

1970

Initial findings from a study in low-cycle fatigue of welded astm a514 steel, April 1970 Trans., Conference on Fatigue on Welded Structures, Brighton England July 1970

L. Tall

Follow this and additional works at: <http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports>

---

#### Recommended Citation

Tall, L., "Initial findings from a study in low-cycle fatigue of welded astm a514 steel, April 1970 Trans., Conference on Fatigue on Welded Structures, Brighton England July 1970" (1970). *Fritz Laboratory Reports*. Paper 2000.  
<http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports/2000>

This Technical Report is brought to you for free and open access by the Civil and Environmental Engineering at Lehigh Preserve. It has been accepted for inclusion in Fritz Laboratory Reports by an authorized administrator of Lehigh Preserve. For more information, please contact [preserve@lehigh.edu](mailto:preserve@lehigh.edu).

INITIAL FINDINGS FROM  
A STUDY IN LOW-CYCLE FATIGUE OF WELDED ASTM A514 STEEL

by

Lambert Tall

FRITZ ENGINEERING  
LABORATORY LIBRARY

Paper prepared for the Conference on Fatigue of Welded Structures, to be held in Brighton, England, July 1970.

April 1970

Fritz Laboratory Report No. 358.15

Low-Cycle Fatigue

INITIAL FINDINGS FROM

A STUDY IN LOW-CYCLE FATIGUE OF WELDED ASTM A514 STEEL

by

Lambert Tall

This work was conducted as part of a study of Low-Cycle Fatigue, sponsored by the Office of Naval Research, Department of Defense, under Contract N 00014-68-A-514; NR 064-509. Reproduction in whole or part is permitted for any purpose of the United States Government.

Fritz Engineering Laboratory  
Lehigh University  
Bethlehem, Pennsylvania

April, 1970

Fritz Engineering Laboratory Report No. 358.15

## TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	1
1. INTRODUCTION	2
2. FATIGUE STRENGTH	3
3. THE STATE OF STRESS IN CRACKED PLATES	4
4. FRACTURE MECHANICS	6
5. STUDIES UNDERWAY AND PROJECTED	10
6. SUMMARY	11
7. ACKNOWLEDGEMENTS	12
8. REFERENCES	13
9. TABLES AND FIGURES	15

## ABSTRACT

This paper summarizes some of the initial findings in a major long-term research program recently commenced on the general topic of low-cycle fatigue. The study is seeking an advancement of understanding in fundamental as well as in practical terms.

The initial studies are on welded joints of ASTM A514 steel, a quenched and tempered constructional alloy steel with a minimum yield point of 70 kp/mm<sup>2</sup>. "Low-cycle" has been defined as corresponding to magnitudes of applied stress which approach the yield level, and which encompass a range of cycles of load application from 0.5 to 100,000.

- When the maximum stress is below the proportional limit, the stress range accounts for nearly all the variation in cycle life.
- It is possible to develop a mathematical model to predict the redistribution of stress in a plate with a crack, as the crack propagates.
- It appears that the crack-opening-dislocation characterizes the stress intensity factor for levels approaching the yield value.
- There appears to be a relationship at the onset of rapid fracturing such that the rate of change of crack-opening-dislocation is equal to the rate of crack extension.
- After initiation of a crack, further growth is without regard to microstructural features.

The propagation of fatigue cracks is being studied through macroanalysis (fracture mechanics and plasticity), and microanalysis. Different variables are under consideration, such as load cycle, microstructure, zone sizes, geometry and constraint, and the experimental studies have been formulated on a statistical basis. The eventual objective of this study is to prepare background information on the design of structures which will have a finite life under repetitive loading.

## 1. INTRODUCTION

This paper summarizes some of the initial findings in a major long-term research program recently commenced on the general topic of low-cycle fatigue, conducted under the sponsorship of the U.S. Department of Defense.

Many structures or structural components subjected to cyclic loading are intended to have a relatively short life. In actual practice, however, they are designed on the basis of sustaining a very long or infinite life. This can be wasteful. Other structures are designed for static loading with brief periods of cyclic loading, such as buildings during earthquakes. Current design of such structures does not reflect fatigue behavior. The eventual objective of this study is to prepare background information on the design of structures which will have a finite life under repetitive loading. This information will be referred to the design of critical areas of the structure; these critical areas, such as joints and similar discontinuities, would tend to have the same basic properties irrespective of the type or form of parent structure. Examples of critical areas are butt and fillet joints in pressure vessels, ordnance vehicles, and structural components. It seems clear that the behavior of a joint in low-cycle fatigue in a pressure vessel (submarine, space vehicle, reactor casing, etc.) is no different from that in a structural component (a tension member acting as a structural component of a bridge, a ship, a space vehicle, etc.) These critical areas are the "weak links" in the "chain", and very little is known of this basic behavior.

The material being studied initially is ASTM A514 steel, which is a quenched and tempered constructional alloy steel with a yield point of  $70 \text{ kp/mm}^2$  (100 ksi.) Butt- and fillet-welded joints (with the reinforcement removed for butt welds) are being considered first, and the propagation of fatigue cracks is being studied through macroanalysis (fracture mechanics and plasticity), and microanalysis. Different variables are under consideration,

such as load cycle, periodic overloads, microstructure, zone sizes, geometry and constraint, and the experimental studies have been formulated on a statistical basis. The initial studies have been limited to crack propagation, using precracked specimens, and have been stress-controlled.

In this study, the designation of "low-cycle" corresponds to magnitudes of applied stress which approach the yield level, and which encompass a range of cycles of load applications from 0.5 to 100,000. This upper limit will allow correlation with the substantial body of data from "high-cycle" studies.

This study seeks advancement of understanding in fundamental as well as in practical terms. For instance, 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.<sup>(1)</sup> The material at the crack tip is in a plastic state of stress, irrespective of the stress level in the surrounding continuum. Thus, low-cycle fatigue is the connecting field between the long-life fatigue studies and the static strength measurements. A clarification of this should lead to an understanding of the relationship between information from tests conducted at low stress levels and at high stress levels. In particular, in low-cycle fatigue, the crack growth per cycle and the associated plastic strains are amplified, thus presenting favorable conditions for studies of the dependency of fatigue damage upon strain aging, creep, and environment.

## 2. FATIGUE STRENGTH

Traditionally, fatigue has been studied with the aid of S-N diagrams, and the influences of the different factors have been noted through differences in the S-N diagrams.<sup>(2)</sup> For instance, it has been shown in high cycle fatigue that it is the stress range which is the predominant variable.<sup>(3)</sup> Many studies in low-cycle fatigue have extended the range of the S-N diagram towards zero cycles.<sup>(4,5)</sup>

Figure 1 presents a plot of stress range versus number of cycles to failure for a series of tension tests on unwelded A514 steel, summarized in Table 1.<sup>(6)</sup> These tests are pilot tests in the higher-cycle range of low-cycle fatigue, and were designed to study the effect of maximum stress  $S_{max}$ , the applied stress range  $S_r$ , and the suitability of the proposed specimen configuration. The tests were performed at a constant load amplitude, and the experiment design was undertaken to permit a rational evaluation of the influence of the controlled variables; the test data was statistically analyzed for variance and regression. When  $S_{max}$  is below the proportional limit, the stress range  $S_r$  accounts for nearly all the variation in cycle life.

A major factor to be considered in low-cycle fatigue is the accumulation of strains through cycling.<sup>(7,8)</sup> Figure 2 summarizes some strain history data for three unwelded A514 tensile stress specimens. The recorded data points are shown, and the measured plastic strain accumulation is represented by the heavy line, while the light broken lines indicate assumed behavior. Very little plastic strain occurred; substantial amounts were observed only in the first few cycles of life, as well as near failure.

For these tensile specimens, all fracture surfaces showed a dual character. Fracture was initiated by a flat fatigue crack followed by non-homogeneous plastic flow and fracture across the remainder of the specimen. Flat fatigue cracks showed no tendency to delaminate near the surface and gradually increased their delamination tendency as they grew through the plate thickness.

### 3. THE STATE OF STRESS IN CRACKED PLATES

The state of stress at any point reflects the applied load, the stress concentrations, and the residual stress. In particular, residual stresses<sup>(9,10)</sup> are important and could play a dominant part in influencing behavior.



The cyclic loading of a material with a crack produces a gradual plastification which is exaggerated in the low-cycle fatigue range, particularly by the presence of residual stresses. This history of plastification, in effect the redistribution of stress and strain, is being studied experimentally and attempts are being made to duplicate it by a mathematical model.<sup>(11)</sup> It is hoped that this phase of the study will result in the prediction of crack propagation.

The relationship between the crack propagation rate and stress redistribution were observed from a test conducted on a full-size welded beam with a pre-existing crack.<sup>(12)</sup> The beam was welded of A514 steel fabricated from flame-cut plates, and had been tested in high-cycle fatigue until the appearance of a crack at the juncture of flange and web.<sup>(3)</sup>

The mathematical model has used the method of "lumped parameters" or "lumped mass", where the plate under consideration is discretized into a finite number of points. The initial mathematical model has used a 20 x 20 mesh for half the plate width. The distribution of stress at various stages of crack growth is shown in Fig. 3 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. The strain history in terms of the cracked elements of the mesh are shown in Fig. 3b.

The rate of crack propagation  $\frac{da}{dN}$  versus the non-dimensional ratio  $\frac{2a}{W}$  is plotted in Fig. 4, where W, the width of the flange, is 173 mm. (6.82 inches.) Theoretical values are shown for both the high- and low-cycle portions of the test for the crack propagation rate.<sup>(12)</sup> This computation did not take into account the restraining influence of the three-ended crack (web effect), or of the residual stress distribution, both of which are under consideration.

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.

#### 4. FRACTURE MECHANICS

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. The concept was introduced by Wells<sup>(13)</sup> a decade ago, and Irwin<sup>(1,14)</sup> 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 propagation are, in effect, a series of low-cycle fatigue crack propagations of the plastified zone of material on the leading edge of the crack.<sup>(14)</sup>

It may be derived<sup>(14)</sup> that  $\delta$ , the C-O-D, is given by

$$\delta = \frac{4}{\pi} \cdot \frac{g}{\sigma_y}, \text{ or } \delta \approx \frac{g}{\sigma_y} \quad (1)$$

where  $g$  is the strain energy release rate, corrected by the plasticity adjustment factor, and  $\sigma_y$  is the yield strength. Further,

$$g = \frac{K^2}{E^2} \quad \text{for plane stress} \quad (2)$$

$$g = \frac{K^2}{1-\mu^2} \quad \text{for plane strain} \quad (3)$$

where  $K$  is the stress intensity factor.

The result of the development of mathematical models<sup>(14)</sup> to see whether the proportionality between  $\delta$  and  $g$  remains valid for stress levels approaching general yielding, is summarized in Fig. 5. 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. <sup>(14)</sup>  $\tau_N$  is the average shear stress on the net section, and  $\tau_y$  is the yield point in shear.

Significantly, both plasticity models indicate (Fig. 5) that the proportionality of Eq. 1 holds true even up to the situation of general yielding for finite plates; for infinite plates, the validity ceases at somewhat lower stress 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. 6, an approximate value for C-O-D is given by <sup>(14)</sup>

$$\delta = \frac{12P^2 a^2}{E \sigma_y w h^3 w_n} \quad (4)$$

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 Eq. 4 to obtain  $\delta$  from  $w_n$  the results of cyclic DCB tests on 50 ksi yield specimens initially tested in this program, and the results from other sources <sup>(14)</sup> 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,

$$\Delta\delta \approx \frac{da}{dN} \quad (5)$$

It was noted that the position where Equality 5 was approached occurred in a region for which a substantial amount of yielding through thickness reduction would be expected. Further, the Equality 5 held true for the upturn portion of the  $(\ln \frac{da}{dN} \text{ vs. } \ln \Delta K)$  curve, which represents the approach towards the onset of rapid fracture. Thus, Equality 5 represents a preliminary result, but it does reflect a potential application to low-cycle fatigue.

The studies are continuing with A514 steel specimens, and the dimensional size effect is being considered for face-notched DCB specimens.

Fatigue crack propagation results for A514 steel are shown in Fig. 7 for three different thicknesses of single - edge-notch tension fatigue specimens. <sup>(15)</sup> The log-log plot used indicates that the crack propagation rate is independent of metallurgical variation (as indicated by specimen thickness) and (through correlation with other studies) of the relative size of the plastic zone for thicknesses to one inch. <sup>(15)</sup>

From the study, the growth rate at the lower stress levels was shown to be best represented by two straight lines on the log-log plot, as

$$\frac{da}{dN} = C\lambda^m \Delta K^n \quad (8)$$

where  $\lambda = \frac{K_{\max}}{\Delta K}$ ,  $K_{\max}$  is the maximum stress intensity factor, and where  $m$  and  $n$  are 0.4 and 2.4 respectively at the low growth rates, and somewhat higher in the high growth rates. At the high  $K$  levels, the greater dependence of  $K_{\max}$  on growth rate may be related to a greater degree of local cracking of inclusions during the fatigue process. The exponents of Eq. 8 indicate that the crack growth rate is more sensitive to  $\Delta K$  than to  $\lambda$ . It was noted in the study that the dependence of crack growth rate on the stress intensity level in the weld metal and heat-affected zone decreased as a result of heat treatment.

## 5. STUDIES UNDERWAY AND PROJECTED

The above has outlined the progress of the study. Work underway but not yet completed, as well as studies planned, are given below.

1. Tests on tension specimens both welded and plain, notched and unnotched, with groove or fillet welds. There are 200 specimens, and the test factorials have been designed to allow statistical evaluation, in particular, of the significance of different variables. A broad framework was established to permit future expansion as needed.

The loadings and test procedure were designed to:

- obtain data in the stress ranges of practical use in structural engineering
- record accumulation of plastic damage and strain redistribution for different specimen configurations
- relate to the control strain test data
- observe crack initiation and propagation.

The first studies on weldments are being made on 16mm.

(5/8") thick plate, MIG butt-welded with AIRCO Ax110 filler metal wire 1.1mm. (0.045") diameter. The weld preparation is machined 60° included angle, V-grooves, and the welding atmosphere is argon -2% oxygen. Heat inputs of 18-22  $K_j/cm$  (47-55  $K_j/in.$ ) are being used to produce multi-pass welds with mechanical properties matching the base plate.

2. Tests directly correlated to theoretical investigations (double-cantilever specimens for the C-O-D concept); tests on butt-welded specimens for the measurement of crack propagation, with respect to heat treatment and residual stresses; and tests to measure residual stresses and rate of plastification on flexural members of I and T sections.
3. Compliance observations using an I-beam with a saw-cut notch will be used to obtain estimates of the C-O-D applicable to the last stages of fatigue life of the beam, when substantial plastic yielding occurs between the ends of the flange crack and the side borders of the flange. The results will be compared to theoretical estimates and to measurements of plastic strain.

4. Crack propagation studies are being extended to the lower cycle life range, and are being evaluated in terms of C-O-D plastic zone size and the stress intensity factor.
5. Mathematical model studies of both the two-ended crack and the three-ended crack are continuing. The accumulation of plastic strain in low-cycle fatigue will be related to crack initiation.
6. The commercial production of the weldments is being monitored, as is the fabrication of weldments containing known and controlled defects for fatigue testing. Fundamental studies are underway on solidification phenomena in the weldments under study, and the relationship of these phenomena to weldment behavior.
7. The fabrication of weldments with known defects, in the initial case porosity, will be undertaken. Techniques for reproducibly making weldments with specific porosity levels will have to be developed. Additional welding defects, for example, lack of fusion will be studied later.
8. The magnitude and distribution of residual stresses in welded specimens is being determined by both destructive and x-ray methods, and related to the studies of crack propagation rates.
9. Strain-recording methods are being evaluated, and x-ray stress techniques are being explored as non-destructive indicators for the following of changes during cyclic straining and fatigue.
10. Within the next few years, a move will be made towards structural elements. This will involve the prediction of the low-cycle fatigue behavior of very simple structures, as well as the possible extension of the study to check the basic behavior of joints of other steels, and other welding processes.

## 6. SUMMARY

This paper summarizes some of the initial findings in a major long-term research program recently commenced on the general topic of low-cycle fatigue. The study seeks an advancement of understanding in fundamental as well as in practical terms.

1. When the maximum stress is below the proportional limit, the stress range accounts for nearly all the variation in cycle life.
2. It is possible to develop a mathematical model to predict the redistribution of stress in a plate with a crack, as the crack propagates. The present model does not include the rate of crack propagation.
3. The residual stress distribution, in addition to the applied load and the size of the crack, must be considered as an influencing factor for crack propagation in a plate.
4. 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.
5. It appears that the crack-opening-dislocation characterizes the stress intensity factor for levels approaching the yield value.
6. 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.
7. After initiation of a crack in a beam, further growth is without regard to microstructural features; as the stress on the remaining net section increases, delamination of plate microstructures occurs along lines of inclusions.

#### 7. ACKNOWLEDGEMENTS

This paper presents the results of some phases of Project 358, a major research program designed to provide information on the behavior and design of joined structures subjected to low-cycle fatigue.

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-A514; NR 064-509.



The program manager for the overall project is Lambert Tall.

The guidance of, and the suggestions from, the members of the special Advisory Committee on Low-Cycle Fatigue is gratefully acknowledged. The author is indebted to his colleagues on the project for their assistance in the various phases of the study, and to which reference is made in the paper; in particular, John W. Fisher made a number of valuable suggestions.

Sincere thanks are due to Miss Joanne Mies who typed the report, and to John M. Gera who prepared the drawings.

This report was prepared in Fritz Engineering Laboratory, of which Lynn S. Beedle is Director. Joseph F. Libsch is Vice-President for Research, Lehigh University.

#### 8. REFERENCES

1. G. R. IRWIN, "Theoretical Aspects of Fracture Failure Analysis", Metals Engg. Quart., Vol. 3, 1963, p. 24.
2. W. H. MUNSE AND L. M. GROVER, "Fatigue of Welded Steel Structures", Weld. Res. Council, 1964.
3. J. W. FISHER, "Fatigue Strength of Welded A514 Steel Beams", Fritz Laboratory Report 358.16, March 1970. Prepared for Conference on Fatigue of Welded Structures, Brighton, England, July 1970.
4. J. B. RADSIMINSKI, R. W. HINTON, D. F. MEINHEIT, H. A. OSMAN, W. H. BRUCKNER, AND W. H. MUNSE, "Fatigue of Plates and Weldments in High-Strength Steels", Civil Engg. Studies, Struct. Res. Series No. 318, Univ. of Illinois, February 1967.
5. Y. ISHII AND K. IIDA, "Low and Intermediate Cycle Fatigue Strength of Butt Welds Containing Weld Defects", Journ. Soc. NDT in Japan, Vol. 18, No. 10, 1969.
6. R. J. SMITH, P. MAREK, M. PERLMAN, A. W. PENSE, K. H. FRANK, AND J. W. FISHER, "Pilot Study on the Fatigue of Tensile Specimens", Fritz Laboratory Report 358.3, October 1969.
7. A. M. FREUDENTHAL, "Some Remarks on Cumulative Damage in Fatigue Testing and Fatigue Design", Welding in the World, IIW, Vol. 6, No. 4, 1968.
8. S. S. MANSON, "Report on Cumulative Fatigue Damage in the Low-Cycle Range", Weld. Res. Council, August 1964.
9. L. TALL, "Residual Stresses in Welded Plates -- A Theoretical Study", Weld. Journ., Vol. 43, No. 1, 1964.

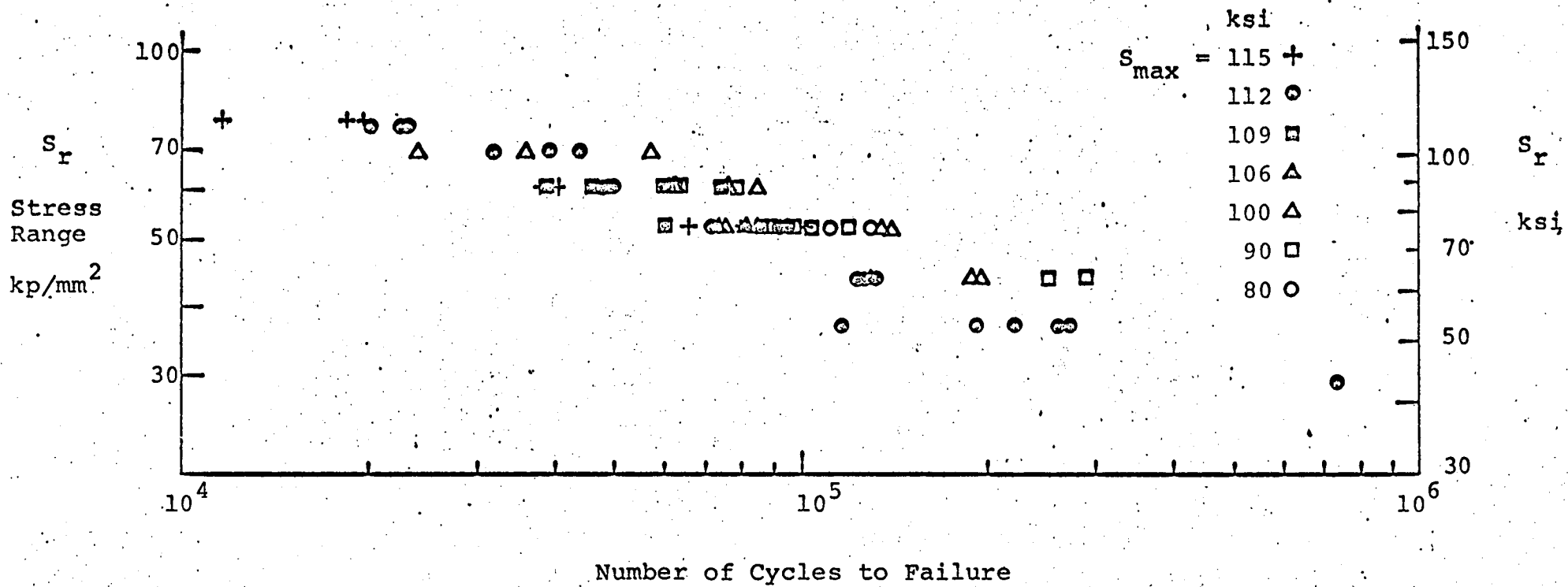
10. L. TALL, "The Strength of Welded A514 Steel Structural Components", Trans., Public Session, 1969 Annual Assembly, IIW, Kyoto, Japan.
11. R. J. SMITH, P. MAREK, AND B. T. YEN, "Redistribution of Stress and Strain in a Plate with a Crack", Fritz Laboratory Report 358.8, in preparation.
12. P. MAREK, M. PERLMAN, A. W. PENSE, AND L. TALL, "Fatigue Tests on Welded Beams with Pre-Existing Cracks", Fritz Laboratory Report 358.4, May 1969. To be published in Weld. Journ.
13. A. A. WELLS, "Notched Bar Tests, Fracture Mechanics, and the Brittle Strength of Welded Structures", British Weld. Journ., Vol. 12, No. 2, 1962.
14. G. R. IRWIN, B. LINGARAJU, AND H. TADA, "Interpretations of the Crack-Opening-Dislocation Concept", Fritz Laboratory Report 358.2, July 1969.
15. R. W. HERTZBERG AND H. NORDBERG, "Fatigue Crack Propagation in A514 Steel", Fritz Laboratory Report 358.7, November 1969. To be published in Weld. Journ.

TABLE 1 COMPLETED TESTS

Experiment Factorial

		Experiment Factorial						
		80	90	100 [102]	106	109	112	115 ksi
$S_{max}$	$S_r$	56	63	70 [ 71]	74	76	78	81 kp/mm <sup>2</sup>
42	29						1	
52	36						5	
62	43		3	3			4	
75	51	3	3	3	4	3	3	3
87	61		3	3	3	4	3	3
99	69			[3]			3	
109	76						4	
112	78							4

ksi    kp/mm<sup>2</sup>



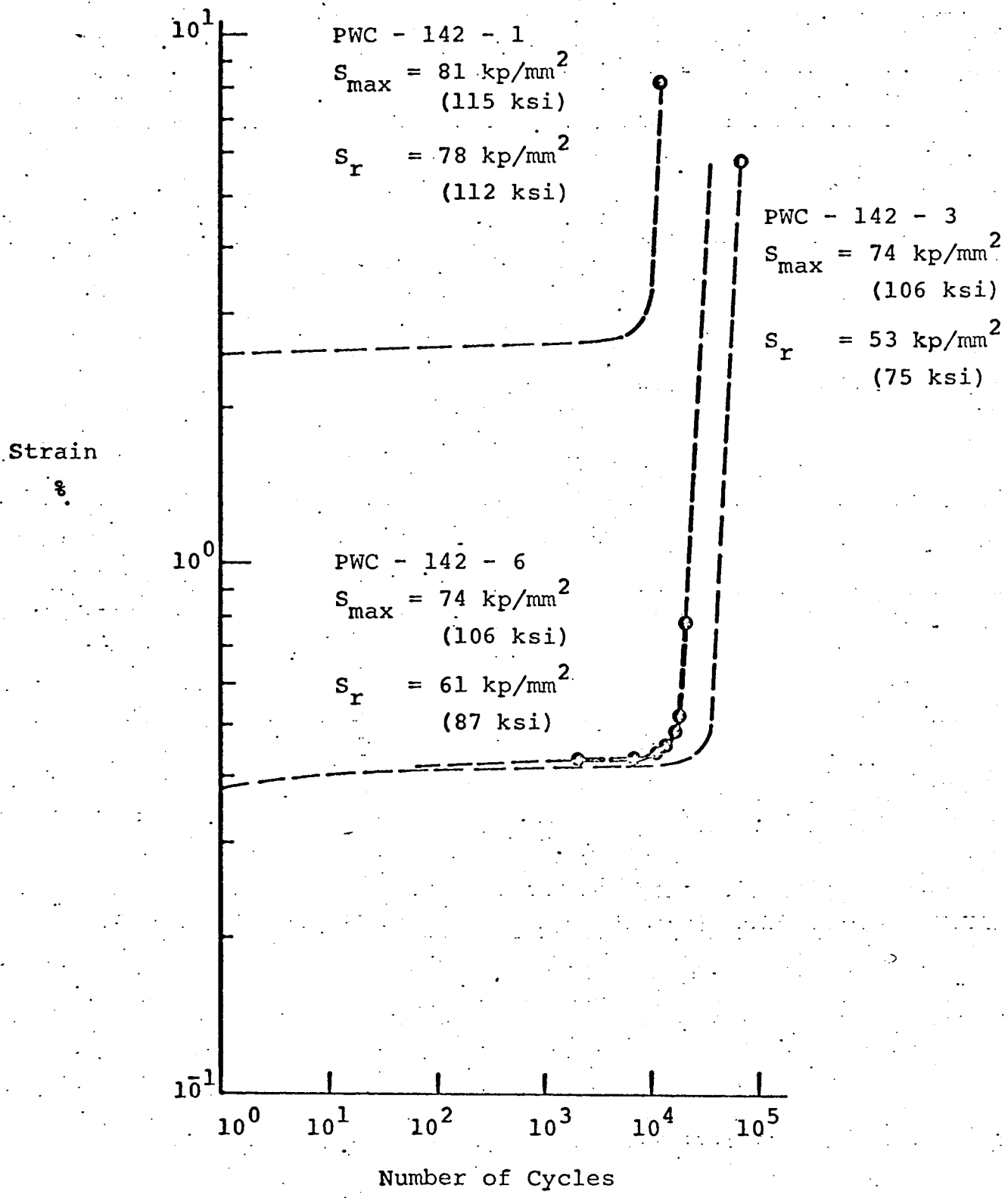


Fig. 2 Percent Strain versus Number of Cycles

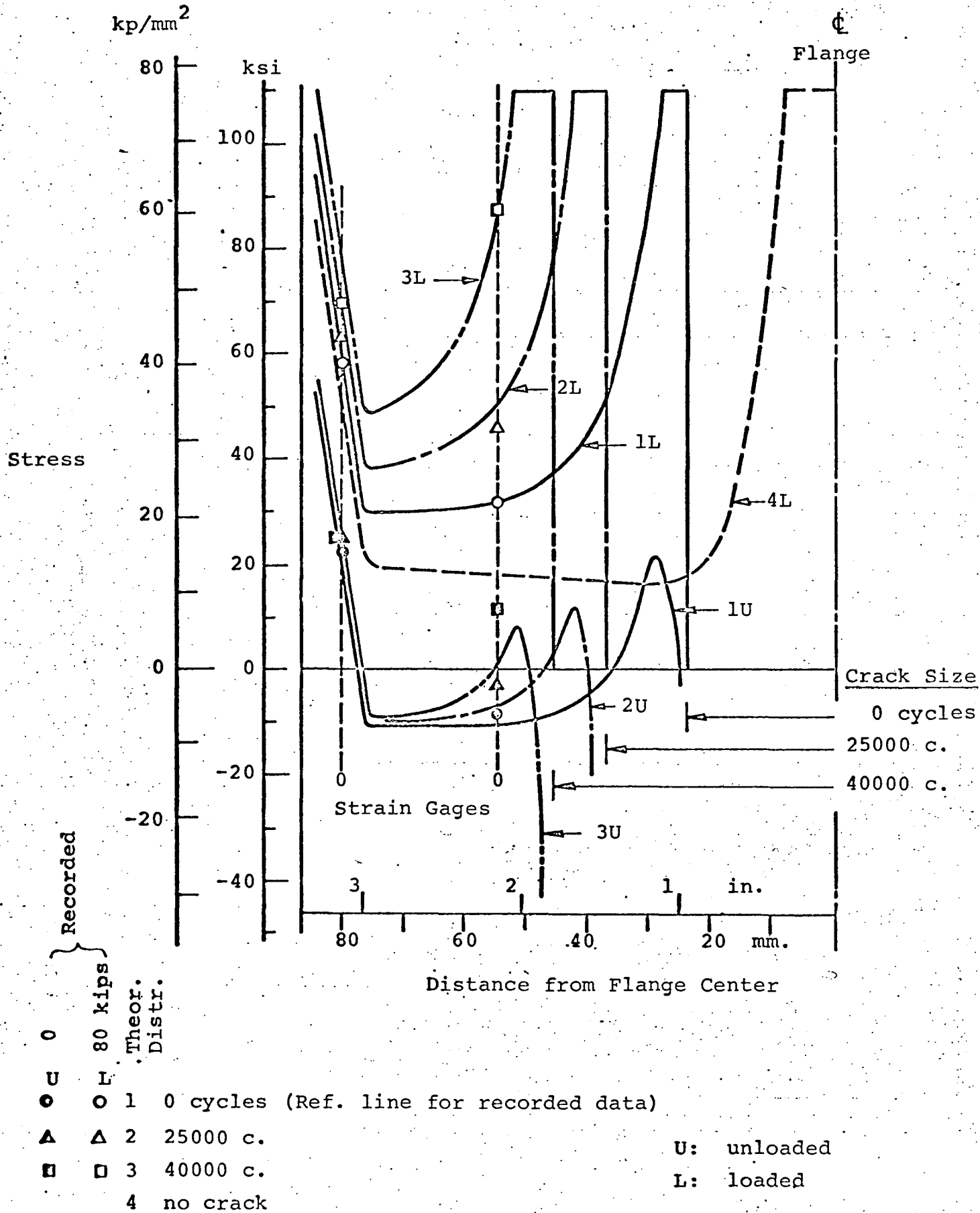


Fig. 3a Stress Distribution in Flange with Crack

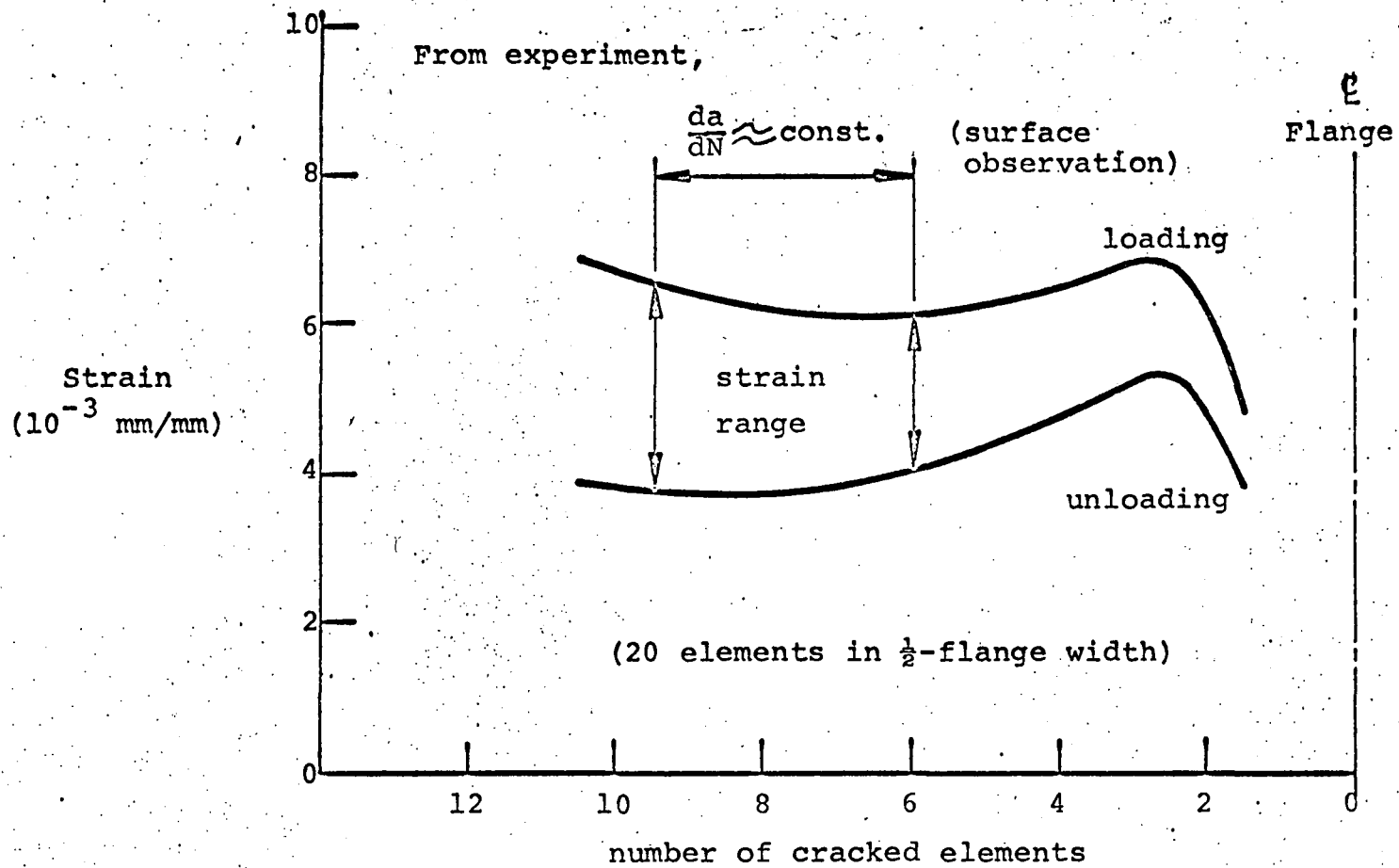


Fig. 3b Strain History from Mathematical Model

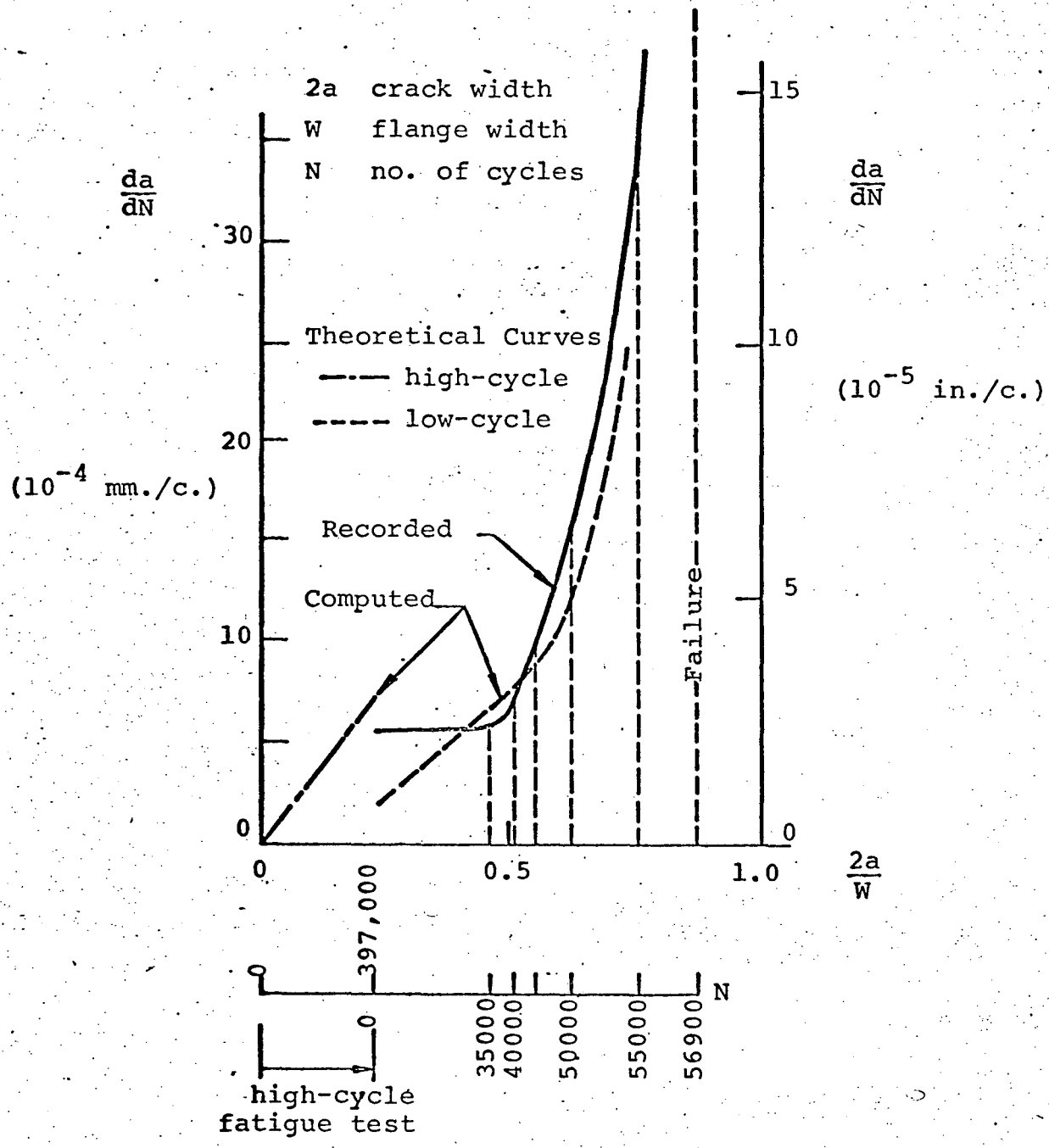


Fig. 4 Crack Propagation Rate versus Position in Flange



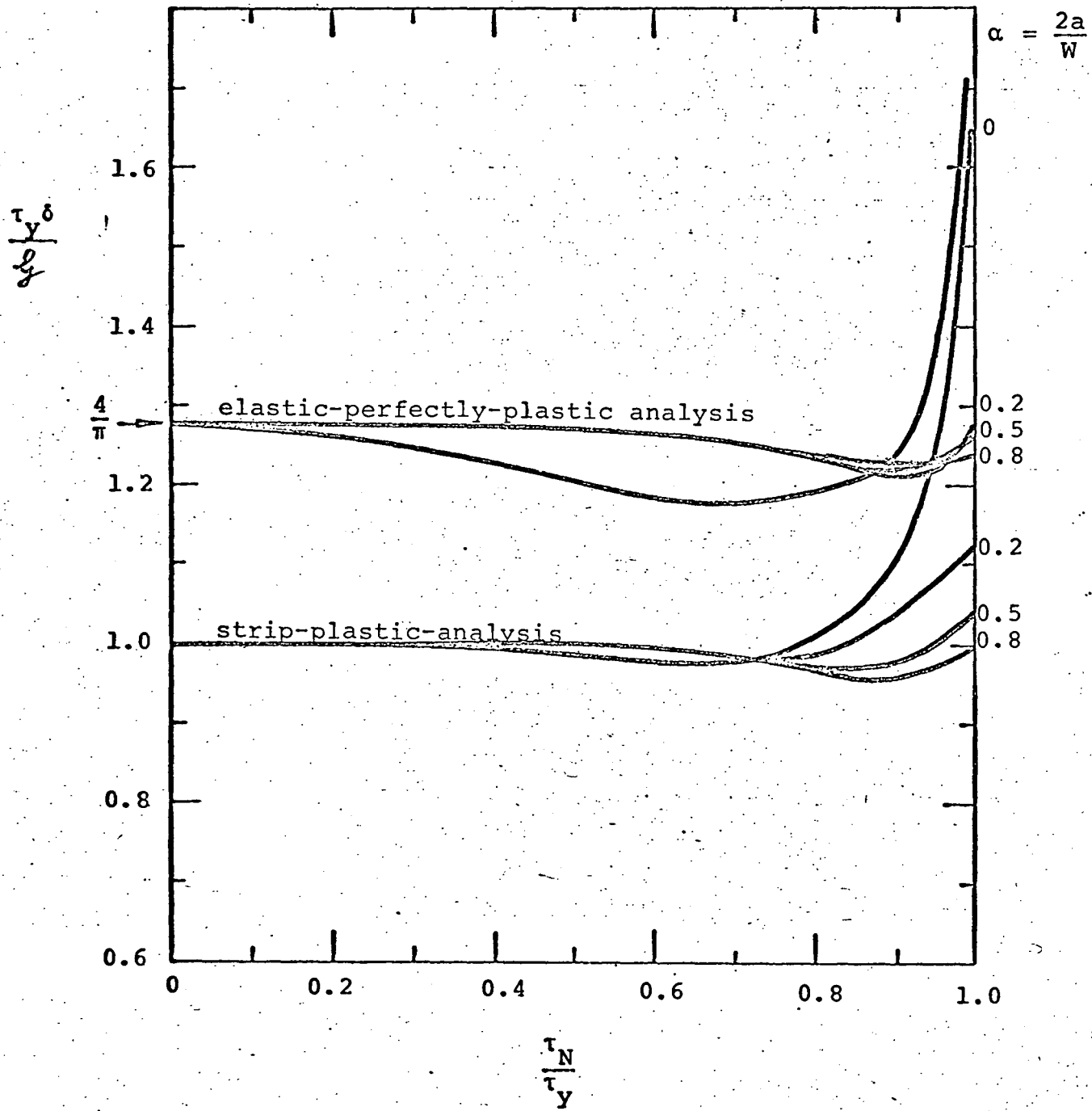


Fig. 5 Relationship between C-O-D  $\delta$  and crack size  $a$

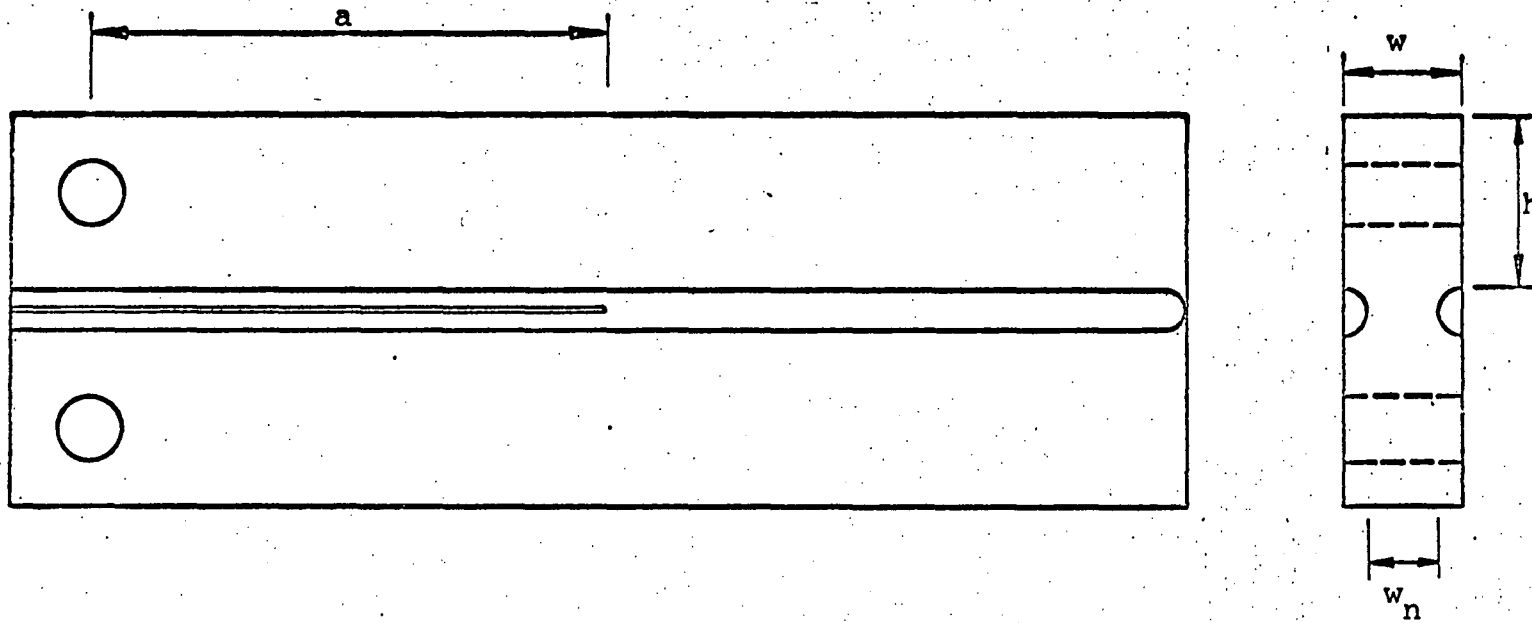


Fig. 6 Face-Grooved Double-Cantilever-Bend Specimen

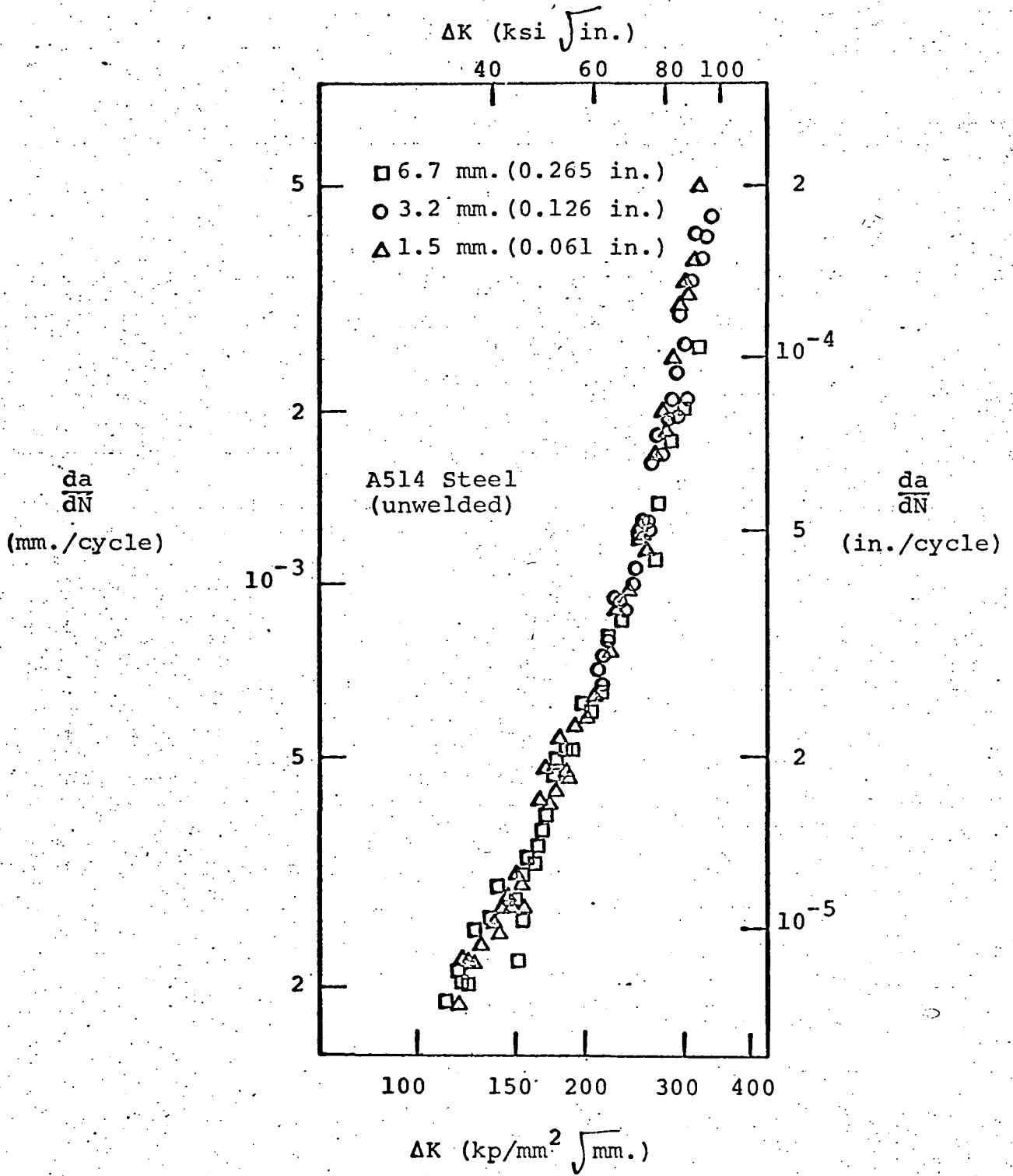


Fig. 7 Specimen Thickness and Crack Propagation