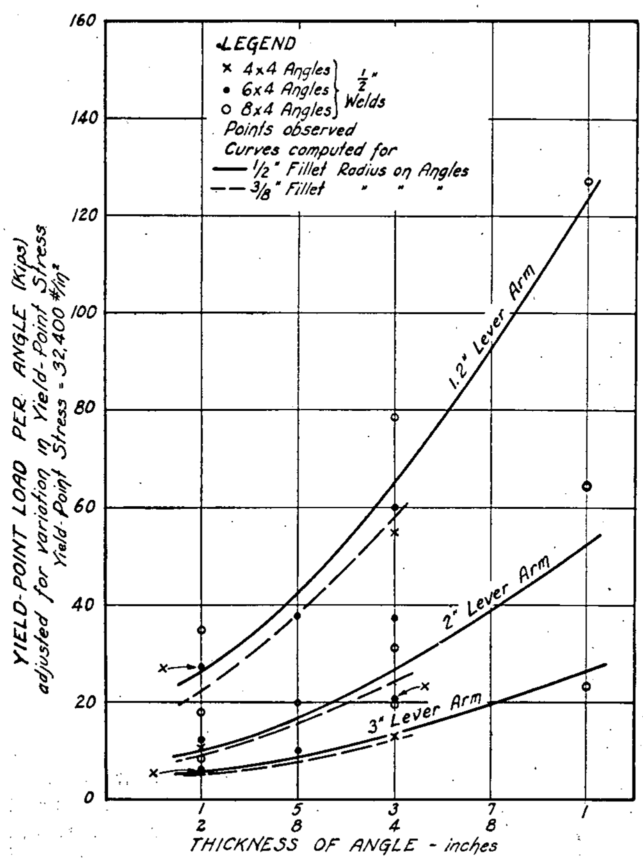


FIGURE 15. RELATION BETWEEN THICKNESS AND STRENGTH OF ANGLES.

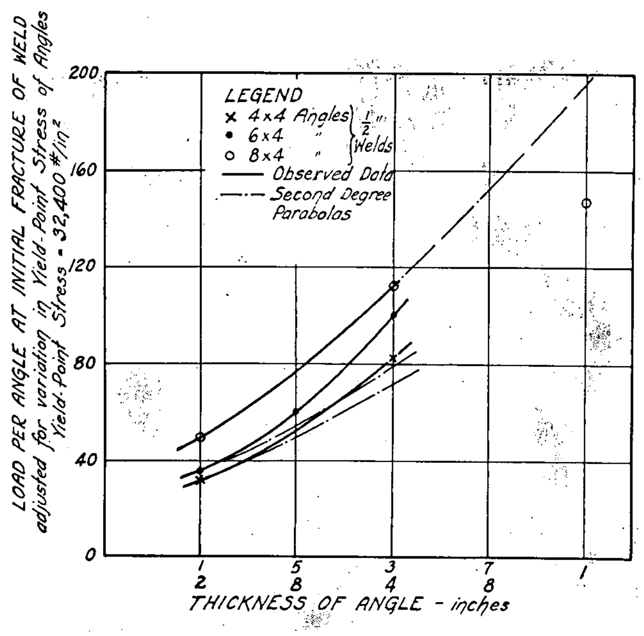


FIGURE 16. RELATION BETWEEN THICKNESS OF ANGLES AND STRENGTH OF WELD.

(*f*) *Effect of Type of Welding Rod.*—Specimens A 444C-1, A 644C-1 and A 644D-1 were welded with several commercial brands of heavily coated electrodes and may be compared with their companion specimens A 444-1 and A 644-1 which were welded with "bare wire." The qualification specimens indicated a gain of 23.5 per cent in the ultimate strength for the coated-wire specimens over the bare-wire specimens. A comparison of the seat angle specimens indicated that the deflections of the angle and its yield-point load were approximately the same regardless of the type of welding rod used. The results obtained from A 444C-1 must be corrected for the difference in yield-point strengths of the material before comparison can be made with the results obtained from A 444-1. The load at which the weld scaled was about 5 per cent greater for the coated-wire specimen than for those welded with bare wire. The load at which the welds actually cracked was approximately 29 per cent greater for the coated-wire specimens. This compares favorably with the increase in ultimate strength of the coated wire over the bare wire shown in the qualification tests mentioned above. The type of failure of the coated-wire specimens was also more advantageous to the connection. Evidently owing to the greater ductility of the metal, the readjustments in stress distribution after the yield point of the weld metal was reached were more gradual in the coated-wire specimens, and there occurred no sudden drop of the beam; the load slowly increasing until fracture occurred. The fracture always started at the root of the weld and proceeded across a section at an angle of about twenty degrees with the end of the outstanding leg of the angle (definitely less than the corresponding angle that occurred with the bare-wire welds). The fusion in all cases was good and the resulting weld metal very homogeneous. The welding time using coated wire was approximately two-thirds of that required for bare wire.

Summing up the results of the coated-wire tests it appeared that the use of coated wire increased the ultimate strength of the connection in about the same ratio as the strengths of the welds without greatly increasing the load at which scaling first occurred. However, the yield point of the outstanding leg of the angle was unaffected by the type of welding wire used. It was, therefore, the reserve strength of the connection which was increased by the use of coated wire. Other advantages were the more favorable type of failure, the better weld metal characteristics and the saving in welding time. On the other hand, welding with the fastest types of coated wire must be done in a horizontal position, which is satisfactory in shop work, but may be impractical in the field.

(*g*) *Auxiliary Tests.*—In addition to the regular schedule, a test was made incorporating certain features which seemed to lead to more economical design. This was A 444a in which the total length of welding was only 4 in., 2 in. at each end, starting from the heel of the angle. These welds failed at the top end in the usual manner and upon further addition of load continued to tear until the angles suddenly split off. Inspection of the break exhibited a typical tension fracture in the upper half of the weld, while the lower half showed the silky texture of shear failure. It is to be noted that the shorter length of weld used in this specimen did not decrease its carrying capacity in any respect, and significantly points out the inefficiency of the welding on the lower half of the vertical leg of the angle.

(*h*) *General Remarks.*—It is to be noted in Table 2 that the results obtained from Specimen A 443-1 were somewhat low as compared to those of later specimens. This was probably due to the outward deflection of the

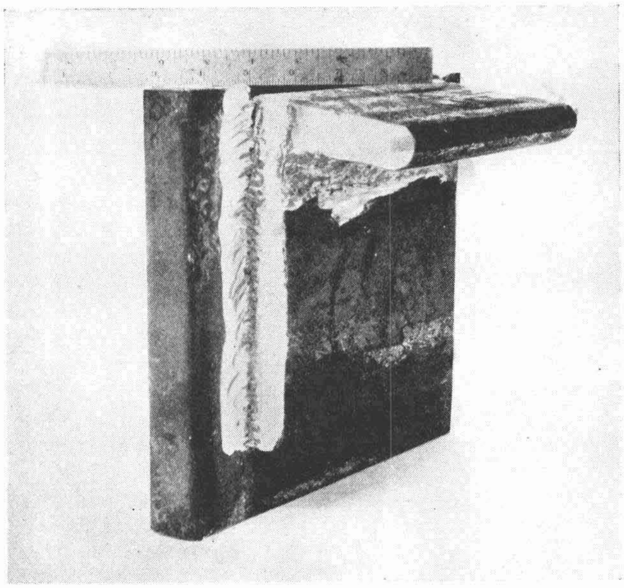


Fig. 17—Typical Example of Weld Failure in Shear—Specimen A 884-1

vertical legs of the loading rig allowing the lever arm of the load to increase and causing a lowered carrying capacity of the angle, as shown in columns 7, 8 and 9.

The high values observed for A 843-1 and A 844-1 were due primarily to the high yield-point strength of the parent metal. Because of the one-sided type of failure of A 844-1 its ultimate load (columns 8 and 9) was lower than that of A 843-1.

2. *Series B.*—In discussing the results of the few tests made in this series certain general phenomena will be pointed out. Consideration will first be given to the action of the beam end in transferring the load to the seat angle. Since the beam flange was quite heavy relative to the outstanding leg of the angle, the reaction was concentrated near the very end of the beam, causing a rapid increase in compressive stress at the junction of the flange and the web and subsequent yielding of the web at a low load. At the same time, the outstanding leg of the seat angle deflected downward under the action of this load, being restrained only to a slight degree by the fillet welds connecting the flange to the outstanding leg. The toe of the angle at the center pulled away from the bottom surface of the flange to such an extent that at 100,000 lb. total load it was possible to insert a feeler 0.040 in. thick between the flange and the toe of the angle for a distance of approximately $1^1/_4$ in. This threw considerable stress in the tack welds and slight cracks were noticeable in the near ends of them. As the web yielded near the end of the beam, it borrowed on adjacent web and flange material for assistance and the reaction tended to move outward, thus increasing the deflection of the outstanding leg considerably. The point at which this deflection ceased to be proportional to the applied load corresponded generally with the observed yielding of the beam web, while the yield point of the angle, as determined by a slope of the curve 50 per cent greater than the original slope, corresponded generally with the observed scaling of the whitewash on the angle fillet. Figure 18 shows a typical failure of one end of a full-sized connection.

Figure 10*a* shows the strains set up in the lower flange of the loading beam as determined by the Whittemore gage. The strains measured in this manner were greatly in excess of those which would be expected at the center of the gage length by the common beam theory. This may be explained by the yielding of the beam web referred to above, which had the same effect as a slit in the web of the beam, causing this end section to act independently of the main body of the beam and increasing the stress in the lower flange.

Figure 10*b* shows the relative motion between the flange and the outstanding leg of the angle. The end of the beam pulled away from the heel of the angle thus inducing considerable stress in the tack welds between the flange and the outstanding leg. The restraint offered by these welds may also account for the high values of the measured strains in the beam flange.

If B 444 is compared with A 444-1, its companion, we note the following: yielding of the angle in the Series B test occurred at 36,200 lb. (corrected for yield point of 40,260 lb. per sq. in.), as compared to approximately 30,000 lb. in the test of Series A at 1.2-in. lever arm. Evidently the resultant reaction of the beam acted closer to the heel of the angle than 1.2 in. From Fig. 11 we conclude that the carrying capacity increases rapidly as the lever arm decreases, hence this resultant reaction probably lies somewhere between 1.0 and 1.2 in. from the heel of the angle. Similar reasoning and the high yield point of the parent metal will account for the high strength of the welds.

The results from Specimens B 643 and A 643-1 may also be compared. Yielding of the angles occurred at a load of 28,000 lb. in Series B and at approximately 29,000 lb. at the 1.2-in. lever arm in Series A. Scaling of the whitewash on the top end of the welds first occurred at a load of 33,500 lb. in Series B corresponding to a like phenomenon on the companion specimen at 33,800 lb. in Series A. From the above comparisons it seems safe to assume that the position of the resultant reaction was quite close to 1.2 in. from the heel of the angle.

Specimen B 444 B may also be compared with A 444-1. Owing to the fact that the loading beam was used on previous tests, the lower flange for a distance of 3 in. from either end had an initial slope of approximately 0.042 in. per in., because of the yielding referred to previously. This initial slope caused the beam to rest on the toe of the angle. As the load was applied, the reaction moved toward the heel of the angle. The deflection curves of the outstanding leg indicated that the lever arm of the resultant reaction was between 1.2 and 2.0 in., and the load of 24,600 lb. (corrected) at which the angle scaled,

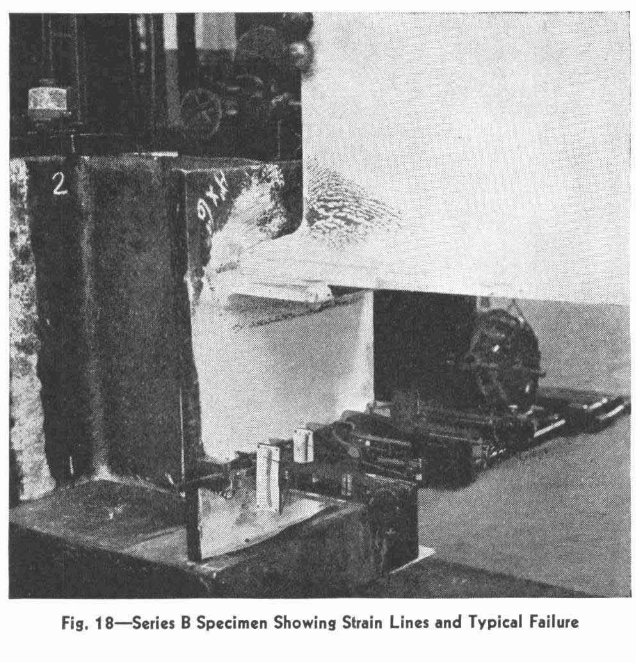


Fig. 18—Series B Specimen Showing Strain Lines and Typical Failure

is to be compared with 30,000 and 18,850 lb. for these respective lever arms of Specimen A 444. Scaling of the weld and final fracture occurred at only slightly greater loads than those of Specimen B 444. The influence of the prebending of the beam was especially noticeable in the more even distribution of load over the lower flange of the beam. At the load at which the web scaled, the stress in the web as computed by the method of section VII-1, assuming $1^7/_8$-in. bearing was 30,800 lb. per sq. in., which corresponds to the yield-point stress of 31,300 lb. per sq. in. for the web material of the beam.

Turning to Fig. 10*a*, the measured strains in the lower flange correspond closely to those calculated by the beam theory up to the load at which scaling of the angle was observed. Beyond this point the strains correspond closely to those of the previous tests in this series. Here again it seems that the reaction was rather uniformly distributed over the full contiguous surface of the beam and angle and induced no additional strains in the lower flange of the beam while the angle was taking the same slope as the end of the beam. However, when the angle yielded and the reaction moved closer to the end of the beam, local concentrations of stress increased the strains in the lower flange in the same ratio as in the previous tests.

The ends of this beam were bolted to the outstanding legs of the angle and the resulting greater flexibility is evident from Fig. 10*b*.

For these tests the end of the beam was set $^7/_8$ in. from the face of the column in order to get the worst condition probable in practice. This figure was calculated in the following manner. Specifications permit beams to be cut to the detailed length plus or minus $^3/_8$ in. Design practice allows for a clearance of $^1/_2$ in. between each end of the beam and the column. Any deviation from detailed length should be taken up symmetrically in laying out the beam; thus, a maximum gap of $^{11}/_{16}$ in. is possible. However, the layout is often made from one end which gives a possible gap of $^7/_8$ in. at the other end.

VI. Theoretical Analysis

(*a*) *The Angle.*—In the following theoretical analysis use has been made of the beam formula with its accompanying assumptions, many of which do not fully hold. However, the test results agreed very well with the values computed by the method presented herewith. In addition, test results were in most cases higher than those shown by theory and hence the theoretical loads and stresses given will be conservative.

The stress obtained by the use of the formula for beams with parallel faces may be transformed into tangential stress in the case of beams with non-parallel faces by dividing by the $\cos^2\theta$, where θ is the angle which the face makes with the perpendicular to the section under consideration,[3] since the maximum stress must be parallel to the surface and both the shear and the stress at right angles to the surface must be zero. However, when applied to the case at hand, this formula did not fit the observed data, probably due to the large inclination of the fillet of the angle to the assumed plane section.

In the following analysis use is made of a circular cross section which is normal to both surfaces of the angle and to the neutral axis, assuming it to lie in the center of the section. The assumption is made that the circular section before bending remains circular after bending (see Fig. 19). The ordinary beam formula is then used which gave the stress at the surface σ_t equal to:

[3] William Cain, "Stresses in Wedge-Shaped Reinforced Concrete Beams," *American Society of Civil Engineers, Transactions*, Vol. 77, p. 745 (1914).

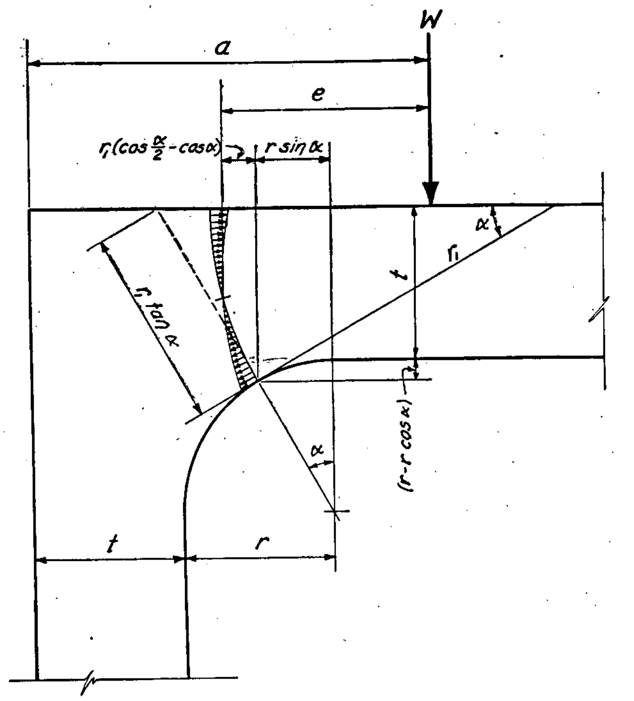


FIGURE 19. SECTION USED IN THEORETICAL ANALYSIS

$$\sigma_t = \frac{6We}{bd^2} \tag{1}$$

where W = the total load per angle
e = the effective lever arm of the load
b = the length of angle
d = the length of the circular section considered

From Fig. 19, e and d may be evaluated:

$$e = a - t - r + r\sin\alpha + r_1\left(\cos\frac{\alpha}{2} - \cos\alpha\right) \tag{a}$$

$$d = r_1\cdot\alpha = \left(\frac{t + r - r\cos\alpha}{\sin\alpha}\right)\alpha \tag{b}$$

Substitution of (*a*) and (*b*) in equation (1) gives:

$$\sigma_t = \frac{6W}{b}\;\frac{A + (t+r-r\cos\alpha)(\cos\frac{\alpha}{2}-\cos\alpha)\alpha\sin\alpha}{[(t+r-r\cos\alpha)\alpha]^2} \tag{2}$$

$$A = (a-t-r+r\sin\alpha)\sin^2\alpha$$

There is also a direct stress due to the inclination of the section assumed, varying from zero at the horizontal face to a maximum at the fillet of the angle (the point of maximum inclination). This stress at the fillet may be approximated by considering the component of the load, $W\sin\alpha$, distributed over the plane tangent to the cross section at this point. The area of this plane is $br_1\tan\alpha$. Then σ_c, the compressive stress at the face of the fillet, equals:

$$\sigma_c = \frac{W\cos\alpha}{br_1} = \frac{W\sin\alpha\cos\alpha}{b(t+r-r\cos\alpha)} \tag{3}$$

The total stress is:

$$\sigma = \sigma_t + \sigma_c \tag{4}$$

It will be noted that σ is dependent upon the angle α for its maximum and we should therefore obtain a value for α which makes σ a maximum. Obtaining the maximum by calculus is so arduous and the resulting expression so cumbersome, that a graphical method furnishes the most convenient method of attack and yields values within 2 per cent of the maximum by using values of α no closer than every five degrees. Table 4 gives these results for the angles tested.

Table 4—Computed Values for Maximum Stress in Seat Angles

Thickness of Angle	Radius of Fillet of Angle	Value of α (Degrees) Giving Maximum Stress Lever Arms			Value of Stress Factor K Lever Arms		
In.	In.	1.2	2.0	3.0	1.2	2.0	3.0
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1/2	3/8	33.2	15	0	11.720	28.284	50.500
1/2	1/2	30	15	0	10.096	25.839	48.000
5/8	1/2	45	15	0	6.037	15.255	28.800
3/4	3/8	45	15	15	4.475	10.705	20.595
3/4	1/2	45	30	15	4.001	9.722	19.350
1	1/2	60	30	15	2.096	4.941	9.833

Maximum compressive stress on fillet of angle is given by:

$$\sigma = \frac{WK}{b}$$

where W = the end reaction per angle in pounds
K = the stress factor
b = the length of seat angle in inches

Loads per angle calculated from these results and the yield-point stresses given in Table 1 are plotted on Figs. 11 and 15, and their general agreement with the test data will be noted. The calculated values average about 10 per cent less than those actually obtained by observation from the load-deflection curves.

(*b*) Consideration of the weld stresses showed that they cannot be solved by the use of the ordinary theories of flexure when the weld is used in this position. The failure of the weld is brought about as a secondary effect caused by excessive deflection of the angle as it is stressed beyond the yield point.

VII. Recommendations for Design

On the basis of the results of this investigation, the following methods for designing seat angle connections are recommended.

1. *Design of Beam and Location of Resultant Action.*—The beam which is supported by the seat angles is subjected to high compressive stresses in the web immediately above the point of support. These compressive stresses will cause failure of the web in "crippling"[4] if they become very large. The web should therefore be designed against crippling failure. Tests[5] have indicated that the crippling will take place when the compressive stress in the web exceeds the yield-point strength of the material. The maximum stress permitted should therefore be computed by the formula:

$$\sigma_c = \frac{W}{(m + N)\, t} \qquad (5)$$

where σ_c = permitted stress in compression
W = reaction of the beam on the seat angle
m = length of bearing on the seat angle
N = thickness of the flange including the fillets of the beam
t = thickness of the web of the beam

[4] "Crippling" is defined as the local failure of the web produced by excessive compressive stresses under a concentrated load.
[5] Inge Lyse and H. J. Godfrey, Discussion, "Investigation of Web Buckling in Steel Beams," *Proceedings, American Society of Civil Engineers,* Nov. 1934, p. 1354.

Since it will generally be the case that the seat angle will be more flexible than the flange of the beam, the reaction will tend to be concentrated near the end of the beam, and it will, therefore, reach the yield point first. The length of bearing "m" under these conditions will be zero and the necessary dimensions of the beam become:

$$Nt = \frac{W}{\sigma_{yp}} \qquad (6)$$

where σ_{yp} is the compressive yield-point stress of the web material of the beam.

Local yielding of the web will cause redistribution of stress with a consequent higher carrying capacity. It seems safe, therefore, to permit web stresses very nearly equal to the yield-point stress when zero bearing length is assumed.

2. *Design of Angle.*—The outstanding leg of the angle must be designed to resist the flexural stresses developed due to the eccentricity of the reaction. The stresses set up in the angle will reach a maximum in compression on the fillet surface of the angle. The location of the point of maximum stress may be determined by the use of Table 4, where α is the angle between a vertical through the junction of the fillet with the outstanding leg and the plane of maximum stress.

The value of the stress factor "K" is given and the maximum compressive stress in the angle may be obtained from the formula:

$$\sigma = \frac{WK}{b} \qquad (7)$$

where b is the length of the seat angle in inches.

3. *Design of Weld.*—In all of the tests included in this investigation, the yielding of the angle at the fillet was the first cause of excessive deformations. Consequently, the welds were all sufficiently strong to develop the full yield-point value of the angle. The yielding of the angle introduced secondary stresses into the weld which fractured from the top downward. This failure was very gradual with ample warning of impending danger. Where shear failure in the weld occurred, it followed the initial fracture of the weld in tension suddenly and with little warning. If, then, we prevent failure of the weld in shear, the strength of the connection will be dictated by the yield-point strength of the angle. Since a shear failure in the weld is a sudden break, with little or no warning, the factor of safety against shearing should be greater than against flexure.

The ultimate strengths these seat-angle welds developed in shear were found to correspond well with the ultimate strengths of the qualification welds. It is, therefore, recommended that the weld be designed for a shearing stress in conformity with the A. W. S. Code for Fusion Welding and Gas Cutting in Building Construction—Code 1, Part A, when the unit shearing stress, τ, is computed by the general formula:

$$\tau = \frac{W}{l} \qquad (8)$$

where l is the total length of weld subjected to longitudinal shear.

VIII. Summary

Based upon the observed behavior of the specimens tested, the following general summary is presented:

1. The strength of a seat angle connection with welds at the ends of the vertical leg of the angles varies roughly as the square of the thickness of the angle, inversely as the effective lever arm of the resultant reaction, and is

influenced by the length of the vertical leg of the angle, and by the size of the weld.

2. Vertical shear has only a slight effect on the strength of the weld unless the angle is thick enough so that the bending deflection of the vertical leg is reduced to a minimum, in which case the vertical shear is a criterion. However, even in this case the tops of the welds were found to be most highly stressed and fractured first.

3. The centers of rotation for the calculation of the resistance of the weld were not located in these tests, but it is evident that they were not at the midheight of the weld.

4. Concentration of load longitudinally over varying lengths of the outstanding leg has no effect on the strength of the connection. A local yielding occurs directly under the point of application of the load.

5. The outstanding leg acts as a cantilever beam so long as the load is applied near the toe. As the load moves in toward the heel of the angle, the weakest section is somewhere across the fillet of the angle. This section can best be analyzed by studying the stress distribution on cross sections perpendicular to both faces of the outstanding leg.

6. Increase in size of weld increases the strength of the connection but not in proportion to the increase in weld size; furthermore, the added strength of the connection is far less in proportion to the increase in welding costs. Economically it would be desirable to keep the weld as small as possible.

7. The length of weld does not increase markedly the strength of the connection. It is probable that the weld needs be only slightly longer than is necessary to prevent shear failure, figured simply as the total load divided by length of weld. It appears evident that the bending moments set up give rise to no appreciable stresses in the lower portion of the welds.

8. An increase in the radius of the fillet of the angle decreases the stresses at the fillet to a marked degree. This is shown not only by the test data but also in the theoretical analysis and by the photoelastic studies.

9. The failure of the welded seat angle connection is gradual, except when the lever arm is so small that shear and not bending predominates. The weld gradually tears at the top allowing the angle to bend outward and downward.

10. The principal lever arm, i.e., the distance between the column face and the load for Series A was 1.2 in., which was estimated to be a proper value from considerations of the maximum possible gap between the beam and the column face and the probable position of the resultant reaction. This assumed value for the lever arm was rather closely substantiated in the tests of Series B.

11. Coated-wire welds were found to be effective in increasing the ultimate strength of the connection in approximately the same ratio that the ultimate tensile strength of the coated and "bare" wire bear to each other. However, the type of wire had no effect upon the yield-point load of the angle or on the first cracking of the weld.

12. On the basis of the observations and the simplified theoretical analysis made, it is recommended that seat angle connections with vertical fillet welds on the ends of the angles be designed first with respect to the strength of the angle itself and secondly with respect to the strenght of the weld in vertical shear.

A Photoelastic Study of Bending in Welded Seat Angle Connections*

By INGE LYSE and DOUGLAS M. STEWART†

Introduction

A PHOTOELASTIC investigation of the properties of welded seat angle connections was undertaken at the Fritz Engineering Laboratory of Lehigh University in conjunction with actual seat angle tests being carried on in cooperation with the Structural Steel Committee of the American Bureau of Welding. The investigation was limited by the nature of the apparatus to two-dimensional problems under plane loading, and consequently this study is confined to the lateral bending effect of the angles themselves. Furthermore, ideal welding conditions must be assumed and perfect continuity of welding material and parent metal. Since we note that, where sufficient weld metal is present to prevent a shear failure, the first symptoms of failure in actual seat angle tests are always a disproportionate increase in deflection of the outstanding leg, followed by chipping of scale or whitewash on the fillet of the angle, this bending effect is of prime importance as regards failure of the connection. Consequently, a correlation could be made between the results of the photoelastic tests and the data on the first signs of bending failure in actual tests, and the results of this are shown later in this report. In addition, a photoelastic model will show the distribution of stress in the angles at various loads and will permit the study of other factors which might affect the strength; in this case, the effect of increasing the size of the fillet in the angles as rolled was investigated as being of importance in causing bending rigidity.

Test Specimens

Three models were made and tested, these being half-scale sections of a pair of 4 x 4 x $^1/_2$ in., 6 x 4 x $^5/_8$ in. and 8 x 4 x 1-in. seat angles mounted on $1^1/_4$-in. thick plates exactly as in the actual welded steel specimens. These models were accurately machined from sheets of $^1/_4$-in. thick transparent bakelite and carefully polished and annealed to remove initial stresses. At the same time a calibration beam was cut from the same sheet of bakelite as each model, and subjected to the same conditions of annealing and storing. The models were then loaded by means of dead weights through rollers placed at the desired distance from the back of the angles, in a manner identical with the tests on the full-sized steel specimens. The two larger of these models were made with a 1-in. fillet on the angles, which was then cut down successively to $^3/_4$ in. and $^1/_2$ in., the latter being the standard size rolled.

Photoelastic Method of Analysis

It is possible by passing plane polarized light through such a transparent model, to obtain a series of dark lines on an image of the model from which the directions of the two principal stresses at any point, that is, the stress trajectories, may be determined. Furthermore, each fringe as shown when the model is subjected to circularly polarized light, represents a definite value of the difference of the two principal stresses (P-Q), at that point. Since the maximum shear is likewise proportional to (P-Q), these fringes are also lines of constant maximum shear. At the free boundaries of a model, where the stresses have in general their critical values, one of the principal stresses vanishes, and thus the fringe order is a direct measure of the fiber stress along the boundaries. This latter fact was made use of in this investigation and from the calibration beam under uniform bending moment, the value of the stress difference corresponding to the fringe values of each model was determined. From the values of the extreme fiber stress in the outstanding leg of the angles, moment curves were then plotted, and a first integration of these gave the slope at any point, while a second integration gave the deflection curve of the outstanding leg.

Variables Studied

The variables studied were as follows:

1. With the load at 2 in. from the back of angle, the load was varied.
2. With the load constant the lever arm was varied, the points selected being 1.2 in., 2.0 in., 2.5 in. and 3.0 in. from the back of angle.
3. From these results a comparison was made of the three fillet sizes, all other variables remaining constant.
4. The effect of the length of the vertical leg was studied by cutting down the 8 x 4 x 1-in. model in successive steps.
5. The effect of the size of the angle on the stresses produced was determined from the preceding results.

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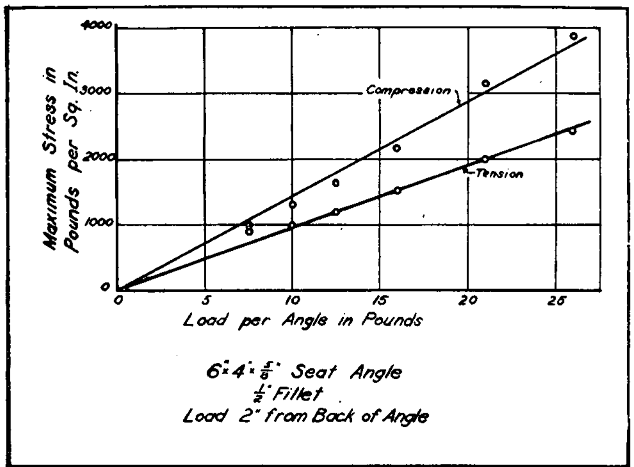
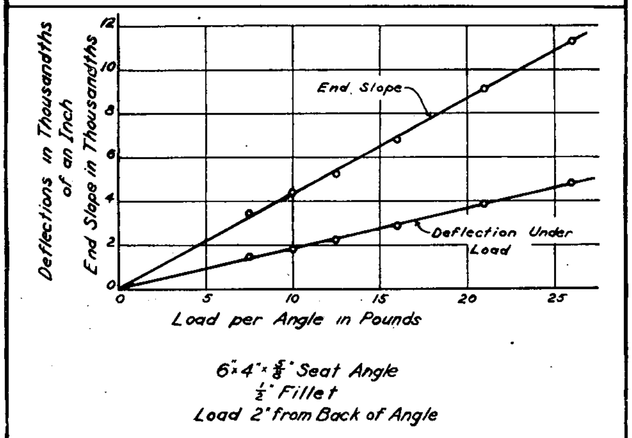
† Research Associate Professor of Engineering Materials and Research Fellow in Civil Engineering, respectively, Lehigh University, Bethlehem, Pennsylvania.

Fig. 1—Variation in Maximum Stress with Load





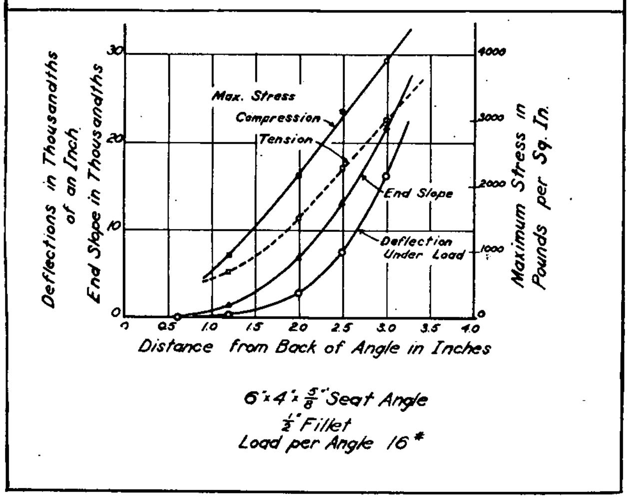


Fig. 2 (Center)—Variation in End Slope and Deflection under the Load with Load

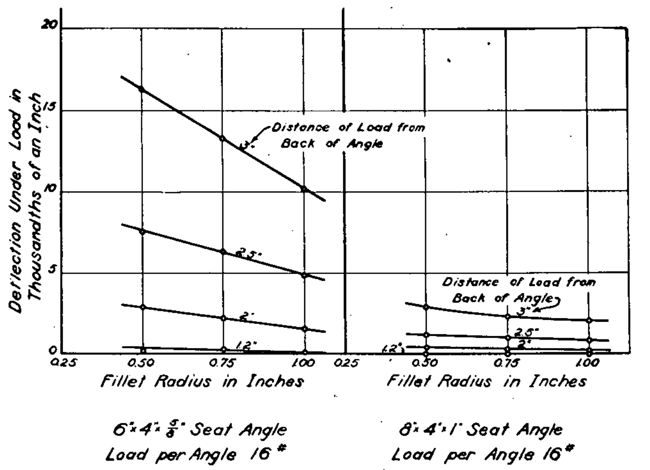
Fig. 3—Variation in Stress, Slope and Deflection under Load with Distance from Back of Angle

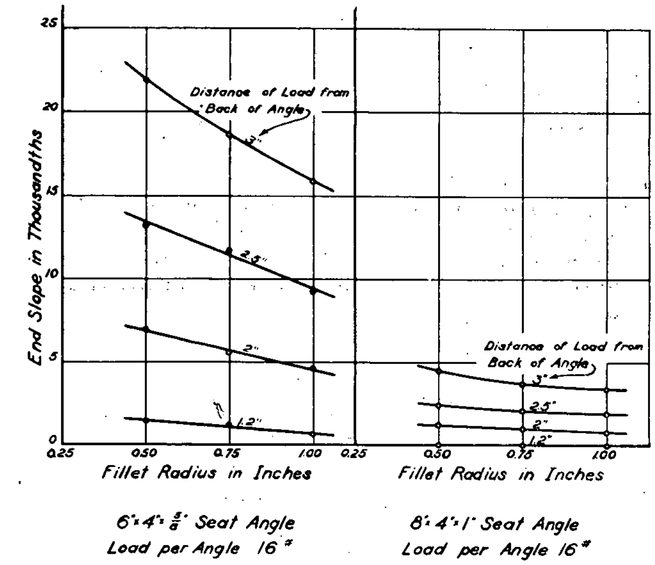
Discussion of Variables

Figure 1 shows the effect of the variation of load upon the maximum stress on both the tension and compression sides of the angle. As is to be expected, the relation is linear, the stress increasing directly with the load, and the compressive values exceed the tensile ones, indicating that the compressive stress at the fillet limits the strength of the angle.

In Fig. 2 is shown the variation in end slope and deflection under the load with varying loads and a constant lever arm. In this case the values lie more closely on the

Fig. 4—Deflection under the Load for Two Sizes of Angle with Variable Fillet Size





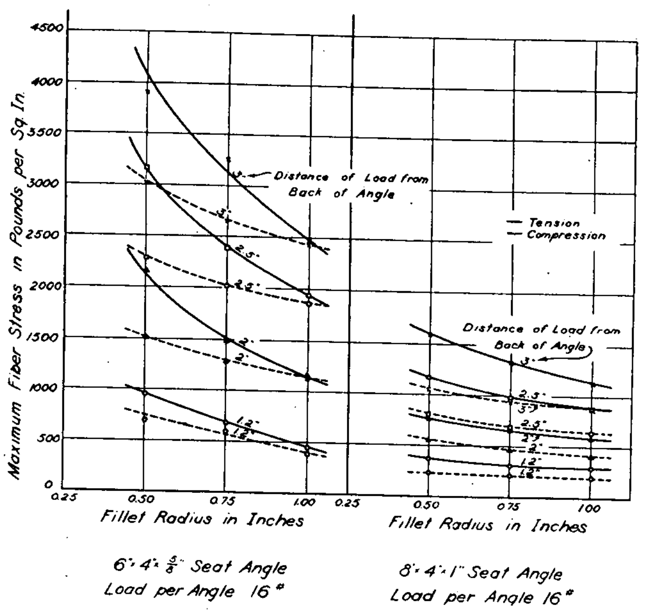


Fig. 5 (Center)—End Slope for Two Sizes of Angle with Variable Fillet Size

Fig. 6—Maximum Fiber Stress for Two Sizes of Angle with Variable Fillet Size

theoretical straight lines, since the process of integration by which they were obtained tends to iron out any irregularities in the data.

The constant load of 16 lb. per angle was then applied to each of the four lever arms, and Fig. 3 shows a typical set of results for the 6 x 4 x $^5/_8$-in. model with $^1/_2$-in. fillet. The maximum stress, both in tension and compression, is seen to vary linearly down to a point where the influence of the fillet is felt. The curve for the end slope is a parabola, while that for the deflection under the load is a cubic parabola, both modified at low values by the restraint caused by the fillet.

The quantitative effect of the size of the fillet in the angle as rolled is shown in Figs. 4, 5 and 6 for the three sizes tested. The first two figures showing the deflection under the load and the end slope at each of the four lever arms, indicate clearly the added rigidity caused by the larger fillets, and give as well a comparison of the stiffness of a 6 x 4 x $^5/_8$-in. and an 8 x 4 x 1-in. angle. Figure 6 shows the variation in maximum stress, both in tension and compression, as the fillet size is increased; it shows plainly that the less rigid angle is strengthened more by the addition of a larger fillet than is the stiffer angle. The amount of this stiffening has been summarized in Table 1, in which the maximum stress is expressed as a percentage of the maximum stress with a standard $^1/_2$-in. fillet. In addition, the percentage increase in weight of the standard angle caused by the increase in size of the fillet, has been tabulated. Since the compressive stresses limit the strength of the angle in every case tested, it is these values that are of the greatest significance, and the reduction of stress caused by the addition of only a very small amount of material is remarkable.

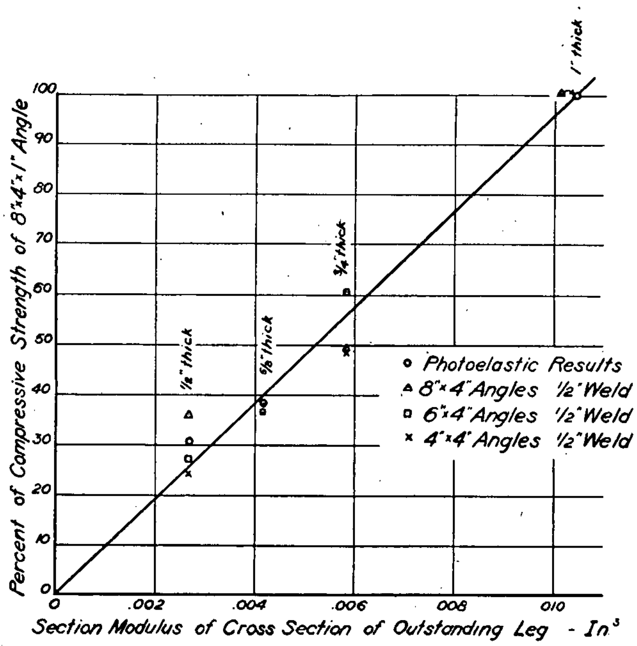
Table 1—Maximum Stress Expressed as a Per Cent of the Stress with $^1/_2$-In. Fillet

Load per Angle 16 Lb.

	Distance from Back of Angle	$^3/_4$-In. Fillet	1-In. Fillet
6 x 4 x $^5/_8$-In. Seat Angle			
Compression	3.0″	84.7	63.0
	2.5″	75.8	61.5
	2.0″	69.0	52.1
	1.2″	71.3	47.0
	Average	75.2	55.9
Tension	3.0″	89.3	80.5
	2.5″	88.5	81.5
	2.0″	84.5	77.5
	1.2″	90.5	55.8
	Average	88.2	73.8
Per Cent Increase in Weight of Section		1.2	2.7
8 x 4 x 1-In. Seat Angle			
Compression	3.0″	83.8	71.0
	2.5″	84.3	75.0
	2.0″	87.1	76.8
	1.2″	84.1	78.6
	Average	84.8	75.3
Tension	3.0″	88.9	83.0
	2.5″	86.3	79.1
	2.0″	85.0	75.0
	1.2″	92.8	88.5
	Average	88.2	81.4
Per Cent Increase in Weight of Section		0.6	1.5

The vertical legs of the 8 x 4 x 1-in. model, with a $^1/_2$-in. fillet, were cut down by $^1/_2$-in. steps, corresponding to 1 in. on the full-sized specimen, until they were $1^1/_2$ in. long and then by $^1/_4$-in. steps until 1 in. long. Photo-

Fig. 7—Curve Showing Relative Strength in Bending of Different Sizes of Seat Angles



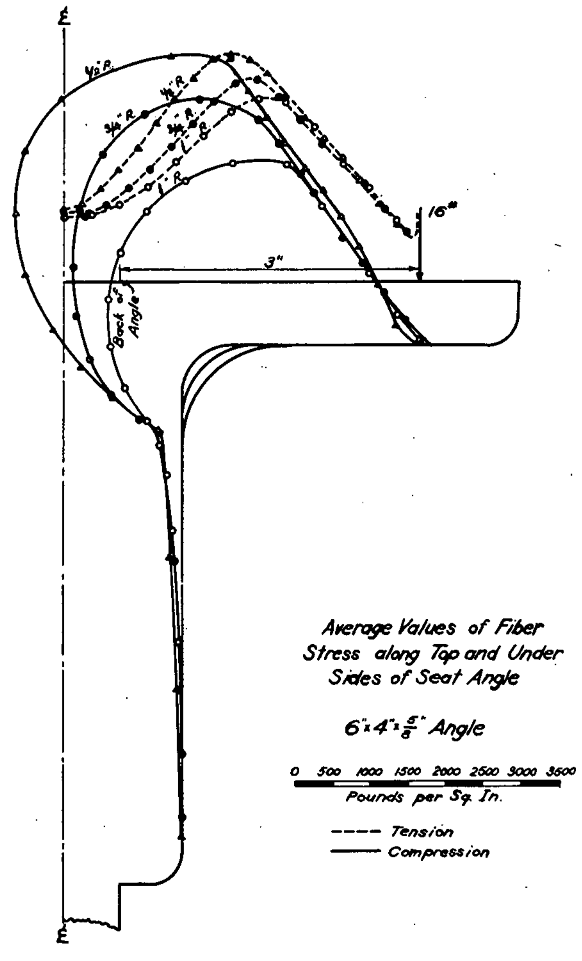
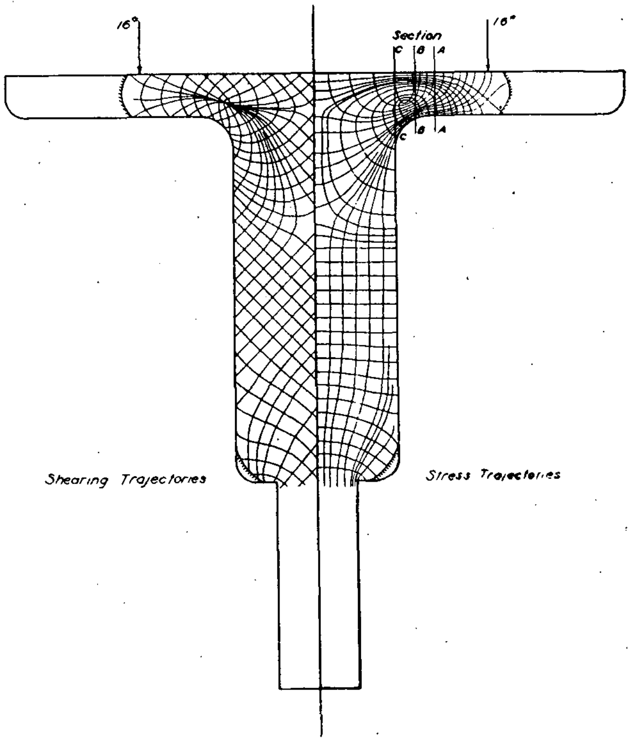


Fig. 8—Average Values of Fiber Stress along Top and under Sides of Seat Angle

Fig. 9—Stress and Shearing Trajectories, 6 x 4 $^5/_8$-In. Angle



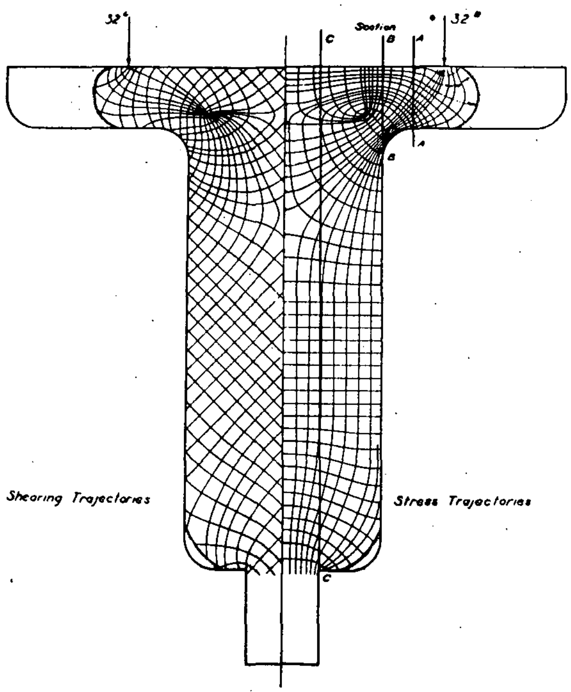


Fig. 10—Stress and Shearing Trajectories, 8 x 4 x 1-In. Angle

graphs taken of the fringes around the base of the angle show no increase in the tensile or compressive stresses until a length of 1$^1/_2$ in. was obtained, corresponding to a 3-in. vertical leg below which the compressive stresses were slightly increased and redistributed. This is lower than used on any seat angles in practice, since considerable length of weld is needed to provide against shear failure, a factor which is not apparent from photoelastic results.

The relative strength of the three sizes of angles tested is shown in Fig. 7. Each angle has the standard $^1/_2$-in. fillet and the strength, or load required to produce the yield-point stress in each angle, has been plotted as a per cent of the strength of the 8 x 4 x 1-in. angle *vs.* the section modulus of a cross section of the outstanding leg of the angle. The points group themselves along a straight line, values for the 4 x 4 x $^1/_2$-in. angle being more in error because of difficulties in observing the large number of fringes present. Each point is the average for the four lever arms used. In addition, there is shown on this figure the relative strengths of actual full-sized welded steel specimens, these values being the loads at which the load-deflection curves for the outstanding legs had a slope 50% greater than the initial slope. Each point here is the average for the three lever arms used in the tests. A similar plot based on the yield point as determined by chipping of the whitewash on the fillet of the angle, shows a wider spread in values, due to the inaccuracy of such observations. This figure shows a fairly good correlation between photoelastic tests and the actual welded specimens and indicates that the section modulus of a cross section of the outstanding leg should dictate the selection of the thickness of a seat angle.

Stress Distribution

The distribution of stress in the extreme fibers along the boundary of the 6 x 4 x $^5/_8$-in. model is shown in Fig. 8 for the three different fillet sizes. This figure shows the load at 3 in. from the back of angle, the other lever arms showing identical effects. On the tension side, we may note that all the curves practically coincide outside of the fillet. Also they reach a maximum value directly above the point where the fillet commences, and this maximum value increases as the fillet size decreases; the effect of a local concentration of stress under the load point is likewise shown. On the compression side, ordinates around the fillet have been plotted radially. Again we note that the curves coincide beyond the fillet and that they reach zero values under the load. The maximum compressive stress occurs on the fillet at an angle of roughly 20–30° with the vertical, and the values increase with decrease in fillet size. It might be noted that chipping of the whitewash in full-sized tests, where shear failure does not occur, commences at this point on the fillet as nearly as can be observed. Finally, in the compressive portion of the specimen, the extreme fiber stress falls off rapidly and the lower tip of the angle takes no stress at all.

The directions of the two principal stresses have been determined by means of plane polarized light for the 6 x 4 x $^5/_8$-in. and the 8 x 4 x 1-in. models and are shown on the right halves of Figs. 9 and 10. These stress trajectories consist of two sets of mutually perpendicular lines, and at all free boundaries one set of lines is normal to the boundary. It is seen that the fibers are in almost pure tension just above the fillet and that pure compression exists at the fillet and in the main body of the model. The portions of the outstanding leg outside the load point and the lower tip of the vertical leg are under zero stress. On the left side of these figures are shown the directions of the maximum shearing stresses, or shearing trajectories, which are two sets of mutually perpendicular lines inclined at 45° to the stress trajectories. A singular point just over the fillet, shown in these two figures, has been found to be a point of zero stress, which may be said to correspond to the neutral axis. A similar study was made of each of the three fillet sizes, to determine whether this variable affected the stress distribution greatly. Slight variations were noted, but the distribution of stress was not markedly altered.

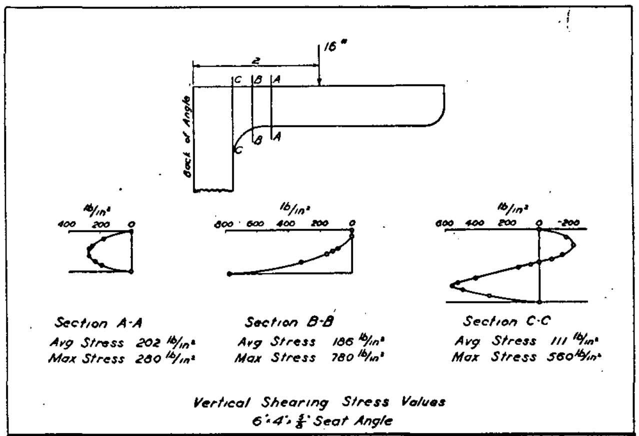
The vertical shearing stress was then analyzed by use of Mohr's Stress Circle along sections *A*, *B* and *C* as shown on Fig. 9 for the 6 x 4 x $^5/_8$-in. angle and the results are shown in Fig. 11. On section *A* we have the usual parabolic distribution of the vertical shear. At *B* the stress trajectories are horizontal and vertical for a short distance down from the top; hence, there is no vertical shear for a short distance. Also, since the lower edge of the section is inclined, the vertical shear has a value at this point. At *C* quite a different form of distribution is observed, an explanation of which may be seen by referring to Fig. 9. At *C*, down to a certain point, the lines of stress (in tension) are pulling up on the right side of the section instead of down as at *A*; in other words, the sign of the shear is reversed. Below this point the compressive forces are pushing down as at *A*, and the sign of the vertical shear is again positive. The worst section is at *B*, which is the transition point between diagrams of types *A* and *C*. Figure 12 shows the distribution of vertical shear on sections *A*, *B* and *C* of Fig. 10. In this case, the transition section lies between *B* and *C*, and we note again the reversal in sign of the shear on section *C*. Values of the average vertical shearing stress and also the maximum values are shown on these figures. The area under these curves, representing the internal shear, has been found to check the external shear within 10% in each case.

Conclusions

From the above results the following conclusions have been drawn with respect to the bending of seat angles below their elastic limits:

1. Provided sufficient metal is available in the fillet welds to prevent shearing failure, the limiting condition for permanent set in ordinary welded seat angle connections is determined by the bending strength of the angles.
2. The maximum compressive stress at the fillet of the angle is approximately $1^1/_2$ times the maximum tensile stress along the top side of the angle; accordingly, the strength of the angle in bending is determined by the compressive stress existing in the fillet of the angle.
3. The maximum stress, end slope and deflection for a constant lever arm, vary linearly with the load.
4. For a given load, the maximum stress varies linearly with the lever arm of the load, and the end slope and deflection under the load vary as second and third order parabolas, respectively, except near the fillet where these curves are all modified somewhat due to local concentrations of stress.
5. The addition of a very small percentage of material in the form of a larger fillet in the angles gives marked reductions in both tensile and compressive stresses, the effect being more marked on the weaker angle sections.
6. The length of the vertical leg has little or no effect on the stresses in the angle above a length equal to that of the outstanding leg; sufficient length must be provided, however, to prevent failure by shearing of the welds.
7. The strength of the seat angle itself in bending is governed by the section modulus of a cross section of the outstanding leg.

Fig. 11—Vertical Shearing Stress Distribution, 6 x 4 x $^5/_8$-In. Angle



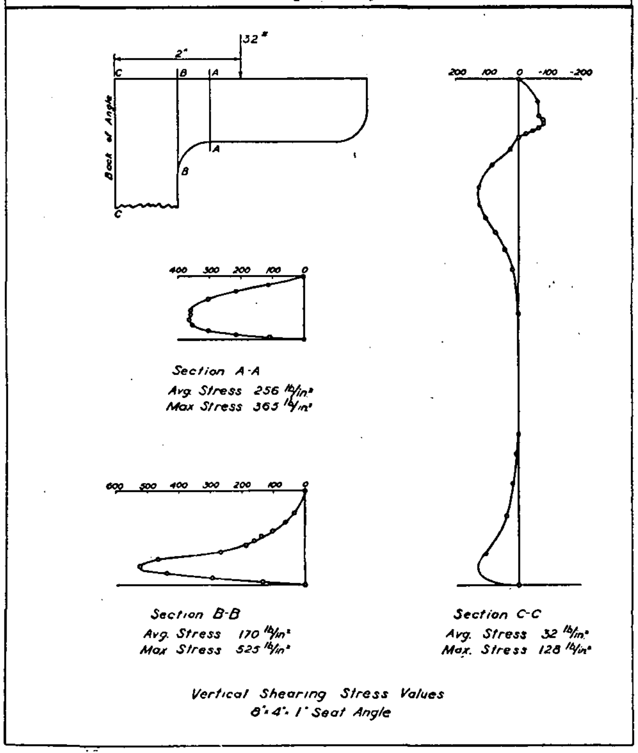


Fig. 12—Vertical Shearing Stress Distribution, 8 x 4 x 1-In. Angle

8. The greatest tensile stress in the angle occurs directly above the point where the fillet commences, while the greatest compressive stress occurs on the fillet at an angle of from 20 to 30° with the vertical.
9. The vertical shearing distribution is not uniform on any section of the angle, and on sections near the back of the angle shows a reversal of sign. The maximum vertical shearing stress may be as high as five times the average stress over the section.

Especial thanks are due to Mr. N. G. Schreiner for assistance in performing and correlating these experiments.