Fillet Weld Keyhole T Bend Test

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A fillet weld keyhole bend test is proposed for gaging the quality of automatic and semi-automatic fillet welds in structural steel fabrication. The report covers the development of the test and the standard results to be expected from it.

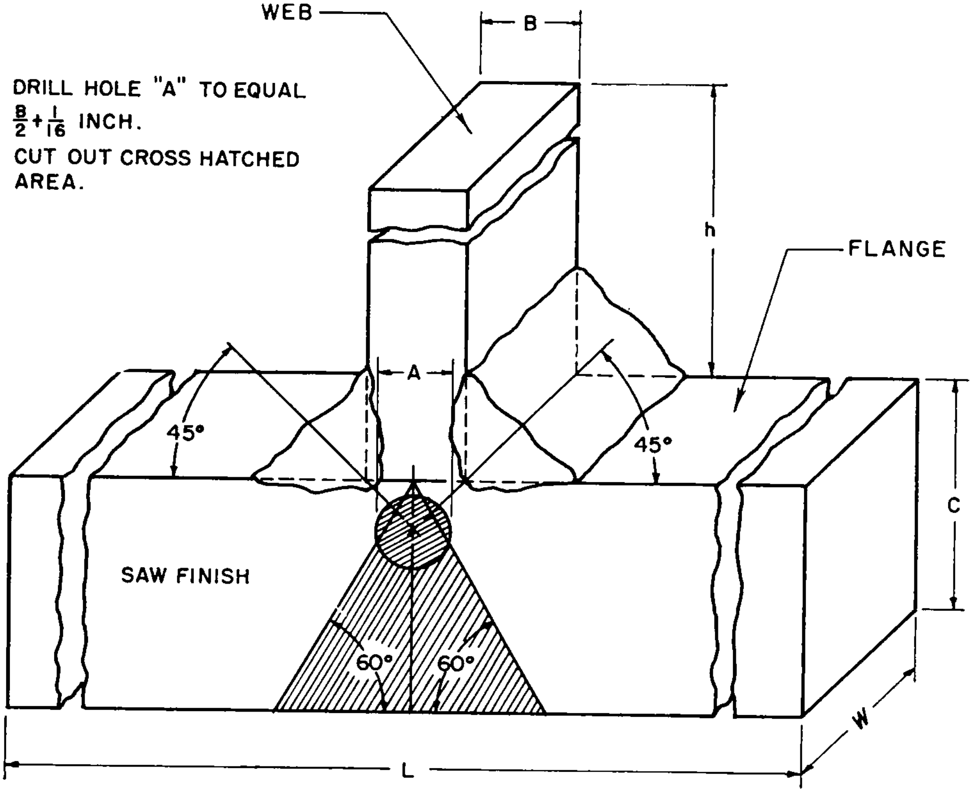
The test is similar in form to the standard AWS tee bend test. A transverse slice of a test section (in the form of a T) is relieved with a notch in the flange section of the T, on the side opposite the stem of the T formed by the web section, and bent to produce a uniform transverse elongation across the surfaces of the fillet welds connecting the web and flange. This test is called a fillet weld keyhole T bend test because of its appearance. Its purpose is to fill a gap not covered by currently accepted test procedures.

• THE PRESCRIBED TESTS employed in the pre-qualifications of structural fillet welding are unrealistic insofar as the major use of fillet welding is concerned by the California Division of Highways.

This state's major use of fillet welds is the connection of webs to flanges of highway bridge girders and the current testing procedures do not insure metallurgical properties in accord with this purpose. The orthodox procedure which finds most use at present is outlined in the American Welding Society (AWS) specifications (*2*).

This lack of correlation between tests and practice first led the Division to abandon the prescribed test and substitute a qualitative visual soundness inspection and a hardness requirement in the weld metal and heat-affected zone of a full-size test specimen. However, this too has been troublesome, since the heat-affected zones in many fillet welds exceeded the specified hardness (175 Brinell, maximum, when welding A7 or A373 steel) without apparent sacrifice in joint toughness. Other welds met the hardness requirement but lacked the ductility to provide protection against shock and against residual stresses developed in the member, particularly during the cooling of the joint. Furthermore, hardness tests and visual inspection provided no yardstick for gaging the effects of hidden porosity, cracking, dendritic segregation, and weld profile on the mechanical properties of the joint. Consequently, a test was desired which would evaluate the combined effect of all these factors on the toughness and ductility of fillet welded joints. Such a test was developed and is shown in Figures 1 and 2.

The need for this type of test has been evidenced by inspection problems encountered since 1951, when the Division of Highways first started to specify the extensive use of welding for primary bridge connections. In 1952, a program to develop a quantitative fillet-weld test was initiated to fill this need. Most difficulties involved disputes over the qualitative evaluation of porosity and weld profile, and over the validity of using hardness alone as a criterion of fillet-weld quality. These difficulties were magnified when welds, which met requirements for hardness and appearance, demonstrated suspiciously brittle fractures at relatively low stress levels when subjected to a standard



Minimum h > 4B or 2"
Minimum L > 3C or 5"
Minimum W > 1 ¼ C or 1 ¾"

At least 2 specimens must be prepared from each sample.

Figure 1. Details for preparing test specimen.

fillet-weld break test, whereas welds of doubtful appearance and excessive hardness frequently appeared quite ductile when subjected to the fillet-weld break test. Figure 3 shows samples exhibiting this reversed behavior.

The problem, therefore, was to devise a test which would separate samples according to the toughness and ductility of the fillet-welded joint and to determine what toughness or ductility level could be defined as undesirable. The problem was pursued using polarized light, strain gages, and destructive testing with plastic and metal models to study the stressing effects of various test geometries and testing fixtures.

CRITERIA

Resistance to stress seldom governs the size of fillet welds in bridge and girder design. For instance, shear load at the junction of the web and flange in an average welded beam 80 ft long and 4 ft deep may approach 4,000 lb per lin in. of fillet

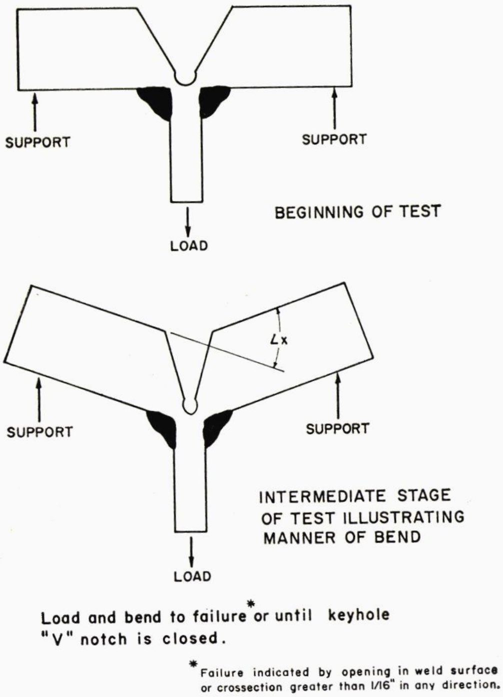


Figure 2. Method of testing.

weld at the maximum condition. A cross-section large enough to withstand this stress would need only ¼-in. fillet welds while actually the minimum size used would be about 5/16 in. This is because the minimum fillet size allowable is governed in most cases by the mechanical and metallurgical limitations inherent in the applied welding processes. These limitations make it difficult to consistently produce a sound fillet weld smaller than 5/16 in. on the steel thickness commonly used in welded bridge-girder fabrication.

It is impractical to calculate completely all possible stresses in a fillet weld as they may be altered by the indeterminate triaxial strains which are inevitably applied to the fillet by the reaction of the structure to unpredictable combinations of live load and differential thermal and residual stresses. For protection against such uncertain quantities, it is considered that complete continuity of mechanical properties across the joint from parent metal to weld metal is desirable.

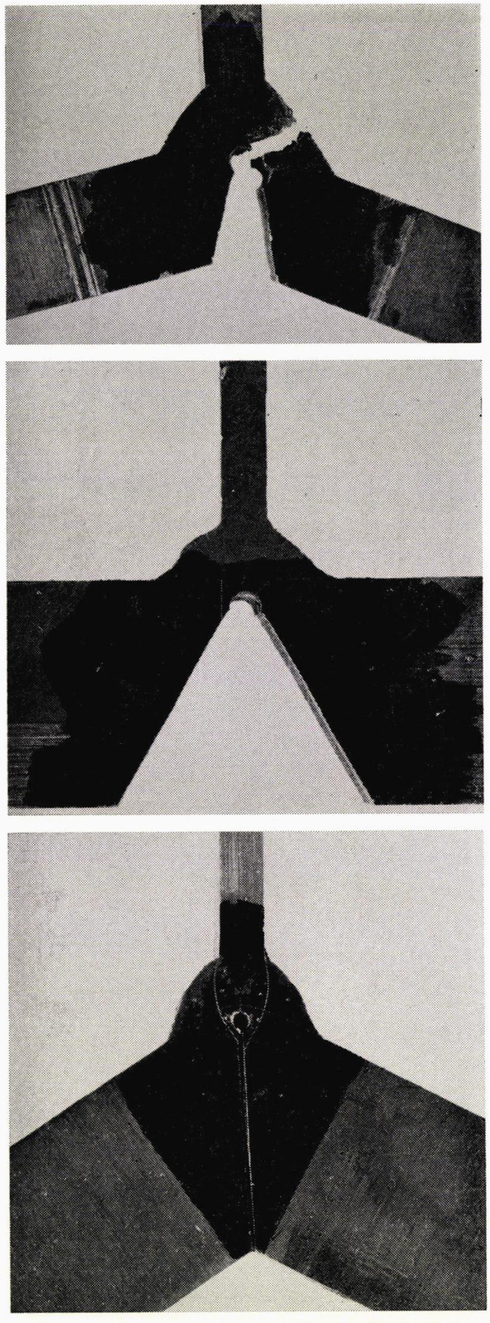


Figure 3. Post-test appearance of (top) specimen with 1⅛-in. flange and failure of soft weld metal of RB 87 hardness due to segregation and porosity; (center) specimen (before satisfactory test) with 1⅞-in. flange and weld metal of RB 87 hardness; (bottom) specimen with 2½-in. flange and weld metal of RB 90 hardness exhibiting no failure.

Thus, a test devised to evaluate fillet weld quality would not necessarily duplicate the applied design stresses to measure the adequacy of the fillet weld from the design intent standpoint. However, it should measure those mechanical properties of the joint which enable one to gage the soundness and uniformity of the structure in the weld area.

Those fillet weld properties which can be compared conveniently and quantitatively are limited to ultimate strength and ductility. Ultimate strength is related to hardness and can be so measured adequately for this purpose. Fillet joint integrity as measured by the fillet weld keyhole T bend test is dependent upon joint and weld shape, weld and heat-affected zone hardnesses, weld metal soundness and continuity, and weld metal segregation and chemical composition. When using a suitable welding procedure, these factors can be controlled by a competent welder to produce a joint with sufficient ductility and strength to satisfy the requirements for this test. Thus fillet-weld hardness and ductility can be used to compare quantitatively and to evaluate welding processes or procedures and welders.

DESIGN OF TEST CONFIGURATION

Four types of standard AWS tests are presently in use which deal with fillet weld soundness and strength. These are the tee-bend test, the fillet-weld-break test, fillet-weld-soundness test, and the transverse and longitudinal fillet weld shear tests. Only the shear tests are quantitative, and these are not designed to test machine welds or simulate fillet-welded T-shaped joint geometry, nor do these tests provide any means of quantitatively comparing ductility. The fillet-weld break and soundness tests are qualitative tests for soundness, and the usual tee-bend test is a qualitative test of parent metal weldability requiring the preparation of a specified test shape. None of these latter tests lends itself to any quantitative evaluation of the weld. They also require preparation from sections and shapes which may not resemble the girder fillet geometry they are intended to represent.

The geometry of the joint is important in that the action of a thick section of steel in quenching an adjacent fillet weld will provide weld metal and heat-affected zones with ductilities and toughnesses different from those obtained when placing the same weld against a thinner section. Furthermore, the parent metal structures are different for different flange thicknesses because of the refinements in grain structure affected by the additional rolling undergone with thinner plates. Therefore, extrapolating presently prescribed weld-test results from one extremity of plate thickness to another is not a good procedure.

Two other means of testing remain to be considered. Fillet welds can be compared using small tensile tests cut longitudinally from the fillet. Judging a weld by this means is difficult since the tensile section includes only a small portion of weld metal and none of the heat-affected zone, and it parallels the direction followed by most of the discontinuities occurring in the weld. Furthermore, this type of test is insensitive to weld shape or geometry. These limitations and the expense and time involved in preparing such specimens make a tensile test impractical as a means of testing fillet welds.

Lastly, one can attempt to duplicate the design geometry and loading with a shear test. During this study, such a test was performed by preparing a T-shaped specimen. The specimen was locked in a punch and the leg representing the web sheared from the top or flange portion of the T. In this test the shear strength correlation with hardness was acceptable but correlation between ductility and weld defects was poor. This would indicate that the volume of weld metal tested was too small and the strain orientation was wrong and so could not be considered as a representative test of weld quality.

Guided by the premises and considerations reflected in the previous paragraphs, minimum prerequisites for the form of a workable test can be inferred as follows:

1. The test should strain the largest

volume of fillet-weld metal that is practical. Therefore, the test specimen should include a complete section of the entire fillet weld, and would necessarily have to include portions of the web and flange.

2. It would not be practical to pull or shear such a specimen nor to bend it about any axis not parallel to the axes of the fillets. Therefore, the specimen would have to be bent transversely about an axis adjacent to or coinciding with the fillet axis and away from the web portion in a fashion similar to the standard tee bend test.

3. The specimen geometry must be altered in some regular fashion so the test will produce similar strain configurations in fillet welds for the majority of flange and web thicknesses encountered in welding fabrication. Therefore, the flange portion of the test specimen would have to be relieved with some type of notch in order to locate the strain in the fillets.

EXPERIMENTAL DESIGN PROCEDURES

The average bridge fillet-weld size is approximately proportional to the web thickness. Thus the width and depth of a notch necessary to relieve the flange so as to distribute stresses uniformly across the fillet was assumed to be related to web thickness. Starting with this assumption and the prerequisites cited previously, several trial shapes were designed and studied.

Polarized light was used to determine the elastic stress distribution in plastic models of various notch configurations. Those which seemed favorable were reproduced in fillet-welded metal specimens. These were tested by a fixture which stressed the specimen by beam loading the flange portion on either side of the notch (Fig. 4). The results of testing with notches of several different shapes are shown in Figures 3, 5, and 6.

Stress analysis proved to be impractical as a means of determining the best notch, but it has proven helpful in interpreting the statistical analysis of experimental test results. Strain gages and polarized light proved useful, but here again the strain range was too limited and the strain distribution in a homogeneous plastic model could not be accurately extrapolated to a heterogeneous structure of wrought and weld metal with discontinuities at the junction of the web and flange. The program consisted of applying estimated

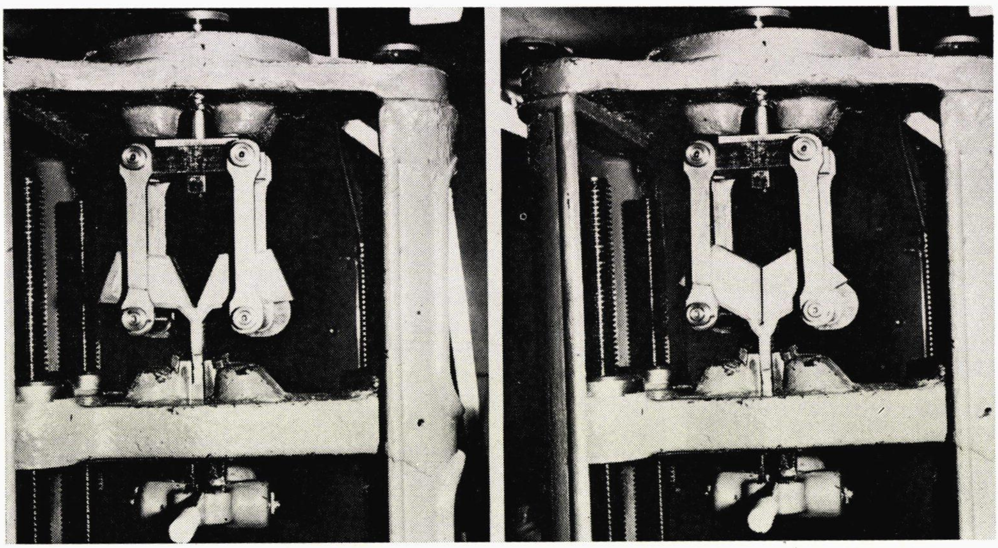


Figure 4. Testing fixture showing (left) initial and (right) final stage of sample with no failure. Spacers are used to prevent lower linkage from moving (nearest spacer removed to show test specimen).

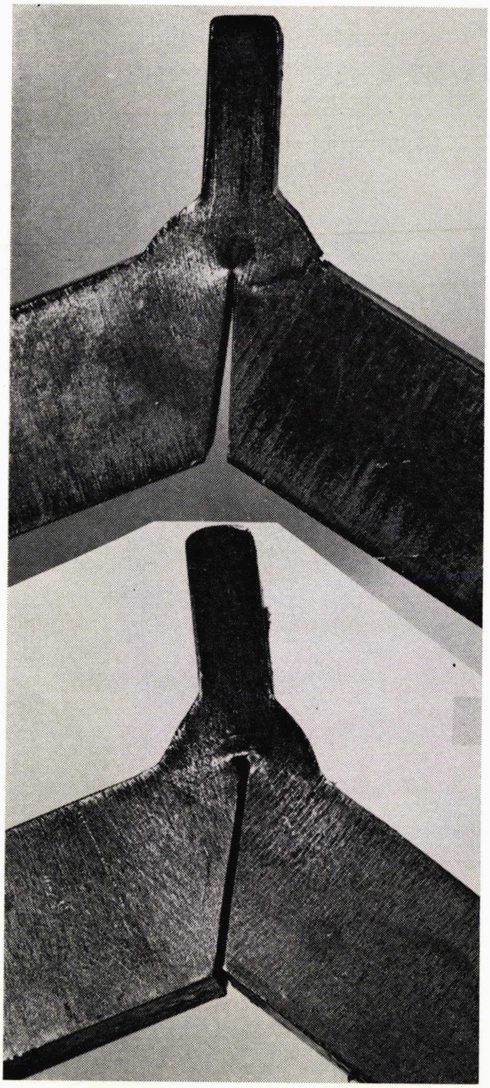


Figure 5. Experimental specimens, showing (top) first simple V-notch tried, which consistently caused failure of fillet toe, and (bottom) second modification with notch milled out to relieve the center and raise the neutral axis toward the flange fillet toe. Elongations and angles improved, but failures remained consistently in the fillet toe region.

stresses to the notch design using plastic models. These were studied under polarized light and further refined to produce the acceptable strain distribution. Subsequently this notch was reproduced in a steel specimen and tested. Results were used to re-evaluate the stress estimates

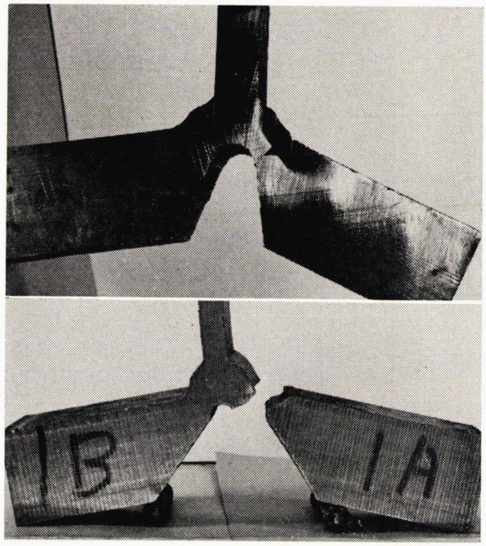


Figure 6. Specimen of upper type was beam loaded by means of a narrow plunger that contacted the specimen at the bottom of the notch, with test results governed by geometry rather than weld quality. Specimen of lower type, loaded as shown in Fig. 4, has a 90° included notch opening relieved with a central hole, indicated by tests as too far away from the fillets to control the break.

used in designing new plastic models. The notch was refined to its final form by repeating this step sequence several times until the results of testing actual pieces were consistent and seemed commensurate with the desired aims. Then a program of testing was begun to accumulate sufficient data to set a standard requirement (Fig. 7).

SPECIMEN PREPARATION

The test specimens were prepared and tested as shown in Figures 1, 2, and 4. The fillet-weld samples were sawn transversely into pieces of selected lengths which were given a finish of sufficient smoothness to provide accurate hardness readings. Then the relief hole was located and drilled. Following this, the sides of the notch were located and sawn with a band saw.

Elongation was determined at the fillet weld surface by means of marks made at the web and flange toes of the fillets. The distance between these marks was meas-

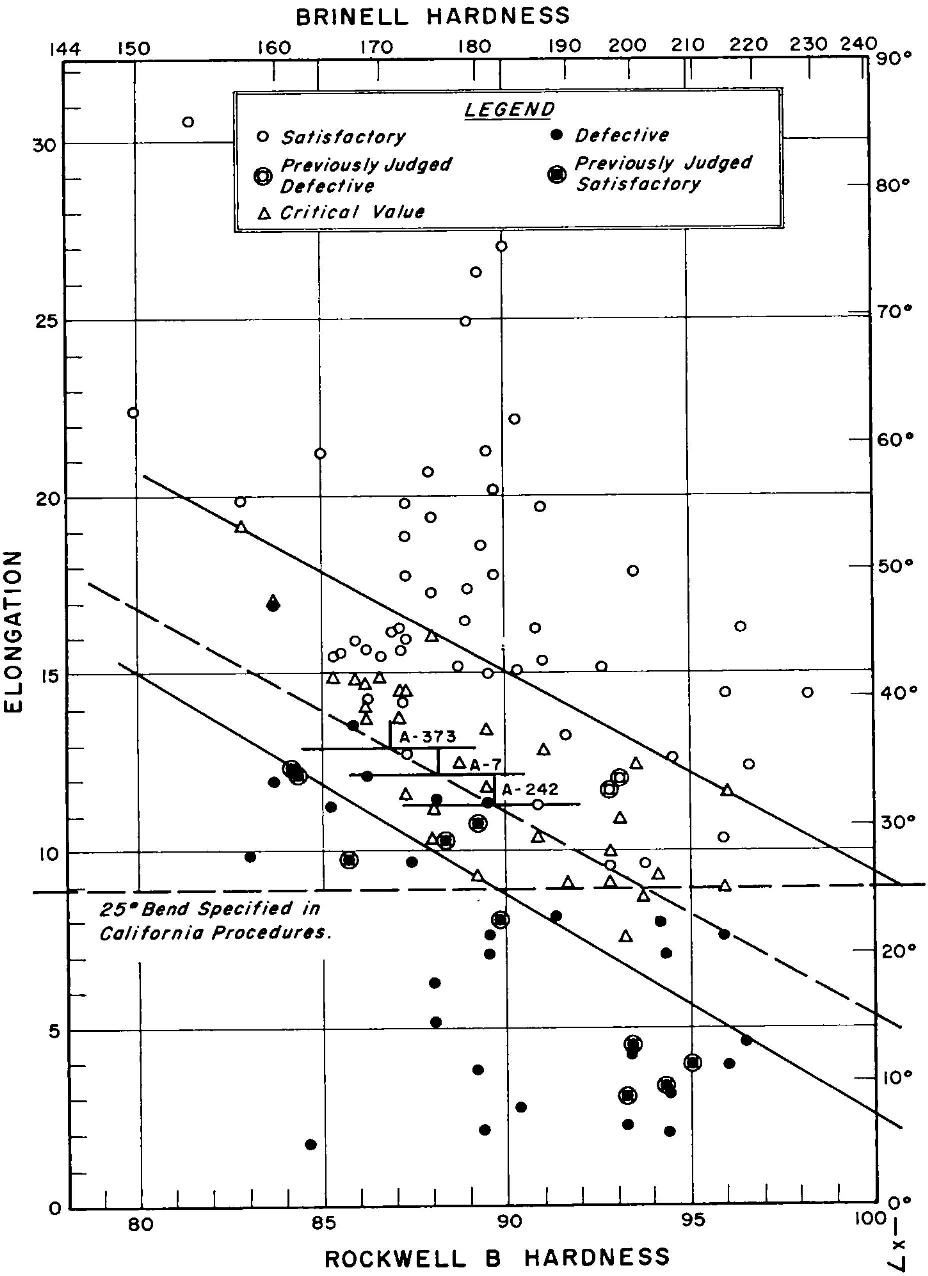


Figure 7. Fillet weld keyhole T bend test results, showing apparent minimum elongation and angle of failure vs weld hardness necessary to eliminate defective fillet welds. Experimental data average for each specimen plotted to show correlation with previous qualitative evaluation of specimen.

ured before and after the test and the percent elongation was calculated from these measurements.

Figure 7 was prepared with data accumulated from 400 actual procedure test specimens taken from slightly over 100 test samples. Each point plotted on the graph represents an average of tests performed on a single sample. The number of test specimens per sample varied with the length of the sample and was from two to sixteen T-bend specimens per sample. The purpose of this graph is to show correlation of keyhole T bend test to test procedures previously used by California. Whether or not the sample was judged satisfactory was based upon whether or not the majority of test specimens from it were judged satisfactory. This judgment was qualitative and based on the following factors:

1. Porosity, slag, and/or cracking (visible before or after failure) in accordance with the limits of currently accepted specification practice;

2. Undesirable weld profile—undercut, roll over, unequal leg, lack of penetration, excessive penetration, excessive crown or concavity—as generally described in AWS Handbook D2.0-56, Articles 508 and 509;

3. Hardness of such extremes as to produce: (a) a sharp audible snap at failure accompanied by intergranular fracture with negligible elongation (5 percent or less) and (b) a failure in parent metal with negligible elongation in the weld; and

4. Segregation sufficient to produce an intergranular fracture with elongations less than about 8 percent under small loads.

As a secondary check on the slope of the go-no go line on the chart, certain "critical" points were plotted on the graph. These were determined from samples which had both acceptable and defective specimens. This was done by averaging the average of acceptables, the average of defectives, the high defective, and the low acceptable for the particular sample the point represents.

The solid lines represent the extremes of these "critical" values. The dashed line represents the apparent parting line for the defective and non-defective judgments, taking into consideration the majority of points plotted. The critical area falls along the same slope as the over-all average and apparently indicates general correlation.

The 25-deg bend limit was based on a discontinuity in the test results which was apparent in the initial data taken from the test program. Results grouped above and below this value correlated well with observed weld quality, hence the 25-deg limit has been in use in judging fillet-weld procedures.

The Brinell maximum of 175, specified in the past for the heat-affected zones of fillet welds on A7 steel, represents the average tested unit tensile strength of the parent metal plus 25,000 psi. If this same formula is applied, in terms of hardness, to fillet-weld metal on A373, A7, and A242 steels, the hardnesses obtained are about 171, 175, and 182 Brinell, respectively. By plotting these hardnesses, a corresponding minimum elongation can be obtained which would match the hardness requirement. This information is presented in the conclusions of this paper. At present this is an arbitrary but logical correlation. Later statistical analysis may show that less stringent hardness requirements coupled with elongations or bend requirements may be practical.

The angles represented in the right-hand ordinate (Fig. 7) correspond approximately to the elongations in the left-hand ordinate for an average specimen. Actually this is not strictly true, because the elongation for a given angle of bend will change slightly with web thickness and hardness. However, the preliminary statistical study of the data indicates that a minimum quality requirement for A7, A373, and A242 steels which is based on the graphed separation line, will be low enough to compensate for any variation brought about by changes in section geometry. Statistical results indicate that the following equation may be used to express average results (not minimum) to be expected from keyhole T bend tests performed on sound fillet welds on A7, A373, and A242 steels:

$$\text{Bend } \angle{}^{\circ} = 113.6\text{-}0.58 \text{ (Weld Hardness)} - 0.23 \text{ (HAZ* Hardness} + \text{Web Hardness)} - 2.59 \text{ (Web Thickness)}$$

in which hardness is Rockwell B, and thickness is in inches.

Thus when the specimen is prepared as shown in Figure 1, the bend and elongation test results can be predicted from weld hardness, heat-affected zone hardness, web parent metal hardness, and web thickness for sound welds (provided the web thickness is less than the flange thickness). The effect of flange thickness can be neglected, considering that the principal effects from this source are measured indirectly by the character of the weld metal and heat-affected zones. The effects of flange metal hardness are such that no positive correlation with test results is possible.

CONCLUSIONS

(1) The fillet weld keyhole T bend test fulfills the need for a quantitative quality control test for use with automatic and semi-automatic welding procedures.

(2) The test is suitable for use in the average structural steel welding shop, since (a) the test specimen may be prepared by simple sawing and drilling operations, and (b) evaluation of results can be stated as a simple go-no go value.

(3) Based on the data in Figure 7, the average tolerable elongation and bend of failure of a structural fillet weld is as follows:

Base Metal	*Min. Elongation* (%)	*Min. Angle* (deg)
A373	13	36
A7	12	34
A242	11	32

Note: Failure is denoted by the appearance of any opening in the fillet weld (face or section) which exceeds $1/16$ in. in any direction in the course of bending.

(4) Practical experience indicates that a 25-deg minimum angle can be used as a minimum specification limit for the bend test specimen.

* HAZ = heat-affected zone.

REFERENCES

1. AMERICAN WELDING SOCIETY. "Welding Handbook." 3rd Ed., Chap. 59, p. 1442-1470 (1950).
2. "Standard Specifications for Welded Highway and Railway Bridges." Amer. Welding Soc., D2.0-56.