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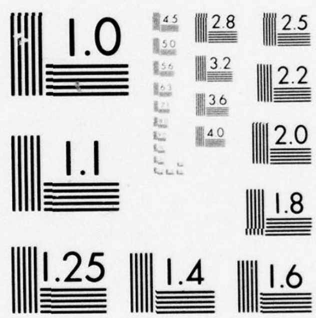
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NRL Report 8085

Concepts of Fracture Toughness and Structural Integrity

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The concept of fracture toughness is introduced. The factors that determine the toughness levels of structural steels are discussed in terms of strength and temperature transitions, strain rate dependence, and mechanical constraint. Test procedures for measuring toughness are highlighted, beginning with linear-elastic fracture mechanics and including such engineering tests as the Charpy-V, Dynamic Tear, and Drop-Weight NDT tests. However, advanced research topics involving elastic-plastic toughness, such as the J-integral, are beyond the scope of the discussion. Finally, the applicability of the various test procedures to analysis of structural integrity is discussed.

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CONTENTS

CONCEPTS OF FRACTURE TOUGHNESS AND STRUCTURAL INTEGRITY

INTRODUCTION

Fracture toughness is a property of metals that defines their resistance to brittle fracture. This report explains the concept of fracture toughness and its dependence on such variables as temperature, strain rate, section thickness, and strength level. A description is given of the linear-elastic fracture mechanics (LEFM) approach which lends itself to a quantitative analysis of fracture in terms of critical flaw sizes and stress levels. Also discussed are the more common engineering tests that provide qualitative measures of toughness beyond the region of LEFM applicability.

In design with ductile materials, the failure-safe load carrying ability of an engineering structure is normally based on a stress analysis to assure that nominal stresses are below yield.* Failures that occur under the resulting elastic loading are broadly classified as brittle fracture. These failures can result from the effects of small flaws or cracklike defects that do not greatly alter the nominal stress distribution and are customarily neglected in stress analysis. Nevertheless, a conservative analysis of the structural integrity of welded structures must be predicated on the existence of such flaws (e.g., weld discontinuities).

Under conditions of high mechanical restraint, a flaw can greatly decrease the high ductility that may have been predicted on the basis of smooth tensile specimens and could cause brittle fracture in the structure. It is apparent that a complete fracture-safe analysis requires proper attention to the role of the flaw. For alloys of high toughness, the loss of ductility due to the flaw may not be significant and an exact knowledge of the location and size of flaws may not be required. With low-toughness alloys, however, the toughness must be well characterized in terms of environmental factors and especially in terms of metallurgical variations within a structure, often associated with heat treatment and welding. In addition, the exact size and location of potentially critical flaws and the stress distribution in their vicinity must be ascertained.

The motivation for the application of fracture mechanics is the possibility of designing safely against the effects of flaws and discontinuities that normally occur. For example, a designer may wish to use welded joints that are entirely free of flaws, but this is not realistic. The practical approach is to recognize that flaws are present or may occur during service and to place a limit on their size. While conventional toughness testing procedures are not able to deal with this problem directly, fracture mechanics tests, where applicable, specifically define a relationship between flaw size and fracture stress for a given material and thus permit a direct estimate of allowable flaw sizes for different geometric configurations and operating conditions.

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*Failure can occur even when stresses are below yield, due to such other phenomena as fatigue crack propagation, stress-corrosion cracking, hydrogen embrittlement, etc. However, these are beyond the scope of the present discussion.

As new materials and designs evolve there will be less engineering experience upon which to rely, and thus a greater need for the designer to take an analytical approach to fracture-safe design in the presence of flaws.

To maintain perspective in the discussion of structural integrity, one must realize that structures may be so complex that it is impractical to accomplish the stress analysis required by a fracture mechanics approach. In other cases, advanced designs may use high-strength alloys of very low toughness for which flaws of critical size cannot be precluded during fabrication or after a short service lifetime. In that case, use of an alternate alloy of higher toughness may be indicated. Conversely, a redesign resulting in lower stresses or the use of redundant load-carrying members may be required. Clearly, there is no single method for fracture-safe assurance for all toughness levels and structural designs. The wide current emphasis on LEFM procedures, in college curricula, design codes, and technical publications, tends to give a misleading impression that LEFM can provide assurance of fracture safety in all instances. For this reason it is necessary to define the limitations of LEFM and to understand other procedures for evaluating toughness and how they relate to structural behavior.

CONCEPTS OF FRACTURE TOUGHNESS

Mechanical Constraint

The concept of mechanical constraint is central to a firm understanding of fracture toughness. This concept can be illustrated by the behavior of a notch in a uniformly loaded plate in tension (Fig. 1). The tensile stress σ_y causes a small element bordering the notch tip to contract in the x direction and to assume a new shape (shaded). A similar element further removed from the flaw will contract less because the stress elevation in σ_y, due to the notch, diminishes with the distance from the notch. Consequently, a stress σ_x is created between the two elements. A similar stress σ_z results in a direction normal to the plane of the figure and limits contraction in that direction. The triaxial stress distribution thus created inhibits plastic flow of the metal and results in the phenomenon of mechanical constraint. For example, σ_x and σ_z stresses will restrict stretching (or plastic flow) in the y direction. All real metals exhibit some plasticity at the tip of a flaw in a stressed body, however, and the fracture resistance, or "fracture toughness," is directly proportional to the extent of this plastic zone. Consequently, the reduction in plasticity attributable to triaxial stresses (mechanical constraint) is equivalent to a reduction in fracture toughness.

With nominal section stresses still below yield, the triaxial stress distribution near the notch tip may cause the local stress to reach a magnitude several times greater than the value of yield stress as measured in a smooth tensile specimen. This local stress elevation, by inhibiting plastic flow, may cause the metal grains to separate by cleavage* (a brittle mechanism) in low-alloy structural steels, rather than by a ductile tearing process (e.g., shear or dimpled rupture in a fractographic sense). The magnitude of triaxial stress, or

*High-strength steels exhibit brittle fracture as a result of a ductile or shearing micromode process. For these steels, however, the local ductility can be so low that the elastic stresses provide sufficient energy for unstable or brittle separation of the metal grains.

simply the "triaxiality," increases with thickness and notch depth to a maximum or plane-strain value, as described below. To prevent brittle fracture due to localized reduction of ductility at the notch tip, the metal must exhibit a corresponding resistance to fracture or fracture toughness. Unfortunately, the toughness of a given alloy is fixed for a given temperature, strain rate, and metallurgy and does not increase to offset the effects of increasing triaxiality. To deal with conditions of insufficient toughness that may therefore arise, one may (a) eliminate the flaw, (b) reduce the stress, (c) change the design, or (d) substitute a new alloy of higher toughness.

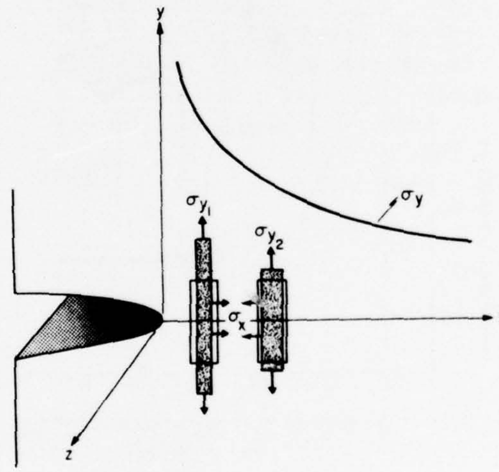


Fig. 1 — Stress in the x- and z-directions result from nonuniform elongation of the elements in the direction of applies stress (the y-direction). This triaxial stress distribution inhibits plastic flow and produces mechanical constraint.

The degree of triaxiality or mechanical constraint developed by the notched body of Fig. 1 depends on both notch depth and section thickness. With a shallow notch, the illustrated elements at the crack tip "sense" the presence of the free surface, and the σ_x and σ_z stresses cannot greatly exceed the yield stress level. Similarly, if the body is thin, the σ_x stress cannot achieve a level above the uniaxial yield stress. A condition of plane-strain constraint (It is important to note that the definition of plane-strain constraint used in reference to fracture toughness does not correspond to that used in theory of elasticity [1].) is said to exist when further increases in notch depth or section thickness do not further increase the stress triaxiality (Fig. 2). A grasp of this thickness-induced mechanical constraint is vital to an understanding of fracture test methods. Without it serious errors in fracture safety projections could result. It is worth emphasizing that fracture toughness is customarily assessed by testing a small, inexpensive test specimen. Because of its small size (thickness), the specimen may not exhibit plane-strain conditions. The resulting unconservative (high) value of measured toughness will not represent the fracture resistance of a structural prototype of thicker section. On the other hand, if the thickness of the test specimen is identical to that of the structure, but the test specimen does not exhibit plane-strain constraint, a requirement to test thicker, but plane-strain, specimens can result in unduly conservative assessments of the fracture toughness of the structure.

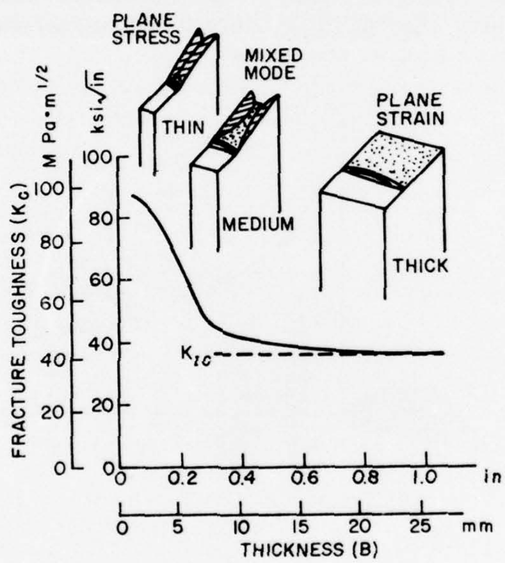


Fig. 2 — Effect of specimen thickness on fracture toughness

Temperature and Strength Transitions

The fracture toughness of ferritic alloys exhibits significant variations with changes in yield strength and temperature. The interaction of toughness with strength level and temperature is illustrated in Fig. 3 by a three-dimensional plot of these variables. Here fracture toughness is taken simply as energy for fracture of a test specimen; later the correspondence between fracture toughness and energy absorption will become clear.

Consider first the plane of energy and yield strength in the figure. The "strength transition" illustrates the characteristic decrease in toughness, from ductile to brittle, with alloys of increasing yield strength. However, these items are subject to certain qualifications:

- The ductile level of toughness means that brittle fracture will not occur even under the adverse conditions of large flaws and plane-strain constraint; the material will fail by plastic overload.

- The label "brittle" does not mean that these alloys will always exhibit brittle behavior, for without high triaxial stresses and appropriately large flaws, these alloys can exhibit significant ductility.

• The strength transition curve depicts the behavior of the best (highest toughness) alloys of a given strength level. Because of poor heat treatment or high impurity content it is possible to encounter brittle behavior at any strength level.

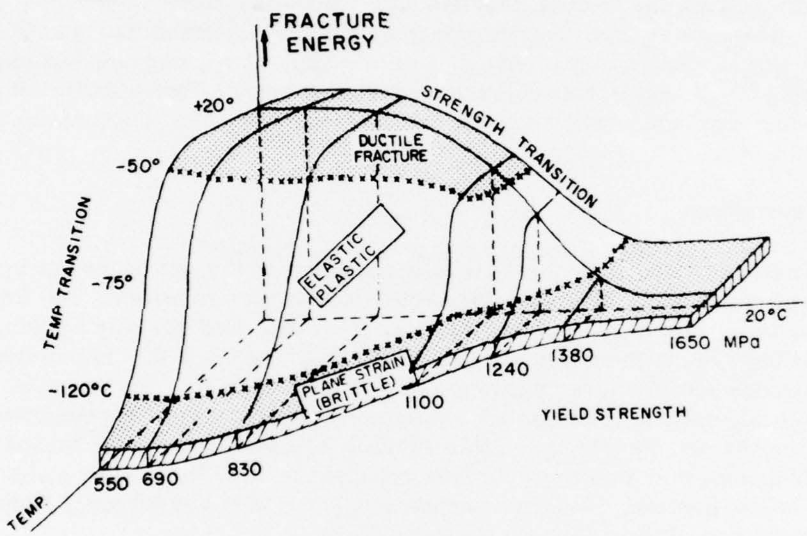


Fig. 3 — The interrelationship of fracture energy, temperature, and strength level with respect to fracture behavior

The "temperature transition" in Fig. 3 illustrates the change from brittle to ductile behavior with increasing temperature. The characteristic S-shaped curve reaches a plateau or upper shelf at which toughness is no longer temperature dependent. Note that the temperature dependence of toughness diminishes with increasing yield strength and that the toughness of the ultrahigh strength steels is relatively insensitive to temperature variations.

It can be generalized that ultrahigh strength steels always behave in a brittle manner under the appropriate conditions. On the other hand, the more common structural steels, with yield strengths between 200 and 900 MPa (30 and 130 ksi), can exhibit a range of toughnesses, depending on the alloy and the temperature.

Unfortunately, a single method by which to define all levels of fracture toughness does not exist. Alloys in the shaded band of Fig. 3, labeled "plane strain (brittle)" can be best characterized through LEFM procedures, which yield a quantitative relationship between fracture toughness and the critical flaw size and stress level required for brittle fracture. However, these methods are restricted to toughness levels in the brittle fracture zone. The region labeled "ductile fracture" is not considered to lie in the province of fracture in the present context, since alloys at this toughness level generally fail by plastic overload, with or without flaws. Thus, it appears that most common structural steels fall within the nominal ductile range at ordinary service temperatures, and outside the scope of LEFM. Recall, though, that Fig. 3 depicts the behavior of only the best (toughest) alloys. Many common structural steels still being produced may be classified as "brittle" at ambient temperatures.

The region between the "brittle fracture" and "ductile fracture" areas in Fig. 3 is termed the elastic-plastic regime. Current research, like LEFM, emphasizes quantitative analysis of fracture toughness in this regime, with the hope of evolving new techniques such as the J-integral [2]. However, conventional characterizations of elastic-plastic behavior for engineering applications are largely empirical and subject to different interpretations.

Strain Rate Dependence

Figure 4 illustrates the sharp change with temperature of the size of the crack-tip plastic zone (and thus toughness), referred to earlier as the temperature transition. The fracture toughness variation in this regime is complex, since it is influenced not only by temperature but also by loading rate, or more specifically, strain rate at the crack tip. In practice, the strain-rate dependence of fracture toughness can be quite significant. For example, at a given temperature the large plastic zone formed under quasi-static (slow) loading conditions may preclude high mechanical constraint and thus result in improved toughness. On the other hand, dynamic loading may result in sufficient reduction in ductility (and thus plastic-zone size) to cause brittle fracture. This phenomenon is believed to result primarily from the strain-rate dependence of yield strength for these alloys.

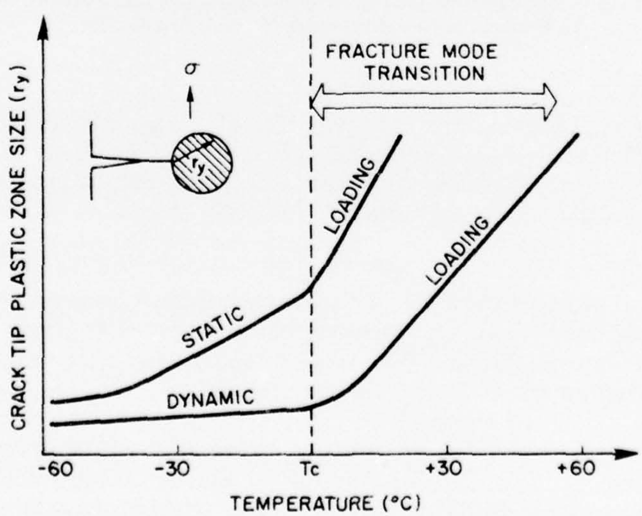


Fig. 4 — Brittle-ductile transition in toughness with increasing temperature, known as the fracture mode transition, exhibited by carbon and low alloy steels. Dynamic loading of these steels reduces the toughness below the "static" values.

The question of what loading rate a fracture toughness specimen should be subjected to simulate structural conditions has been raised. Fracture experts disagree on this for structures, such as pressure vessels, that are subjected to constant or slowly changing loads. One school feels that toughness is best determined from a notched test specimen loaded slowly as in a conventional tensile test. Another school maintains that the toughness of a structure, especially a welded structure, is not uniform throughout because of material inhomogeneities. If a preexisting defect should grow (by fatigue, stress corrosion, etc.) into such a region of low toughness the flaw could exhibit sudden, unstable propagation over the distance perhaps as small as a few grains (called popin). The metal grains at the perimeter of this popin behave as if dynamically loaded and therefore exhibit a dynamic toughness value below that of the static toughness. Hence, a dynamic fracture toughness test is required.

It appears that a conservative fracture-safe assessment requires use of the lower, dynamic toughness of the metal. If static toughness values are employed, the fracture analyst must be confident that the toughness in all regions of his structure is above some minimum value and devoid of local inhomogeneities that may lead to a popin. This may require a difficult statistical analysis. In some cases the use of static toughness can be justified. An example is a plate that has no welded connections and whose material has been produced by a high-quality melting practice resulting in a low inclusion level (i.e., slag or other oxides). For general engineering structures this may be the exception rather than the rule.

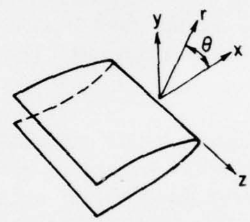
If dynamic analysis is justified, the proper loading rate for the test specimen must be chosen. Again, differences of opinion exist. Some maintain that the relevant strain rate is the average value experienced by the structure. Others claim that the average strain rate of the structure is irrelevant when a popin occurs. In other words, the popin can result in a rapid (localized) strain rate that may bear no relationship to the overall structural loading rate. Partly because of these uncertainties, dynamic fracture toughness tests are usually conducted by impact loading of the entire test piece with the hope that this may result in a lower bound value of toughness. The field of strain rate effects on fracture toughness is an open question and the subject of current research.

LINEAR-ELASTIC FRACTURE MECHANICS

Basic Relationships

Fracture mechanics, or, more correctly, linear-elastic fracture mechanics, refers only to fracture behavior under plane-strain conditions. As indicated previously, this analysis can be applied only if the plastic zone at the crack tip is small enough compared with the dimensions of the crack to ensure overall linear behavior. The concept of LEFM can be traced to Griffith [3], who in 1920 evolved a means to predict the conditions for fracture of a brittle solid (glass) containing a crack. A balance of the stored elastic strain energy and the energy needed to form new surfaces associated with crack extension yielded a relationship for crack instability. Modern LEFM, however, has abandoned the energy approach of Griffith in favor of a stress analysis approach more easily relatable to the language of the designer. Irwin [4] and Williams [5] are credited with modifying Griffith's approach for glass to (a) include the notch-tip plasticity associated with real metals and (b) describe the behavior of the material close to the leading edge of a sharp crack in terms of a stress analysis like that illustrated in Fig. 5. The stresses in Fig. 5 have resulted from an infinite series expression in which higher order terms in r have been neglected. Hence, the use of LEFM is restricted to the region where r is small compared with other dimensions in the x-y plane.

CRACK TIP STRESS FIELD APPROACH



$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left[1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right]$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left[1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right]$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}$$

$$\sigma_z = \nu(\sigma_x + \sigma_y) \qquad \text{PLANE STRAIN}$$

$$\sigma_z = 0 \qquad \text{PLANE STRESS}$$

Fig. 5 — Elastic stresses near the crack tip for a through-thickness crack in a linear-elastic, isotropic body subjected to Mode I loading

Parameter K_I in Fig. 5 is the plane-strain stress intensity factor for Mode I, or the opening mode (e.g., tensile opening of the crack surfaces). The cracked region can also be loaded in shear, that is, Modes II and III. (Mode II refers to the in-plane shearing (sliding) of the metal at the crack tip whereas Mode III refers to out-of-plane shearing, or tearing.) However, Mode I has received the greatest emphasis because it commonly occurs in structures. At $\theta = 0$, the stresses achieve the maximum value:

$$\sigma_x = \sigma_y = \frac{K_I}{\sqrt{2\pi r}} \; . \qquad (1)$$

The unique feature of the $1/\sqrt{r}$ crack-tip stress distribution of Eq. (1) is that this behavior is common to all cracks, regardless of the shape of the body containing the crack, be it a laboratory specimen or a prototype structure. For this important reason, a laboratory specimen can be used to simulate conditions in a structure provided that plane-strain conditions are maintained. Note that Eq. (1) predicts an infinite stress at $\theta = 0$. In reality the metal at the crack tip assumes some finite radius, due to plasticity, so that the stresses are finite.

Inspection of Eq. (1) indicates that the stresses in two different bodies will be identical for identical values of K_I. Hence, K_I provides a single-parameter characterization of the stress field near the crack tip. The K_I parameter, in turn, is a function of the geometry of the body, the loads at the boundaries, and the size of the crack. For a given geometry, the value of K_I may be computed by a stress analysis at the crack tip, where all terms in the expressions for σ_x or σ_y except $1/\sqrt{2\pi r}$ are combined to give stress intensity K_I. Expressions for many different loadings and body configurations have been catalogued by Paris and Sih [6]. All expressions for K_I have the form

$$K_I = C\sigma\sqrt{\pi a} \tag{2}$$

where σ is the nominal stress field in which the crack resides, C is a function of the specimen geometry, and a is the depth of the crack.

The level of K_I at fracture initiation (under plane-strain conditions) is termed K_{Ic}. This quantity is a property of the material in the same sense as the yield stress (σ_{ys}); that is, both vary with temperature, strain rate, and metallurgical structure. The utility of Eq. (2) is readily apparent when it is realized that the form or shape of the stress distribution in a notched laboratory specimen is identical with that in a flawed prototype structure and differs only in intensity as expressed by K_I. The K_{Ic} value determined from Eq. (2) therefore provides the means to relate the critical flaw size and stress level from a simple specimen to those of a more complex structure.

Measurement Procedures

A standard method for measuring K_{Ic} is given by ASTM Standard E-399 [7]. The specimen geometries (a three-point bend specimen and a compact toughness (CT) specimen) are described in this standard; the CT specimen is illustrated in Fig. 6. In concept, a K_{Ic} value can be obtained for any geometry for which a stress analysis is available. However, all specimens must have a sharp notch terminating in a fatigue precrack. The K_{Ic} level is defined experimentally with a laboratory specimen record of load vs crack mouth opening (using a displacement or clip gage) by noting the load at which the crack extends. Typical records of these measurements are illustrated in Fig. 7. Some brittle materials exhibit complete fracture at the maximum load (line a, Fig. 7), whereas others exhibit a rounding (line c, Fig. 7) for which the critical load is determined by methods specified in Ref. 7. K_{Ic} is computed from an expression, similar to Eq. (2), for the geometry of interest in conjunction with the critical load (or stress) and crack length. The latter quantity is customarily determined from post-test measurements of the completely fractured specimen.

To ensure plane-strain conditions, ASTM E-399 places the following restriction on the thickness B and crack depth a:

$$B \text{ and } a \geq 2.5 \left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 . \tag{3}$$

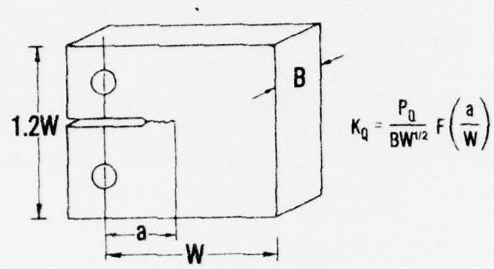


Fig. 6 — The compact toughness (CT) specimen. This specimen and the three-point notched-bend specimen are used to measure the plane strain fracture toughness K_{Ic} in accordance with ASTM E-399.

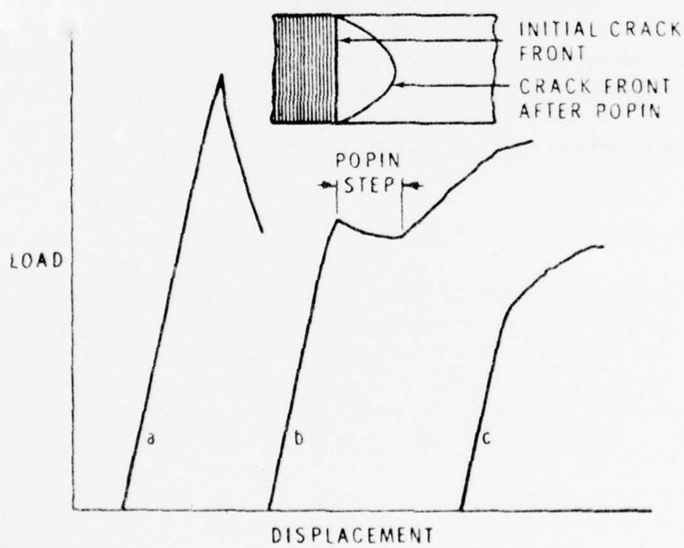


Fig. 7 — Typical test records of load vs crack mouth opening or displacement of a notched specimen. Type *a* and *b* records give unambiguous load points with which to compute K_{Ic}. The type *c* record, however, is typical of that for ductile behavior; to determine if this record is useful for K_{Ic} calculations requires strict adherence to the ASTM Standard Method [7].

This requirement is unusual in that it is not possible to assess the "validity" of the result until completion of the test and computation of a "tentative" K_{Ic}. The ratio $(K_{Ic}/\sigma_{ys})^2$ is an indication of the size of the plastic zone at the crack tip. The actual shape of this plastic zone is not simply defined. Therefore, the region of plasticity is formally represented as a circle, centered on the crack tip, whose radius r_p is

$$\frac{1}{\alpha\pi}\left(\frac{K_I}{\sigma_{ys}}\right)^2$$

where $\alpha = 6$ for plane-strain conditions and $\alpha = 2$ for plane-stress* conditions. Note that r_p varies with the applied K-level (K_I). Failure to meet the requirements of Eq. (3) will result in fracture values that are larger than the true K_{Ic} values, as illustrated in Fig. 2. These values are usually referred to as K_c and occur because the constraint in the specimens is insufficient. The increase in K_c from the K_{Ic} level represents a geometry dependence; this phenomenon masks the K_{Ic} value and prevents the translation of the stress intensity from a specimen to a structure of different geometry.

A common flaw geometry encountered in service is the surface flaw. The equation for this geometry is given in Fig. 8 for a plate in tension, where σ is the nominal stress and Q is a geometry factor that depends on the flaw's aspect ratio (ratio of depth to length). Critical crack depths are plotted in terms of the K_{Ic}/σ_{ys} ratio, which determines the specimen thickness required for that level of toughness in accordance with ASTM E-399 (Eq. (3)). The K_{Ic}/σ_{ys} ratio is the more appropriate expression of toughness than is K_{Ic} by itself, since the former is a measure of the plastic zone size; as discussed previously, it is the size of the plastic zone, i.e., the amount of plasticity, that correctly reflects the level of fracture toughness.

Figure 8 points out a simple graphical means for structural application of LEFM for the case of surface flaws. Given (a) the K_{Ic} of the material at the specific temperature and strain rate and (b) the nominal stress at the point of interest, it is possible to judge the critical defect size from Fig. 8 and to ascertain the appropriate levels of nondestructive inspection required to preclude fracture. However, an important limitation of LEFM becomes apparent in this exercise. If one postulates the existence of, say, a 25-mm (1-in.) flaw in a region that approaches yield stress loading, it is seen that the material must exhibit a toughness ratio between 7 and 11 $\sqrt{\text{mm}}$ (1.4 and 2.2 $\sqrt{\text{in.}}$), depending on the aspect ratio. Furthermore, a section size of 125 to 300 mm (5-12 in.) is required to measure this level of toughness. If, on the other hand, the structural thickness is less than that required, plane-strain conditions would not be achieved; this inhibits the use of LEFM except as conservative lower bound that could preclude use of the material. In the absence of plane strain, the analysis must be treated by more sophisticated elastic-plastic techniques, currently in the research stage. As an alternative, empirical methods of lesser quantitative accuracy (described in the following section) may be employed.

*The term "plane strain" is difficult to interpret since the fracture mechanics definitions of plane stress and plane strain do not agree with those of elasticity theory. For purposes of the present discussion, it is sufficient to think of plane stress as related to yielding through the specimen thickness.

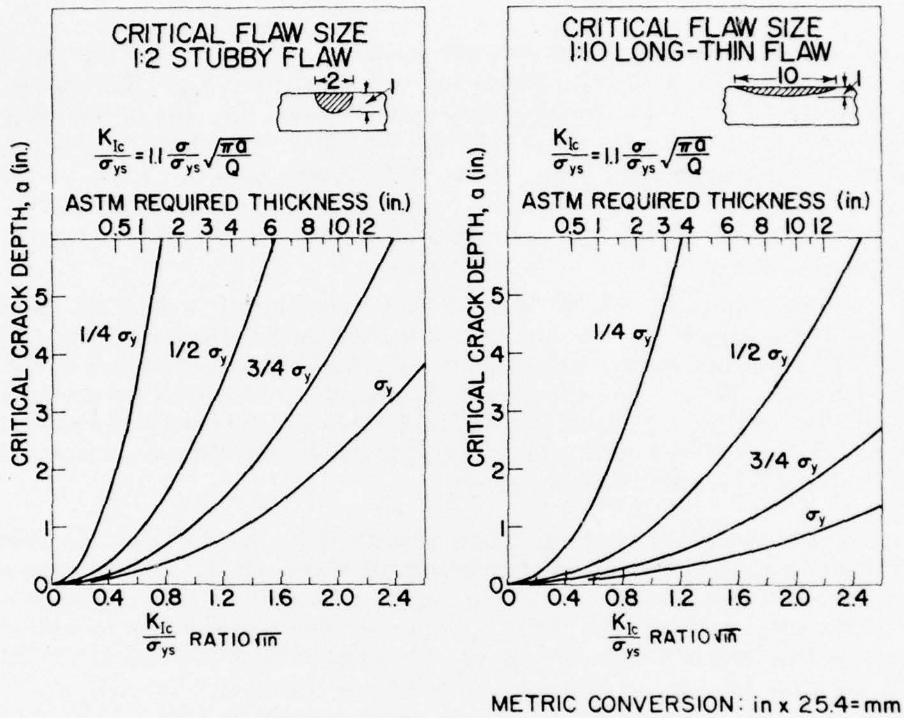


Fig. 8 — Critical crack depths for a plate containing a surface flaw and subject to a nominal tensile stress σ. These depths are plotted in terms of the K_{Ic}/σ_{ys} ratio; this ratio determines the thickness specimen required for that level of toughness in accordance with ASTM E-399 (Eq. (3)). The family of curves represents the values of σ for two different flaw geometries. The Q factor in the K_{Ic} equation is a tabulated function of the flaw geometry.

Another limitation to the practical application of LEFM is illustrated in Fig. 8 For commonly used section thicknesses of 50 mm (2 in.) and less, subjected to yield stress loading, the critical depth for a fully constrained flaw (i.e., one meeting the requirements of Eq. (3)) is only a fraction of an inch. Larger flaws can be tolerated only when stress levels are appropriately reduced. This limitation must be seriously considered, since most structures have regions of stress concentration where the stresses reach the yield level. It is apparent that the use of LEFM must be approached with caution for these regions where it is most needed. If follows that the application of LEFM to areas of high stress may require elimination of even very small flaws, which may escape nondestructive inspection.

Dynamic K_{Id} Characterization

Up to this point, LEFM methods have been described in terms of static loading. Because the toughness of ferritic structural steels decreases with elevation in strain rate, dynamic (K_{Id}) analyses are important to conservative assessments of structural reliability. Unfortunately, a standard test method for dynamic K_{Id} testing similar to that of ASTM E-399 [7] for static testing, has no yet been evolved. Therefore, investigators of the K_{Id} toughness trends have generally applied the concepts and restrictions of E-399 [8,9].

One difficulty with dynamic testing lies in defining the load at fracture initiation. Under rapid loading the mass of the test specimen creates "inertial loads" which are transmitted to a transducer, e.g., load cell, in the loading train [10]. The inertial load does not represent the true load on the specimen and in general cannot be used to compute K_{Id}. Current research is exploring the use of transducers mounted directly on the specimen to circumvent the inertial problem. For relatively slow loading rates, say, $\dot{K}$ less than 1.1 × 10^4 $MPa\sqrt{m}$ s^{-1} (10^4 ksi$\sqrt{in.}$ s^{-1}, the dynamic effects are not large and the load cell appears to give an acceptable representation of the specimen load. For these "slow" dynamic tests, K_{Id} is determined from the maximum load in conjunction with the statically derived K-equation (viz Eq. (2)). This method is expected to be of engineering value but may not achieve the same accuracy limits as those for static tests conducted in compliance with ASTM E-399 [7].

A second difficulty with dynamic testing rests in the determination of the crack length at fracture initiation. This length is defined from post-test measurements in which the profile of the fatigue precrack has been exposed. Near the upper levels of the plane-strain regime and into the elastic-plastic regime it appears that crack extension can occur prior to maximum load. In this case, the use of the maximum load is not consistent with the crack length at fracture initiation and could result in unconservative (high) K_{Id} values.

Considerable effort is under way to investigate dynamic toughness testing procedures and to evolve standard methods. The ASTM Committee E-24 on Fracture Testing of Metals is developing standardized procedures for dynamic K_{Id} testing using the three-point bend and compact specimens. Because of its small size the precracked Charpy-V (PC_v) specimen has been investigated by several laboratories as a way to characterize K_{Id} and Committee E-24 is also investigating this specimen in terms of a standard test method. Unfortunately, current applications consider only the maximum load point in K_{Id} determinations from this specimen. Other investigators [11] have evolved procedures that minimize the effects of inertial loads by limiting the maximum impact velocity and attaching restrictions to the electronic response of the associated instrumentation so that the toughness based on the maximum load may better reflect the K_{Id} values. It should be cautioned that a straightforward application of PC_v techniques in the elastic-plastic region, using maximum load in conjunction with J-integral methods, can result in an overestimate of the K_{Id} value as determined with larger specimens that exhibit plane-strain behavior [12].

Structural Applications of Linear-elastic Fracture Mechanics

At present, LEFM procedures are for several reasons not widely used in industry. First, a stress analysis of the structure is required; this may not be economically feasible for structures of complex geometry. Second, most commerical structures (e.g., bridges, ships, buildings) are constructed from relatively thin sections, say 25 to 50 mm (1-2 in.). These sections may exhibit an elastic-plastic level of toughness at the service temperature for which it is not possible to measure a plane-strain K_{Ic} value. Finally, the cost of LEFM testing is considerably greater than that for conventional (albeit, less qualitative) engineering procedures. Primary LEFM applications have been in (a) the aerospace industry [13], which employs high-strength, low-toughness alloys, and (b) the nuclear industry, which deals with low upper-shelf toughness caused by neutron bombardment and with thick-section mild steels in temperature regions where the metals do not exhibit full upper-shelf (plastic) toughness levels.

In the nuclear industry, the concepts of LEFM are employed in the ASME Boiler and Pressure Vessel Code, Sections III and XI [14]. Section III, on Nuclear Power Plant Components, employs a concept call the K_{IR} curve to assess the fracture safety of nuclear structural components. This curve represents a lower bound of dynamic K_{Id} data as a function of temperature for bainitic pressure vessel steels (SA 508 Class 2 and SA 533-B Class 1). (The K_{IR} curve is based also on K_{Ia} or "arrest" values determined from the loads and crack lengths when a moving crack is arrested. This concept is beyond the scope of the present discussion.) This technique is attractive in that full-thickness measurements of K_{Ic} from the actual material are not required. In other words, it is assumed that the toughness-vs.-temperature trend of the material is predetermined in a conservative manner through the K_{IR} curve. Possibly, further use and statistical documentation of this concept may permit application of LEFM to other structural steels without the requirement for large-section testing once a K_{IR} curve is established for the alloy of interest. With respect to thin sections, of sufficient thickness to achieve plane-strain constraint, a conservative fracture safety analysis could be evolved through the use of the K_{IR} concept. On the other hand, such a lower bound toughness analysis may necessitate structural redesign to limit stress concentrations or otherwise limit the stress levels and allowable flaw sizes to the point where the structure is noncompetitive from an economic standpoint.

ENGINEERING PROCEDURES FOR ELASTIC-PLASTIC TOUGHNESS

It was pointed out in connection with Fig. 3 that LEFM applies only to a limited toughness regime where plane strain conditions can be achieved. For this region LEFM presents a reliable, quantitative method for assessing critical flaw size levels. Similar quantitative analysis procedures for the elastic-plastic regime are in the research stage [15, 16] and are not yet available for general engineering applications. As a result, present engineering methods for characterizing elastic-plastic fracture behavior are largely empirical and rely on either experience or service failure correlations.

A variety of fracture toughness procedures are used throughout the world and, in the interest of brevity, only four procedures will be discussed here: the crack-opening displacement (COD) test [17], the Charpy-V (C_v) test [18], the Dynamic Tear (DT) test [19], and the Drop Weight-NDT test [20]. The COD test is a tentative British Standard Institution (BSI) test. Both the C_v and drop-weight tests are ASTM standard methods; the DT test is a military standard and has been published as an ASTM recommended practice. Several other procedures are used in the United States and Europe but will not be described because of their limited applications or complex natures. For example, the Drop Weight Tear Test (DWTT) [21] is a derivative of the DT test that uses a fracture-appearance criterion to assess the toughness level. Its primary application has been to line pipe steels. The PC_v as previously discussed, is receiving limited application in terms of a J-integral analysis, but this technique is not yet ready for general engineering application. For thin sections, K_c [22,23] and R-curve approaches [24] are employed in the United States. These methods represent more complex analyses that are not suitable for inclusion in the present context. In Europe, the Robertson Crack Arrest Test (CAT) [25] procedures are widely used. The Robertson test will be discussed briefly in connection with the DT test.

Crack-Opening Displacement Test

One of the tests developed to measure toughness primarily for elastic-plastic conditions is the crack-opening displacement (COD) test. This test permits fracture toughness assessments to be made from specimens that do not meet the requirements for linear-elastic fracture toughness. The specimens used for these tests need not be different in configuration or size from those used in LEFM tests, but may merely use different toughness criteria than those applied to the test data in LEFM tests. For example, when making tests of fracture toughness using the K_{Ic} approach, the load on the specimen is used to determine the K_I value at fracture. In COD tests, the clip gage opening (crack-mouth opening displacement) at onset of fracture is measured and used to calculate the crack-opening displacement (COD) at the crack tip. The critical value of COD at fracture, known as Δ_c, is believed to be a critical strain parameter analogous to the critical stress intensity parameter K_{Ic}. The value of Δ_c is calculated from the COD and specimen geometry [17]. It should be noted that in both types of tests the fracture toughness specimen has a fatigue-crack sharpened notch to serve as the sharp-ended flaw required by the analysis.

The COD concept assumes that prior to fracture the material at the crack tip plastically strains to a blunt crack. Thus Δ_c can be considered a measure of crack toughness in terms of the amount of plastic strain that a material will tolerate at a crack tip before failure. Like K_c, Δ_c can be related to stress and flaw size, and can thus provide a quantitative measure of allowable stress for each flaw size. To provide applicable data, the specimen must have the same thickness as the structure for which the data are intended. It should be noted that the COD concept is similar to the J-integral approach used in the United States to characterize elastic-plastic toughness. However, the COD concept has generated little support in the United States.

Charpy-V Test

The Charpy-V (C_v) test was developed in 1905 to give qualitative assessments of the influence of notches on the fracture behavior of steels in the transition-temperature range. This procedure has gained worldwide acceptance and today is used routinely for steel specification and quality assurance. The test determines the energy absorbed in fracturing a three-point bend bar. The bend specimen contains a relatively blunt notch and is fractured by impact loading with a pendulum. Dynamic loading is used in recognition of the strain rate sensitivity of mild steels. Generally, the test procedure is used to generate a curve of energy vs temperature similar to that shown in Fig. 3. The asymptotic energy level defined by the curve at higher temperatures is called "upper-shelf energy." The energy absorbed is considered by some to be a measure of fracture toughness, but fracture experts disagree as to the practical usefulness of the C_v test.

In the 1940s, correlations were evolved to relate the maximum C_v energy to the fracture behavior of ship plates [26]. Specifically, it was discovered that fractures would initiate from small cracks when the C_v energy at the service temperature was below 14 J (10 ft-lb). These fractures continued to propagate in plates having a maximum energy of 27 J (20 ft-lb) at the fracture temperature but arrested in plates having a maximum C_v energy in excess of 27 J. By 1952, a 20-J (15 ft-lb) C_v energy was accepted as a criterion for purposes of design and metallurgical improvement [27]. Unfortunately, it was soon demonstrated [28] that for steels whose chemistry and steelmaking practice differed from that comprising the original ship fracture correlations, the critical value of C_v energy for fracture-safe assurance was not a unique value of 20 J. Consequently, engineers could not use a particular C_v energy for prediction of structural integrity without first evolving a correlation of service failures using the specific steel of interest. To make matters worse, variations in C_v energy-vs temperature trends for a given ASTM steel specification could be as great as the variation between different steel types of comparable chemistry, yield strength, and metallurgical structure. Consequently, it has been extremely difficult to use the C_v test as a rational procedure for fracture-safe assurance. Nevertheless, steel producers have gained wide experience with the C_v test and continue to use it as a means for quality control for steel.

To evolve a more useful structural interpretation of C_v behavior, we often define the fracture toughness in terms of the lateral expansion (LE) of the specimen at the point where it is impacted by the hammer. The lateral expansion is said to provide a fixed level of ductility (and hence toughness) regardless of the energy absorption values [29]. Proponents of this approach claim that it circumvents the problem of C_v energy variability. Consequently, LE values have been incorporated in the ASME Boiler and Pressure Vessel Code and in certain ASTM steel specifications. However, a critical evaluation of the LE criterion leads one to conclude that it does not appear to offer any advantage over the C_v energy by itself. In fact, there exists a 1:1 correlation between C_v energy and LE [30], so that one quantity is identically equal to the other. The problem rests with the design of the C_v specimen itself. The following features of the C_v specimen prevent its simulation of the critical structural aspects related to fracture.

- The dull and shallow notch that can prevent propagation under plane strain conditions. (Clausing [31] has shown a state of plane-strain stress to exist at fracture initiation in the C_v specimen. However, this fact does not necessarily have a bearing on C_v energy absorption, which is related to fracture propagation.)

- The constraint level fixed by the specimen thickness may be inadequate to simulate structural conditions.

- The unbroken ligament is insufficient to simulate a fully developed fracture.

Puzak and Lange [30] have illustrated the linear correspondence between C_v energy and LE trends in the temperature-transition region. A subtle difference in the slope of this linear correspondence is evident for steels of different microstructure (pearlitic, bainitic, or martensitic). Possibly it is this difference that has led others to conclude that LE values present and advantage over the use of C_v energy values. However, this advantage evaporates when one considers structural safety assessments for steels of a fixed microstructure, as are usually required. Further discussion of the problems with LE interpretation is given in Ref. 30.

With the advance of LEFM procedures, attempts have been made to evolve empirical correlations between C_v energy and the static K_{Ic}. Barsom and Rolfe [32] produced a correlation within the temperature-transition region for a limited number of steels (primarily rotor steels). Corten and Sailors [33] evolved a correlation somewhat different from that of Barsom and Rolfe in the transition region when different steels were considered. Corten and Sailors concluded that no single correlation between K_{Ic} and C_v energy in the transition region could be devised to accurately fit all the available data. On the other hand, Rolfe and Novak [34] evolved a correlation between C_v energy and static K_{Ic} for the upper-shelf region of steels having yield strengths above 760 MPa (110 ksi). This correlation appears to have a rational basis and fits the available data well.

It should be cautioned that the above correlations are not generally applicable to all steels and must be restricted to the alloys for which they were developed. In particular, it is not possible to extrapolate such correlations beyond the range of data comprising the correlations, even though this is tempting. Also, it should be noted that the correlations apply only to LEFM behavior and therefore may not suffice for engineering requirements necessitating elastic-plastic behavior.

Drop Weight-NDT Test

Because of a lack of correlation between C_v energy values and critical flaw size and stress level for structural safety analysis, it was clear that improved test procedures were required. This need led to the development of the Drop Weight Test, beginning in 1953, as a means of indexing the brittle-ductile transition behavior of carbon and low-alloy steels. This test is now an ASTM standard (ASTM E-208).

The Drop Weight test specimen design was based on service failures resulting from brittle fracture initiation at small flaws located in regions of high stress. To simulate this behavior, a specimen consisting of a small plate section containing a brittle weld region was devised. The specimen (Fig. 9) is dynamically loaded in bending by a falling weight which causes the specimen to deflect a fixed distance (restricted by "stops"). During the test the weld is fractured, and the plate is subject to a strain of several percent if the base metal does not fracture.

The fractures illustrated in Fig. 9 (top) show a change from break to no-break performance that evolves sharply within a 6°-11°C (10°-20°F) temperature increment. The highest temperature at which the specimen breaks is termed the Nil Ductility Transition (NDT) temperature. The sharp change in break-vs-no-break performance is an indication of the brittle-ductile transition phenomenon exhibited by the mild steels. The specimen behavior with the deflection stops removed (Fig. 9, bottom) illustrates the sharp increase in the steel's capacity for plastic deformation within a few degrees above the NDT temperature. It should be apparent, however, than an NDT temperature can be obtained only for steels that do exhibit a sharp temperature transition, thereby excluding the high-strength steels. Also excluded from the test methods are steels that develop a tough heat-affected zone (HAZ) resulting from the brittle weld deposit. In other words, the brittle weld fracture could arrest in the tough HAZ and thereby produce an erroneously low value for the NDT temperature.

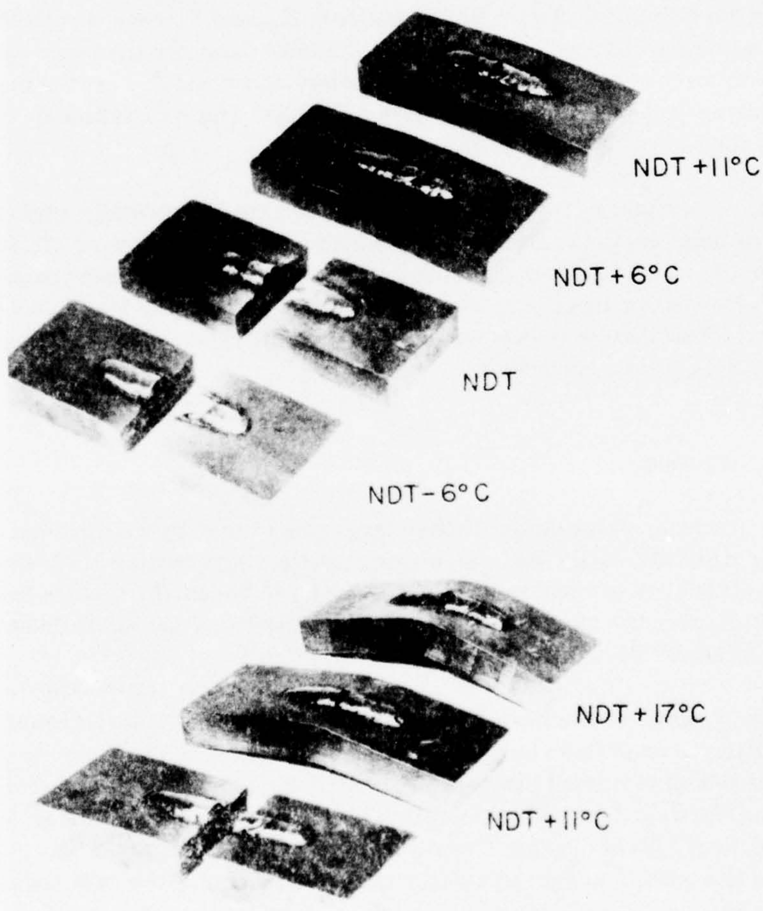


Fig. 9 — Fracture appearance of Drop-Weight NDT specimens. The upper four are from tests conducted according to ASTM E-208. In the lower series the specimen deflection stops have been removed to demonstrate the sharp increase in plastic deformation exhibited by the material within 11°C (20°F) above the NDT temperature. The specimens are 51 X 127 X 16 mm (2 X 5 X 0.625 in.).

The NDT temperature has provided a means for correlation with the World War II ship fractures as well as other service failures. On the basis of such service failures, Pellini and Puzak [35] have evolved a fracture analysis diagram (FAD) for the correlation of critical flaw lengths and stress levels with temperature above the NDT temperature. In the FAD analysis it was shown that the NDT temperature corresponds to fractures that initiated from small (thumbnail-size) flaws subjected to yield stress level loads. It is noteworthy that the NDT temperature determined from a dynamically loaded specimen has been correlated to failures of structures loaded statically in service. Although developed over 15 years ago, the FAD is still used in various parts of the world. However, the FAD analysis has been generally superceded by Dyanmic Tear (DT) test techniques, also developed by Pellini and coworkers [26].

On the basis of an analytical fracture mechanics analysis for a flawed plate in bending it has been shown that the NDT temperature corresponds to a K_{Id}/σ_{yd} ratio of approximately $2.5\sqrt{\text{mm}}$ ($0.5\sqrt{\text{in.}}$) where σ_{yd} is the dynamic yield strength [36]. Shoemaker [8] has measured a K_{Ic}/σ_{yd} ratio of $3.2\sqrt{\text{mm}}$ ($0.63\sqrt{\text{in.}}$) at the NDT temperature for 25-mm (1 in.) bend specimens loaded dynamically. Tetelman and Server [37], on the other hand, have measured a K_{Id}/σ_{yd} ratio of $2.0\sqrt{\text{mm}}$ ($0.4\sqrt{\text{in.}}$) for PC_v specimens loaded to a higher rate than the ones in the preceding investigation. These experimental results are in agreement with the theoretical analysis and give a firm basis for the interpretation of the NDT temperature in terms of LEFM. In other words, given the K_{Id}/σ_{yd} ratio at the NDT temperature, one can judge the critical flaw size/stress level correspondence for the structure from plots similar to those illustrated in Fig. 8 for the geometry of interest.

Confusion has occasionally accompanied the interpretation of the NDT temperature for the fracture behavior of very thick sections. Some investigators have stated that the NDT temperature for a given heat of steel increases with thickness. However, this has no basis in fact. It can be seen that the thickness of the smallest Drop-Weight specimen (16 mm or 5/8 in.) is sufficient to measure a K_{Id}/σ_{yd} ratio of 2.55 mm ($0.5\sqrt{\text{in.}}$) according to Eq. (3). Consequently, the Drop-Weight specimen is under plane-strain constraint at the NDT temperature; further increases in thickness cannot by definition provide increased constraint (and lower associated toughness). This fact has been demonstrated experimentally by Puzak and Babecki [38].

Dynamic Tear Test Procedures

As just discussed, the Drop Weight test serves to define the beginning of the brittle-ductile temperature-transition region and, in conjunction with the FAD, can be used to project structural integrity. In the early 1960s it became apparent that a new fracture test procedure was required to characterize the properties of (a) ultrahigh-strength steels as well as aluminum and titanium alloys, which do not exhibit temperature-transition behavior, and (b) steels of intermediate strength level, which feature a low value of upper-shelf energy (above the brittle-ductile transition range).

In view of the above needs, the Dynamic Tear (DT) test specimen (Fig. 10) was designed to simulate the critical structural features that affect fracture toughness [26]. The specimen thickness may be adjusted to match that of the structure and thus produce the proper mechanical contraint. However, the standard speciment (Fig. 10, top) [18] is of 16-mm (5/8 in.) thickness. The DT specimens feature a deep, machined notch* with a knife-sharpened tip so as to achieve maximum constraint for a given thickness. The unbroken ligament is of sufficient length to simulate a fully developed fracture. The specimen is tested by impact loading, to account for the strain rate sensitivity of some steels, and the absorbed energy is recorded. The above features combine to produce a test of high severity that has not been exceeded by any other known test method. In other words, if ductile behavior is indicated by the DT test for a given thickness, temperature, and loading rate, there appears to be no possibility for that alloy to exhibit brittle fracture in service under the same conditions (hostile environments excepted). A similar statement cannot be made for the C_v test. In some cases a very high C_v energy (i.e., ductile behavior) can be synonomous with brittle behavior in service.

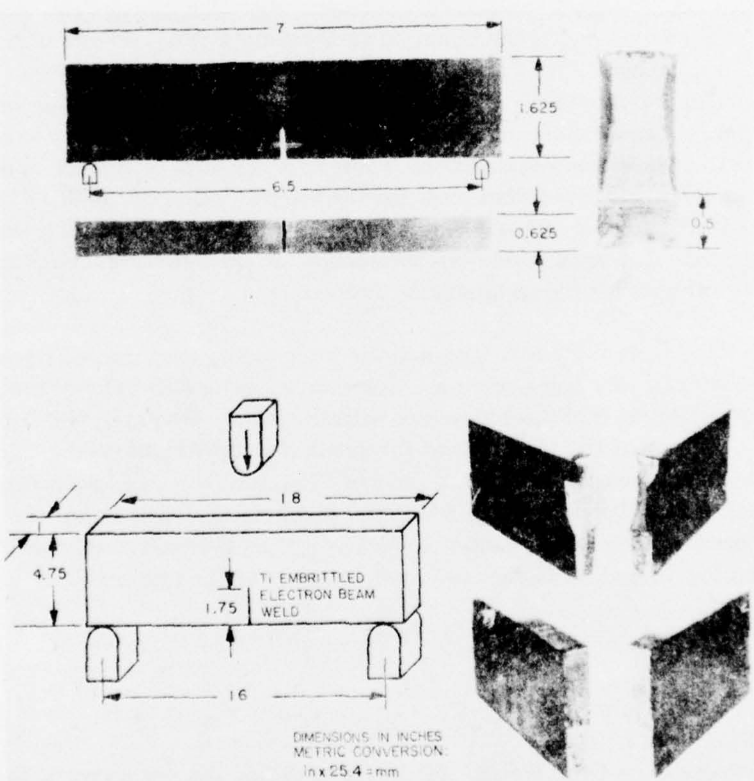


Fig. 10 — **Dynamic Tear (DT) test specimen configuration.** The standard specimen (top) [19] features a machined notch with a knife-pressed tip. The other specimens (bottom) use a brittle crack starter region in place of the notch.

*Alternate specimen des'gns use a brittle weld region in place of the machined notch. For steels with a hardness above HRC 36 a knife blade will no longer sharpen the machined notch tip, and a fatigue precrack is being considered.

The important features of DT test performance are illustrated in Fig. 11 for a steel that exhibits a temperature transition. For steels such as these, which have high upper-shelf energies, the DT energy exhibits a sharp increase above the NDT temperature. It is important to note that the NDT temperature is consistently indexed by the lower toe region of the 16-mm DT curves.

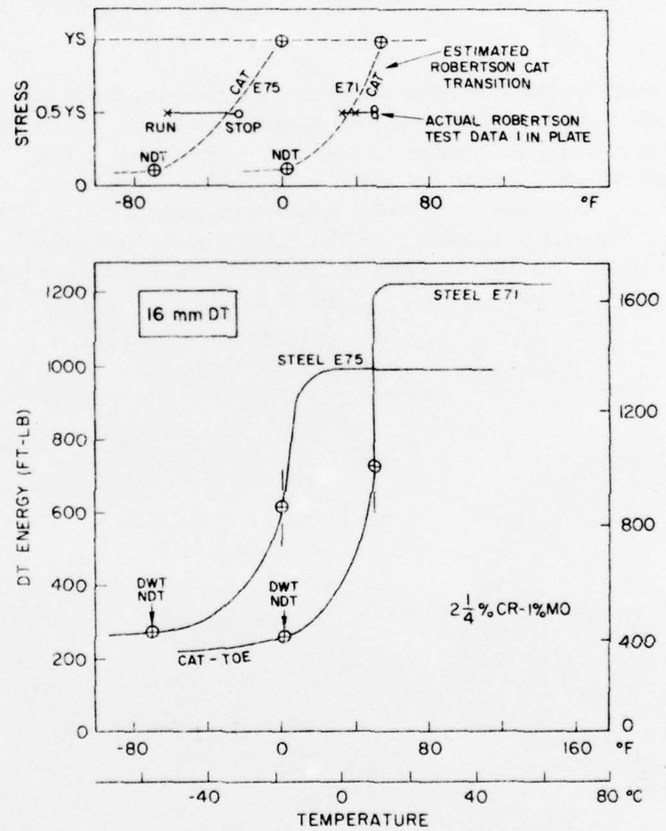


Fig. 11 — Dynamic Tear energy trends for steels that exhibit temperature transitions. Note that the NDT temperature is indexed by the toe region of the 16-mm DT curve. The correspondence of DT energy with the Robertson CAT curve provides a structural interpretation of the DT energy.

The correspondence of the DT trends with those of the Robertson Crack Arrest Test (CAT) is also illustrated in Fig. 11. The Robertson specimen consists of a tension-loaded plate in which a running crack is introduced. Depending on the applied stress level and temperature, the initial crack will arrest in the test plate or result in a complete break. The curve of "run" vs "stop" behavior as a function of temperature is called the CAT curve. The correspondence of the DT and CAT curves illustrated in Fig. 11 gives the former a structural significance (since the Robertson test specimen is, in effect, a structural member). Also note that the middle energy range of the DT curve relates to yield stress loading of the Robertson test. Hence the energy level of the DT test can be related to nominal stress level in a structure. Further discussion of this point is given in Refs. 39 and 40.

A DT test analysis has also been developed for the structural interpretaton of upper-shelf level behavior (i.e., the energy-vs-yield strength plane of Fig. 2) [41]. This procedure is termed the Ratio Analysis Diagram (RAD) and is illustrated in Fig. 12. The RAD for steels was formed by plotting the DT shelf energy values for a range of structural steels in the "weak" fracture orientation. (Similar RADs have been developed for aluminum and titanium alloys.) The upper boundary of the RAD is a technological limit that indexes the best quality steels. As improved steels are developed, the technological limit line is elevated accordingly.

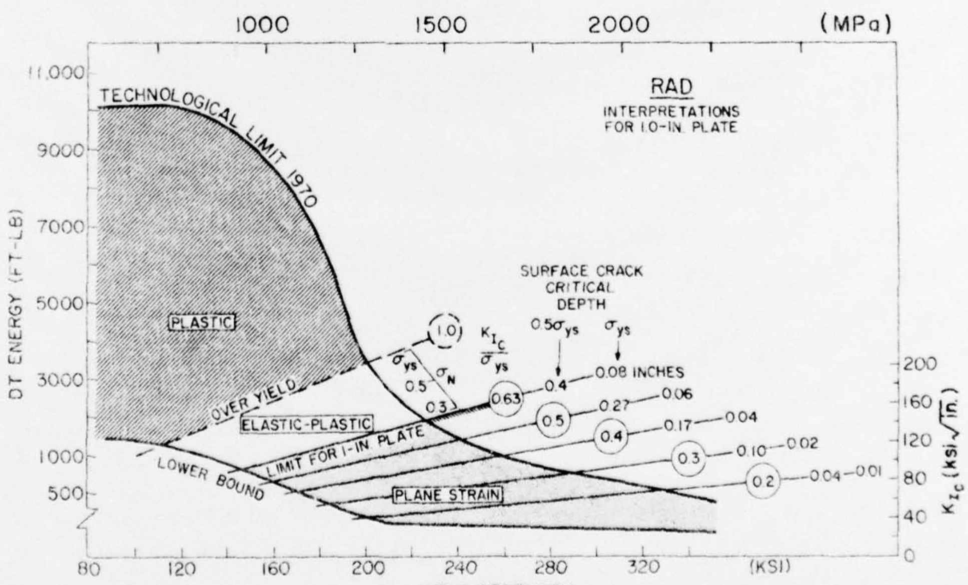


Fig. 12 — The RAD for 25-mm (1 in.) thicknesses is used for projecting fracture behavior on the basis of DT upper-shelf energy of K_{Ic} level. The critical depth for surface flaws is given in terms of the nominal stress level ($0.5\ \sigma_{ys}$ and σ_{ys}) in a tension plate.

In the linear-elastic regime, the DT energy has been correlated with K_{Ic} values for intermediate-strength steels [42]. Since these steels are not generally considered strain rate sensitive, the correlation between static and dynamic test procedures is considered acceptable by experts in this field. The use of K_{Ic} and yield strength scales permits formulation of lines of constant K_{Ic}/σ_{ys} ratio (hence the name Ratio Analysis Diagram). These ratio lines are used to define the critical flaw sizes and stress levels as illustrated in Fig. 8. Furthermore, the K_{Ic} scale permits a three-part division of the RAD into plane-strain, elastic-plastic, and plastic behavior. The ratio that separates the elastic-plastic and plane-strain regions is based on Eq. (3) for the section thickness of interest. The boundary between the elastic-plastic and plastic regions is computed from Eq. (3) using a 1.0 factor in place of the 2.5 value; this is based on engineering judgment [40]. Various RAD diagrams have been developed at the Naval Research Laboratory to index specific steel, titanium, and aluminum alloys and to illustrate the effects of melting practice on fracture performance [41]. As a result, the RAD can be of considerable value in trade-off studies between fracture toughness and strength level for alloy selection in design.

Dynamic Tear Test Correspondence with Linear-elastic Fracture Mechanics

As previously described, the DT specimen provides maximum constraint for the thickness of interest. Studies with DT specimens up to 300 mm (12 in.) thick have been conducted to investigate the effect of thickness for transition-temperature steels [43]. This research defined an elevation of the transition region along the temperature axis with increasing thickness as illustrated schematically in Fig. 13 (based on the SA 533-B steel described in Ref. 43). Also shown in the K_{Id} trend based on large specimens of the same steel plate [9]. The correspondence between the DT curves and the K_{Id} trend is apparent. The DT curve for a particular thickness "tracks" the K_{Id} curve to the level that can be measured with a given thickness (Eq. (3)). The increase in DT energy beyond this point is attributed to the loss of plane-strain constraint and marks the transition to fully plastic (upper-shelf) performance.

At the upper-shelf energy for a given thickness, failure can occur only by plastic overload (see the "plastic" region in Fig. 3). Therefore, the flawed structure will tolerate yield stress levels prior to failure at some DT energy level between the toe and shelf region. In view of this behavior, and on the basis of Robertson test correlations previously described, it appears reasonable to approximate the energy and temperature associated with the yield condition (YC) in the structure by the middle energy range of the DT curve for the thickness of interest.* It is important to note the increase in YC temperature with thickness and its interpretation. For example, at a temperature of 38°C (100°F), a 16-mm (5/8 in.) section will exhibit plastic behavior in the vicinity of a fully constrained flaw, whereas a 150-mm (6 in.) section could exhibit brittle fracture.

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*The YC level of toughness can be approximated by the DT middle energy range only for steels that exhibit high upper-shelf toughness; steels of low shelf toughness are analyzed with RAD procedures.

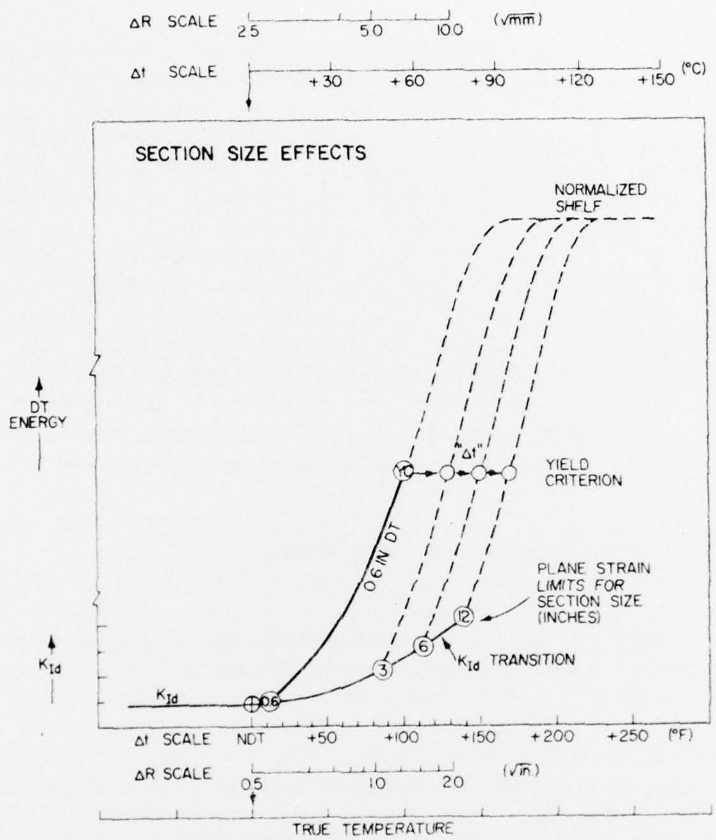

Fig. 13 — Schematic of correspondence between DT and K_{Ic} toughness trends. Curves from both tests represent results from thick specimens, as required for plane-strain conditions. The ΔR scale defines the K_{Id}/σ_{yd} ratio.

The structural significance of the DT energy is apparent from the correspondence with LEFM. However, the DT curve is not limited to the plane-strain region, as is the case with fracture mechanics, but defines the full range of toughness. With further correlation of DT and K_{Id} trends for various steels it should be possible to use only the 16-mm DT curve for engineering design and specification purposes. The foregoing has been suggested by Rolfe and coworkers [44] in evolving fracture control guidelines for ship hulls. In effect, Rolfe suggests that a given level of K_{Id}/σ_{yd} can be guaranteed by specifying a minimum 16-mm DT level; to maintain a fixed K_{Id}/σ_{yd} ratio the 16-mm DT energy is adjusted for steels of different yield strength.

Dynamic Tear and C_v Test Comparisons

The problems of structural interpretation of C_v energy were discussed earlier. Some examples of this behavior are presented below in terms of the DT test. Figure 14 illustrates the C_v and DT behavior of different grades of ship hull steels [45]. The top portion indicates a good correspondence between the two test procedures at the NDT temperature for ABS (American Bureau of Shipping) Grade B material. When the energy curves are normalized to the same position on the figure (as for plate U-21), however, it is seen that the C_v test indicates the attainment of upper-shelf toughness at temperatures that can correspond to the middle energy range of the DT test. Figure 14 (bottom) is an example of the extremes in behavior of the two test specimens. Here the energy from the C_v specimen was sufficient to stall the C_v testing machine at the NDT temperature. The high C_v energy suggests that the structure will fail only by plastic overload (i.e., corresponding with the "ductile" regime in Fig. 3). However, the previous description of the Drop Weight-NDT test has shown that the NDT temperature is indicative of brittle behavior, given the proper flaw size and stress level. Clearly, the different interpretations from the two test procedures are mutually exclusive.

Note that the C_v energy at the NDT temperature for the steels in Fig. 14 ranges from 20 to more than 217 J (15 to 160 ft-lb). Recall that the NDT temperature represents a fixed ratio of toughness (i.e., $K_{Id}/\sigma_{yd} \approx 2.5\sqrt{\text{mm}}$). If this is the case, then a 20-J C_v corresponds to $K_{Id}/\sigma_{yd} = 2.5\sqrt{\text{mm}}$ (0.55 in.) for one steel whereas for another steel of approximately the same type, a C_v energy greater than 217 J corresponds to the same K_{Id}/σ_{yd} ratio. Other examples of the variability of the C_v energy at a fixed level of toughness (that is at the NDT temperature) are given in Refs. 42, 45, and 46. In view of these facts it is difficult to attach a practical significance to a fracture toughness value based on C_v energy in the transition-temperature region.

In connection with the above, it should be noted that C_v energy requirements form a portion of the specifications for certain steel alloys. It is unfortunate that these specifications do not also include a statement of their structural significance; that is, the fracture toughness to be expected as a result of adherence to these energy requirements. As these specifications are written, a designer who is unfamiliar with the toughness behavior of a particular alloy could be misled into believing that they imply a given level of fracture toughness. Unfortunately, the above facts tend to disprove such an assumption.

SPECIAL PROBLEMS OF WELDED JOINTS

The welded joint presents a special problem in evaluating fracture toughness because it contains a wide gamut of microstructures oriented as thin layers adjacent to the weld metal. Any test for evaluating the toughness of welded joints, therefore, should assess the effects of these varied microstructures and if possible assign a toughness index to each. This has the value of establishing which of these structures is the most critical, the "weak link," and what the relative behavior of each zone is. It is, however, not at all certain that a weak link will fail in actual service. For example, in some steels the heat-affected zone (HAZ) is known to be less tough than the base metal or weld metal. However, this zone may be rather narrow and irregular and the fracture may not be restricted to it. As a result, fracture behavior may not reflect the toughness of the HAZ alone, but may be affected by the portion of the crack front that passes through tougher regions. Since it is a requirement that the notch or crack in the specimen be in a specific zone, that zone should therefore tend to dominate the fracture properties that are measured.

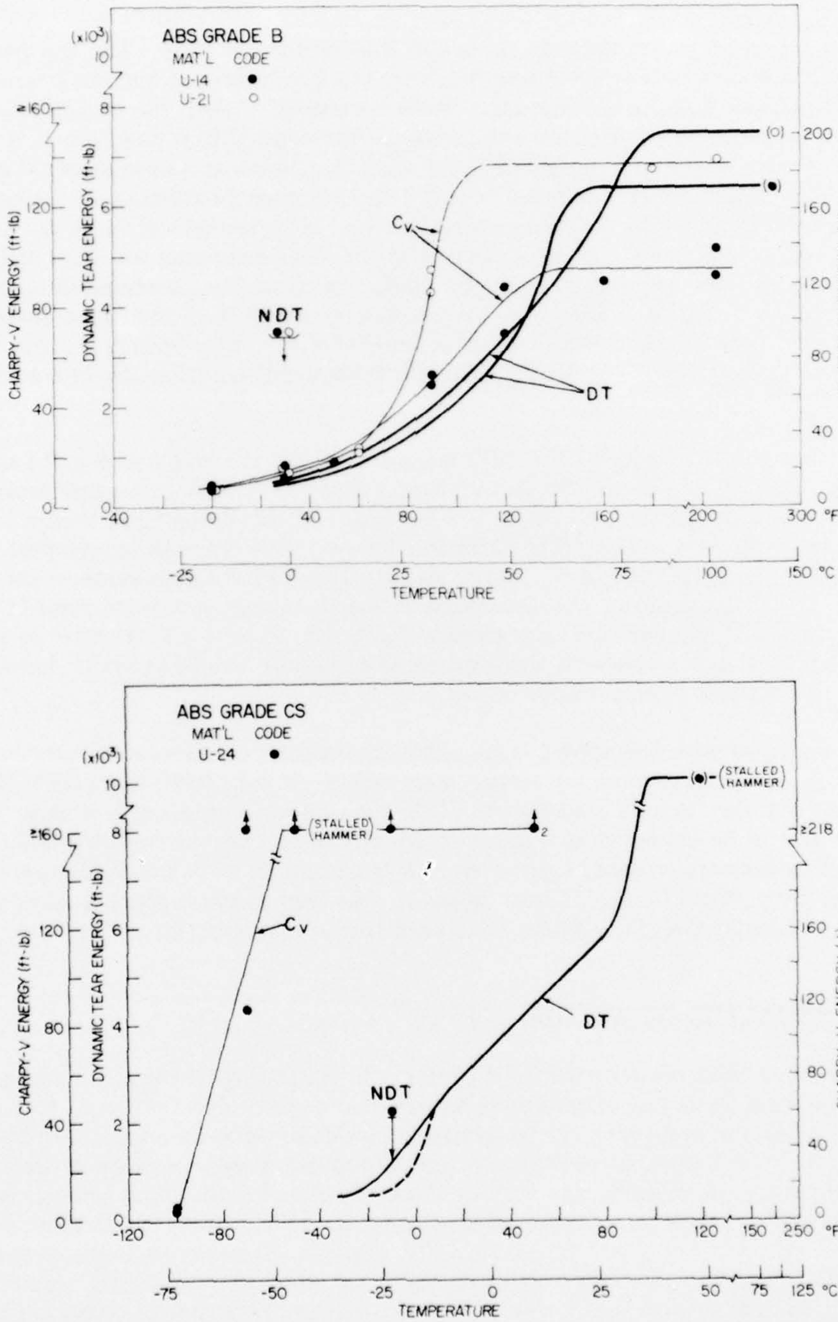

Fig. 14 — Comparison of C_v and 25-mm (1 in.) DT energy trends for ABS ship hull steels. The NDT temperature is consistently indexed by the toe region of the DT curve, whereas the C_v energy can exhibit a wide range at the same temperature. For the sake of clarity only the C_v energy points are illustrated; the DT data appear in Ref. 45.

Fatigue precracking of the specimens may cause difficulty in preparing LEFM or COD test specimens. Although the initial notch may be located in a specific zone, it has been observed that the fatigue cracks may curve away from this zone again, and the fracture may not run in this zone. Thus a test intended for the HAZ may eventually end up failing in the weld metal or the base metal, and data intended to represent the HAZ may, in fact, not represent this zone at all. It has been found that in some combinations of weld metal, base metal, and HAZ, the locus of a crack directed into one of the zones, especially the HAZ, is very hard to control.

Another problem in these tests is the complex nature of the zones themselves. The HAZ in reality encompasses a series of zones. Therefore a judgment must be made on which part of this zone to test. Most engineers prefer to test the zone in its least favorable region, the coarse-grained zone near the fusion line.

The HAZ also differs from the other zones in another significant respect; it does not exist by itself in a specimen and is usually too small to test alone. Weld metal and base metal may be tested by cutting a specimen from the regions of interest. If the weld metal itself is too small a region to test, it may be built up with additional passes to make a weld metal pad to use for testing. This is not possible with the HAZ; which must be tested either in position or as an artificial zone created by use of thermal cycle simulation. Simulated heat-affected zones are currently available only in small sizes (Charpy specimen size) and are thus not suitable for other tests.

In any case, removing small specimens from welded joints tends to relieve residual stresses and thus can change the fracture characteristics. The best test is one that retains the residual stress pattern around the weld, and such tests usually require a large weld specimen. The larger specimen also preserves the elastic constraint of one zone, such as a hard HAZ, on surrounding zones, and this may be important in welded joint behavior.

The geometry problem in testing welded joints is usually overcome by use of special weld groove preparations, especially with respect to the weld HAZ. One of the more common methods is to prepare a "*K*" type of joint, with one side cut straight and the other containing a double bevel. This joint provides a straight-sided HAZ for notching and testing. In this case, however, the joint is not realistic from the standpoint of service joints, which do not often contain straight HAZ. The testing of a weld composite, it can be argued, must use geometry that truly represents the service joint. For this reason, there are a number of tests to be conducted on specimens cut from actual, rather than artificial, joints so that failure is not prejudiced by arbitrary joint design. In many respects this is a more realistic test since failures that occur in specific joint locations (say in the HAZ at a weld toe) must always traverse some base metal, and perhaps even weld metal, to propagate through the joint.

Weldment tests that meet the above requirements have been evolved by the Naval Research Laboratory. Known as explosion bulge and explosion tear tests [26], the methods are realistic from a structural point of view in that the specimens simulate all facets of weld joints in flat plates (i.e., welding process, mechanical processes, and residual stresses).

The specimen is fabricated by welding together two plates, and the weld metal contains a crack-starter region. The entire specimen is explosively loaded to provide a dynamic (lower bound) toughness characterization. The crack, while initially placed in the weld metal, is free to choose its own path as the fracture progresses. Like most engineering toughness tests, the results are qualitative and require interpretation as to the specific flaw size and stress level that will be tolerated by the structure.

SUMMARY

Since real structures do contain flaws or cracklike defects, structural integrity assessments must take into consideration their presence and ensure that the material exhibits sufficient toughness to prevent unstable flaw extension. Fracture toughness of structural steels is a function of temperature, strain rate, mechanical constraint, and metallurgical condition. These factors interact in a complex manner such that the toughness must be established experimentally, with properly designed test specimens that reflect the critical features of the structure.

Linear-elastic fracture mechanics (LEFM) has received wide emphasis as a quantitative method for relating critical flaw size and stress level. Careful examination of the restrictions that accompany LEFM formulations points out its major limitation, namely: it applies only to alloys that can exhibit brittle behavior. On the other hand, it is generally the intent of the designer to choose structural steels that have sufficient ductility to preclude brittle behavior. Unfortunately, the toughness of the resulting structures does not always meet the designer's expectations. In either event, LEFM methodology has not generally been applied to engineering structures. Notable exceptions are the nuclear and aerospace industries, which pioneered the development of fracture mechanics.

The conditions necessary for using LEFM may be stated as follows:

- The fracture toughness of the steel, including welds and heat-affected zones, must be well characterized. This may entail a statistical analysis of toughness data.

- The stress distribution, including weld residual stresses and thermal stresses, in all regions of the structure must be defined.

- A commensurate nondestructive inspection is usually required to define the nature of existing flaws and their subsequent growth during service.

The above limitations are difficult to achieve in any but the simplest designs. The use of LEFM, therefore, may require redesign of complex structures or to simplify stress analysis and permit nondestructive inspection.

For certain cases (e.g., bridges), a recent design philosophy that applies the principles of fracture mechanics but does not fully adhere to the above conditions has evolved. Instead, redundancy in the load-carrying members is substituted to partially off set the need

for rigorous inspection or stress analysis. Thus, a brittle steel may be employed provided it exhibits sufficient toughness to prevent crack extension. In this case it should be understood that once a crack begins extending in a brittle manner, it is not usually arrested and the entire section will fracture. The structural redundancy is then called upon to prevent complete collapse.

The ASME Boiler and Pressure Vessel Code (Nuclear Power Plant Components) has incorporated LEFM principals to a limited extent since 1972. There also appears to be a trend in ASME Code committees to revise existing fracture criteria to include LEFM procedures. In this way the existing rules, which have an empirical basis, may be replaced by more rational procedures, permitting updating as new data and methods become available.

Many engineering structures contain materials that exhibit an elastic-plastic level of toughness, which precludes the use of LEFM analysis. To address this problem, advanced research methods, such as the J-integral approach, are being developed in an effort to provide a quantitative assessment of the critical flaw size and stress level on a parallel with LEFM. For the most part, these procedures are not yet available for engineering applications. Consequently, toughness in the elastic-plastic regime is often determined with test methods that do not provide for an explicit relationship between critical flaw size and stress level. The validity of these procedures has been justified through correlation with service failures or through experience gained over long periods.

The C_v test is perhaps the most widely used of the qualitative test methods. Unfortunately, it is difficult to demonstrate a firm correlation between C_v energy absorption and service failures, especially the brittle-ductile temperature-transition regime. The Drop Weight-NDT test represents a major improvement over the C_v test, in that the former provides a reliable indication of the beginning of the plane-strain to elastic-plastic temperature transition for carbon and low-alloy steels. With this knowledge it has been shown for most structural steels that the critical flaw size or stress level increases dramatically within, say, 28° to 56°C (50° to 100°F) above the NDT temperature. Consequently, structural integrity can be assured by restricting minimum service temperatures to values only slightly above the NDT temperature.

More recently, the Dynamic Tear (DT) test has been developed to characterize the newer, high strength steels as well as nonferrous alloys such as aluminum and titanium that do not exhibit temperature transitions. The advantage of the DT test is its ability to define the complete constraint transition from brittle to ductile behavior. This permits the designer to choose the level of toughness desired for the structure. The DT energy levels must be correlated with structural performance, just as in the C_v test. However, the excellent correspondence of the DT test with dynamic LEFM values, in the appropriate toughness regime, has shown it to be superior to the C_v test.

Fracture toughness is not widely employed in codes and standards except in a few industries. Clearly, expansion of existing codes is desirable, to provide for inclusion of rational test procedures for the elastic-plastic regime as well as the linear-elastic regime. Different criteria must be formulated for the different levels of performance desired. For example, to prevent failure resulting from a small flaw residing in a stress concentration at yield stress loading, an elastic-plastic level of toughness is required; plane-strain materials will generally not suffice. This fact emphasizes the dominant role that must be assigned to the material's fracture resistance in achieving a particular reliability level. With a choice of fracture-safety criteria the risks associated with the structure can be logically related to the probability and the consequences of failure. This action will provide the designer with the option of assigning the reliability level of the structure.

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