Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified
	2b. GROUP

3. REPORT TITLE

THE INFLUENCE OF YIELD STRENGTH AND FRACTURE TOUGHNESS ON FATIGUE DESIGN PROCEDURES FOR STRUCTURAL STEELS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final report on one phase of a continuing NRL problem.

5. AUTHOR(S) *(First name, middle initial, last name)*

T.W. Crooker and E.A. Lange

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
February 19, 1970	22	48

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
NRL Problem M01-25	NRL Report 7036
b. PROJECT NO. RR 007-01-46-5432	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Department of the Navy (Office of Naval Research), Washington, D.C. 20360

13. ABSTRACT

The failure of welded structures by fatigue can be viewed as crack growth between two flaw sizes forming fixed boundary conditions. The initial condition is a rapidly initiated or pre-existing flaw, and the terminal condition is the critical flaw at failure. This report outlines the modes of failure and methods of analysis for fatigue design for structural steels ranging in yield strength from 30 to 300 ksi. Fatigue crack propagation characteristics of steels seldom vary widely in response to broad changes in yield strength and fracture toughness. However, strength and toughness do vary widely among structural steels and thereby exert profound effects on the fatigue failure process. By applying the principles of the NRL Ratio Analysis Diagram, an analysis shows that the ratio of plane strain fracture toughness to yield strength (K_{Ic}/σ_{ys}) can be employed to determine fatigue design procedures. The full spectrum of structural steels can be divided into three groups on the basis of fracture behavior: ductile plastic fracture mode ($K_{Ic}/\sigma_{ys} > 1.5$), elastic-plastic fracture mode ($1.5 > K_{Ic}/\sigma_{ys} > 0.5$), and brittle elastic instability fracture mode ($K_{Ic}/\sigma_{ys} < 0.5$). The probable mode of failure, the important factors affecting both fatigue and fracture, and fatigue design procedures are discussed for each group.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Weldments						
Structural steels						
Weld defects						
Fracture properties						
Fatigue (materials)						
High strength steels						
Crack propagation						
NRL Ratio Analysis Diagram						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

Security Classification

CONTENTS

ABSTRACT

The failure of welded structures by fatigue can be viewed as crack growth between two flaw sizes forming fixed boundary conditions. The initial condition is a rapidly initiated or pre-existing flaw, and the terminal condition is the critical flaw at failure. This report outlines the modes of failure and methods of analysis for fatigue design for structural steels ranging in yield strength from 30 to 300 ksi. Fatigue crack propagation characteristics of steels seldom vary widely in response to broad changes in yield strength and fracture toughness. However, strength and toughness do vary widely among structural steels and thereby exert profound effects on the fatigue failure process. By applying the principles of the NRL Ratio Analysis Diagram, an analysis shows that the ratio of plane strain fracture toughness to yield strength (K_{Ic}/σ_{ys}) can be employed to determine fatigue design procedures. The full spectrum of structural steels can be divided into three groups on the basis of fracture behavior: ductile plastic fracture mode ($K_{Ic}/\sigma_{ys} > 1.5$), elastic-plastic fracture mode ($1.5 > K_{Ic}/\sigma_{ys} > 0.5$), and brittle elastic instability fracture mode ($K_{Ic}/\sigma_{ys} < 0.5$). The probable mode of failure, the important factors affecting both fatigue and fracture, and fatigue design procedures are discussed for each group.

PROBLEM STATUS

This report completes one phase of the problem; work on other aspects of the problem is continuing.

AUTHORIZATION

NRL Problem M01-25
Project RR 007-01-46-5432

Manuscript submitted December 9, 1969.

THE INFLUENCE OF YIELD STRENGTH AND FRACTURE TOUGHNESS ON FATIGUE DESIGN PROCEDURES FOR STRUCTURAL STEELS

INTRODUCTION

It is now generally recognized that fatigue failures in welded structures are primarily cuased by crack propagation. Numerous laboratory studies and service failure analyses have repeatedly shown that fatigue cracks were initiated very early in the life of the structure or propagated to failure from pre-existing flaws (1-6).

Recognition of this cause of failure has lead to the development of analytical techniques for fatigue crack propagation and the gathering of a sizable number of crack propagation data on a wide variety of structural materials. However, a degree of organization and perspective has been lacking in much of this work. Preoccupation by researchers with crack propagation laws has obscured the fact that crack propagation is only a portion of the fatigue failure process. Furthermore, it is probably the portion of the fatigue failure process least amenable to a substantial improvement.

The failure of welded structures by fatigue can be viewed as a crack growth process operating between fixed boundary conditions (Fig. 1). The lower boundary condition assumes the existence of a rapidly initiated or pre-existing flaw, and the upper boundary condition is terminal failure. The initial conditions primarily rely on fabrication procedures, quality control, nondestructive testing, or proof testing. Crack propagation and terminal failure are design and material problems, and fatigue design procedures must take into account both crack propagation and terminal failure.

This report provides guidelines for the use of thick-section steels in fatigue-loaded structures. Later in this report steels ranging in yield strength from 30 to 300 ksi will be divided into three groups on the basis of their fracture behavior. The probable mode of failure, the important factors affecting both fatigue and fracture, and fatigue design procedures will be discussed for each group.

BASIC ASPECTS

The influence of yield strength and fracture toughness on the fatigue failure process is largely a manifestation of the role of plasticity in influencing the behavior of sharp cracks in structural metals. The degree of plasticity involved in a given situation influences both the mechanical behavior of cracks and the methods of analysis which can be applied to the problem.

The degree of plasticity associated with a crack can be categorized into one of three situations (7). The first situation is gross ductile yielding, wherein the fully plastic state extends beyond the vicinity of the crack and dominates the behavior of the entire cracked body. The second situation is large-scale localized yielding, wherein the nominal deformations away from the vicinity of the crack are elastic, but wherein a plastic zone exists at the crack tip which, although contained in an elastic field, is large in relation to the length of the crack and dimensions (usually thickness) of the cracked body. The final situation is small-scale localized yielding, wherein the plastic zone at the crack tip is small in relation to the crack size and thickness of the body.

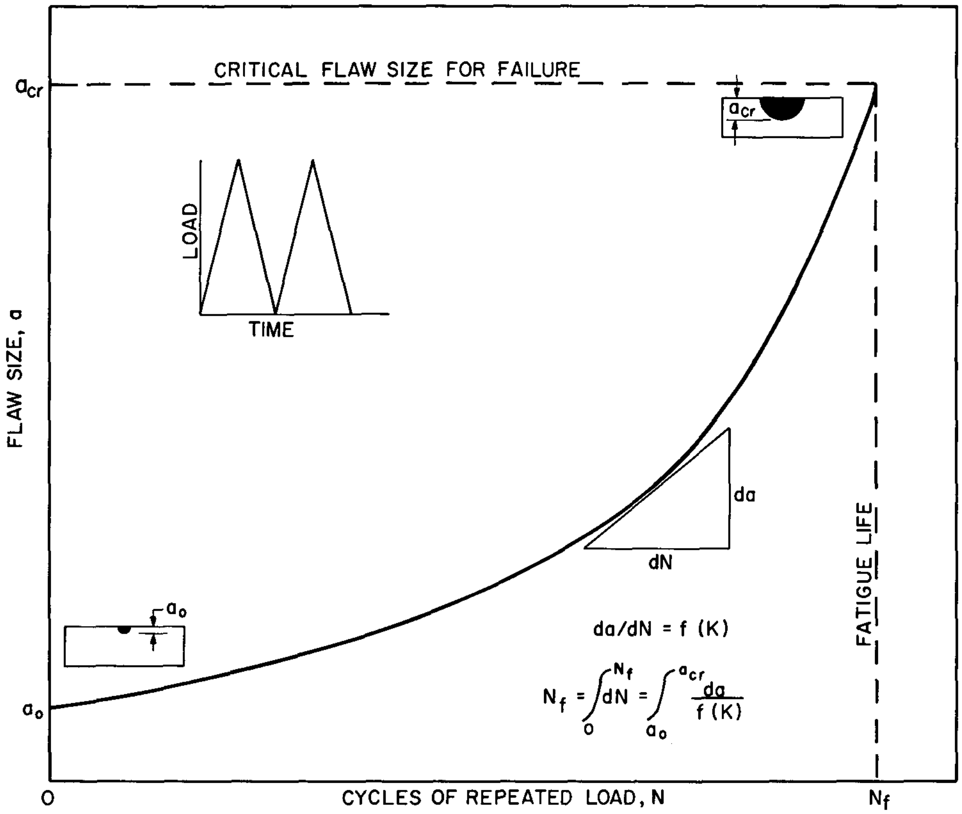

Fig. 1 - Schematic illustration of the process of failure by fatigue crack propagation operating between two flaw sizes, a_0 and a_{cr}

Figure 2 schematically illustrates some of the mechanics of localized yielding, where the plastic zone at the crack tip is enclosed in an elastic stress field. Under these conditions the size of the plastic zone ($2r_y$), i.e., the distance it extends directly in front of the crack tip, is considered to be a function of the stress-intensity factor (K), the yield strength of the material (σ_{ys}), the stress state at the crack tip (plane stress or plane strain), and the mode of load application (monotonic or cyclic) (7). For plane stress,

$$2r_y = \frac{1}{\pi}(K/\sigma_{ys})^2; \tag{1}$$

for plane strain,

$$2r_y = \frac{1}{3\pi}(K_I/\sigma_{ys})^2; \tag{2}$$

and for fatigue

$$2r_y = \frac{1}{4\pi}(\Delta K/\sigma_{ys})^2. \tag{3}$$

In actuality these equations merely provide rough estimates of the scale of yielding, mainly for the purposes of calculating an "effective" crack length, based upon the actual crack length plus a plastic zone size correction (r_y) for fracture mechanics analyses (8).

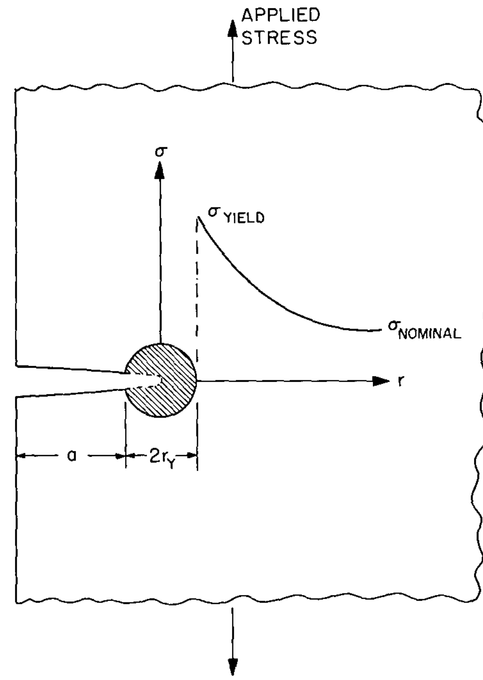

Fig. 2 - The fracture mechanics model for localized yielding at the crack tip

Mechanically, large degrees of plasticity tend to inhibit fracture. High fracture toughness is associated with the ability to develop large plastic zones or fully plastic yielding before fracture. However, fatigue crack propagation properties do not seem to be as sensitive to such distinctions, as will be discussed in a later section.

Analytically, the degree of accuracy available for treating the mechanics of sharp cracks in structural metals decreases with increasing plasticity (7,8). Fatigue and fracture under fully plastic loading must be approached largely on an empirical basis. Linear-elastic fracture mechanics can be applied where the plastic zone resides within an elastic stress field. However, rigorous analyses are limited to small-scale yielding. As the degree of yielding increases and the crack tip plastic zone becomes large in relation to physical dimensions, successive corrections must be applied, and empiricism creeps into the fracture mechanics analysis. Nevertheless the remainder of this report will be presented using fracture mechanics terminology, because, despite analytical limitations, it provides a common language basis.

FATIGUE CRACK PROPAGATION

Crack Propagation Laws and Mechanisms

With the recognition that crack propagation is more critical than crack initiation for analyzing fatigue failure in many structures, numerous efforts to develop engineering approaches to the problem were undertaken. Much of this work was aimed at revealing crack propagation laws which would remain valid over a sufficiently broad range of experimental conditions. In their critical review of crack propagation laws, Paris and Erdogan (9) showed that seemingly contradictory results could be normalized to fit a single power-law curve by relating the fatigue crack growth rate (da/dN) to the range of the stress-intensity factor (ΔK). The resulting equation was of the power-law form

$$da/dN = C(\Delta K)^m, \tag{4}$$

where C is a material constant and m is the slope of the power-law curve. More recent research (10,11) has shown that the entire curve of the fatigue crack growth rate (da/dN) for most materials is actually of sigmoidal (S-shaped) form when plotted versus ΔK on log-log coordinates, as shown in Fig. 3. The power-law portion of the curve given by Eq. 4 is limited to a region between upper and lower inflection points. The lower inflection point is indicative of nonpropagating fatigue cracks and occurs under exceedingly low stress intensities, where the crack growth rates are of the magnitude of the atomic spacing in the crystal lattice (about 10^{-7} to 10^{-8} in./cycle). The upper inflection point is caused by the onset of rapid unstable crack extension prior to terminal fracture and places a critical limit on the fatigue resistance of structural metals.

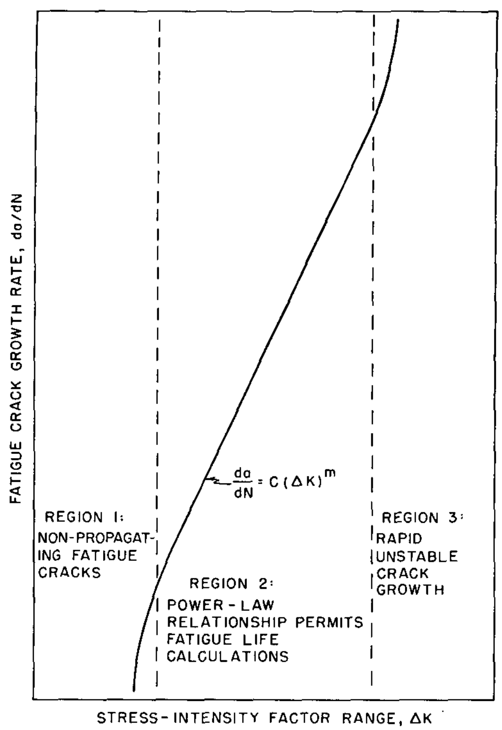

Fig. 3 - The sigmoidal fatigue crack propagation curve on Log-Log coordinates

The application of fracture mechanics to fatigue set the trend for nearly all subsequent fatigue crack propagation studies. It is a successful approach to crack propagation to the extent that the stress-intensity factor describes the plasticity at the crack tip. Fatigue crack propagation occurs through cyclic plastic deformation occurring at the crack tip, regardless of how far plastic deformations exist beyond the crack tip region (12,13). The relationship between gross cyclic plastic strain and fatigue failure was recognized a number of years ago and is treated in detail by Manson (14). It was used as the basis for a hypothesis for fatigue crack propagation by Weiss (15). More recently, Lehr and Liu (16) have shown that fatigue crack propagation is caused by damage accumulation due to strain cycling at the crack tip and that the crack growth rate can be calculated using strain cycling properties.

Consequently, both the proposed mechanisms for fatigue crack propagation and the crack propagation laws which seek to describe the phenomenon in engineering terms are based on cyclic plasticity at the crack tip. Specifically, fatigue crack propagation is primarily related to the range of strain cycling rather than the extent of the plastic zone.

Crack growth rates have been shown to correlate with ΔK but are relatively insensitive to changes in stress state (plane strain vs plane stress) and are frequently unaffected by changes in yield strength (17). Therefore, the range of stress intensity (ΔK) provides common basis for comparing fatigue crack propagation data from many sources.

Crack Propagation Data

A fairly extensive number of fatigue crack propagation data have been generated for steels (18-33). Many of these data are summarized in Figs. 4 through 6, which are log-log plots of da/dN vs ΔK for zero-tension loading in ambient room air environments. These data have been separated into three plots on the basis of yield strength. The scatterband limits shown for each plot attempt to encompass virtually all of the data cited and are not intended to represent the curve for any individual steel.

The striking feature of these three plots is that, despite the broad differences included in the steels considered, the scatterbands overlap one another to a large degree. This overlap is even more striking if we examine a plot (Fig. 7) of the crack growth rate

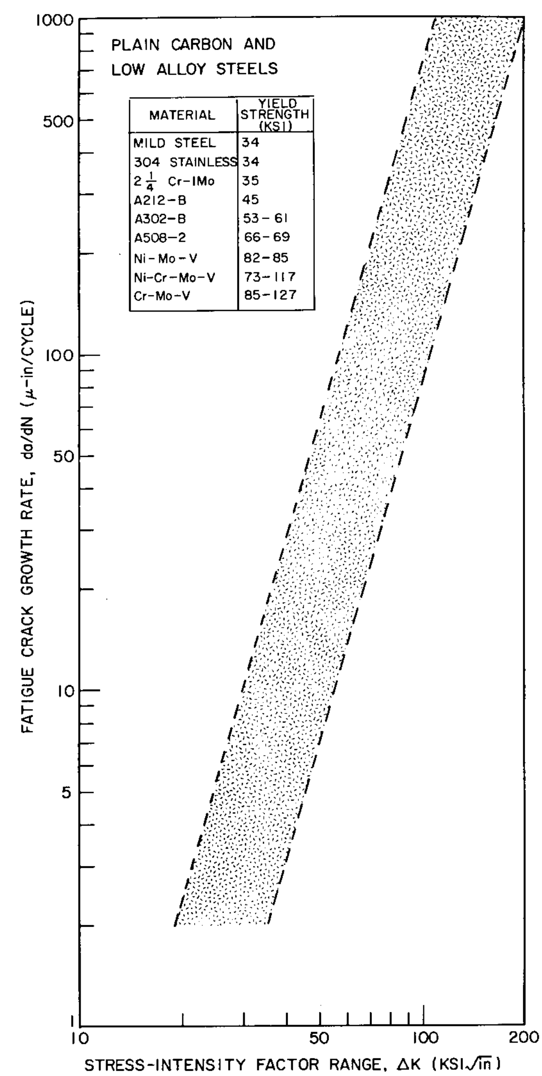

Fig. 4 - Scatterband limits for fatigue crack propagation data in low-strength (plain-carbon and low-alloy) steels

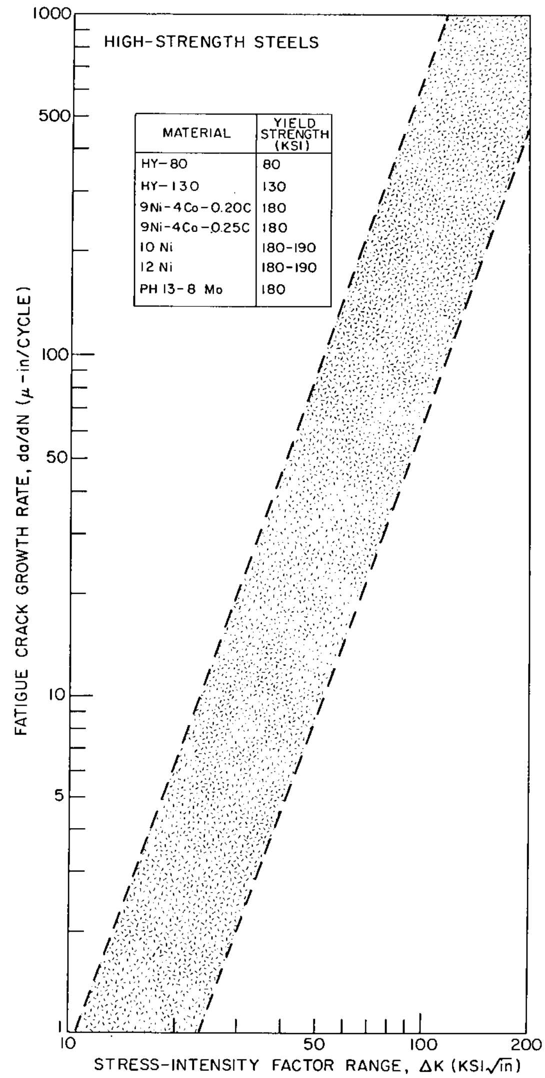

Fig. 5 - Scatterband limits for fatigue crack propagation data in high-strength steels

exponent (m) vs yield strength for these steels. It can be seen that, with few exceptions, m varies from values slightly greater than 2 to values slightly greater than 4 in a rather consistent scatterband over the entire yield strength range from 24 to 300 ksi. This does not imply that all steels are essentially the same, since a variation in the value of m from approximately 2 to 4 is significant, but there does not appear to be a basic irresistible trend for the fatigue crack propagation power law to change with a change in yield strength such as that which exists for fracture toughness as a function of yield strength.

The only consistent and progressive change with yield strength that is apparent in the data cited in Figs. 4 through 6 is the occurrence and location of the upper inflection point. Few low-strength steels exhibit an upper inflection point under elastic fatigue cycling. However, the upper inflection point appears more frequently in data from steels with progressively higher yield strengths. The upper inflection point is associated with impending fracture and occurs at progressively lower stress intensities with increasing yield strength. This feature of the fatigue curve has been related to a critical percentage of the plane stress fracture toughness (K_c) (27), to observations of monotonic crack extension (23), and to a critical value of crack opening displacement (δ) (26). In all

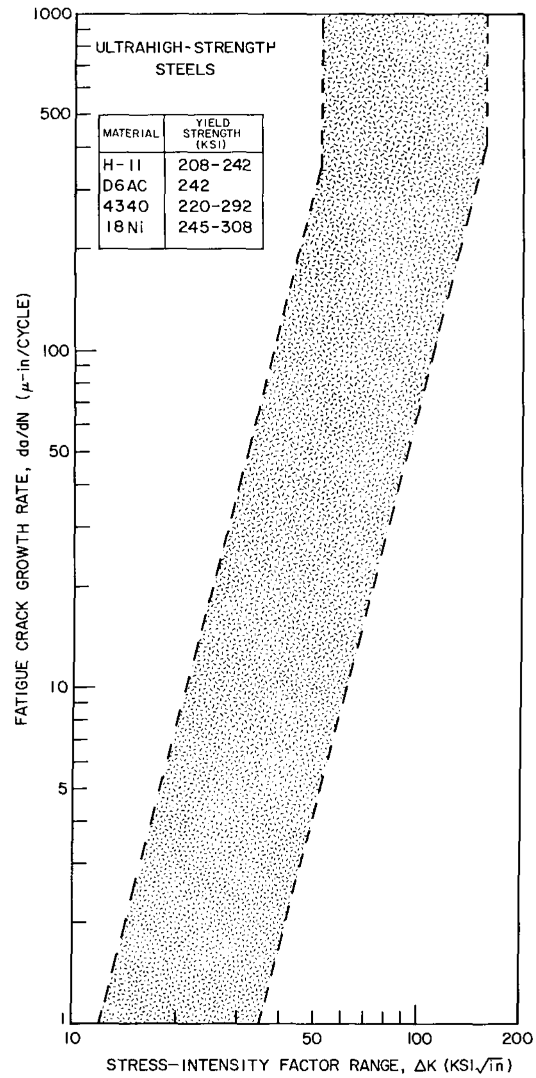

Fig. 6 - Scatterband limits for fatigue crack propagation data in ultrahigh-strength steels

probability this phenomenon is environmentally controlled in ultrahigh-strength steels (34). Nevertheless it appears to be the one feature of the sigmoidal fatigue crack propagation curve which is consistently influenced by yield strength and fracture toughness.

Factors Which Affect Crack Propagation Characteristics

Although fatigue crack propagation characteristics are not profoundly influenced by strength and toughness, except for the occurrence of upper inflection points, it is of interest to examine some of the causes for the scatter observed in Figs. 4 through 7. The authors previously presented (35) an analysis for the fatigue crack propagation characteristics of steels ranging in yield strength from 50 to 200 ksi, and for these materials a gradual increase in the crack growth rate exponent (m) was observed with increasing yield strength. Brothers and Yukawa report an opposite effect in low-alloy heat-treated steels over yield strength ranges from 73 to 127 ksi (22). Miller studied several, mainly ultrahigh-strength, steels and concluded that m is inversely related to K_{Ic} (28). Anctil and Kula (29) and Throop and Miller (36) conducted systematic investigations to

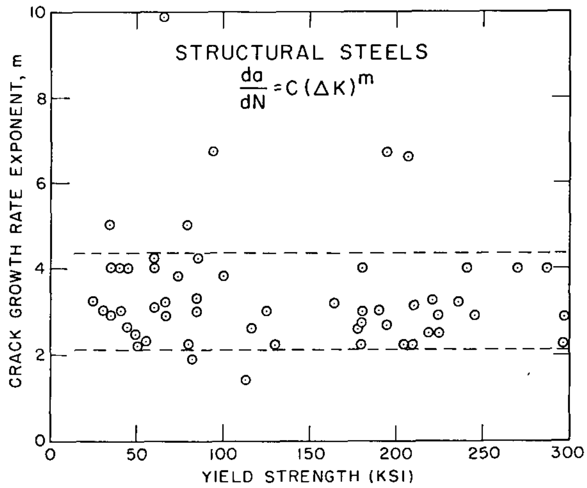

Fig. 7 - Summary plot of crack growth rate exponent values vs yield strength for a broad sample of structural steels (Refs. 18-33)

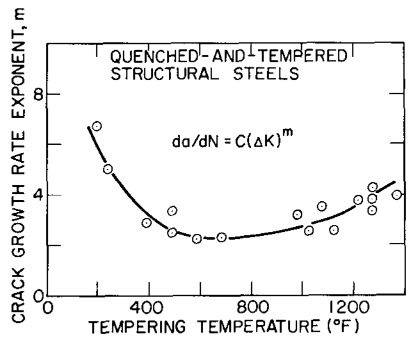

Fig. 8 - Variation in the value of the crack growth rate exponent with tempering temperature for AISI 4340, Cr-Mo-V, Ni-Cr-Mo-V, and XAR-30 quenched-and-tempered structural steels (Refs. 22, 28, and 29)

determine the effect of tempering temperature on fatigue crack propagation in AISI 4340 steel. These results, shown in Fig. 8, reveal that proper tempering can produce an optimum fatigue crack propagation resistance (minimum value of m) in several quenched-and-tempered steels. The present authors also studied three high-strength steels at the 180-ksi yield strength level and observed that significant variation in the value of m occurred with changes in fracture toughness (25). So it appears that although a broad trend in fatigue crack propagation characteristics does not necessarily occur with large changes in yield strength, significant variations can occur as a result of heat treatment and among various alloy compositions.

Apparent variations in fatigue crack propagation characteristics of ultrahigh-strength steels can be due to the test environment. One need only note that the broadest scatter-band among Figs. 4 through 6 occurs for the ultrahigh-strength steels. Dahlberg has shown that fatigue crack propagation in a heat-treated 4340 steel is sensitive to the water vapor content of the room air environment (37). Spitzig, Wei, et al. have also shown that fatigue crack growth rates in ultrahigh-strength steels respond to water vapor (30,31) and that growth rates measured in uncontrolled room air correspond with test results obtained in a humid argon (100-percent relative humidity) environment. However, since welded structures normally operate in ambient-air (or worse) environments, and since virtually all fatigue data are obtained in air, we shall consider such data to adequately represent baseline fatigue crack propagation characteristics for the purposes of this report.

FRACTURE TOUGHNESS

Influence of Yield Strength

Fracture toughness is strongly influenced by yield strength, as indicated schematically in Fig. 9. Although brittle steels can be found at any strength level, the maximum toughness that can be obtained tends to remain about constant up to a yield strength level of 150 ksi, then falls off rapidly for higher yield strengths. Generally, the effect of heat treating a given alloy to obtain higher strength is to drastically reduce fracture toughness. Almost invariably, decreased fracture toughness is the price that must be paid for obtaining higher strength. Some advanced-technology steels can balance this trend by maintaining high toughness up to about the 180-ksi yield strength level. However, such steels are rare and expensive, and their use is limited to critical applications.

The Ratio Analysis Diagram

The Ratio Analysis Diagram (RAD) provides a means of measuring fracture toughness using a simple, inexpensive test and of quantitatively relating the results to structural performance (38). Basically the RAD (Fig. 10) is a cumulative plot of 1-in. Dynamic Tear (DT) test fracture energies vs yield strength for the full spectrum of structural steels (39). In addition the DT energies are correlated with K_{Ic}, which allows a quantitative interpretation of the results (40). This method possesses several advantages; it is applicable to the full spectrum of structural steels, and one need only conduct two relatively simple tests to use the method.

A rational approach to the use of this information can be achieved by considering fracture performance in terms of the K_{Ic}/σ_{ys} ratio. On this basis the diagram has been divided into three regions. Case 1 consists of the toughest steels, for which the K_{Ic}/σ_{ys} ratio exceeds 1.5. It is extremely difficult to obtain valid K_{Ic} measurements on steels for toughnesses in excess of this ratio in accordance with ASTM recommended practices (41). The thickness requirement for plane strain restraint to prevail at the crack tip is expressed by the relationship

$$B \geqslant 2.5\ (K_{Ic}/\sigma_{ys})^2. \qquad (5)$$

So in essence this region consists of those steels whose fracture behavior cannot be analyzed by linear-elastic fracture mechanics. It includes steels up to a maximum yield strength of 190 ksi. Steels in the Case 1 category fracture in a ductile manner requiring very large critical flaw sizes and large plastic strains. Many of these steels undergo a fracture behavior transition from ductile to brittle with decreasing temperature. Fracture problems with these steels are generally associated with low temperature service, and fracture-safe use can be assured by using the principles of the NRL Fracture Analysis Diagram (42).

Case 2 consists of an intermediate region where the K_{Ic}/σ_{ys} ratio varies from 1.5 to 0.5. This region takes in a great many structural steels for which high toughness is either prohibitably expensive from an economic standpoint or is difficult to obtain because of a desire to use higher yield strengths. Typically such steels fracture in what is termed an elastic-plastic manner. Some measurable plasticity is associated with the fracture process, but it tends to be localized; i.e., there is large-scale localized yielding (7). Under these conditions linear-elastic fracture mechanics can be applied with some degree of success (33). For steels in this category, thickness is very important in determining fracture behavior, since thickness will determine whether there is adequate restraint

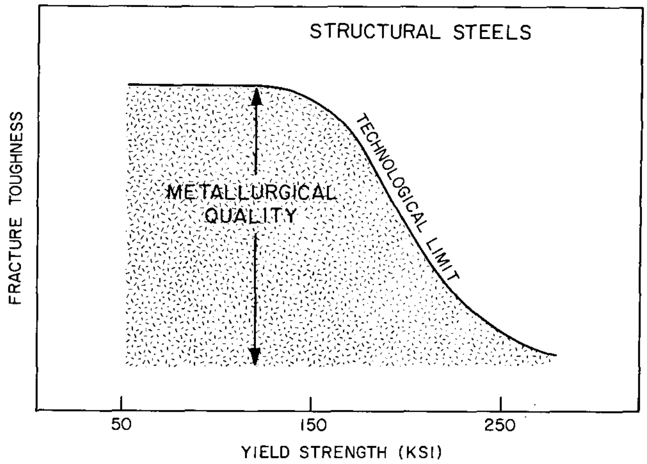

Fig. 9 - Schematic illustration of the effects of yield strength and metallurgical quality on fracture toughness for structural steels

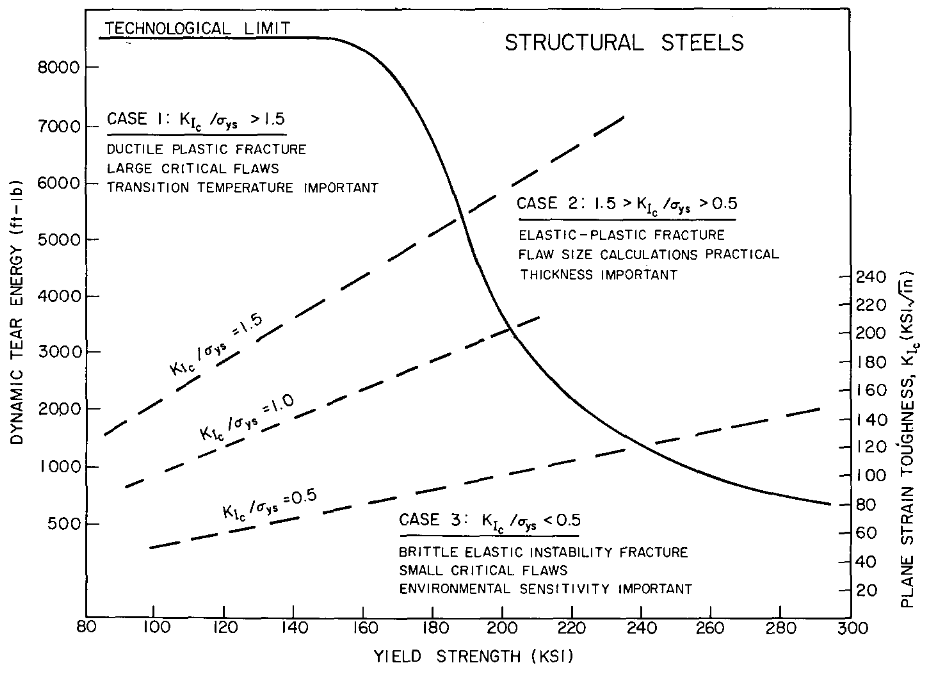

Fig. 10 - Ratio Analysis Diagram for structural steels. The diagram is divided into three regions on the basis of the K_{Ic}/σ_{ys} ratio, and the prominent characteristics of steels in each region are listed.

for plane strain conditions to prevail. A considerable increase in fracture toughness can be assured by avoiding sections thick enough to permit plane strain conditions. This, in turn, can have a very large effect on critical flaw sizes.

In addition some distinctions should be made within this region. The subregion between ratio values of 0.5 and 1.0 is well defined. However, above the ratio 1.0 a number of severe limitations begin to take effect limiting our knowledge of plane strain fracture behavior. Relatively few high-strength steels which can generate valid K_{Ic} values are sufficiently tough to be above the 1.0 ratio line. Therefore one must turn to lower strength steels to define this subregion. But, as yield strength decreases, thickness requirements increase rapidly, thereby imposing experimental difficulties for conducting such tests. The upper limit ratio of 1.5 for this region is arbitrary but appears to be well justified on the basis of current technology. However, it must be emphasized that this region is not well defined, and as the ductile fracture region is approached, a closely spaced family of ratio lines ranging from values slightly greater than 1.0 to infinity is likely to emerge (43).

Finally, Case 3 consists of steels with the lowest level of fracture toughness, with the K_{Ic}/σ_{ys} ratio less than 0.5. Generally this condition is avoided wherever possible, and only the ultrahigh-strength steels necessarily fall into this category. Fracture behavior of these steels in plate thickness sections is virtually always brittle elastic plane strain instability fracture which corresponds to small-scale localized yielding (7). Critical flaw sizes in such steels are very small, and an accurate analysis is necessary to prevent catastrophic brittle fracture at the high design stress levels for which these steels are normally intended.

Critical Flaw Size Relationships

The essence of the importance of fracture toughness in fatigue design procedures is in determining the mode of failure and, in the case of potential fast fracture, the critical flaw size for failure. Complex welded structures that are cyclically loaded frequently tend to contain flaws, and the significance of these flaws can be judged only in terms of their potential to cause failure.

Critical flaw sizes can be related to the K_{Ic}/σ_{ys} ratio by applying the principles of linear-elastic fracture mechanics. Figure 11 illustrates such a relationship for the case of the long, shallow flaw in plane strain. A family of curves is shown corresponding to nominal stress levels expressed as fractional values of the yield strength stress.

Relating this figure to the three cases presented in the previous section, one can make several observations. First, for ratios less than 0.5 critical flaw sizes are very small, except under very low stresses. Further, except in thin sections, plane strain conditions apply for these steels, and little can be done mechanically to gain added toughness.

For ratios between 0.5 and 1.5 flaw sizes remain fairly small but for the most part are within a magnitude such that detection by nondestructive inspection methods is practical. Also a departure from plane-strain to plane-stress conditions increases the critical flaw size values by a substantial amount. Plane stress fracture does not lend itself to a similar general analysis; however, the following relationship provides some guidance in this regard:

$$a_{cr}/a_{Icr} = (K_c/K_{Ic})^2, \tag{6}$$

where the terms refer to the critical flaw sizes and critical stress intensities in plane stress and plane strain respectively. Further, steels in this category may be sufficiently thick for an initial crack instability to occur under plane strain, only to have further crack movement arrested by localized plasticity. Therefore, it must be emphasized that fracture in this category of steels is highly dependent on thickness. As yield strength decreases, plane strain conditions prevail in only very heavy sections.

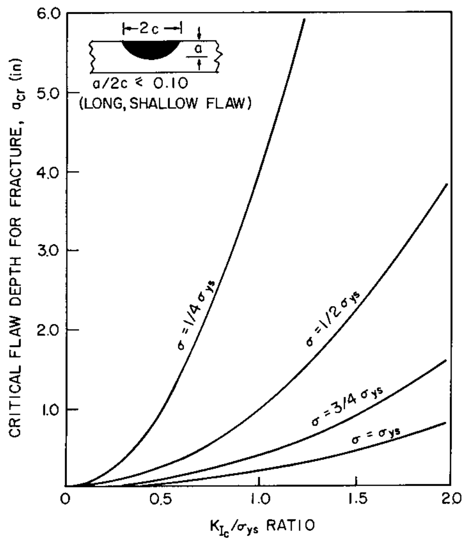

Fig. 11 - Fracture mechanics relationships between critical flaw depths of long, shallow flaws in plane strain and the K_{Ic}/σ_{ys} ratio. The family of curves represents stress levels expressed as fractional values of the yield strength stress.

Finally, for ratios greater than 1.5, this plane strain, linear-elastic analysis generally does not apply. Plane strain elastic fracture can occur only in extremely heavy sections or at low temperatures (44). Therefore, the critical flaw sizes indicated, large as they are, are only extremely conservative estimates.

COMMENTS ON DESIGN PROCEDURES

The following comments are offered as guidelines as to the manner in which a broad knowledge of crack propagation and fracture characteristics can influence fatigue design procedures.

Case 1: $K_{Ic}/\sigma_{ys} > 1.5$

The failure mode for steels in the Case 1 category will not, in most instances, be unstable fast fracture except for service applications below the nil-ductility transition temperature. These steels are capable of tolerating large flaw sizes, within the detection capability of even the most unsophisticated nondestructive inspection techniques. If allowed to propagate to failure, cracks in these steels will ultimately lead to large inelastic deformations or to leakage in the case of pressure vessels.

Further, crack growth rates in lower strength, high-toughness steels will tend to be substantially slower than in higher strength steels. Since crack growth rate characteristics are not inherently affected by yield strength, lower working stresses in lower strength steels will almost invariably result in slower growth rates.

The lower strength steels, which require heavier sections to maintain low stresses, present the fewest fatigue problem areas. Here, crack growth is contained by the large amount of material, growth rates tend to be slow, and high toughness, which permits large flaw sizes, is easily attainable. Also, these steels present the fewest welding problems to complicate this favorable picture.

Service experience justifies these observations. Barring unusual circumstances, low-strength welded structures seldom fail by fatigue. Design procedures for common, low-strength welded steel structures are well documented and are prescribed in detail in building and design codes. Problems arise when a critical application requires a departure from code procedures or when unfamiliar higher strength materials are employed. Frequently this involves low-cycle fatigue at points of geometric discontinuity.

Design procedures for low-cycle fatigue crack propagation in lower strength steels are not well established. Most designs for low-cycle fatigue do not assume a growing crack and are based on plastic fatigue crack initiation. The fact that this approach works as well as it does simply substantiates the fact that fatigue is not a highly critical process in such steels.

The fracture mechanics fatigue data referred to in Fig. 4 pertain only to elastic loading and are useful only for high-cycle fatigue situtations in which most of the fatigue life of the component or structure involves small flaws and nominal working stresses below the yield point.

Harrison (45) has shown that a linear-elastic fracture mechanics analysis works quite well for predicting the fatigue life of low-strength-steel laboratory specimens in which plastic strains develop in only the final stages of failure. For low-cycle fatigue crack propagation involving gross plastic deformation over the entire fatigue life, empirical approaches based on gross strain are required. The authors conducted strain-cycle crack propagation tests on several pressure-vessel steels and showed that an arbitrary index of fatigue life based on their studies corresponded reasonably well with the fatigue life of full-scale-model vessels of the same materials (46). McEvily (47) has proposed a strain-intensity-factor approach to fatigue crack propagation which is not limited to elastic loading, and this approach seems well worth further investigation.

Case 2: $1.5 > K_{Ic}/\sigma_{ys} > 0.5$

The failure mode for steels in the Case 2 category will, in most instances, be elastic fracture. However, the critical flaw size and the degree of localized plasticity can vary widely, depending on the toughness and thickness. Fatigue problems are likely to be important for many steels in this category for several reasons. Working stresses are likely to be higher in these steels, thereby substantially increasing crack growth rates. The premium to be sought in using higher strength materials is smaller section sizes; therefore less material is available to contain cracks. The concomitant penalty of higher strength materials is lower toughness and smaller critical flaw sizes, thereby severely limiting the upper boundary condition for fatigue failure. However, many new designs are contemplating new steels in the yield strength region of 100 to 180 ksi, which will include many Case 2 steels. Fatigue is likely to take on a new urgency in the failure-safe design of such high-strength structures.

Linear-elastic fracture mechanics works rather well for analyzing crack propagation and the potential for fracture in Case 2 steels, especially if heavy sections are involved (33). In thinner or tougher steels within this category fracture mechanics continues to be the best analytical approach for crack propagation, but its application to fracture becomes less well understood when the fracture mode departs from plane strain instability fracture. Also, "leak-before-fracture" situations can be attained for many applications with these steels, especially for ratio values between 1.0 and 1.5. In other words, large visible flaws and considerable localized plastic deformation will precede terminal fracture. These conditions may preclude a physical catastrophy, but in many instances, such as industrial pressure vessels, a through crack represents an economic catastrophy. Crack growth in these steels may proceed at surprisingly rapid rates, especially if assisted by corrosion. Further, many steels in this category are prone to welding problems. So, even though a high degree of assurance against brittle fracture can be achieved in these steels, failure by fatigue crack growth remains a serious problem which must be dealt with on a design basis and cannot be precluded by attaining improvements in basic fatigue crack propagation characteristics of materials.

Case 3: $K_{Ic}/\sigma_{ys} < 0.5$

The failure mode for steels in the Case 3 category will be brittle elastic instability fracture. The critical flaw sizes will be very small. The application of this category of steels in large welded structures poses extreme difficulties from a fatigue and fracture standpoint and should be avoided except where extreme necessity imposes severe requirements on the strength-to-weight ratio.

Although these steels are the most difficult to apply in service, they are the easiest to deal with from an analytical point of view. Hence, literature is abundant on fracture mechanics experiments conducted on such steels as 4340, H-11, D6AC, and 18Ni maraging. These steels are incapable of gross plastic deformation, and they fracture elastically under plane strain conditions in plate thickness sections. However, an analysis of their fatigue crack propagation behavior is complicated by the fact that they are hypersensitive to environment. Even the water vapor content of laboratory room air is an important factor in determining their fatigue behavior. Successful fatigue applications of these steels require that they be coated or otherwise protected to remove their surface from the atmosphere.

Tiffany et al. (4,48) have proposed and extensively applied a sophisticated approach of plane strain linear-elastic fracture mechanics to low-cycle fatigue and fracture in plate-section ultrahigh-strength materials. It includes all three elements of the fatigue failure process, the initial flaw severity, the conditions for terminal failure, and the duration of the growth process linking these boundary conditions. However, despite the ample analytical tools available to deal with ultrahigh-strength steels, the actual physical problems involved severely limit their application.

SUMMARY

In summary, abundant evidence supports the premise that fatigue failure in large, complex welded structures is predominately caused by crack propagation originating at pre-existing defects too small and too numerous to totally eliminate. It has been proposed that fatigue failure by crack propagation can be viewed as a growth process operating between fixed boundary conditions, i.e., the initial and terminal flaw sizes. Fatigue design procedures must take into account all three aspects, namely; the two boundary conditions and the growth process between them. The problems of determining initial flaws come under the scope of quality control and nondestructive inspection. Crack growth and failure are materials problems whose nature and seriousness vary widely with variations in yield strength and fracture toughness. It has been shown that the baseline characteristics of fatigue crack propagation in steels are not fundamentally influenced by yield strength, although significant variations can be obtained at any strength level. Fracture characteristics of steels do, however, respond strongly to yield strength with significantly decreased toughness at higher levels of yield strength.

As a means of categorizing these problems quantitatively, it has been proposed that the K_{Ic}/σ_{ys} ratio can provide significant information relevant to fatigue design procedures. Further, the use of the NRL Ratio Analysis Diagram permits these determinations to be made on the basis of two relatively simple engineering tests (a 1-in. Dynamic Tear test and a tensile test). The value of the K_{Ic}/σ_{ys} ratio thereby obtained can be used to determine the probable severity and potential for fatigue failure, the probable mode of terminal failure to be designed against, the most applicable analytical approach, and estimates of the critical flaw size.

It is intended that the broad scope of fatigue and fracture information brought together in this report will thereby serve to influence fatigue design procedures, especially for design situations involving the use of newer, higher strength steels.

ACKNOWLEDGMENT

The authors are grateful to the Office of Naval Research for their financial support of this work.

REFERENCES

1. Signes, E.G., Baker, R.G., Harrison, J.D., and Burdekin, F.M., "Factors Affecting the Fatigue Strength of Welded High Strength Steels," British Welding J. 14 (No. 3), 108 (Mar. 1967)

2. Kooistra, L.F., Lange, E.A., and Pickett, A.G., "Full-Size Pressure Vessel Testing and Its Application to Design," ASME Trans., J. Engineering for Power 86A (No. 4), 419 (Oct. 1964)

3. Srawley, J.E., and Esgar, J.B., "Investigation of Hydrotest Failure of Thiokol Chemical Corporation 260-Inch-Diameter SL-1 Motor Case," NASA TM X-1194, Jan. 1966

4. Tiffany, C.F., and Lorenz, P.M., "An Investigation of Low-Cycle Fatigue Failures Using Applied Fracture Mechanics," Air Force Materials Laboratory Technical Documentary Report ML-TDR-64-53, May 1964

5. Weck, Richard, "How Dangerous Are Weld Defects?," Metal Progress, 92 (No. 3), 93 (Sept. 1967)

6. Christopher, P.R. and Crabbe, D.R., "A Discourse on Factors Which Control Fatigue Behaviour in High Yield Low Alloy Steel Structures," Ocean Engineering, 1 (No. 5), 497 (July 1969)

7. Rice, J.R., "Mechanics of Crack Tip Deformation and Extension by Fatigue," in "Fatigue Crack Propagation," ASTM STP 415, Philadelphia, American Society for Testing and Materials, 1967, p. 247

8. Weiss, V., and Yukawa, S., "Critical Appraisal of Fracture Mechanics," in "Fracture Toughness Testing and Its Applications," ASTM STP 381, Philadelphia, American Society for Testing and Materials, 1965, p. 1

9. Paris, P., and Erdogan, F., "A Critical Analysis of Crack Propagation Laws," J. Basic Engineering, ASME Trans. 85D (No. 4), 528 (1963)

10. Paris, P.C., and Wei, R.P., "Fracture Mechanics in Fatigue," ASM Symposium on Engineering Aspects of Fatigue, 1969 Materials Engineering Congress, Philadelphia, Pennsylvania, Oct. 13-16, 1969

11. Johnson, R.E., "Some Observations of Cyclic Crack Propagation from a Fracture Mechanics Viewpoint," ASM Symposium on Metallurgical Aspects of Fatigue Fracture, Materials Engineering Congress, Philadelphia, Pennsylvania, Oct. 13-16, 1969

12. Grosskreutz, J.C., "A Theory of Stage II Fatigue Crack Propagation," Air Force Materials Laboratory, Technical Report 64-415, Mar. 1965

13. Laird, C., "The Influence of Metallurgical Structure on the Mechanisms of Fatigue Crack Propagation," in "Fatigue Crack Propagation," ASTM STP 415, Philadelphia, American Society for Testing and Materials, 1967, p. 131

14. Manson, S.S., "Thermal Stress and Low-Cycle Fatigue," New York, McGraw-Hill, 1966

15. Weiss, V., "Analysis of Crack Propagation in Strain-Cycling Fatigue," in "Fatigue - An Interdisciplinary Approach," Proceedings, 10th Sagamore Army Materials Research Conference, Syracuse University Press, 1964, p. 179

16. Lehr, K.R., and Liu, H.W., "Fatigue Crack Propagation and Strain Cycling Properties," International J. Fracture Mechanics 5 (No. 1), 45 (Mar. 1969)

17. Johnson, H.H., and Paris, P.C., "Sub-critical Flaw Growth," Engineering Fracture Mechanics 1 (No. 1), 3 (June 1968)

18. Gurney, T.R., "An Investigation of the Rate of Propagation of Fatigue Cracks in a Range of Steels," The Welding Institute Research Report E18/12/68, Dec. 1968

19. Schwab, R.C., "Use of Tapered Double Cantilever Beam Specimens for Fatigue Crack Growth Studies," ASME Paper 69-MET-16

20. Brothers, A.J., "Fatigue Crack Growth in Nuclear Reactor Piping Steels," U.S. Atomic Energy Commission Research and Development Report GEAP-5607, Mar. 1968

21. Mowbray, D.F., Andrews, W.R., and Brothers, A.J., "Fatigue-Crack Growth-Rate Studies of Low-Alloy Pressure Vessel Steels," ASME Trans., J. Engineering for Industry 90B (No. 4), 648 (Nov. 1968)

22. Brothers, A.J., and Yukawa, S., "Fatigue Crack Propagation in Low-Alloy Heat-Treated Steels," ASME Trans., J. Basic Engineering 89D (No. 1), 19 (Mar. 1967)

23. Clark, W.G., Jr., "Subcritical Crack Growth and Its Effect Upon the Fatigue Characteristics of Structural Alloys," Engineering Fracture Mechanics 1 (No. 2), 385 (Aug. 1968)

24. Clark, W.G., Jr., and Wessel, E.T., "Influence of a Synthetic Seawater Environment on the Fracture Behavior of HP 9-4-25 and HP 9-4-20 Alloy Steels," in "Materials Performance and the Deep Sea," ASTM STP 445, Philadelphia, American Society for Testing and Materials, 1969, p. 93

25. Crooker, T.W., and Lange, E.A., "The Influence of Salt Water on Fatigue Crack Growth in High-Strength Structural Steels," in "Effects of Environment and Complex Loading History on Fatigue Life," ASTM STP 462, American Society for Testing and Materials (pending)

26. Barsom, J.M., "Investigation of Subcritical Crack Propagation," Ph.D. Thesis, University of Pittsburgh, 1969

27. Carman, C.M., and Katlin, J.M., "Low Cycle Fatigue Crack Propagation Characteristics of High Strength Steels," ASME Trans., J. Basic Engineering 88D (No. 4), 792 (Dec. 1966)

28. Miller, G.A., "The Dependence of Fatigue-Crack Growth Rate on the Stress Intensity Factor and the Mechanical Properties of Some High-Strength Steels," ASM Trans. Quarterly 61 (No. 3), 442 (Sept. 1968)

29. Anctil, A.A., and Kula, E.B., "Effect of Tempering Temperature on Fatigue Crack Propagation in 4340 Steel," in "Effects of Environment and Complex Loading History on Fatigue Life," ASTM STP 462, American Society for Testing and Materials (pending)

30. Spitzig, W.A., and Wei, R.P., "A Fractographic Investigation of the Effect of Environment on Fatigue-Crack Propagation in an Ultrahigh-Strength Steel," ASM Trans. Quarterly 60 (No. 3), 279 (Sept. 1967)

31. Wei, R.P., Talda, P.M., and Li, Che-Yu, "Fatigue Crack Propagation in Some Ultrahigh-Strength Steels," in "Fatigue Crack Propagation," ASTM STP 415, Philadelphia, American Society for Testing and Materials, 1967, p. 460

32. Crooker, T.W., and Lange, E.A., "Corrosion-Fatigue Crack Propagation Studies of Some New High-Strength Structural Steels," ASME Paper 69-MET-5

33. Clark, W.G., Jr., and Wessel, E.T., "Application of Fracture Mechanics Technology to Medium-Strength Steels" (to be published in ASTM STP 463, pending)

34. Wei, R.P., and Landes, J.D., "Correlation Between Sustained-Load and Fatigue Crack Growth in High-Strength Steels," Materials Research and Standards 9 (No. 7), 25 (July 1969)

35. Crooker, T.W., and Lange, E.A., "Low Cycle Fatigue Crack Propagation Resistance of Materials for Large Welded Structures," in "Fatigue Crack Propagation," ASTM STP 415, Philadelphia, American Society for Testing and Materials, 1967, p. 94

36. Throop, J.F., and Miller, G.A., "Optimum Fatigue-Crack Resistance," Symposium on the Achievement of High Fatigue Resistance in Metals and Alloys, 72nd Annual, ASTM, Atlantic City, New Jersey, June 22-27, 1969

37. Dahlberg, E.P., "Fatigue-Crack Propagation in High-Strength 4340 Steel in Humid Air," ASM Trans. Quarterly 58 (No. 1), 46 (Mar. 1965)

38. Pellini, W.S., "Advances in Fracture Toughness Characterization Procedures and in Quantitative Interpretations to Fracture-Safe Design for Structural Steels," Welding Research Council Bulletin, No. 130, May 1968

39. Puzak, P.P., and Lange, E.A., "Standard Method for the 1-Inch Dynamic Tear Test," NRL Report 6851, Feb. 13, 1969

40. Freed, C.N., and Goode, R.J., "A Correlation Between Fracture Toughness Test Procedures for Ferrous Alloys," Pressure Vessel Technology, Part II, Materials and Fabrication, ASME, 1969, p. 723

41. Brown, W.F., and Srawley, J.E., "Plane Strain Crack Toughness Testing of High Strength Metallic Materials," ASTM STP 410, Philadelphia, American Society for Testing and Materials, p. 126, 1966

42. Pellini, W.S., and Puzak, P.P., "Fracture Analysis Diagram Procedures for the Fracture-Safe Engineering Design of Steel Structures," NRL Report 5920, Mar. 15, 1963

43. Pellini, W.S., "Evolution of Engineering Principles for Fracture-Safe Design of Steel Structures," NRL Report 6957, Sept. 23, 1969

44. Loss, F.J., and Pellini, W.S., "Dynamic Tear Test Definition of the Temperature Transition from Linear Elastic to Gross Strain Fracture Conditions," ASME Trans., J. Basic Engineering 91D (No. 1), 108 (Mar. 1969)

45. Harrison, J.D., "The Analysis of Fatigue Test Results for Butt Welds with Lack of Penetration Defects Using a Fracture Mechanics Approach," BWRA Report E/13/67, Dec. 1967

46. Crooker, T.W., and Lange, E.A., "Low Cycle Fatigue Crack Propagation in A201B, A302B, and A517F Pressure Vessel Steels," Welding J. Research Supplement (No. 7), 322-s (July 1967)

47. McEvily, A.J., "Fatigue Crack Growth and the Strain Intensity Factor," Air Force Conference on Fatigue and Fracture of Aircraft Structures and Materials, Miami Beach, Florida, Dec. 15-18, 1969

48. Tiffany, C.F., and Masters, J.N., "Applied Fracture Mechanics," in "Fracture Toughness Testing and Its Applications," ASTM STP 381, Philadelphia, American Society for Testing and Materials, 1965, p. 249