

**REQUIREMENTS FOR CONSIDERATION OF FRACTURE
EXTENSION RESISTANCE PARAMETERS
IN FRACTURE-SAFE DESIGN INVOLVING
NON-FRANGIBLE METALS**

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ABSTRACT

A case is presented to redirect the current emphasis on frangible behavior in fracture research to consider the nonfrangible metals that comprise the majority of engineering applications. Fracture-safe design (FSD) principles for structures using these materials can be evolved only through a procedure which integrates a fracture extension resistance property of the metal with the fracture extension propelling force that is unique to a given structural configuration. Consequently, a unification of effort must be achieved on the part of the designer who has not thought in terms of flawed structures and the fracture expert who has not thought in terms of structural response. This unification is particularly relevant to the increasing use of intermediate strength steels of 70 to 130 ksi yield strength (50 to 90 kg/mm²) and to lower strength steels that have been irradiated to higher strength levels. To preclude failure, the traditional concept of designing to the plastic collapse strength, when using these metals in the ductile regime, must be abandoned in favor of modern FSD principles geared to the behavior of flawed structures.

An analytical approach to the fracture characteristics of nonfrangible materials presents a formidable challenge. This difficulty can be circumvented most easily by means of an experimental approach. This will enable FSD principles, in an engineering sense, to be evolved on a near term basis. The approach being developed at NRL characterizes the material toughness in terms of a fracture extension resistance parameter, or R-curve, that is based on modified dynamic tear specimens. Interpretation of the R-curve to the performance of a flawed structural prototype can be assessed in terms of an Instability Analysis Diagram (IAD) which incorporates the results of structural element prototype tests that exhibit the dominant fracture extension characteristics of the prototype.

1. INTRODUCTION

Fracture research has been concerned primarily with brittle instabilities leading to catastrophic failure of elastically loaded structures. This fact is particularly evident in the field of nuclear power where the area of major concern has been the integrity of the pressure vessel of PWR and BWR systems. For these thick-section structures laboratory methods as well as analytical procedures based upon linear elastic fracture mechanics (LEFM) have been evolved to define the critical sizes for flaws under plane strain constraint. On the other hand, plane strain, brittle fracture is but a small portion of the area which must be

considered in fracture-safe design (FSD). In the broadest sense this field encompasses ductile as well as brittle materials.

Fracture in the ductile regime can involve considerable localized plasticity. Also, fracture initiation is not always synonymous with catastrophic failure as is the case with frangible materials. This suggests that development of FSD concepts for nonfrangible materials should not be predicated on initiation and that LEFM theory is not applicable. Similarly, restriction of service temperatures to above the cleavage-to-ductile fracture transition does not necessarily provide positive assurance of fracture-safe performance. Therefore, transition temperature concepts may not be applicable. This fact is particularly relevant to the intermediate strength steels of 70 to 130 ksi yield strength (50 to 90 kg/mm²) which can display low levels of toughness (i.e. low shelf level energy). Structural application of these materials requires specialized analysis techniques to describe a performance which is not brittle and yet may not be highly ductile. It should also be noted that the normal nuclear pressure vessel operating region is above the brittle-ductile transition in fracture toughness even subsequent to a high fluence. However, postulated nuclear accident conditions and toughness-degrading, size-effect considerations for thick sections present a requirement for analysis techniques for the behavior of these structures considering flaws.

The above requirements have been met by a conspicuous lack of suitable methods for FSD. Considering nuclear systems, this observation applies not only to the pressure vessel but to other system components such as piping, the containment vessel and support structures. For low-strength structural steels used at shelf level temperatures, FSD considerations have been generally ignored because the metal possesses sufficient ductility such that the stress intensification from small, sharp flaws is not critical. Thus, the "strength" of the structure has been defined by the plastic collapse load for a flaw-free structure, augmented by a safety factor. However, the plastic collapse strength is only the theoretical upper limit that a flawed structure can attain as the size of the flaw decreases and the ductility or strain tolerance increases. Moreover, the traditional reliance upon yield strength and strain hardening exponent as the only material properties required to predict plastic collapse may be insufficient to characterize the flawed structure performance of the intermediate strength steels. The same is true for the lower strength steels after irradiation. Application of the existing philosophy to these steels of marginal shelf toughness suggests that failures are to be expected. Recognition of this fact for frangible materials was the major reason for the emergence of LEFM. Similar analysis techniques which reflect modern FSD principles for nonfrangible materials are now required.

With nonfrangible materials it is of major importance to recognize that it is the interrelation of the structural driving force for fracture extension and the fracture extension resistance of the metal that determines how the structure will behave. This area must now become a focal point for fracture research. Since the structural response is of marginal interest with frangible materials, research in this area resulted in the fact that the fracture research specialists did not think in terms of structural response and neither did the structural mechanics field study the load response of flawed structures. These viewpoints have led to a dichotomy in structural research which may lead to unconservative designs unless a unification is achieved between structure mechanics and metal fracture resistance aspects of FSD.

When considering fracture of nonfrangible metals certain observations have been made which attest to the difficulties involved in a unified analytical approach to the area. First, nuclear structural components exhibit thickness variations from a few thousandths of an inch to several feet. These thickness variations are associated with degrees of mechanical constraint which may vary from plane strain to mixed mode to plane stress. These levels of constraint result in different material behavior and dictate that various analysis techniques must be used. Secondly, even under the same degree of constraint a material may behave differently (after crack initiation) depending on the compliance of the structure and the type of loading, such as pneumatic versus hydraulic. For example, a primary area of fracture research must deal with nuclear piping systems. Here flaws which are large with respect to the section thickness are possible and they can result in ductile failures because of a geometric instability (i.e. local plastic collapse). The critical stress level-flaw size condition under which fracture will occur depends both on the material resistance to fracture extension as well as the driving force (load response) of the structure. Finally, proven criteria do not exist with which to assess reliability of structures employing nonfrangible materials. This is to be contrasted with frangible materials where the Fracture Analysis Diagram [1] and LEFM methods [2,3] have been used effectively in FSD.

FSD using nonfrangible material is significantly more complex than with frangible material primarily due to the lack of knowledge of the plasticity effects inherent to ductile metals. Secondly, one cannot simply measure the material toughness from a laboratory specimen and translate this value to the structural response because the specimen may not "model" the behavior of the structure which contains flaws. A simple laboratory specimen for fracture toughness models the structure only in the brittle, plane strain regime suitable for LEFM analysis where the compliance features are usually of minor significance. There the K_{Ic} specimen acts as a structural element prototype because the high stress intensification at the notch tip and the limited plasticity override the effects of the boundary. Therefore, for this situation the results from simple specimen tests apply to structures of different geometries. Near-term solutions for the behavior of flawed structures of nonfrangible materials cannot be evolved from first principles because of the difficulties in analytical modeling of the structures. These difficulties are concerned with requirements to formulate a suitable fracture criterion, to consider toughness gradients and to consider the previously mentioned relationship between fracture propagation and system compliance. It is felt that engineering solutions for the present will best be obtained through direct experimental techniques.

The essence of all FSD reduces to an overmatching of the material's resistance to fracture extension (R) in comparison with the crack extension force supplied by the structure. A rational solution to the problems posed above, therefore, rests in an analysis of the metal type-structural type interaction. This paper describes the experimental fracture extension resistance concept currently being developed by NRL for nonfrangible materials. The application of this concept to FSD is explained in terms of Instability Analysis Diagrams (IAD) which characterize the material's response to fracture extension in a specific structural configuration.

2. THE R-CURVE CONCEPT OF FRACTURE EXTENSION RESISTANCE

It is generally accepted that the resistance to fracture extension is dictated by the

behavior of the material near the crack tip. For frangible metals this behavior is effectively described through LEFM even though the treatment of the plastic zone at the crack tip is approximate. Figure 1 (top) indicates the cylindrical shape of the formalized plastic zone. Under plane strain constraint the size of this zone is not influenced by the specimen boundaries. Crack extension commences when the plastic zone reaches a critical size as determined when the crack extension force \mathcal{J} at the crack tip exceeds the crack extension resistance R of the material. Thereupon, new plastic zones are formed by the release of stored elastic energy which results in unstable propagation.

The relationship between \mathcal{J} and R is illustrated in Fig. 2. (See Ref. 2 for a complete description.) The term \mathcal{J} is also defined as the strain energy release rate and refers to the stored elastic energy released during crack extension. \mathcal{J} is a function of the applied stress and the crack length; its dependence upon increasing applied stress, σ , is indicated by the lines of increasing slope in Fig. 2. The point of tangency of the \mathcal{J} and R curves defines the lowest level of strain energy which will cause unstable propagation and therefore defines the critical flaw size-stress level. For frangible materials such as glass the R -curve reaches a plateau (R_3) which does not increase with crack extension. For real materials a very small degree of crack movement can take place before unstable fracture, as illustrated by the curve labeled R_2 . As plane strain constraint is lost for higher toughness materials, the R -curve exhibits increasing amounts of stable crack growth before fracture. However, the specimen is still subject to a nominal elastic stress level at fracture. This behavior is customarily designated as K_{Ic} or plane stress fracture and it is currently being analyzed for thin sheet applications at several laboratories.

It is desirable to apply the concept of the R -curve to nonfrangible metals, thicker than sheet, which require high degrees of plastic deformation for propagation. The rationale used here is that the local deformation at the crack tip continues to define the resistance to fracture extension even when the plastic zone is large with respect to the dimensions of the crack. The latter concept is easy to envision but difficult to put into practice since it is not clear what quantities to measure in defining R . Figure 1 (bottom) illustrates the large plastic zone and gross (through-thickness) yielding associated with fracture for ductile materials. In concept, the plastic zone still attains a critical size at fracture just as for frangible materials. However, attainment of its final size can be preceded by significant amounts of slow, stable tearing. It is, therefore, important to realize that the fracture extension resistance for nonfrangible materials is no longer dictated solely by the conditions for the first increment of crack extension as with frangible materials. In addition, the plastic zone size is a function of the specimen boundaries and can be strongly dependent on thickness. The difficulties in evolving a fracture criterion for this behavior are formidable. Such criteria as are being explored elsewhere include crack opening displacement and strain at a fixed distance from the crack tip. The R -curve approach is being explored at NRL to circumvent the years of research still required to define crack tip fracture behavior. (The current research at NRL in this area is described in Ref. 4, 5.) At the sacrifice of some degree of quantitateness it is felt the latter approach can be used to formulate FSD principles for the immediate structural problems.

2.1 DT Test Definition of the R -Curve

It is clear that the fracture extension resistance is defined by the energy absorbing capacity of the deforming metal at the crack tip. An assessment of this process must

therefore be possible from the energy absorbed in fracturing a test specimen. Using this rationale, modified versions of the dynamic tear (DT) [6] specimen are being employed to define the R-curve behavior. The DT specimen, developed at NRL, has been used for several years to indicate the relative toughness of structural materials which range from brittle to ductile. The specimen geometry (Fig. 3) which incorporates a deep, sharp notch is sufficient to provide the maximum mechanical constraint for a given thickness and is representative of a real flaw in a structure.

The behavior depicted in Fig. 1 is modeled by fracturing several DT specimens of a fixed thickness and having different unbroken ligaments (crack run). The resistance parameter is defined as fracture energy per unit fractured area (E/A). For a frangible material, as indicated in Fig. 1 (top), the plastic zone is of a localized nature and is fully developed within a short distance from the crack tip. As the crack extends, the size of this zone is not expected to change (for non-rate sensitive materials). Consequently, the E/A value from specimens of different crack runs must be constant.

A behavior different from the above is expected for ductile material. As depicted in Fig. 1 (bottom), the plastic zone can be large with respect to the dimensions of the crack and may not be fully developed within the confines of a DT specimen having a short crack run. The result is the development of a plastic hinge as the DT specimen is loaded. For longer crack runs this hinging involves a larger amount of plastically deformed material until a limiting condition is eventually attained with sufficiently large values of crack run. The increasing plastic zone size is reflected by increases in E/A with crack run.

A second characteristic of nonfrangible materials is concerned with slow, stable crack extension before instability is attained. This facet of the fracture process appears to be associated with a constraint transition. In other words, the high constraint at the tip of a flat-bottom fatigue crack can be diminished as through thickness yielding begins ahead of the crack; thereupon the crack front extends by slow tearing to take on a natural shape as dictated by the fracture process. This slow crack growth begins in the central region of the ductile material as illustrated by the V-shaped zone in Fig. 1. The plastic enclave size continues to increase during the period of slow growth and is reflected by increasing fracture extension resistance E/A as the constraint is reduced.

At this time a separation of the above two phenomena is not possible. Further research is required to determine if the plastic hinging occurs before or simultaneously with the stable growth and what portion of the absorbed energy must be attributed to each process. Nevertheless, it is concluded that an R-curve developed in this fashion must reflect the basic metallurgical resistance of the material and that such a curve can be evolved in a simple, straight-forward manner.

Typical R-curves from 1-in. steel plate of widely differing toughness levels are shown in Fig. 4. The material comprising the lower R-curve is brittle in the sense that valid K_{Ic} values can be determined with this thickness and only nominal elastic stress levels are required for fracture. As expected, the curve is flat with increasing fracture extension increments. On the other hand, the R-curve for the ductile material increases sharply with fracture extension increment, for reasons previously set forth, and plastic stresses are required for fracture.

2.2 Interpretations of the R-Curve

To develop FSD principles it is necessary to have a simple test procedure that is

capable of defining the full range of toughnesses exhibited by different materials; the test procedure must be interpretable in terms of the structural behavior. Most test procedures are restricted to a narrow range of toughness (e.g. LEFM tests), define a fixed toughness level (e.g. Drop Weight - NDT test), or are difficult to interpret in terms of structural behavior, such as the Charpy-V test. With the latter the problems of generalized structural correlation are complex for the intermediate strength steels of 70 to 130 ksi yield strength (50 to 90 kg/mm²) [7]. The R-curve avoids the shortcomings of the above test methods and provides the necessary range of toughness measurement capacity. As will be explained, this method can be interpreted in terms of structural behavior and is, therefore, attractive as a means to develop FSD principles.

A simple model illustrating the R-curve behavior for steels exhibiting toughness levels from highly brittle to highly ductile is presented in Fig. 5. An initial fracture extension increment labeled "notch blunting" is taken to describe the slow, stable crack extension. Thereupon the R-curve may exhibit any one of the six shapes indicated. Curves 1-3 are flat and relate to fracture behavior under increasing levels of elastic stresses. As the R-curve begins to exhibit a rising slope, ranging from low to steep, the material is no longer able to propagate a fracture under nominal elastic stresses.

R-curves of the type shown in Fig. 5 have been obtained for a variety of materials and thicknesses. The significance of these curves will be defined in terms of the level of the R-curve (e.g. curves 1-3) and the slope (e.g. low, medium, steep). Initial evaluations [8,9] have indicated that the slope of the R-curve for cases 4-6 in Fig. 5 can be expressed as

$$\frac{E/A}{\Delta a} = \frac{r_p}{B} l/2 \tag{1}$$

where E/A is fracture extension resistance (ft-lb/in²), Δa is the fracture extension (in.), B is the specimen thickness (in.) and r_p is a material property having the units lb/in^{3/2}. This equation applies only up to the point of saturation of E/A with crack extension as the plastic zone is fully developed. For a given thickness, the R-curve must therefore be linear with run*.

The significance of Fig. 5 is that it begins to bridge the concepts used by the materials specialist and the designer. The ordinate (left) describes a material parameter relative to fracture ductility while the ordinate (right) relates to the stress level and structural force system considered by the designer. The zone of demarcation between stable and unstable fracture is given by the change from flat to rising R-curves. It is, therefore, possible to relate to the designer, on the basis of level and slope of the R-curve, whether low level elastic stresses or stresses greatly over yield are required to propagate an existing flaw.

It is a characteristic trait of the designer to require quantitiveness when applying FSD principles, (e.g. an exact correspondence of the R-curve with a critical flaw size and stress level). This quantitiveness is available only for the R-curves of flat slope which relate to LEFM. Unfortunately, the current state of the art requires that a certain amount

* The rising R-curve in Fig. 4 deviates somewhat from linearity due to insufficient specimen span length. This leads to excessive brinelling of the hammer into the specimen which results in a high total energy absorption.

of qualitiveness must be accepted to interpret the rising R-curves or any other procedure relating to nonfrangible metals. On the other hand, it must be realized that the correspondence between the rising R-curve and the critical flaw size-stress level need not be any more quantitative than the designer's ability to describe the strain distribution when high levels of localized plastic strain are required for fracture extension. Quantitative descriptions of the plastic deformation of a cracked body by the designer do not appear to be presently available. Consequently, an acceptable method with which to evolve FSD criteria for nonfrangible materials and one which can be developed over the near term is offered by the R-curve approach.

2.3 Effect of Thickness-Induced Constraint

The thicknesses investigated to establish the R-curve behavior ranged from 0.4 to 3-in. (10-76 mm). For these thicknesses the r_p parameter is constant for a given material. The significance of this fact can be seen from eq. (1). This equation relates the fracture extension resistance R (or E/A) to a material parameter r_p and a geometry parameter $\Delta a/B^{1/2}$. The evidence that r_p is a constant over a range of geometries permits a direct interpretation of resistance in terms of geometry. With this in mind, it is apparent that the slope $\frac{E/A}{\Delta a}$ of the R-curve decreases as thicknesses increases. From the previous description of Fig. 5 it is concluded that decreasing R-curve slopes are synonymous with decreasing levels of plastic stress for instability. Consequently, one may interpret the structural performance in the ductile regime as being degraded with increasing thickness. The physical significance of this observation appears to be that the strain tolerance decreases with increasing thickness as a consequence of the thickness-induced mechanical constraint.

To further clarify this point recall that the specimen energy absorption is an indication of the volume of plastically deformed metal. This energy is expressed by eliminating the area term A from eq. (1) as follows:

$$E = r_p \Delta a^2 B^{1/2} \tag{2}$$

It is seen from this equation that the specimen energy absorption increases with thickness for a given crack run. However, the energy does not increase in proportion to the thickness increase*. Thus, a decrease in the R-curve slope with increasing thickness is observed. It is important to realize that the fracture extension resistance (E/A) can be used to define the toughness of various materials with a fixed specimen geometry. However, this parameter by itself is insufficient to characterize the effect of thickness. For example, since E/A varies as the ratio $\Delta a/B^{1/2}$, any value of E/A can be obtained as thickness is varied, depending on the choice of Δa . In other words, the value of Δa must be fixed in order to characterize the effect of thickness; this is accomplished through the R-curve slope parameter $\frac{E/A}{\Delta a}$.

Another example of the reduced strain tolerance with thickness for different type specimens is apparent from the results of geometrically similar, surface-flawed tensile specimens tested by Southwest Research Institute [10]. These specimens indicate a size effect or reduction in net strain to fracture from 9% to 4% for 1-in. and 6-in. thick specimens,

* Given geometrically similar specimens of different thickness, one would expect the volume of plastically deformed metal to increase as the cube of a specimen dimension. However, experimental evidence shows this not to be the case for flawed specimens.

respectively. The structural implications of this behavior must now be explored. The subject tensile test represents a high constraint geometry with a small crack run. The tensile test results may provide only a characterization of the initial extension of plastic fracture. Flawed tensile tests of larger size would be required to determine conditions related to structural failure that are associated with longer crack runs.

For large thicknesses one may postulate that the reduction in R-curve slope could be sufficient to seriously affect the structural behavior if fracture safety is predicated on thin section tests. Considering the R-curve trends in Fig. 5, the effect of thickness would be particularly serious if the reduction in R-curve slope is sufficient to reduce a type 4 behavior exhibited by a thin section to a type 3 (frangible behavior) when the full thickness is tested. This is particularly significant to the irradiated beltline region of a nuclear vessel if credible accident analyses require an assessment of resistance to plastic fracture. (Note that the beltline region in normal operation sees only elastic loading and the preceding considerations would not apply.) The R-curve for 6-in. thick A533-B steel is presently under investigation to clarify this point. The issue will receive additional emphasis through correlation with the behavior of 6-in. thick A508-C1 2 flawed pressure vessels under investigation as part of the AEC Heavy Section Steel Technology (HSST) Program [11]. In these tests the effects of longer crack runs would be definable because the natural constraint transition for the section size would be manifested.

3. INSTABILITY ANALYSIS DIAGRAMS

As previously described, FSD principles for nonfrangible metals cannot be evolved solely on the basis of a material property and must involve an integration of the metal response and structural response. A means for determining the metal response in terms of the R-curve has been presented. The application of this material property for the case of rising R-curves must come through an experimentally-derived, interpretative procedure based on the structural response. To satisfy this requirement it is proposed to conduct structural element prototype (SEP) tests for flawed structures in a manner analogous to the prototype tests conducted to determine the plastic limit loads for unflawed structures. A test element representative of only a portion of the structure is required. This type of structural element may be considered as a flat plate, beam, cylinder, etc., which is large enough to define the behavior of the material in the structure. In other words, the characteristic fracture extension force of the structure must be developed in the SEP test. The particular SEP test for a given application is dictated by the prototype geometry, the nature of the flaw that may be expected and the type of loading.

The integration of the R-curve and the SEP tests is best presented in graphical form for engineering interpretation. A schematic formulation of this type, called an Instability Analysis Diagram (IAD), is illustrated in Fig. 6 for a tubular configuration. The graph displays fracture trends for flawed tubes of a given thickness and type of loading in terms of the slope of the R-curve and the nominal hoop stress for materials which do not exhibit transition temperature characteristics. It is desirable to depict the structural behavior in terms of nominal stress since this is the quantity used in design calculations. However, the fracture process is governed by local strains near the crack tip. The IAD implicitly takes cognizance of the fact that the crack extension forces may result in significant yielding in the vicinity of the flaw and that this phenomenon may allow fracture extension

at nominal elastic stress levels.

The IAD in Fig. 6 is divided into two parts by the K_{Ic}/σ_{ys} ratio of 0.63. This is the highest value for which LEFM can be used for a 1-in. thickness according to the recommended practice of the ASTM Committee E-24 on Fracture Testing of Metals. The region to the left of the 0.63 ratio relates to brittle behavior characterized by a flat R-curve. The shaded band indicates the approximate range of critical hoop stress required for instability of through-thickness flaws ranging in length from 1-in. to 20-in. (1T to 20T). This band has been calculated from equations for an infinite flat sheet, as available in the literature, augmented by the Follas geometry correction factor for cylinders [12], using a range of geometries. The point to note here is that these flaws become unstable at elastic stress levels that are well below yield. As contrasted with the region above the 0.63 ratio there is relatively little change in the critical nominal stress level over a wide range of flaw sizes.

Above the 0.63 ratio limit for LEFM, the R-curve begins to exhibit a rising slope and greater stresses are required for instability. A point in the center of the shaded region at the 0.63 ratio has been arbitrarily selected, for purposes of illustration, to indicate the beginning of a region in which the critical stress level is strongly dependent on the slope of the R-curve. The "fan" of flaw lengths illustrates that for small increases in R-curve slope the hoop stress for instability of a 1T or 2T flaw increases sharply so that stresses in excess of yield are soon required. On the other hand, large increases in R-curve slope will have relatively little effect on the critical hoop stress required for a large (20T) flaw. In this case the flaw presents a long, unsupported region which is locally overloaded by the pressure forces. The mechanical advantage so derived makes the instability condition relatively insensitive to toughness level.

Through proper choice of SEP test specimen and type of loading, the compliance of the prototype system can be accurately modeled. The compliance is customarily defined as the flexibility of the structure, but in this case it must also include the type of load (i.e. hydraulic or pneumatic) which relates to the magnitude of the force as a function of time on the extending crack at instability. Compliance is an important factor to be considered in FSD of structures involving nonfrangible materials. This fact is vividly demonstrated in pipeline for gas transmission where a fine balance between the R-curve of the material and the compliance of the pressurizing medium determines the difference between a few feet or several miles of rupture.

An IAD of the form shown in Fig. 6 can be readily applied in an engineering sense. Consider the case where design specifications require a 1-in. thick tube to be stressed to a hoop stress equal to $0.5 \sigma_{ys}$. If the material is used above the frangible region and the R-curve slope is known, then the size of the permissible flaw is easily obtained from the IAD through comparison of the critical flaw size lines with the horizontal line at the hoop stress level of $0.5 \sigma_{ys}$. This type of analysis may be required for the piping in a nuclear plant where a certain size flaw in ductile material must be considered as part of a postulated accident analysis.

The IAD approach is useful in the case of transition temperature materials as well. For a given material the R-curve slope increases with temperature in the transition temperature region. A lower limiting temperature can, therefore, be chosen graphically to guarantee the required flaw tolerance. This same rationale cannot be directly applied with conventional approaches, such as Charpy-V (C_v) energy or fracture appearance, which do not

incorporate the fracture extension force characteristics of the structure. For example, a fracture appearance technique can define the temperature for maximum (i.e. shelf) toughness of a carbon steel, generally by the absence of cleavage. However, the level of the shelf may not always be sufficient to guarantee safety with materials of low shelf toughness. Likewise, in the absence of an interpretative procedure, the C_V shelf energy cannot define the flaw tolerance of structure where the length of the flaw results in localized plasticity that permits propagation at nominal elastic stresses. The application of the IAD approach, of course, depends on experimental data to generate the required plots. However, a procedure has been defined with which FSD principles for nonfrangible metals can be developed in a straight-forward manner.

An example of the behavior of burst cylindrical vessels is presented in Fig. 7. The vessels contained flaws which were approximately 20T in length and 0.8 through the wall thickness [1]. The upper photo illustrates a vessel having a flat R-curve. The failure occurred at a hoop stress level of 1/4 yield, and the failure point lies in the LEFM region of the IAD in Fig. 6. The vessel material in the lower photo exhibited a steep R-curve and also failed at low elastic stress levels (hoop stress of 1/3 yield) as implied by the 20T line in Fig. 6. The high R-curve slope for this material translates to bulging and gross deformation of the flawed region, with fracture extension occurring by ductile tearing. The lower photo provides an excellent example of how the structural features act to control the type of fracture. The fracture would normally propagate in the direction of maximum stress, that is, in an axial direction. Instead, the cylindrical geometry caused the fracture to turn and form the indicated "flap".

4. FRACTURE CHARACTERISTICS OF THICK-WALLED PRESSURE VESSEL STEELS EXHIBITING A RADIATION-INDUCED EMBRITTLEMENT GRADIENT

An interesting application of the R-curve concept derives from the gradient in toughness exhibited by the material in the wall of a nuclear pressure vessel. The wall is subjected to neutron radiation emanating from the reactor core; sufficiently high fluence levels can embrittle the steel. The resulting toughness degradation, however, decreases through the wall in the direction away from the core; this is a consequence of the self-shielding effect of the wall which attenuates the neutrons with a commensurate decrease in the related damage. After an appropriate period of operation the vessel wall can exhibit a gradient in toughness which ranges from frangible at the inside surface (nearest the core) to ductile at the outside surface. Current AEC fracture-safety regulations consider the embrittlement as uniform through the entire wall and of a degree equal to that occurring at the inside surface. This is a conservative criterion which has been necessitated by a lack of information concerning the actual response of a flawed nuclear vessel containing such a gradient. Considerable increase in the lifetime of the pressure vessel is possible if this conservative criterion could be relaxed based on a more realistic analysis. Until recently there was no technique to predict this behavior; LEFM techniques, for example, can be used only to predict fracture initiation at the frangible inside wall surface. This analysis cannot be used to project the structural response resulting from this type of initiation since the vessel exhibits considerable ductility at the outside wall surface. The R-curve concept has been found to be a useful practical tool for this case.

An initial investigation of this problem was undertaken [13] in which the irradiated vessel wall was simulated by a 3-in. thick, low alloy steel plate containing a metallur-

gically induced toughness gradient. The gradient through one-half of the plate is taken to represent that occurring in the wall of an irradiated pressure vessel (Fig. 8). Dynamic tear test trends were developed from material representing the inside wall surface, the outside wall surface and the composite behavior of the complete wall. DT specimens having various crack runs were used to develop R-curves for these same locations. The results are indicated in Fig. 8. At a temperature of -25°F (-13°C) the R-curve for the simulated inside surface material is flat and indicates frangible behavior as described previously. However, the R-curve from the simulated outside surface exhibits a steep rising trend. Significantly, the R-curve from the complete wall (1-1/2-in. composite) exhibits an R-curve of rising slope similar to that of the outside surface. This trend indicates that the fracture behavior of the complete wall would be dominated by the ductile outside surface. Consequently, fracture initiation at the inside wall is unlikely to result in complete fracture of the structure.

The significance of the rising R-curves is further amplified by the DT curves from the same locations. At the temperature of -25°F (-13°C) the outside surface exhibits shelf level behavior while the inside surface is characterized by the lower toe region of the DT curve which is associated with frangible behavior. The 1-1/2-in. composite DT indicates that the complete structure is strongly influenced by the outside surface material. Further interpretation of this behavior in terms of an IAD will be evolved in the course of the current research program. The consequences of the fracture behavior of a vessel exhibiting a severe toughness gradient are particularly important to the safety analysis of a nuclear plant. Positive assurance of vessel integrity in this case will preclude the generation of missiles capable of breaching the containment and producing a related release of radioactive material.

5. SUMMARY

A case has been presented to redirect fracture research to the area of nonfrangible metals. These materials constitute the vast majority of structural applications and yet the majority of research has concentrated on frangible metals analyzable with LEFM methods. The nonfrangible area has received reduced emphasis because of the analytical difficulties in defining the plasticity effects inherent to flawed structures. These difficulties have been circumvented to a large measure by the designer's use of low strength steels at the temperature of maximum shelf toughness. In this case the material is generally tolerant of flaws which arise in normal service operation. However, this approach cannot be carried forward to the intermediate strength steels of 70 to 130 ksi yield strength (50 to 90 kg/mm^2) which are receiving increased emphasis; similar considerations apply to nuclear pressure vessel steels which have been irradiated to exhibit higher strength levels. These materials can display low shelf toughness levels and yet are not brittle in the sense of LEFM requirements. To preclude failures with these materials the traditional concept of designing to the plastic collapse strength of an unflawed structure must be abandoned in favor of modern FSD principles geared to the behavior of flawed structures. This approach requires a unification of effort on the part of the designer who has not thought in terms of flawed structures and the material research expert who has not thought in terms of structural response.

Certain factors must be considered in evolving FSD principles for nonfrangible metals.

These materials may exhibit significant slow stable flaw extension at rising load before unstable fracture commences. Thus, conditions for fracture initiation are not synonymous with catastrophic failure as is the case with frangible materials. The fracture characteristics of nonfrangible metals are strongly dependent upon specimen geometry; this derives from the large plastically deformed region associated with fracture of these metals. Consequently, the results of laboratory specimens are not directly relatable to structural performance. It follows that evaluation of a material toughness parameter by itself is not sufficient to evolve FSD principles. This is to be contrasted with the K_{Ic} parameter in LEFM that can be directly related to conditions for instability of a structure of any given geometry. Successful FSD for nonfrangible metals requires an interrelation of the material resistance to fracture extension and the fracture extension force supplied by the structure. The essence of FSD is an overmatching of the material's resistance compared to that of the fracture extension force.

The material's resistance to fracture extension is determined by the local deformation processes at the crack tip. The analytical difficulties in defining and interpreting the behavior in this region are avoided through use of an experimental approach. Specifically, the fracture extension resistance of the material is defined by means of R-curves based on the fracture energy of modified DT specimens. It is clear that the specimen fracture energy must reflect the basic metallurgical resistance of the metal. The specimen also provides a means to simulate the extension of a flaw in nonfrangible metals.

The use of the R-curve slope provides a bridge between the fracture research field and the designer. Materials which exhibit a flat R-curve slope must exhibit fracture at elastic stress levels and this behavior can be analyzed with LEFM. The R-curves of rising slope define the demarcation point which separates fracture propagation at fixed levels of elastic stress and fracture requiring the applications of plastic stresses for extension.

The IAD presents a conceptual means with which to interpret the R-curves and thereby analyze a complex area of fracture. The model provides the necessary integration between a material toughness property and the fracture extension force related to the structural configuration and method of loading. Experimental data and modifications as to thickness and transition temperature effects are required to evolve the IAD to the point of providing useful engineering guidelines. However, the R-curve-IAD approach provides a procedure to evolve these engineering guidelines for FSD in a rational way.

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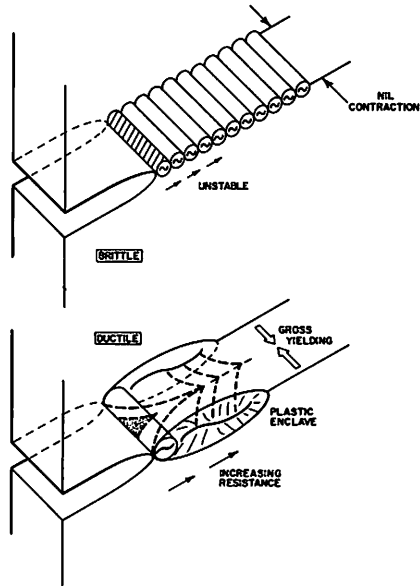


Fig. 1 - Schematic illustration of the plastic zone associated with the extension of unstable (brittle) and stable (ductile) fracture.

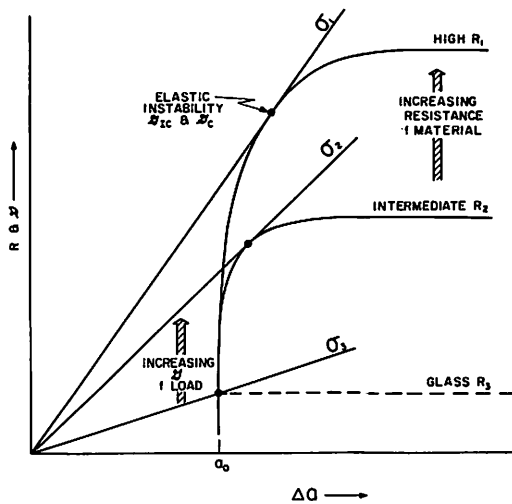
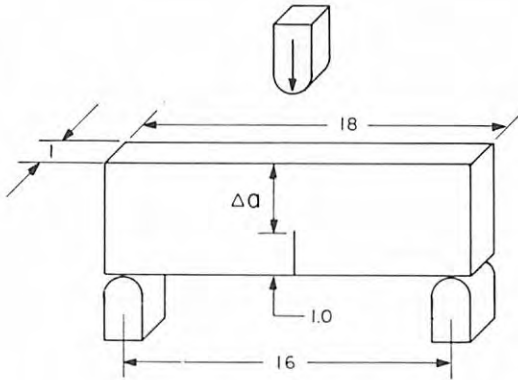
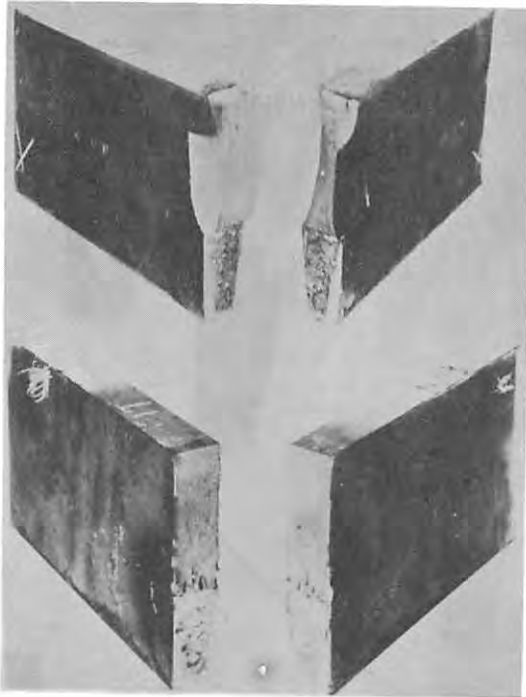


Fig. 2 - Fracture mechanics definition of elastic instability as defined by the tangent of the J and R -curves. The variation in J with increasing levels of applied stress σ is indicated by the lines of increasing slope which pass through the origin. This basic concept is extended to visualize R -curve aspects for nonfrangible materials.



DIMENSIONS IN INCHES

DYNAMIC TEAR TEST

Fig. 3 - Geometry of the standard 1-in. DT test specimen illustrating the fracture surfaces of a ductile, high-shelf level steel (top) and a frangible steel (bottom). The fracture extension length or crack run (Δa) is varied to define an R-curve for a particular thickness. The dynamically loaded specimen contains a brittle crack-starter to simulate the worst conditions encountered in a structure.

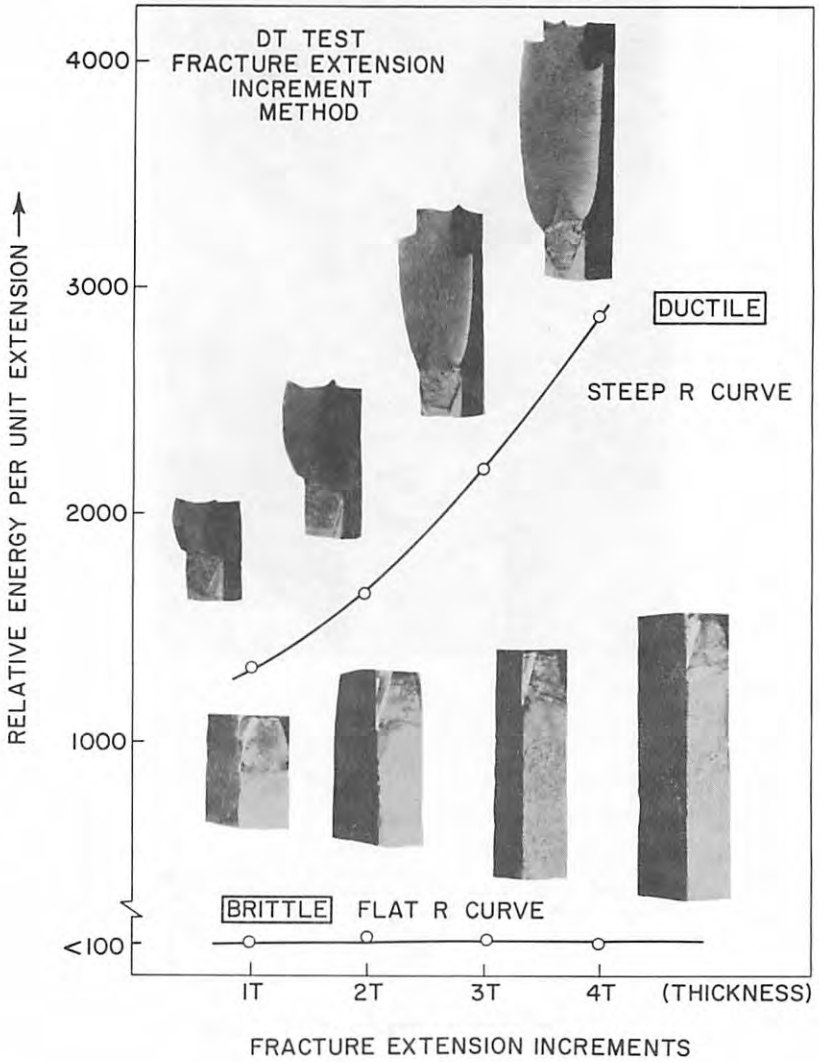


Fig. 4 - Representative R-curves for brittle and ductile steels of 1-in. thickness. The increasing fracture-path lengths allow measurement of the decreased constraint in the process of fracture extension. This is indicated by the V-shaped zone at the base of the crack-starter weld for the ductile material.

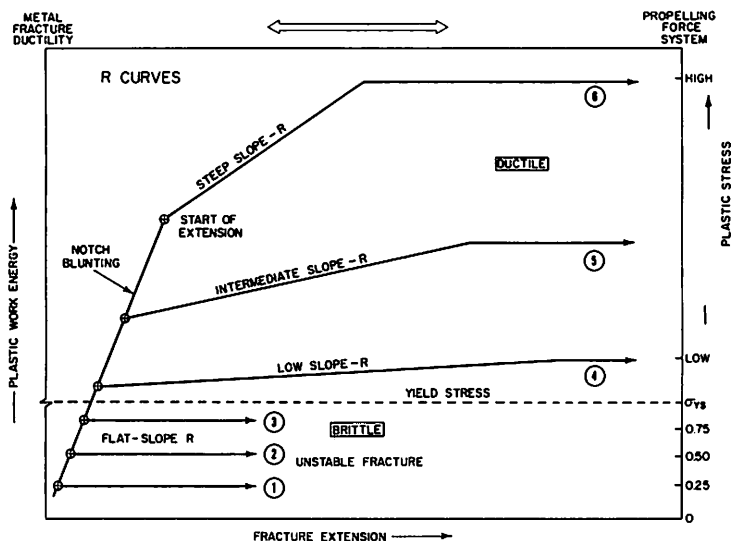


Fig. 5 - Schematic illustration of the R-curves exhibited by materials ranging from brittle to highly ductile. These curves provide a correspondence of the propelling force requirements of the structure as compared to the fracture extension resistance (energy) developed by the metal ductility.

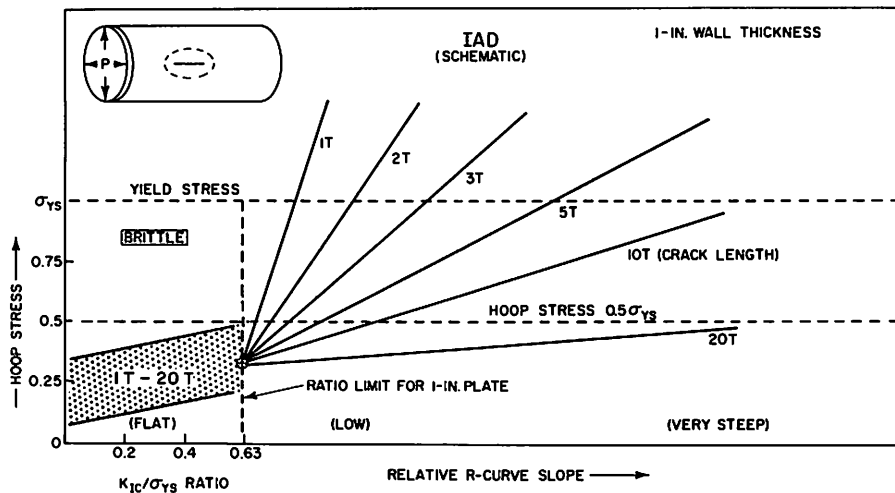


Fig. 6 - Schematic IAD plot for a tubular configuration using metals which do not exhibit transition temperature characteristics.

FLAT
R CURVE



STEEP-SLOPE
R CURVE



Fig. 7 - Illustration of the burst test behavior of cylindrical vessels whose materials exhibited a flat R-curve (top) and a steep R-curve (bottom). The lower photo indicates how the structural features act to control the type of fracture; the vessel did not exhibit the expected axial split based on propagation in the direction of maximum stress before instability.

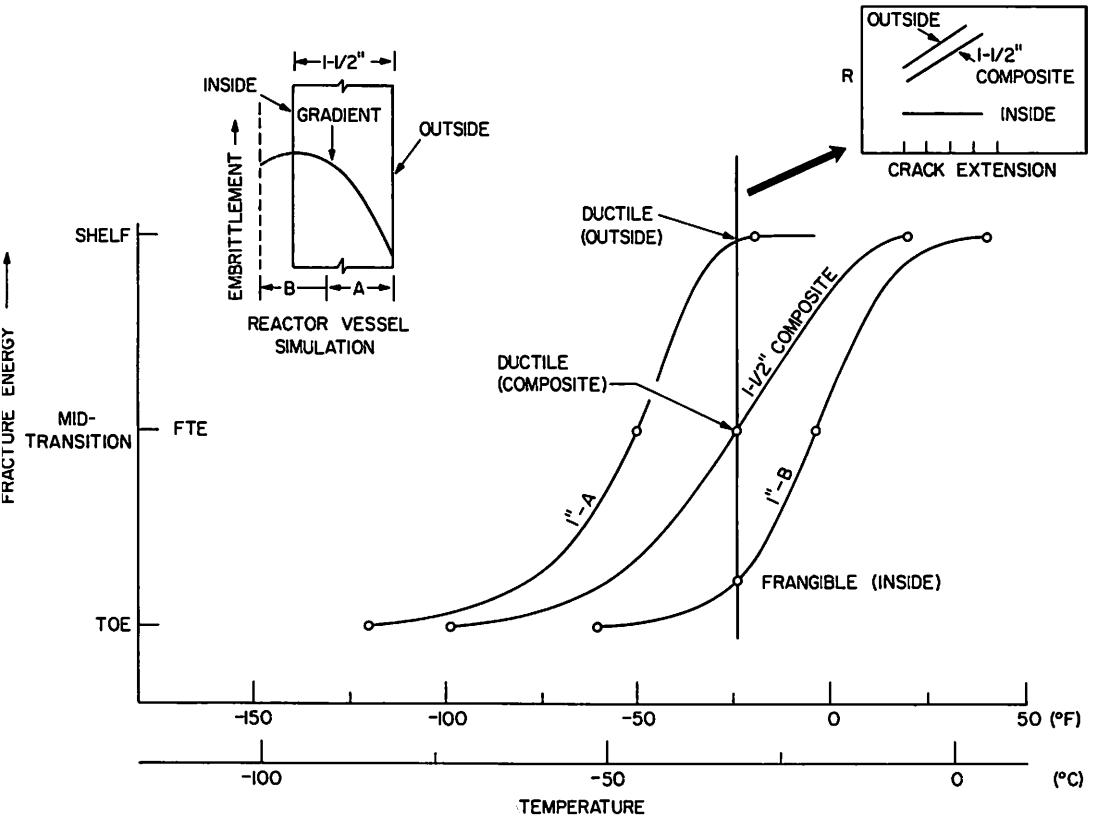


Fig. 8 - Comparison of DT fracture characteristics and R-curve trends of a low alloy steel plate containing a metallurgically induced toughness gradient. The gradient is assumed to be similar to that occurring in the thicker wall of a pressure vessel. The R-curve trends, shown schematically in the insert, indicate that the fracture behavior of the complete thickness is strongly influenced by the surface material of increased toughness.

DISCUSSION

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Q

Is the rise in the R-curve a characteristic of the particular specimen geometry tested? Can the results be extrapolated to other geometries such as, for example, center-notch plates or pressurized cylinders?

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A

We believe the rising R-curve is a reflection of the material toughness as explained in the text. The absolute slope of the R-curve is probably linked to the particular specimen configuration. A specimen, such as a center notched plate, that is of different geometry from the three point bend specimen described herein is nevertheless expected to exhibit a similar type of R-curve, and a program is currently underway to demonstrate this point.

The application of the R-curve to a pressurized cylinder will be through the IAD method described in the text. The important point is to have a method of defining the toughness of non-frangible material and a means of relating this toughness to the performance of the flawed structure. It may not be necessary to demonstrate that specimens of different geometry exhibit the same R-curves since the relationship of the experimentally determined R-curve to structural behavior is through the structural element prototype test described.