Fatigue and Fracture Testing of WELDMENTS

McHenry/Potter
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Foreword

The symposium on Fatigue and Fracture Testing of Weldments was held on 25 April 1988 in Sparks, Nevada. The event was sponsored by ASTM Committees E-9 on Fatigue and E-24 on Fracture Testing. The symposium chairmen were John M. Potter, U.S. Air Force, and Harry I. McHenry, National Institute of Standards and Technology, both of whom also served as editors of this publication.

Overview

The symposium on Fatigue and Fracture Testing of Weldments was organized to define the state of the art in weldments and welded structures and to give direction to future standards activities associated with weldments.

Weldments and welded joints are used in a great variety of critical structures, including buildings, machinery, power plants, automobiles, and airframes. Very often, weldments are chosen for joining massive structures, such as offshore oil drilling platforms or oil pipelines, which themselves can be subject to adverse weathering and loading conditions. The weldment and the welded joint together are a major component that is often blamed for causing a structure to be heavier than desired or for being the point at which fatigue or fracture problems initiate and propagate. The study of fatigue and fracture at welded joints, then, is of significance in determining the durability and damage tolerance of the resultant structure.

This volume contains state-of-the-art information on the mechanical performance of weldments. Its usefulness is enhanced by the range of papers presented herein, since they run the gamut from basic research to very applied research. Details of interest within this volume include basic material studies associated with relating the metallurgy and heat treatment condition of the weld material to the growth behavior in a weld-affected area, often including the effects of corrosive media. Also addressed are the residual stress and structural load distributions within the weldment and their effects upon the flaw growth behavior. At the application end of the spectrum are papers concerning the flaw growth behavior within weldments where the sizes of the sub-scale test elements are measured in feet or metres. The broad range of the topics covered in this Special Technical Publication makes it an excellent resource for designers, analysts, students, and users of weldments and welded structures.

This volume is also meant to serve as a means of setting the directions for future efforts in standards development associated with fatigue and fracture testing of weldments. The authors were charged with defining the "holes" or deficiencies in standards associated with fatigue and fracture testing. As such, this volume will be of significance to the standards definition communities within ASTM's Committees E-9 on Fatigue and E-24 on Fracture Testing, as well as to other relevant industry standards development organizations.

Weldments provide efficient means of ensuring structural integrity in many applications; this type of joining is often used where there is no other competitive, in terms of cost or mechanical strength, approach to getting the job accomplished. The subject of weldments deserves significant attention in both the technical and the standards communities because of the importance of the structures that are welded and the consequences associated with their failure.

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G. S. Booth[1] *and J. G. Wylde*[2]

Procedural Considerations Relating to the Fatigue Testing of Steel Weldments

REFERENCE: Booth, G. S. and Wylde, J. G., "**Procedural Considerations Relating to the Fatigue Testing of Steel Weldments,**" *Fatigue and Fracture Testing of Weldments, ASTM STP 1058,* H. I. McHenry and J. M. Potter, Eds., American Society for Testing and Materials, Philadelphia, 1990, pp. 3–15.

ABSTRACT: Although fatigue design rules for welded steel joints are well developed, many cyclically loaded structures and components contain details that are not covered by these rules. It is often necessary, therefore, to generate fatigue data so that service performance may be rigorously assessed. However, for fatigue data to be of value, it is essential to identify and control many factors associated with the fatigue test itself.

The present paper summarizes the main parameters to be controlled when performing weldment fatigue tests. Four distinct areas are discussed—specimen design and fabrication, specimen preparation, testing, and, finally, reporting. Based on experience, recommendations are given regarding suitable practices in each of these areas.

KEY WORDS: weldments, steel, welded joints, fatigue

Fatigue failures remain a depressingly common occurrence, despite the century or so of research effort that has been directed to this area since the first fatigue failures in mine hoists and railway axles were documented [*1*]. Many structures and components that are subjected to cyclic loading are now fabricated by welding, and recent experience has shown that a high proportion of fatigue failures are associated with weldments [*2*].

The importance of designing welded structures against fatigue failure has been recognized for some time, and current standards and codes of practice include fatigue design rules for welded joints [*3,4*]. Despite the continuing occurrence of fatigue failures, there does not seem to be any evidence of an inadequacy in current design rules. In some fatigue failures the possibility of this failure mode was never considered, although the incidence of this category of fatigue failure is steadily decreasing. In others, fatigue design was not carried out sufficiently thoroughly, the main deficiencies being incorrect estimates of the stress range, unexpected cyclic loading, and the presence of significant weld flaws arising from poor welding and inspection practices.

Conventional fatigue design of welded joints is based on *S-N* curves provided in design rules for various joint geometries. The designer, however, is often faced with assessing the fatigue strength of a joint under circumstances that are not expressly covered in the design rules. For example, this may be because the specific joint geometry is not included or because the structure will be operating in an environment other than air at room temperature. In these cases, there is often a need to generate fatigue data upon which to base the design.

For fatigue testing to be of value it is vital to ensure that the data obtained are relevant

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to the final application. In essence, this means that the laboratory fatigue tests must mirror as closely as possible the anticipated service conditions. It is important, therefore, to identify and control a large number of factors associated with the fatigue testing of weldments to ensure the validity and applicability of the data thus obtained.

The present paper summarizes the major parameters to be controlled when performing fatigue tests on weldments. Its scope is restricted to steel weldments and tests to obtain *S-N* curve data—fatigue crack growth rate testing applied to weldments is not considered.

Specimen Design and Fabrication

Material

For as-welded joints loaded in air, fatigue strength is independent of the steel specification [*2*]. Figure 1 shows that, over the range of 300 to 800 N/mm^2, ultimate tensile strength does not influence weldment fatigue strength, whereas increasing tensile strength results in an increase in fatigue strength for unwelded components. For joints loaded in corrosive environments and for joints that are postweld treated to improve fatigue strength, the steel type is more important in determining fatigue behavior. It is therefore considered sound practice to manufacture laboratory specimens from steel similar to that used in the structure or component.

Specimen Geometry

Detailed joint geometry is by far the most important factor in determining fatigue performance, and accurate representation of the structural detail is therefore essential. In its simplest form, this implies that the specimen geometry reflects the detail under consideration, for example, a transverse butt weld or longitudinal stiffener. Under these circumstances a simple planar specimen may model the joint sufficiently accurately. In an increasing number of cases, however, it is not possible to model the joint by a simple geometry and some form of full-scale test is necessary. This is particularly important for tubular joints and large beams

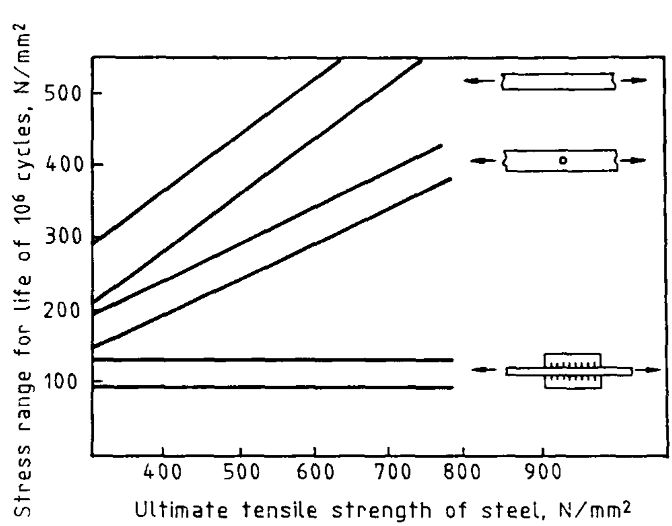

FIG. 1—*The influence of tensile strength on the fatigue strength of plain, notched, and welded steel.*

where the geometry precludes simple modeling. The remarks in this paper apply to both simple joints and full-scale joints.

In many joint geometries, failure may occur from more than one crack initiation site. For example, in trough-to-deck fatigue tests used to model steel bridge decks, fatigue cracking may initiate at three locations—the toe of the weld in the deck, the toe of the weld in the trough, and through the weld throat. Clearly data relating to one failure location are not relevant to others, and care must be taken to ensure that the failure location in the laboratory specimen is the same as that of concern in the structure.

Specimen Size

Specimen size is important for two reasons that are easily confused. First, the specimen must be sufficiently large to be able to contain realistic residual stress levels. Second, assuming that the specimen meets the first criterion, there is a significant effect of specimen size and, in particular, plate thickness on fatigue behavior.

Residual Stress Levels

Residual stresses are those stresses that exist in a body in the absence of any external load. They are always self-balancing and may be divided into two types, "residual welding stresses" and "reaction" stresses. Residual welding stresses are formed during welding primarily as a result of local heating and cooling (and hence expansion and contraction) in the vicinity of the weldment. In an as-welded structure, residual welding stresses are usually of yield tensile magnitude in the vicinity of the weld. Reaction stresses are due to long-range interaction effects, such as those introduced when fabricating a large frame structure. Reaction stresses may be either tensile or compressive in the vicinity of a weld.

For design purposes it is usually assumed that the residual stresses in the vicinity of the weldment are tensile and of yield magnitude. During fatigue loading, the stresses near the weld cycle from yield stress downwards, irrespective of the applied mean stress [*5*]. Hence, nominally compressive applied stresses become tensile near the weld and the whole of the stress range is damaging. This is illustrated in Fig. 2, which demonstrates that fatigue behavior is independent of the stress ratio (i.e., the mean stress) for as-welded longitudinal fillet welded joints [*6*]. Should a laboratory specimen not contain yield tensile residual stresses, then under partly compressive cycling a fraction of the stress cycle may become compressive near the weld and hence less damaging. This would lead to a lifetime of the laboratory specimen in excess of that of the structure.

Relatively large specimens are required to ensure that yield magnitude residual stresses are created. In general, the specimen width must be greater than approximately 100 mm and the stiffener or attachment length must be of similar dimensions. To confirm residual stress levels, nondestructive techniques such as hole drilling can be used. If there is a concern that the specimen may not provide sufficient restraint to allow yield level residual stresses to form during welding, then a technique involving spot heating can be used to introduce local residual stresses of yield tensile magnitude.

Effect of Thickness

The fatigue strength of welded joints is to some extent dependent on the absolute joint dimensions [*7*]. For geometrically similar joints loaded axially, fatigue strength decreases with increasing plate thickness. Although, in reality, geometric similarity is not maintained as plate thickness increases, one code of practice [*8*] requires that the fatigue strength of

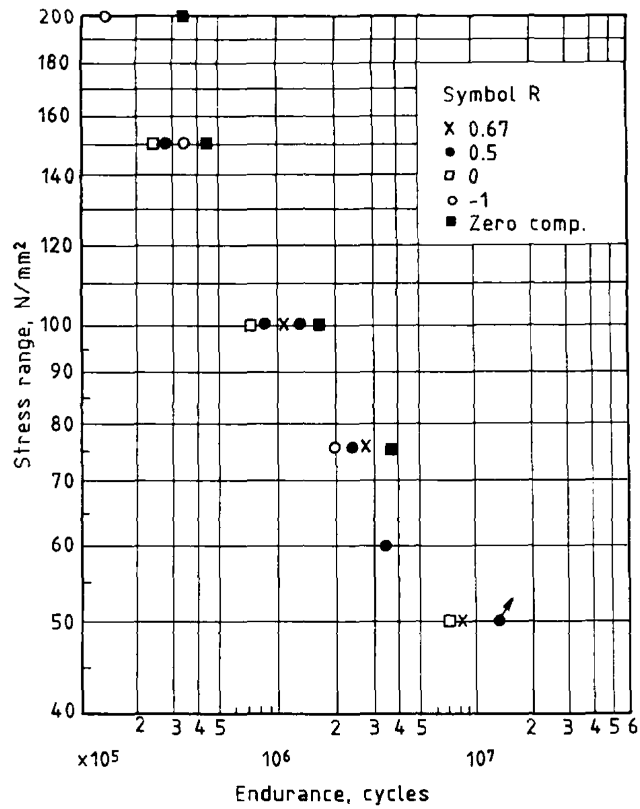

FIG. 2—*Fatigue results for as-welded longitudinal fillet welded joints tested at various applied stress ratios.*

planar joints be reduced in proportion to (plate thickness)$^{-0.25}$ for thicknesses greater than 22 mm. The experimental data supporting this expression are summarized in Fig. 3.

There is not yet a complete understanding of the role of thickness in fatigue strength, nor is there agreement on how to incorporate thickness effects in fatigue design codes. Nevertheless, the implications for weldment fatigue testing are clear—the dimensions of the laboratory specimens must be as close as possible to those of the structure and particular attention must be paid to plate thickness.

Welding Procedure

For fillet welded joints there is conflicting evidence regarding the influence of the welding procedure on fatigue strength. The effect, if any, is relatively small and fatigue design rules do not distinguish on the basis of welding procedure or process. In contrast, as shown in Fig. 4, the behavior of butt welded joints is strongly dependent on the reinforcement shape [2] and this, in turn, is dependent on the welding procedure. In particular, positional and site welds are downgraded [3] because of the difficulty of controlling the weld shape.

In view of this, it is important to fabricate the laboratory specimens using a welding process and procedure similar to those to be used in practice. Furthermore, some investigations have specifically compared the fatigue behavior of joints made by a range of welding processes—for example, shielded metal arc, submerged arc, friction, laser, and electron beam processes.

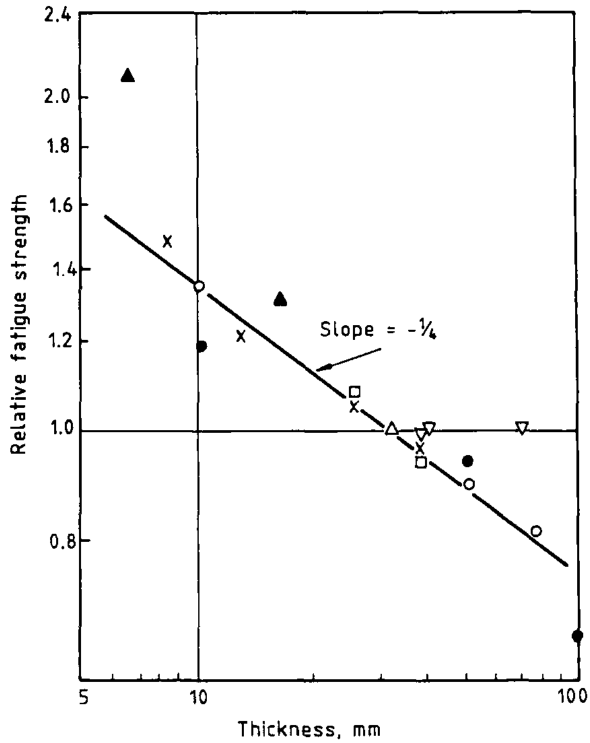

FIG. 3—*Influence of plate thickness on fatigue strength (normalized to a thickness of 32 mm).*

Postweld treatments may also conveniently be considered as forming part of the total welding procedure. As discussed earlier, residual stress levels play an important role in determining fatigue strength, and hence postweld heat treatment or stress relief by mechanical vibration may significantly affect fatigue behavior. Many investigations have studied methods of improving fatigue strength, such as toe grinding, hammer peening, and shot peening [*9*]. Adequate control of these operations is essential for consistent fatigue data.

Specimen Preparation

Strain Gages

It is obviously important when performing fatigue tests on welded joints to have information regarding the load on the specimen. This can be determined either directly from the machine, provided it has been adequately calibrated, or from strain gages located on the specimen. One of the advantages of using strain gages is that they can be used to detect any secondary bending stresses in the specimen. However, when strain gages are used, considerable care is required with regard to their location [*10*] and to the surface preparation.

Strain gages should be set back from the weld toe for two reasons:

1. They should not be so close to the weld that they pick up the local stress concentration associated with the weld itself. This is sometimes referred to as the "notch effect."
2. The preparation of the surface of the specimen to accommodate the strain gage must not encroach on the weld toe.

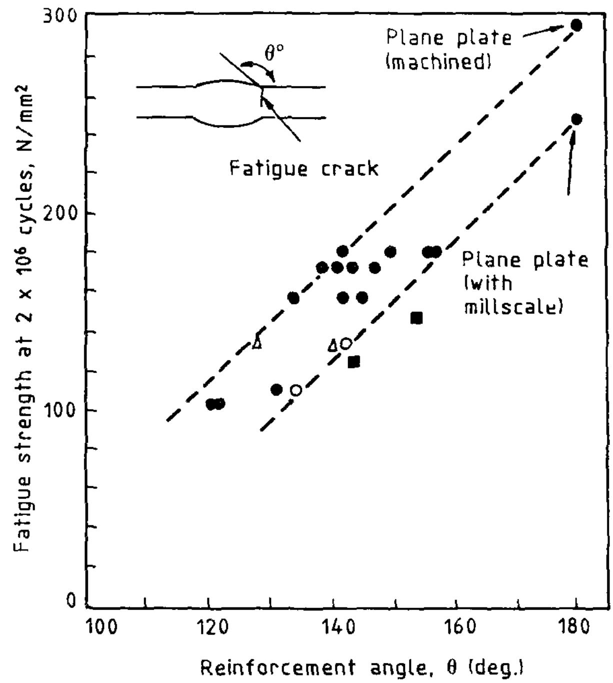

FIG. 4—*The relationship between the reinforcement angle and fatigue strength of transverse butt welds.*

It is conventional to express fatigue results for welded joints in terms of the nominal stress remote from the weld. This approach is sensible because the very local stress adjacent to the weld toe will be influenced by the local geometry and shape of the weld. This is a feature over which the designer can have no control. By expressing the stress as a nominal value, any variations in the local stress at the weld toe can be accounted for as scatter in the test data. Thus, by adopting a lower bound to the experimental data, the designer is effectively taking account of normal variations in the geometric shape of the weld. It has been found that the notch effect associated with a weld toe decays to the nominal value in the plate within about 0.2 of the plate thickness. Thus, it is recommended that strain gages be at least 0.4 of the plate thickness away from the weld toe.

If an attempt is made to locate a strain gage so close to the weld that the local effect of the weld toe is recorded by the gage, it is inevitable that the weld toe itself will be ground when preparing the surface for the strain gage. This is extremely important, as it is likely to lead to an artificially high fatigue endurance for the specimen. In essence, this is the same as the weld toe grinding technique, which is used to improve fatigue strength.

When using strain gages it is conventional to locate a pair of strain gages on each side of the specimen. The advantage of this is that the gages will record any secondary bending stresses in the specimen due to misalignment or nonaxiality of applied loading. If the specimen does have any geometric irregularities, the secondary bending stresses can be very high and the strain gage results will be essential in the interpretation of the fatigue results.

Specimen Straightness and Alignment

Under axial loading, bowing and misalignment give rise to local bending stresses, which may be considerably greater than the nominal axial stress [*11*]. This results in a false measurement of specimen endurance, which is much smaller than would have been obtained from straight or aligned specimens. Both butt welded and fillet welded joints are susceptible to bowing, but the situation can be remedied by using plastic deformation to straighten the joint. However, plastic deformation of the weld itself is equivalent to a tensile overload and hence affects fatigue endurance. It is usual to straighten specimens in a four-point bending device, thus ensuring that the plastic deformation is remote from the weldment.

A major problem with transverse butt welds is axial misalignment. The stress concentration factor (K_t) is given by

$$K_t = 1 + \frac{3e}{t}$$

where

e = eccentricity, and
t = thickness.

Examination of this equation shows that a small misalignment gives rise to a relatively large stress concentration factor, and a much greater effect on endurance. There is little that can be done to correct misalignment—adequate control of the welding procedure is required. The importance of minimizing misalignment is shown in Fig. 5 [12], which illustrates that even relatively small degrees of misalignment significantly reduce fatigue strength.

The most useful method of assessing the effects of bowing or misalignment is to install

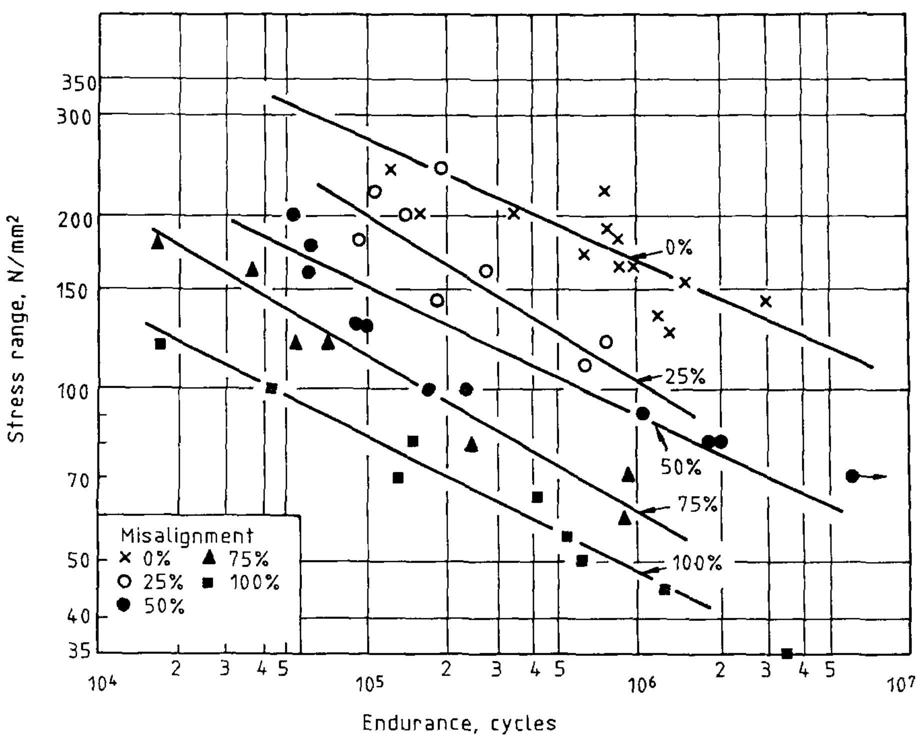

FIG. 5—*Fatigue test results for transverse butt welds containing axial misalignment plotted against nominal stress.*