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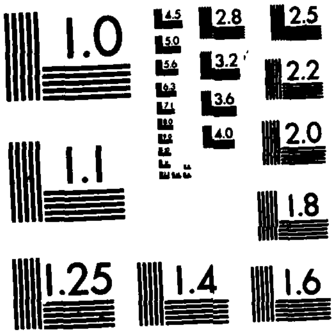
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T. W. CROOKER AND J. A. HAUSER II

Mechanics of Materials Branch
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New design concepts are being developed for deep ocean offshore platforms in depths exceeding 1,000 feet (300 meters). One such design is the tension leg platform (TLP). TLP designs contemplate the use of tension members connecting the floating platform to anchors embedded in the sea floor. High-strength steel is the indicated material of choice for the tension legs in order to minimize weight and provide adequate buoyancy. However, the use of high-strength steel members under tension loads in seawater raises serious questions concerning long-term structural integrity owing to the possibility of

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environmental cracking. This report provides a summary of state-of-the-art technology for assessing environmental cracking of high-strength steels in seawater. Factors to be considered in assuring the adequacy of proposed design concepts are delineated. Recommendations for minimizing the risk of environmental cracking in TLP tension legs are included.

Contents

ASSESSMENT CRITERIA FOR ENVIRONMENTAL CRACKING OF HIGH-STRENGTH STEELS IN SEAWATER

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INTRODUCTION

Plans are being developed for petroleum production facilities in the deep ocean depths exceeding 1,000 feet (300 meters). Such depths will require new structural design concepts for production platforms [1]. One new concept is the tension leg platform (TLP), Fig. 1.

The TLP consists of a bouyant hull tethered to the sea floor by slender tension members. The tension members hold the hull with sufficient force that they will not become slack, even in the roughest sea states. Thus, the TLP is a compliant structure which can yield to waves in a controlled manner. TLP's offer several potential economic advantages for deep ocean service. First, they can be adapted to varying depths by changing the length of the legs. Second, they can be untethered and moved from one site to another.

The floating hull of a TLP must be designed with a careful balance between buoyancy and freeboard. Thus, to a degree, they are weight-critical. Because of this factor, high-strength steel is favored as the material for the tension legs.

The use of high-strength steel members under tension loads in seawater raises serious questions concerning long term structural integrity owing to the possibility of environmental cracking[1]. High-strength steels can, under certain circumstances, be highly sensitive to environmental cracking in seawater. It is imperative that these specific circumstances be avoided or minimized in the design, construction, operation and maintenance of TLP's.

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[1] For the purposes of this report, the term "high-strength" shall refer to steels with minimum 0.2 percent tensile yield strengths in excess of 80,000 psi (550 MPa). Also, the terms "environmental cracking", or synonymously "environmentally assisted cracking", shall mean any form of crack initiation, crack growth or final fracture which is caused, aggrevated or hastened by the presence of seawater.

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This report will address this issue, both in terms of existing technology and needs for further technological development.

ENVIRONMENTAL CRACKING OF STEELS IN SEAWATER

Aspects Relating to Tension Leg Platforms

Virtually all structural steels are susceptible to some form of environmental cracking in seawater. For new and unproven design concepts, such as TLP's, the relevent questions are: (1) what kinds of environmental cracking may affect a particular candidate steel, (2) how sensitive is this steel, and (3) what can be done to minimize or eliminate the problem for a particular application?

Current TLP design concepts envision high-strength steel tension legs held under relatively high static tensile stresses for long periods of time. Superimposed on these static tensile stresses will be many small-amplitude cyclic stresses generated by wave motions. Either of these two stress conditions, by itself, can potentially lead to environmental cracking of many high-strength structural steels. However, under certain conditions, combined static and cyclic loading can interact to severely degrade environmental cracking resistance of high-strength steels. This is a consideration of special importance in TLP tension members which will be discussed in subsequent sections of this report.

Environmental cracking of steels falls into two separate, but fundamentally related, categories which can occur separately or can act together. These are termed corrosion-fatigue crack growth and stress-corrosion cracking, as described below.

Corrosion-Fatigue Crack Growth

Corrosion-fatigue crack growth refers to environmental cracking caused by *cyclic* stresses in the presence of a seawater environment. In many instances, the corrosion aspect is viewed as an aggrevating factor added to the more general problem of metal fatigue. Virtually all structural steels can be affected by this category of environmental cracking. However, as a general rule, the problem is more acute in high-strength steels. Therefore, corrosion-fatigue problems, which have not as yet assumed major proportions in conventional offshore platforms constructed from low-strength carbon-manganese steels, may loom larger with the higher strength alloy steels contemplated for TLP tension members.

Stress-Corrosion Cracking

Stress-corrosion cracking (SCC) refers to environmental cracking caused by *sustained* tensile stresses in the presence of a seawater environment. Most low-strength structural steels are virtually immune to SCC in seawater [2], thus SCC has not been a consideration in conventional offshore platforms. The problem begins to occur in steels at yield strengths of about 80,000 psi (550 MPa). SCC is neither a widely understood nor fully appreciated problem. It can be insidious, lying dormant or progressing slowly for long periods of time before becoming apparent with catastrophic suddenness. As an example, SCC is thought to have played an important role in the collapse of the Point Pleasant Bridge in 1967 [3]. Because SCC only occurs in certain susceptible steels and can only occur when a corrosive environment is present, material selection and corrosion protection offer two promising routes to SCC prevention [4].

CHARACTERIZATION CRITERIA AND TEST METHODS

Fracture Mechanics Approach

Characterization criteria and test methods for environmental cracking utilize linear elastic fracture mechanics parameters [5]. Linear elastic fracture mechanics technology is based on an analytical procedure that relates the stress field magnitude and distribution in the vicinity of a crack tip to the nominal stress applied to a structure, to the size, shape and orientation of a crack or crack-life discontunity, and to the material properties. The basic parameter used to characterize environmental cracking is the crack-tip stress-intensity factor (K). The parameter K provides a description of the magnitude of the elastic stress field in the vicinity of a crack tip and is proportional to the product of nominal elastic stress (σ) and the square root of crack size ($\sqrt{a}$). The importance of a fracture mechanics approach to environmental cracking problems lies in the fact that, if proper test procedures are followed, events at a particular K value in a laboratory specimen can be scaled on a one-to-one basis to events in a structural member at the same K value. Thus, fracture mechanics provides a rational basis for normalizing test specimen data in a format which can then be applied to structural analysis. For a thorough treatment of applied fracture mechanics technology, the reader is referred to [6].

Corrosion-Fatigue Crack Growth Criteria

Fatigue crack growth, with or without the presence of corrosion, is characterized in terms of the average increment of crack extension per cycle of applied load (da/dN) expressed as a function of the range of crack-tip stress-intensity (ΔK) [7]. da/dN versus ΔK data are generally plotted on log-log coordinates and the resulting curves often have a three-part sigmoidal shape, Fig. 2. da/dN-ΔK curves, by themselves, offer the structural engineer little information regarding fatigue life prediction. However, when combined with knowledge of initial defect sizes (either known or probable), terminal or critical crack sizes, nominal stresses, loading spectra, etc., da/dN-ΔK curves can form the basis of fatigue life prediction methods [6-8].

For the purposes of analyzing environmental crack growth in TLP tension members, long-life aspects of corrosion-fatigue crack growth will be of great importance. Hence, attention should be focused upon the lower portion of the da/dN-ΔK curve where an apparent fatigue crack growth threshold is indicated as shown in Fig. 2. The fracture mechanics characterization parameter which defines the fatigue crack growth threshold is termed ΔK_{th}. Below the crack growth threshold defined by ΔK_{th}, fatigue cracks will not grow in service; above ΔK_{th}, cracks will grow in accordance with the power law expression

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

where C and m are numerical parameters. In simple terms, ΔK_{th} is an endurance limit parameter for structural members which contain cracks [9,10].

Methods have been proposed for incorporating the ΔK_{th}, nonpropagating fatigue crack, concept within traditional approaches to long-life fatigue analysis for offshore structures [11], Fig. 3. Basically, traditional fatigue data in the form of stress versus cycles-to-failure (S-N) curves provide an engineering basis for selecting nominal design stress levels and estimating the required sizes for structural members. However, for designs which utilize inherently crack-sensitive high-strength alloys, a fracture mechanics fatigue analysis provides a rational basis for assessing defect severity. Such information is required for establishing accept/reject and fitness-for-purpose criteria in structures where defects are likely to occur.

Stress-Corrosion Cracking Criteria

The characterization of SCC using fracture mechanics parameters is analogous to the previously discussed approach to corrosion-fatigue crack growth. Time-based crack extension rate (da/dt) values are expressed as a function of K. The resulting curves generally have a three-part sigmoidal shape when plotted on log-log coordinates, Fig. 4, and emphasis is placed on the lower da/dt versus K threshold, termed K_{Iscc} [12]. Here the subscript I refers to the opening mode of crack surface displacement [6].

One point of apparent similarity between corrosion-fatigue crack growth and SCC characterization criteria does not, in fact, exist. Actual threshold values of K_{th} and K_{Iscc} for high-strength steels of the general type being considered for TLP tension members (i.e., low-alloy quenched-and-tempered steels with yield strengths between 80,000 and 130,000 psi) tend to differ by about an order of magnitude, with K_{Iscc} values being the greater [6].

However, an actual point of similarity between K_{th} and K_{Iscc} threshold parameters is that, in actual practice, they seldom define absolute thresholds. Rather, operational definitions involving acceptably low rates of crack growth are usually adopted in defining K_{th} or K_{Iscc} for steels. To a significant degree, K_{th} and K_{Iscc} can reflect the patience of the investigator as well as the characteristics of the material being investigated.

Test Methods

The principal organization which promotes the development of materials testing standards in the U.S. is the American Society for Testing and Materials (ASTM). To date, no standards for environmental cracking of metallic materials have been published by ASTM; however, progress on draft standards development has been made by the ASTM Joint Task Group on Methods for Measurement of K_{Iscc} and SCC Growth Rate [13] and by the U.S. Navy [14]. ASTM and Navy test method documents applicable to various aspects of environmental cracking of high-strength steels are cited in [15-17].

In part because of a lack of verified standard test methods and in part because of the inherent complexities of the phenomenon, measurement of environmental cracking characterization parameters is seldom without some degree of ambiguity [5]. In recognition of the lack of comprehensive test method standards, environmental cracking characterization tests for TLP materials should simulate actual service conditions to the maximum degree practicable. Also, in reporting and evaluating characterization data, it should be incumbent upon investigators to provide a fully detailed report of test procedures and experimental conditions.

FACTORS AFFECTING ENVIRONMENTAL CRACKING

General Phenomenology

Although, from a fundamental point of view, corrosion-fatigue crack growth and SCC of steels in seawater share some basic mechanisms (i.e., hydrogen embrittlement), they tend to exhibit rather different phenomenology [18,19]. Some important similarities and distinctions are cited below, beginning with a reiteration of three points cited earlier.

- Fatigue-crack growth is basically a mechanical failure mechanism which can proceed in an inert environment solely on the basis of cyclic stress. Corrosion can be considered as a secondary factor which generally, but not always, hastens the fatigue-crack growth process. However, SCC can only proceed under the conjoint action of a sustained tensile stress and the presence of a corrosive environment.

- Virtually all steels are susceptible to corrosion-fatigue crack growth whereas only high-strength steels are susceptible to SCC in seawater.

- There appear to be operationally-definable thresholds below which corrosion-fatigue crack growth and SCC do not occur.

- Both phenomena are strongly time-dependent. Corrosion-fatigue crack growth in steels is aggrevated by the slow cyclic loading rates (less than 1 cycle per minute) associated with offshore platform loading [20]. SCC in steels often proceeds slowly, often not manifesting itself until thousands of hours under sustained tensile stress have accrued [5].

- SCC, but not corrosion-fatigue crack growth, is highly dependent upon material thickness. SCC of steels only occurs in heavy section materials where there is adequate thickness to assure plane strain crack-tip constraint [6]. For this reason, SCC test specimens must be of sufficient thickness to simulate structural behavior [21].

- Environmental cracking, in effect, locally embrittles metal at the tips of growing cracks, even in steels which exhibit high levels of tensile ductility and fracture toughness such as Navy "HY" steels. This applies to both corrosion-fatigue crack growth and SCC.

Strength and Hardness Levels

The high-strength steels contemplated for TLP tension legs fall into the yield strength range (80,000 to 130,000 psi) and hardness levels [22] where SCC sensitivity becomes a matter of concern. SCC in salt water has been reported in HY-80 weld metal [23], in HY-100 and HY-130 base plate and weld metal [24] and in A514E and A514F [6].

As yield strength level increases above 100,000 psi, apparent K_{Iscc} values can decrease substantially with increasing yield strength indicating increased sensitivity to SCC [25]. An example of this trend for 4340 steel, is shown in Fig. 5. Admittedly, not all steels in the 80,000 to 130,000 psi yield strength range exhibit significant SCC susceptibility and interpretation of their SCC characterization behavior can be somewhat uncertain. However, factors such as interaction with cyclic loading, cathodic protection and hydrogen sulfide contamination of seawater can potentially worsen the problem, as discussed in subsequent sections of this report.

Strength level effects on corrosion-fatigue crack growth tend to follow the same general trend as for SCC [6]. However, near-threshold region behavior in corrosion-fatigue is not sufficiently well characterized to offer specifics. For near-threshold behavior of steels in the absence of a corrosive environment, a complex interaction of yield strength and grain size effects has been identified [26]. However, yield strength, per se, is unlikely to be a significant factor in affecting the overall corrosion-fatigue crack growth behavior of steels for TLP construction.

Alloy Chemistry, Microstructure and Processing

The most important consideration in this category of effects is that weld metal is typically more sensitive to SCC than is base plate material [23, 24]. There are several possible reasons for offering this generalization. Weld metal is more likely to contain tensile residual stresses, fabrication defects, less refined microstructures and impurities. Also, in many structures, weld metal is intentionally "overmatched" in terms of yield strength versus the adjoining base plate, Fig. 6. A recent Navy study on HY-100 and HY-130 steels concluded that "in general, low yield strength, a tempered martensitic microstructure, and low levels of impurities such as sulphur, oxygen and nitrogen appear to favor improved SCC properties for these metals" [24].

Load Interactions

It is known that loading interruptions or superimposed cyclic loading can have profound effects on SCC behavior [5, 27]. For consideration in TLP applications, it is important to note that small-amplitude cycle stresses superimposed on sustained tensile stresses can significantly reduce the apparent threshold for SCC to occur, Fig. 7. This suggests that the static load K_{Iscc} characterization parameter may represent an upper bound level of SCC resistance and that actual SCC resistance under long-term service conditions may be much less. This rather alarming aspect of SCC behavior is not well documented at the present time [28].

Seawater Composition

Limited evidence suggests that for high-strength steels, environmental cracking characterization data obtained in natural seawater are somewhat more conservative than data obtained in laboratory substitute solutions [29, 30].

Natural seawater is not widely available for materials testing purposes except at a few oceanfront laboratories. Thus, data generated in most laboratory environments may represent chemical conditions that are less severe than service conditions. Also, hydrogen sulfide contamination of seawater caused by biological degradation of marine growth or sour crude oil poses a further threat to environmental cracking which is difficult to assess from existing data.

Cathodic Protection

Cathodic protection in some form and degree is a necessity on offshore platforms constructed of steel. It is an effective means of controlling corrosion in seawater. However, the effects of cathodic protection on environmental cracking are complex and incompletely understood [31-33]. What is known is that cathodic protection can cause hydrogen cracking in steels. The degree to which cathodic protection can be either beneficial or detremental to overall structural performance depends, in part, upon the cathodic potential involved. At the potentials typically applied to offshore structures (~ -1.0V versus Ag/AgCl reference electrode), an abundance of data have been published which show that da/dN values are significantly increased and K_{Iscc} values are significantly decreased by cathodic protection [34-36]. Fig. 6. The effects of cathodic protection on ΔK_{th} are not known with any certainty at the present time. On the other hand, there is some evidence to suggest that lesser levels of cathodic protection (~ -0.8V versus Ag/AgCl) may provide general corrosion protection without being detrimental to environmental cracking [31, 37].

Crack Size

Small initial defects may play an important role in long-life environmental cracking behavior. There is growing evidence that small cracks (less than 1 mm deep) do not always behave in a manner that is consistent with classical linear elastic fracture mechanics [38]. Specifically, in the near-threshold fatigue crack growth rate region small cracks tend to exhibit lower ΔK_{th} values and higher da/dN values than a fracture mechanics analysis ordinarily predicts. Also, for reasons thought to be associated with electrochemical conditions within small cracks, they grow at a much faster rate in aqueous corrosion-fatigue than ordinary test data would predict [39]. Various rules and analyses for dealing with small crack behavior in fatigue and SCC have been formulated [10, 38, 40].

FRACTURE CONTROL PLANNING

Perspective

The details of environmental cracking discussed above in this report are only one aspect of the overall fracture control planning required for safe utilization of TLP's in coastal waters. However, environmental cracking may prove to be the most difficult and least understood aspect of the fracture control planning for TLP's. Fracture control practices for metal structures which encompass consideration of brittle fracture and fatigue are numerous and well documented [6, 41, 42]. However, no general practices for designing against environmental cracking have yet been developed for general use [5, 28, 42].

Control Versus Prevention

The thrust of this report has focused on materials characterization parameters for environmental cracking which are essential to a prevention-oriented approach to fracture control. This is by no means a universal approach to fracture control. For example, military aircraft and nuclear pressure vessel operators utilize fracture control technologies which place considerable emphasis on methodologies for controlling anticipated crack growth in service [43, 44]. However, neither of these examples offers any guidance on how to deal with SCC; both limit their treatment of environmental cracking to corrosion-fatigue crack growth.

The alternative approach to prevention is to accept the possibility of environmental crack growth in service and to develop a design strategy to deal with its consequences. Under this scenario, aircraft designers opt for either a fail-safe or safe-life design approach [41]. For offshore structures, which are constructed and maintained to less exacting standards than aircraft, and are subject to the uncertainties of the sea, the fail-safe approach would seem virtually a necessity as a fall-back position if environmental cracking prevention fails. The problem with abandoning the prevention approach in TLP design is that, based on the present level of technology, there can be little certainty as to how quickly environmental cracking will proceed once the process is initiated.

Critical Crack Sizes

In the final analysis, the quintessential question is likely to be "what size defect can be tolerated without leading to cracking problems and can it be found by nondestructive inspection?" In order to answer this question, a comprehensive analysis including loads, stresses, materials characterization and nondestructive inspection (NDI) capabilities must be undertaken.

Defect Characterization

Given the existence of fabrication defects in a structure, how to treat these defects analytically becomes a matter of major consideration. Essentially, there are two approaches: (1) treat all NDI indications of defects as sharp cracks and utilize a fracture mechanics approach [44] or (2) adopt a more discriminating approach which recognizes that not all defects are, in fact, sharp cracks and establish defect characterization criteria based upon defect severity [45]. The first approach is more conservative and is appropriate where catastrophic consequences may result from failure. However, for situations involving long-life design of structures which have some degree of redundancy, it may be necessary to recognize that many defects will have an initiation period before they become cracks and start to grow. Unfortunately, data to support the more discriminating British Standards approach have yet to be developed for high-strength alloys under for environmental cracking.

CONCLUSIONS AND RECOMMENDATIONS

- Current TLP design concepts which envision the use of structural steels having yield strengths in excess of 80,000 psi (550 MPa) under long-term tension loads of varying amplitude in seawater with applied cathodic protection must consider the possibility of environmental cracking as a threat to structural integrity.

- The technology for designing against environmental cracking has yet to be developed to the point where examples of general principles are readily available. An ad hoc approach specific to TLP design must be developed and proven.

- The most promising approach to control of environmental cracking in TLP tension members is prevention achieved through corrosion control, materials selection and establishment of defect acceptance standards based on the best available fracture control technology.

- Owing to the uncertainties that surround the problem of environmental cracking of high-strength steels, TLP tension member design concepts must also include fail-safe principles.

- With specific reference to materials considerations for TLP tension members, candidate steels should be screened for susceptibility to environmental cracking. Materials committed to actual construction should be further tested to establish environmental cracking characterization parameters on representative lots under mechanical, chemical and electrochemical conditions which include all relevent aspects of service conditions.

- To the maximum degree possible, TLP tension members should be constructed from steels which exhibit little or no sensitivity to stress-corrosion cracking, as determined by fracture mechanics test methods which utilize current best practices.

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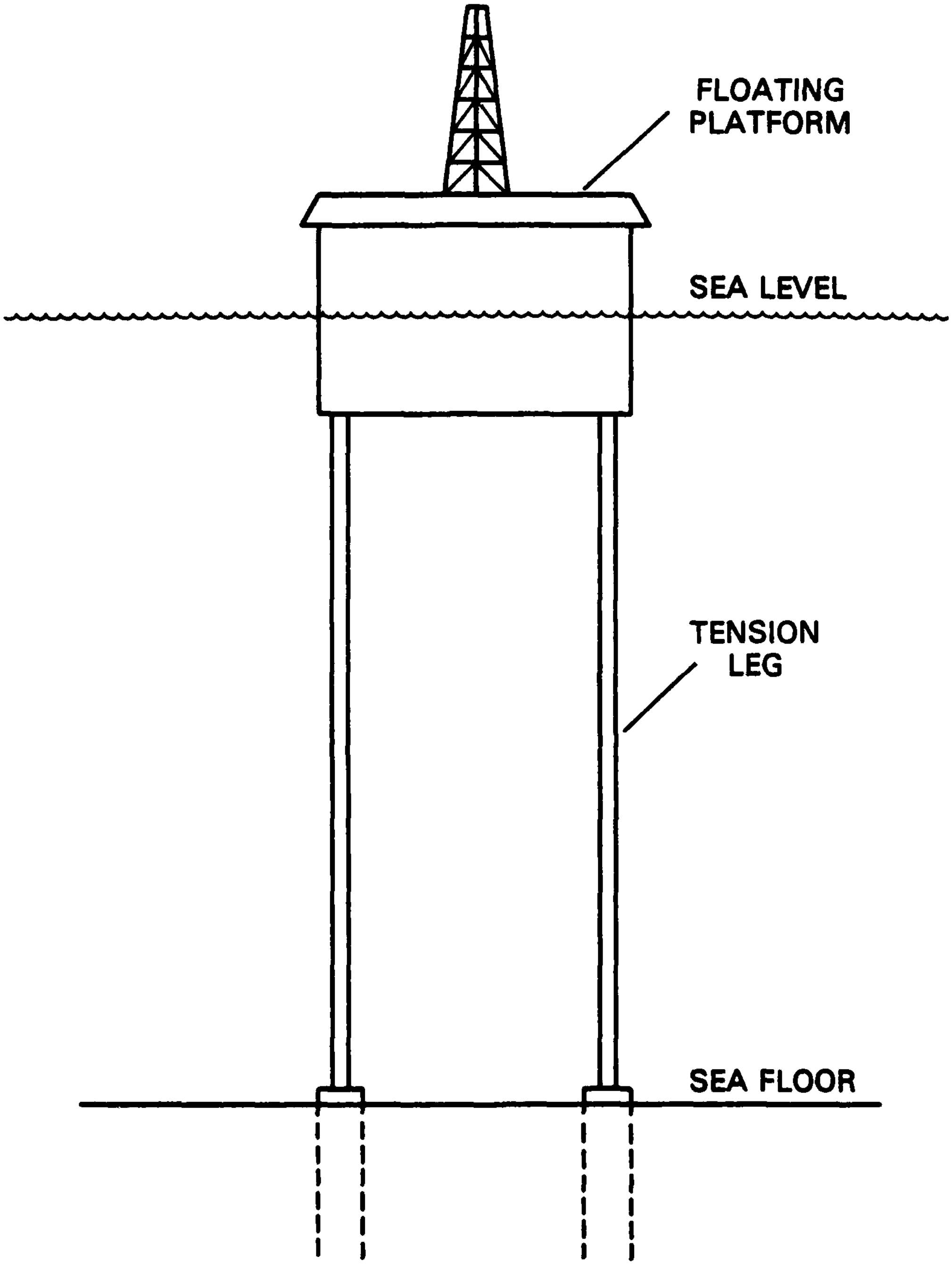

Fig. 1 — Schematic view of a tension leg platform (TLP).

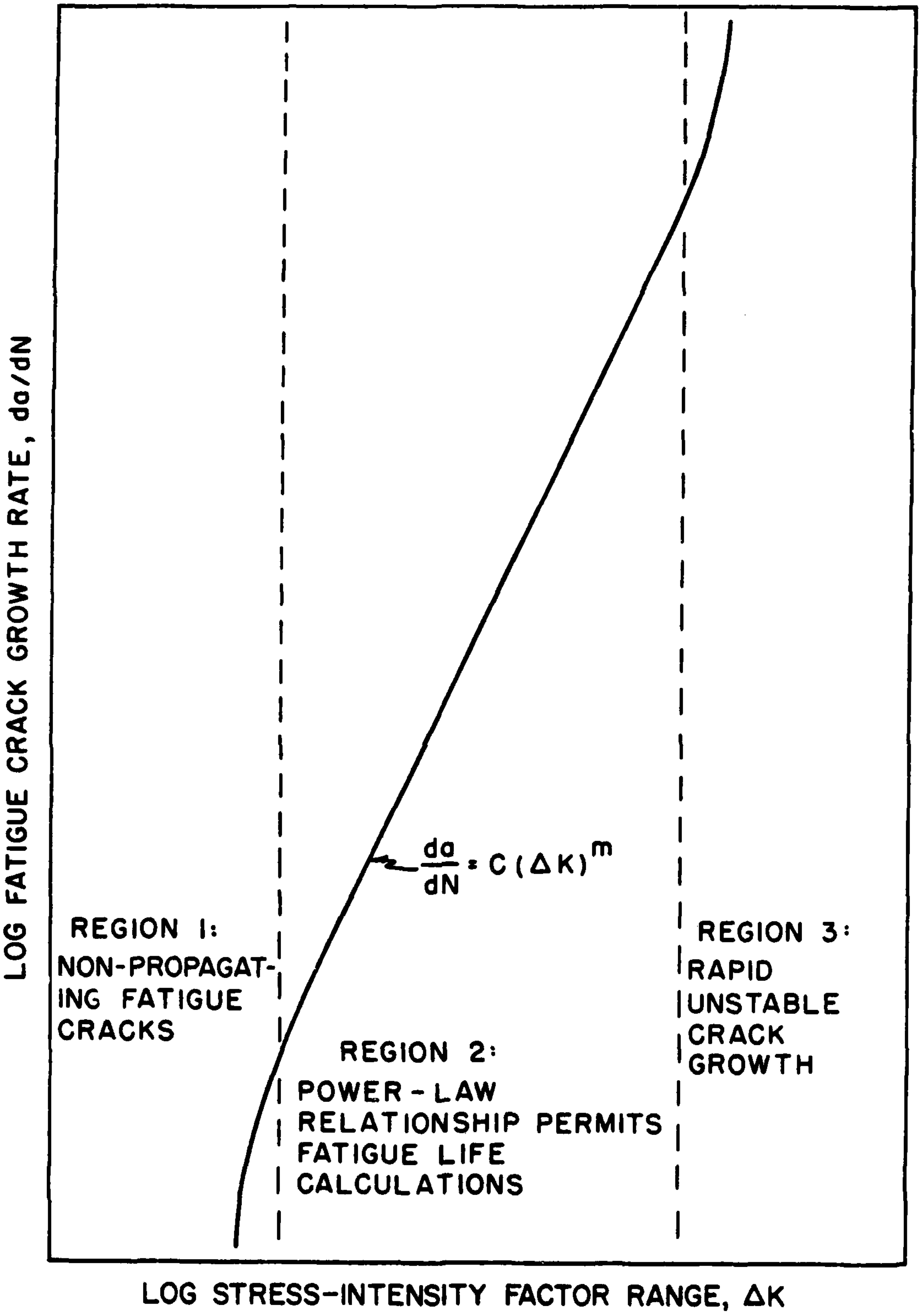

Fig. 2 — Typical relationship between fatigue crack growth rate (da/dN) and stress-intensity range (ΔK). The Region 1 non-propagation threshold defines ΔK_{th}.

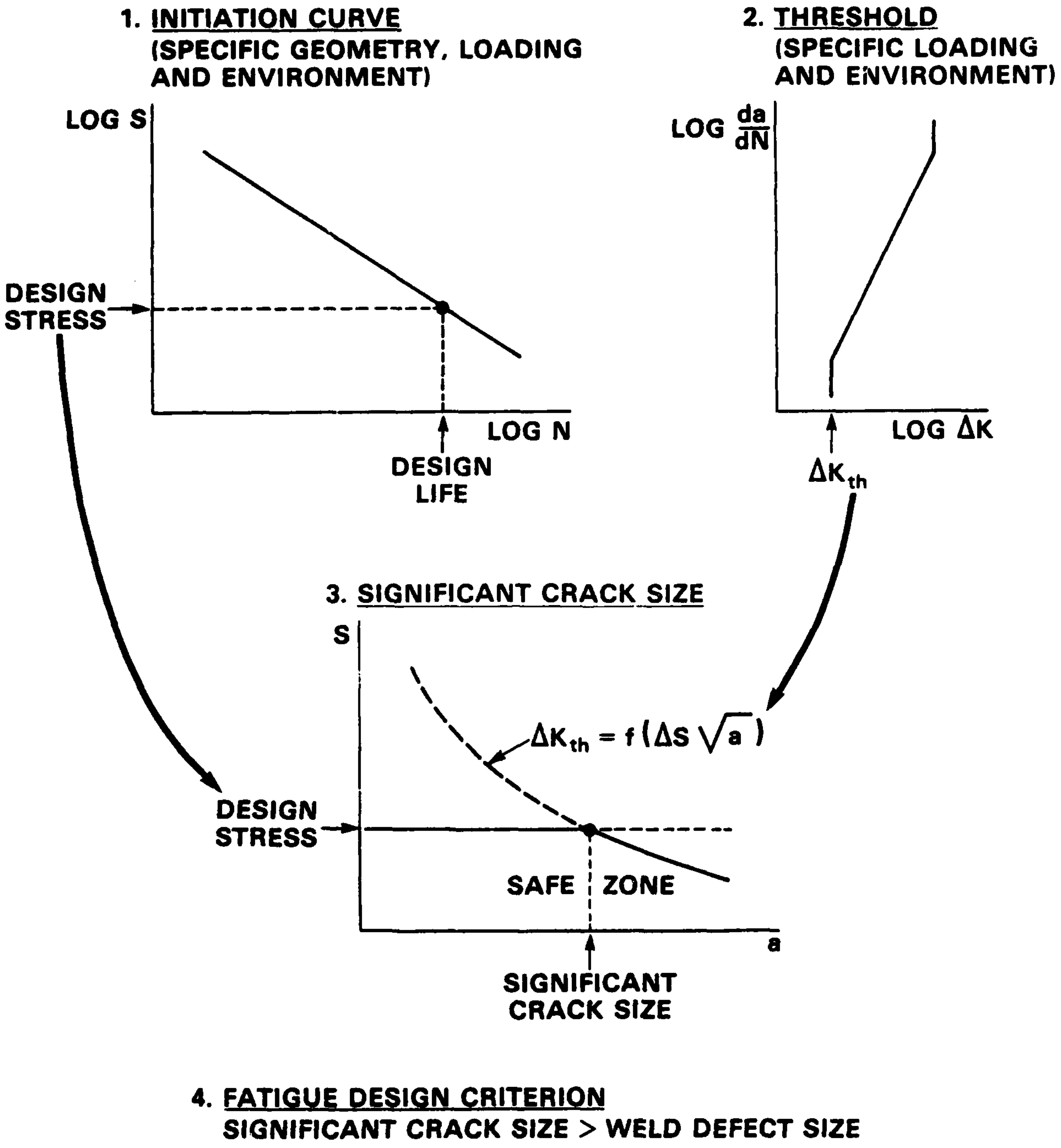

Fig. 3 — Scheme for integrating the ΔK_{th} concept into traditional fatigue design procedures for offshore structures [11].

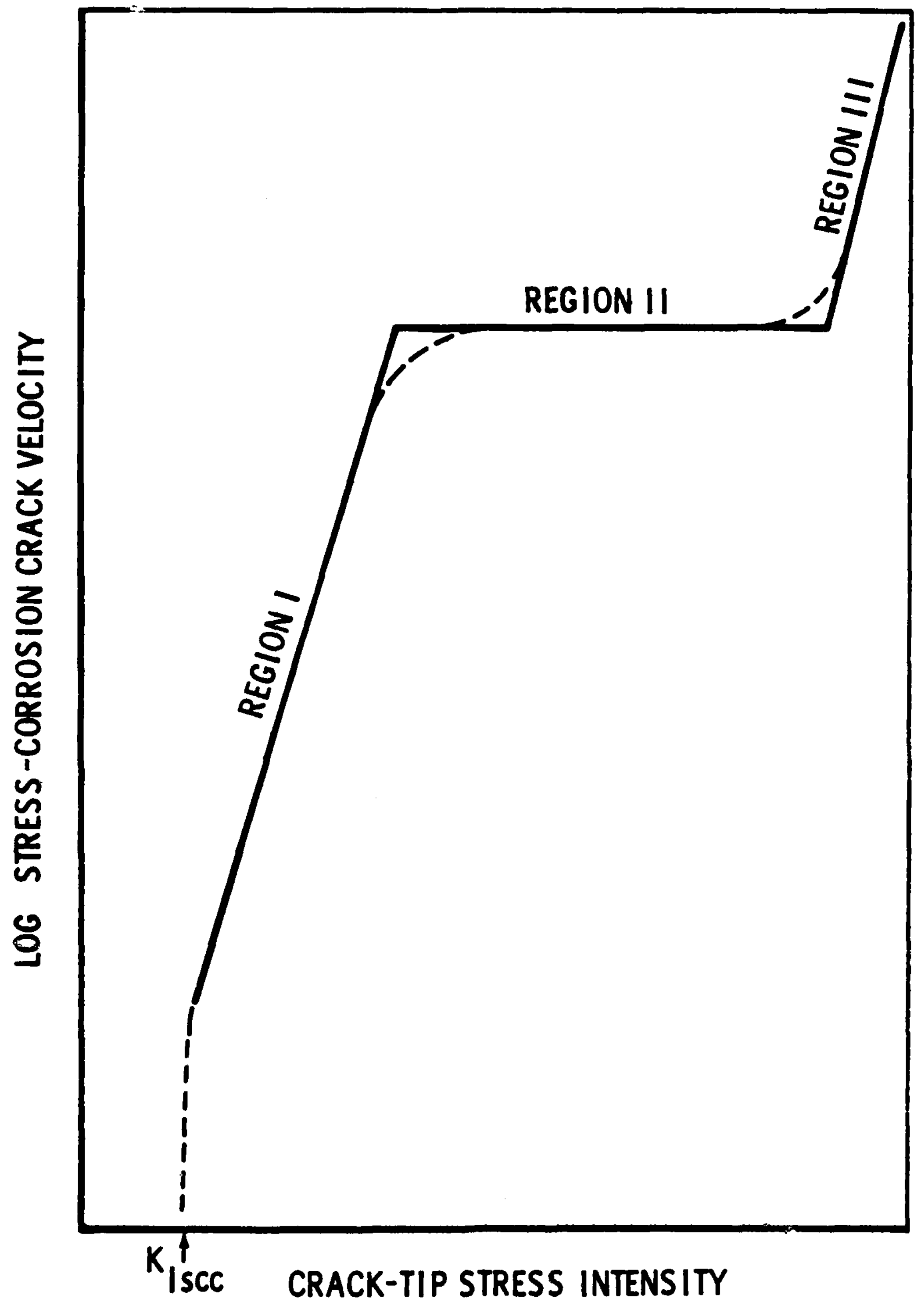

Fig. 4 — Typical relationship between stress-corrosion crack growth rate (da/dt) and stress-intensity-factor K_I. The Region I threshold defines K_{Iscc}.

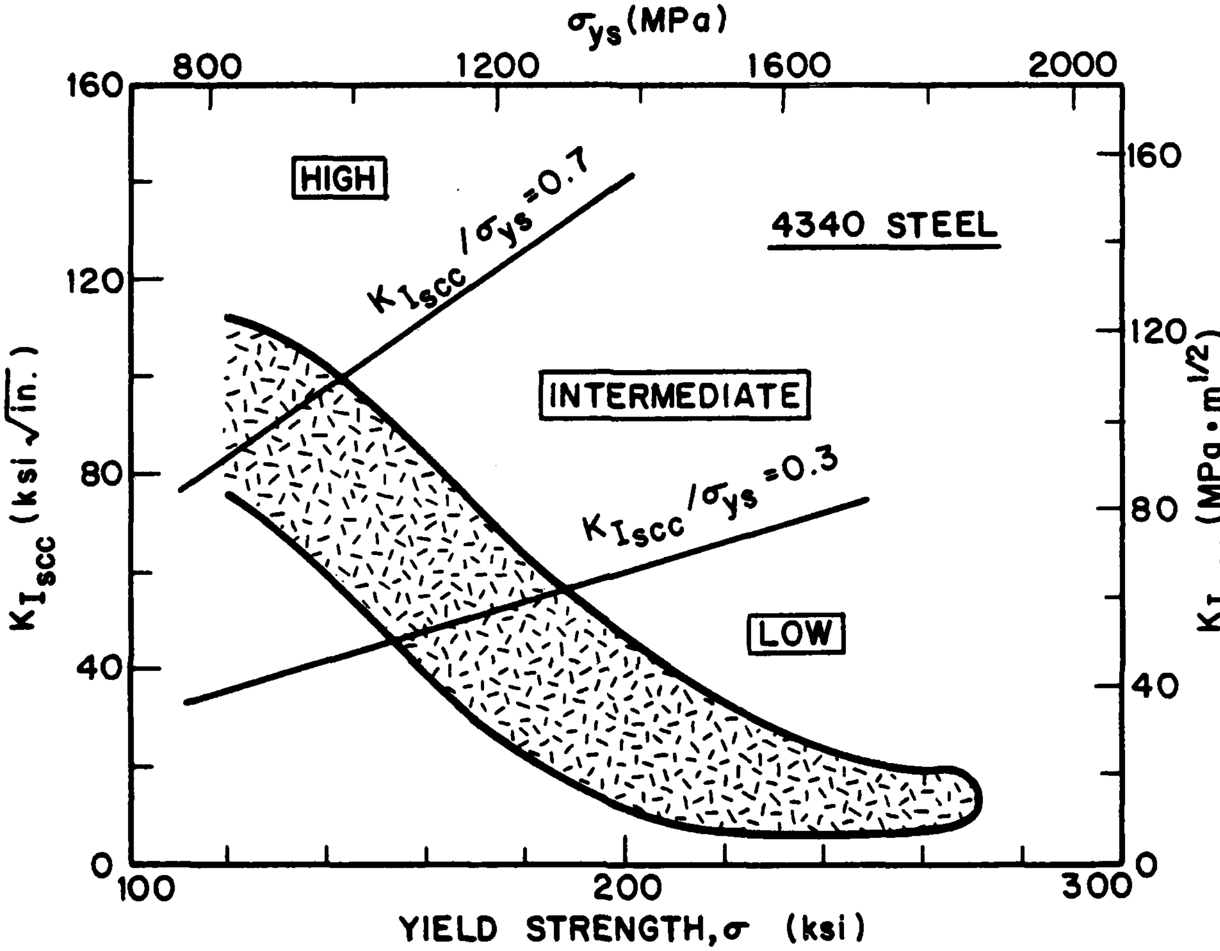

Fig. 5 — Influence of yield strength (σ_{ys}) on K_{Iscc} for a high-strength steel [25]. SCC sensitivity is categorized on the basis of K_{Iscc}/σ_{ys} ratios.

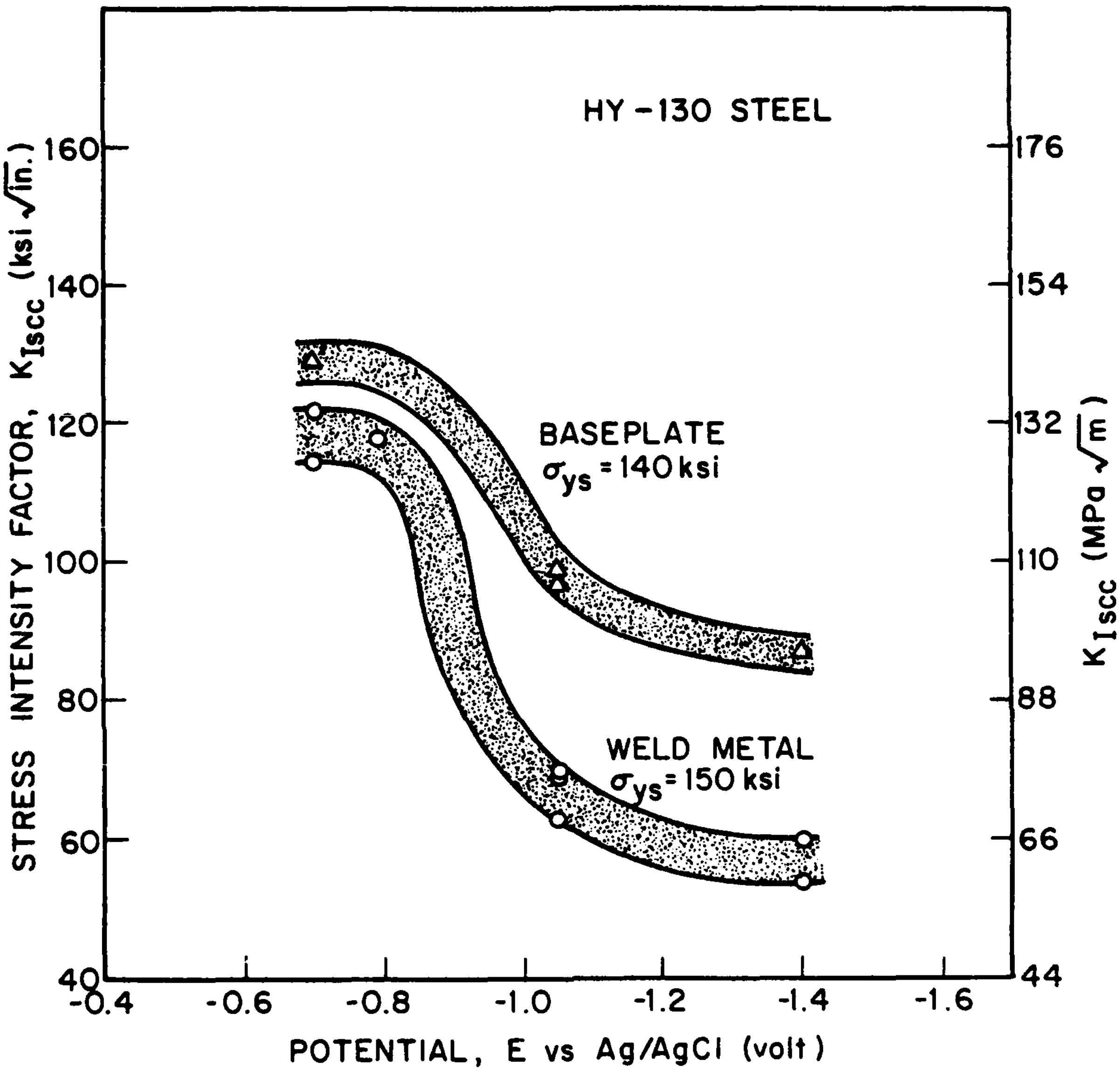

Fig. 6 — Typical relationships between K_{Iscc} and applied cathodic potential for a high-strength steel baseplate and overmatched weld metal [36].

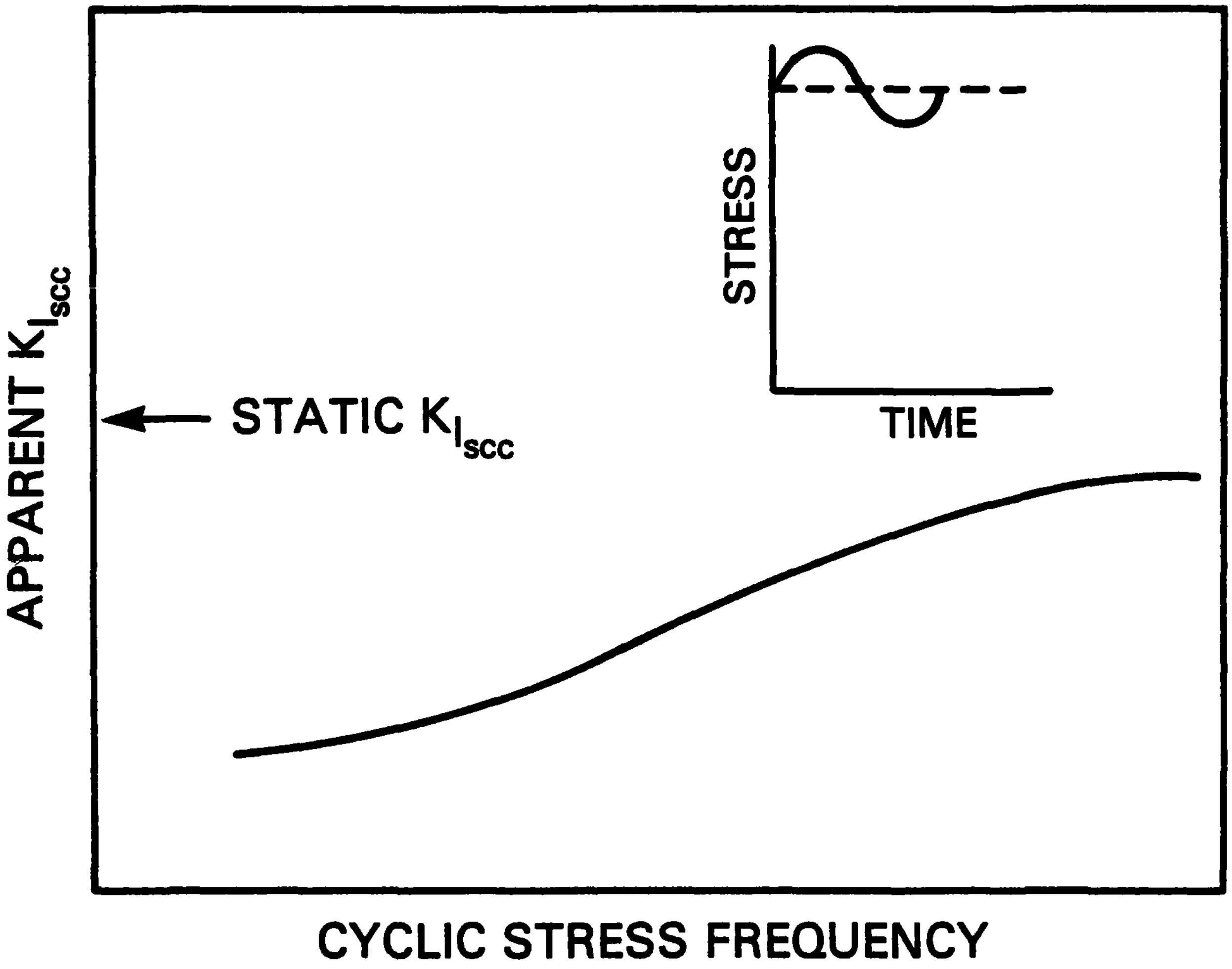

Fig. 7 — Schematic relationship between apparent K_{Iscc} and frequency of small secondary stress fluctuations.