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Integration of Analytical Procedures for Fracture-Safe Design of Metal Structures

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Metallurgy Division

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PREFACE

The aim of this report is to assemble information of primary interest to engineers into a coherent framework which provides an essential overall perspective of the subject.

Seemingly divergent factors are unified by normalizing metal properties in terms of fracture-extension resistance—R—parameters. The unified metal parameters may be related to structural mechanics aspects of fracture-extension-force systems. The relationships of these two factors are presented in the form of analysis diagrams.

The procedural simplicity of the analysis diagrams provides for iterative cross-referencing between mechanical requirements and metal properties. Thus, trade-off analyses, which are basic to the realistic practice of fracture-safe design, are made feasible for generalized engineering use.

Most importantly, a case is presented for modernization of fracture-safe design practices, in consonance with the state of scientific knowledge and with full appreciation of engineering realities.

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13. ABSTRACT

An interpretive review is presented of the development of scientific knowledge of fracture processes and of the technological application of this information to the evolution of rational engineering principles for fracture-safe design. Discussions of mechanical, metallurgical, and structural aspects of the subject emphasize that engineering design practices must involve detailed consideration of all factors.

The evolution of modern fracture-safe design practices began in 1950. The results of the earlier research provided a base from which definitive studies were evolved. The development of significant fracture-characterization test methods and of procedures for their analytical interpretation paced the rate of progress during this time period. A description is provided of fracture tests which are suitable for evolving data-bank references of metal properties, required for general engineering practice of fracture-safe design.

Major emphasis is placed on procedures based on the use of analysis diagrams, which provide for cross-referencing between structural factors and metal properties. The primary aim of the text is to present the case for the utilization of modern practices in the design of engineering structures.

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CONTENTS

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PROBLEM STATUS

This is a special summary and interpretive report covering the results of a wide spectrum of investigations within the Metallurgy Division of NRL. These investigations are aimed at the general problem of metallurgical optimization and fracture-safe design. The major portions of the studies are continuing under the established problems.

AUTHORIZATION

NRL Problem Nos. M01-25 and M01-24
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NOMENCLATURE

CAT	Robertson Crack Arrest Temperature
C_v	Charpy-V Test
COD	Crack Opening Displacement
DT	Dynamic Tear Test—all sizes
DTE	Dynamic Tear fracture energy for standard specimen
DWT	Drop Weight Test
E/A	Energy per unit fracture area measured in DT test
ECST	Explosion Crack Starter Test
FAD	Fracture Analysis Diagram
FM	Fracture Mechanics
FSD	Fracture-Safe Design
FTE	Fracture Transition Elastic
FTP	Fracture Transition Plastic
$\mathcal{G}$	Strain energy release rate with crack extension
$\mathcal{G}_{Ic}$	Critical values of $\mathcal{G}$ for elastic fracture
IAD	Instability Analysis Diagram
K, K_I	Stress intensity factor; the subscript I denotes the opening mode of crack extension (ksi $\sqrt{\text{in.}}$)
K_{Ic}	Slow-load (static) plane strain fracture toughness (ksi $\sqrt{\text{in.}}$)
K_{Id}	Dynamic-load plane strain fracture toughness (ksi $\sqrt{\text{in.}}$)
K_{Iscc}	Lowest critical value of K for slow extension of cracks in stress corrosion environments
NDT	Nil Ductility Transition temperature obtained by DWT or indexed by DT test
PWE	Plastic work energy for fracture
R	Resistance to fracture extension
RAD	Ratio Analysis Diagram

SCC	Stress corrosion cracking
ΔK	Range of K values in fatigue-crack extension
σ or σ_n	Applied stress (psi or ksi)
σ_{yd}	Yield strength for dynamic loading (psi or ksi)
σ_{ys}	Yield strength for static (slow) loading (psi or ksi)
Enclave	Fracture propagation condition involving through-thickness yielding (plastic contraction) and dimpling of the region in advance of the crack
Plastic zone	Fracture extension conditions limited to a small plastic volume at the crack tip
Ratio	Signifies K_{Ic}/σ_{ys} or K_{Id}/σ_{yd}
Shelf	Highest level of ductility attained at completion of transition due to temperature
Strength transition	Decrease in fracture resistance resulting from increase in strength level

INTEGRATION OF ANALYTICAL PROCEDURES FOR FRACTURE-SAFE DESIGN OF METAL STRUCTURES

PART I. INTRODUCTION

Within the past decade dramatic advances have been attained in the field of structural design. The best-known advance has involved the use of computers for optimizing structural configurations. This advance has been defined as *rational* design because it provides for detailed consideration of the total stress system; i.e., the interactions of primary, secondary, and peak stresses. Equally dramatic advances have involved the development of new engineering principles for fracture-safe design (FSD). The departure from past practices is likewise of sufficient scope to justify the term *rational* FSD.

Within the scope of available knowledge prior to the 1950's, the past practices were rational. The only recourse in FSD was to limit stresses to a low fraction of the yield strength, as directed by Rules and Codes. Within the scope of presently available knowledge, the past practices cannot be considered rational—for lack of a valid scientific base, and because they do not provide reliable assurance of fracture prevention.

The rational FSD practices to be described have a sound scientific base and do provide positive assurance of service reliability. Since the new practices are based on advances in the state of knowledge, it is essential that the subject be understood as a matter of professional responsibility.

The essence of subject may be summarized in succinct fashion:

> FSD implies and requires full consideration of the structure, as viewed from principles of structural mechanics. It is *not* a subdiscipline of fracture research. It represents a self-consistent framework of structural mechanics procedures for the case of flawed structures. In practice, it involves selection of the metal appropriate for the structural purpose, with full consideration of metallurgical realities.

Modern FSD procedures should replace the traditional concept of designing on strength as the primary factor and then considering fracture parameters as a secondary issue. The problems that evolve from such practices have involved both radically new structures for advanced systems and ordinary structures. The following adverse experiences have been recorded:

• <u>Design based on very high levels of attainable strength for weight-limited structures.</u> We cite cases of failures in rocket case development programs, Fig. 1. In all such cases the design was based initially on excessively high levels of metal strength in relation to FSD factors. We may cite similar experiences for aircraft structures. For all of these, the initial error may be traced to design practices.

• <u>Design based on ordinary strength levels obtained at lowest possible metal costs.</u> We cite a very wide variety of failures resulting from the selection of lowest-cost steels featuring inadequate transition temperature properties (Fig. 2). Again, for all of these cases the original error may be traced to design practices.

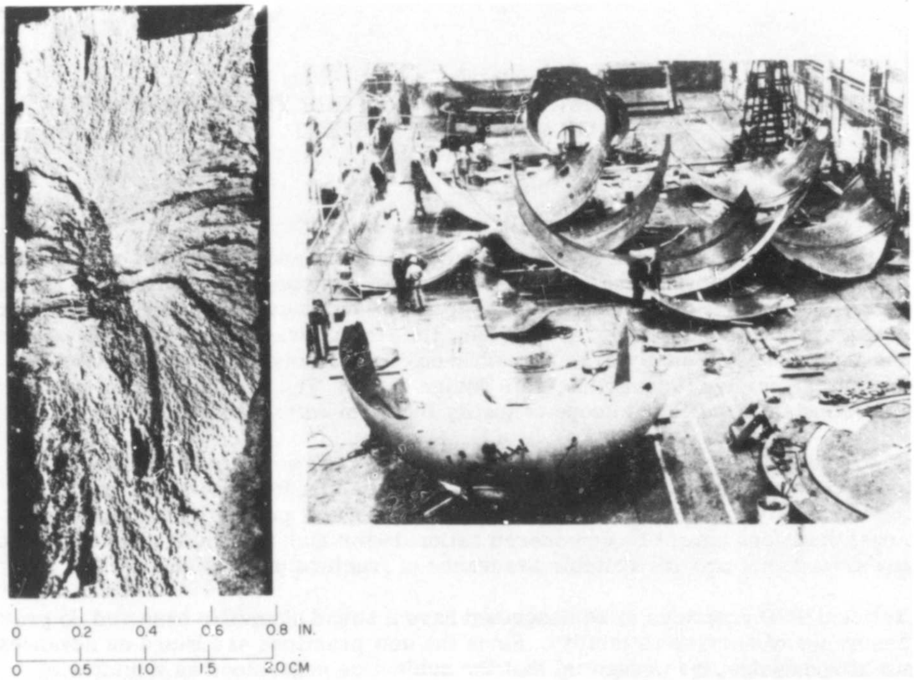

Fig. 1 - Failure of high-strength steel rocket case in proof test. The dark region in the center of the fracture surface indicates the crack (in a weld) which was responsible for initiation of brittle fracture at this point. Flaws of this size cannot be detected reliably by the best nondestructive test methods.

The metallurgical development of high-strength metals has been seriously affected by erroneous concepts of design requirements. New metals were metallurgically "designed" (microstructure, etc.) to develop the highest possible strength, on the premise that this was the primary factor which would decide selection in competition for new applications. The *inverse* relationship which exists between increased yield strength and the fracture-strength reliability of the structures resulted in a return to the drafting board for the designer and a return to the furnaces for the metallurgist.

In general, the new and most advanced engineering applications of metals have suffered from design confidence, which evolves from considering strength aspects as the primary factor in metal selection. Engineering groups that have been adversely affected by such misplaced confidence are today the most adept practitioners of FSD. On the other hand, the specific practices adopted by such groups tend to be recognized by the general engineering field as the most advanced and therefore the best practices.

> It is emphasized most strongly that FSD practices must be customized to the specific structural problem. Practices that apply for rocket cases and aerospace components constructed of high-strength metals may not apply to thick-walled pressure vessels, ships, bridges, etc. involving conventional steels.

The foremost problems in the rational evolution of advanced engineering structures lie squarely in the field of design practices. All other requirements, including metal

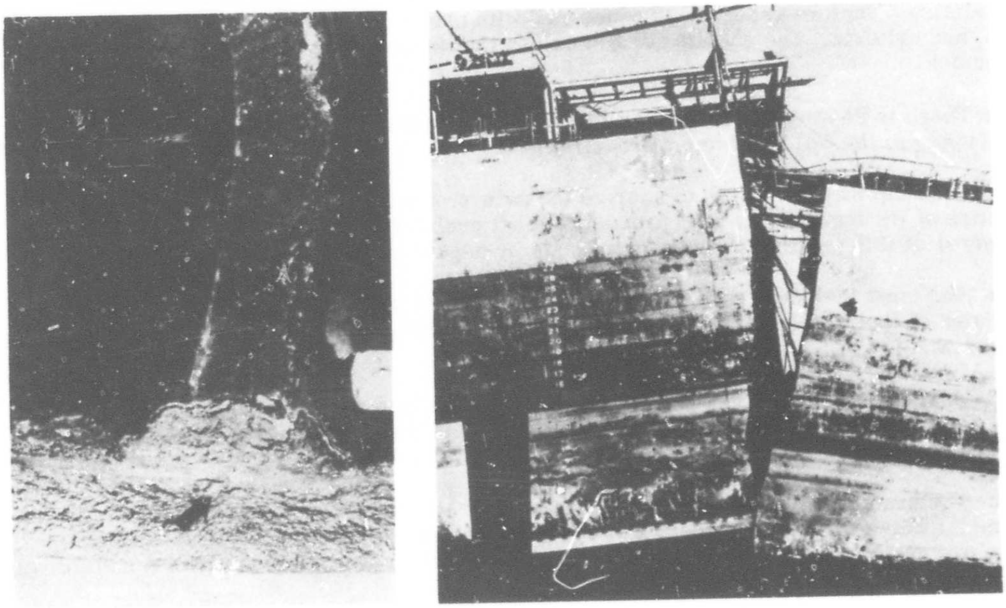

Fig. 2 - Ship fracture at 35°F (2°C) resulting from tiny cracks within an arc-strike, located at the toe of a chock-bracket fillet weld. The failure is typical of fracture-initiation conditions of World War II ships. The fractures always initiated below the NDT temperature of the steel, 50°F (10°C) in this case. The initiation sites were always associated with small cracks located in regions of yield-stress loading due to geometry or to weld-residual stresses.

property characterization, metal improvements, nondestructive inspection, etc., evolve from design considerations. Thus, any deficiencies in design practices translate to erroneous definition of requirements.

In the case of the engineering development of radically new systems, design practice errors affect the totality of requirements for metals research and development, metal selection, specifications, quality control, and lifetime surveillance objectives.

Perspectives

Details of complex subjects can only be appreciated in the context of a mental view of the interrelationships of the parts. The following factors should be appreciated in order to evolve a proper overall perspective for FSD.

- FSD procedures represent structural mechanics design methods which specifically apply to flawed structures. Structural configuration and response to loading are basic considerations, as for any other form of design evolved from classical structural mechanics.

- The practice of FSD is the province of the engineer, not of fracture research specialists. Fracture research is concerned with evolving basic information, test specimens, and criteria. The question of how to use this information is a matter of structural mechanics.

- There is no singular procedure for FSD. However, specific procedures are available which apply to the full spectrum of requirements.

- The first step in FSD is to analyze the nature of the potential fracture problem. Selection of the appropriate FSD procedure must evolve from analyses of this type. Selection error at this point will either complicate or negate any sequential step.

- FSD must include a reserve factor for reasons of protection against deviations from estimates of flaw sizes and stress levels, as well as statistical variations in metal properties.

- The mandatory addition of a substantial reserve factor simplifies the process of FSD. Complexities arising from expectations of exact flaw size—stress definitions are eliminated.

- The practice of FSD within bounds of engineering realities resolves to the selection of a metal which provides a substantial reserve of fracture resistance. While requirements are established by mechanical factors, the solutions are necessarily of a metallurgical nature.

PART II. EVOLUTION OF RATIONAL FSD PROCEDURES

The rate of evolution and engineering application of scientifically sound principles for FSD has been remarkably rapid. The starting point may be traced to the first attempts, in 1950, to introduce design factors which included a fracture resistance parameter. Prior to this time the only available procedure was to limit design stresses to low levels. A description of the problems associated with FSD based solely on stress limitations provides a starting point for the discussions to follow. The new procedures represent a radical departure from the previous practices.

Problems of FSD Based Solely on Stress Limitations

The range and distribution of stresses that exist in a structure depend on the design quality of geometric details, Fig. 3. Both factors also depend on the nature and vectors of the applied loads. The prediction of working stresses at complex points of ordinary structures can be resolved only within fairly broad limits. Whenever it is essential to establish working stresses within narrow limits, it is necessary to utilize procedures of experimental stress analysis. This means building a model and applying strain gages at the locations of interest. Structures of highest design quality are optimized by such procedures.

The terms *allowable stress* or *limit stress* represent calculated (or experimentally verified) maximum permissible working stresses, established by a consensus of expert authorities in the field of the particular type of structure. The stress values are usually referenced to positions of simple geometric form. These limits are specified by Codes and Rules and as such have a semilegal status.

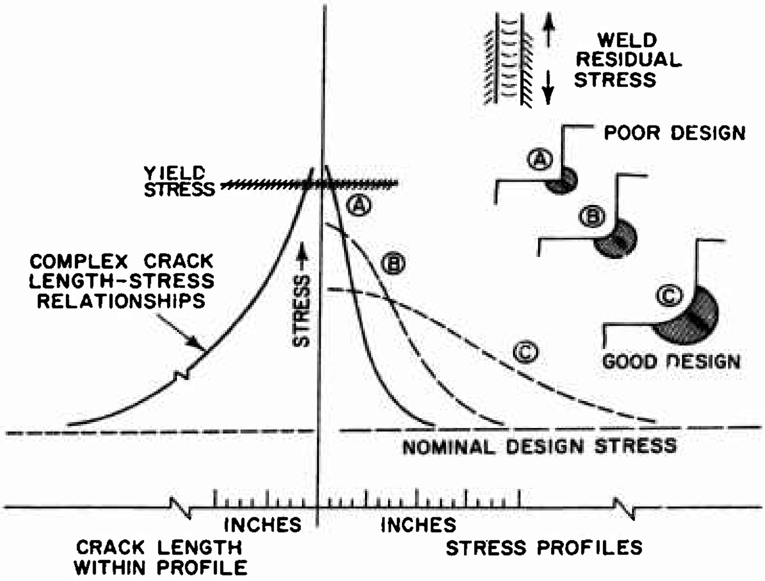

Fig. 3 - Dependence of local stress levels on the design quality of geometric transition points. A complex relationship exists between stress levels and the crack size that can be included within the high stress regions. Small cracks can be contained within yield-level residual stress regions of weld zones. The ship failure of Fig. 2 was due to the location of the arc-strike in the residual-stress zone of the fillet weld.

The term *factor of safety* relates to an outdated form of generalized rules. The following textbook quotations of factors of safety provide examples which clearly illustrate the long-term concern of the design engineer with problems of fracture safety.

- For metals of high tensile ductility subjected to static loads, the lowest factor of safety should be 3 in relation to the yield strength.
- When position of the load is variable, the factor of safety should be not less than 4.
- When the stresses are reversed, the factor of safety should be not less than 6.
- When repeated shocks arise, the factor of safety should be not less than 10.

In retrospect, the concept of factors of safety may be considered the first rudimentary form of fracture-safe design. The evolution of Codes and Rules resulted in enforcing "quality" in design and fabrication, with a "reward" for such practices in terms of decreasing the factor of safety to the range of 3 to 5. We may consider such practices as a second generation of rudimentary fracture-safe design.

Unfortunately, these practices do not provide reasonable assurance that failure by fracture will not evolve. A large body of well-documented engineering disasters provide proof of this statement. High rates of failure were experienced for World War II ships,

Fig. 4, designed to Ship Rules which placed permissible calculated stresses at a 4 to 5 factor of safety. Failures of pressure vessels designed to Codes requiring 3 to 5 factors are not uncommon.

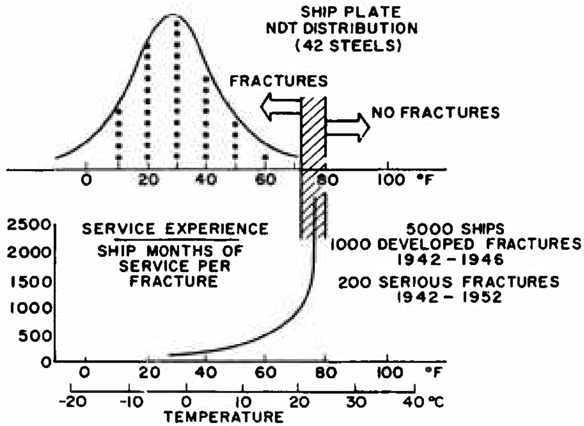

Fig. 4 - Ship failure experience, illustrating a dramatic increase in casualty rates in a narrow range of decreasing temperature. The service experience is clearly related to the fracture characteristics of the ship steels, as indicated by the NDT frequency-distribution curve.

There is a well-documented safe-service record for brittle cast iron, involving the usual factors of 10 to 20 for this metal. Although this experience points to a route for a stress-limit solution of FSD problems, it is not acceptable for practical reasons. Clearly, the only logical route for the prevention of fracture is to utilize design practices which are based on the fracture resistance properties of the metal. Modern Rules and Codes are rapidly being converted to include the rational FSD practices described below.

FSD Generations

The course of evolution of rational FSD procedures is traced in the diagram of Fig. 5. The date of first literature publication for each generation is indicated by the "step." None of the generations to be described have been found deficient for the purpose that they were meant to cover at the time of inception. The various generations should be viewed as providing progressive increases in the span of problems that can be resolved—as to flaw state, metal type, and structure type. In effect, each generation was evolved in consideration of the most serious and general problems of the time.

The first generations were concerned with mild steel, temperature-transition problems of enormous scope, Fig. 4. The ship failure problem resulted from the first large-scale use of welding, i.e., from the introduction of monolithic structural design. Succeeding generations were evolved as a consequence of a dramatic increase in the use of high-strength metals, and are closely related to new engineering systems.

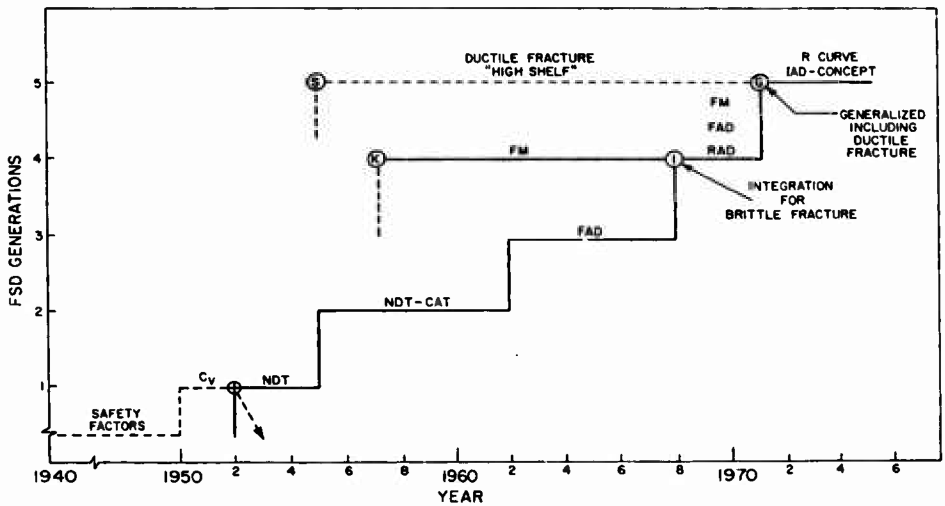

Fig. 5 - Sequence of FSD generations leading to generalized procedures which provide practical solutions to problems of brittle and ductile fracture.

The ship failure problem directed attention to the inadequacies of design for fracture prevention based on stress limitations. While these problems were apparent prior to the large-scale use of welding, it became evident that the nature of welded structures provided for continued extension of a fracture, which could result in total failure. Prior experience with riveted structures indicated that fractures were usually limited to single plates. Thus, there was no urgency to resolve the problems of FSD inadequacies prior to the 1940's.

The first FSD procedure based on fracture properties of the metal was believed to have been attained in 1950, following a decade of extensive research involving the conventional laboratory test specimen in existence at the time. This was the Charpy-V-notch (C_v) test criterion of 15-ft-lb fracture energy, which emerged as the result of ship fracture correlations (Fig. 6). The correlations indicated that ship fractures did not occur at temperatures above the 15-ft-lb C_v energy temperature. The ship steels were used in the as-rolled state and featured relatively high C/Mn ratios. As such, they represented a low-quality, low-cost metal, developed for riveted construction. At the time, the solution was believed to be "general"; however, by 1952 it was demonstrated not to apply to steels of different C/Mn ratio, or even to the same steels when improved by aluminum deoxidation and normalizing heat treatment.

Thus, the only FSD practice, which emerged from the large-scale World War II research effort, was invalidated within two years. The primary result of the effort was to direct attention to the use of natural-sharp-crack test methods and to dynamic-load conditions for studies of fracture problems involving transition-temperature-sensitive steels. This information was basic to the evolution of the Drop Weight Test (DWT) criterion of Nil Ductility Transition (NDT) temperature in 1952. The DWT invalidated the 15-ft-lb C_v criterion for general use and replaced it by the NDT criterion as the primary standard.

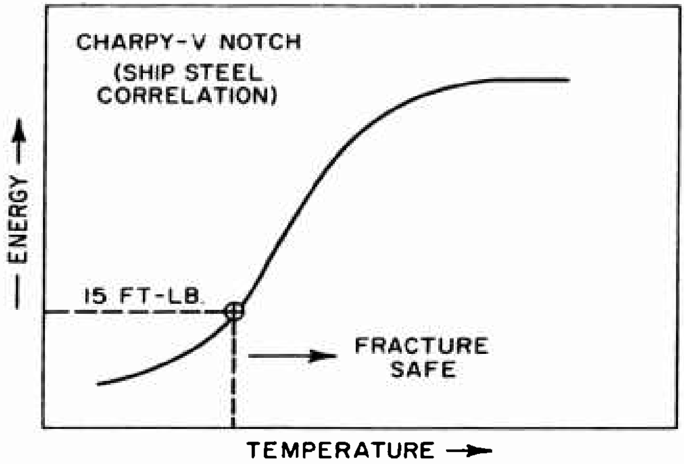

Fig. 6 - C_v test correlations which defined the critical temperature above which ship fractures did not develop. This specific index point does not apply to other types of steels.

The primary aspects of the generation sequence outlined in Fig. 5 are described below for purposes of introduction. More detailed explanations will be provided in the sections to follow.

- *First Generation (NDT)*

The FSD procedure involves restricting the lowest service temperature to a modest increment above the NDT temperature of steel, Fig. 7 (G1). The method applies to low- or intermediate-strength steels when used in the transition temperature range. It protects against fracture *initiation* due to the presence of small flaws (<1 in.), which are subjected to dynamic stresses up to and including yield levels. The procedure provides a solution to the majority of failure problems for welded structures of complex design (Fig. 4).

- *Second Generation (NDT-CAT)*

The FSD procedure involves restriction of the lowest service temperature to a modest increment above the Crack Arrest Temperature (CAT) curve, as located on the temperature scale by the NDT index point, Fig. 7 (G2). The procedure provides positive assurance that brittle fracture *propagation* cannot evolve, irrespective of flaw size, for specified nominal elastic stresses up to yield levels. The CAT procedure may be described as non-provisional, i.e., it does not depend on flaw-size aspects.

- *Third Generation (FAD)*

The Fracture Analysis Diagram (FAD) procedure integrates NDT and CAT considerations with the additional feature of defining the initiation-stress aspects for a wide range of flaw sizes, Fig. 7 (G3). The reference index is the NDT temperature, with other aspects

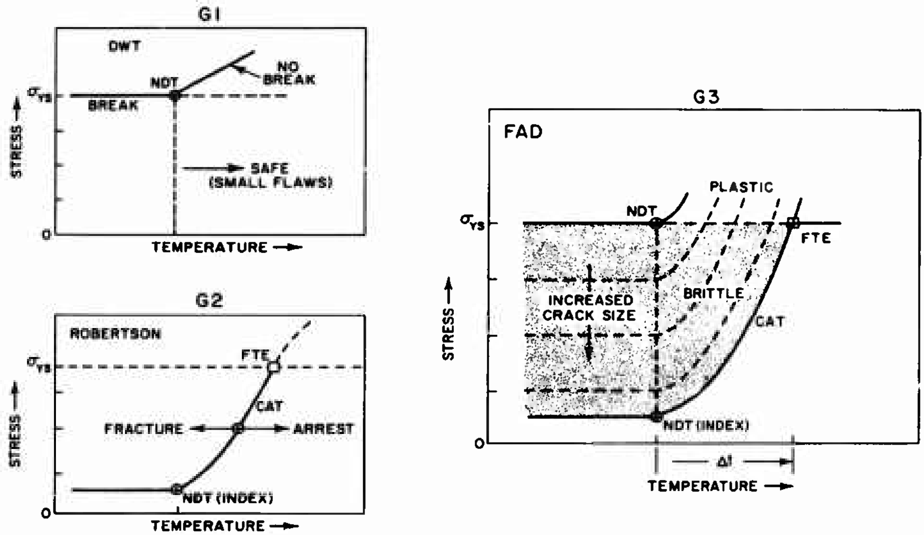

Fig. 7 - Generation steps leading to the evolution of the FAD. The NDT index indicates the temperature point above which there is a sharp rise (transition) in fracture resistance. Thus, all of the FAD curves must rise sharply above this temperature point.

defined by Δt temperature increments. The FAD represents the first and most widely used of the analysis diagram procedures. The diagram provides broad flexibility in the solution of transition temperature problems for steels. For example, it provides for choice between the use of provisional (flaw size) or of nonprovisional (fracture propagation prevention) FSD methods.

- *Fourth Generation (FM-FAD-RAD)*

The starting point may be traced to the birth of the "K" concept, derived from fracture mechanics (FM) theory. The FM aim was to evolve fully generalized *provisional FSD* procedures for defining flaw size—stress relationships for initiation of brittle fracture, irrespective of metal type (see Fig. 20). The fourth-generation goal was attained at point I, which represents the integration of the *transition temperature* procedure (FAD) with FM. In addition, a Ratio Analysis Diagram (RAD) was evolved (see Fig. 25) which simplified the application of FM for *strength transition* (not involved with temperature effects) metal problems. The integrated procedures provide for complete flexibility in the solution of brittle fracture problems.

- *Fifth Generation (R Curve-IAD)*

The previously described procedures have included rudimentary considerations of FSD problems involving fracture extension for *ductile* metals. The solutions involved placing emphasis on "high shelf," i.e., high-level resistance to plastic fracture. Recent developments of test methods for defining metal resistance to plastic fracture (R curve) provided the essential first step for the evolution of design practices which include ductile fracture (see Fig. 27). Structural mechanics aspects of load response for plastic fracture are represented by a new procedure defined as the Instability Analysis Diagram (IAD) concept (see Figs. 28 and 29). With the attainment of the goal for relating R-curve parameters to structural mechanics factors, fully generalized (G) FSD practices will be available—covering both brittle and ductile fracture problems.

Summation

It is not inferred that the described evolution of FSD generations will fully complete all required studies in this field. The important point is that a flexible capability for designing against all types of fracture will be attained equal to the capabilities for designing against buckling or other classical forms of overload failure. Continuing studies will represent refinements, similar to those which are being made for shell stability, buckling, etc.

It is imperative that FSD be considered a process of "looking forward" from the drafting table to the requirements of the structure in terms of fracture prevention. The process of designing the structure, selecting the metal, proceeding to fabrication and *then* "looking backward" at questions of fracture reliability is all too common. Fully rational design which looks forward must begin at the conceptual and preliminary design stage. If appropriate engineering analyses are made through the entire design process, the correct FSD procedure, choice of metal, quality control, and specification methods (Q/S) will evolve in rational, sequential form.

It is fortunate that the described advances have been attained. Recent events emphasize increasing public concern with questions of hazards arising from potential technological disasters, such as illustrated in Fig. 8. Failures of ships, bridges, aircraft, commercial transport systems (for toxic or flammable materials), nuclear power plants, etc., are not acceptable. Regulatory governmental bodies are becoming knowledgeable in this area. Increased participation in Codes and Rules formulation by representatives of public interests is evolving. It is to be expected that concepts of corporate and individual professional responsibility will apply, for those who should be in a position to understand and prevent causes of potential disasters. The FSD generations also represent established analytical capabilities to trace the cause for cases involving failure by fracture.

PART III. UNIFICATION OF METAL CHARACTERIZATION AND STRUCTURAL MECHANICS ASPECTS OF FSD

The dichotomy of interests that has separated the literatures of fracture research and structural mechanics is fortunately beginning to be eliminated. The differences among those who have been involved with fracture research from different points of view are beginning to be resolved. Acceleration of these trends is essential because it is evident that the various parts fit together in a rational framework.

The practice of FSD involves a close coupling between considerations of the *mechanisms of fracture* and of *structural response* in the presence of flaws. Structural response establishes the FSD requirements, whereas the intrinsic fracture resistance characteristics of the metal determine if the requirements are met. The design process is involved with the balance between these factors and, as such, it involves tradeoffs in the classical tradition of engineering practice.

A close, continuing connection must be established between the fracture research field and the structural mechanics field. An additional connection must be established with the metallurgical research field, so that improved metals can emerge to satisfy

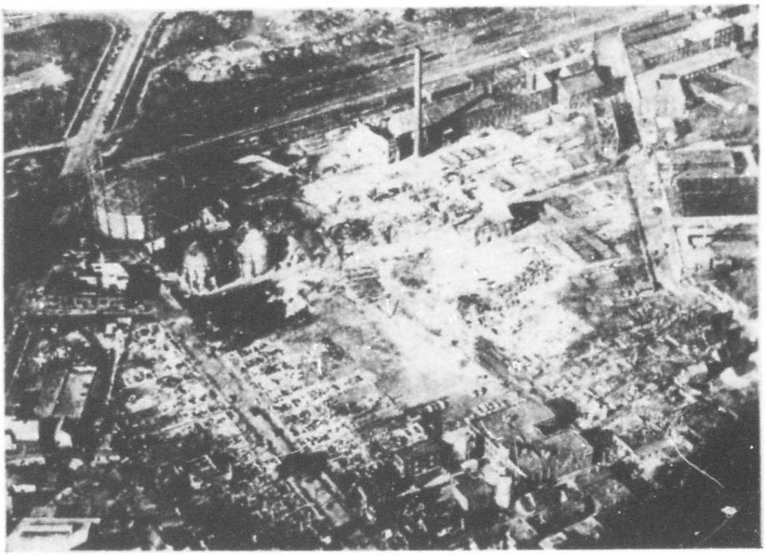

Fig. 8 - Area disaster resulting from the brittle fracture of large storage tank for liquified natural gas

structural requirements involving higher strength, thicker sections, lower service temperatures, improved fabricability, and minimization of cost.

The engineer should consider the enormous literature on fracture research as baseline information which leads to the described FSD procedures but has to be understood only in a very general sense. As a parallel, the engineer does not have to understand details of physical metallurgy theory which determine the fracture properties of the metal. All that is necessary is to recognize the significance of fracture test parameters which serve as the index of metal quality. The crucial questions lie in the interpretation of these index values in terms of structural performance. The interpretations are provided by analysis diagrams of simple form.

The sequence diagram presented in Fig. 9 illustrates the role of the various research activities which have contributed to establishing FSD procedures.

The block marked *fracture mechanisms* represents the activities of fracture research specialists. The basic scientific objectives of the specialists justify the development and use of fracture research test specimens of any degree of desired complexity, instrumentation, and cost. The loop marks the publication and conference activity of this field—usually confined to a relatively small and specialized membership.

The block marked *standardized tests and criteria* represents the most important product of fracture research, insofar as the engineer is concerned. Very few tests become standardized because there must be a consensus of scientific and engineering groups on technical significance and practical value. In general, the tests must be procedurally simple and of low cost to satisfy routine test-laboratory requirements for specification and quality control (S/Q) use.

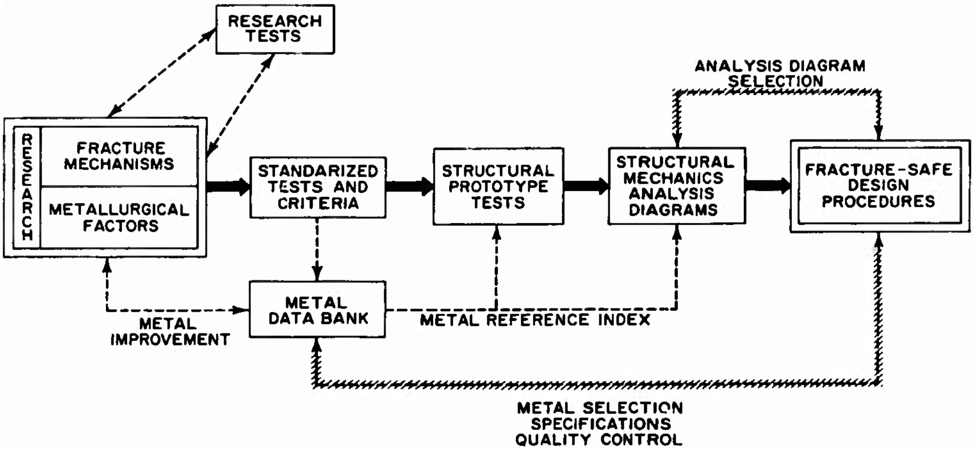

Fig. 9 - Research activities leading to the development of practical FSD procedures. The aspects involved in general engineering practice of FSD are noted by the dashed lines.

The standardized tests are essential for the evolution of data-bank compilations of metal properties for engineering reference. It is from these data banks that the selection of metals will be made for FSD purposes. The loop indicates a cycling back into a research phase involving metallurgical factors. It represents activities for metal improvement, so that the data bank is enlarged as to selection quality.

The block marked *structural prototype tests* represents the first step in the direction of evolving structural mechanics interpretations of the index values obtained by standardized test specimens. Structural prototype tests represent simple structural elements featuring the presence of flaws of selected sizes. These may be flat plates in tension, plates in elastic or plastic bulging, flawed pressure vessels, etc. Structural failures, when properly analyzed, also serve structural prototype purposes. The important factor is that the elastic or plastic load requirements for fracture extension must be related experimentally to the standardized fracture-test values. In general, structural prototype tests will be performed for a range of flaw sizes and a range of metal quality levels, i.e., ranging from low to high values of fracture resistance.

The information derived from the structural prototype tests is then reduced to graphical presentation of flaw size—stress relations which apply for metals of specified fracture-test index values. This step is indicated by the block marked *structural mechanics analysis diagrams*. Thereafter, if the fracture-test index value is known, the structural capabilities of the metal to withstand elastic or plastic stress in the presence of a specified flaw can be defined. Conversely, if the flaw size and stress are specified, the fracture-test index value required of the metal can be defined.

The practical end point of these various research activities is the evolution of rational FSD procedures. The dashed lines of Fig. 9 indicate that the procedures depend on selection of the appropriate structural mechanics analysis diagram and related metal—properties data-bank parameters. The FSD procedure must include establishing of metal-purchase specification criteria and fabrication-quality control practices. These aspects must be in match with the design parameters that decided the metal selection.

There are four basic types of graphical structural mechanics analysis diagrams—

Fracture Analysis Diagram (FAD)

Graphical Fracture Mechanics (GFM)

Ratio Analysis Diagram (RAD)

Instability Analysis Diagram (IAD)

At this point, it is essential to understand that the selection among these is determined by the type of metal (transition temperature sensitive or not), the fracture resistance quality of the metal (ductile or brittle), and the general features of the structure (rigid or compliant). When the selection of the appropriate analysis diagram is made by relatively simple processes of estimation, the engineer is ready to practice FSD.

The author's emphasis on analysis diagram procedures derives from considerations of engineering realities involved with trade-off aspects between metal properties and structural mechanics factors. The use of graphical representations provides for the simple, iterative cross-referencing of these factors. We state the case as follows—in the absence of such diagrams, the cross-referencing problem can only be resolved by specialists and then only with excessive difficulty. If FSD is to be practiced by the general engineering field, graphical presentation of structural mechanics-vs-metal properties interactions is essential.

This introduction emphasizes that FSD can be practiced by the use of predefined procedures and preestablished metal data-bank values. In fact, the consideration of elementary structural mechanics factors emerges as being more important to the selection of the appropriate FSD procedure than detailed knowledge of fracture-processes theory. A general introduction to the factors which determine the resistance of a metal to fracture extension should suffice to provide the level of knowledge required for most engineering purposes.

PART IV. CHARACTERIZATION OF FRACTURE RESISTANCE

Failure by fracture connotes separation of the metal by a process of extension of a preexisting crack. The most definitive measure of fracture-extension resistance is provided by test specimens featuring deep sharp cracks (or very sharp notches). This requirement follows from the fact that natural cracks are sharp; therefore, this feature must be reproduced by the test specimen.

The ideal fracture test specimen should feature a crack depth which is at least one-half of the thickness of the test piece (crack depth $\geq$0.5 crack front breadth). If the requirement of a deep, sharp crack is met, a correspondence will be established between test-specimen and natural crack-extension conditions in a structure. Since the ideal test specimen "models" the process of crack extension in a structure, it provides for measuring the resistance to crack extension of specific metals in the laboratory.

The process of crack extension involves the application of a force which causes localized plastic deformation at the crack tip and *plastic* rupturing of the metal in sequential steps. All aspects of fracture extension, brittle or ductile, involve localized absorption of plastic work energy by the metal. Irrespective of units used, all fracture test parameters are fundamentally energy-related terms, because fracture resistance can only derive from absorption of plastic work energy. The only basic difference between various types of ideal fracture tests (deep, sharp crack or notch) is the *range* of metal fracture-extension resistance that is measured.

The full range includes glasslike brittleness to tensile-test-like ductility. The important engineering demarcation point between these two limits is the "transition" between unstable (brittle) and stable (ductile) fracture extension. Fig. 10 illustrate the two types of fracture. Unstable fracture propagates at high velocities (1000 to 3000 ft/sec) by release of elastic strain energy, i.e., through elastic stress fields. Stable fracture involves the sequential plastic rupturing of a relatively large volume of metal (plastic enclave) in advance of the crack front. The time-related inertial response of the metal, required for sequential yielding and rupturing of the plastic enclaves, results in relatively slow rates of propagation. Fracture extension by enclave rupture requires yield stress levels to be exceeded; thus, stable fracture can only extend through plastic stress fields.

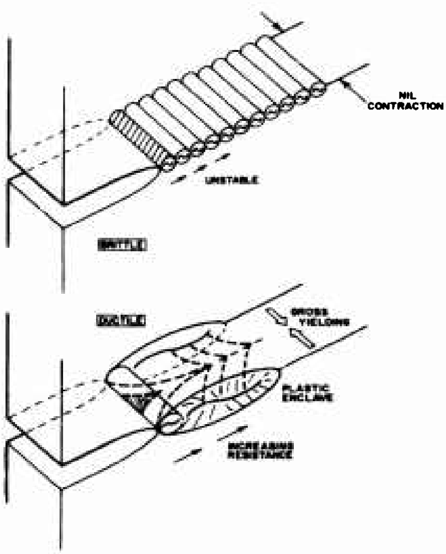

Fig. 10 - Schematic illustration of the crack-front-plasticity conditions associated with the extension of unstable (brittle) and stable (ductile) fracture. The early stages of crack growth for the ductile metal are illustrated by V profiles.

The specific mechanical conditions for fracture propagation may be summarized as follows:

- *Conditions for brittle fracture*

The degree of metal resistance to fracture extension is decided by the intrinsic ductility of the metal subjected to the triaxial state of stress acting at a crack tip. As this stress is increased, a small plastic zone forms and grows in size. At a critical strain level, decided by the metal ductility under triaxial stress, the plastic zone ruptures. The elastic stress field in advance of the plastic zone is illustrated in Fig. 11. The brittleness behavior of the metal decreases with increase in the critical size of the plastic zone attained at the point of rupture. Higher levels of elastic stress field intensity K are required to rupture plastic zones of increasing size; therefore, the level of nominal elastic stress must be increased.

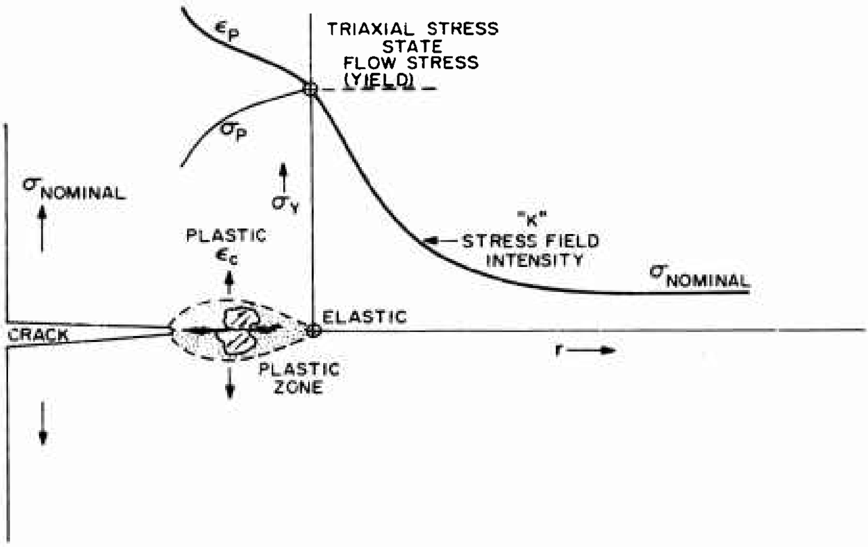

Fig. 11 - Features of elastic stress fields in advance of crack-tip plastic zones, at the time of rupture (instability) for the case of brittle fracture. The plastic zone size is enlarged for purposes of the illustration. In actuality, the critical plastic zone sizes for brittle metals are close to the dimension of the crack-tip radius, i.e., very tiny. The fracture mechanics K parameter is an index of the steepness of slope of the intensified elastic-stress field acting to rupture the plastic zone. K_I . signifies the K intensity level at the point of rupture of the initial plastic zone.

The common features of brittle metals is that unstable fracture evolves as a consequence of force levels which result in elastic stresses, in advance of the crack-tip plastic zone. The high-speed propagation results from the fact that the elastic stress fields can move forward at velocities which are limited only by elastic stress waves and the inertial response of the metal.

- *Conditions for ductile fracture*

The intrinsic ductility of these metals under a triaxial stress state is too high to permit rupturing at the level of small plastic zones. The consequences are that the crack tip is blunted and a large region of plasticity (plastic enclave) is developed, as illustrated in Fig. 10. In order to rupture the large plastic enclaves, the stress resulting from the applied load must rise to greater-than-yield levels. The plastic strain field which provides the propelling force is illustrated in Fig. 12. The plastic work energy for rupture is proportional to the extent of the plastic enclave and the magnitude of the plastic strain therein. The shaded area in the figure represents the plastic work energy. It may be compared with the very low levels of plastic work energy represented by the small plastic zones of Fig. 11.

During the period of crack blunting and enclave growth, the resistance to fracture extension for ductile metals increases with extension. The crack growth during this

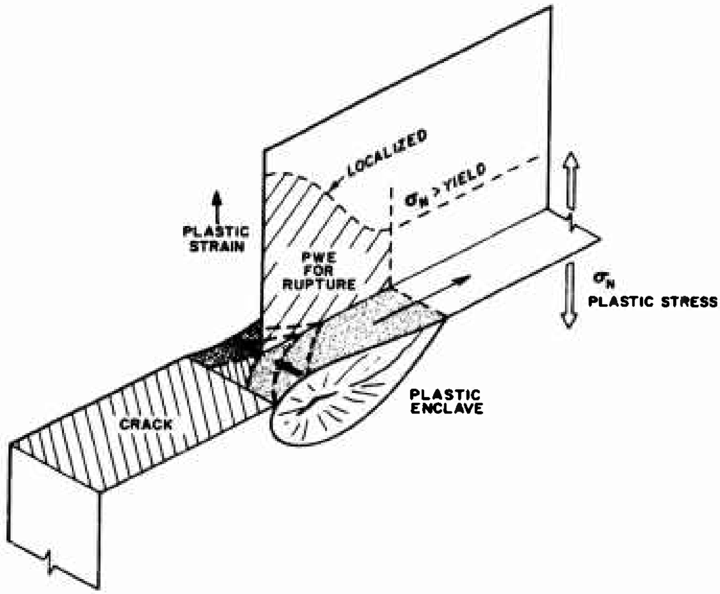

Fig. 12 - Features of plastic-stress fields in advance of plastic enclave regions for the case of ductile fracture. The plastic-work energy (PWE) for rupture increases with increase in the enclave size, i.e., with increased degree of through-thickness yielding. Increased PWE and, therefore, increased resistance R to extension is developed during the first stages of sequential internal rupture, as the initial plastic enclave increases in size. The nominal stress required to initiate and continue the fracture-extension process must exceed yield levels.

period occurs in the central region of the section, as will be explained. Thus, there are a number of sequential rupture steps, which evolve with increased resistance due to the increase in plastic enclave size and increased lateral contraction (increased plastic work energy) in the process of the first stages of extension. In effect, the constraint level of the initial crack front is reduced by relaxation of the triaxial stress field. The distance over which increased resistance is developed is a function of the intrinsic metal ductility.

Engineering Significance of Fracture Tests

The key to understanding the engineering significance of fracture test parameters lies in considering the events described above as an expression of Newton's third law— "to every action there is an equal and opposing reaction." The propelling force system is that level which results in elastic or plastic stresses required to cause extension. The reaction is the resisting force system evolved by the coherence of the metal as it undergoes plastic flow and work hardening in the plastic zone or enclave-rupture region.

The relationships between the propelling force system and the metal-resistance (reaction) force system are illustrated schematically in Fig. 13. The critical plastic zone or enclave size determines the local rupture resistance and, therefore, the intensity of the required propelling force system. Fracture involving small plastic zones features a low reaction-force capability; thus, elastic stresses suffice for fracture initiation and extension. Fracture involving plastic enclave yielding features high reaction-force capability; therefore, plastic-load propelling stresses are required.

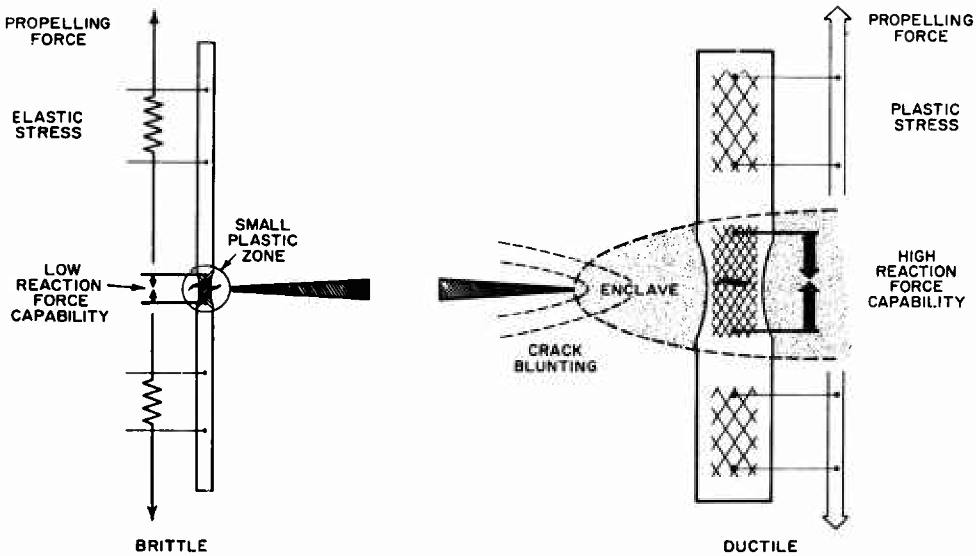

Fig. 13 - Relationships between propelling stress levels and metal reaction-force capabilities. Fracture extension at elastic stress levels for the case of brittle metals is due to low reaction-force capabilities, evolving from sequential rupturing of small plastic zones. The high reaction-force capabilities of ductile metals require application of plastic stresses for fracture extension.

The fracture-extension resistance process may be visualized in terms of a resistance curve, which relates to the increased plastic work energy absorbed per unit increment of initial extension (R curve). The slope of the R curve determines the required increase in the propelling force, as follows:

- Brittle fracture—Plastic work energy does not increase with extension. The R curve is flat. Therefore, there is no requirement for increase in the propelling force with extension.

- Ductile fracture—Plastic work energy increases in varying degrees with initial extension, depending on the intrinsic ductility of the metal. The R curve will feature a slope of varying related degrees. Therefore, there is a proportional increase in propelling force required to continue the initial extension process.

In brief, brittle metals fracture "spontaneously" by propagation through steady-state elastic stress fields. For such metals, the test specimen must measure to resistance to fracture initiation. This is equivalent to measuring the *level* of a flat R curve. Highly brittle metals will have a very low level of initial and propagating resistance, i.e., flat R curves of low value. The index of merit for ductile metals is the slope of the R curve.

Figure 14 illustrates a recently developed (1970) procedure for definition of R-curve slopes. It is based on modeling the fracture-extension process by the use of Dynamic Tear (DT) test specimens of increasing fracture path length. The two test series illustrate a brittle steel featuring a flat R curve and a highly ductile steel characterized by a steep R curve. R-curve slope determinations by this technique may be made for any metal and thickness of interest.

It is emphasized that DT specimens of various fracture-path lengths serve as geometric models of the change in triaxial-stress constraint in the initial stages of fracture extension. It is not implied that the distance over which the modeled effects are measured is the same as for the case of uninterrupted extension. The specific distance over which increased resistance is developed may be approximated by noting the length of the V (flat fracture region), which marks the leading edge of the subsurface crack during the initial process of fracture extension. The plastic enclave size increases during the period of tunnellike extension of the subsurface crack, and thereby requires an increase in fracture-extension force. The mechanical constraint conditions which apply during the period of crack extension are discussed in the Appendix.

A metal of high R-curve slope will feature a very short V in the order of one-half the section thickness. The V contour becomes much longer for metals of low R-curve slope. The important point is that specific differences in fracture-extension resistance may be measured by utilizing procedurally simple techniques.

A simplified model, which illustrates the R-curve features for metals ranging from highly brittle to highly ductile characteristics, is presented in Fig. 15. The demarcation zone between unstable and ductile fracture is related to a change from flat to sloping R curves. The demarcation zone also separates fracture propagation at fixed levels of elastic stresses and fracture requiring the application of increased plastic stresses for extension. The levels and slopes of the R curves are related to the levels and slopes of the propelling force system.

The full range of metal properties that must be measured by fracture tests becomes evident from this figure. The relationships to the performance expected in structural prototype tests (or structures) also begins to emerge, by consideration of the propelling force system requirements.

The significance of the coding in terms of six levels of metal ductility (1 to 6) is explained below for purposes of future reference in discussions to follow. The reference system will greatly simplify the discussion of otherwise complicated interrelationships.

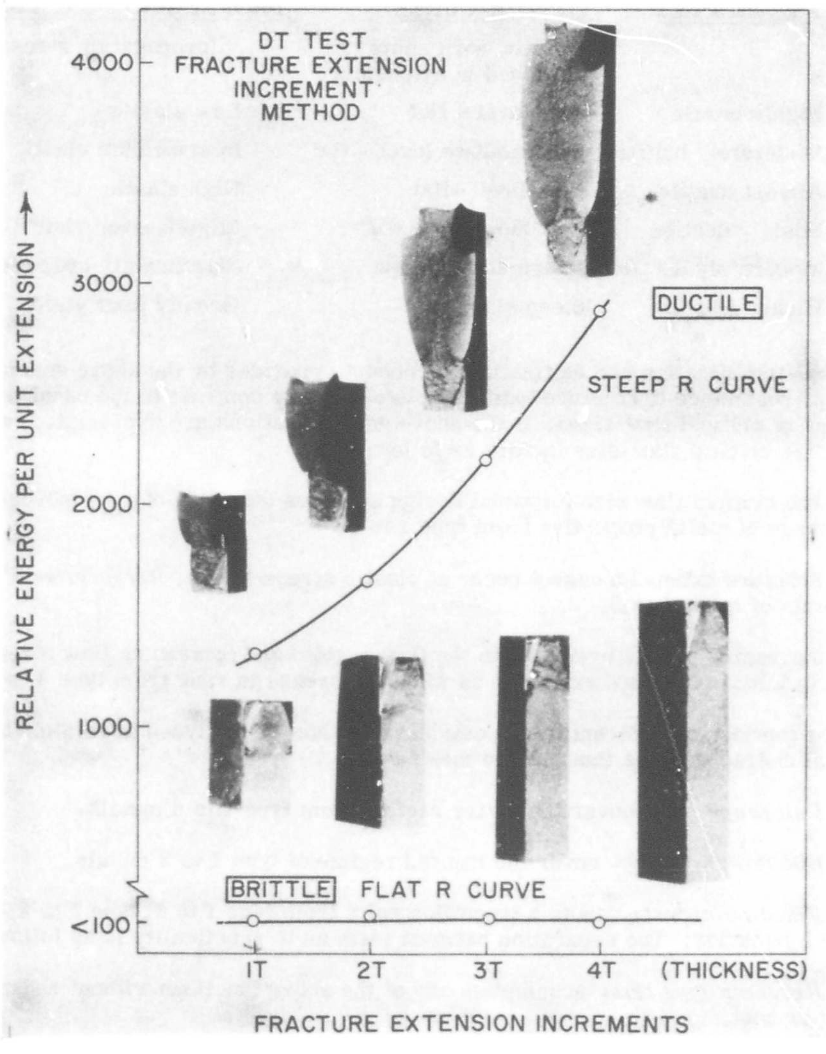

Fig. 14 - Representative R-curve slopes for brittle and ductile steels of 1-in. thickness. The relative increase in plastic-work energy for fracture extension is modeled by the use of Dynamic Tear (DT) test specimens of increasing fracture-path lengths. The increased lengths allow measurement of the effects of decreased triaxial stress constraint in the process of fracture extension. Note the short internal V for the case of the ductile metal.

METAL DUCTILITY RANGE

METAL TYPE	R-CURVE (plastic work energy absorbed in extension)	PROPELLING FORCE SYSTEM (propagation stress)
1. Highly brittle	Low level - flat	Low elastic
2. Moderately brittle	Intermediate level - flat	Intermediate elastic
3. Almost ductile	High level—flat	High elastic
4. Slightly ductile	Low slope	Slightly over yield
5. Moderately ductile	Intermediate slope	Significantly over yield
6. Highly ductile	Steep slope	Greatly over yield

The simplification and unification of concepts provided by the above descriptions, in terms of resistance to fracture extension, are in sharp contrast to the usual descriptions in terms of critical flaw sizes. If the above generalizations are appreciated, we may then generalize critical flaw-size factors as follows:

- The critical flaw size for usual design stresses (say 0.30 of σ_{ys}) increases rapidly with change of metal properties from type 1 to 3.

- Fracture extension cannot occur at elastic stress levels, *irrespective of flaw size*, for metals of types 4 to 6.

- Increasing plastic overload (in the flaw region) and increasing flaw sizes are required to initiate fracture extension as metals increase in rank from type 4 to 6.

The function of different test specimens may now be analyzed in relation to the range of metal characteristics that may be measured:

- *Full range tests* cover the entire regime from type 1 to 6 metals.

- *Elastic range tests* cover the limited regime of type 1 to 3 metals.

- *Fixed-point tests* denote a transition point from type 1 to 2, type 2 to 3, or the limit of type 3 behavior. The separation between tests as to practicality is as follows:

- *Research-type tests* accomplish any of the above functions without regard to complexity or cost.

- *Standardized specification/quality control tests* accomplish any of the above functions by procedurally simple and low-cost methods.

- *Arbitrary notch tests* do not feature natural crack conditions and, therefore, can be utilized only by complex correlation procedures. Calibration is required for the particular metal involved. In general, the metals for which calibration is possible are limited to low- and intermediate-strength steels.

Section Size Effects

Discussions of the role of specific fracture tests and their interpretation requires a general understanding of the effects of section size. Ordinarily, it is desirable to conduct tests of relatively small size and then reference the test values to conditions involving

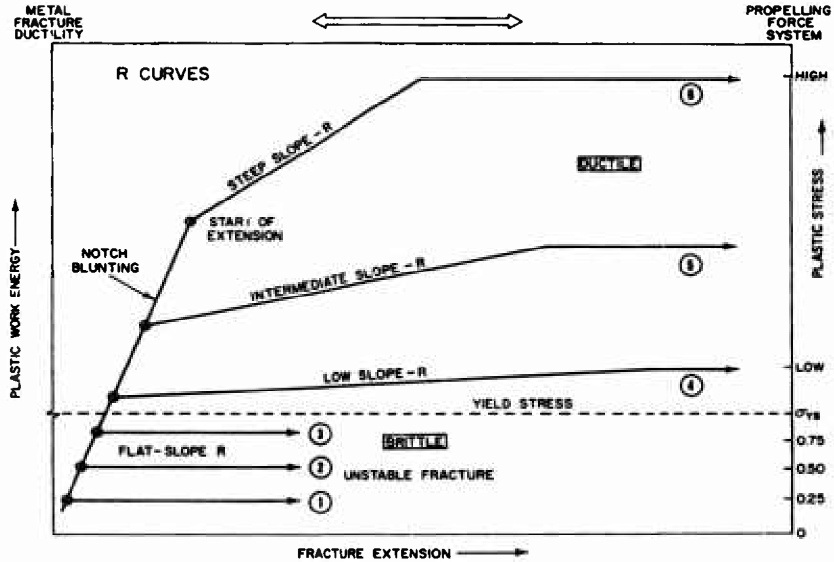

Fig. 15 - Range of metal fracture-extension-resistance properties in relation to R-curve levels and slopes. The correspondence to propelling stress levels is indexed by the relative stress scale. The coding of metal types, 1 to 6, is explained in the text.

thicker sections. The analysis diagrams include provisions for defining section size effects due to mechanical factors.

The mechanical effects are best described in terms of metals of essentially uniform through-thickness metallurgical properties. With increase in section size, there is an enhancement of constraint resulting in higher triaxial stresses, with a related degree of suppression of the capability of the metal to develop plastic flow at the crack-extension front. In brief, increased section size causes a given metal to "slip" backward in the scale of 1 to 6 metal characteristics described previously. Moderate increases in section size (say 1.2 to 2X) may cause a decrease in the order of one quality step. Large increases in section size (say from 5 to 10X) may cause a decrease in the order of two quality steps. The decrease becomes less as the intrinsic metal quality, measured by tests of 0.5- to 1.0-in. thickness, increases to levels of 5 and 6 quality steps. Thus, a metal of very high R-curve slope will not be degraded mechanically as much as a metal of intermediate or low slope. From an engineering viewpoint, the effects of section size are most important when metals of type 4 features are caused to fall back to the type 3 (unstable fracture) level.

In general, increased section size requires increased improvement in the intrinsic (microfracture ductility of the grain structure) quality of the metal. In effects, metallurgical improvement can offset the mechanical effect and, therefore, result in retention of the desired metal quality level. There are practical limits to this offsetting operation, i.e., there are limits to which the transition temperature can be lowered or strength increased with retention of specified quality levels (say over type 3). These limits are defined by metal data-bank properties, when properly related to the analysis diagrams.

The only difficult problem of section size effects interpretations arises when the through-thickness properties of the metal are not uniform. These effects are usually found in relatively thick sections, for which it is essential to determine center and surface properties. Fortunately, recent R-curve studies of metals featuring property gradients have provided a practical solution to this problem. The R-curve determination "integrates" the composite effect. For purposes of this introduction to the subject, it may be generalized that the metallurgical composite will behave mechanically as if controlled by the properties (brittle or ductile) of the major fraction. Conventional "rule of mixtures" do not apply. Thus, test specimens of small dimensions may be used to plot the gradient, and reasonable estimates can be made of the nature of the composite R curve to be expected, i.e., flat, or the degree of integrated slope.

The various tests to be described are conducted for standardized specimen dimensions. The effects of section size or the procedure for interpreting these effects will be explained.

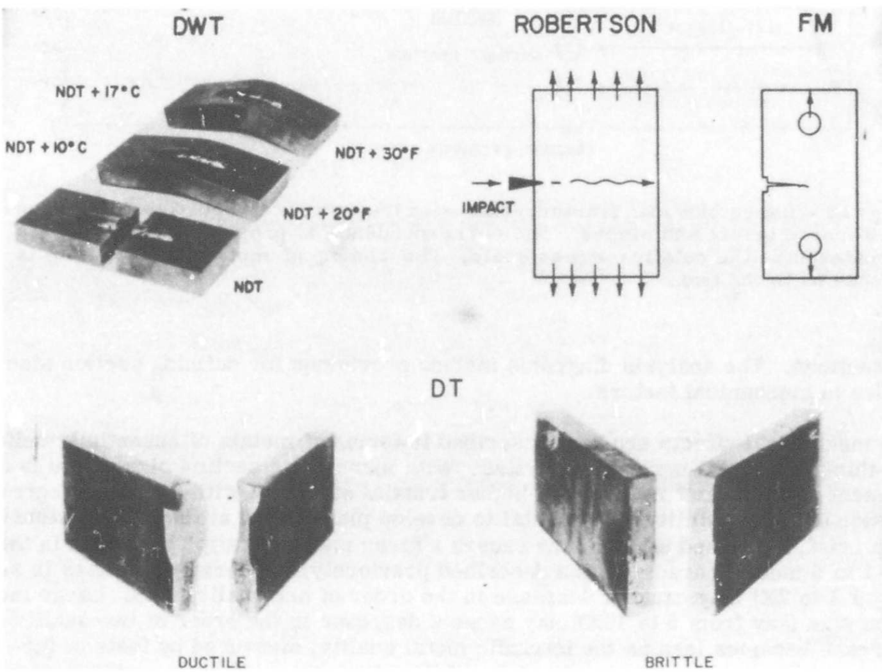

Fig. 16 - Features of modern fracture tests

PART V. PRINCIPAL LABORATORY TEST PROCEDURES

The status of fracture tests is best described in terms of their time of development and projections for future use. The features of the new tests are illustrated in Fig. 16.

Charpy Keyhole Notch

The test features an arbitrary drilled-hole notch. It was developed circa 1905 and was recognized as wholly unsuitable for design purposes by 1945 as the result of ship fracture studies. While it is an ASTM standard test, there is no valid case for continued use. No attempt has been made to relate this test to section size effects.

Charpy-V Notch

The test features an arbitrary machined notch. Developed circa 1905, it is the most widely used test and has been standardized internationally. Its primary use is restricted to steels. The FSD significance of the test must be calibrated by correlation to the primary standard tests described below. The problems of generalized correlations are insuperable because of complex dependencies on the type of steel, strength level, etc. A rational scientific and practical engineering case can be made for eventually discarding this test. Section size effects must be interpreted by correlations with the primary standard tests.

Drop Weight (NDT)

The DWT is a fixed-point test which serves to establish the temperature of transition between type 1 to 2 characteristics for low- and intermediate-strength steels. The test utilizes a brittle weld which cracks when the drop-weight loading of the specimen attains yield stress level. Thus, it reproduces the effects of dynamic loading in the presence of a small, sharp crack. The Nil Ductility Transition (NDT) temperature represents the highest (limit) temperature of fracture under these conditions. The DWT was developed in 1950 and ASTM-standardized in 1963. Because of the large-tonnage utilization of low-strength steels, it is the most widely used modern test (first sharp crack test) and has displaced the C_v test for many specification purposes. Since the test is a fixed-flaw-size test, it is not influenced by section size; i.e., changes in section size will not cause changes in the NDT unless the metallurgical quality of the steel is changed. The NDT is a section-size-independent parameter.

Robertson Crack Arrest Temperature (CAT)

In its various modifications since initial development in the late 1940's, the Robertson test is a partial range test which defines the fracture-extension resistance in the elastic load range, i.e., type 1 to 3 metals. It is used to determine the temperature range over which a steel undergoes a transition from low to intermediate levels of fracture-extension resistance. In most cases, the test is conducted at a fixed level of stress (say 0.5 σ_{ys}). It is then a fixed-point test, which defines the temperature above which the fracture-extension resistance becomes sufficient to preclude propagation at 0.5 σ_{ys}-level stresses, i.e., transition from type 2 to 3 metal characteristics. Because of procedural complexity and cost, its use is ordinarily restricted to research purposes. It may be conducted for any section size of interest; however, practical considerations dictate thicknesses in the order of 0.5 to 1.0 in. as the usual practice. Section size effects may be interpreted by the shift of the CAT curve, best described in terms of the FAD, as will be cited.

Fracture Mechanics (K_{Ic}-K_{Id})

Fracture-mechanics, plane-strain tests measure the resistance to fracture extension (initiation) for the case of brittle metals, Fig. 11. The totality of the extension resistance is determined by the rupture of the initial crack-tip plastic zone for these metals. The K_{Ic} or K_{Id} parameters are expressions of the degrees of fracture-extension resistance for brittle metals. As such, the range of fracture-extension resistance that is measured is limited to types 1 to 3 metals.

Two specific configurations of the K_{Ic} (slow loading rate) test are entering ASTM-standardized practices. High cost and procedural difficulties restrict the tests to research purposes, except for cases involving essential use of brittle metals, such as ultrahigh strength metals.

FM tests are not practical for transition temperature problems which depend on the K_{Id} (dynamic) parameter. The K_{Id} index rises sharply at the NDT temperature and follows the course of the CAT curve.

FM tests must be conducted for specified thicknesses which relate to the K_{Ic}/σ_{ys} ratio of the metal. These aspects will be clarified by discussion of the GFM plot and the RAD (see Figs. 20 and 25).

Dynamic Tear (DT)

The DT test is the only full-range test with capabilities for defining type 1 to 6 metal characteristics. It was first evolved in 1962 and has been standardized for U. S. Navy use in 0.6- and 1.0-in. thicknesses. It is presently under consideration for ASTM standardization. The test is similar in configuration and deep-crack acuity features to the side-bend FM test. The index of fracture-extension resistance is the energy absorbed in the propagation of the fracture through a specified distance. It features low cost, procedural simplicity, and applicability to all types of metals, including the transition temperature aspects for steels. An extensive, integrated data bank of DT test-defined metal properties has been evolved, which exceeds any other test in existence in terms of range of metals, section size effects, etc.

The DT test may be conducted for any thickness of interest; however, procedures have been evolved to relate thickness effects to the properties measured by the small sizes cited above.

Crack Opening Displacement (COD)

The COD tests are basically K_{Ic} tests which are extended into the range of plastic fracture, i.e., type 4 to 6 metals. The *plastic* crack-opening displacement is monitored by a clip gage or equivalent device. The basic premise is that the plastic displacement of the initial crack is indexed at the point of initial extension of the ductile tear. Since there is considerable scientific debate concerning the significance of the COD measurement, we shall restrict further discussions to questions of practicality. Requirements for fatigue cracking, testing for the specific section size of interest, and other high-cost aspects indicate severe restrictions for generalized engineering use of the method. It has been proposed that correlations could be made with the C_v test, as a route to evolving specification use for specific steels.

Charpy V—Fatigue Crack Notch

The addition of a fatigue crack at the tip of the V notch represents an attempt to transform the C_v test to a modern equivalent of a sharp-crack test. In effect, it represents a small DT test except for inadequate fracture-path length to establish the characteristic change in fracture mode. Procedural difficulties and cost of fatigue cracking indicate that it is not practical for general engineering use. This test should not be considered as a C_v test because the ASTM standardization for the C_v test is based on the V-notch geometry.

The only tests which have been utilized to evolve an *extensive* data bank of metal properties which can be referenced to structural mechanics analysis diagrams include

DWT - reference-index NDT temperature

C_v - as correlated to NDT temperature

DT - reference-index DT energy and R-curve slope

K_{Ic} - only for high-strength, brittle metals.

PART VI. ROLE OF STRUCTURAL PROTOTYPE TESTS

Refined limit analysis design procedures for buckling and other deformation failure modes have emerged from laboratory tests of structural configurations—beams, flat plates, cylinders, etc. Similarly, generalized structural mechanics analytical procedures for FSD must evolve from laboratory tests of structural configurations containing flaws. In either case, it is possible to evolve basic models, based on metal resistance or ductility parameters of the metal, and to arrive at first-order mathematical expressions of the structural response to loading from the models. However, proof and refinement of the models depend on laboratory experiments. For example, the R-curve model illustrated in Fig. 15 has been analyzed extensively from first principles for the case of brittle fracture and is being investigated on the same basis for the case of ductile fracture. However, in all cases the engineer must undertake to extend these scientific principles to practice by laboratory experiments.

Structural prototype tests involve the use of a sufficiently large section of metal such that crack-extension response effects can be determined. The emphasis is on measuring the levels of elastic or plastic stresses in regions sufficiently removed from the flaw to represent the levels of the *fracture-extension-force* system. The prototype test values are in terms of the usual designer's frame of reference—elastic stress, plastic stress, or plastic strain. The connection to fracture-extension-resistance properties, defined by the standardized laboratory tests, is provided by the reference index used to characterize the metal for data-bank purposes. This is analogous to relating the instability conditions of a flaw-free structure to the yield and tensile strength parameters derived from standardized laboratory tensile tests. The only difference is that a fracture-resistance parameter must be an added consideration for the case of flawed structures. The low effective strength of structures that have failed due to brittle fracture is not predictable solely by tensile test parameters.

The type of structure, flaw state, and nature of loading decide the type of structural prototype test that must be used. The metal characteristics, brittle or ductile, decide the reference index that must be used from the data-bank values.

The relationships between the range of *structural conditions* and the range of *metal parameters* are represented by the broad spectrum illustrated in Fig. 17. These relationships are best understood by the separation of structures into the following principal categories:

- *Rigid structures* represent configurations of low compliance which are load-limited to elastic stress levels. Fracture in such structures can only evolve in unstable-brittle mode. The appropriate parameters of reference are the nominal elastic stress of the structure and the level of flat R-curve metal properties. The R-curve level is best expressed by the CAT curve for the case of transition temperature considerations and by K_{Ic}/σ_{ys} ratio values for all other cases. Tension-loaded flat plates are ideal for prototype test purposes.

- *Compliant structures* represent configurations of low stiffness which are highly sensitive to local changes of this factor. For example, if the flaw is sufficiently large, the *local* driving forces in the flaw region may cause yield stresses to be exceeded due

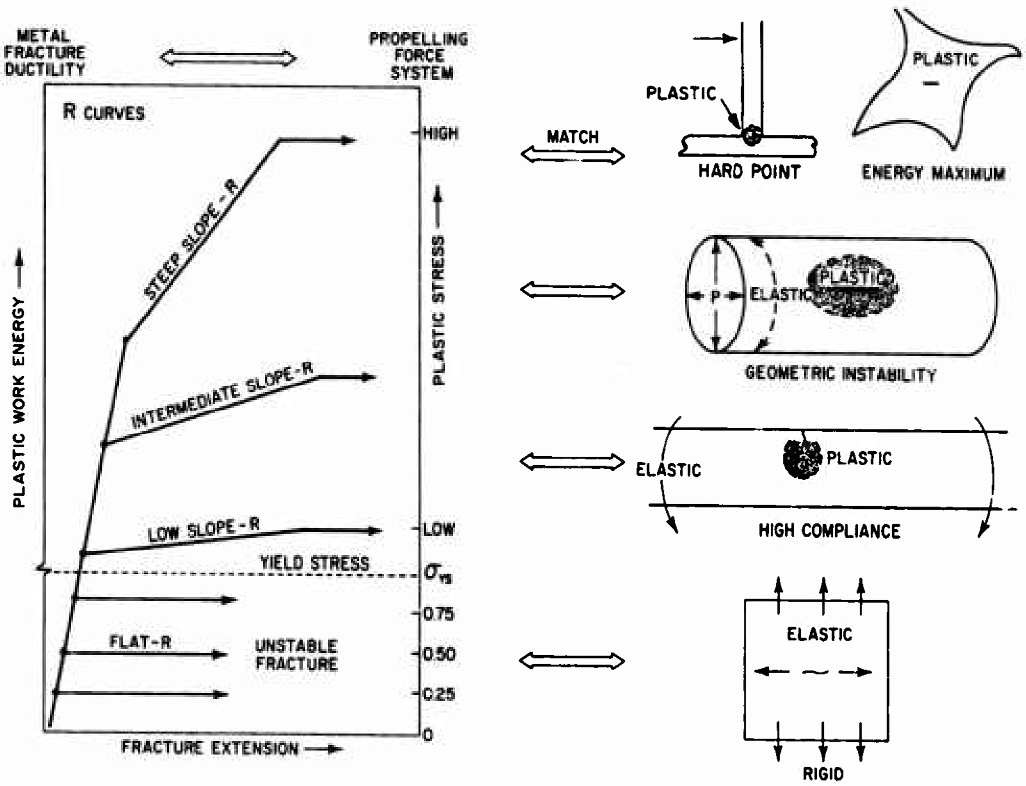

Fig. 17 - Range of structural problems involving increased levels of fracture-extension stresses. The bold arrows denote the correspondence to the range of metal R-curve levels and slopes. As the level of the fracture-extension stresses increases, there must be a matching increase of metal fracture-resistance properties.

to the increase in structural compliance. Thus, fracture extension may evolve for semi-ductile metals featuring low-slope R curves. Structural prototype tests which reproduce the compliance features are required. The metal reference parameter must be relatable to the R-curve slope.

• *Geometric instability* represents special cases of compliant structures featuring pressurization (pressure vessels, side-pressurized flat plates, etc.). If the flaw is sufficiently large, local plastic bulging will result. The plastic load driving forces acting in the bulge area may cause the extension of ductile tears. Structural prototype tests of tubular or plate-bulge features are required. The metal-reference parameter must be relatable to the R-curve slope.

• *Energy Maximum* represents structures which are intended to absorb finite levels of energy and are expected to enter into some degree of plastic deformation without failure by fracture (submarine hulls, highway guardrails, etc.). Component parts of ordinary structures may be subjected to similar conditions. For example, bending at hard-point locations may result in a high degree of localized deformation, while the general stress level of the structure as a whole remains in the elastic range. A wide variety of structural prototype simulations may be made. However, the practical deciding factor in such cases is the use of metals having the highest possible R-curve slope. The Explosion Bulge Tests (ECST) featuring cracks is an example of a structural prototype test directed to answering hard-point questions, for structures requiring highest reliability. It led to the concept of high shelf (high R-curve slope) in 1954 as the protection index.

The first use of structural prototype tests for developing structural mechanics analyses was a recourse to failed structures. We cite the ship failure correlations and other extensive failure correlations evolved in the period of 1950 to 1960. Most importantly, these correlations validated the ECST as an effective and reliable structural prototype test for defining the consequences of transition from brittle to ductile fracture. As such, they provided for extensive studies of wide varieties of new steels for which there was inadequate service experience.

The relationship of ECST and the Robertson CAT curve is illustrated in Fig. 18. The Robertson test provides exact structural prototype simulation in the elastic load range. The ECST served the additional function of extending the structural prototype test procedure to include the plastic fracture range (increasing R-curve slope). The more recent cylindrical-type ECST have been particularly valuable for indexing the degree of decrease of plastic fracture-extension resistance, from high shelf regions of the RAD to low regions involving brittle fracture (decreasing R-curve slope). These tests served to evolve the first rudimentary version of the RAD by 1965.

More recently, there has been extensive use of burst tests for flawed pressure vessels and gas transmission pipelines, which include failure problems involving geometric instability.

The move to more sophisticated structural prototype tests of flawed structures represents a recognition, by the field of structural mechanics, that factors other than brittle fracture of rigid structures are of serious consequences.

Because of the practical importance of the compliant structure—geometric instability case, additional discussions of prototype test procedures are of interest at this point. In particular, it explains why tension-loaded, flat-plate prototype tests and K_{Ic} test parameters are not pertinent to this problem. R-curve slope parameters must be used. Any attempt to practice plastic-limit design for points of hard connection must likewise be based on R-curve slope parameters.

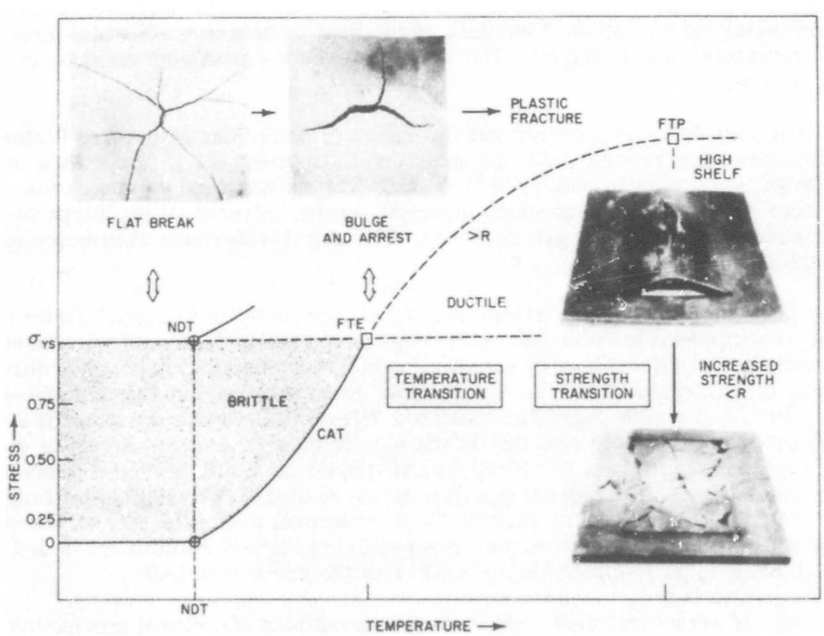

Fig. 18 - Examples of structural prototype tests and relationships to laboratory test parameters. The Explosion-Crack-Starter Tests feature sharp cracks resulting from the use of a brittle weld which cracks when high elastic-level stresses are reached. Note the sharp change in ECST fracture-extension characteristics between the NDT and FTE temperature points of the CAT curve. The full plastic ductility attained at the FTP temperature (shelf) is best indicated by the cylindrical-type ECST test which features a crack-extension path of uniform plastic strain level. With increased strength level (strength transition), the fracture-extension resistance decreases, as noted by the shattered test plate at the bottom.

A simple example, which applies to pressure vessel configurations, should illustrate the procedure. Cylinders containing flaws of known size are pressurized. The laboratory test index of fracture-extension resistance is expressed by DT energy or the equivalent R-curve slope. The metal index is then related to the prototype test measurement of the degree of elastic or plastic stress required to cause fracture extension. Very low resistance to fracture extension (flat R curve) as measured by the laboratory test translates to low stress (elastic) force field requirements for extension of the fracture in the structure, Fig. 19 (top). Conversely, high resistance to fracture extension (steep R curve) translates to bulging and gross deformation of the flaw region as the local force field requirement for extension of a ductile tear, Fig. 19 (bottom). The differences in failure mode involving prevention of shattering are of particular importance in many cases.

The history of the Fig. 19 examples is of interest, since it represents the first systematic investigation of this type (1959). The brittle failure developed at below-NDT temperatures and at nominal elastic hoop stresses, due to the presence of a long lamination. The production of the air flasks involved drawing through a die and then forging the end closures. Thus, metal laminations were oriented in the longitudinal direction and

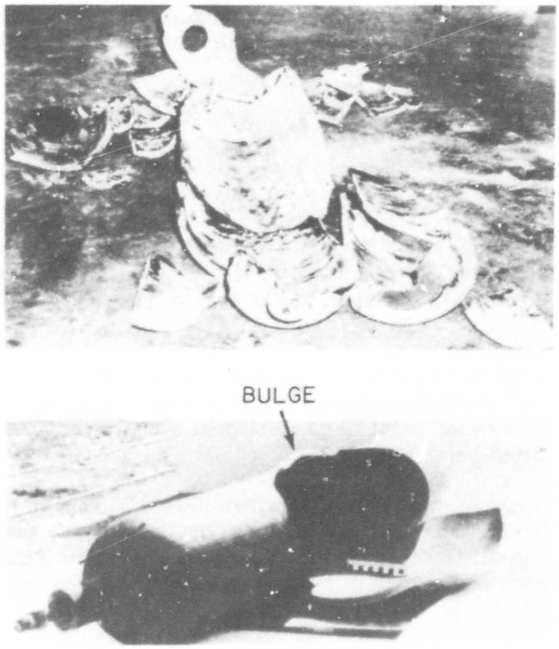

Fig. 19 - Illustrating a brittle service failure, due to the presence of a long longitudinal flaw (metal lamination) in a high-pressure air flask of 1-in. wall thickness. The failure developed at temperatures slightly below the NDT (flat R curve). The FSD problem involved obtaining maximum protection against the presence of metal laminations and prevention of missile-fragment damage to the surrounding area. The solution was achieved by using a metal of highest possible R-curve slope. Note the huge bulge (high fracture extension force) required for rupture in the presence of a 20-T long, 0.8-T deep, sharp-slit notch used for the pneumatic burst test. The intensity of energy release is indicated by the flattening of the ductile tear segment.

subjected to hoop-stress loading. In this particular case, the flight of sharp-brittle fragments could not be tolerated because of secondary catastrophic consequences. Nondestructive tests for detecting long laminations (tightly closed semicracks) were ineffective. The solution had to be found in the use of a steel of maximum R-curve slope. A double benefit ensued—maximum protection against failure due to long laminations and prevention of projectile effects. The results of burst tests for slit-flawed vessels (0.8 of nominal 1.0-in. wall thickness and of variant T lengths) are illustrated in a figure related to IAD discussions (Fig. 29).

Generalized structural mechanics procedures for buckling and deformation were evolved from limited structural prototype test investigations. Similarly, generalized elastic-plastic FSD procedures can be evolved from limited structural prototype tests of flawed type. In fact, there is already sufficient information available from structural prototype tests of this type (for cylindrical configurations) to characterize elastic or plastic load requirements for fracture extension for structural steels of 0.3- to 1-in. plate thickness. These relationships may be refined in the same manner that buckling and deformation failure mode definitions are continually improved on with time.

PART VII. ANALYSIS DIAGRAMS

General

The case for the use of analysis diagrams lies squarely in the realities of engineering design practices. A brief listing should suffice to illustrate that in reality FSD, or any form of design, must be practiced in terms of best estimates of the mechanical state and within reproducibility limits of metallurgical properties. In brief, it is *realistic* to recognize that:

- *The stress state is not always analytically definable with a high degree of exactness.* Previous discussions have emphasized that a broad spectrum of stresses ranging from nominal to yield stresses exist in conventional structures. Design- and fabrication-quality aspects must be considered.

- *The flaw state is extremely difficult to define.* This is true even for large flaws when they are tightly closed. Nevertheless, nondestructive inspection is usually driven to locating very small flaws when it is known that metal is sensitive to such flaws and, therefore, the margin of error is minimal. Such practices are unrealistic, to say the least.

- *The properties of the metal will vary within limits that are relatable to metal costs.* Statistical variations should be expected within a given plate and within a given heat or heat-treatment lot. Any attempt to decrease practical limits to very narrow "property bands" will result in large increases in cost.

In general, the laboratory fracture-test parameters are more exact than they need to be for most practical purposes. The real limits to which FSD can be practiced are dictated by structural mechanics, flaw state, and metallurgical factors—not by test specimen deficiencies.

These considerations apply to both conventional and highly sophisticated design practices that have been evolved by special Codes (nuclear pressure vessel, aerospace devices, etc.). The differences are of degree rather than kind—with increase in the allowable cost of the structure, the estimated limits can be refined. However, the engineer must always recognize that design is predicated on estimated *probabilities and confidence limits*.

Thus, we may eliminate most of the second-order contentions that complicate the literature of fracture research and proceed to evolve practical analysis procedures. The analysis diagrams provide easily understood, graphical presentation of flaw size—stress relationships for fracture initiation or propagation in structures. They are indexed to engineering stress parameters as well as to fracture-extension resistance parameters evolved from laboratory fracture tests. Thus, the structural mechanics connection may be made between metal properties, the estimated flaw state, and the estimated failure stress. The nature of the problem decides the appropriate analysis diagram that should be used and, therefore, the appropriate metals parameter.

Since the analysis diagrams provide best estimates of failure conditions, it is essential to remember that FSD is concerned with a non-event i.e., *exclusion* of failure by fracture. Thus, a reasonable reserve of fracture resistance must be introduced. The reserve factor is usually defined in terms of exceeding credible flaw sizes or credible stress levels.

For example, one may add reserve by increasing the *analyzed case* to a flaw size that is two to three times that which is credible. An equivalent method is to increase the analyzed case to a stress that may be 30 to 50% above the credible level. If these procedures do not provide adequate confidence, it is then essential to use a nonprovisional FSD procedure which provides positive safeguards for the case of prevention of brittle fracture. These various procedures will then indicate the minimum fracture resistance property of the metal that is required to provide the desired degrees of assurance that fracture is prevented. The degree of conservatism is fully under the control of the designer, as is conventional for any other design and metal selection procedure.

Once understood, the analysis diagrams are very simple to use. Analyses which would be impossible by any other procedure can be readily made. In particular, they provide for rapid trade-off analyses between stress, flaw state, and metal factors. Cost aspects involved in flaw inspection requirements can be traded off against higher metal costs, by selection of metals which provide insensitivity to the presence of large flaws, or positive resistance to fracture extension. Protection against fracture ordinarily lies with the metal—this is the lowest cost approach to FSD in the long run. Whenever possible, the metal selection should be based on exclusion of unstable fracture, i.e., by using nonprovisional FSD procedures which do not depend on flaw size considerations.

Descriptions

Four types of graphical FSD analysis procedures provide generalized coverage of fracture problems. The following is an introductory description of each type. For additional details, the reader is directed to the Bibliography.

Graphical Fracture Mechanics (GFM)—Fracture mechanics calculations of crack size—stress relationships are based on the expression

$$K_{Ic} = \frac{1.1}{\sqrt{Q}} \sigma \sqrt{\pi a} \quad \text{(for a surface crack in a tensile stress field),}$$

where

K_{Ic} is the fracture-extension resistance parameter measured by the FM test

Q is a crack geometry parameter derived from tables

σ is the nominal stress

a is the crack depth.

Ordinarily, the Q factor is bracketed by surface cracks of two general geometrical features: stubby (length-to-depth relationship 3:1) and long-thin (relationship 10:1). The long, thin crack features greater stress intensification and, therefore, is more severe. As a rough generalization, the stubby crack depth should be 20 to 30% deeper to provide corresponding effects in fracture initiation. Since natural crack geometries generally lie between these two extremes, it is conservative to reference the calculations to the case of the long thin crack. In any event, the calculations are approximate, and a concern with differences in Q factors deriving from crack geometry is not justified, when all questions of metal variations and problems of exact crack-size definitions are considered in engineering practice.

The complexities of calculations and adjustments for crack geometry may be avoided by graphical presentations of the above expression, as related to the realistic limiting conditions of long, thin cracks. The metal parameter may be normalized by the ratio K_{Ic}/σ_{ys}, which is proportional to the metal fracture resistance. K_{Ic} values do not have specific meaning unless referenced to the yield strength. For example, a metal of 50 K_{Ic} value and a yield strength of 50 ksi (ratio 1.0) will represent a much higher level of fracture resistance than a metal of the same K_{Ic} value, but of 200 ksi yield strength (ratio 0.25). Metals of the same ratio value will represent equal levels of fracture resistance; i.e., the critical flaw sizes at a specified stress level, relative to the yield stress, will be the same.

Graphical presentations of these FM relationships (GFM) provide easily understood plots, Fig. 20. The curves of the GFM plots relate K_{Ic}/σ_{ys} ratios to critical crack depths for four levels of relative stress—0.25, 0.50, 0.75, and 1.0 σ_{ys}. The K_{Ic}/σ_{ys} ratios range from 0.1 to 2.0 in steps of 0.1. For most purposes, the lowest ratio limit for structural reliability is 0.3. Below the 0.3 ratio, the critical flaw sizes are too small to permit reliable use of any type of known nondestructive inspection. We may consider this ratio as a lower-bound cutoff for practical reasons.

The section size-related upper limits for the ratios are indicated by the vertical dashed lines. For example, ratios in the range of 0.3 to 0.63 apply for plates of 1-in. section size; 0.3 to 1.0 ratios apply for 2.5-in. section size; 0.3 to 1.5 ratios apply for 6-in. section size. The validity of metal values reported as ratios above 1.5 is questionable because of deviations from the established practices generally used in making these measurements. There is no practical justification for FSD analyses in "finer cuts" than 0.1-ratio steps and 0.25-σ_{ys} relative stress steps. Calculations involving finer cuts may be made, but they will not be meaningful in practice.

The K_{Ic}/σ_{ys} ratios indicate different levels of flat R curves, ranging from type 1 to 3, in ascending order of the ratio values. Fracture mechanics tests of increasing section size must be used to measure metal properties involving increased ratios. The vertical dashed lines of Fig. 20 also indicate the *minimum* section size that must be used for the K_{Ic} laboratory tests.

It should be noted that K_{Id}/σ_{yd} ratios may be substituted in the GFM plot for cases involving rate-sensitive steels (transition temperature problems). However, there is no practical way to define K_{Id} and σ_{yd} (dynamic yield stress). Thus, the research laboratory definitions of such parameters cannot be translated to practical engineering use. In brief, FM procedures are not practical for engineering use in the transition temperature range of steels. The K_{Id}/σ_{yd} ratios rise sharply from a 0.5 value at the NDT temperature following the course of the CAT curve. Correlations of this type are provided in the references.

Fracture Analysis Diagram (FAD)

Because of the described limitations of FM procedures, the FAD (Fig. 21) represents the only practical FSD procedure that has been evolved for transition temperature problems. It is validated by long-term, international engineering use. It is fully rational on terms of K_{Id} analyses.

The metal index parameter is the NDT temperature, as defined by the DWT or by other NDT-correlatable tests. The CAT curve is indexed to the NDT temperature by the Δt temperature scale. The principal reference points are the NDT, the 0.5-σ_{ys} CAT the 1.0-σ_{ys} CAT (FTE), and the FTP.

The engineering reference scale is the relative stress acting across the flaw, expressed as 0.25, 0.50, 0.75, and 1.0 σ_{ys}. The effects of absolute flaw sizes ranging from <1.0 in. to 2 ft are indicated by the system of flaw size curves. The extension of the curves into

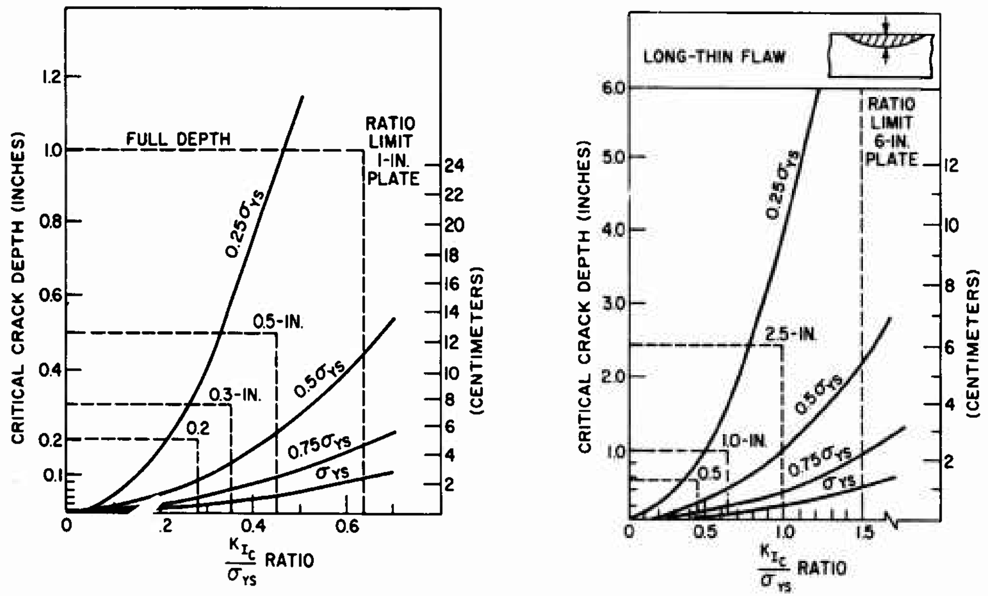

Fig. 20 - Graphical plot of crack size—relative stress calculations indexed to K_{Ic}/σ_{ys} ratios. The plot relates to the case of a long-thin crack geometry. The Graphical Fracture Mechanics (GFM) analysis diagram provides a simple form of cross-reference between metal properties (ratio), critical crack depths, and nominal elastic stress level. The cutoff limits represent the highest ratio value that can be measured for a plate of specified thickness. The range of critical crack depths, for metals of specified maximum ratio values, are indicated by the corresponding horizontal dashed lines. Note the very small critical crack sizes associated with metals of low ratio values.

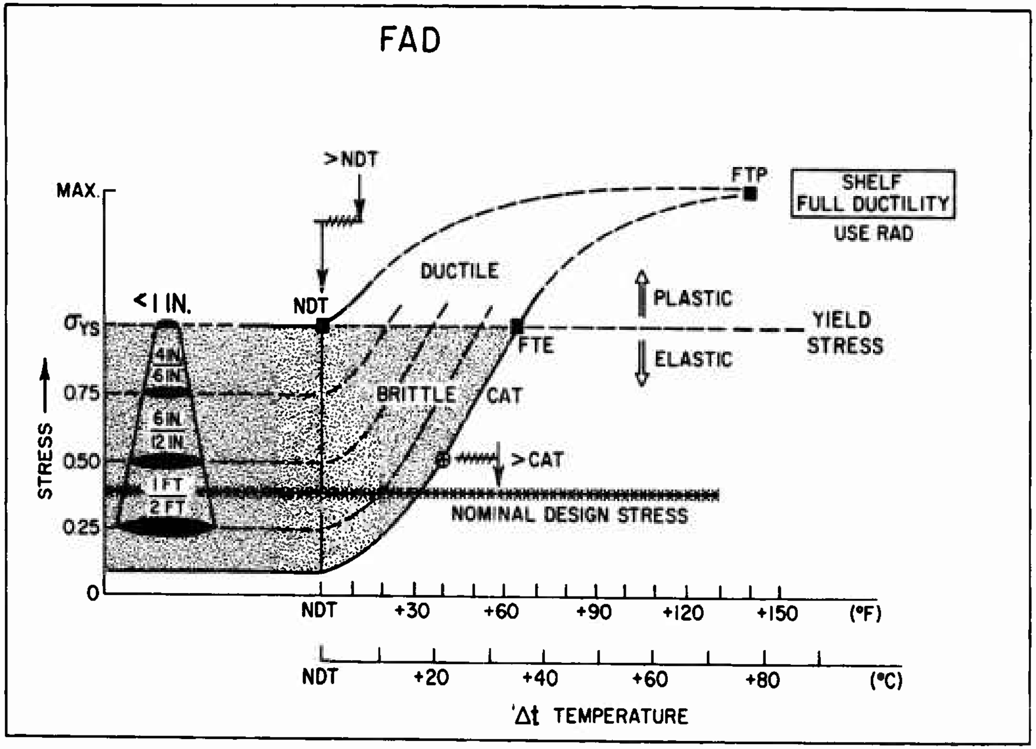

Fig. 21 - Fracture Analysis Diagram (FAD). In practical FSD use, primary reference is made to two critical design points. Design based on a small temperature increment above the NDT temperature is provisional, in that protection is provided against fracture initiation due to small flaws located at points of yield-level stresses. Design based on a small temperature increment above the 0.5 σ_{ys} CAT is nonprovisional, because it precludes extension of brittle fracture through elastic stress fields of usual design level, irrespective of flaw size. The FTE and FTP design points are ordinarily used for conditions involving high compliance or geometric instability (plastic fracture).

the plastic load region indicates transition to semiplastic and finally to fully plastic fracture (FTP). The plastic load scale is relative and is not specifically indexed.

The diagram shown in Fig. 21 relates to section sizes in the range of 0.5 to 3.0 in. An expanded diagram is available for section sizes ranging from 6.0 to 10 in. It involves a shift of the FTE point by a temperature increment of 70°F (40°C). The NDT reference point is not affected by section size; i.e., the CAT-curve rise begins at the NDT temperature for all section sizes. The effects of large increases in section size are to decrease the slope of the CAT-curve rise with temperature.

The elastic-load fracture portion of the diagram provides all the information required to resolve brittle fracture problems of transition temperature type. Because of the sharp transition effect of temperature increments above the NDT temperature, only four reference points suffice for most design purposes—NDT, midpoint of NDT-to-FTE, FTE, and FTP. The FTP point indicates the temperature of full (maximum) "shelf" ductility.

The NDT temperature of the steel defines the absolute temperature scale location of the diagram. In practice, reference is then made to the anticipated lowest service temperature. Any desired point of fracture resistance is attainable, at the lowest anticipated service temperature, by using a steel of desired NDT temperature features (Fig. 22). In effect, a selected design point in the diagram is located at the lowest service temperature by selection of the steel.

It should be noted that the Δt temperature reference scale is equivalent to an R-curve scale. R curves for type 1 to 3 metals apply in the NDT to FTE range. Type 4 to 6 metal R curves apply in the FTE to FTP range, depending on the level attained at full ductility.

The relationship of temperature transition features for the DT test to the CAT curve of the FAD are shown in Fig. 23. The FTP (shelf) value is an independent variable; i.e., it depends on metal quality factors which are not related to the specific range of the transition temperature. The DT shelf energy is used in the RAD plot for steels. The decrease in DT energy with increased strength level is defined as the strength transition.

The combined effects of temperature and strength transition factors are illustrated schematically by the three-dimensional diagram in Fig. 24. The R-curve slopes change from steep to flat in following the downward course of the temperature and strength transitions.

Ratio Analysis Diagram (RAD)—The RAD procedure applies generally to all metals which are not rate sensitive. For steels it applies for the shelf, i.e., the FTP temperature region. As noted in Fig. 25, the reference metal index is the DT energy value and the K_{Ic} scale (when applicable). The K_{Ic} relation to metal yield strength provides for inserting K_{Ic}/σ_{ys} ratio lines. The system of ratio lines is interpreted by means of the GFM plot described previously.

The C_v scale indicates an approximate correlation to the DT energy scale. It represents the C_v shelf energy value. The C_v scale provides a general reference whenever other data are not available. It should not be used for FSD purposes, particularly in view of the fact that temperature location of the C_v shelf is not a reliable index of the true transition temperature range. Thus, we shall not repeat this scale on the other RAD plots.

There are two metallurgical-quality boundary curves which indicate the upper and lower limits of DT energy or K_{Ic}/σ_{ys} ratios for any yield strength of interest. The upper curve is defined as the technological limit. It is based on the latest information (1970) evolved from metallurgical research. The sharp drop of this limit curve (or any other intermediate curve) with increasing strength level is defined as the strength transition.

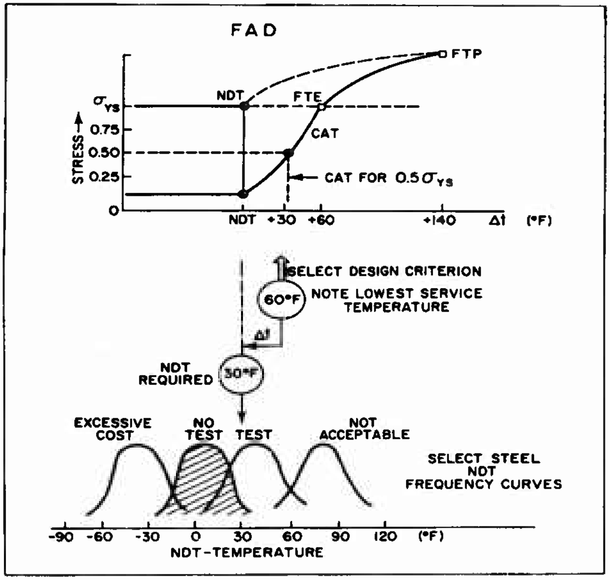

Fig. 22 - FAD procedures for selection of steels required for specific structural applications. The "test" and "no-test" notations for the NDT frequency plots indicate requirements for use of NDT-indexing tests in the purchase of the steel. If the production quality range of the steel is clearly below the desired NDT temperature, there is no need for testing, except on a statistical (limited) basis.

The upper bound is important because it indicates that there is no purpose in attempting to design on metal properties beyond attainable limits for the strength level.

The K_{Ic}/σ_{ys} ratio lines "cut off" at specified section sizes; for example, for 1-in. plates the highest measurable ratio is 0.63. Metal value points (DT energy) which lie above this ratio line indicate type 3 to 6 metals, depending on the level above the line. Metal value points (DT or K_{Ic}) which lie below the ratio cutoff line indicate type 1 to 3 metals. With increased section size, the K_{Ic}/σ_{ys} ratio cutoff lines move to higher ratios, as defined by the GFM plot. This simply means that type 1 to 3 metal behavior is moved to higher DT energy and K_{Ic} values, in keeping with FM definitions of section size effects.

The most important feature of the RAD is that it quickly indicates whether a metal is susceptible to brittle fracture and, therefore, the limits to which GFM procedures can be used. The region of the diagram which lies above the ratio line cutoff for the section size does *not* permit use of FM because type 4 to 6 metal (semiductile to ductile) conditions dominate. With increasing DT energy, there is an increase in the R-curve slope, i.e., a climb from type 4 to 6 metal characteristics. The R-curve slope relationships to the RAD are illustrated in Fig. 26.

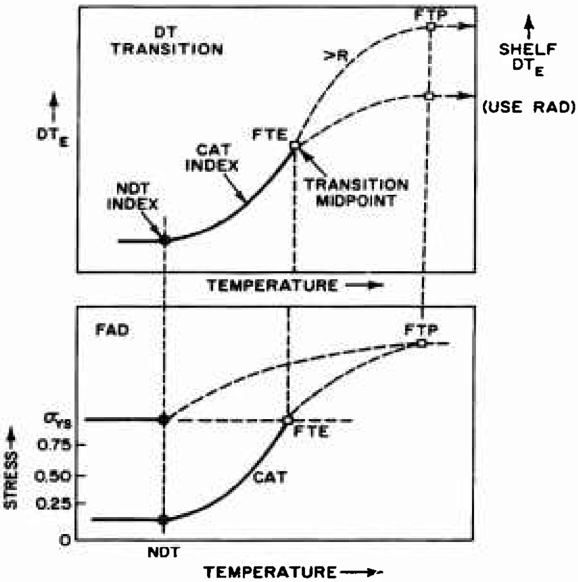

Fig. 23 - Relationship of DT test transition to the CAT range, i.e., NDT to FTE. The DT test procedure provides an inexpensive method of defining the temperature location of the CAT curve. The DT test also provides a definition of the increased slope of the R curve in the FTE to FTP (shelf) temperature range. Decreases in shelf-level DT energy with increased strength level correspond to decreased R-curve slopes related to the strength transition (see RAD).

Experimental verification of the increased R-curve slopes with increases in the RAD-DT energy location above the ratio line is provided in Fig. 27. The figure illustrates the case for a 1.0-in.-thick plate which has a 0.63 ratio cutoff. Steels of 1.0-in. thickness were heat treated to various levels of yield strength, and the DT energies were plotted as indicated by the circled points. Point B or any other point that lies below the ratio line for this thickness should represent a brittle steel featuring a flat R curve. Such materials should be characterized by the K_{Ic} scale.

The metal DT energy points which lie in ascending order above the ratio line should relate to R curves of increasing slope. The figure also presents fracture-extension-increment DT test (see Fig. 14) data which define the R-curve slopes. The excellent relationships of R-curve slope to the DT energy scale of the RAD should be recognized as evolving from the fact that the standard DT test measures the DT energy for a fracture run which is several times the section size. In effect, it "reports" as a point on the R-curve plot. The DT energy point must rise with increase in fracture-extension resistance. If an RAD plot of the metal is available, there is no need to conduct R-curve tests—the location of the DT energy in the RAD plot automatically defines the degree of R-curve slope.

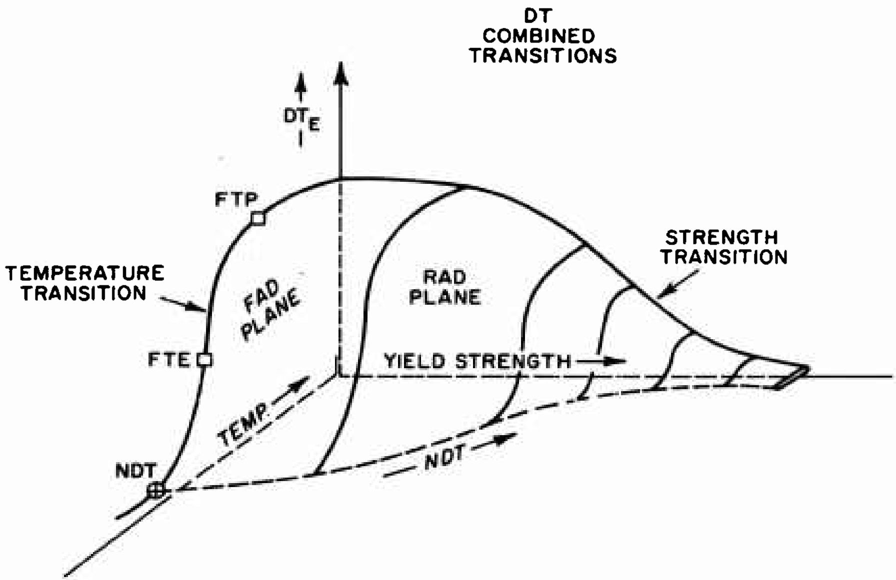

Fig. 24 - Three-dimensional representation of temperature and strength transitions for steels. Note that ultrahigh-strength steels are relatively insensitive to temperature effects. Nonferrous metals, such as aluminum and titanium alloys, are relatively insensitive to temperature effects for all strength levels.

In practice, the RAD may be used to select the highest strength level that should be used for specified (desired) levels of fracture resistance. For strength levels involving a broad range of metal quality, it provides a DT energy index for lower bound (minimum) specification values. For most practical purposes, metals falling significantly below the ratio values for the section size will require repeated proof test during the service life to validate the structure (crack growth may evolve). Metals that fall above the ratio line for the section size should be considered safe with respect to unstable fracture.

An important aspect which emerges from the RAD is the steep fall of fracture resistance in narrow ranges of yield strength. The importance of cutting back to lower strength levels, to avoid falling below the ratio line for the section size, becomes evident, particularly for metals of section sizes less than 1.0 in. A cutback of only 20 to 30 ksi (8 to 15 kg/mm^2) may suffice to provide assured fracture safety and to *allow* increasing of the absolute stress level applied to the structure, with retention of safety.

Instability Analysis Diagrams (IAD)—These diagrams are in the process of evolution (fifth generation FSD). They relate to the plastic load regions of the FAD and ductile fracture regions of the RAD. In these regions, the metal properties range from type 4 to 6.

The previously described diagrams are useful for defining flaw size—stress conditions for fracture extension involving brittle metals. For this case, it does *not* matter if the structure is rigid or compliant. The independence of type of structure and load response results from the fact that fracture is initiated and translated in elastic stress fields.

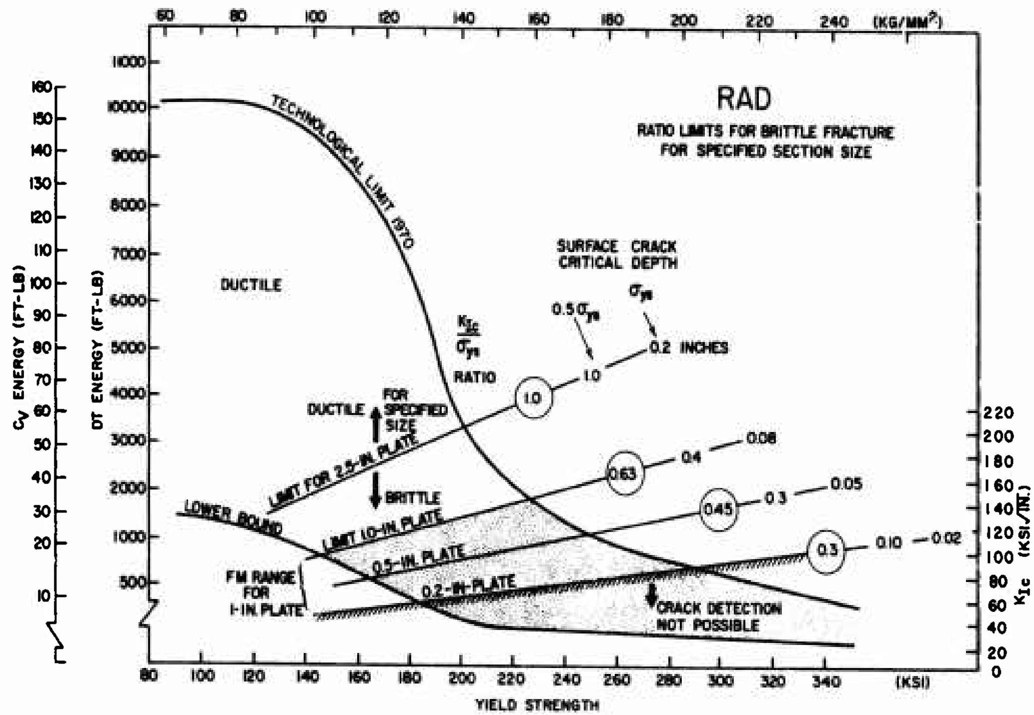

Fig. 25 - Ratio Analysis Diagram (RAD). Combines metal data-bank summarization (upper and lower bounds) with a structural mechanics interpretive system based on K_{Ic}/σ_{y}, ratio lines. The lower (dashed) ratio line indicates limits of reliable crack inspection. The notation of "FM range" denotes the range of K_{Ic} values that can be used for practical flaw size—stress calculations for 1.0-in. thick plates. Above the ratio line for the specified thickness, the metal may propagate fracture only at stresses above yield levels (FM not applicable). Below the 0.3 ratio line, FM calculations indicate that proof testing will be required to ensure that very small cracks are not present. The critical crack sizes are derived from the GFM plot of Fig. 20.

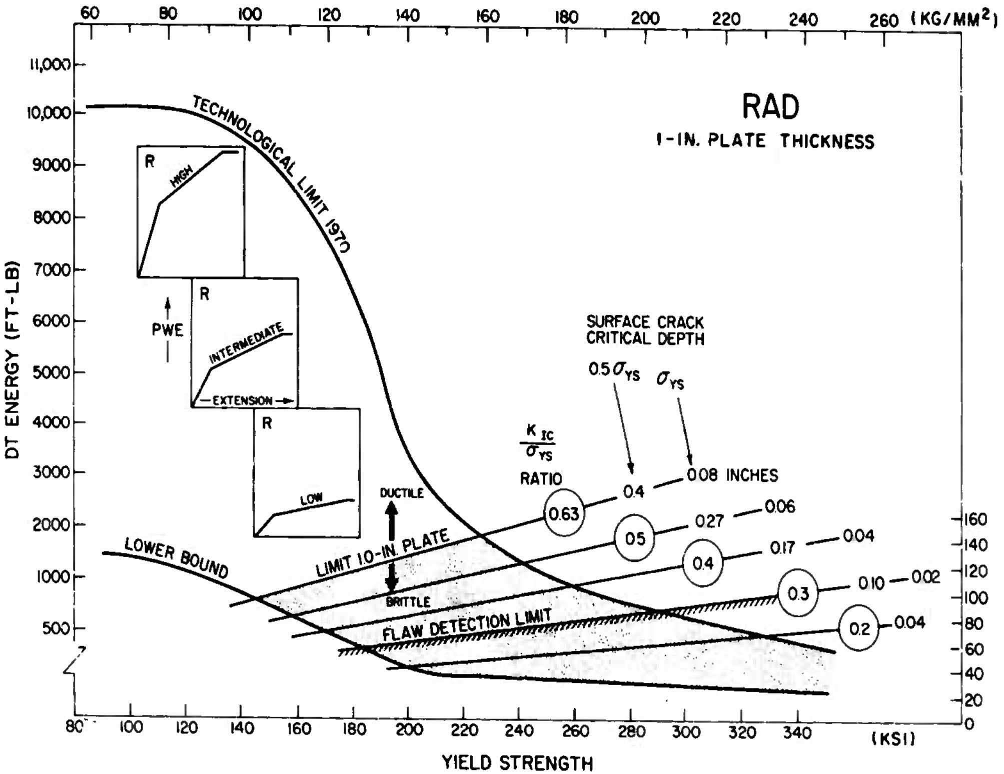

Fig. 26 - Illustrating FSD use of the RAD by presentation of mechanical factors related to 1-in.-thick plates. Decreasing metal fracture resistance below the 0.63-ratio line (which is the upper limit for 1-in. thickness) defines a rapid decrease in critical crack sizes. Increasing metal fracture resistance above the subject ratio lines defines R curves of increasing slope, as noted. Similar analyses may be made for metals of 0.2, 0.5, and 2.5-in. section size (see Fig. 25). The ratio line for the section size always defines the transition zone between unstable and stable fracture. Thus, section size effects may be analyzed in a simple fashion.

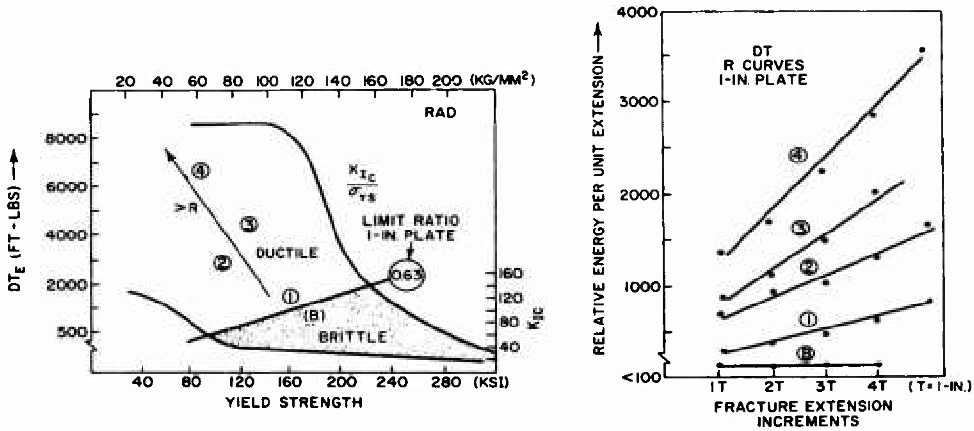

Fig. 27 - Experimental R-curve slope data for 1-in.-thick plates based on DT test, fracture-extension-increment procedure (see Fig. 14). Note that a flat R curve is obtained for metal B which is below the 1-in. section-size ratio line. Increased R-curve slopes are recorded as the DT energy position of the steels rises in the RAD.

Since ductile metals require the local application of plastic stresses for fracture extension, it does matter if the structure is compliant and if geometric instability is possible. *Local* plastic driving forces may then evolve, and fracture extension in a ductile mode becomes possible at nominal elastic stress levels for the structure as a whole.

IAD diagrams are being evolved by the use of structural prototype tests of generic configurations, such as flawed tubes under internal pressure, flawed flat plates under uniformly applied pressure, etc. The structural prototype tests data may be recorded as the nominal hoop stress value or the local plastic strain level at a specific point in the geometrically unstable (bulge) region of the flaw. The metals parameter is the R-curve slope, as defined by DT test energy.

Figure 28 presents a generalized description of the IAD features expected for tubular configurations. The plot assumes a metal of 1-in. thickness which is not involved with transition temperature effects. The starting point is the zone of flat R curves which is scaled in terms of ratios up to the 0.63 limit for this section size. Within this zone, the effects of crack size on the hoop stress level for fracture may be defined directly from the GFM plot (Fig. 20). The critical crack sizes are related to the crack depth (as a fraction of the wall thickness—0.1 T, etc.) for a 0.5-σ_{ys} stress level. Note the decrease in crack depth with decrease in ratio value of the metal.

We then consider the case of a through-thickness crack (1T) and note that the failure level of the hoop stress is in the order of 0.3 σ_{ys} at the ratio limit value of 0.63. This analysis provides the stress-level starting point for the "fan" of crack-size curves relating to various lengths in proportion to thickness. The main emphasis of this discussion is to document that GFM predicts a low-level-stress starting point, at the brittle to ductile transition, for flaws of 1T dimension or larger.

The important question to be answered by the IAD plot is the slope of the hoop-stress failure curves, as a function of increased R-curve slope. For purposes of the idealized

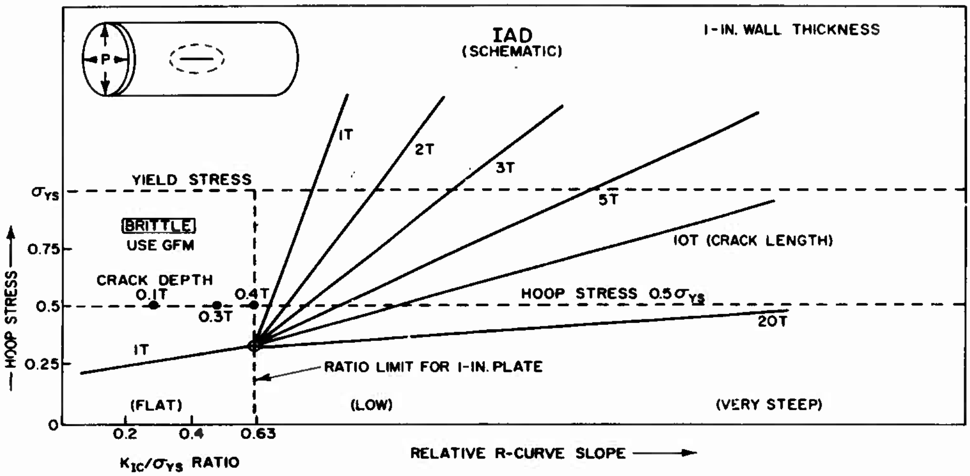

Fig. 28 - Idealization of IAD plots for metals not involved with transition temperature effects. The plot assumes a tube configuration of 1-in. wall thickness. See text for discussions.

model, we indicate that a small increase in R-curve slope should cause a rapid rise in failure stress for flaws of small T length (say 1 to 3T). Conversely, extremely long flaws (say 10 or 20T) should show relatively slow rise of the hoop-stress failure curves with increased R-curve slope. The mechanical advantage of the huge instability regions is too high to be offset greatly by increased metal ductility.

IAD relationships for the case of the transition temperature region should be indexed to the FAD flaw-size curves (below NDT) as the starting point. The slope of the "fan" of T-length flaws in the NDT-to-FTP region is related to the increase in R-curve level and slope in this region. It is also a function of the specific R-curve slope which is developed at the full-ductility (FTP) shelf point. The special form of the IAD fan for the case of the transition temperature range evolves from consideration of K_{Ic} and K_{Id} relationships for rate-sensitive metals (see references on FM analysis of the FAD plot). The experimental observations are predictable from K_{Ic} -K_{Id} analyses of this type.

The plot in Fig. 29 presents data of burst tests for flawed pressure vessels of 1-in. wall thickness (Fig. 19 air flasks). The points marked B and D refer to the two flasks illustrated in Fig. 19, i.e., brittle and ductile. Because of the huge 20-in. (20T) length of the flaw, there is little rise in the hoop stress at failure. Note the huge plastic bulge developed for the case of the ductile flask shown in Fig. 19. Test data were obtained for flaws of 10T length. Estimates are provided for the case of 1, 3, and 5T flaws, as indicated in the figure.

Due consideration should be given to the level of service hoop stress which applies for the case of the transition temperature IAD (Fig. 29), as well as for the case of the metals not involved with transition temperature effects, Fig. 28. If a hoop stress of 0.5 σ_{ys} is considered as the service condition, it evolves that an R curve of intermediate slopes will provide protection against geometric instability due to flaw sizes in the range of 5 to 10T dimensions. These "model" presentations merely highlight the procedures

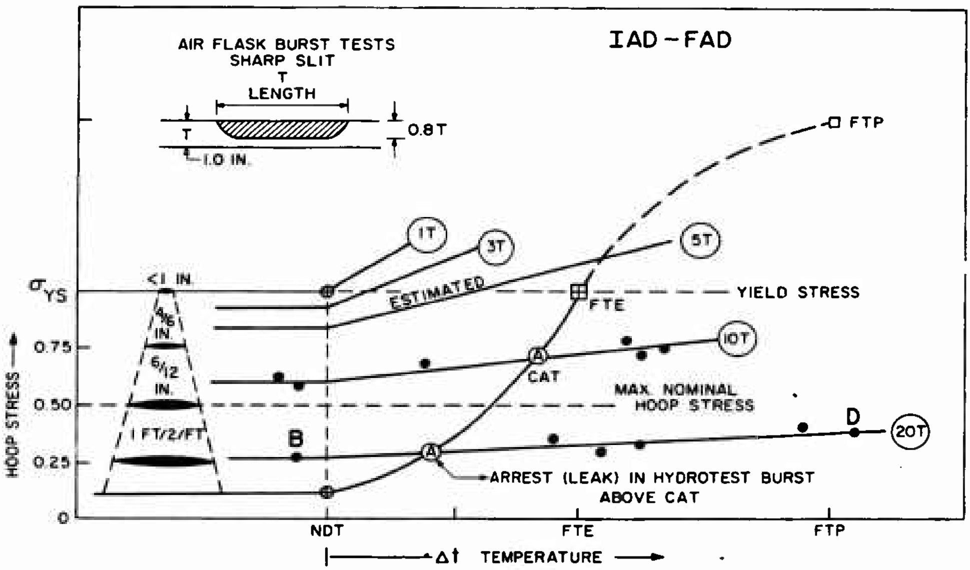

Fig. 29 - Representative IAD plot for the case of steels in the transition temperature range. The points marked B and D relate to the brittle and ductile pressure flasks of Fig. 19. See text for discussions.

to be used. Experimental data are required to evolve specific IAD plots. However, the procedures to be used are now evident.

PART VIII. PREDESIGN SELECTION OF APPROPRIATE FSD PROCEDURES

The foregoing discussions have emphasized that the nature of the fracture-extension-force system must be estimated as a prerequisite for the selection of the appropriate FSD procedure. The spectrum of force systems is described by Fig. 17 in relation to types of structures and the nature of loading. Estimates of this type are not difficult to make, within limits required for preliminary assessments. In general, the problems resolve to

- Propagation through elastic stress fields in regions of smooth geometry

- Propagation through plastic stress fields of localized nature; regions of geometric transition, hard-points, etc.

- Propagation *within* regions of geometric instability resulting from the presence of a crack—pressure vessels, side-pressurized plates, etc.

Most of the FSD literature has been concerned with the problem of unstable fracture, i.e., propagation through elastic stress fields. When assessment is made that these conditions apply, the choice of the analysis diagram resolves to the FAD for the case of transition temperature problems and the RAD (GFM) for the case of strength transition problems.

At this point, it is essential to decide on a design philosophy, i.e., whether a *provisional* or *nonprovisional* FSD solution is desired. Provisional solutions must be based on limiting stress levels or flaw sizes so as to prevent attainment of critical combinations which lead to fracture initiation. Nonprovisional solutions depend on prevention of fracture extension through elastic stress fields of specified level, i.e., they do not depend on flaw size aspects.

The FAD and RAD analytical procedures provide for FSD solutions of both provisional and nonprovisional type. Most importantly, the engineering feasibility and confidence levels which evolve from either approach are readily assessed. These assessments require consideration of statistical variances in metal properties. See discussions in the summary of this report.

In the case of localized plastic-level force systems, it is necessary to consider the degree of plastic-strain intensification due to crack length. A significant separation may be made in terms of relatively short and very long flaws in comparison to section size. The use of type 5 metals should solve most problems involving limited compliance features. These solutions are obtained with high assurance of safety and without regard to specific differences in crack sizes of usual scope, i.e., relatively small flaws.

In the case of geometric instability for tubular configurations, IAD plots are required, but only if the metal characteristics are in the type 4 to 6 range. If the metal is of type 1 to 3 the usual FAD-RAD procedures apply. The practical solution, for most cases involving geometric instabilities of high plastic-load intensity, is to use a metal of highest possible R-curve slope. In many cases this is not an expensive solution. We shall refer to this simple procedure as *maximum possible* protection.

The preselection process is simple. Ordinarily, one factor dominates and points to the analysis diagram that should be used. The metal-fracture parameter is then decided by the selection of the analysis procedure.

The FAD plots are general to steels in the transition temperature range. In this case it is essential to consider the lowest service temperature and NDT data-bank properties for steels of interest. The plots in Fig. 32 provide general guidance for preliminary assessments. RAD plots exist for steels, titanium, and aluminum alloys. Figures 30 and 31 illustrate RAD plots for the two nonferrous metals. In this case the range of metal properties is indicated directly by the metallurgical limit lines. Thus, assessments of metal requirements may be made with ease.

In the case of metals for which there is no established RAD plot, it is necessary to proceed as follows:

- Conduct DT tests to establish the R-curve slope for the specific thickness and strength range of interest.

- A flat R curve indicates K_{Ic} properties. Conduct K_{Ic} tests to determine the K_{Ic}/σ_{ys} ratio and refer to the GFM plot.

- A rising R curve indicates type 4 to 6 properties, depending on slope.

- The slope will indicate the relative RAD position above the ratio line for the thickness, even though the RAD plot is not available.

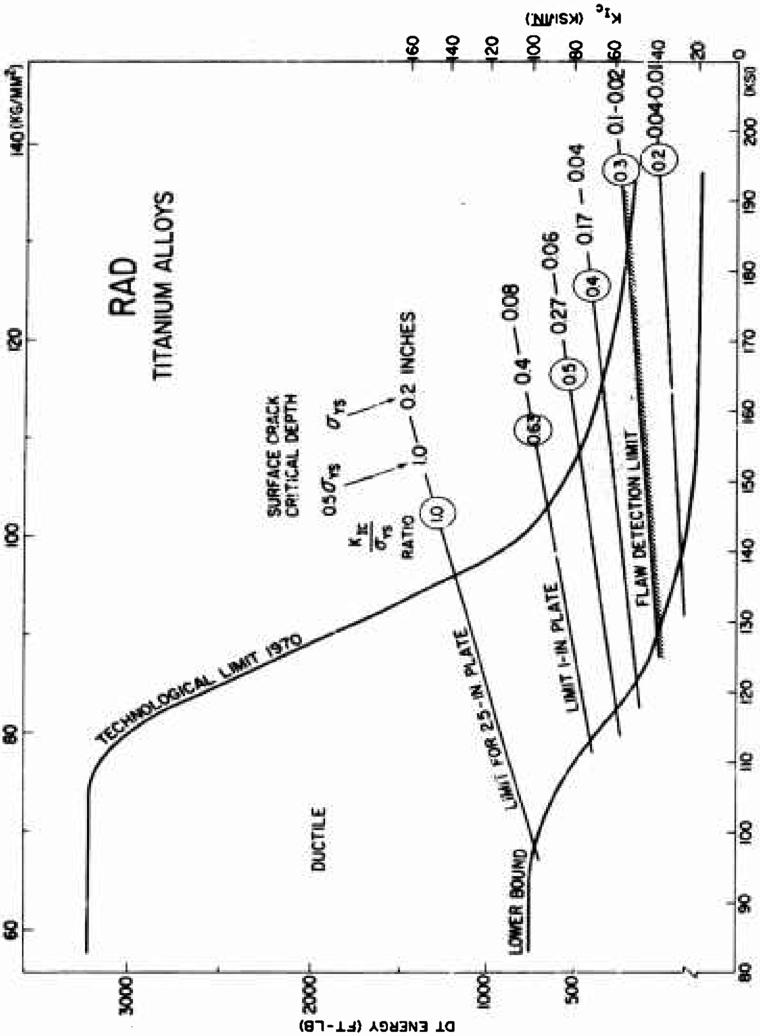

Fig. 30 - RAD for titanium alloys produced in 1- to 3-in. plate thickness

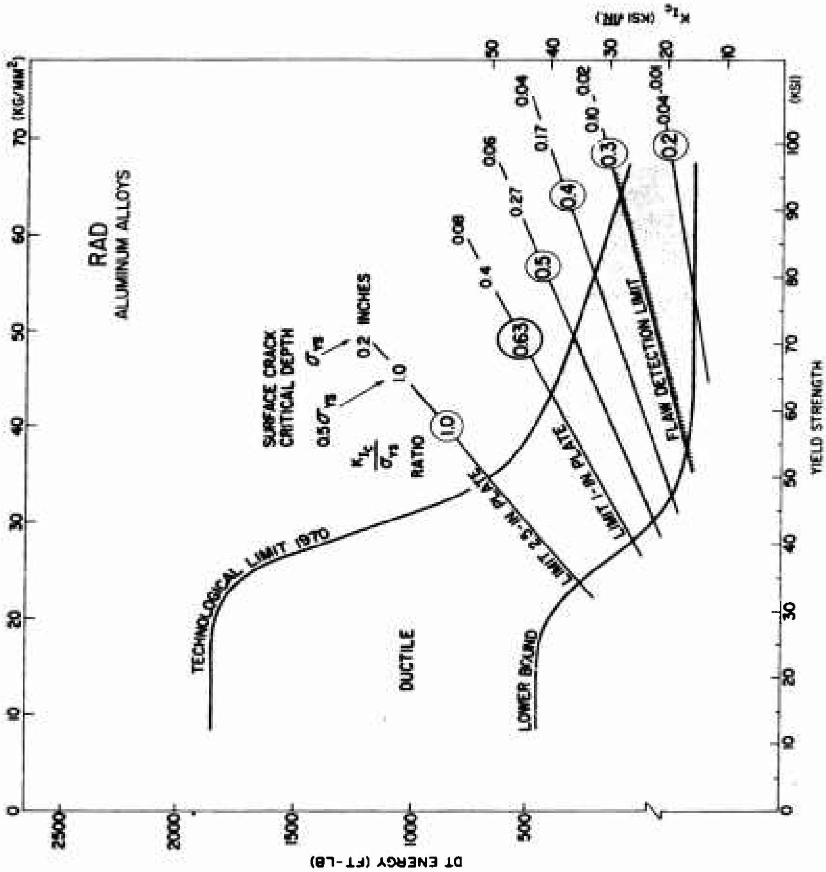

Fig. 31 - RAD for aluminum alloys produced in 1- to 3-in. plate thickness

• Sufficient preliminary information is provided at this point for the case of rigid structures and for problems involving various degrees of compliance or local geometric instability.

These discussions serve an additional purpose. It is suggested that the engineer may become adept in the use of FSD by problem-solving exercises of this type for hypothetical cases. The simplicity of the analyses procedures will become apparent. Most importantly, it will become obvious that the solutions normally tend to gravitate to the selection of metals which provide for assured protection against the extension of unstable fracture; see discussions in the Summary.

PART IX. METALLURGICAL ASPECTS OF FSD

The role of the metallurgist in FSD is to "design" the metallurgical microstructure and other quality factors, so as to evolve metals of improved characteristics. The problems generally resolve to two principal aspects:

• Lowering the transition temperature range of steels while minimizing cost for the degree of "shift" to lower temperatures.

• Increasing the yield strength of any metal, with minimum decrease in fracture resistance and minimum cost for the improvement.

The metallurgical factors are now well understood and the fracture resistance levels that are attained are definitely not a matter of chance. The growth in specific knowledge of *metallurgical* design factors parallels the time of evolution of the FSD generations described previously. Prior to this time, the metallurgist practiced rudimentary metal design based on C_v test data without specific information as to the structural significance of the degree of improvement attained. The importance of the evolution of rational standardized laboratory tests, and their correspondence to structural design factors, as expressed by the analysis diagrams, cannot be overstated.

We shall illustrate the case by describing events covering the period of 1948 to 1952. The point of reference is provided by Fig. 32, which summarizes the present knowledge of NDT frequency-distribution curves for weldable structural steels.

• Distribution A represents the NDT quality range of the World War II ship steels (see Fig. 4).

• Distributions B and C document 1948 to 1952 improvements obtained by adjusting the C/Mn ratio and by normalizing heat treatments.

• Distribution C also indicates the *apparent* shift in the 15-ft-lb C_v index obtained for the B-type steels. In effect, the C_v test indicated a degree of improvement that was not real.

The point to be made is that an enormous, amount of research on metallurgical factors was conducted from 1948 to 1952 for ship steels, on an erroneous premise. The implications to ship structure performance were in error. While *trends* of improvement factors were valid, the implied degree was incorrect. For ship service at 20 to 30°F (-10 to 0°C) the C_v test predicted safe performance for the B-type steels. The NDT frequency plot indicated that approximately one-third of the population would not be fracture-safe in the presence of small flaws. This prediction was proven by later events.

The frequency plots of Fig. 32 represent a partial NDT data bank for weldable structural steels. Most importantly, they indicate the specific metallurgical factors required to shift

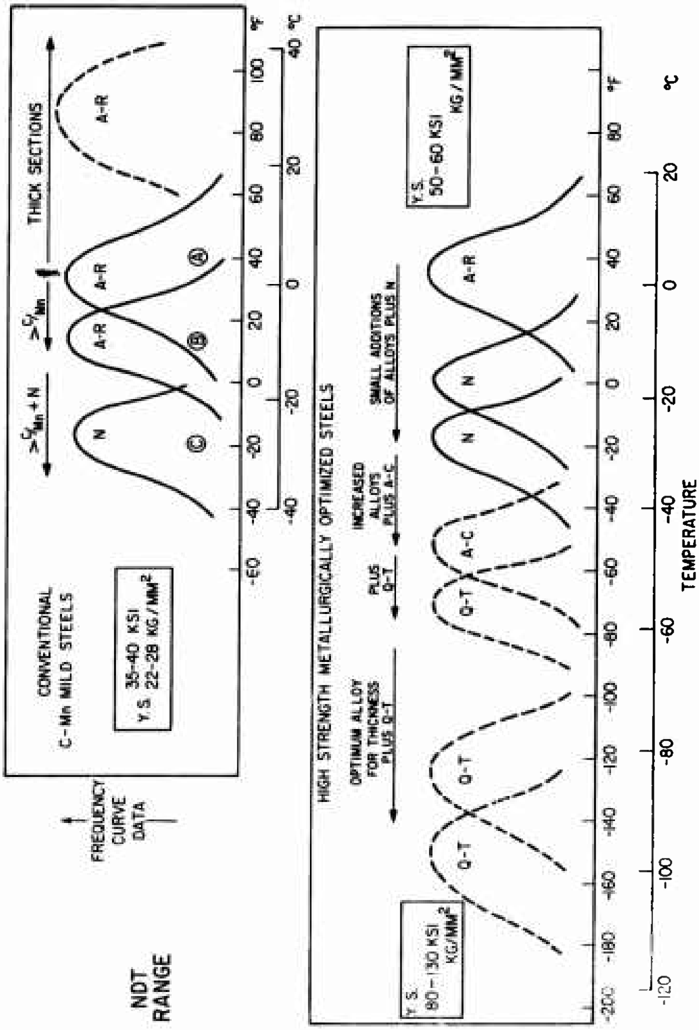

Fig. 32 - Representative NDT frequency distributions of commercial structural steels. The figure notations relate to alloy contents and heat treatment factors as follows: <C/Mn, decreased C to Mn ratio; A-R, as rolled; N, normalized; A-C, accelerated cooling; and Q-T, quenched and tempered.

the NDT (and, therefore, the FAD) to lower service temperatures. Note that steels are available with NDT temperatures in the range of -180 to -140°F (-115 to -90°C). This means that full ductility (FTP) is attained at subzero temperatures.

The metallurgical factors which determine the transition temperature range and those which determine the strength transition are entirely different. The transition temperature range is decreased by "suppressing" the incubation of cleavage microcracks. The strength transition is shifted to higher strength ranges by "suppressing" the development and enlargement of plastic microvoids. In this respect, steel cleanliness (absence of nonmetallic inclusions) is paramount; cross-rolling to minimize directionality effects is also important.

Ductile fracture is sensitive to anisotropy effects, i.e., weak and strong directions as related to the rolling plane. Brittle fracture is insensitive to these aspects. Thus, the NDT, CAT, and K_{Ic} or K_{Id} criteria are insensitive to direction with respect to the rolling plane. The R-curve slope is very sensitive to this aspect. Whenever plastic fracture is involved, it is essential to conduct the test in the direction of expected fracture extension. For example, highest resistance to geometric-instability fracture in a pressure vessel is obtained by orientation of the plate such that the fracture extends across the direction of primary rolling (strong direction). The reason is that the R-curve slope will be maximized. Thus, metallurgical quality effects also enter directly into design considerations by choice of orientation of the metal.

The effects of microstructure, metallurgical cleanliness aspects, and cross-rolling are illustrated in Fig. 33. The steel RAD is subdivided into metal-quality "corridor" regions. Note that transition to brittle fracture for 1-in.-thick sections (K_{Ic}/σ_{ys} ratio 0.63) is developed at higher strength levels with increase in metal quality. There is an increase in the 0.63 ratio strength-transition point from approximately 140 ksi (90 kg/mm^2) to 220 ksi (155 kg/mm^2) yield strength. If a moderate degree of R-curve slope is desired, the shift is from approximately 120 ksi (80 kg/mm^2) to 190 ksi (130 kg/mm^2) yield strength. At a fixed level of yield strength, in the range of 130 to 170 ksi (90 to 115 kg/mm^2), improved metal quality increases the attainable R-curve features from very low to very steep slopes.

The effects of decreasing strength level in the order of 20 ksi (15 kg/mm^2) yield strength, or of changing to higher-quality metal-melting practices are illustrated by the arrows in Fig. 33. The range of 180 ksi (125 kg/mm^2) to 220 ksi (155 kg/mm^2) yield strength is highly sensitive to the specific strength level and metal quality. In this range, it is possible to change metal properties from brittleness levels related to *undetectable* critical-flaw sizes, to very high ductility relating to steep-slope R curves. Most importantly, changes of this type can elevate the metal index quality to above the ratio lines. By exceeding the ratio line *for the thickness involved*, positive assurance of fracture prevention in the brittle mode can be attained, i.e., nonprovisional FSD.

The following changes are noted from the arrows of Fig. 33.

- Average-quality metal, involving the usual furnace practices for the 220 ksi (160 kg/mm^2) yield strength level, results in critical flaw sizes which are at or below inspection limits.

- Very little is gained by reducing the strength level to 200 ksi (140 kg/mm^2) without changing the melting practices.

- The combination of decreased strength level and improved melting practices places the metal above the ratio line at 200 ksi (140 kg/mm^2).

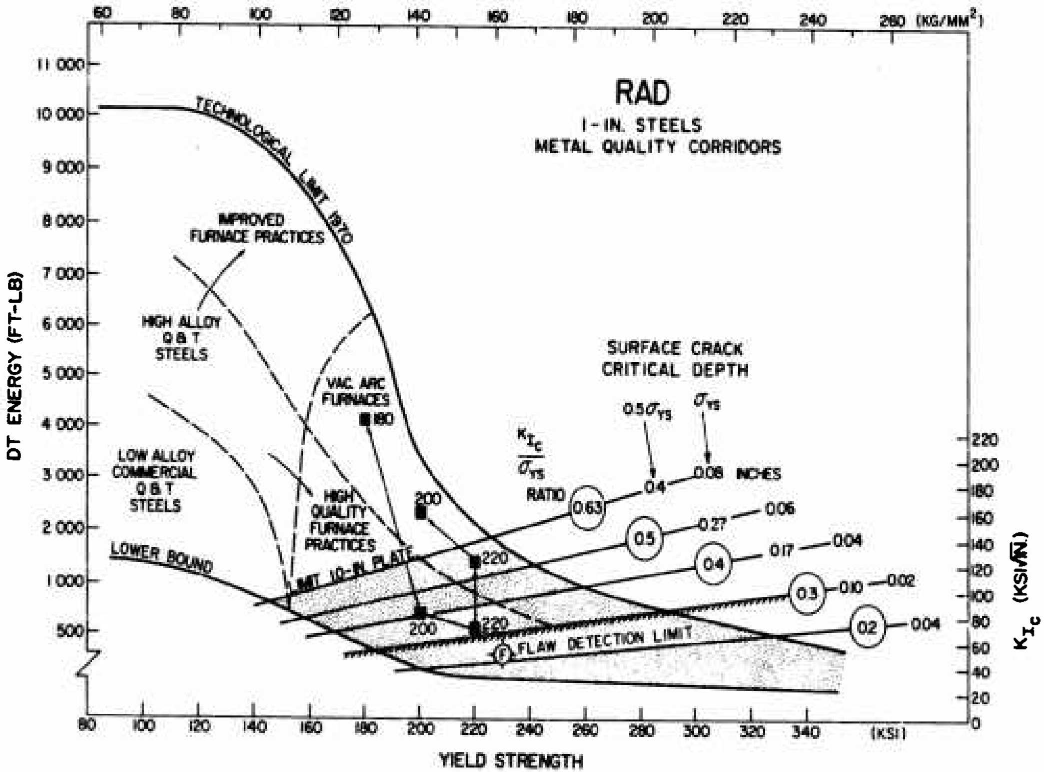

Fig. 33 - Metallurgical quality zoning of the steel RAD. The arrows denote changes in metal fracture resistance properties evolving from small decreases in strength level, and/or changes in metal quality aspects related to furnace practices. The point marked F denotes the properties of the rocket case shown in Fig. 1.

- An additional decrease in strength level to 180 ksi (130 kg/mm^2) and use of the best melting practices results in metal of intermediate R-curve slope.

These analyses clearly indicate that a sharp transition in fracture resistance properties of the metal is evolved over a very narrow strength range. If usual design practices based on minimum yield strength (or average aim) are considered, it follows that the metal selected will statistically feature a respectable R-curve slope or will be of small-critical-flaw-size type. It is very difficult to select and *control* exactly at an "in-between" point because the statistical yield strength range will span the transition region.

The unfortunate aspects of FM procedures, for metals exceeding 180 ksi (130 kg/mm^2), is that they provide analytical accuracy in critical flaw-size predictions that is difficult to use reliably in engineering practice. The very important value lies in denoting the section size limit ratio locations above which nonprovisional FSD can be practiced. This is the engineering importance of the RAD ratio lines. Its use should be based on selecting the *metal quality* which provides for significantly exceeding the ratio lines at the strength level of interest.

If very high strength levels are absolutely required, it generally follows that proof-test procedures must be utilized to determine whether critical flaws exist. Figure 1 provides an illustration of failure in proof test caused by undetectable flaw sizes which were predictable by K_{Ic} tests of the metal involved, but could not be detected. While the the postmortem results confirmed FM theory, they also confirmed the engineering impracticality of practicing FSD by proof-test procedures. The F point in Fig. 33 indicates the K_{Ic}-yield strength location of the subject metal.

PART X. SUBCRITICAL FLAW GROWTH

The increase in crack size by fatigue or by stress corrosion cracking (SCC) may lead to service-time-dependent attainment of critical crack sizes, for the initiation of unstable fracture. For purposes of this report, we shall discuss only the FSD aspects; the test methods are explained in the references contained in this Bibliography.

The FSD aspects relate to the possibilities of attainment of critical crack sizes. These are defined by the ratio lines of the RAD. In this respect, the importance of FM analyses for crack growth rates is paramount. It would be difficult to rationalize the fatigue and SCC aspects in the absence of FM parameters.

The crack propagation rates in SCC are dependent on the level of stress intensity K acting at the crack tip. Figure 34 illustrates the case of a steel of approximately 220 ksi (155 kg/mm^2) yield strength featuring a K_{Ic} value of 110 ksi $\sqrt{in.}$ and a (normally expected) K_{Iscc} value of 50 to 60 ksi $\sqrt{in.}$ The K_{Iscc} value signifies the lowest K value for crack extension in the presence of water or moist air. At 0.5-σ_{ys} stress levels, cracks of less than 0.1-in. depth will enlarge in a stable progressive fashion by SCC and grow to approximately 0.27-in. size (point B). At this point the critical K_{Ic} value is reached and unstable fast fracture evolves. The time to failure may range from minutes to hours, depending on the exact size of the small initial crack.

Figure 30 also illustrates the case of 190-ksi (135 kg/mm^2) yield strength steel of similar K_{Iscc} value, but a metal quality which lies considerably above the 1-in. plate 0.63-ratio line (point A). Assuming that the section size is 1 in. and that the same stress level is applied (0.5 σ_{ys}), it is indicated that flaw growth by SCC will continue without the development of unstable fracture. If the subject structure represented a pressure vessel, it is possible that ductile fracture would eventually evolve by enlargement of the

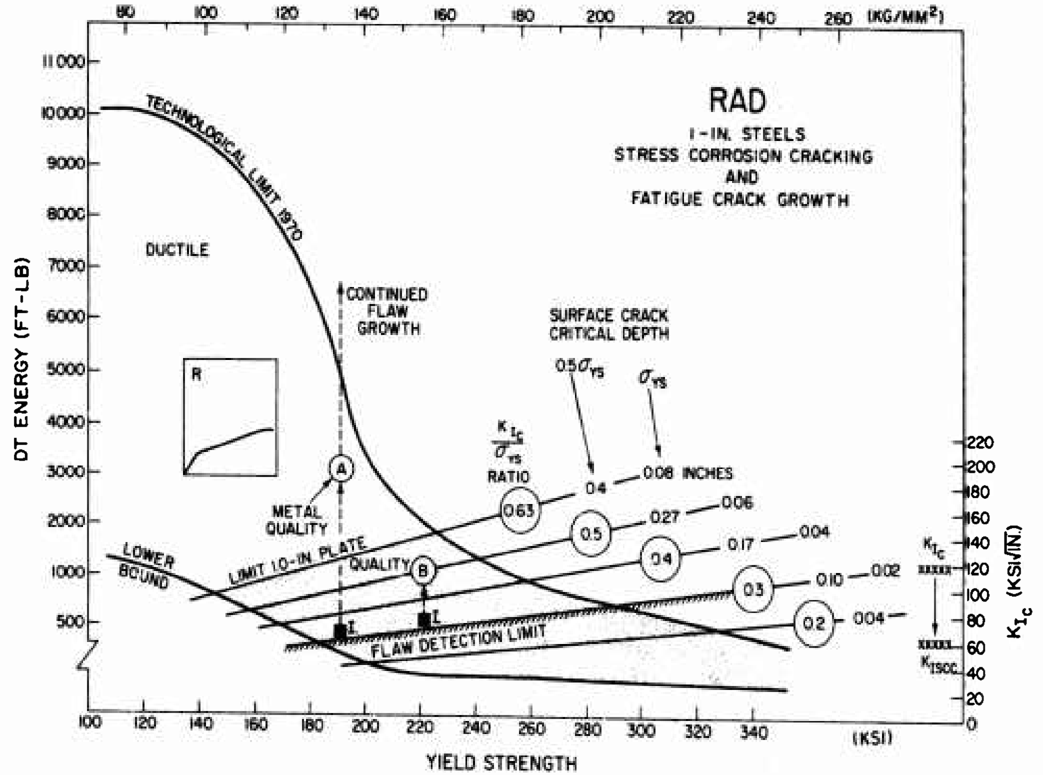

Fig. 34 - Terminal-event analyses for subcritical crack growth due to stress-corrosion cracking (SCC) and fatigue. The dashed line terminating at point B indicates growth of very small flaws to critical instability size (in the order of 0.2-in. depth) for a metal of 0.5-ratio properties. The dashed line relating to metal of A properties (moderate R-curve slope) indicates that continued crack growth would evolve which could only terminate in ductile failure by geometric instability. The terminal-event differences are relatable to improvement in metal properties, resulting from a relatively small decrease in yield strength, combined with use of improved furnace practices (see Fig. 33).

flaw and development of geometric instability. In most cases, it should be expected that leakage or penetration of the wall would occur and, therefore, the crack would be detected.

Fatigue crack propagation data are ordinarily obtained in terms of crack extension increments as a function of ΔK (stress intensity range). The crack extension rate per cycle increases rapidly with ΔK range and metal strength level. The fatigue crack extension rates of high-strength steels, at their respective levels of 0.5 σ_{ys}, are very fast compared to those of low-strength steels at their levels of 0.5 σ_{ys}. In brief, fatigue cracking problems become increasingly severe with increase in yield strength.

The same analyses may be made for the case of fatigue crack growth as were made for SCC growth. The same *termination* events will apply for the case of the two metals cited above. In effect, when fatigue or SCC conditions cause subcritical crack growth, it becomes *imperative* to adopt FSD practices which depend on metal quality factors which exceed the ratio line for the section size. The only exception is when the time of service or the number of load cycles is very low. These conditions apply to rocket cases and certain aerospace structures. For general engineering purposes, these approaches based on time-dependent, provisional FSD practices are unacceptable.

SUMMARY

The foregoing discussions have described FSD in the context of engineering realities evolving from structural mechanics and metallurgical factors. Much of the complexity that results from idealized treatment of this subject as an extension of fracture research is thereby eliminated.

Engineering assessments of the potential span of fracture problems indicate that there is no singular procedure for FSD. Protection against failure involving ductile fracture may be the deciding issue for particular problems. However, the foremost problem remains that of avoiding the development of brittle fracture.

Engineering realities dictate that the stress state and crack conditions cannot be defined exactly. In any event, most structures do not feature singular stress states—a wide range of stress levels will be developed, including incipient yielding for points of complex geometry. These considerations lead to the conclusion that crack states and structural mechanics aspects must be defined in terms of statistical confidence limits.

The idealization that the *metal* can be characterized exactly in terms of fracture initiation properties has led to FSD concepts based on confidence limits for mechanical factors. These include upper-bound statistical definition of the mechanical stress state and of anticipated crack sizes.

The case for the use of fracture-initiation FSD procedures, evolving from fracture mechanics K_{Ic} parameters, rests on this premise. It provides for definition of the lower-bound K_{Ic} value that is required, i.e., the minimum value that should be specified in purchase of the metal. However, the other implicit premise—that the metal can be characterized exactly—requires detailed consideration from a metallurgical point of view. The question is again one of statistical confidence limits, as will be explained.

The appeal of fracture mechanics to the designer is obvious—the FSD use of brittle metals becomes possible, in principle. However, the metallurgist has been conditioned to recognize that sharp transitions resulting from temperature and strength-level effects are a fact of nature. The reasons are to be found within the metal itself and relate to changes in microfracture ductility of the metal grain aggregates. When these transitions develop, any type of deep-sharp-crack test will sense the large changes involved—FM tests included. Thus, the question of sharp transitions is not a matter of type of test or of metallurgical attitudes.

Fracture mechanics tests also appeal to the metallurgist, but for reasons inherent to his particular responsibilities. Sufficient evidence has been available for a long time to document temperature-transition aspects, in terms of microstructural factors (see Bibliography). With the advent of fracture mechanics, it became possible to analyze the effects of metallurgical factors on exactly defined transition ranges as a function of strength level. The consequences of falling below the K_{Ic}/σ_{ys} ratio transition point, for a specified section size, became exactingly clear in terms of critical crack sizes and elastic stress levels (see Fig. 20, GFM plot). The consequences are most serious because of the extremely rapid decrease in critical crack sizes which evolve in these transition ranges for metals of ordinary plate-section sizes, say 1 in.

In such analyses, the statistical aspects of metal properties in the transition ranges also become glaringly evident. Pondering this question leads to the rational conclusion that exact control of metal properties based on K_{Ic} test parameters which are "micrometer" measurements of metal ductility is not possible within reasonable economic constraints.

Thus, metallurgical analyses imply that engineering use of fracture mechanics in strength transition regions is not feasible. Accordingly, what was already known for the case of the temperature transition would appear to apply to the strength transition. The implications are of major consequence because, if true, all aspects which dominate the "transition" approach for the temperature transition would have common meaning with those of the strength transition.

At this point we remind the reader that the transition philosophy is simply an expression of realities, that exact FSD cannot be practiced within the sharply falling temperature transition. It leads to the rational conclusion that FSD must be based on "staying above" the transition range for reason of a statistical nature.

Reality of Metallurgical Transitions

The implied statistical aspects of metal properties in the strength transition range could not be accepted as reality, without engineering proof that the analytical procedures of fracture mechanics were correct. Metallurgical studies could be made; however, the engineering significance would remain in doubt.

Failure analyses have demonstrated that the fracture initiation conditions are in close match to the analytical predictions. Thus, there is a sound basis of confidence in the predictions. At this point, the engineer should recognize that the properties are measured postfact, for metal closely adjacent to the fracture source. Accordingly, the metallurgical analyses must be accepted as indicating that predictive capabilities for a specific, small piece of metal are not the same as predictive capabilities for a "lot" of the same metal. Questions of statistical variations in metal properties must be considered for the strength transition.

When realities of metallurgical variances are examined, it becomes clear that the failure analyses demonstrate the opposite of what might be implied. Proof that analytical procedures are exact in real-life cases is simultaneously proof that metal that provides for such exact analytical treatment is a statistically unreliable structural material. Brittleness levels which provide for exact analytical prediction for a given sample imply statistical variations of large magnitude. For the very low ductility levels involved, minor changes in metallurgical structure will produce large changes in properties. It is unrealistic to expect metallurgical control to micrometer-scale ductility-difference levels. The required control limits are of excessively narrow band.

The metallurgical transitions are statistical expressions of metal properties trends, as a function of strength level changes. When a proper analysis is made of these trends, it is evident that a sharp statistical transition is evolved for a specific class of metal, as a narrow strength-level range is crossed. The population "dumps" from statistically above-yield levels of fracture-extension properties to statistically below this level. The population change may be considered a metallurgical precipice, above which all of the metal is safe and below which a broadband statistical distribution of brittle fracture properties dominates. There will be high, medium, and very low levels of brittle fracture resistance within the population. Accordingly, FM predictions will rightly relate to large, medium, and very small critical crack sizes, for a specified stress level. FSD must involve a dual consideration of the metallurgical population transitions and of fracture mechanics-defined consequences.

The parallel to temperature transitions is striking—we may substitute temperature for strength in these discussions. Accordingly, we shall continue discussing the metallurgical transition question in these common terms.

The intent of these summarizations is not to present a case for transition procedures. This is not an issue because all fracture tests respond to metallurgical transitions. The real issue is that realistic solutions to FSD problems must be found in the selection of metal which is statistically reliable. This premise is exactly the same as that which involves placing statistical limits on flaw size and stress for reasons of structural mechanics. If reliability principles should apply for mechanical aspects, they should likewise apply to metallurgical case; the logic is the same.

Consequences of Metallurgical Transitions

The precipice aspects of metallurgical transitions for a particular class of metal (composition, processing, and section size) are readily recognized by the FAD and RAD systems. In the case of the FAD, the analysis must be coupled with the NDT frequency-distribution plots. All factors are fully included in the RAD plot because the production range aspects are defined by the metal quality bounds and quality corridors. The ratio lines of the RAD index the section size effects.

The consequences of crossing into NDT frequency-distribution bands or dropping below RAD ratio-limit lines for a specified section size may be described as entering a "box" of statistical uncertainty. Such an unappealing point of view requires documentation. It also requires emphasis because it is basic to FSD which considers metallurgical realities.

Analyses of the transition aspects for a metal sample (small section of a 1-in.-thick plate) are provided to document the case of sharp transition, without consideration of statistical effects. The effects of similar sharp transitions, for a statistical population of the same class of steel, are then analyzed to document the uncertainty aspects.

Combined analyses for the transition temperature aspects are illustrated in Fig. 35. The FAD plot indicates that the transition-temperature range for a specific steel (NDT to FTE) is only 60°F (35°C) wide. However, most FSD problems may be resolved by the use of the 0.5-σ_{ys} CAT point. Thus, the transition interval is actually only 30°F (17°C) wide. If we are concerned only with a single, small piece of steel, it would be necessary to section this interval into 5°F (3°C) steps in order to practice FSD based on flaw-size—stress fracture-initiation considerations. Obviously, the limiting engineering reality becomes that of temperature measurement.

If the NDT frequency plot is analyzed, it is apparent that the metallurgical population features a 60°F (35°C) NDT bandwidth. Thus, selection of a steel class, which places a

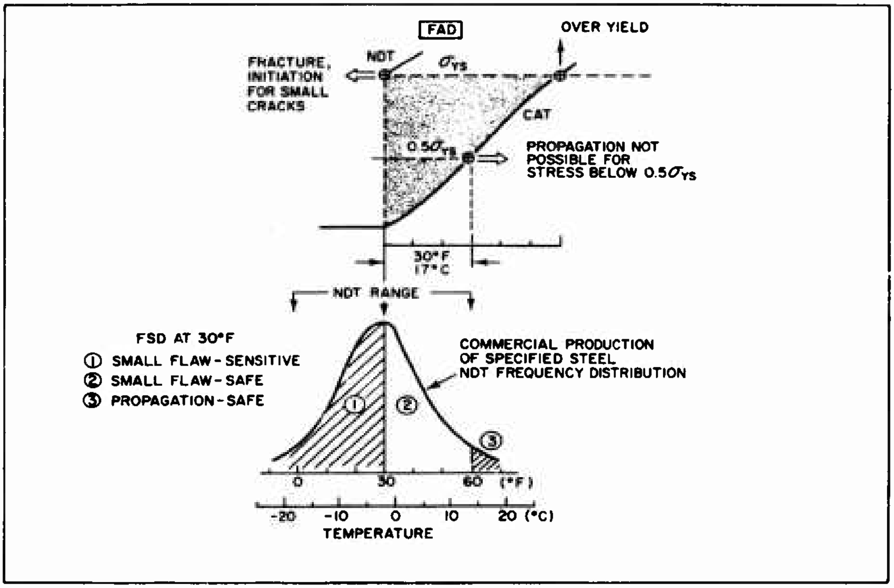

Fig. 35 - Determination of NDT properties provides an exact definition of the critical, 30°F (17°C) transition-temperature range of a specific steel sample. However, in commercial production, the statistical NDT distribution of steels will vary over a range of 60°F (35°C). It is illustrated that a structure comprised of a large number of steel plates will feature a wide range of fracture-resistance properties, at a service temperature equivalent to the average NDT of the steel class. Small shifts in the service temperature, within the NDT frequency range, will result in large changes in the fracture resistance properties of the steel population.

service temperature within the band, results in a wide variation of metal properties. The shaded areas in Fig. 35 will change radically with a small shift in temperature. Again, the limiting engineering reality becomes that of temperature measurement. The proper FSD approach is defined by selecting a steel which features all of the NDT population below a specified service temperature. Thus, the metal population is kept above the critical-temperature band of statistical uncertainty; i.e., the metallurgical transition range *decides* the issue.

Problems which arise for the case of the strength transition are related to the sharp decrease in fracture resistance which evolves for the best steels above 180 ksi (125 kg/mm²). These problems are of serious consequence because aerospace designers tend to select materials of strength levels moderately above this limit. For metals of plate section assembled by welding (monolithic construction), reliance must then be placed on exacting control of the crack state and metal properties.

Combined analyses for the case of the strength transition are presented in Fig. 36. The figure illustrates that a sharp transition is developed for a specific steel over a yield strength range of 30 ksi (23 kg/mm²). The points of reference are the intersections with the 0.63- and 0.3-K_{Ic}/σ_{ys} ratio lines. The FM significances of these points is that of transition from ductile (over yield stress) to a highly brittle state, involving undetectable critical-flaw sizes. Purchase of steels will include statistical variances of yield strength within the range of ±15 ksi (±10 kg/mm²). Significant statistical variances of metal-fracture resistance are ordinarily to be expected for the metals within this strength range.

If the statistical variaticns in *strength level* are combined with statistical variations in *fracture resistance* of the metal, it evolves that two frequency distributions will be superimposed. The superimposition may be considered as a "box" (see Fig. 36). The box may be visualized as having a yield strength span of approximately 30 ksi (23 kg/mm²) as the base, and a ratio span of at least ±0.10 K_{Ic}/σ_{ys} for the vertical axis. As purchased, the metal will fall statistically within the box. The differences in critical flaw sizes, for a specified nominal stress, are quite large even for the normal expectancy point; i.e., the range is from nondetectable to potentially detectable sizes. The range of fracture resistance for the total box is obviously larger.

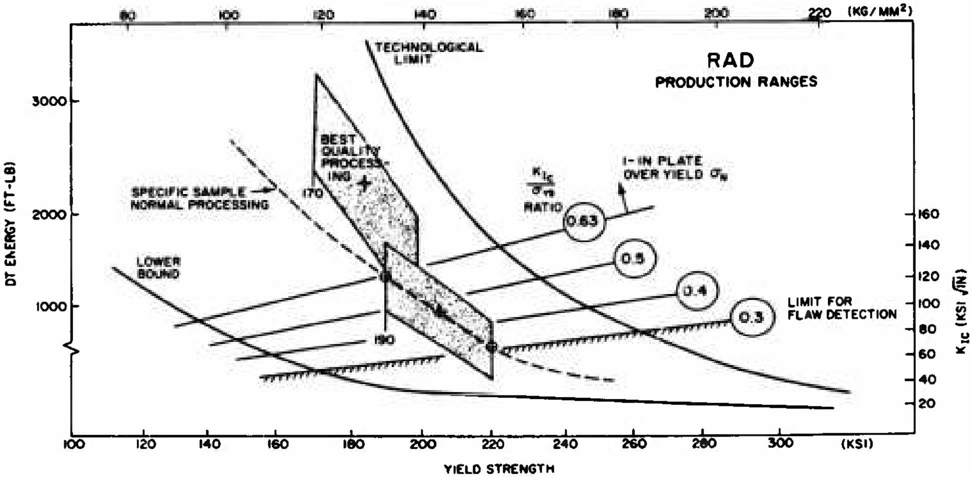

Fig. 36 - A sharp transition from ductile to highly brittle levels of fracture resistance evolves as a specific steel of 1-in. thickness is heat treated to increasing levels of yield strength. The critical transition zone is developed within a 30-ksi (23 kg/mm²) strength range. Commercial production of steels results in a statistical distribution of yield strength in the order of 30 ksi (23 kg/mm²). Variations in fracture resistance for a specified metallurgical quality will cover at least a 0.2-ratio range, for any level of yield strength below the ratio line for the section size. The statistical "boxes" illustrate the results of decreasing the minimum yield-strength specification from 170 to 190 ksi (115 to 130 kg/mm²), combined with the use of improved metal-processing practices. The precipicelike aspects of statistical metallurgical-population transitions in this critical strength interval are clearly evident.

It may now be recognized that design based on the lower strength levels which lie *above* the intrinsic metallurgical population transition provides positive specification control in the purchase fracture resistant metal. The metal variables are of minor consequence. Design based on higher strength levels becomes involved with the "box" aspects, as defined above. Pragmatically, the design problem changes dramatically from assured safety to that of the box—uncertainties. Metallurgical considerations dictate that there is little in-between territory. This is particularly true if the best of metal practices are used in production (Fig. 33) to attain the highest possible level of yield strength associated with retention of high fracture resistance. The metallurgical transition is then truly of precipicelike features.

There is obvious temptation to drive the metallurgical producer to provide metals of very narrowband quality features for yield strength levels above the metallurgical-population transition. This means squeezing the box to very small yield-strength and fracture-resistance ranges. It also means increasing the lower bound value for the K_{Ic}/σ_{ys} ratio toward at least the 0.5 ratio level. It is apparent from the RAD plots (Fig. 36) that at this point, a decrease in the order of 20 ksi (15 kg/mm^2) yield strength level will result in a population which resides above the metallurgical precipice. Thus, it is the desire to utilize strength levels which are higher, by this small degree, that causes a "dump" of fracture resistance to the level of exceedingly small and variable critical crack sizes.

The above statements apply for the case of section sizes in the order of 1-in. thickness. As the section size is decreased to 0.5 in. or less, the critical ratio-line limits fall to lower values. Thus, the higher strength levels may be utilized with assured safety, provided that the metal properties remain significantly over the ratio line. In effect, the metallurgical-population transition is shifted to higher strength levels.*

It should be noted that the same metallurgical precipice considerations, for 1-in. plate section sizes, apply for titanium alloys (Fig. 30) at approximately the 130-ksi (90 kg/mm^2) yield strength level. For aluminum alloys (Fig. 31) the precipice evolves at approximately the 50-ksi (35 kg/mm^2) yield strength level. The box analyses are thus applicable, as for the case of steels.

Other distressing assessments may be made for the case of metals which lie below the metallurgical precipice. The stress corrosion-cracking sensitivity and fatigue-crack-propagation rates increase markedly with increase in strength level (see Bibliography). Thus, the metallurgical precipice also marks the point at which these effects become highly critical to service reliability (Fig. 34). In brief, the statistical aspects of the box also become involved with these factors. For example, statistical variations in K_{Iscc} must be considered. Statistical variations in fatigue life due to crack-size variations, etc. apply. Again, the demonstrations of exact analytical capabilities for defining these effects are simultaneously demonstrations of engineering unreliability in the box area.

Conclusions Evolving from Metal Factors

The metal-population transition factors are of major importance in the development of statistically reliable FSD solutions for most engineering problems. It is unfortunate, but nevertheless realistic, to conclude that, in general,

- A metal which is characterizable by exact, linear elastic FM procedures (K_{Ic}, K_{Id}, K_{Iscc}) is simultaneously defined as being a statistically unreliable engineering material.

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*As the thickness level falls below 0.5 in., plane stress K_c considerations will apply. These involve the possibility of fracture extension at elastic stress levels for metals above their respective K_{Ic} limits. This text is not intended to cover such "thin plate or sheet thickness" aspects of plane stress fracture.

• The great importance of these exact definitions is in denoting the metallurgical transition limits (temperature or yield strength) for which the metal can be used reliably.

• The limits are best placed significantly *above* the metal quality point, which ensures that K characterizations become statistically impossible.

• Data-bank summaries of NDT, K_{Ic}, or K_{Iscc} must be examined to define these critical metallurgical-transition points. The DT test may be used to define K_{Ic}/σ_{ys} ratio limits by reference to the R-curve slope.

It may appear that this is a negative view of the most advanced analytical capabilities that have been evolved. In fact, it is not, because exact definition of these limits is crucial to establishing statistical engineering-confidence points. The summarization simply emphasizes that FSD cutoff points are to be found by *consideration of the metal.* Analytical procedures cannot offset metallurgical failure. The endpoints are those which exceed the capability of the metallurgist to provide statistically fracture-safe metal. These points are very sharp—"Why?" is a good question for basic metallurgical research. The fact that such metallurgical endpoints do exist is an engineering reality.

These various considerations clearly support the premise that FSD is best practiced on the basis of nonprovisional procedures. These procedures are included in FM considerations as the second-line-of-defense concept. Thus, they are not in conflict with principles of fracture mechanics.

For conditions involving plastic fracture, it is essential to consider the problem as an extension of the metallurgical transitions, i.e., extrapolation to higher temperatures or lower strength levels. The starting point of the plastic-fracture transition is easily located by the FTE and ratio-lines positions of the FAD and RAD plots. If the absolute temperature or strength levels of these transition points are known, the extrapolations (added temperature or decreased strength level) are of simple form.

The combined metal data-bank and structural-mechanics analytical capabilities of the FAD, RAD, GFM, and the projected IAD procedures for FSD are most impressive. We leave the reader to imagine how the human mind, reference books, or a computer would serve to store and retrieve such an enormous amount of metallurgical, mechanical, and structural-related information. The combined use of these procedures should provide for generalized coverage of FSD problems.

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Appendix A

BASIS FOR UNIFIED EXPRESSION OF FRACTURE PARAMETERS IN R-CURVE TERMS

If fracture tests could be discussed in terms of a single reference parameter, the foremost problems of communication between the fracture research field and the engineer would be resolved. Resistance to metal separation is the singular factor which is measured by all procedures for fracture testing. Thus, the term R may be used as the generalized reference parameter. R is an energy term because the basic mechanism of metal resistance involves the absorption plastic-work energy.

Other aspects of fracture are simply a matter of understanding the effects of mechanical constraint states on R. Since R is the basic factor which decides the stress level required for metal separation, it is important that the effects of constraint state on R be understood in principle by the engineer.

Mechanical constraint states define the degree of inhibition to plastic flow that is imposed on the metal by the existence of a crack. As a first approximation, we may state that large cracks feature high constraint and small cracks feature low constraint.

The next point to consider is that extension of the fracture may cause a change in mechanical constraint, if the metal is of intermediate or high *intrinsic* (microstructural) ductility. The change is always to a lower constraint level than that which was applied initially by the existing crack. The R-curve slope is simply an expression of the increase in R, which results from decreased constraint in the process of fracture extension.

The physical aspects of fracture extension from a preexisting crack may be characterized by separation into three possible stages—initiation, extension with change in constraint state, and steady-state extension. The second stage is absent for the case of brittle fracture; i.e., the R curve is flat.

These stages may be referenced to engineering stress levels by consideration of the R-curve features of the metal. The connection between the metal R curve and the structural stress level is the key to all aspects of fracture-safe design. The physical significance of fracture tests may be unified in terms of the R-curve *level* and *slope*. The simplified model presented in Fig. 15 provides the broad interpretive framework which additionally unifies fracture-test and structural-mechanics relationships.

Since all mechanical aspects of fracture are relatable to constraint, it is essential to understand the connection between constraint and the measured metal R-curve properties. If constraint effects are understood, other aspects will become evident in terms of the R-curve features.

MECHANICAL CONSTRAINT RELATIONSHIPS TO CRACK GEOMETRY

The distance from free surfaces of an element of the metal located at the crack tip determines triaxiality of the stress state, i.e., the degree of triaxial constraint to plastic flow. For a through-thickness crack located in a plate section, there are two distances of reference—crack depth and crack-front width. If the crack is visualized to be of depth equal to or greater than approximately 0.5 of the plate thickness, the constraint effect is the maximum possible which is attainable, due to the depth factor. The other dimension of interest is the distance of the element from the plate surfaces. Mechanical constraint is increased due to this factor, in proportion to increase in thickness. Section-size effects derive from increased mechanical constraint, because the central regions of the crack front are located at increased distances from the free surfaces. It also means that fracture initiation will evolve first in the central region because the stress intensity is highest at this point and restriction to metal flow is maximum.

While the mechanical constraint effects are a matter of the crack geometry, the response of the metal is a function of its intrinsic resistance to microscopic separations within or between metal grains. This aspect is "designed" into the metal by the nature of the microstructural phases. The constraint state is the *imposed* factor and the metal response is the *reaction* factor. Fracture-extension resistance is intrinsic to the metal for a specified condition of mechanical constraint. Thus, the stress required for fracture extension is intrinsic to the metal for a specified section size. A most important point remains—the intrinsic ductility of the metal may be of such order that no conceivable increase in mechanical constraint can cause the metal to be brittle.

In general, the engineer is concerned with definition of the stress required for fracture extension for a specified section size. Further discussions will center on this point.

Whether or not increased resistance to crack extension evolves after the first extension increment depends on the effects of metal ductility on changing the applied mechanical constraint level. In brief, metal ductility may exact a price for extension, in terms of causing a decrease of the originally applied mechanical constraint level. Whether the mechanical constraint "overcomes" the metal or the converse evolves is the basic theme of the R-curve concept. For brittle metals, the imposed constraint is the deciding factor. For ductile metals, loss of constraint is the deciding factor. The basic mechanism, which relates to stress-level requirements for extension of fracture, is the nature of the constraint transition. That is, whether a mechanical constraint transition evolves and if so, to what degree.

CONSTRAINT TRANSITIONS

The principal difference between unstable (brittle) fracture and stable (ductile) fracture is that:

- For brittle fracture, metal resistance ceases to increase when the first small increment of crack extension is developed. The applied constraint level decides the issue. Steady-state extension conditions apply thereafter.

- For stable fracture, there is a continued increase in metal resistance during a specifiable period of continued extension of the crack. This is the period of constraint transition, consequent to initiation of crack extension. Steady-state extension conditions apply only after this second stage of metal resistance is passed.

Constraint factors were well understood and intensively investigated during the 1950's and 1960's. The early literature of fracture mechanics in the 1950's emphasizes these aspects in terms of $\mathcal{G}$ (strain energy release rate or crack-extension force). R was defined as the crack-extension resistance of the metal opposing the applied extension force.

The K parameter is simply a stress field intensity redefinition of $\mathcal{G}$. For brittle metals, the critical instability value of $\mathcal{G}$ ($\mathcal{G}_{Ic}$) is relatable to the critical K value (K_{Ic}), as follows:

$K_{Ic}^2 = E \delta_{Ic}$, where E is the elastic modulus.

This relationship applies when the fracture is initiated at elastic stress levels and continued extension is through steady-state elastic-stress fields. This is equivalent to stating that fracture extension resistance is *not* involved with a second stage of increased metal resistance. Most importantly, the relationships imply that K_{Ic} does not apply for metals which feature a second stage of increased resistance to extension.

Confusion results from attempts to characterize brittle and ductile metals by the same definition of first-event conditions for fracture extension. Such attempts are in conflict with basic theory because they amount to neglecting the most important aspects of the second-stage processes involving the constraint transition. However, there is continuing effort in fracture research to find methods for defining all conditions for crack extension in terms of initiation factors. The reason is a belief that commonality of definition should provide for unified FSD solutions, which are the same for brittle or ductile fracture. In fact, the opposite result is achieved—the test procedures become unnecessarily complex. Moreover, the engineer is led to believe that initiation is always followed by continued extension at the initiation stress level.

It is not implied that those who are involved in such research believe that this is the case for ductile fracture. The detection of first movement of the crack is simply a means of characterization of the metal; however, this is not the proper point of reference.

It is essential to recognize that the conditions for extension of brittle and ductile fracture *are different* and thus, the characterization procedure should be different. The constraint transition cannot be neglected when it evolves—due credit should be given to the metal for causing a decrease in mechanical constraint. This factor is important because it results in increasing the stress level required for continued extension.

CONVENTIONAL DEFINITIONS OF CONSTRAINT TRANSITIONS

The physical processes of increased resistance to fracture extension, during the initial stages of extension for ductile metals, have been explained in terms of visual appearance, stress-state, and deformation aspects. All of these are fully equivalent, but they "appear" to be different because the descriptions are couched in different terms. Thus, it is important to clarify this point by explanations of the various terminologies that are used.

- *Fracture-mode transition*. This description of the constraint transition is the oldest and most easily understood. It relates to the visual observation that fracture extension is related to a transition from low-ductility flat fracture close to the original crack tip, to slant fracture involving an obviously greater degree of oblique slip. The transition may be complete (full slant) or partial (mixed mode) i.e., involving a combination of flat fracture at the center and slant fracture at the free surfaces (Fig. A1).

- *Plane-strain to plane-stress transition*. This description is in terms of fracture-mechanics definitions of mechanical constraint states, which apply to the fracture-mode transition. The flat fracture regions are considered to represent metal separation under plane strain conditions (high triaxial constraint). The slant-fracture regions are related to metal separation under plane stress conditions (low triaxial constraint). The section, as a whole, is said to fracture in plane stress when a significant degree of slant fracture is attained—the exact point is a matter of arbitrary definition.

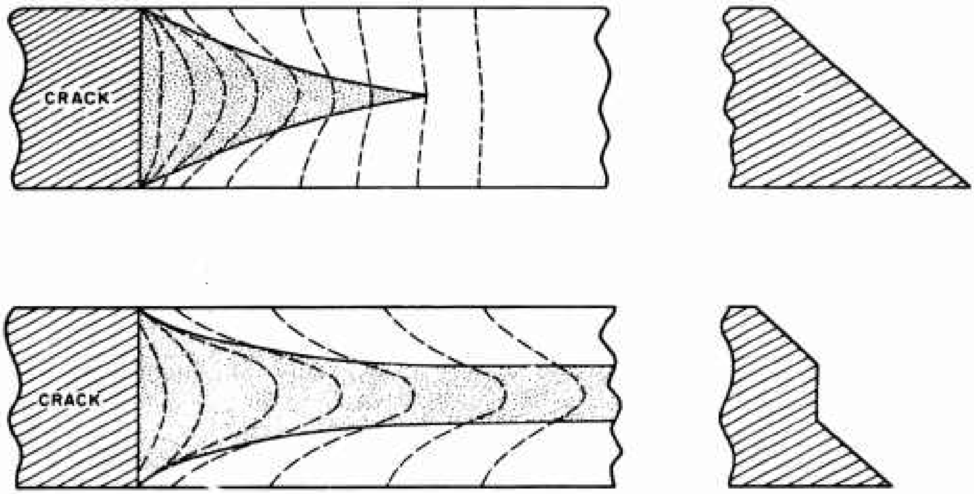

Fig. A1 - Fracture extension sequences which relate to metals of steep (top) and intermediate (bottom) R-curve slopes. The distances over which the constraint transition is evolved for these two examples are indexed by the points of attainment of a stable fracture-mode configuration.

• *Through-thickness-yielding transition* . The constraint transition events are related to an increase in the degree of yielding, as measured by lateral contraction. Increased contraction will evolve in the course of the constraint transition because the degree of oblique slip is increased as the triaxial stress state is relaxed.

• *Yield-zone-size transition* . This description is the formal fracture-mechanics definition of constraint transition events. The reference is the ratio of the yield-zone (r_y) to the section thickness T. A very small yield-zone size in proportion to thickness relates to plane strain and a large size relates to plane stress. However, the exact r_y/T ratio, which marks the constraint transition from plane strain to plane stress, is a matter of arbitrary definition.

These various definitions of related events, also illustrate the semantic problem involved in the use of the plane-strain and plane-stress nomenclatures. Thus, it is necessary to consider what these terms imply.

The origins are derived from abstract mathematical definition of mechanical states, in terms of two-dimensional stress or two-dimensional strain. In effect, the mathematician finds it easier to calculate load response in terms of idealized two-dimensional planes—involving either stress or strain. The complexities of the third-dimension response (Poisson effects) which involves work-hardening and geometrical aspects are eliminated.

In the context of mathematical usage, plane strain is defined as a condition of zero plastic-flow parallel to the crack front. Plane stress is defined as a condition of zero stress in the same direction. The mathematical definitions represent extreme conceptual limits, ranging from total constraint to plastic flow to zero constraint.

For real metals, the constraint level cannot extend to either of these two extremes; i.e., it can neither be total nor zero. Brittle metals develop very little plastic flow and, therefore, fracture under conditions close to idealized plane strain constraint. Highly ductile metals develop large amounts of plastic flow and, therefore, fracture under conditions which approximate the idealized plane stress constraint.

The conventional fracture-mechanics definition of plane strain evolves from empirical observations in K_{Ic} tests. It is based on the concept that maximum constraint is achieved when the section size B, used for the K_{Ic} test, is equal to or exceeds a specified relationship to the $(K_{Ic}/\sigma_{ys})^2$ ratio, as follows:

$$B \text{ (inches)} \geqq 2.5\,(K_{Ic}/\sigma_{ys})^2.$$

Since the K_{Ic} value does not change by additional increase in section size above that of the 2.5 relationship, it is considered that maximum constraint to metal flow was applied. That is, the metal cannot be made to behave in a "more brittle" fashion. The measured K_{Ic} value is then the lowest possible plane-strain value for the metal. Thus, it is necessary to preestimate the K_{Ic} value, so that the minimum section size of the test specimen can be defined.

Fracture mechanics tests are unique, in the sense that it is not known if the tests are "valid" until the measured K_{Ic} value is fitted to the above expression and the section size used conforms to the stated relationship. As first measured, the value is defined as K_Q or K_c; if the relationship holds, it is then called valid and specified as K_{Ic}.

The primary point of this discussion is that fracture mechanics definitions of plane strain are not specific—they relate to lowest measured K value expressed as valid K_{Ic}. It is now necessary to clarify the significance of K_c which is defined as plane stress fracture toughness. This is a critical value of K which is measured for conditions such that fracture is initiated below yield stress levels, but otherwise is not valid in terms of the above-stated relationship. In practice, K_c conditions apply only to metals of thin plane or sheet thickness. For plate thickness, the K_c state is usually eliminated by the constraint transition. In an R-curve sense it means that a very slight slope is evolving and that the stress required for fracture initiation is close to yield level. Thus, continued extension is not possible, unless plastic stresses are imposed. At this point K definitions no longer apply.

The engineer is advised to adopt the following simplified view of constraint states and constraint transitions:

- *Plane strain* signifies fracture under high levels of triaxial constraint, such that the metal response is limited to very low values of oblique slip.

- *Plane stress* signifies fracture under low levels of triaxial constraint, as a consequence of metal response involving a high degree of oblique slip.

- *Constrain transition* signifies a marked change from plane strain to plane stress constraint.

- *Reference points for constraint transitions* signify arbitrary reference indexes, based on stress required for extension or on visual observations of change in fracture mode.

The fracture-mode transition is a faithful reflection of the degree of oblique slip that evolves prior to separation, at the point of visual reference. Thus, a change in fracture mode appearance from flat to slant is an index of a marked change in constraint level. As such it is an index of a marked increase in metal resistance to fracture extension.

A metal (of plate section), which shows a marked fracture-mode transition emanating from the original (through-thickness) crack tip, is faithfully indexed as requiring initiation and propagation stresses in excess of yield.

R-CURVE SLOPE DEFINITION OF CONSTRAINT TRANSITION

The fracture extension process may now be considered in terms of R-curve slopes. The interval of R-curve rise is best defined as the distance over which the fracture mode (constraint) transition is evolved to a stable configuration.

The sequence of extension events may range over broad limits, as illustrated in Fig. A1. The constraint transition, as reflected by the fracture mode, may be sharp or gradual. The initial extension develops in the central regions because the triaxial stress intensity is highest at this point. The fracture mode is flat because of limited oblique slip.

The forward progression of the crack is V or U shaped; i.e., it involves a leading component at the center and a lagging component closer to the free surfaces. The changes in contour are illustrated by the sequential steps noted in Fig. A1. As the lagging component approaches the free surfaces, it senses a decreased constraint; slant fracture then begins to develop at the surfaces. During this time, the region which envelops the growing internal crack continues to yield and a plastic enclave (contraction) is developed. All of these aspects evolve simultaneously as the internal crack front is extended away from the original crack tip; see Figs. 10 and 11.

The intrinsic ductility of the metal decides the rate of change in the proportions of flat and slant fracture to a stable configuration and, therefore, the slope of the R curve during this period. The constraint transition is developed over a short extension increment (steep R-curve slope) if the metal is of high intrinsic ductility. Conversely, it is developed over a longer interval (low R-curve slope) if the intrinsic ductility is low.

For ductile fracture, the constraint transition begins prior to the first extension increment, and is then accentuated by additional extension. A metal which features a steep R-curve slope also features a high-level resistance to initial extension. The converse relationships apply—R curves of low slopes signify lower-level resistance to initial extension. The model presented in Fig. 15 evolves from these considerations.

Confusion arises if the flat central regions are considered to represent plane strain behavior equivalent to brittle (unstable) fracture. This is *not* the case because extension of the flat-fracture regions is of stable type, when rising R curves are developed. The confusion evolves from the indefinite definitions of plane strain conditions, as described previously. It is emphasized that the FM definition of brittle-level plane strain is that which provides for fracture extension at elastic stresses. Since K_{Ic} cannot be measured for conditions of rising R curves, the mechanical state is not of brittle-level plane strain. The early development of the constraint transition prevents K_{Ic} characterization, because the stress level exceeds yield.

The appeal of FM procedures, based on measurement of initiation events for brittle fracture, has directed plane stress fracture research to similar pursuits. Dedication to this convention forces the research field to find ways for detecting—and thus characterizing—the metal, by reference to the points of "initiation," noted in Fig. 15. These initiation points are extremely difficult to detect because there must be evidence that the COD (crack opening displacement) measurement relates specifically to the first-extension increment. Separating plastic crack-opening effects from crack-extension effects is very difficult. In fact, these issues have not been resolved to date.

It should now be apparent that first-order definition of the FSD capabilities of a metal (of specified section size) may be made simply by visual observation of the fracture mode transition, for a DT-type test specimen. Provided with the essential background information, the engineer may read the fracture appearance, deduce the R-curve slope, visualize the location in the FAD or RAD, and arrive at valuable *predesign* assessments of capabilities of the metal for meeting FSD requirements.

The above procedure is scientifically defensible. The primary requirement is to understand the significance of the constraint transition, in stress level-related terms.

The correspondence of the fracture mode transition to relative plastic stress requirements for fracture extension is clear cut for the case of steels and aluminum alloys. The first appearance of thick shear lips, always marks a transition to over-yield stress requirements for fracture extension.

DT Test Modeling of the Constraint Transition

The characterization of the plane stress fracture resistance of the metal must involve a measurement of the constraint transition. The "barrier" resistance to fracture extension is not defined simply by measurement of conditions for initiation of the constraint transition. A short extension of the crack, at the point of initiation, is not of engineering significance. Ideally, it would be desirable to measure the point at which a stable fracture mode is attained and no further increase in metal resistance is developed. However, this end point is equally indefinite and difficult to measure, as the point of initiation of the fracture mode transition.

The alternative method is to measure a number of "points" during the course of the constraint transition. Such measurements would be the equivalent of plotting the R-curve slope. Irrespective of the method of measurement, the basic objective is to characterize the metal in terms of the R-curve slope. That is, to define the degree of change from the *applied* mechanical constraint at the original crack tip, to the natural *allowed* constraint state which is characteristic of the metal for a specified section size.

The DT modeling technique is procedurally simple and meets low-cost requirements for general engineering use. The modeling procedure provides geometric control over the mechanical constraint state. A short-run DT test specimen *enforces* a high constraint level. The longer runs feature gradually decreasing geometric constraint to the point of *permitting* the natural, full transition in mechanical constraint to evolve. The standardized DT configuration is of this latter type.

The modeling technique does not attempt to measure the endpoint of the R-curve slope-increase. To accomplish this purpose, the rate-of-change aspects in E/A (energy per unit area) rise must be separated exactly from other aspects. However, no problem is posed by neglecting definitions of endpoints, because the change of fracture mode provides direct visual evidence of the extension-path length over which the mechanical transition was evolved. Thus, the exact distance over which the R-curve slope increases for an uninterrupted run is definable.

It is interesting to note that visual observation of the fracture-mode transition path-length provides for a reasonable estimate of the R-curve slope. The standard DT test fracture-mode transition may be "read" in these terms. A more refined reading may be made in terms of the fracture energy of the standard DT test, as indexed to R-curve slopes.

Direct use of DT tests for determining R-curve slopes is required when the section size is considerably different from that of the standard DT tests. It is required also when through-thickness metal-gradient effects are involved. Procedures for deducing the effects of these variables are being evolved. For example, it appears that R-curve slopes measured for a specified section size can be translated to those which relate to other section sizes.

All of these questions relate to the limits of predictive capability that are required for FSD, involving localized plastic fracture. These limits are established by the definition of structural mechanics response, inherent to the analysis diagram procedure. Exactness in test characterization of metal properties which is not in match with exactness of definitions of structural mechanics aspects is not of benefit. The real limits are not related to test-finesse—they are determined by structural mechanics analyses and metal reproducibility aspects.

The importance of thinking in terms of R-curve "slope and level" lies in the unification fracture resistance parameters, best expressed by the relationships presented in the model of Fig. 15. If these relationships are understood, then all other factors are clarified.