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Lambert Tall

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ON CRACKS IN WELDS AND WELDED STRUCTURES

by

Lambert Tall


Fritz Laboratory Report No. 358.30
Low-Cycle Fatigue

ON CRACKS IN WELDS AND WELDED STRUCTURES

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Division for Fatigue and Fracture
Fritz Engineering Laboratory
Lehigh University
Bethlehem, Pennsylvania

May 1971

Fritz Engineering Laboratory Report No. 358.30
ON CRACKS IN WELDS AND WELDED STRUCTURES

by

LAMBERT TALL

B.E., M.S., Ph.D.

Professor of Civil Engineering
Director, Division for Fatigue and Fracture
Fritz Engineering Laboratory
Lehigh University, Bethlehem, Pennsylvania

May 1971

ABSTRACT

This paper summarizes some findings on cracks in welded structures made during various research studies -- in particular, certain aspects of a major long-term research program on low-cycle fatigue are included.

- The structural behavior of welded plate girders is relatively unaffected by large cracks for a substantial proportion of life.
- Initiation of a crack in a welded plate girder is usually due to exhaustion of ductility caused by secondary bending.
- Both the lumped-parameter method and the use of finite elements are successful in predicting the state of stress in a cracked plate or in a cracked weld.
- Significant reduction in test scatter can be realized through consideration of geometric effect of penetration in fillet welds.
- The error in predicting total life is due to the error in the estimation of growth rates when the crack is small.
- A relationship exists at the onset of rapid fracturing such that the rate of change of crack-opening-dislocation is equal to the rate of crack extension.

The overall study is seeking an advancement of understanding in fundamental as well as in practical terms.
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1. INTRODUCTION

The strength of an engineering structure often depends on the welds within it. Welding sets up very high magnitudes of residual stresses which can influence the global strength of the structure. On the other hand, high stresses in the weld can precipitate localized cracking which can lead to crack propagation and overall failure.

While the behavior of some welded structures such as plate girders does not suffer unduly from the presence of quite large cracks, this is not the case for most structures. In general, a crack in an engineering structure will reduce strength and alter the engineering response -- repetitions of load will cause the crack to propagate, and structural failure must be considered.

Perhaps the strongest tool in the study of critical fatigue situations is a knowledge of the crack propagation. Experimental behavior is correlated and extrapolated to the behavior of engineering structures and their components. Although crack propagation behavior can also be correlated with fracture mechanics theories, nonetheless it is not the complete answer. This paper includes, in brief, some results of a unified program which is attempting to study the basic behavior of a welded joint. Currently, the study is limited to low-cycle fatigue of welded joints of ASTM A514 steel, a quenched and tempered constructional alloy steel with a minimum yield point of 70 kp/mm². However, the study is not limited to this steel, or to this range of load repetitions.

The state of stress around a crack is being studied by mathematical models, both lumped parameter and finite elements, with the eventual objective of relating, theoretically, the state of stress with the rate of crack propagation.
This paper presents a few results of an overall study which is seeking advancement of understanding in fundamental as well as practical terms.

2. CRACKS IN WELDED PLATE GIRDERS

Generally, cracks in welds exist almost from the moment of cooling after welding -- the study of their formation is complicated and involves a knowledge of thermal and mechanical properties. The formation of such cracks is not treated in this paper.

Cracks in welds may also form long after the welding process has been completed. Such cracks include those due to an exhaustion of ductility caused by the buckling of a plate, and are considered here.

Steel plates used in welded construction may buckle under some conditions of applied load\(^1\) -- for example, the web of a plate girder bridge. In some cases, buckling may occur as soon as the weld has begun to cool\(^2\) -- this type of buckling is called "out-of-straightness" or "welding deformation". Both types of buckling are the same phenomenon, and are due to the formation of residual stresses.\(^2\)

Thus, at some stage in the life of the plate girder, there is considerable deflection in the web plate, Fig. 1. At the edges of the web plates, ductility of the weld material becomes exhausted, and cracking takes place. It has been shown\(^3\) that the initial location of cracks along the flanges were in regions of the highest web bending. Interestingly, the crack initiates visibly, only after about one or two million cycles of load, and even then, propagates very slowly, perhaps 50 mm. each 100,000 cycles.\(^4,5\) Indeed, even when the crack length is 250 mm. no appreciable loss of carrying capacity or increase in deflection occurs; the cracks initiate at a secondary
part of the girder, as far as load-carrying capacity is concerned.\(^{(4)}\) The crack in the web of the plate girder in Fig. 2 hardly affected structural behavior!

Figure 3 shows some initial results indicating an apparent relationship between cycles at first observation of the crack and the secondary bending stresses referred to above.

3. CRACK PROPAGATION: MATHEMATICAL MODEL

The study of low-cycle fatigue must use an approach different from that of the traditional S-N diagram. At low cycles, the S-N diagram loses its usefulness since the curve becomes horizontal at the yield point level. Factors which help determine life at the high stress levels are the accumulation of strains through cycling,\(^{(6)}\) and a knowledge of crack propagation.\(^{(7)}\)

This has led to the development of a mathematical model using the lumped-parameter method to define the state of stress around the crack, and to try to lead towards a theoretical method of predicting crack propagation rates. The method is applicable to fatigue in general. In this study, the method was correlated with test results.

The relationship between the crack propagation rate and stress redistribution was observed from tests conducted on a full-size welded beam with a pre-existing crack.\(^{(8)}\) The mathematical model of "lumped parameters" considered the separate plates of the beam, and discretized them into a finite number of points. The initial mathematical model has used a 20x20 mesh for half the plate width. The distribution of stress at various stages of crack growth is shown in Fig. 4 for an initial crack covering 4 elements, and a final crack covering 10 elements; the final crack corresponds to half the plate width. The computed distribution of stress is compared with the stress measured experimentally.\(^{(9,10)}\) The computed strain
history is shown in Fig. 5. The computed strain history has shown a reasonable correlation with the recorded surface crack propagation. (10)

The study of the fracture surface of the crack in the full-size beam has revealed a transition from smooth to rough texture as the crack grows from initial size to final beam failure. The initial fracture is normal to the applied stress, while the final fracture is inclined. The fracture path follows inclusions, carbides, and microstructure boundaries, and the microstructure is sufficiently fine so that its effect is minor and the overall fracture path is responsible primarily to loading conditions.

The crack initiated at a tack weld while testing in the high-cycle fatigue range, and grew very slowly through the flange-to-web welds, the central part of the flange, and the top of the web. During the testing in the low-cycle fatigue range, the observed fracture surface transition correlated to the very significant stress redistribution, and to the increasing size of the yield stress zone at the crack tip. The high-cycle range showed only a very slight tendency for delamination along rolled-out inclusions -- but this tendency was very obvious during the low-cycle range.

Examination of the effects of yielding in unwelded material showed that, for a plate that had undergone net section yielding, a propagating crack accelerated immediately to high crack growth rates. There was a change in slope of log \( \frac{da}{dN} \) vs \( \Delta K \) from about 2.5 to about 17. (11)

4. **STATE OF STRESS BY FINITE ELEMENTS**

The state of stress around a crack has also been studied by the use of finite elements. (12) Both the lumped parameter method and the finite element method involve the use of discrete elements. The
lumped parameter method is faster and more economical, but it does not offer the refinements and sophistication of the finite element study.

The finite element method has been applied to the study of the fatigue behavior of cruciform joints, Fig. 6a, which are typical of welded joints found in stiffened plate structures. The state of stress, the distance of weld penetration, and the joint geometry, are being studied theoretically, and are being compared to experimental data of fatigue life and crack propagation.

Figure 6b shows the joint, and Fig. 7 shows the mesh geometry of the finite elements for one-quarter of the joint; the mesh geometry is variable and dependent upon the crack length chosen. The crack considered is that due to incomplete penetration of the weld. The elements used are elastic constant strain triangles;\(^{(12)}\) the outer node points along the lines of symmetry are roller supported.

Figure 8 shows the variation of the stress at the toe of the weld with root penetration. For large penetration (small \(2a/t_p\)) the stress at the toe remains essentially constant.\(^{(12)}\)

The finite element analysis was used in the computation of the stress intensity factor \(K\), and its variation with root penetration (crack size). Figure 9 shows a comparison\(^{(12)}\) made between the curve from the finite element study, and that of another analytical study\(^{(13)}\) where the actual geometry of the weld and plate was simplified. The third curve is a simple empirical curve to correspond to that of the finite element analysis -- this curve was used to analyze earlier fatigue test data\(^{(14)}\) concerning weld penetration in cruciform shapes. The analysis\(^{(12)}\) assumed that \(\frac{da}{dN} = CAK^n\) and showed that, when the stress was modified by the difference between the initial crack length and crack length at failure, the S-N curve becomes linear on a log-log plot. (The values for \(C\) and \(n\) were found by a least squares analysis.)
The fatigue data\(^{14}\) is plotted in Fig. 10a. The same data is plotted in Fig. 10b making the correction for the effect of root penetration -- the scatter band is much narrower. It seems clear then, that the finite element analysis technique allows the prediction of the effect of joint geometry upon fatigue behavior.

5. **ERROR IN USE OF CRACK PROPAGATION RATES**

The knowledge of fatigue crack propagation rates is important and basic in the analysis of fatigue behavior.

Usually, the test data is plotted simply as crack length versus cycles for a number of discrete points. It is then used to predict fatigue behavior of other components of a structure of the same material. A log-log plot of the crack propagation rate versus the range of stress intensity factor, \(\Delta K\), is the most useful form for the test data. Empirical equations of the type, \(dN = C\Delta K^n\), are fitted to the data, and the evaluation of the empirical constants leads to conclusions about the stability of crack growth and the onset of fracture.

Although the crack growth may be measured with great accuracy, it is not usually realized that substantial errors may result from the analysis of this data.\(^{15}\) The numerical methods used to determine the slope between any two data points may vary from a simple straight line to the use of a higher-order polynominal. The error discussed is the difference between a measured number of cycles and the estimated number obtained from integration of the fitted empirical equation; in other words, the error is that resulting from the determination of the rate of crack propagation from the test data, and then using that rate in an empirical equation.\(^{15}\)

The error associated with the various methods used to determine growth rates was estimated by numerically integrating the rates to
determine their estimate of cycles at the measured value of crack length. Figure 11 compares the measured crack length versus cycle data given in Ref. 16 with the computed results obtained from the growth rates determined by the secant, modified difference, and second order polynomial method. (15) The difference between the cycles estimated from integrating the crack growth rate and the measured cycles varies with crack length. Thus, an error criterion based on the number of cycles estimated for a particular crack length would not be consistent since it would be a function of the crack length selected.

The study (15) also considered two empirical equations relating \( \frac{da}{dN} \) and \( \Delta K \), which were fitted to the crack growth rates -- no correction for plasticity at the crack tip was made. Figure 12 shows the relationship computed for crack length versus cycles after the coefficients were determined by least squares from the growth rate computed by the modified difference and second order polynomial methods. The variation within each method is small, but the computed curves both are in considerable error for the last 200,000 cycles.

The error in total life is due to the error in estimation of the growth rates when the crack is small. Since the major part of the specimen's life is in this region, small errors do have a large effect. The results of the error analysis of the experimental data appears to be due to the fact that the empirical relationship between \( \frac{da}{dN} \) and \( \Delta K \), as expressed by the two empirical equations (Fig. 12) does not describe the true relationship. (15)

6. FRACTURE MECHANICS IN LOW-CYCLE FATIGUE

The current study has included an attempt to extend the principles of fracture mechanics to the realm of low-cycle fatigue, and to correlate this attempt with plasticity analyses, experimental testing, and microstructure investigation. Since linear fracture mechanics is based on elastic stress analyses, its application to
low-cycle fatigue would be expected to lead to some difficulties.

In low-cycle fatigue, the plastic strain zone often intersects free surfaces of the component, and the cyclic strains promoting development and extension of cracks are a function of the geometry of the component in terms of plasticity analysis. A different situation occurs for high-cycle fatigue, in which the stresses remain generally in the elastic range, and the cyclic plastic strains at the leading edge of a crack are confined to a small plastic zone.

Application of fracture mechanics techniques to low-cycle fatigue requires a characterization of a plasticity type to indicate the severity of the cyclic straining at the leading edge of the crack both before and after yielding. The simplest available characterization is the concept of the crack-opening-dislocation, the so-called C-O-D, also called the crack-opening-stretch. The concept was introduced by Wells (17) a decade ago, and Irwin (18,19) more recently extended its use to plasticity-type situations.

The behavior of a crack in high-cycle fatigue and in low-cycle fatigue are related, since successive elements of the high-cycle fatigue crack are, in effect, a series of low-cycle fatigue crack propagations of the plastified zone of material on the leading edge of the crack. (19)

It may be derived (19) that $\delta$, the C-O-D is given by

$$\delta = \frac{4}{\pi} \cdot \frac{\delta}{\sigma_y}, \text{ or } \delta \approx \frac{\delta}{\sigma_y}$$

where $\delta$ is the strain energy release rate, corrected by the plasticity adjustment factor, and $\sigma_y$ is the yield strength. Further, $\delta = \frac{K^2}{E^2}$ for plane stress, and $\delta = \frac{K^2}{1-\nu^2}$ for plane strain, where $K$ is the stress intensity factor.

The result of the development of mathematical models (19) to see whether the proportionality between $\delta$ and $\delta$ remains valid for stress
levels approaching general yielding, is summarized in Fig. 13. In the figure, \( \alpha = 0 \) refers to the case of an infinite plate, and the two separate groups of curves refer to the assumptions used, namely that of strip-plastic-analysis, and of the elastic-perfectly-plastic analysis, respectively. \( \tau_N \) is the average shear stress on the net section, and \( \tau_Y \) is the yield point in shear.

Significantly, both plasticity models indicate (Fig. 13) that the proportionality, \( \delta \sim \frac{\sigma}{\sigma_Y} \), holds true even up the situation of general yielding for finite plates; for infinite plates, the validity ceases at somewhat lower levels. In other words, the C-O-D, \( \delta \), characterizes the stress intensity factor \( K \), almost to the point of general yielding.

It is not possible to study immediately the behavior of a structural component such as a welded beam. The preliminary studies have been on a double-cantilever bend test specimen, pre-cracked.

Since it is quite difficult to measure the actual C-O-D, this is usually related to some dimension which can be measured. For the face-grooved double-cantilever bend (DCB) specimen considered in Fig. 14, an approximate value for C-O-D is given by \( \delta = \frac{12 P^2 a^2}{E \sigma_Y w h^3 w_n} \) where \( P \) is the applied load, \( a \) the distance from the leading edge of the crack to \( P \), \( w \) the unnotched specimen thickness, \( w_n \) the net section thickness between the face grooves, and \( h \) the beam length of each loading arm.

Using this equation to obtain \( \delta \) from \( w_n \), the results of cyclic DCB tests on 35 kp/mm\(^2\) yield material, \( (19) \) on 77 kp/mm\(^2\) yield material, \( (20) \) and on other material, \( (19) \) all indicate that there is a correlation between the crack extension rate \( \frac{da}{dn} \) and the cyclic rate of change of C-O-D, \( \Delta \delta \), such that at the onset of rapid fracturing,
\[ \Delta \delta \approx \frac{da}{\Delta N} \]

In the tests on the 77 kp/mm\(^2\) material, (20) six specimen geometries were included, and are shown in Fig. 15.

It was noted that the position where the equality, \( \Delta \delta \approx \frac{da}{\Delta N} \), was approached occurred in a region for which a substantial amount of yielding through thickness reduction would be expected. The equality holds true for the upturn portion of Fig. 15, which represents the approach towards the onset of rapid fracture. Thus, the equality, \( \Delta \delta \approx \frac{da}{\Delta N} \), represents a preliminary result, but it does reflect a potential application to low-cycle fatigue.

7. SUMMARY

This paper summarizes some findings on cracks in steel plate made during various research studies — in particular, certain aspects of a major long-term research program on low-cycle fatigue of A514 steel are included.

1. The structural behavior of welded plate girders is relatively unaffected by large cracks for a substantial proportion of life.

2. Initiation of a crack in a plate girder is usually at the weld and is due to secondary bending stresses at the web boundary. An exhaustion of ductility is caused by the combination of the bending stresses with the welding residual stresses.

3. Both the lumped-parameter method and the use of finite elements are successful in predicting the state of stress in a cracked plate, or in a cracked weld.

4. The finite element analysis technique has been successfully employed in determining the geometric effect of weld geometry and penetration in fillet welds. Significant reductions in test scatter have been made using the analysis.
5. Upon net section yielding, the exponent in the fatigue crack growth rate equation, \( \frac{da}{dN} = C \Delta K^N \), was shown to increase from 2.5 to 17.

6. An error analysis of the use of experimental data and empirical crack propagation rates has shown that the empirical equations do not describe the true relationship. The error in total life is due to the error in estimation of the growth rates when the crack is small.

7. Successive elements of high-cycle fatigue crack extensions may be considered as constituting a series of low-cycle fatigue failures of a small region adjacent to the leading edge of the crack.

8. It appears that the crack-opening-dislocation characterizes the stress intensity factor for levels approaching the yield value.

9. There appears to be a relationship at the onset of rapid fracturing such that the rate of change of the crack-opening-dislocation is equal to the rate of crack extension.

8. ACKNOWLEDGEMENTS

This paper presents the results of some phases of a major research program designed to provide information on the behavior and design of welded structures subjected to low-cycle fatigue. Also presented are some results of an earlier study on the fatigue behavior of welded plate girders.

The investigation is being conducted at Lehigh University, Bethlehem, Pennsylvania, in Fritz Engineering Laboratory, in the Materials Research Center, and in the Departments of Civil Engineering, Metallurgy and Materials Science, and Mechanical Engineering and Mechanics. The Office of Naval Research, Department of Defense, sponsors the research under contract N 00014-68-A-0514; NR 064-509. The program manager for the overall project is Lambert Tall.
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FIGURES

Fig. 1 Deflection Under Load in Web Plate of Plate Girder

Fig. 2 Crack in Web of Plate Girder

Fig. 3 Secondary Bending Stresses Along Flange Versus Cycles to Crack (Plate Girder)

Fig. 4 Stress Distribution in Beam Flange with Crack

Fig. 5 Strain in Beam Flange Near Crack Tip

Fig. 6 Cruciform Joints

Fig. 7 Finite Element Mesh Geometry in Cruciform Joint

Fig. 8 Stress at Toe Versus Root Penetration

Fig. 9 Root Penetration: Comparison of Analytical Studies

Fig. 10 Fatigue Data and Correction for Root Penetration Effect

Fig. 11 Crack Growth Rates: Comparison with Predictions

Fig. 12 Crack Growth Rates: Errors in Predicted Values

Fig. 13 Relationship between C-O-D and Crack Size a

Fig. 14 Face-Grooved Double-Cantilever Bend Specimen

Fig. 15 Crack Growth Rate Versus Change of C-O-D
STRESS \( \sigma_B \) (kp/mm\(^2\))

LOG N (CYCLES)
FIG. 4

- Strain Gages
- Crack Size
- DISTANCE FROM FLANGE CENTER
- Stress
- Recorded

0 cycles (Ref. line for recorded data)

- 0 cycles
- 25,000 cycles
- 40,000 cycles
- No crack

- Unloaded (U)
- Loaded (L)
$\sigma_{\text{max.}} = 25.3 \text{ kp/mm}^2$

$\sigma_{\text{min.}} = 0 \text{ kp/mm}^2$

Mesh Division (20 x 20)

$\Delta \varepsilon = \varepsilon_{\text{max.}} - \varepsilon_{\text{min.}}$

**FLANGE**

**FIG. 5**
FIG. 6a

NO LOAD CARRYING WELD

LOAD CARRYING WELD
\[ K = \frac{P}{t_p \sqrt{\pi a}} \]

Finite Element

\[ K = P \left[ \frac{1}{t_p} + \frac{2H}{t_p} \right] \sqrt{\pi a} \]

FIG. 9
FIG. 11
\[ \frac{\tau_y \delta}{g} \]

\[ \alpha = \frac{2a}{W} \]

Elastic - Perfectly - Plastic Analysis

Strip - Plastic - Analysis

FIG. 13
CRACK GROWTH RATE
$\frac{da}{dN}$ (mm/CYCLE)

CHANGE OF C-O-D, $\Delta \delta$
<table>
<thead>
<tr>
<th>SPEC. No.</th>
<th>w</th>
<th>( w_N )</th>
<th>h</th>
<th>L</th>
<th>( \frac{W}{W_N} )</th>
<th>( \frac{L}{h} )</th>
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<td>5.20</td>
<td>6.33</td>
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Material: A514 Steel \( \sigma_Y = 77 \text{ kp/mm}^2 \)

**Table To Go Inside Fig. 15**
This paper summarizes some findings on cracks in welded structures made during various research studies -- in particular, certain aspects of a major long-term research program on low-cycle fatigue are included.

- The structural behavior of welded plate girders is relatively unaffected by large cracks for a substantial proportion of life.
- Initiation of a crack in a welded plate girder is usually due to exhaustion of ductility caused by secondary bending.
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- Significant reduction in test scatter can be realized through consideration of geometric effect of penetration in fillet welds.
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