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FILLET WELD KEYHOLE "T" BEND TEST

By

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P. G. Jonas

and

C. B. Kendrick

To be presented at the 39th Annual Meeting
of the Highway Research Board
Washington, D. C., January 11-15, 1960

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SYNOPSIS

A Fillet Weld Keyhole "T" Bend Test is proposed for the purpose of gauging the quality of automatic and semi-automatic fillet welds in structural steel fabrication. This paper covers the development of the test and the standard results to be expected from such.

The test is similar in form to the standard American Welding Society Tee Bend Test. A transverse slice of a test section (in the form of a "T") is relieved by a notch in the flange section of the "T" on the side opposite the web and is bent to produce a uniform transverse elongation across the surfaces of the fillet welds connecting the web and flange.

The purpose of this test is to fill a gap which at present is not covered by accepted test procedures.

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To be presented at the 39th Annual Meeting of the Highway Research Board, Washington, D. C.
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INTRODUCTION

The presently 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 presently employed 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 Standard Specifications for Welded Highway and Railway Bridges.

This lack of correlation between tests and practice first led the California Division of Highways 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; while 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 gauging 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

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ductility of fillet welded joints. Such a test was developed and is shown in the Appendix, Exhibits 1 and 2.

History

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. Therefore, starting in 1952, a program to develop a quantitative fillet weld test was initiated to fill this need. As inferred previously, 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 especially magnified when welds, which met requirements for hardness and appearance, demonstrated suspiciously brittle fractures at relatively low stress levels when subjected to a standard fillet weld break test, whereas welds of doubtful appearance and excessive hardness frequently appeared quite ductile when subjected to the fillet weld break test. Exhibit 3 in the Appendix 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 gauges, and destructive testing with plastic and metal models to study the stressing effects of various test geometries and testing fixtures.

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DISCUSSION

Criteria for Judging Structural Fillet Welds

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 feet long and 4 feet deep may approach 4000 pounds per linear inch of fillet weld at the maximum condition. A cross section large enough to withstand this stress would need only 1/4" fillet welds while actually the minimum size used would be about 5/16". 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" on the steel thickness commonly used in welded bridge girder fabrication.

It is impractical to completely calculate 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.

Thus a test devised to evaluate fillet weld quality would not necessarily duplicate the applied design stresses in order to measure the adequacy of the fillet weld from the design intent standpoint. However, it should measure those mechanical properties

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of the joint which enable one to gauge 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 weldor 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 evaluate welding processes or procedures and weldors.

Design of Test Configuration

Four types of standard A.W.S. 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 and also require prepara-

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tion from sections and shapes which may not resemble the girder fillet geometry they would intend 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

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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, one can infer minimum prerequisites for the form of a workable test 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

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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 in the previous section, several trial shapes were designed and studied using the methods enumerated in the subsequent paragraphs.

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 (see Exhibit 4). The results of testing with notches of several different shapes are shown (in Exhibits 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 gauges 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 stresses to the notch design using

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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 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 aims desired of the test. Then a program of testing was commenced in order to accumulate sufficient data to set a standard requirement. For the graphed results of these tests see Exhibit 7.

Specimen Preparation

The test specimens were prepared and tested as shown in Exhibits 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 measured before and after the test and the percent elongation was calculated from these measurements.

The graph (Exhibit 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

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procedures previously used by this State. 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, Article 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% or less).

(b) A failure in parent metal with negligible elongation in the weld.

(4) Segregation sufficient to produce an intergranular fracture with elongations less than about 8% 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.

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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. As will be noted the "critical" area falls along the same slope as the over-all average and apparently indicates general correlation.

The 25° bend limit shown on the graph 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° limit has been in use by this State on judging fillet weld procedures.

The Brinell maximum of 175, specified in the past by this State 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 as shown on the graph, 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 of the graph 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

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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:

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

where Hardness is Rockwell B,

and Thickness is in inches

Thus when the specimen is prepared as illustrated in Exhibit 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 if one considers that the principle 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.

* HAZ = heat affected zone

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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 Fillet Weld Keyhole "T" Bend 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 graphed in Exhibit 7, the average tolerable elongation and bend of failure of a structural fillet weld (as determined by the Fillet Weld Keyhole "T" Bend Test) is listed in the following table:

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

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

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

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APPENDIX

Fillet Weld Keyhole "T" Bend Test

Exhibit 1	Test Specimen
Exhibit 2	Method of Test
Exhibit 3	Post-Test Appearance
Exhibit 4	Testing Fixture
Exhibit 5	Experimental Specimen
Exhibit 6	Experimental Specimen
Exhibit 7	Graphed Test Results

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(1) American Welding Society. Welding Handbook, 3rd Edition, New York, New York, 1950, Chapter 59, pages 1442-1470.

(2) Standard Specifications for Welded Highway and Railway Bridges of the American Welding Society, D2.0-56.

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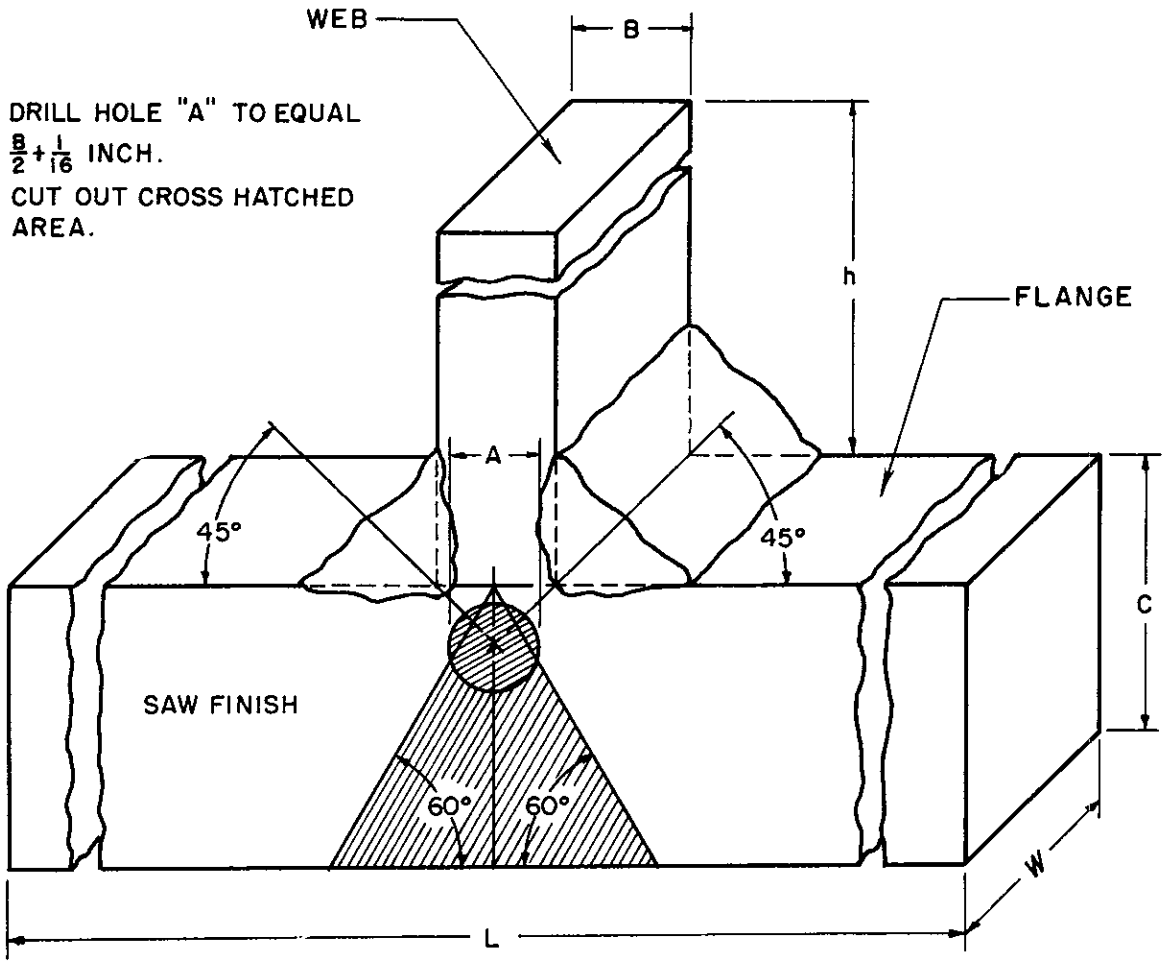

Minimum h > 4B or 2"
Minimum L > 3C or 5"
Minimum W > 1 ¼ C or 1 ¾"

At least 2 specimens must be prepared from each sample.

SPECIMEN

FILLET WELD KEYHOLE "T" BEND TEST

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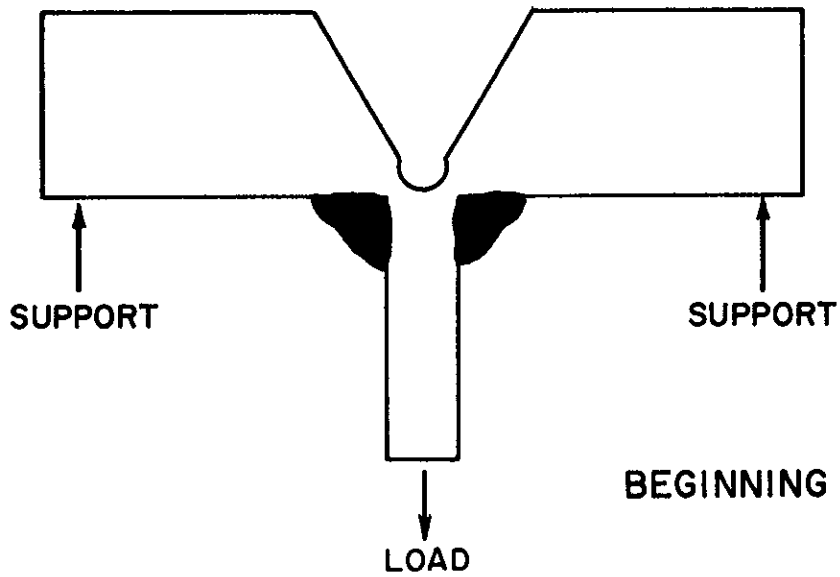
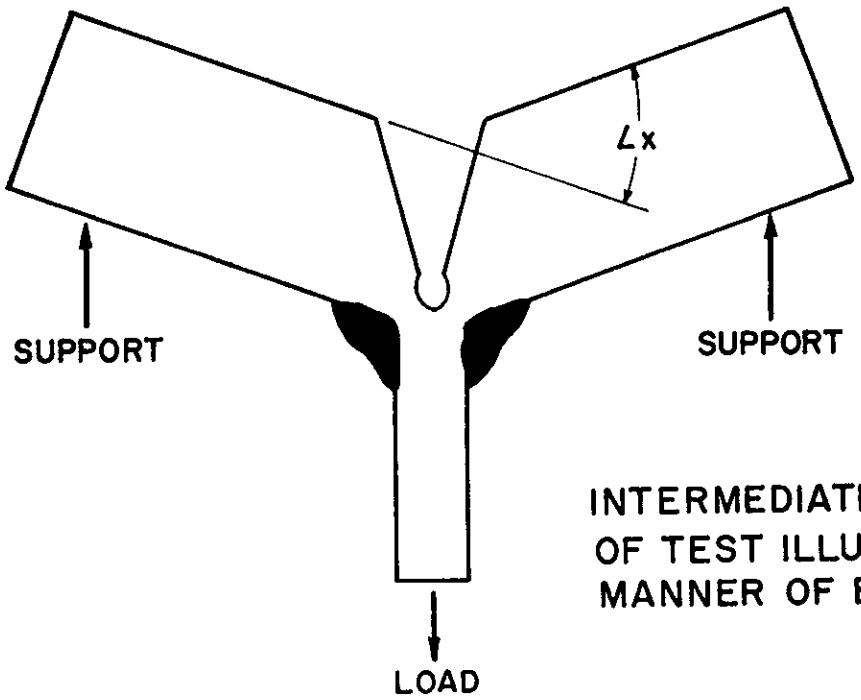
METHOD OF TESTING



BEGINNING OF TEST



INTERMEDIATE STAGE OF TEST ILLUSTRATING MANNER OF BEND

Load and bend to failure* or until keyhole "V" notch is closed.

*Failure indicated by opening in weld surface or cross section greater than 1/16" in any direction.

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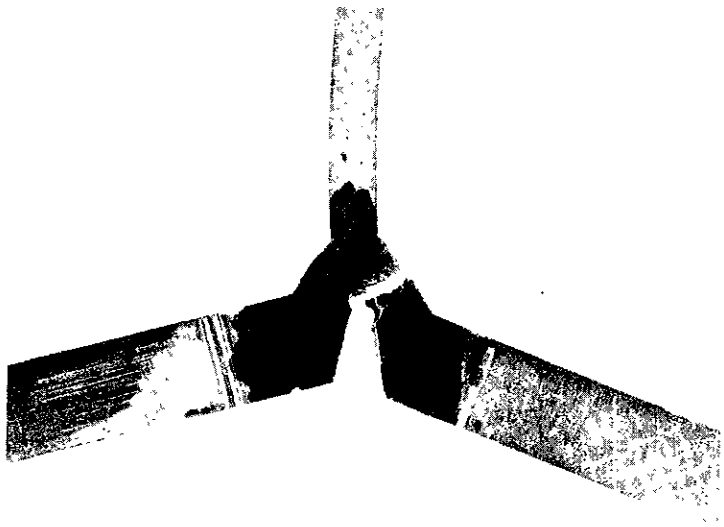
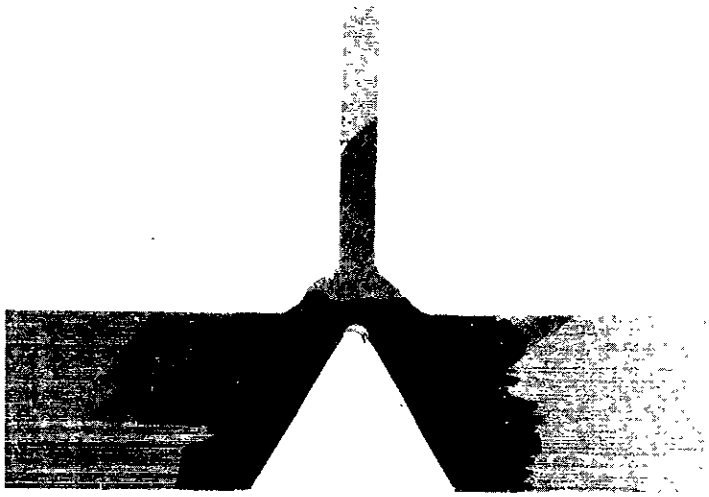
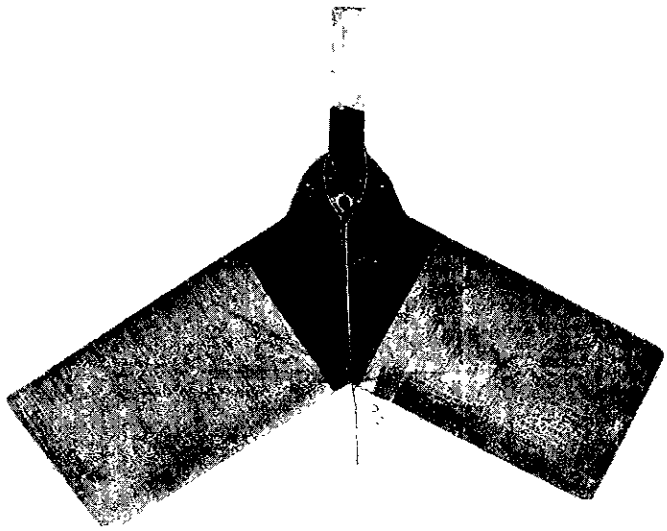


Specimen with 1 1/8" flange. Failure of soft weld metal (RB 87 hardness) due to segregation and porosity.



Specimen (before testing) with 1 7/8" flange and weld metal of RB 87 hardness. Test was satisfactory.



Specimen with 2 1/2" flange and weld metal of RB 90 hardness. Test resulted in no failure.

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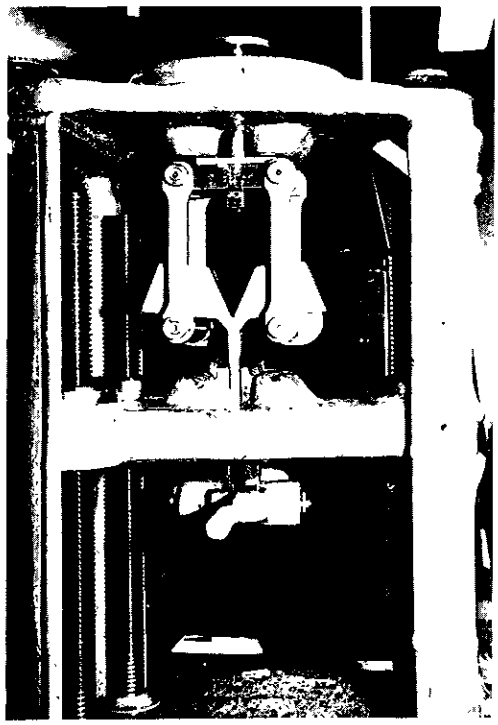

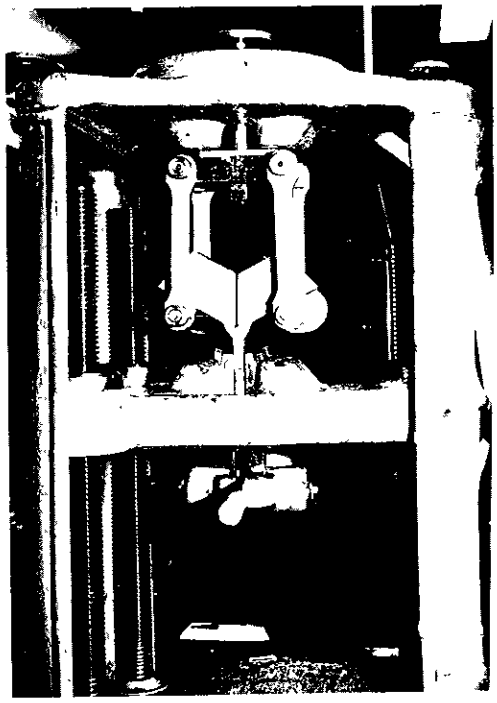

Testing fixture showing initial and final stage of sample tested with no failure. Spacers are used to prevent the lower linkage from moving. The nearest spacer has been removed to show test specimen.

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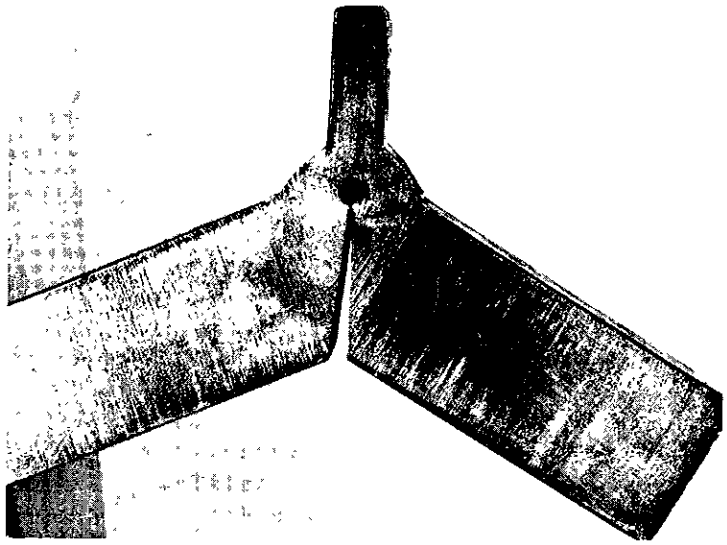
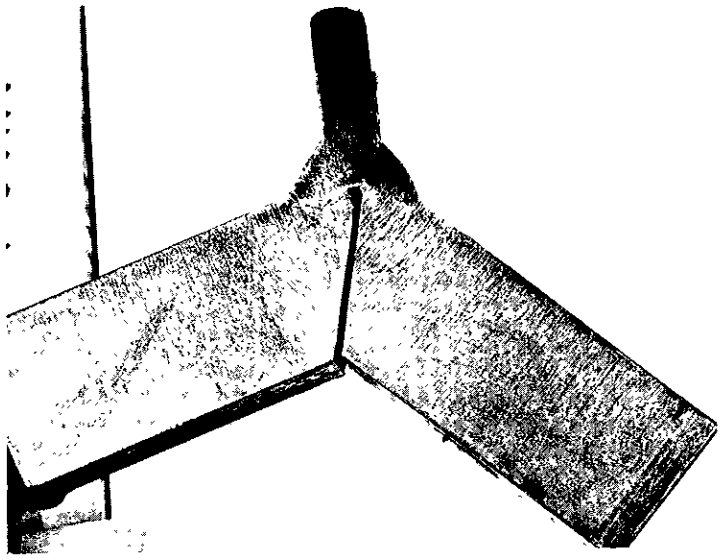


First simple "V" notch tried. This notch consistently caused failure of the fillet toe as illustrated here.



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.

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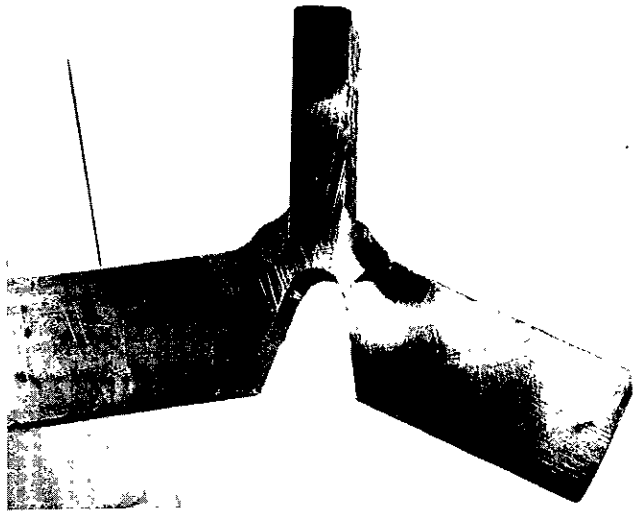
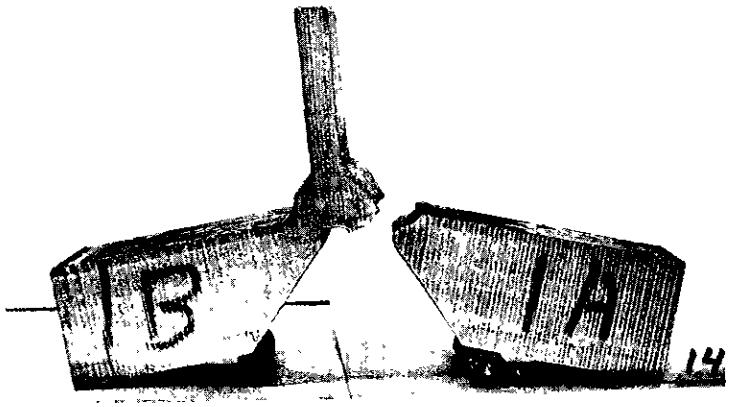


This type specimen was beam loaded by means of a narrow plunger which contacted the specimen at the bottom of the notch. The test results were governed by geometry rather than weld quality.



This specimen loaded as shown in Exhibit 4 has a 90° included notch opening relieved with a central hole. Tests indicated the hole was too far away from the fillets to control the break.

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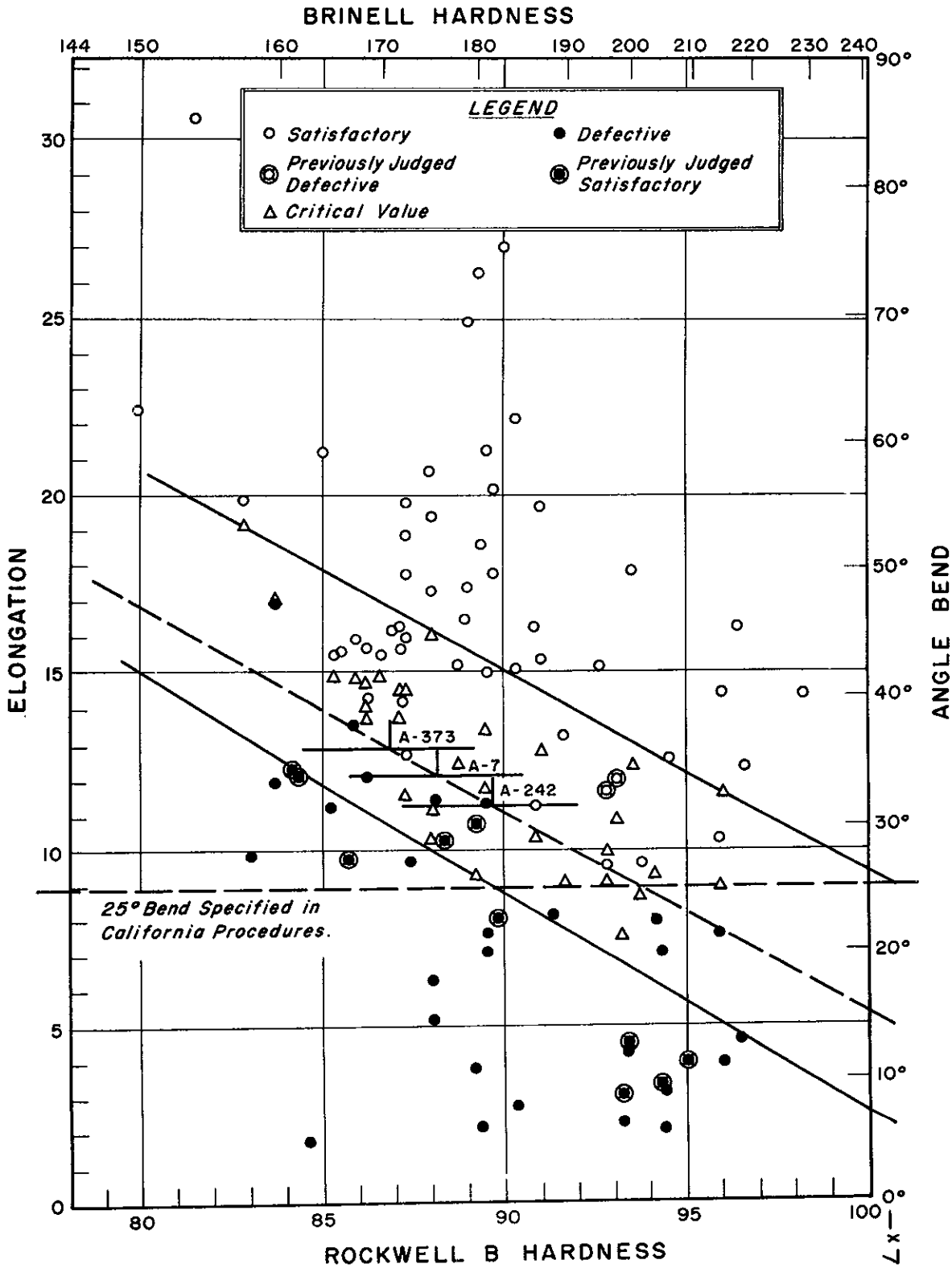
FILLET WELD KEYHOLE T-BEND TEST

Apparent minimum elongation & angle of failure vs. weld hardness necessary to eliminate defective fillet welds.
Experimental data average for each specimen is plotted to show correlation with previous qualitative evaluation of specimen.



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