Strength of Fillet Welds as a Function of Direction of Load

Transverse welds show about a 44% strength increase over longitudinal welds but show a decrease in deformation capacity in that longitudinal welds are nearly four times more ductile than transverse welds

BY L. J. BUTLER AND G. L. KULAK

Introduction

The strength of a fillet weld is dependent upon the direction of the applied load with respect to, say, the longitudinal axis of the weld.[11] Most of the reported experimental studies have been directed toward strength properties only, however, and little attention has been paid to deformation[9, 10]. As with most engineering materials, an increase in fillet weld strength could be expected to be accompanied by a decrease in deformation capacity. This reduced ductility can be of considerable importance and could influence a designer to orient fillet welds in one direction in preference to another. In addition, an evaluation of the complete load response curve would be useful in assessing the validity of present design methods for fillet welded connections, most of which assume an elastic weld response.[8]

In the course of an investigation into the behavior of eccentrically loaded fillet weld groups, basic information with respect to the load-deformation response of fillet welds was developed.[3] The results of this portion of the study are reported herein.

Test Program

Description of Tests

A series of 23 tests were conducted on ¼ in. fillet welds in order to establish the load-deformation response for elemental lengths of fillet weld. The 23 coupons were grouped in four categories. Group 1, with five coupons, had the weld axis parallel to the direction of the applied load. Groups 2–4 had six coupons each with the welds inclined at angles of 30, 60, and 90 deg, respectively, to the direction of the applied load.

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All coupons were made by a recognized steel fabricator from CSA G40.12 steel plate,[4] which has a specified yield stress of 44 ksi and a minimum tensile strength of 62 ksi. The welds were made using AWS E60XX electrodes.[1] In every case the cross-sectional area of the connected parts was proportioned to assure weld failure before rupture of the plates. At the same time, the thickness of the parts was limited by the weld size, in conformance with present building codes.[2] A schematic drawing of the coupons is shown in Fig. 1A for longitudinal welds and in Fig. 1B for inclined weld coupons. The dimensions shown are nominal and in all cases actual dimensions were taken, including weld leg size.

The welds were made as uniform as possible by having all welding done by the same operator, using electrodes all from the same lot and having the start and finish of all welds sawn free. The five coupons of the longitudinal weld group (θ = zero deg) were fabricated individually while the coupons of the other groups were obtained by sawing six 1 in. wide strips from a single assembly.

Test Procedure

Two 0.001 in. dial gauges were fastened to each specimen in order to measure the weld deformation. The gauges were mounted on steel brackets soldered to the specimen and the arrangement was such that the deformation measured included only a negligible contribution from the plate itself. The location of the gauges is shown in Fig. 2.

The specimens were loaded in tension in a 440,000 lb capacity electromechanical testing machine. Generally, readings were taken at 5 kip increments in the lower ranges and at 2.5 kip increments as the response became noticeably inelastic. As the ultimate load was approached, the increment was further reduced. Deformation readings were taken until the ultimate load was reached and then the gages were removed as loading continued to failure.

Test Results

The results of the coupon tests are presented in Figs. 3 through 6 in the form of load vs. deformation plots. (The solid lines in these illustrations relate to the theoretical expressions developed below). The mean values and standard deviations of the ultimate load and maximum deformation for each group are given in Table 1. As expected, all specimens failed in the fillet welds. Further details of the failure modes, etc. are available elsewhere.[3]

Theoretical Analysis

It has been shown[5] that the load-deformation response for mechanical fasteners can be expressed by the following relationship:

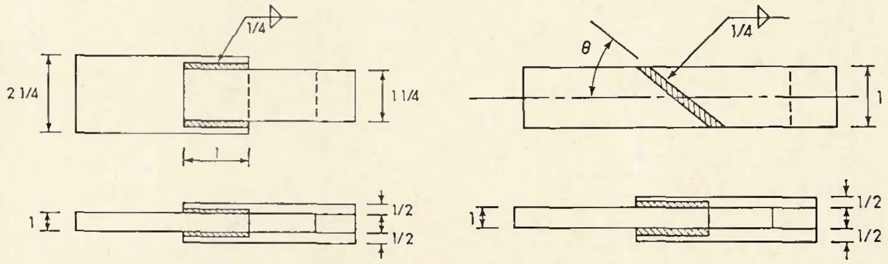

Fig. 1—Schematic representation of coupons. A (left)—longitudinal weld coupons; B (right)—inclined weld coupons

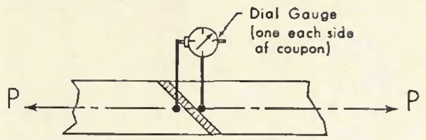

Fig. 2—Location of dial gauges

$$R = R_{\mathrm{ult}}\,(1 - e^{-\mu\Delta})^{\lambda} \qquad (1)$$

where R = fastener load at any given deformation; R_{ult} = ultimate load attainable by fastener; Δ = shearing, bending, and bearing deformation of fastener and local bearing deformation of the connected plates; μ, λ = regression coefficients; e = base of natural logarithms. The constants R_{ult}, μ and λ are determined for the particular fastener under investigation.

It should be possible to use this same expression for welds. However, unlike a mechanical fastener such as a high-strength bolt, the direction of the applied load must be taken into account.

The 23 coupons which made up the test series represent only a small sample and the curve-fitting was limited therefore to a trial-and-error procedure. In addition to fitting an individual curve, the equation developed must be a general expression valid for any angle of applied load. After trial, the following expressions were chosen for the variables in eq (1). These have been developed specifically for ¼ in. fillet welds made using E60XX electrodes. The angle θ is that between the direction of the applied load and the longitudinal axis of the weld.

$$R_{\mathrm{ult}} = \frac{10 + \theta}{0.92 + 0.0603\theta} \qquad (2)$$

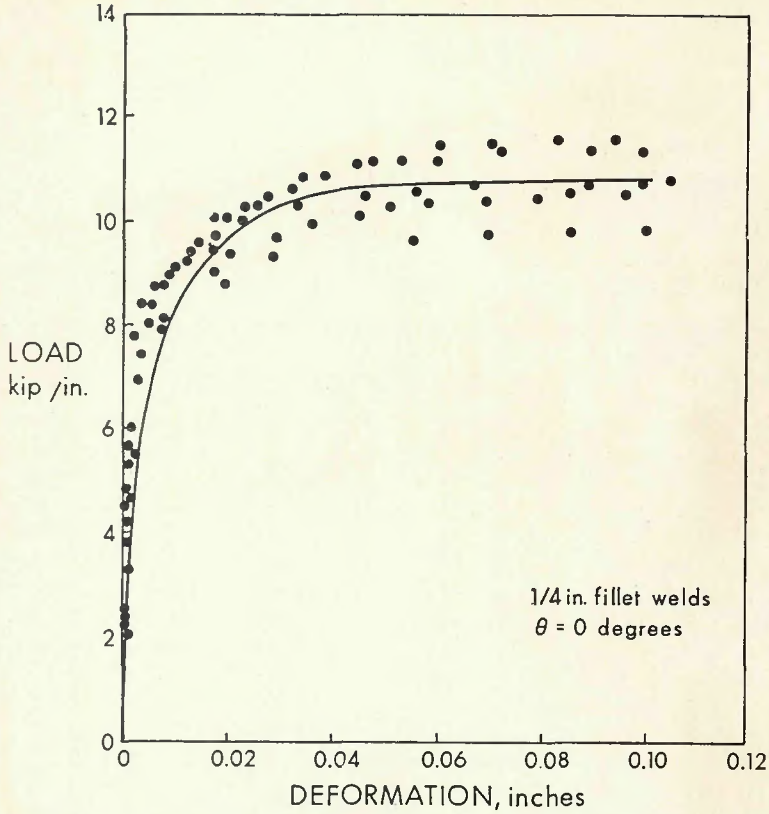

Fig. 3—Load (kips/in.) v. deformation (θ=0 deg.)—¼in. fillet welds

$$\Delta_{\max} = 0.225\,(\theta + 5)^{-0.47} \qquad (3)$$

$$\mu = 75\,e^{0.0114\theta} \qquad (4)$$

$$\lambda = 0.4\,e^{0.0146\theta} \qquad (5)$$

A plot of eq (2) is given in Fig. 7. The ultimate loads as calculated from this expression are within 2% of the mean test data except for the 60 deg group coupons where the discrepancy is about 9%. From Table 1 it can be noted that the mean ultimate load of this group does not follow the progression of the other groups. Equation (3) is plotted in Fig. 8. The maximum deformations as calculated from this expression are in good agreement with the test data.

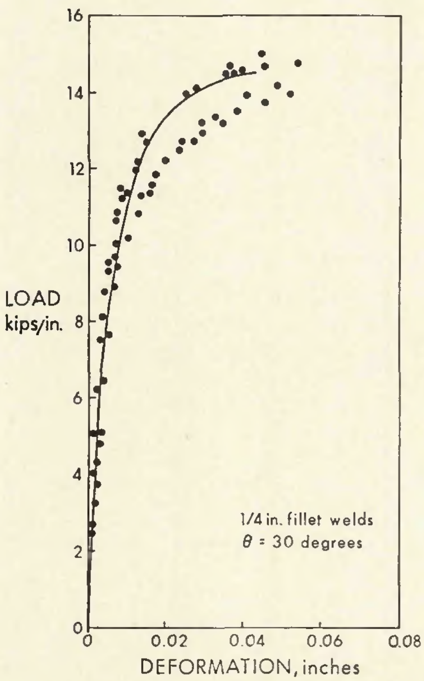

Fig. 4—Load (kips/in.) vs. deformation (θ=30 deg)—¼in. fillet welds

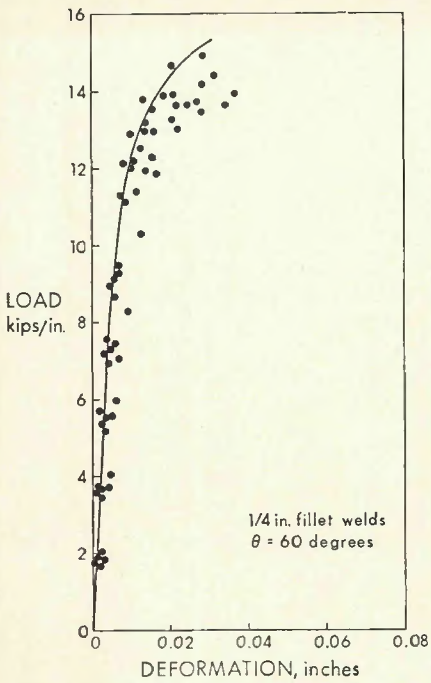

Fig. 5—Load (kips/in.) vs. deformation (θ=60 deg)—¼in. fillet welds

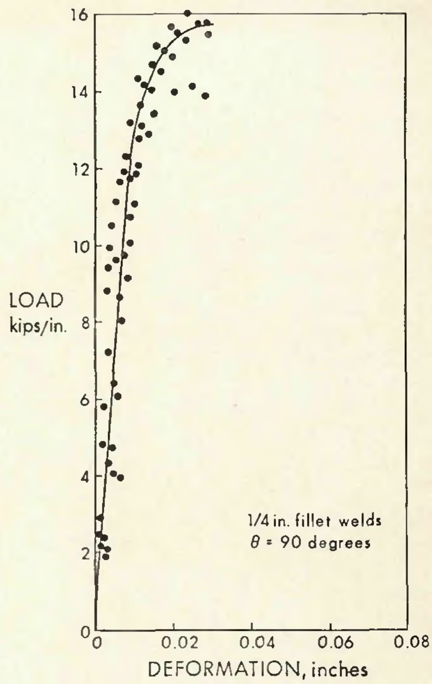

Fig. 6—Load (kips/in.) vs. deformation (θ=90 deg)—¼in. fillet welds

Table 1—Test Results and Predicted Values

Group θ, deg	Ultimate load, kips/in. Mean	Std. deviation	Maximum deformation, in. Mean	Std. deviation	Predicted values Ultimate load, kips/in.	Maximum deformation, in.
0	10.9	0.67	0.101	0.008	10.9	0.105
30	14.6	0.03	0.049	0.011	14.6	0.042
60	14.1	0.51	0.031	0.004	15.4	0.031
90	15.5	0.95	0.026	0.002	15.7	0.026

Equation (1) can now be used with the substitutions given by eqs (2)–(5). The results are shown against the basic test data in Figs. 3 to 6. Agreement between the theoretical and actual load-deformation responses is excellent for the two extreme cases (θ = zero and 90 deg) and adequate for the two intermediate angles tested.

Discussion

The increase in strength of the fillet welds tested in this program was approximately 44% as the angle of load changed from zero degrees (longitudinal weld) to 90 deg (transverse weld). Although this represents a substantial increase, the decrease in deformation capacity was also substantial. Welds oriented parallel to the direction of the load were nearly four times as ductile as those oriented transversely to the load. The shape of the load-deformation diagram was also more favorable in the ductile case—that is, a considerable portion of the curve was in the region where only small increments in load produced relatively large increases in deformation. It should be recognized that any detail using welds inclined at about 30 deg or more to the load will be much less ductile than it would have been otherwise.

It is clear from Figs. 3 to 6 that, like high-strength bolts,[12] there is no well-defined yield point for fillet welds acting in shear. Any arbitrary definition of yield, such as use of an offset method, gives neither consistent nor meaningful values as the angle of load changes. Furthermore, it appears that the total response cannot be idealized by any of the conventional representations like elastic or elastic-perfectly plastic. To satisfactorily describe the load-deformation behavior of fillet welds acting in shear, equations such as those given in this paper are necessary.

In using the results of the tests reported in this study for other cases, a number of variables arise which should be examined. These include basic electrode strength, use of other electrodes, use of other base metals, and changes in weld leg size.

The electrodes used in these tests represent E60XX electrodes of substantially minimum strength. Using the coupons in which the welds run parallel to the load, virtually the same test configuration as prescribed by AWS, these tests give an ultimate strength of 61.6 ksi. This is only 2.7% greater than the minimum specified value of 60 ksi. It can be expected then that the strength of fillet welds made using other lots of E60XX electrodes will be the same or greater than the values reported herein while the ultimate deformations will be the same or less than these reported values.

The most common electrodes in use today are probably AWS E60XX and E70XX. Since these electrodes have specified ultimate elongations which are nearly the same,[1] the results of the tests reported herein could be applied to connections using E70XX electrodes by a proper consideration of the increase in electrode strength. Furthermore, it has been shown[7] that the strength of welds made using electrodes of grades E60XX and E70XX is not appreciably affected by the grade of base metal involved. It shou'd be possible, therefore, to use the results of this study for all steels commonly used in conjunction with these two electrodes.

Within the common range of structural weld sizes, it has been shown that the throat stress for fillet welds is independent of weld leg size.[6] Deformation could likewise be expected to be independent of weld leg size since shear area is a direct function of the leg dimension.

Conclusions

The conclusions that may be drawn as a result of this study are as follows:

1. The strength and ductility of

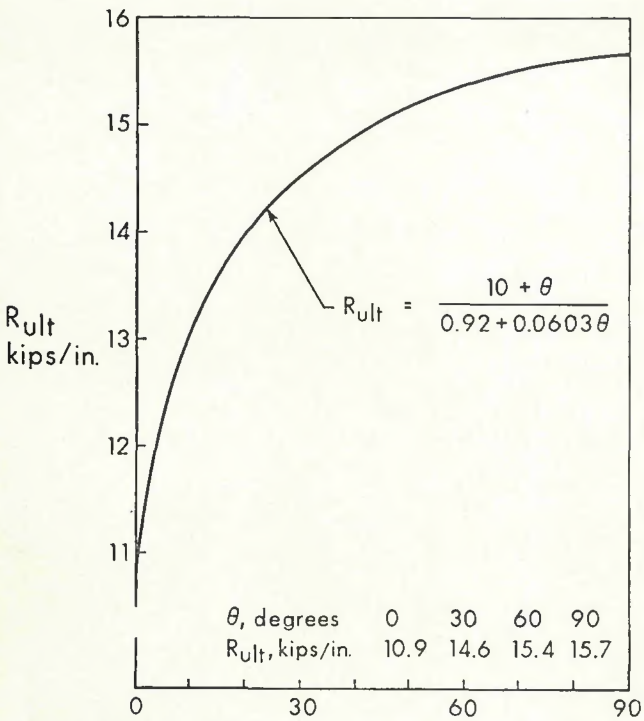

Fig. 7—Ultimate load vs. weld angle

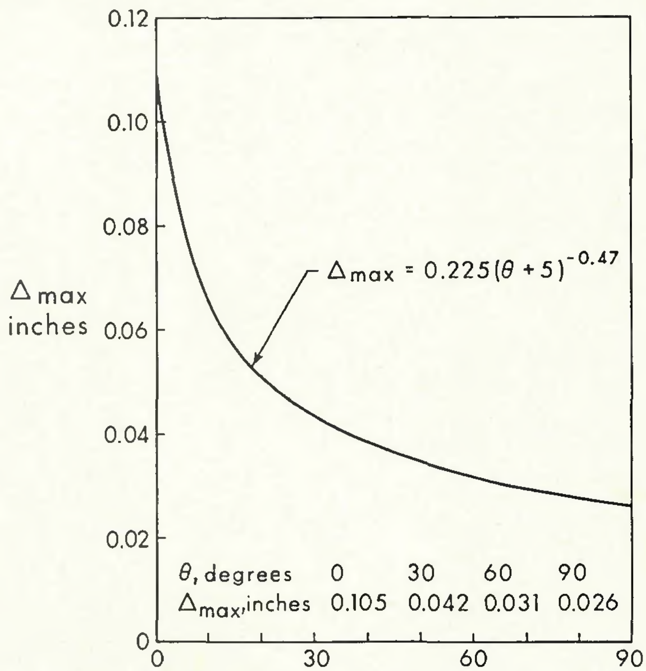

Fig. 8—Maximum deformation vs. weld angle

fillet welds loaded in shear are markedly dependent upon the orientation of the weld with respect to the line of action of the load. Welds placed parallel to the direction of the load have the lowest strength and highest ductility.

2. Fillet welds loaded in shear do not exhibit any well-defined yield point.

3. The load-deformation response of fillet welds cannot be generally represented as elastic or elastic-perfectly plastic. Mathematical expressions have been presented for all values of weld inclination to direction of applied load.

Acknowledgements

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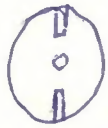
Technical Note: Fatigue Crack Propagation in Zircaloy-2 Weld Metal



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of a plastic strain parameter would then be appropriate. Such a correlation has been made and the results are shown in Fig. 3. The growth rate was found to be proportional to the approximate second power of this parameter, $\Delta\epsilon_p\sqrt{a}$, over two decades (10^{-6} to 10^{-4} in cycle) of growth rate. The data presented are from 11 specimens with surface plastic strain ranges varying from 3,400 μin./in. to 11,100 μin./in. The best-fit curve has a slope of 1.70, and the relationship which holds is:

$$da/dN = C(\Delta\epsilon_p\sqrt{a})^{1.70}$$

where C = constant ≈ 3.3; $\Delta\epsilon_p$ = plastic strain range;* a = half-crack length at specimen surface; N = number of cycles.

The good agreement of the data with this plastic strain range crack growth parameter is encouraging, especially in relation to the results of Boettner et al,[6] who obtained a nearly identical correlation on axially cycled OFHC copper using striation markings to delineate crack growth. Recent additional work by this author on the fatigue of Zircaloy wrought material under completely reversed axial strain cycling in the high strain regime shows continuing correlation with this plastic strain parameter.

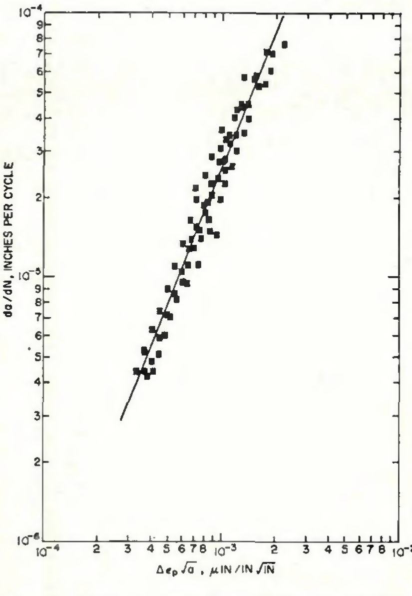

Fig. 3—Fatigue crack growth correlation in Zircaloy weld metal

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* In this study, plastic strain range ($\Delta\epsilon_p$) was approximated by subtracting twice the static yield strain (ϵ_e), determined from a monotonic stress-strain curve, from the applied total strain range ($\Delta\epsilon_T$), a measured quantity. Use was made of the monotonic stress-strain curve because no cyclic stress-strain relationship could accurately be obtained from the load-strain fatigue data gathered during testing. This is due to the bending mode of loading, which causes a non-uniform stress distribution. This approach was considered valid because no cyclic hardening or softening was detectable within the accuracy of the laboratory measurements from the early life load records. In addition, the monotonic stress-strain curves of this material agrees well with the wrought Zircaloy cyclic stress-strain curves reported by O'Donnell and Langer.[4]