Some Applications of Fracture Mechanics in Power Engineering

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Introduction

The object of this paper is to highlight the developments since the 1969 ICF Conference in the practical application of fracture mechanics, particularly to such components as welded steel pressure vessels and thick-section turbine components used in power generation. It is expected that other papers to this conference will outline developments in theoretical treatment and experimental technique, and therefore these topics will only be described as far as is necessary to provide the background to the applicational aspects.

A good starting point for such a survey is the report of the Conference on the Practical Application of Fracture Mechanics to pressure-vessel technology, arranged in 1971 by the Institution of Mechanical Engineers in London, and co-sponsored by the International Congress of Fracture(1). The principal questions that were raised at that conference were:

(a) Are fracture prevention measures beyond the conventional engineering approach necessary?

(b) What fracture prevention methods can be recommended?

(c) What is needed to apply such methods?

(d) Who has taken or should take appropriate measures?

The present paper will attempt to answer these questions in the light, not only of the information presented and discussed at that conference, but also taking account of the numerous subsequent publications in a field where intensive work is in progress throughout the world.

The need for Fracture Prevention measures

The evidence that fracture prevention measures are needed, and that these should extend beyond the traditional current engineering practice is that plant failures by partial or complete fracture still occur. Some examples will be given later in this paper when the application of fracture mechanics to the assessment of failure is discussed; in the London Conference Burdekin(2) drew attention to three examples of major pressure vessel failures between 1965 and 1970 which could probably have been prevented by the prior application of fracture mechanics techniques. When such failures have occurred, it has generally been during fabrication, pressure test or commissioning; it is fortunate that major failures of pressurised components in service have been very rare. There have been examples of partial cracking of pressurised components and of failure of large rotating components in service. Whilst the total number of all of these failures is small compared to the number of items in service, the cost of each individual failure can be high, although such costs are difficult to compute because it largely is made up from the heavy costs of consequential plant outages. Delay to start-up or prolonged outages of a complex plant lead to loss of earnings and additional costs when out-of-date plant must be used to make up the lost production; Van der Post and Wells(3) indicated that the cost of a single failure in power generating plant could well exceed one million pounds sterling; in addition the effects on public confidence can in some cases be of overriding importance. It is such considerations that justify the application of appropriate fracture prevention measures.

Nevertheless the question is still asked - Why use Fracture Mechanics when the V-notch Charpy test has proved effective in many applications? Turner et al(4) and many other authors have pointed out that the level of Charpy property that must be specified to prevent failure depends on the thickness, strength-level, alloy content, applied stress and rate of loading. It can be dangerous to use a particular Charpy specification outside the range of experiences on which it was derived; indeed increased rates of failure have in the past been associated with the change of one or more of these factors in the current engineering practice. In some cases, the Charpy V-notch test may even rate materials in the wrong order of resistance to fracture.

A further objection to the conventional Charpy approach is that it is non-quantitative with respect to permissible stress levels and defect sizes. With the growing sensitivity of non-destructive examination techniques and the realization of the costs and risks associated with the removal and repair of flaws or local defects, there is emphasis on the assessment of the effect of such flaws on fitness for purpose. A more rigorous approach is also needed where the application requires that the failure risk be demonstrably minimal, or where one needs to assess the effect of defects detected in components already in service. These aspects are discussed in more detail in later sections of this paper.

Methods of Fracture Prevention

The methods of preventing fracture in large scale steel components fall into two main types which can be called in short "initiation control" and "propagation control" (or the crack arrest approach). Up to very recently, the most used method has been that of the crack-arrest approach, which has the advantage of simplicity in that it requires only knowledge of the properties of the general volume of plate material and of the general level of 'membrane' stress. It forms the basis of the nil-ductility temperature and fracture analysis diagram approaches that have been used in the United States pressure vessel standard specifications(5) and of other national approaches to fracture-safe design(6,7,8). Such an approach, by attempting to restrict the application of pressure to a temperature range in which the material shows tough behaviour, makes a useful step forward from the earlier situation of almost complete absence of any fracture-control procedure. It provides a general guide which, in many cases of simple engineering application can be regarded as adequate. It is of especial value in reducing the risk of extensive failure from residual or applied stresses during fabrication or during the initial stages of thermal stress relief. A recent change(9) in the ASME Boiler and Pressure Vessel Code recognises that the value for crack arrest temperature previously quoted (NDT + 60°F) only applies to steels of up to about 25 mm thickness; for a 150 mm thick plate the crack arrest temperature corresponds more to a value of NDT + 120°F. Another example where crack-arrest control is appropriate relates to piping and pipe-line applications, where it is recognised that considerable economies can result if damage is limited to short crack lengths, rather than being allowed to propagate to the very great lengths which have occurred. In this respect, papers to the London Conference(4,10,13) showed that the results of dynamic fracture mechanics tests [Measurements at the appropriate strain rate of either Critical Crack-opening Displacement (COD or δ_c) or critical stress intensity (K_{1c}) can be used to predict propagation and arrest behaviour. In such a way it is

possible to avoid these uncertainties in the Crack arrest approach which arise either from machine behaviour aspects of conventional crack arrest tests such as the Robertson, ESSO or Double-tension tests, or from uncertainties in extrapolation or interpolation where reliance is placed on correlations with results of large-scale failure experience.

Perhaps the most important change in attitude since the 1969 ICF Conference has been the growing shift of opinion to prefer fracture control approaches based on the prevention of initiation rather than those based on the crack-arrest approach, at least for stress-relieved pressure vessels and for rotating components such as turbine rotors and discs. There are five reasons for such a change (a) the crack-arrest approach can be demanding in material properties and so difficult to justify economically; (b) it is difficult to use it in a quantitative "significance-of-defect" approach; (c) the size of any arrested crack may be sufficiently large to endanger the continued reliability of the plant especially where leakage must be prevented; repairs would therefore be necessary for continued operation; (d) a growing realisation that reliability is economically justified and in many cases necessitates freedom from arrested cracks rather than only from "catastrophic cracks" so much emphasised in safety assessments; (e) Most important, in pressure vessels and rotating plant the validity of the crack arrest approach has serious limitations. Current revisions to the ASME Pressure Vessel & Boiler Code Section III(14) and Section XI(15) change the emphasis towards reliance on the prevention of the initiation of an unstable crack and the rest of this paper will be devoted to this aspect.

The Prevention of Initiation of Unstable Cracks

The general aim of the various treatments is to develop and justify an analytical model which will allow results obtained on standardized small specimen tests to be applied to the prediction of the failure stress/defect size relationships for the large components and engineering structures. No single analytical treatment is sufficiently general to be applicable to all situations since they all contain some approximating or limiting assumptions; the preferred analytical model for a particular situation depends primarily on the extent of general deformation which would preclude fracture in that case. One point, the importance of which is sometimes underestimated is that the degree of general deformation in the large structure and in the small specimen can be different even for the same local deformation at the tip of the initiating defect. Considering a range of materials with differing strains to failure, it is appropriate to consider different analytical treatments in the following regions:

(a) linear elastic
(b) elasto-plastic
(c) general yield in small specimens but elasto-plastic (or limited general yield) in large structure
(d) general yield (possibly limited in extent) in both specimen and structure
(e) plastic instability.

The conditions of plastic instability are to a large extent covered by conventional engineering practice rather than by fracture mechanics, since they are related more to strength properties than to fracture toughness of the material$^{(8)}$. Moving down to the condition where general yield even in the large structure precedes

failure, recent work by Soete has indicated a method applicable to through-cracked plates$^{(16)}$ which is based on assessment of a geometry controlled critical crack length beyond which failure after general yield occurs at much lower overall strains than with shorter cracks. In the common and important practical situation where one needs to assess the failure conditions for a material which shows general yield before failure in the notched small specimen, but which in the large structure would fail under elasto-plastic conditions there has been growing evidence of the validity of the COD approach although two other methods have been proposed - the Equivalent Energy method due to Witt$^{(17)}$ and the Stress Concentration approach of Irvine and Quirk$^{(18)}$. These three approaches have also been proposed as appropriate to elasto-plastic conditions, for which circumstances analyses based on use of the path-independant integral $J^{(19)}$ or on the "conditional plastic zone size"$^{(20)}$, or on approximations based on the linear elastic theory (K_Q or K_{max})$^{(21,22)}$ have also been proposed. In view of the number of differing treatments proposed, comparative discussion of their status is justified and forms the following section of this paper. To complete the present discussion it only remains to consider the situations when the materials and conditions are such that any failure would occur under linear elastic plane-strain conditions. The Linear Elastic Fracture Mechanics (LEFM) treatment, based upon measurements of material property in terms of the critical stress intensity factor K_{1c} is too well-established to require any substantiation of its validity or detailing of the basic equations here. It is now more widely used than in 1969, one important extension being its application to the assessment of thick-walled nuclear reactor pressure vessels; developments in the period have largely been in the refinement of techniques, the development of methods for higher strain rates, the publication of more K_{1c} data on particular material with discussion of the effect of fabrication variables, the derivation of stress intensity solutions and approximations for more complex situations such as those at pressure vessel/nozzle intersections. Much of this work has been done in connection with light water nuclear reactor applications such as in the U.S.Heavy Section Steel Technology (HSST) programme(23) and corresponding important programmes in the Federal Republic of Germany(24,25)

Comparison of Elasto-Plastic Fracture Mechanics Treatments

The problem with the development of an analytical fracture-mechanics approach to the elasto-plastic situation is the complexity of the mathematical analysis associated with the three-dimensional stress and strain gradients around the tip of a crack-like defect, particularly in the presence of an external stress concentration. Even where exact computer solutions are within the range of available techniques the expense of their derivation militates against their use. The practical application requires simplifying approximations, and it is in the nature of these that the treatments largely differ. Consider first the Equivalent Energy concept(17) which was developed in the course of the HSST programme. Essentially the simplifying assumption in this case is to make use of measurements on appropriate models to provide the calibration between test and service behaviour, using a parameter called "volumetric energy ratio". The whole validity of the approach rests on the practical validity of this parameter, in particular the ability to provide a set of rules for how it should be measured. At the present stage of development no general rules have been defined,

and it is considered that the method has been neither developed nor justified to the stage where it can be regarded as of practical application. A similar remark can be addressed to the K_Q or K_{max} approaches,(21,22) although in this case their use can obviously be satisfactory in situations that are only a small departure from those where LEFM is valid. The danger is that the injudicious use of such approaches under more plastic conditions may not merely be unjustified; it may be dangerously misleading.

The next method to be discussed is that of the Stress Concentration Approach (SCA)(18). This method was developed from the analysis of results from a U.K. programme of tests to failure of 1.5 m dia pressure vessels made from 25 mm thick plates of various steels. The basic idea behind this approach is that as a crack extends, the load previously carried by the cracked material is transferred to the material in the plastic zone just ahead of the top of the crack; when the resulting stress on that zone reaches the tensile failure stress (approximating to the engineering ultimate tensile stress) of the material, it is considered that failure occurs. This leads to the following equation:

$$\sigma_u = \sigma_g \left(\frac{a}{S} + 1\right) \qquad \text{..........(1)}$$

where σ_u = UTS of material

a = half-length of through crack

S = shape factor for the zone of stress parameter concentration

σ_g = general stress at failure

It is considered that S depends on the tensile ductility, tensile yield strength and Charpy energy of the material, the relationship being of the type:

$$S = \text{const}\ (1 - 0.7\ R)^{-1} \left(\frac{\varphi}{\sigma_y}\right)^{\frac{1}{3}} \qquad \ldots\ldots(2)$$

where R is the fractional reduction of area in the conventional tensile test

φ is energy absorbed in standard Charpy V-notch test

σ_y is tensile yield strength

In the period since 1969, Irvine and Quirk(26,27) have published several papers showing good correlation between failure predictions made with the above equations and actual results. Nevertheless numerous criticisms have been made primarily related to the claims of wide-ranging applicability of the treatment. In particular it has been argued that its big dependence on tensile ductility and its use of the Charpy test as the only measure of fracture toughness should not be valid in the transition range where the fracture behaviour varies greatly with specimen size and thickness. Mager et al(28) consider that the basic assumptions are in error under conditions relevant to thick wall pressure vessels, so that the critical crack size calculated by SCA is too small by factors of at least two; they show experimental work which does not agree with the SCA predictions. The conclusion is that this approach can be of value for estimation from conventional properties of the failure conditions for thin section components in relatively ductile materials but it is pessimistically incorrect for thick section situations i.e. those approaching the plane strain region where LEFM is applicable.

A treatment which has received considerable attention recently is that of the "Path-independent Integral (J)", as developed by Rice.(19) J can be defined as the change in potential energy for a unit

extension of crack length a

$$J = \frac{\partial(U/B)}{Da} = -\frac{dU}{da} \qquad \ldots\ldots\ldots\ldots(3)$$

The method is aimed at avoiding some of the uncertainties associated with directing attention on the complex area close to the crack tip, the particular integral being chosen with the intention of path independence. The value of J with increasing deflection can be derived experimentally from load deflection curves of otherwise identical specimens with varying crack depths. To determine the material property J_{1c} it is necessary also to measure the displacement at failure; J_{1c} is then equivalent to the value of J determined from the load/deflection curves of cracked bars at that deflection. J_{1c} is related unambiguously to K_{1c} in that:

$$J_{1c} = G_{1c} = \frac{1 - \nu^2}{E} K_{1c}^{\ 2} \qquad \ldots\ldots\ldots\ldots(4)$$

but the attraction of the J_{1c} approach is to permit the direct extension of LEFM into the elasto-plastic range. J_{1c} is also related to the critical COD value; its advantage over the COD approach is that it avoids some of the experimental and theoretical difficulties which arise in defining conditions close to the crack tip, which necessarily must be done in the COD approach. As for difficulties, it has been argued that the applicability of the J_{1c} concept may be limited to conditions which show similar (or not radically different) slip-line fields; that there is some doubt of the applicability of the J approach under conditions of slow crack growth and that actual path-indepenence has not been demonstrated as a generality. On the other hand its proponents argue that the local crack tip singularity and crack blunting effects will override this slip-line field limitation. Standard methods of tests need to be developed and their lack of sensitivity to testing variables demonstrates. Thus in spite of the very real promise provided by the J approach it must be concluded that considerable further experimental work will be required before its use can be justified as an engineering tool.

The remaining approaches, that of crack-tip radius, of conditional plastic zone size and that of critical COD(δ_c) make use of particular dimensions near the crack tip to provide the singularity necessary for describing the fracture condition. Experimental difficulties of in-practise measuring the crack tip radius or the plastic zone size directly prevent their practical use and indeed it has been shown(21,22) that the "plastic zone size" approach only has theoretical advantages over the COD approach under conditions of load cycling (e.g. for assessment of overstressing techniques). Concentrating attention on the COD approach, there have been further papers demonstrating its validity(21,29-31) theoretically, experimentally and by examination of past failures. Testing methods have been assessed collaboratively and a standardised technique has been published(32). Methods for measuring local δ_c in weldments have been described(33); further assessment of these special specimens and of methods for determining δ_c at high strain rates is currently in progress in the U.K. An important feature of the standardised technique is that it is virtually identical with that for measuring K_{1c}, except that it must be made on specimens of the full section-thickness of engineering interest. If this is done, the same programme of tests would be appropriate to assess a given material, the choice of K_{1c} or δ_c analyses being made on the basis of the results obtained. As for

difficulties, theoretically it has been shown that the approach is only approximately correct at conditions very near to those of LEFM validity, that different calibration factors between surface measurements and crack-tip COD need to be used at conditions of high plasticity - that under conditions of slow crack growth it can be difficult to define the appropriate instability condition, and that COD/Applied Load Analyses are only available for a limited range of geometries. The proponents of the technique argue that it is sufficiently precise over the whole range of practical interest, from the limits of validity of LEFM to those where failure will not occur at stress levels permitted by the engineering specifications; that the calibration factors have been defined(30,32); that where slow crack growth is a problem a pessimistic assumption based on detecting the first stage of crack extension can be used until the present UK work has defined an alternative; that the strip yield model has provided analyses in the more important cases and in others approximations (based for example on calculated stress concentrations) or calibrations can be used. The conclusion is that the technique has been developed and validated to the stage where it can be used as an effective fracture prevention tool applicable to a range of situations where failure would be associated with elastic-plastic conditions, and is the most developed technique for such applications. It is complementary to the LEFM approach and the two together provide fracture prevention methods over the range of current engineering practice; further discussion in this paper is directed particularly to these two methods.

Requirements for a full Fracture Mechanics Treatment

It is not always appreciated what wide-ranging and extensive information and procedural control is required to make a completely reliable approach to fracture preventions by fracture mechanics techniques. Table I highlights this aspect; attention being required at all stages from design, selection of material, fabrication and inspection, and even during operation. The difficulties are most marked with inhomogeneous materials - for example those that show marked variation in properties near to welds. Indeed it is the author's opinion that no present fracture prevention method can effectively cope with such a situation, leading to a requirement for relative uniformity of both fracture toughness and strength properties across a weld as a criterion of materials and process selection. The full application of present techniques give a very real measure of protection against fracture, and indeed allow the margins of safety to be estimated quantitatively(2,34-36).

The obvious expense of such a full treatment makes it unlikely to be used except in specialised components where it is necessary to get licensing approval, or where failure would be exceptionally hazardous, expensive or embarrassing; this explains why one of the most developed applications is to pressurised equipment in the primary circuits of nuclear reactors. Another situation is where a failure has been detected in important plant and it is necessary to define any repair requirements and any remedial treatment in other similar plant. For more common applications it is necessary to simplify and cheapen the analysis, and one of the best ways of doing this is to incorporate as many stages of the analysis as possible in the drafting of an applicational standard specification, so the actual steps to be taken on a particular component are minimised. There are currently basically two developments in the use of fracture mechanics in standards. The first is to use current standards of inspection and rejection for

defects, but to use fracture mechanics to define material selection. In such a case, detailed fracture mechanics analysis of the prototype of a new engineering development would be used to establish type tests and by correlation the levels required in simple quality control test (usually the Charpy V-notch test). The second approach directs attention to assessing the significance of defects and providing new criteria for defect rejection limits based on fracture mechanics - the material toughness and stress limits being defined in complementary standards. Some examples of these aspects follow.

Detailed Application to Nuclear Pressure Vessels

As part of the evidence relating to the reliability of steel pressure vessel reactors, detailed appraisals have been made by LEFM techniques. Typical values of K_{1c} have been assessed from static and dynamic tests on selected casts of the chosen steels(6,34,37) and the effect of representative welding and fabrication conditions studied, essentially with a view to demonstrating the absence of significant inhomegeneity in fracture toughness near a welded joint. Approximations to cover stress conditions at such geometrical features as nozzle attachments have been developed(38,39) and thermal stress values calculated for chosen operating cycles(35). The effect of the estimated neutron irradiation on K_{1c} has been estimated from small specimen tests on typical material. The potential crack growth in service has been estimated from the assumed service operating cycles and materials data on crack growth rate. The reliability of the structure can then be assessed by comparing the calculated critical size with the maximum size which potentially could remain undetected in the commissioned component. Reliance on such an approach necessitates methods of material control to ensure that the service material matches that on which the type tests were made; that the operational effects are as predicted (further information is to be developed on the effect of chemical environment) and that inspection will achieve a 100% search to the sensitivity required. A similar analysis using the COD approach has been used to assess the geometrically simpler zirconium alloy pressure tubes in the SGHW Reactor(40).

Application to the Appraisal of Failed Components

The use of fracture mechanics analyses of a failed component to establish what measures are needed for reliable operation of similar components, or to establish the defect sizes at which repair is appropriate can lead to considerable economies particularly in reducing losses due to outage. Recently Williamson(41) stated that in the UK Central Electricity Generating Board a large amount of plant containing defects was still working because Fracture Mechanics had given the desired assurances. Two examples quoted from CEGB work relate to pressurised equipment. In 1968 complete explosive failure of an intermediate pressure loop-pipe to steam-chest weldment occurred during operation, initiating from extensive circumferential cracks at or near the interface between the 1 Cr 1 Mo 0.3 V cast steam chest and the $2\frac{1}{4}$ Cr 1 Mo weld metal, these cracks coming either immediately after stress-relieving or early in service life. This incident prompted a large program of non-destructive examination of all welds in thick section components operating at main steam temperature and a fracture mechanics basis has been adopted to decide if immediate repair is necessary in cases where defects have been found(42). The second example involved serious cracking found in 1968 at set-through-nozzle to shell welds in boiler drums of large capacity plant, the cracks extending several centimeters from the ends of an unwelded 'land' into the weld metal.

In view of the incentive to run the less severely cracked drums through the winter, a fracture mechanics analysis was made which showed that the critical crack length for fast fracture would be greater than the vessel thickness ($\sim$150 mm). It was argued that a "leak before break" situation existed and there was no risk of fast fracture in service provided that the fracture toughness of the material had been correctly assessed. Fracture mechanics indicated that some lightly cracked drums had no need of repair and in fact some of these drums are still running satisfactorily.

Subsequent repairs to the cracked drums involved full-penetration welding of set-on nozzles. For these repairs defect acceptance standards were devised using fracture mechanics which considered critical defect sizes for fast fracture and subcritical crack growth by fatigue during service(36).

A somewhat different use of Fracture Mechanics in failure examination was described by Kalderon(43) in relation to the failure of a steam turbine at Hinkley Point A. In this case the damage was complex and extensive and it was not self evident which cracks had led to the failure and which were consequential damage. Fracture mechanics were used to test the credibility of particular postulations and demonstrated that the failure was due to the bursting of one of the l.p. discs during rotation, the fracture initiating from small stress corrosion cracks developed in service in the semi-circular keyways at the disc bores, which also acted as stress concentrations; it also indicated that the failure would have been postponed if not avoided by the use of material of higher fracture toughness. Appropriate measures to prevent such failures in future can thus be developed(44)

Application in Specifications

The use of fracture mechanics in national and international standard specifications is only just beginning, although there are several cases where it has been used in drafting requirements for a particular industry or customer. A collaborative programme of the UK Turbine makers and CEGB on materials properties crack growth, plastic yielding effect and defect characterisation has formed the basis for acceptance criteria for rotor forgnings(45). These criteria specify defect acceptability based on fracture toughness - Charpy impact correlations, fatigue crack propagation data and ultrasonic defect sizing. The information from the program is, of course, also used for continuing design studies of turbo-generator rotors.

LEFM has been used to define Non-Mandatory Appendix G of the Summer 1972 Addenda to the ASME Boiler & P.V.Code Section III, which present a procedure for obtaining allowable loadings on the basis of assuming a postulated maximum defect size (~¼ plate thickness in depth) and a reference critical stress-intensity factor K_{IR} determined by correlation with quality control Charpy V and NRL dropweight tests, these being defined in an earlier section of the code (NB 2300). The Appendix states that at present a quantitative evaluation at nozzle geometries is not feasible at this time. A somewhat similar approach is given by Appendix C to BSI 1515 (1972 Amendment) which provides maximum stress levels and minimum service temperatures for low temperature pressure vessels made for particular steels, their fracture toughness being controlled in production by Charpy V-notch tests, but the recommended service conditions being arrived at by correlations with the Wells Wide plate and COD tests of General Yield Fracture mechanics. An

example from Japan(7) has shown how a fracture mechanics analysis can make use of a fully simulative type test, using representative material, welding process, thickness, possible defects, stress level and distortion effects to define the required Charpy V-notch acceptance level, and permissible fabrication limits of defect size and of distortion.

Significance of Defects

A most important use of Fracture Mechanics is in the drafting of standards which will define the acceptable standards of flaws in welded structures. Discussions are currently in progress in the USA aimed at producing a fracture-toughness based "defect-rejection limit" for the Winter 1972 Addenda of ASME Boiler & P.V. Code Sections III & XI. U.K. proposals to the International Institute of Welding, and to the British Standards Institute makes use of both LEFM and COD techniques as appropriate(40). The critical defect dimension "$\bar{a}$ max" is defined as being the depth of the defect in the thickness direction for part-through defects, and only as the <u>length</u> of the defect in the plane of the plate with effectively through-thickness defects. The treatment of residual stresses is simplified by taking different values for the constant A in the equations:

$$\bar{a}_{max} = A \frac{(\delta_c)}{(\epsilon_y)} = A \frac{(K_{1c})^2}{\sigma y}$$

The values of A for various situations are summarised below :

Design stress level (0.67 yield)			Proof test stress level (0.87 yield)			
Shell (s.r.)	Shell (a.w.) or nozzle (s.r.)	Nozzle (a.w.)	Shell (s.r.)	Shell (a.w.)	Nozzle (s.r.)	Nozzle (a.w.)
0.5	0.09	0.06	0.25	0.09	0.03	0.024

a.w. = as welded   s.r. = stress relieved

Of course it is not intended that $\bar{a}_{max}$ becomes the maximum size of flaw that will be accepted; some safety factor to cover uncertainties in information must be introduced.

This trend to use fracture mechanics in setting defect rejection limits can lead to important savings in construction even if only applied qualitatively, since they do indicate that porosity and slag-inclusions (even if quite large dimensions) have little effect on reliability. Indeed this aspect could well be one of the most important developments in the present applications of fracture mechanics, having widespread implications on general engineering practices and on attitudes to techniques for Non-destructive examination and quality control.

TABLE 1

Requirements for a full Fracture Mechanics Analysis

A. Material Properties (K_{1c} or δ_c)

Choose	Environment	As service
	Strain rate	As service
	Specimen type	ASTM
	Specimen thickness	(to plane strain (K_{1c}) (as service (δ_c)
	Material condition	as service
Measure	Load	Dial & electrical output
	Surface displacement	Clip Gauge
	Instability point	(Load or gauge (potentiometer
Interpret	Analysis from load (K_{1c} if valid) Analysis from Clip Gauge (δ_c)	

B. Analysis of Structure

Estimate	General Service Condition	Add Applied Stress residual and thermal stresses
	Local Condition	Stress or Strain Concentration analysis or by calibration

C. Determine Critical Defect Size

Assess	Possible Defect Geometries
Calculate	Use results of A and B for each combination of material, environment, stress

D. Assess Crack Growth in Service

Consider	Possible mechanisms (Creep, Fatigue, Stress Corrosion)
Estimate	Service conditions
Measure Materials Data	Crack growth for correct material, environment and temperature
Predict	Crack growth in postulated service life from above results for initial critical length (consider different positions in structure).

TABLE 1 (Cont)

E. Specify Tolerable Defect Size

Fitness-for-purpose limit	From C and D with appropriate "safety factor"
Other factors	Quality control aspects Corrosion Inspectability (one defect can hide another)

If tolerable size approaches limit of Inspection sensitivity or fabrication limits Change Material to higher Fracture Toughness or Stress to lower value

F. Quality Assurance and Inspection

Material Control) Fabrication Control)	Process control to ensure properties similar to those tested in A. Consider need for Tests. Procedural control to reduce risk of large defects.
Pre-Service Inspection	100% volumetric with method appropriate to reveal critical defects
Operational Control	To ensure service conditions are in fact similar to those assumed in B & D.
Surveillance	Material properties, temperature, stress.
In-Service Inspection	Either monitoring for crack growth or at intervals through life.

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