

How Yield Strength and Fracture Toughness Considerations Can Influence Fatigue Design Procedures for Structural Steels

The K_{Ic} / σ_{ys} ratio provides significant information relevant to fatigue design procedures, and use of NRL Ratio Analysis Diagrams permits determinations based on two relatively simple engineering tests

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ABSTRACT. The failure of welded structures by fatigue can be viewed as a crack growth process operating between fixed boundary conditions. The lower boundary condition assumes a rapidly initiated or pre-existing flaw, and the upper boundary condition is terminal failure. This paper outlines the modes of failure and methods of analysis for fatigue design for structural steels ranging in yield strength from 30 to 300 ksi. It is shown that fatigue crack propagation characteristics of steels seldom vary significantly 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 is presented whereby the plane strain fracture toughness to yield strength ratio (K_{Ic} / σ_{ys}) can be employed to determine fatigue design procedures. The full spectrum of structural steels is divided into three groups on the basis of fracture behavior:

1. Ductile plastic fracture mode ($K_{Ic} / \sigma_{ys} > 1.5$).
2. Elastic-plastic fracture mode ($1.5 > K_{Ic} / \sigma_{ys} > 0.5$).
3. 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.

Introduction

It is now generally recognized that

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fatigue failures in welded structures are primarily caused 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 problem has led to the development of analytical techniques for fatigue crack propagation and the gathering of a sizeable amount 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 paper provides guidelines for the use of thick-section steels in fatigue-loaded structures. Steels ranging in yield strength from 30 to 3000 ksi are 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 are 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 First, there can be gross ductile yielding where the fully plastic state extends beyond the vicinity of the crack and dominates the behavior of the entire cracked body. Second, there can be large scale localized yielding where the nominal deformations away from the vicinity of the crack are elastic. However, 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. Finally, there can be small scale localized yielding where the crack tip plastic zone is small in relation to the crack size and thickness of the body.

Figure 2 schematically illustrates some of the mechanics of localized yielding, where the crack tip plastic zone 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

$$2r_y = \frac{1}{\pi} (K/\sigma_{ys})^2 \text{—plane stress} \quad (1)$$

$$2r_y = \frac{1}{3\pi} (K_I/\sigma_{ys})^2 \text{—plane strain} \quad (2)$$

$$2r_y = \frac{1}{4\pi} (\Delta K/\sigma_{ys})^2 \text{—fatigue} \quad (3)$$

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

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, which 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 paper is 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 Erdogan⁹ 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 stress-intensity factor range (ΔK). The resulting equation was of the power-law form shown in equation (4):

$$da/dN = C (\Delta K)^m \quad (4)$$

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 fatigue crack growth rate curve for most materials is actually of sigmoidal form when plotted on log-log coordinates, as shown in Fig. 3. The power-law portion of the

curve is limited by 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 ($\sim 10^{-7}$ 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.

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 crack tip plasticity. 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 Liu¹⁶ 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 upon cyclic crack tip plasticity. 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, stress intensity provides a common basis for comparing fatigue crack propagation data from many sources.

Crack Propagation Data

A fairly extensive amount of fatigue crack propagation data has been generated for steels.¹⁸⁻³³ Much of this data is summarized in Figs. 4-6, 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

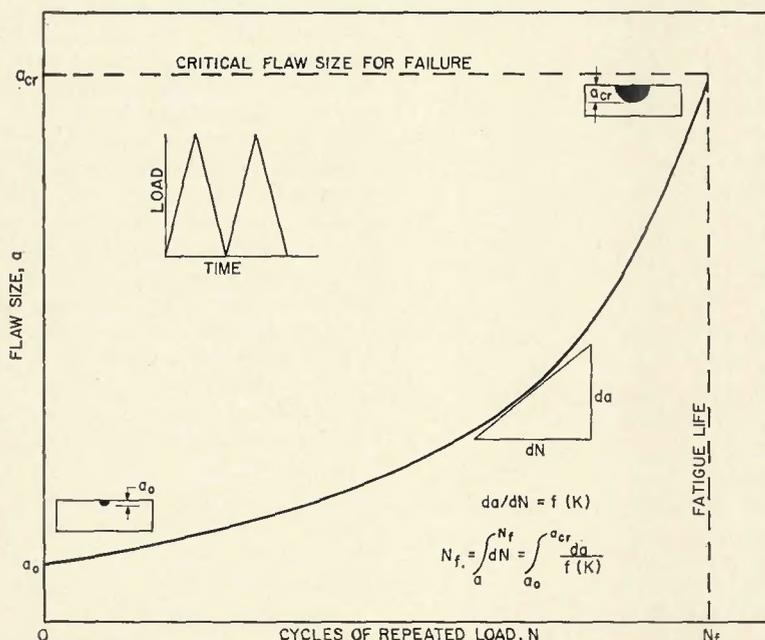


Fig. 1—Schematic illustration of the fatigue crack propagation failure process

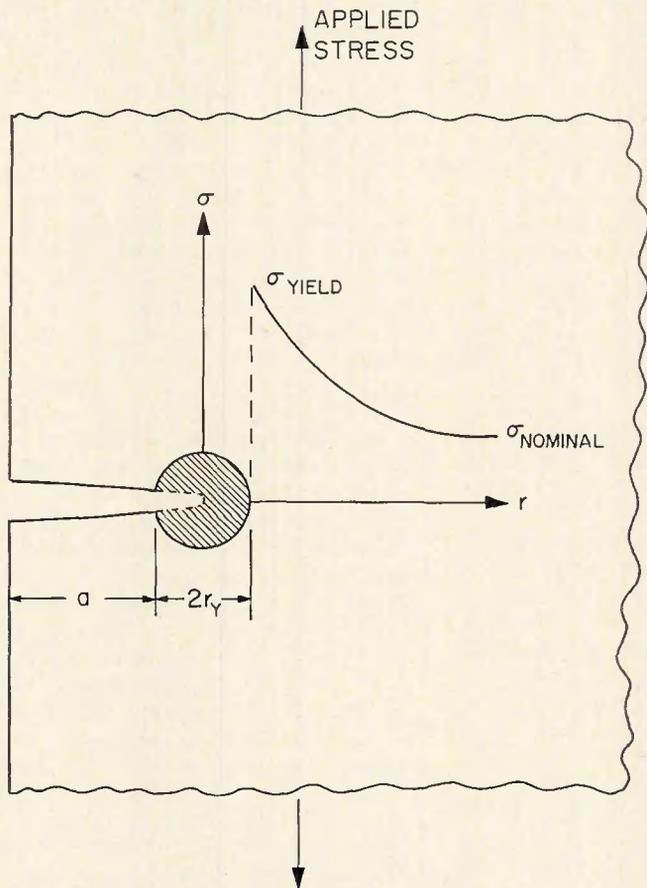


Fig. 2—The fracture mechanics model for localized yielding at the crack tip

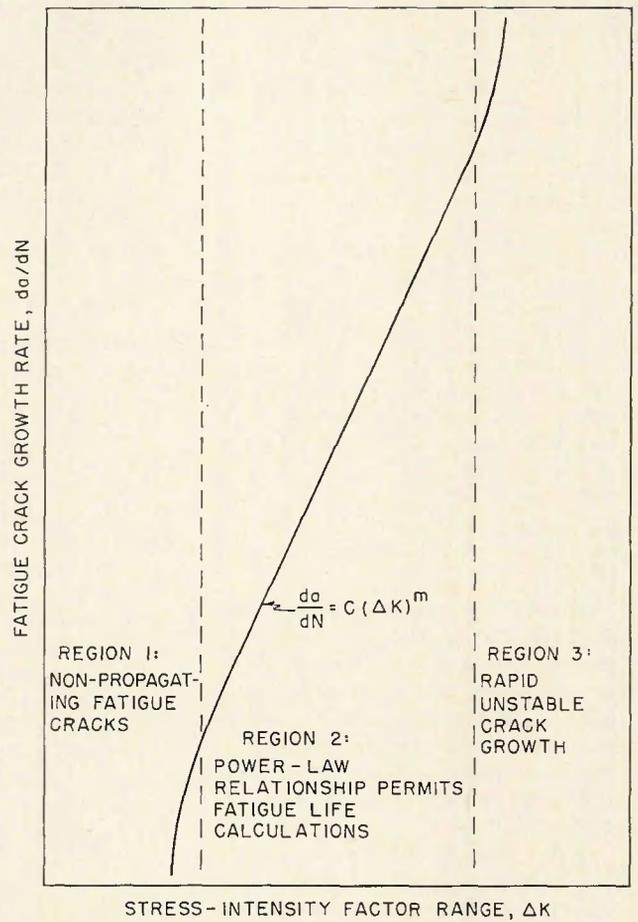


Fig. 3—The sigmoidal fatigue crack propagation curve

intended to represent the curve for any individual steel.

The striking feature of these three plots is the fact that despite the broad differences included in the steels considered, the scatterbands overlap one another to a large degree. This fact is even more striking if we examine a plot of the crack growth rate exponent (m) vs. yield strength for these steels—Fig. 7. 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. However, there does not appear to be a basic irresistible trend in fatigue crack propagation power law curves with yield strength such as that which exists with fracture toughness vs. yield strength.

The only consistent and progressive change with yield strength, that is apparent in the data cited in Figs. 4-6, 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 progressively higher yield strength steels. 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_{Ic}),²⁷ to observations to monotonic crack extension,²³ and to a critical value of crack opening displacement (δ).²⁶ In all probability this phenomenon is environmentally controlled in ultra high-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. 4-7. In a previous paper, the authors presented an analysis for the fatigue crack propagation characteristics of steels rang-

ing 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.³⁵

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 ultra high strength) steels and concluded that m is inversely related to K_{Ic} .²⁸ Anctil and Kula²⁹ and Throop and Miller³⁶ conducted systematic investigations to determine the effect of tempering temperature on fatigue crack propagation in AISI 4340 steel. Their 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 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 treat-

ment and among various alloy compositions.

Apparent variations in fatigue crack propagation characteristics of ultra high-strength steels can be due to the test environment. One need only note that the broadest scatterband among Figs. 4-6 occurs for the ultra high-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% 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 paper.

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 quantitatively relating the results to structural performance.³⁸ Basically, the RAD is a cumulative plot of 1 in. Dynamic Tear (DT) test fracture energies vs yield strength for the full spectrum of structural steels³⁹—Fig. 10. 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 utilize 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 where 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

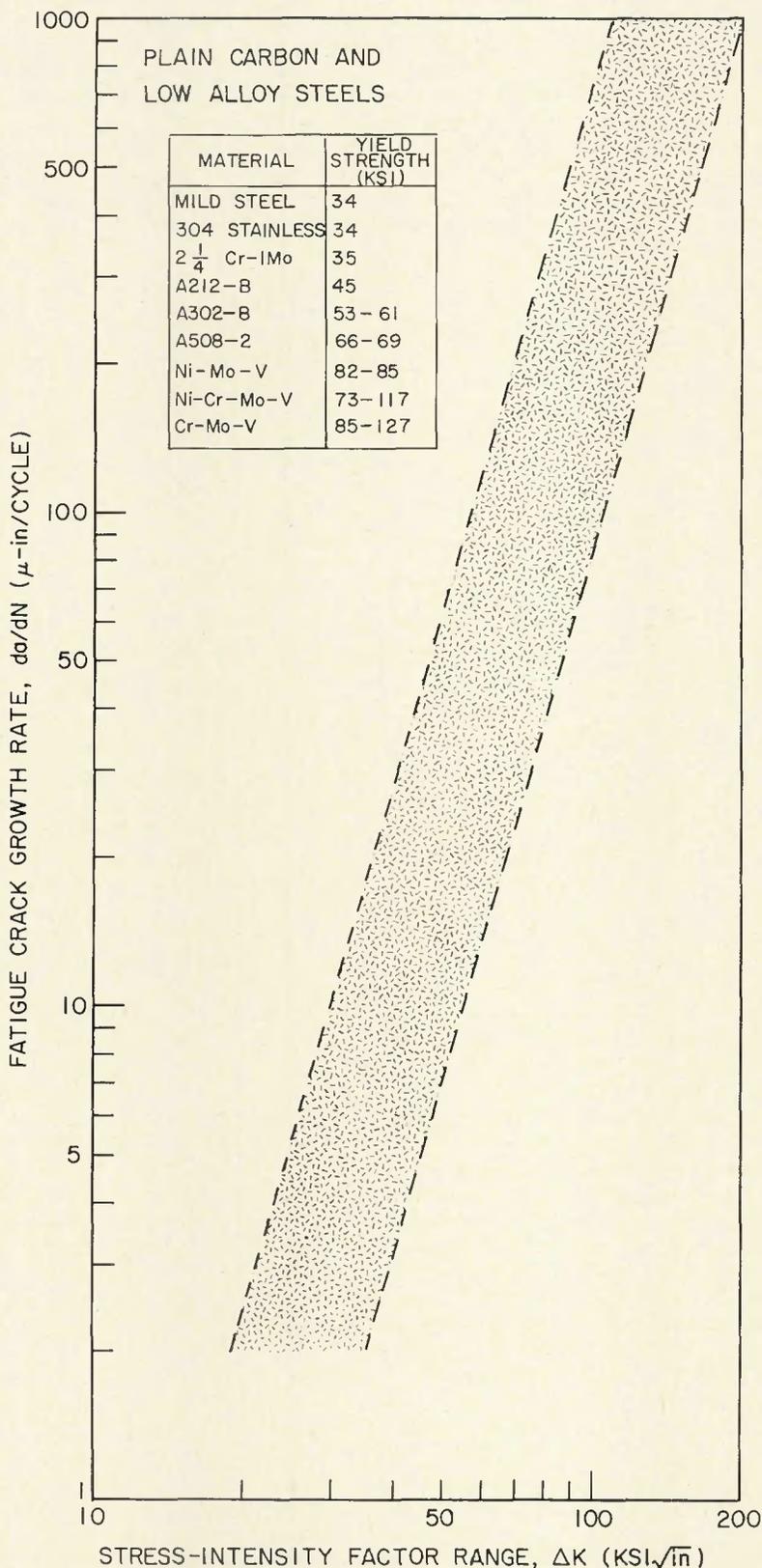


Fig. 4—Scatterband limits for fatigue crack propagation data in low-strength, plain carbon and low-alloy steels

expressed by the relationship:

$$B \geq 2.5 (K_{Ic}/\sigma_{ys})^2 \quad (5)$$

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 utilizing 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 where high toughness is either prohibitably expensive from an economic standpoint or is difficult to obtain because of a desire to utilize 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., 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 a very important factor in determining fracture behavior, since thickness will determine whether there is adequate restraint 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 value of 1.0, a number

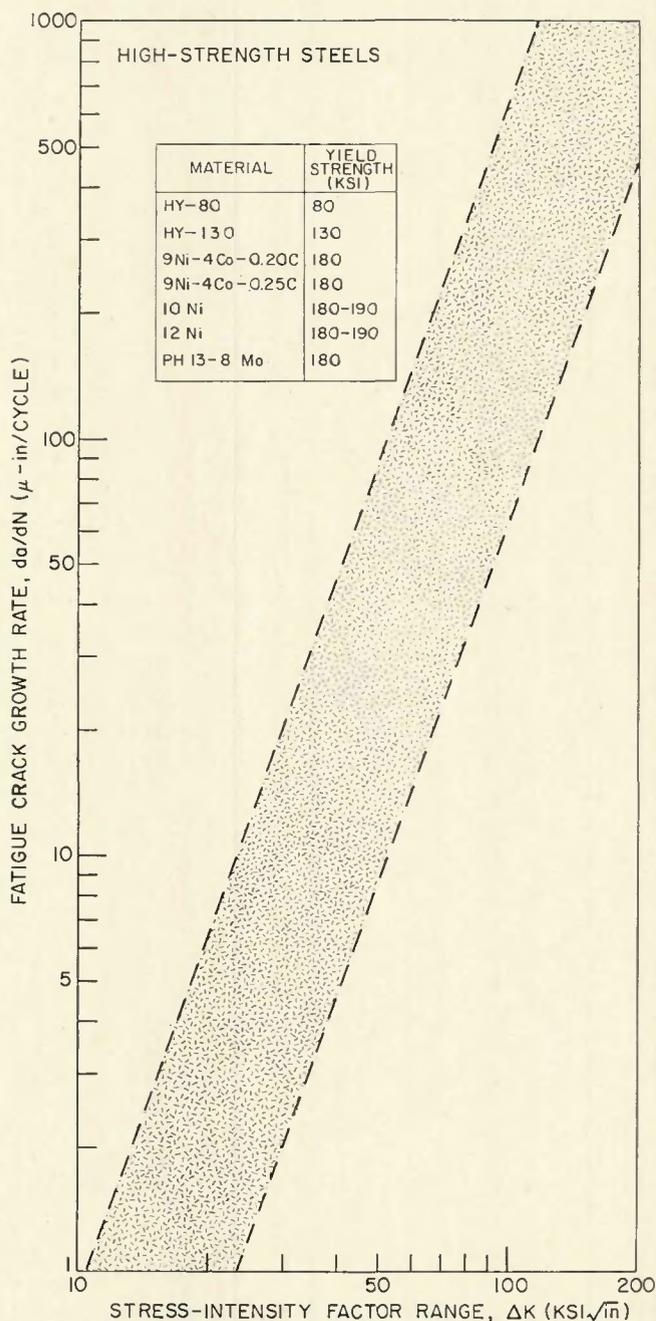


Fig 5—Scatterband limits for fatigue crack propagation data in high-strength steels

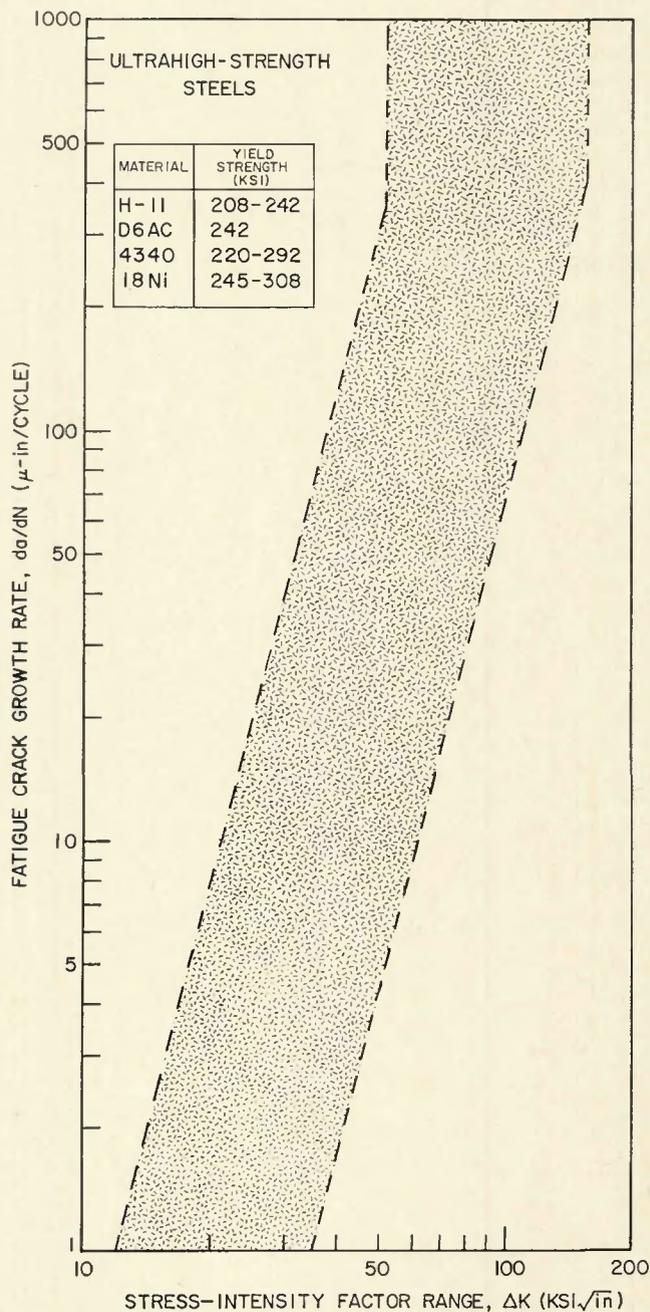


Fig. 6—Scatterband limits for fatigue crack propagation data in ultrahigh-strength steels

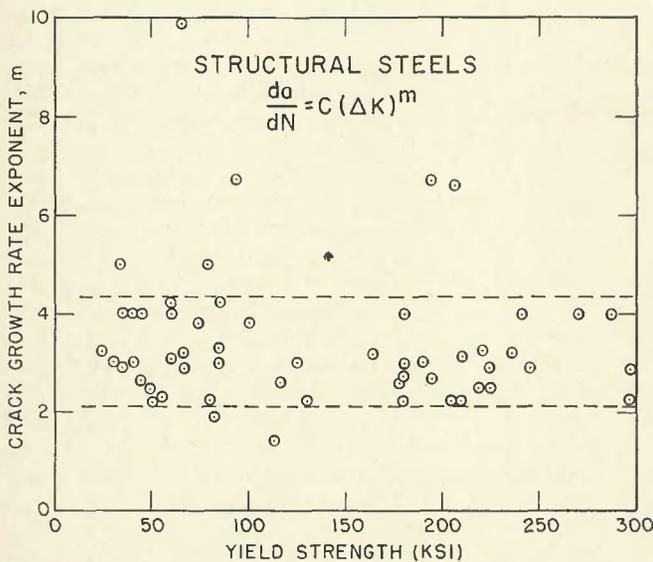


Fig. 7—Summary plot of crack growth rate exponent values vs. yield strength for a broad sample of structural steels 18–33

of severe limitations begin to take effect, thereby limiting our knowledge of plane strain fracture behavior in this subregion. 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, where the K_{Ic}/σ_{ys} ratio is 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. Cyclically-loaded complex

welded structures frequently tend to contain flaws, and the significance of these flaws can only be judged 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. Fig. 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, several observations can be made. 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 where 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:

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

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

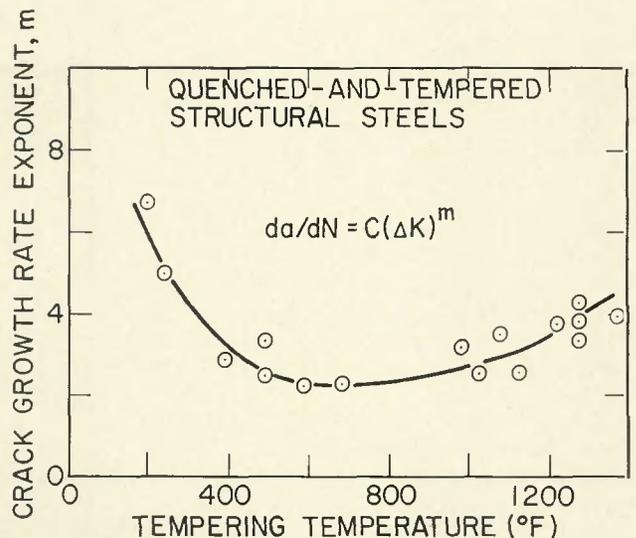


Fig. 8—Variation in the crack growth rate exponent value with tempering temperature for AISI 4340, Cr-Mo-V, Ni-Cr-Mo-V, and XAR-30 quenched-and-tempered structural steels^{22, 28, 29}

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 only prevail in very heavy sections.

Finally, for ratios greater than 1.5, this plane strain, linear-elastic analysis generally does not apply. Plane strain elastic fracture can only occur 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 this 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 which are 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 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, there is a large amount of material to contain crack growth. 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

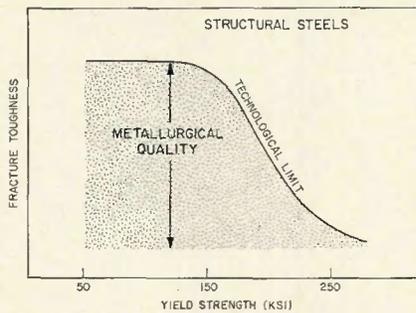


Fig. 9—Schematic illustration of the effects of yield strength and metallurgical quality on fracture toughness for structural steels

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 only useful for high-cycle fatigue situations where most of the fatigue life of the component or structure involves small flaws and nominal working stresses below the yield point.

Harrison⁴⁵ has shown that a linear-elastic fracture mechanics analysis works quite well for predicting the fatigue life of low-strength steel labo-

ratory specimens where plastic strains only develop in 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 McEvily⁴⁷ 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 this category will, in most instances, be elastic fracture. However, the critical flaw size and the degree of localized plasticity can vary widely depending upon the toughness and thickness. Fatigue problems are likely to become a very important consideration 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

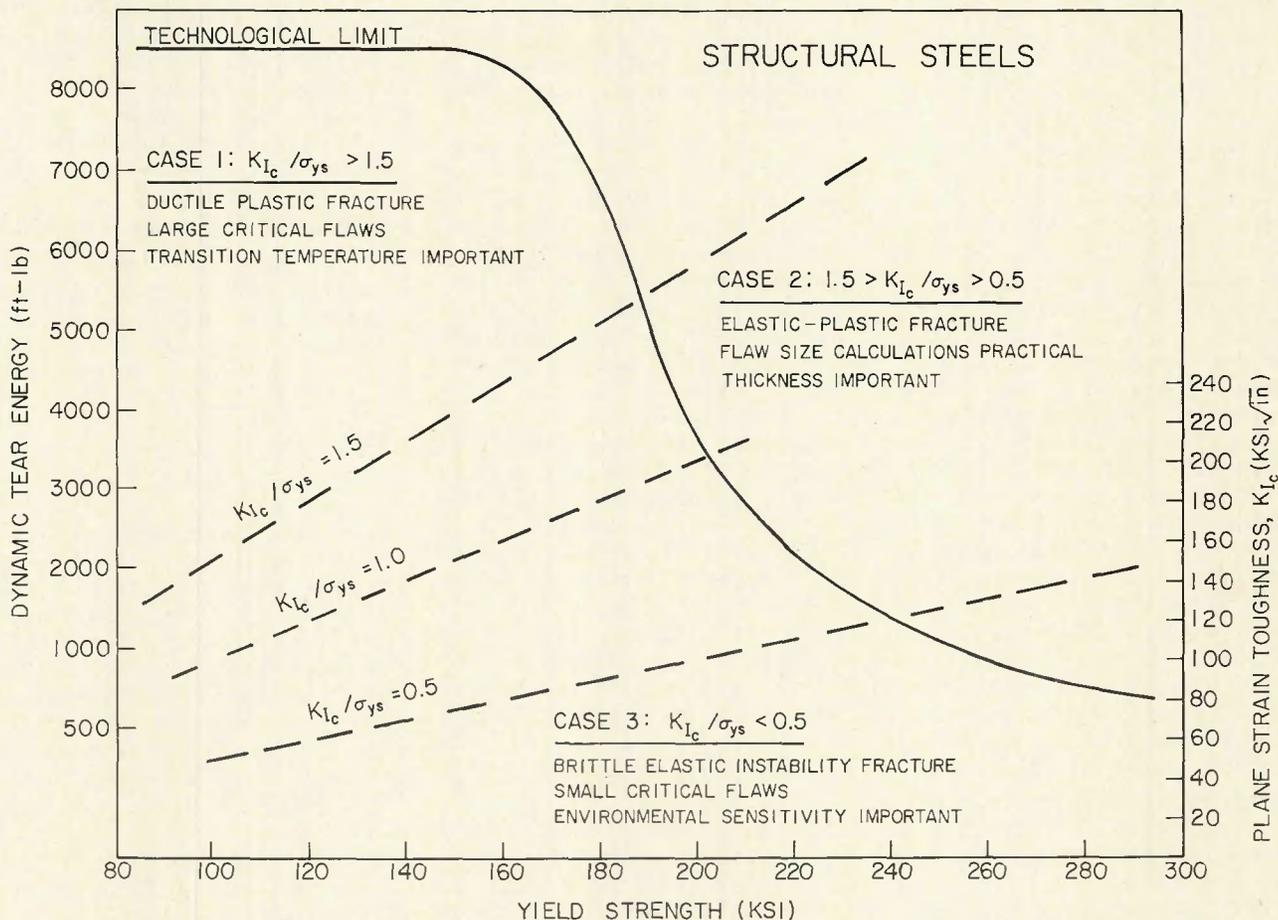


Fig. 10—Ratio Analysis Diagram for structural steels. The diagram is divided into three regions on the basis of the K_{Ic}/σ_{ys} ratio, and the prominent characteristics of steels in each region are listed

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 100 to 180 ksi yield strength region, which will include a great number of 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 as a departure from plane strain instability fracture is achieved. 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 catastrophe. In many instances, however, such as industrial pressure vessels, a through crack represents an economic catastrophe. 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 in 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 this 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 strength-to-weight ratio requirements.

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, there is an abundance of literature 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 plane strain linear-elastic fracture mechanics approach 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 those boundary conditions. However, despite the ample analytical tools available to deal with ultra high-strength steels, the actual physical problems involved severely limit their application.

Summary

There is an abundance of evidence to support the premise that fatigue failure in large, complex welded structures is predominantly caused by crack propagation originating at pre-existing defects which are 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 all three aspects into account. 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 fatigue crack propagation characteristics of 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 yield strength levels.

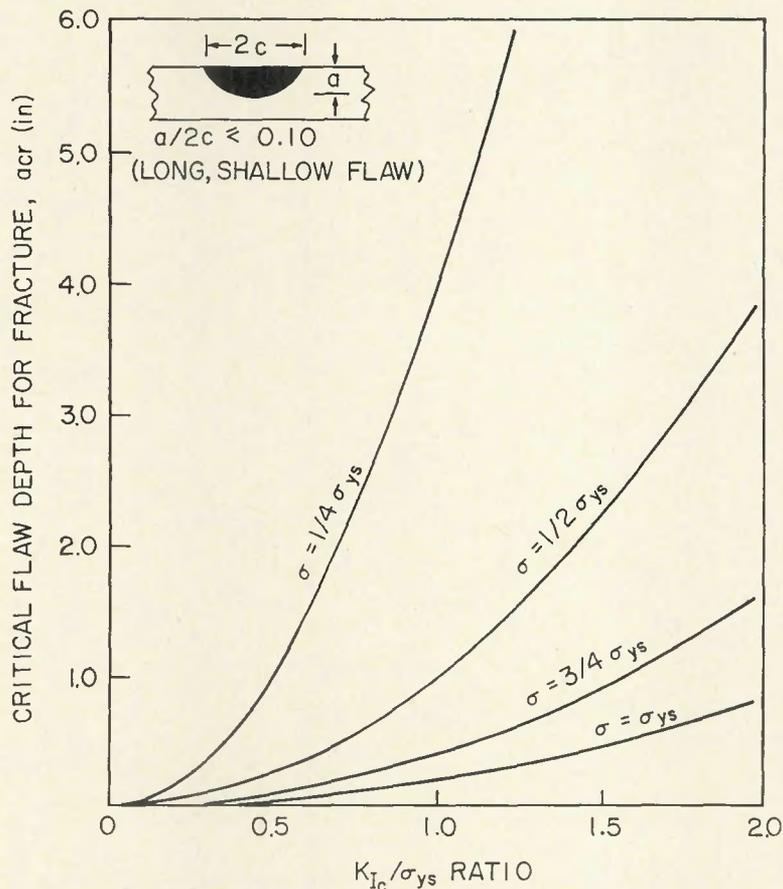


Fig. 11—Fracture mechanics relationships for critical flaw depths of long, shallow flaws in plane strain vs. the K_{Ic}/σ_{ys} ratio. The family of curves represent stress levels expressed as fractional values of the yield strength stress

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. 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 critical flaw size estimates.

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

Acknowledgments

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