Examination of Fillet Weld Strength

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INTRODUCTION

The strength of a fillet weld is influenced by many different factors. For example, the welding process, electrode type and strength, weld-metal chemistry, welder skill, weld profile, joint penetration, joint fit-up and restraint, and preheat and interpass temperatures all contribute, in some part, to the resultant weld strength. Many of these factors, such as skill of the welder, joint fit-up, and preheat and interpass temperatures, are dealt with through particular requirements and provisions of the AWS Structural Welding Code.[3] Weld qualification tests, for instance, are required to demonstrate whether an individual has adequate skill and training to produce a particular weld with a desirable level of quality.

The design methodology used to compute the strength of fillet welds does not directly reflect all of the factors that influence fillet weld strength. The design method utilized for many years to compute the strength of a fillet weld involves multiplying the effective fillet weld area—the product of the effective throat size and the weld length—times an allowable or ultimate stress, depending upon whether an allowable stress or limit states design approach is being used. The effective throat dimension of the weld is taken as the shortest distance from the root of the weld to a line that connects the top and bottom weld toes; this procedure gives an effective throat that is 71 percent of the weld leg size for welds with equal leg sizes. It should be noted that this procedure ignores the influence of the weld root penetration and the weld profile. These factors will result in a true weld throat size that is different than the theoretical effective throat utilized for design purposes.

The purpose of the study reported herein was to study the influence of geometrical factors that influence the true effective throat of fillet welds. Specifically, a series of tests were conducted to evaluate the influence of weld leg size and fabrication gaps on the strength of fillet welds.

Previous Studies

The strength of fillet welds has been studied for many years dating back to World War I. The results of a rather comprehensive study involving 1,395 test specimens with 55 different joint types was published in 1931 by the Structural Steel Welding Committee of the American Bureau of Welding. This study examined differences in weld strength for various weld joint types and established factors of safety relative to allowable weld design stresses. A few years later, the allowable fillet-weld shear stress was increased from 11.3 ksi to 13.6 ksi when Godfrey and Mount[10] demonstrated that covered electrodes produced welds with strengths greater than welds produced using bare wire electrodes. Significant studies to classify fillet weld behavior were conducted also in Great Britain. The Welding Panel of the Steel Structures Research Committee[15] reported the results of 849 test specimens, which were prepared by 61 different manufacturers throughout Great Britain, to evaluate the strength of welds prepared with actual welding practices. Also, Gardner[9] conducted an additional 72 tests to study the influence of weld leg size and weld orientation. All of these early tests demonstrated that fillet welds which are transverse to the applied loading are 35 to 50 percent stronger than welds which are parallel to the applied load.

Due to improvements in welding technology and the introduction of new, high-strength alloy steels, a number of additional welding research studies have been conducted since the late 1960s. Preece,[13] working under the direction of a joint AWS-AISC task group, conducted 132 tests to study the influence of electrode strength, weld size, and weld orientation. Butler and Kulak[6] tested 23 specimens to examine the effect of weld orientation relative to the applied loading. Tests by Dawe and Kulak[8] and Kulak and Timler[11] also examined the influence of weld orientation and described the load-deformation response of ¼-in. fillet welds. Finally, both Clark[7] and Miazga and Kennedy[12] conducted a number of tests to examine the strength of longitudinal and transverse welds.

An examination of previous research studies reveals that there is some disagreement concerning the influence of weld size on the strength of fillet welds. Gardner,[9] who tested welds ranging from ¼-in. to ¾-in., found that the weld size had no effect on the gross throat stress of the weld at failure. However, studies by the Structural Steel Welding Committee[16] indicated that the largest welds had failure stresses that were only 95 percent of the overall average failure stress. Moreover, Preece[13] reported that a decrease in the factor of safety was observed as the weld size increased. While it appears that large fillet welds may not be as strong proportionally as

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Table 1. Primary Test Matrix Specimens			
Specimen No.	Nominal Weld Size (inches)	Weld Orientation Relative to Loading	Root Opening (inches)
1-2-L-0	¼	Longitudinal	None
2-2-L-0	¼	Longitudinal	None
3-3-L-0	⅜	Longitudinal	None
4-3-L-0	⅜	Longitudinal	None
5-4-L-0	½	Longitudinal	None
6-4-L-0	½	Longitudinal	None
7-2-T-0	¼	Transverse	None
8-2-T-0	¼	Transverse	None
9-3-T-0	⅜	Transverse	None
10-3-T-0	⅜	Transverse	None
11-4-T-0	½	Transverse	None
12-4-T-0	½	Transverse	None
13-2-L-1	¼	Longitudinal	1/16
14-2-L-2	¼	Longitudinal	⅛
15-4-L-1	½	Longitudinal	1/16
16-2-T-1	¼	Transverse	1/16
17-2-T-2	¼	Transverse	⅛
18-4-T-1	½	Transverse	1/16

smaller welds, it is not clear how much this factor actually influences weld strength.

EXPERIMENTAL PROGRAM

Test Specimen Description

An experimental study was conducted to examine the strength and deformation behavior of fillet welds loaded in shear.[14] Variables studied include weld leg size, weld orientation, and fabrication weld root gaps. The test program for the weld strength shear tests is shown in Table 1. A total of 18 specimens were tested, with three different nominal weld leg sizes, two different orientations of the load relative to the longitudinal axis of the weld, and three different weld root gap configurations. As indicated in Table 1, the matrix is divided into four portions. Two groups of six specimens were used for the weld orientation tests, with two duplicate specimens for each of the three weld leg sizes. The remaining two groups were used to evaluate the influence of root openings on the weld strength for each of the two weld orientations.

A numbering system consisting of two numbers, a letter, and another number (i.e. 1-2-L-0) was stamped on all specimens to identify the properties of that specimen. The first digit refers to the specimen number in the test matrix, used for quick referencing. The second digit indicates the weld leg size in eighths of an inch. Thus, the number "2" would represent a ¼-in. weld. The subsequent letter refers to a specimen with either a longitudinal or a transverse weld. A longitudinal weld specimen would have the letter "L" while a transverse weld specimen the letter "T." The final number represents the fabrication gap induced, in sixteenths of an inch. Therefore, the number "2" would represent a ⅛-in. gap while the number "0" would represent a specimen with no gap.

The test specimens with the load oriented parallel to the axis of the weld, or at zero degrees, will be referred to as longitudinal weld specimens, while the specimens with the load oriented 90 degrees from the axis of the weld will be referred to as transverse weld specimens. The configuration of the longitudinal and transverse weld specimens is shown in Figures 1 and 2, respectively.

The longitudinal and transverse weld tests were designed so that failure would occur at a particular end. By knowing which end would fail first, the weld deformation could be monitored throughout the test. As noted in the figures, the "anchor end" has a more substantial weld than the "test end." It can be observed in Figure 1 also that a gap exists between the two center plates. Run-off plates were placed in this region, so that the arc strikes and stops could be removed after welding. Clip angles for weld run-off were also used for the transverse test specimens.

Different plate thicknesses were used to accommodate the various weld leg sizes. The specimens were designed so that the failure would occur in the weld, rather than the plate, and such that the plate would remain elastic during all stages of loading. Moreover, to minimize the occurrence of shear lag in the connection, the weld length and configuration were selected so that the U-factor from the LRFD Specification[2] was equal to unity.

Test Specimen Fillet Welds

All of the fillet welds for the test specimens were produced manually using the shielded metal arc welding process. One welder produced all of the welds with the same welding machine to ensure that a consistent procedure was utilized and to minimize differences in the test welds. The steel used for the specimens was ASTM A572 Gr 50. Atom Arc E7018 Alpha, low hydrogen, 3⁄16-in. diameter electrodes were used for all of the welding in the study.

One weld pass was used to fabricate the welds with a ¼-in. weld leg size. Two passes were required to make the ⅜-in. fillet welds, while either three or four passes were needed to produce the ½-in. fillet welds. During the placement of the final weld pass for the two larger weld leg sizes, the welder weaved the electrode to produce a uniform leg with the correct weld size; the weave was across the full face for the ⅜-in. weld, while only a slight weave was needed for ½-in. weld. Most of the welds were deposited in the flat position by tilting the specimens to form a trough. One weld pass, however, for the ½-in. welds only, was deposited in the horizontal position.

Three coupon tests were conducted to evaluate the material response of the weld metal. The all weld-metal test specimens were extracted from a single-V groove weld, which was used to join two 1-in. thick plates. The interpass temperature was not carefully controlled since a number of welding passes were needed to fill the V-groove. The test coupons, which were 0.5 inches in diameter with threaded ends, were fabricated to conform to the requirements given in the AWS Structural Welding Code[3] for weld-metal tension tests.

The weld-metal coupon tests were conducted in the stroke control mode using a MTS 220-kip capacity servo-hydraulic testing machine. Each of the three specimens was instrumented with two high-elongation strain gages and a 2-in. extensometer. During the coupon test, an Optilog data acquisition system was used to record load, stroke, strain, and extensometer output values measured at three-second intervals. The results of the three weld-metal coupon tests are shown in Table 2. The tensile strengths raged from 66.7 to 70.3 ksi with an average value of 69 ksi. This value is slightly below the AWS minimum tensile strength of 72 ksi for E70XX electrodes.[4] The maximum elongation for the three specimens ranged trom 36.1 to 38.9 percent, with an average value of 37.8 percent.

Fabrication Gaps

Six test specimens were fabricated with fabrication gaps intentionally introduced between the plates being welded. The purpose of these tests was to evaluate the influence that

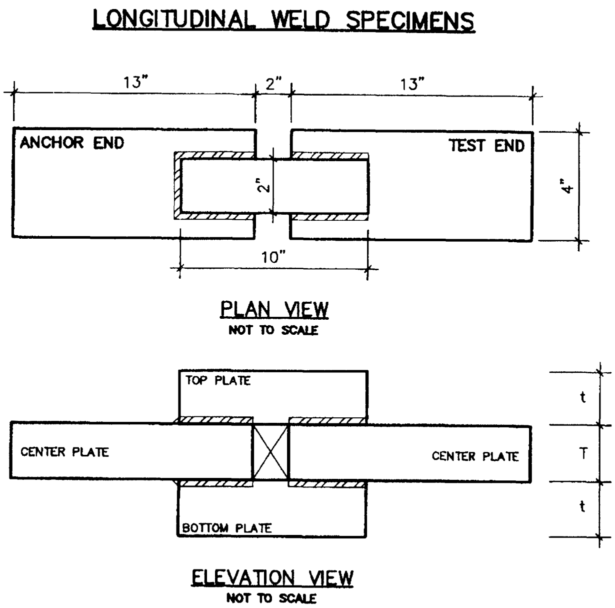

PLATE THICKNESSES		
WELD SIZE	T	t
1/4"	1"	1"
3/8"	1-1/2"	1-1/2"
1/2"	2"	2"

Figure 1

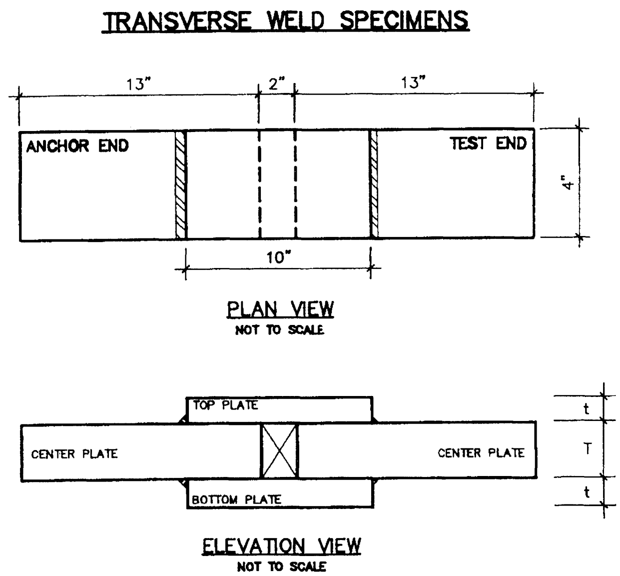

PLATE THICKNESSES		
WELD SIZE	T	t
1/4"	1"	1/2"
3/8"	1-1/2"	3/4"
1/2"	2"	1"

Figure 2

Table 2. All-Weld-Metal Tensile Coupon Test Results				
Specimen No.	**1**	**2**	**3**	**Average**
Description				
Diameter (inches)	0.498	0.500	0.503	0.500
Yield Stress (ksi)	59.0	54.2	60.1	57.8
Yield Strain (Percent)	0.19	0.18	0.20	0.19
Tensile Strength (ksi)	70.1	66.7	70.3	69.0
Maximum Elongation (%)	38.9	38.4	36.1	37.8

weld root gaps have on the weld shear strength. In actual practice, weld root gaps can occur as a result of plate distortion or inadequate fit-up. For the specimens in the test program, however, the gaps were produced by placing spacer rods between the center plate and the two lap plates. The two gap sizes examined were 1/16-in. and 1/8-in.

The AWS Structural Welding Code[3] states that, "if the separation is greater than 1/16-in., the leg of the fillet weld should be increased by the amount of the root opening, or the contractor should demonstrate that the required effective throat has been obtained." For the two gap sizes examined in this study, one size represents the AWS maximum gap allowable without the need for corrective repairs and the other size refers to a plate separation size that exceeds the AWS limit. The same number of welding passes was needed to make the welds with fabrication gaps as without gaps. In some cases, however, the welding speed had to be reduced to produce the correct weld size.

Specimen Test Procedures

All eighteen test specimens were loaded to failure using the 600-kip capacity Baldwin Universal Testing machine in the Structural Engineering Laboratory. The tests were conducted in a load-control mode at a loading rate controlled manually of 0.25 to 0.50 kips/sec.

For each specimen test, an Optim Optilog 200 data acquisition system was used to record the applied load, along with the corresponding weld deformation and remote strains, as the test progressed. The data were collected at specific intervals during the test: every 5-kips for the first 75 percent of the expected failure load; every 2.5-kips up to 90 percent of the expected failure load; and every 1-kip until failure occurred. This data collection procedure provided enough information to define the load-deformation response of the weld specimens.

The weld deformation was evaluated by using linear variable differential transformers (LVDTs) attached to each side of the fillet weld at a specific location. The LVDTs bodies were mounted to a rigid metal frame which was bolted to the stationary upper crosshead of the testing machine. A threaded rod was used to attach the cores for the LVDTs to a metal arm that was glued to the base metal directly adjacent to the top and bottom legs of the weld being monitored. The difference between the deformation values on each side of the weld, measured relative to the rigid crosshead, is the weld deformation at the location of interest.

The weld deformation was monitored at mid-length of one test weld for each of the longitudinal and transverse weld shear test specimens. A photograph of the LVDT instrumentation set-up is shown in Figure 3 for a transverse weld specimen. The design of the LVDT frame allowed the weld displacement values to be recorded all the way up to failure, since the LVDTs did not need to be removed. This is an important feature because a considerable amount of deformation occurs as the weld approaches failure.

Strain values were monitored throughout the test for each of the specimens to evaluate the stress state in the plates at a location slightly removed from the test welds. A pair of strain gages were placed on opposite sides of the middle plate halfway between the grip area and outside lap plates. The measured strains were used to indicate if any significant bending was occurring or if the middle plates were beginning

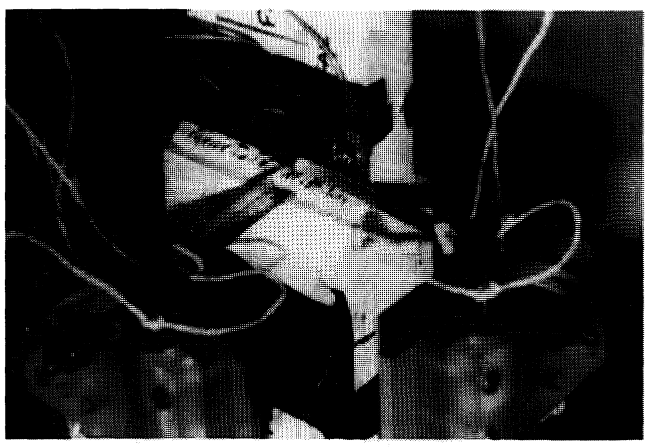

Figure 3

Table 3. Primary Test Matrix Results

Specimen Number	Peak Load (kips)	Ultimate Deformation (inches)	Weld Length (inches)	Average Weld Sizes: Bottom Leg (inches)	Top Leg (inches)	Overall (inches)	Peak Load Per Unit Length (kip/in)
1-2-L-0	247	N.A.	15.76	0.275	0.268	0.272	15.7
2-2-L-0	243	0.129	15.82	0.285	0.276	0.281	15.4
3-3-L-0	336	0.239	15.78	0.409	0.433	0.421	21.3
4-3-L-0	332	0.266	15.71	0.383	0.420	0.402	21.1
5-4-L-0	352	0.311	15.80	0.538	0.532	0.532	22.3
6-4-L-0	380	0.228	16.18	0.571	0.555	0.563	23.5
13-2-L-1	236	0.250	15.86	0.265	0.322	0.294	14.9
14-2-L-2	242	0.147	15.86	0.231	0.326	0.279	15.3
15-4-L-1	388	0.305	15.60	0.570	0.536	0.553	24.9
7-2-T-0	184	0.043	7.93	0.317	0.306	0.312	23.2
8-2-T-0	190	0.083	7.92	0.309	0.367	0.338	24.0
9-3-T-0	247	0.058	8.05	0.412	0.470	0.441	30.7
10-3-T-0	256	0.056	8.04	0.422	0.444	0.433	31.9
11-4-T-0	293	0.044	8.01	0.553	0.498	0.526	36.6
12-4-T-0	294	0.053	8.01	0.541	0.518	0.530	36.7
16-2-T-1	179	0.157	7.94	0.308	0.337	0.323	22.5
17-2-T-2	162	0.121	7.98	0.251	0.354	0.303	20.3
18-4-T-1	286	0.156	8.00	0.617	0.512	0.565	35.7

to yield. The strain values were recorded by the data acquisition system each time the load and LVDT readings were taken.

TEST RESULTS

Fillet Weld Test Loads

The load and weld deformation were monitored frequently throughout the test. The measured values of the peak load achieved during the test and the ultimate deformation at failure are provided in Table 3. Also shown in the table is the total length of the test weld, the average weld leg size, and the peak load per unit weld length. The test weld length is the length of four welds for longitudinal specimens, and two welds for transverse specimens. The average weld size was obtained measuring the leg size at six locations for each 4-in. weld length. A weighted average based on the length of the weld segment between the measurement points was used to compute the average leg size for each test weld.

The results of the load-deformation measurements for Specimen 3-3-L-0 are shown in Figure 4. It should be noted that the measured load has been divided by the test weld length to obtain the weld load per unit length. Another feature worth noting is the apparent ductility of the welds. The ultimate deformation for all of the longitudinal test specimens at failure, as shown in Table 3, was found to be quite large compared with the 0.11-in. value utilized for longitudinal welds in the AISC Manual.

A comparison of the peak load versus the average weld leg size is shown in Figure 5. The test data are plotted in terms of the failure load divided by the total weld length for the actual weld leg sizes tested; the range of weld leg sizes was 0.27-in. to 0.56-in. A distinction in the figure is made between longitudinal and transverse test specimens and between gapped

Table 4. Weld Shear Stress Values at Failure			
Specimen Number	Weld Shear Stress at Failure τ_u (ksi)	$\frac{\tau_u}{\sigma_u}$	$\frac{\tau_u}{\sigma_u/\sqrt{3}}$
1-2-L-0	68.6	0.99	1.72
2-2-L-0	65.1	0.94	1.63
3-3-L-0	60.3	0.87	1.51
4-3-L-0	59.0	0.85	1.48
5-4-L-0	63.5	0.92	1.59
6-4-L-0	60.4	0.88	1.52

and no-gap configurations. One trend that is evident from the results shown in Figure 5 is that transverse welds are stronger than longitudinal welds. The ratio of strengths, based upon use of the actual weld leg size, ranged from 1.3 to 1.7 for the ungapped specimens and 1.2 to 1.4 for the gapped specimens. As noted previously, earlier studies have shown that transverse welds are 30 to 50 percent stronger than comparably sized longitudinal welds.

The weld shear strength is compared with the tensile strength of the weld metal in Table 4 for the six basic shear tests. The weld shear stress at failure, τ_u, was computed as the failure load divided by the weld failure area. The weld failure area was based upon the throat dimension at the failure angle, plus a small additional weld reinforcement due to convexity. The weld convexity was estimated from plaster mold measurements of one test weld for each specimen. From the values indicated in Table 4, it can be seen that the shear stress developed in the weld at incipient failure ranged from 85 to 99 percent of the average weld metal tensile strength.

Also, the values are higher than the von Mises failure criterion of $\sigma_u/\sqrt{3}$.

For the purpose of comparison, the weld strength test results of the present study were compared with test data reported in other studies—see Figures 6 and 7 for longitudinal and transverse welds, respectively. The data from recent studies only were selected for comparison due to changes and advances in welding technology. For equivalence in plotting the results, the weld strength data for other studies were adjusted in proportion to the electrode strength so that all results are based on an equivalent E70XX electrode. The test results from the present study appear to compare favorable with the results reported by Preece[13] and Butler and Kulak[6] for both longitudinal and transverse welds. The weld

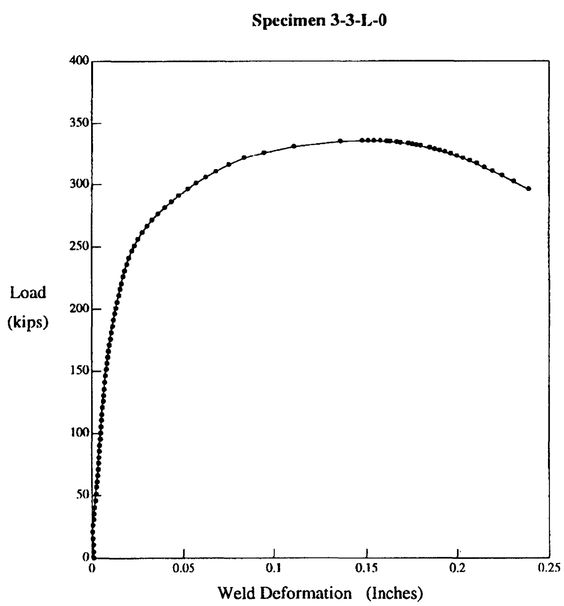

Figure 4

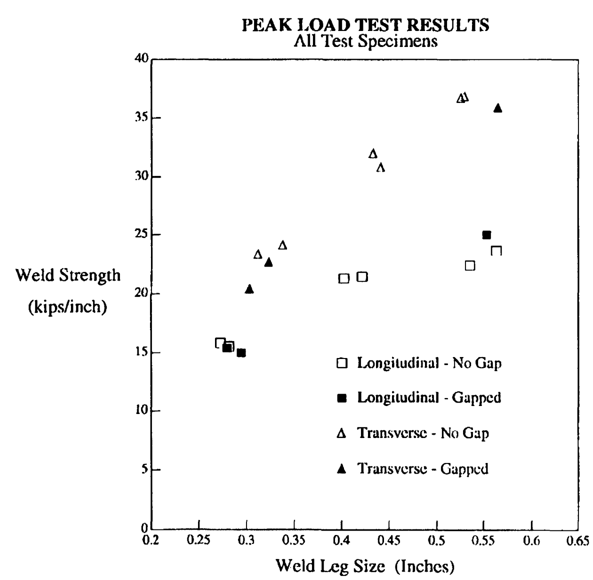

Figure 5

Table 5 Average Weld Failure Angles			
Longitudinal Specimens		Transverse Specimens	
Specimen Number	Failure Angle	Specimen Number	Failure Angle
1-2-L-0	64	7-2-T-0	16
2-2-L-0	65	8-2-T-0	13
3-3-L-0	57	9-3-T-0	14
4-3-L-0	61	10-3-T-0	14
5-4-L-0	57	11-4-T-0	15
6-4-L-0	55	12-4-T-0	16
13-2-L-1	61	16-2-T-1	22
14-2-L-2	53	17-2-T-2	27
15-4-L-1	50	18-4-T-1	25
Average Failure Angle Ungapped 60 Gapped 55 Overall 58		Average Failure Angle Ungapped 15 Gapped 25 Overall 18	

strengths reported by Miazga and Kennedy[12], Clark[7], and Kulak and Timler[11] appear to be somewhat less than the strengths measured in the present study.

All eighteen specimens in the present test program failed as a result of fracture in the weld metal. No significant distress of the lap plates or the middle plate was observed. Strain gages placed between the splice plate and the grips indicated that all of the plates with ¼-in. longitudinal welds, and one plate with ⅜-in. longitudinal welds, experienced some yielding prior to failure. It is believed, however, that plate yielding did not significantly influence the weld deformation values measured because comparable deformations were observed in other specimens where the plates remained elastic up to failure of the weldment.

Weld Failure Angles

The weld failure angle is important when considering the strength of a fillet welded connection. The effective throat dimension used for fillet weld design is the distance from the root perpendicular to the hypotenuse of the largest right triangle that can be inscribed within the cross section of the fillet weld. For equal weld leg sizes, a, the effective throat would by $0.707a$ and occur at an orientation of 45 degrees from the middle plate.

The failure angle of the weld fracture surface was measured at the conclusion of each test. Four separate failure angle measurements were taken for each four-inch test weld. A T-bevel apparatus was used in conjunction with a protractor to measure the angle of failure. The accuracy of the measured values is estimated to be no better than ±3 degrees since many of the failure surfaces were not perfectly planar.

Figure 8 indicates the failure angle measured and Table 5 summarizes the weld failure angle measurements for all of the test specimens. The failure angle shown for each specimen is an average value. A notable difference in the weld failure angle was observed for longitudinal and transverse welds: 58 degrees and 18 degrees, respectively. The average weld failure angle observed for longitudinal specimens without gaps was 60 degrees while the gapped specimen failure angles averaged 55 degrees. The failure angles observed for the no-gap and gapped transverse specimens were 15 degrees and 25 degrees, respectively. The measured values are in general agreement with commonly accepted failure angle values of 45 degrees for longitudinal specimens and 22 degrees for transverse specimens, and would probably be closer to these values if the faces of the weld were ground flat to minimize the influence of weld contour. The reason for the difference in weld failure angle for longitudinal and transverse specimens is due to a difference in the loading for each weldment. Longitudinal welds are loaded primarily in shear, while transverse welds are loaded in combined tension and shear.

Weld Leg Size

The weld design approach utilizes a linear increase in weld strength obtained by multiplication of the throat size, which is dependent upon the weld leg size, times an allowable or ultimate weld stress. As noted previously, test results by Gardner[9] and Preece[13] provide conflicting information regarding the increase in weld strength as the weld leg size increases. Part of the problem in evaluating the influence of weld size is that most of the recent experimental test data which has been collected in various studies is for smaller weld leg sizes, generally about ¼-in. to 5⁄16-in. maximum. For example, the weld strength curves cited in both the LRFD[2] and the ASD[1] versions of the AISC Manual are based upon tests with ¼-in. weld leg sizes.

Specimens with different weld sizes were tested to examine the effect of weld leg size. To compare the test results of various specimens with different weld leg sizes, and to facilitate a basis of comparison with the AISC approach, all test results were compared on the basis of the strength of the ¼-in. weldments. This was accomplished by averaging the ¼-in. specimen strengths (without gaps) and linearly extrapolating to compute the weld strength for other actual weld sizes. The results of all measured weld strengths are compared with the anticipated weld strength in Figures 9 and 10 for longitudinal and transverse specimens, respectively.

For the longitudinal weld tests, the measured weld strengths for both the ⅜-in and ½-in. weld sizes fall below the weld strength predicted from the ¼-in. weld results. The greatest decrease in strength occurred in the ½-in. longitudinal specimens without gaps. The strength of these two specimens was 25 percent below the strength which would have been predicted using the ¼-in. specimen results. The ⅜-in. longitudinal specimens also exhibited a decrease in strength from the predicted strength by an average of eight percent.

The larger transverse specimens do not demonstrate this similar significant decrease in strength. The ⅜-in. specimen strengths are quite close to the predicted values. The ½-in. ungapped transverse specimens do show a slight decrease in strength, with a reduction only about 4.5 percent.

The decrease in strength for the large longitudinal specimens are significant and could lead to decreased factors of safety when linearly extrapolating ¼-in. leg size results to larger weld sizes if only leg size is considered for the strength prediction. The reason for the decrease in strength is probably not strictly due to the leg size. The data presented here have taken into consideration the actual leg size and have used predicted strengths based on the actual leg size. It appears that the exposed weld profile which takes into consideration the throat size may be the reason for the decrease in strength.

Exposed Weld Profile

The variation in weld profile for differing weld sizes may be significant in determining the strength of the specimen. An examination of the ¼-in. weld profiles indicates a typically convex weld profile, resulting in a larger throat size than what would be predicted from the well-accepted design approach which uses the largest right triangle that can be inscribed within the fillet weld cross section. However, as the weld leg size increases, such as in the ⅜-in. and ½-in. welds, the profile tends to be less convex because the welder is putting on more weld passes and tries to obtain an acceptable leg size and profile in the least number of passes. The fact that less weld reinforcement exists for the larger weld leg sizes may be significant in explaining the reduction in strength for the longitudinal specimens. The weld reinforcement provides a larger proportion of the actual weld throat for the ¼-in. specimens than it does for the larger weld leg sizes which have smaller weld reinforcements. Also, the reason that the weld reinforcement does not play a significant role in the transverse

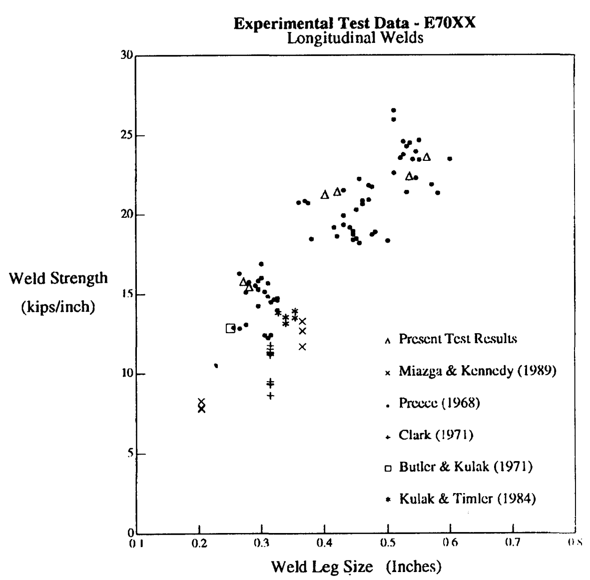

Figure 6

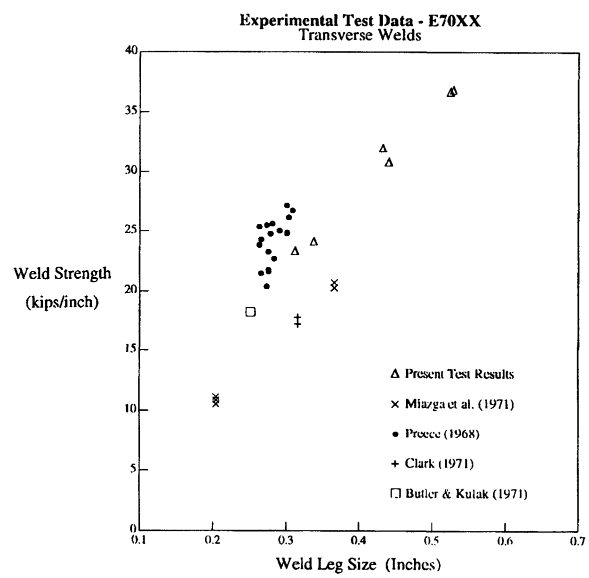

Figure 7

specimens is that weld failures occur at a lower angle where the reinforcement is already small—see Table 5 and Figure 8.

Another possible factor that could influence the effective throat is the weld root penetration. To evaluate the amount of weld root penetration a number of trial plates were prepared using the same welding procedures used to prepare the test specimens. Sections were removed from the trial welds, and then polished and etched for careful examination. The macroetch specimens indicated that the root penetration was small (no more than 1/16-in.) for all of the weld sizes examined. The specimens with a weld root opening were observed to have a slightly larger root penetration than the ungapped specimens.

The exposed weld profile was evaluated using a plaster mold of one test weld for each of the eighteen test specimens. The plaster molds were cut into a number of sections, and each section was then photographed so that the weld profile could be digitized and carefully measured. A sketch of some typical weld profiles is shown in Figure 11. The ½-in. specimens were found to have a much different profile than the ¼-in. and ⅜-in. specimens because of the number of weld passes necessary to achieve the required leg size. Most of the ½-in. specimens required four weld passes to build up a sufficient leg size. As a result of the multiple passes, these specimens had a "dimple" located at an angle between approximately 35 and 65 degrees from the center plate. Therefore, even though the leg sizes were sufficient, the failure throat was shorter than what would be predicted from the leg size because of this "dimple." By examining the plaster molds for the ungapped weld specimens—at four different locations along one weld for each specimen—it was determined that the throat dimension at the dimple was slightly undersized (by 0.02 to 0.03-in.) for three of the four specimens. An undersize of the magnitude measured for the ½-in. welds represents a five to nine percent reduction in the effective throat, which is considerably less than the 25 percent reduction in strength obtained by comparing the test results with the strength predicted by extrapoling the ¼-in. fillet weld strength.

The test results indicated that the failure angle for the ½-in. longitudinal specimens did somewhat "seek" the area where the dimple occurred. The dimple in the weld profile, combined with the fact that the weld reinforcement for the larger weld sizes are proportionally less than for smaller welds, is believed to be the reason why the ½-in. specimen strengths are so much less than the strength based upon the ¼-in. weld leg size.

The ½-in. transverse specimens did not experience a similar reduction in strength. The likely reason for this is the different angle of failure of the transverse welds: the average failure angle for the ungapped transverse specimens was 15 degrees. Because the "dimple" in the ½-in. specimens oc-

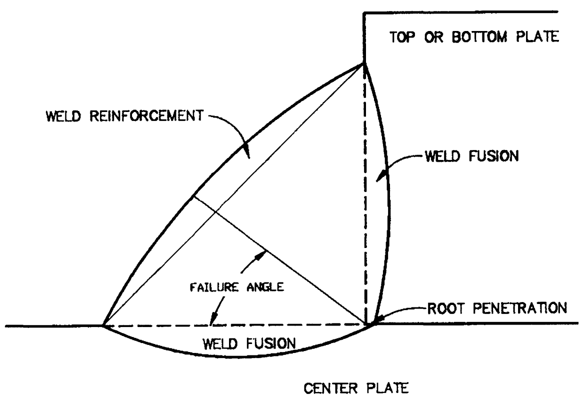

Figure 8

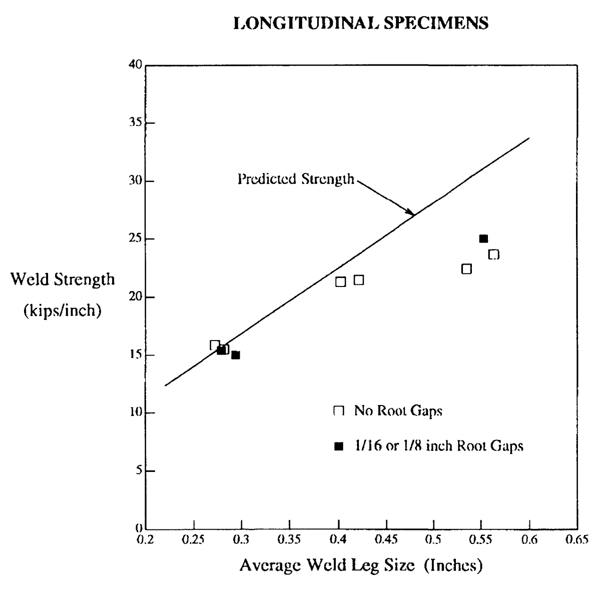

Figure 9

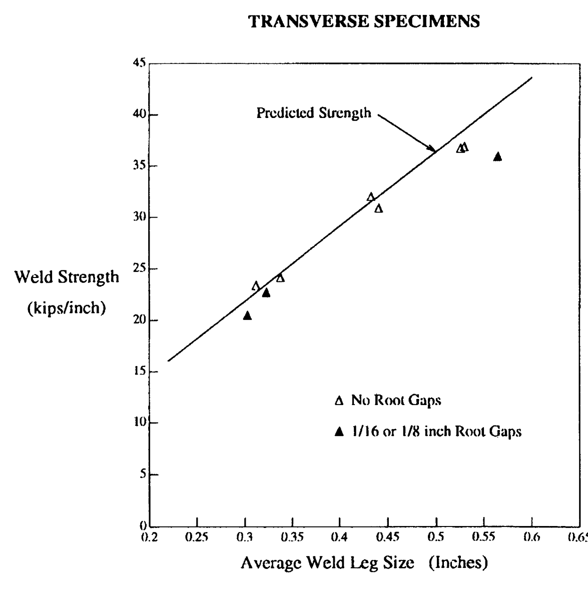

Figure 10

curred at a much greater angle, the specimen failure angle could not be forced to go through this 'dimple' where the reduced throat size was present. Therefore, the larger transverse specimens did not experience a significant decrease in strength from what would be predicted from the ¼-in. results.

Fabrication Gaps

Both the Structural Welding Code[3] and the Bridge Welding Code[5] state that the parts to be joined by fillet welds shall be brought into as close contact as practicable, with a maximum permissible root opening of $^{3}/_{16}$-in., a larger root opening of $^{5}/_{16}$-in. is permitted for welding shapes and thick plates if suitable backing is provided. Both AWS codes indicate that the leg of the fillet weld must be increased by the amount of the root opening if the separation is greater than $^{1}/_{16}$-in.; alternatively, the contractor may demonstrate that the required effective throat has been obtained.

From Table 1 it can be seen that six specimens were tested with weld root openings, or fabrication gaps. These gaps were created by placing wire rods between the plates to be welded to prevent tight fit-up. The root opening sizes examined in these tests were $^{1}/_{16}$-in. and ⅛-in., which are both less than the AWS maximum permissible root opening. The ⅛-in. gap, however, would require an increased leg size to account for the root opening.

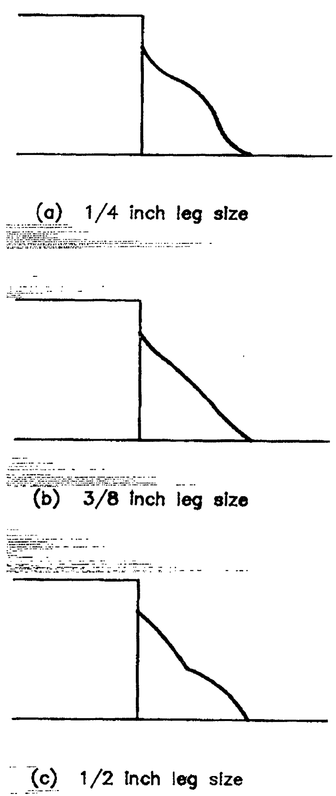

Figure 11

The strength of the longitudinal weld specimens with fabrication gaps can be seen in Figure 9. The specimen with a ¼-in. weld leg and $^{1}/_{16}$-in. gap (13-2-L-1) was approximately 10 percent weaker than the ¼-in. welds without gaps, taking into account nominal weld leg size only. The ¼-in. weld with a ⅛-in. gap was two percent weaker than the ¼-in. welds without gaps. Finally, the ½-in. specimen with a $^{1}/_{16}$-in. gap was about 20 percent weaker than the strength based upon the ¼-in. welds, but it was slightly stronger than the ½-in. specimens without gaps.

All of the transverse weld specimens with fabrication gaps exhibited some decrease in weld strength—see Figure 10. The ¼-in. specimens with a $^{1}/_{16}$-in. and a ⅛-in. gap exhibited a decrease in strength, relative to the ¼-in. ungapped specimens, of about four percent and eight percent, respectively. The ½-in. specimen with a $^{1}/_{16}$-in. gap was about 13 percent weaker than the predicted strength and was also weaker than the corresponding ½-in. ungapped specimens.

It is difficult to draw definite conclusions from the gapped specimen results since only six tests were conducted. Also, the two weld leg sizes were often not equal, making it difficult to assess the effect of the fabrication gap. It appears, however, that only minimal decreases in strength occurred for the two fabrication gap sizes examined. This is probably related to the extra weld material in the gap area. When the gapped specimens were being prepared, the welder decreased the welding speed slightly because weld was flowing into the weld root opening. The extra weld metal is evident in the weld macroetch profile shown in Figure 12. The required weld throat was still achieved by the presence of the additional weld metal that flowed into the root opening. If the weld metal had not been allowed to flow into the gap area, or if the weld penetration in the root opening was minimal or nonexistent, then it is quite possible that the specimen strength would have decreased significantly.

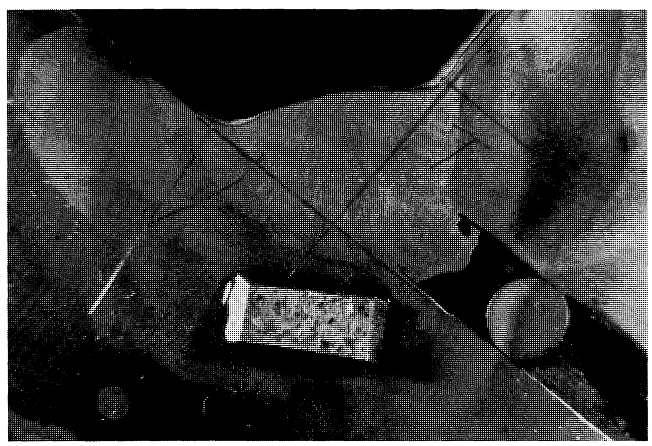

Figure 12

CONCLUSIONS

Based on the limited number of tests conducted in this study, a number of conclusions regarding the static behavior of fillet welds loaded in shear can be stated.

1. All of the transverse specimens were stronger than the corresponding longitudinal specimens. The ratio of strengths, based upon use of the actual weld leg size, ranged from 1.3 to 1.7 for the ungapped specimens and 1.2 to 1.4 for the gapped specimens.
2. It appears that weld strength is closely related to the actual weld profile. A significant decrease in strength, relative to ¼-in. weld specimens, was observed for the ½-in. longitudinal weld specimens. It is concluded that a dimple in the exposed weld profile of the ½-in. welds was responsible for the reduced strength.
3. Root penetration did not appear to affect the weld strength significantly. It should be noted, however, that the test welds had little root penetration. Different welding procedures, or even different welding processes, may produce much deeper root penetrations that could significantly influence the fillet weld shear strength.
4. Weld root openings within the AWS limits do not appear to cause a notable decrease in strength, and in one case the strength was even greater than that observed for the corresponding ungapped weld specimens. Slightly deeper root penetration and the flow of weld metal into the gap area appear to be factors responsible foor the minimal decreases in strength observed.
5. The ultimate deformation of all of the specimens was notably greater than the values noted in the ASD and LRFD Manual. The significant ductility of the weld electrode material may be responsible for the large weld deformations observed. The deformation apparatus, which was capable of measuring values right up to failure of the test specimens, may have provided a more realistic estimate of the deformation capability than the use of dial gages since it could be left in place to measure the large deformations which occur as the load approaches failure.

ACKNOWLEDGEMENTS

The financial support of the American Institute of Steel Construction for an educational fellowship for Mr. Quinn made the study possible. Also, special thanks must be given to the Chicago Bridge and Iron Company for preparing all of the welded specimens. The generous assistance of Ned Bacon, Robert E. Klippel, and James A. Brennan of CBI is gratefully acknowledged. Charlie Crow of the Purdue University Machine Shop provided valuable assistance in the preparation of the test specimens, and Dr. Ronald Hinkel generously provided the use of his laboratory for preparing the plaster weld molds. Finally, the advise and suggestions of Raymond H. R. Tide of Wiss, Janney, Elstner Associates were most appreciated.

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