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Component Assessment: Fracture Mechanics for Added Value

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ABSTRACT The complex and demanding operating conditions of modern structures, coupled with humanitarian, legal, and economic responsibilities placed on manufacturers and operators, make it important to have accurate methods of assessing the integrity and lifetime of components. This is frequently determined by the component's ability to tolerate defects, and there are a number of ways of doing this. Two which immediately spring to mind are fracture mechanics and component testing. This paper concentrates on the fracture mechanics method.

The paper discusses the most recent developments in fracture mechanics codes, highlighting the type of information needed, and the basic objective of the methods. The most common use of fracture mechanics is in calculating defect growth under cyclic loading conditions, or the defect tolerance of a structure. In this mode, it is used either as a diagnostic tool for a failure which has already occurred, or as a predictive tool, to be used in design.

Valuable as these uses are, fracture mechanics can be used much more imaginatively, resulting in major cost benefits. Examples of such use include optimising down-time for plant maintenance and repair, optimising plant operating conditions, developing non-destructive inspection strategies, extending plant life, developing strategic arguments for plant safety. The use of fracture mechanics for these purposes is discussed.

Introduction

The complex and demanding operating conditions of modern structures, coupled with humanitarian, legal, and economic responsibilities placed on manufacturers and operators, make it important to have accurate methods of assessing the integrity and lifetime of components. This is often determined by the components ability to tolerate crack-like defects. Fracture mechanics is the most versatile tool for doing this, finding its main application as either a diagnostic tool to evaluate the causes of failures once they have occurred, or as a predictive tool at the design stage or when a defect has been discovered prior to or during service.

Valuable as these are, by no means the only uses for fracture mechanics. Major cost benefits (and by implication, safety and quality of service benefits) can be achieved by using fracture mechanics strategically. Examples of such use include optimising down-time for plant maintenance and repair, optimising plant operating conditions, developing non-destructive examination strategies, extending plant life and developing strategic arguments for plant safety. This paper presents a digest of fracture mechanics analysis methods, and elaborates on the strategic uses of fracture mechanics.

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Fracture analysis methods

Objectives

The basic objective of a fracture analysis is to quantify the relative integrity of a structure containing (or assumed to contain) a crack-like defect in terms of its fitness for purpose. Thus, if a crack-like defect exists, and it can be shown to be benign in terms of its effects on the integrity of the structure under all foreseeable loading conditions, taking into account all possible methods of defect extension, the structure may be deemed fit for its design function, and the defect ignored. Normally a margin is required between the calculated 'failure' condition of the structure and its relevant loading condition. If this margin is not large enough, a repair may be called for or the structure may be retired from service. Alternatively, the operating conditions of the structure may be modified in such a way that the required margin is achieved.

Used in this way, a logical argument can be constructed for any plant problem, and the most vulnerable conditions and locations of the plant can be identified. It must however be emphasised that the accuracy of the result is dependent upon the accuracy and relevance of the underlying analysis route and data base. This is, more often than not, poor. In such cases, the analysis cannot replace the need for some engineering judgement, but it does ensure that such judgement is correctly focused.

Basic methods of demonstrating integrity

There are four basic routes for demonstrating the integrity of a structure – testing the structure, testing a model or models of the structure, fracture analysis based on the finite element method, and fracture analysis using a simplified analytical or semi-analytic routine.

Table 1 identifies the main advantages and difficulties associated with these. A study of this table reveals shortcomings in all methods, but also virtues. At one extreme, testing the real structure has significant value from the viewpoint of public confidence, but, although such a test can be used to support further operation or operation of other similar components, the value is severely restricted by the inability to evaluate a range of test cases. At the other extreme, the analytical routes depend upon a data base, which is rarely extensive enough for their accurate application. Large factors of ignorance often result which discredit these routines. In any case, their validity always has to be demonstrated by one or more of the other three routes. Notwithstanding these shortcomings, the cheapness, flexibility and depth of understanding often achieved by use of the simplified routes makes them a favoured method. All such methods use fracture mechanics criteria as a basis for their analysis. The background to these, and their links to the fracture mechanics criteria, have been discussed by Milne **(1)**.

Table 1 Alternative methods of assessing structural integrity

	Validity (accuracy)	*Flexibility*	*Applicability*	*Cost*	*Value*
Test on structure	Valid for test condition(s) only. Little use for other conditions. Cannot be used for generalisations	Inflexible. If tested to failure, cannot be reused. Proof test can be used for life estimation	Not always technically possible. Risky without prior analysis. (Time consuming)	Highest	Low, except where no alternative
Tests on models	For modelling specific problem – difficult to demonstrate validity (e.g. crack in old welds). Used for developing empirical rules – cannot extrapolate. Difficult to model thermal stress etc. Models are always simplified. Fracture and plasticity effects scale differently	Relatively inflexible – cost limited. Difficult to get conditions right	Always possible, but often difficult technically. Results cannot be applied without further analysis. Often invaluable to clarify a point. Would not be used for general or repeated applications. (Time consuming)	High (depends on matrix and complexity)	Generally low, but high for specific types of problems
Finite element fracture analysis	Valid when appropriately verified, but code dependent. User sensitive, as no general recommendations for treating input data	In principle totally flexible. Costs and capability of modelling complex situations limit this	Generally calculates applied crack driving forces only, although relationship to other parameters can be incorporated. Useful for developing simplified routines. Technically, difficulties appear at high plasticity. Not appropriate for general use. (Can be time consuming)	Relatively high	Good value for limited applications
Simplified routines (e.g. Table 2)	Valid where appropriately demonstrated. Often provides total solution aimed at clear objectives User often constrained by rules to ensure validity	High flexibility – depends on validity of model. Capable of repeated use to evaluate sensitivities etc.	Generally applicable. No cost constraint.	Cheap	High value

Simplified methods

The most easily available simplified methods for assessing the integrity of structures containing defects are currently being assessed by a working party of the European Group on Fracture (ESIS/EGF), Task Group 1. Three broad classes of such methods exist.

- Screening methods.
- Methods for calculating the applied crack tip driving force (K_I, J or δ) (symbols identified in Table 3).
- Comprehensive methods.

Tables 2(a)–(c) list the most available of these methods identifying the main input requirements. There is a wide choice, and the analyst must know the objectives and limitations of each one before he uses them to solve his problem. The objective of the ESIS/EGF study is to provide a guide to help the analyst choose the most appropriate method.

Table 2(a) Simplified methods of analysis: screening methods

Method	*Purpose*	*Source*	*Requirements and comments*
J-T diagrams	Derived for LWR pressure vessels, but general applicability	Paris **(16)**	Simplified calculation of *J-T* (Structure), *J-T* (Material) Separate calculation of *J* load. (guidance given)
Battelle	Pipework systems	Wilkowski *et al.* **(17)**	Simplified calculation of net section stress, fracture toughness, tensile data
KWU	Pipework systems	Golembiewski and Vasoukis **(18)**	Simplified calculation of net section stress, Charpy energy, tensile data

Table 2(b) Simplified methods of analysis: applied CTOD or *J*

Method	*Purpose*	*Source*	*Requirements and comments*
GE-EPRI scheme	General, to calc. *J*-applied	Kumar *et al.* **(19)**	Calculation of applied *K*, reference limits load. Needs full stress–strain curve. Methods of calculation given in detail for variety of geometries. Does displacement and load control. Use of stress strain data needs better guidance
GKS-ETM scheme	General, to calc. *J*- and CTOD-applied	Schwalbe **(20)**	Calculation of applied *K* and plastic zone corrections, plastic yield load (guidance given)
EnJ	General, to calc. engineering *J*-applied	Turner **(21)**	Calculation of applied *K* (or *G*) at yield stress. Many correction factors needed and poor guidance given for these. Difficult to apply in practice

Table 2(c) Simplified methods of analysis: comprehensive methods

Method	*Purpose*	*Source*	*Requirements and comments*
ASME XI	Explicit to LWR pressure vessels, but often used generally	ASME **(2)**	Calculation of *K* applied, fracture toughness. Highly coded, LEFM only, includes fatigue crack growth, explicit safety factors imposed. Crude crack arrest procedure also included
BS PD6493	General	BSI **(10)(4)**	Calculation of *K*, CTOD applied limit load, fracture toughness, tensile data. Under revision (1989) to include R6 methodology. Highly coded, very flexible. Includes fatigue crack growth and gives guidance on other mechanissm of cracking
R6	General	Milne *et al.* **(22)**	Calculation of *K* applied, limit load, fracture toughness, tensile data. Guidance on fatigue, and other mechanisms of cracking, and derivation of fracture toughness. Well coded and very flexible
DP-FAD	General	Bloom **(23)**	Combination of R6 and GE-EPRI methodology. Has requirements of both and some advantages (but not all)

It should be noted that both the screening methods and the comprehensive methods have an internal consistency, where the user is required to use the material's properties appropriately defined and validated for the method. The comprehensive methods are also written in code form, incorporating safeguards and checks and illuminating important aspects such as the influence of environment, subcritical crack growth, and crack growth interaction effects. In many cases, appropriate allowance for the enhancement in crack growth rate which results from such effects can be made, e.g., the ASME XI 'wet' line for

Table 3 Symbols

CTOD	Crack tip opening displacement
G	Elastic energy release rate
J	The J integral
K	LEFM applied stress intensity factor
LEFM	Linear elastic fracture mechanics
T	Tearing modulus; normalised measure of slope of J crack driving force curve

corrosive fatigue in PWR pressure vessel steels **(2)** or the tearing-fatigue law for C–Mn steels **(3)**. In most cases, these effects are poorly understood, but must not be neglected. Recognition of their existence is an important part of any analysis even when their effects cannot be reliably quantified.

The standard fracture mechanics analysis is deterministic, and consequently underestimates defect tolerance when pessimistic bounds to the data and the analytical input are chosen. At times, the underestimate in defect tolerance is large, especially when the scatter in the material's fracture toughness is large, or when excessively pessimistic assumptions have to be made about the defect size and distribution. It is in these circumstances that deterministic fracture mechanics is inappropriate if rigorously applied, and credibility is lost. In such situations a statistical approach can be used to give an indication of the probability of failure. Reliability statistics can be used on some or all of the input to give a partial or complete probabilistic analysis. The proposed revision of BS PD6493 **(4)** incorporates suggestions for doing this based upon the work of Burdekin *et al.* **(5)**. This allocates partial safety factors on each of the input which depends upon the statistical significance of the data level used. A full probabilistic analysis is also available for the R6 method **(6)**.

Although these statistical methods go a long way to solving the problems posed by a poor, or scattered data base, they should not be regarded as providing a measure of the absolute risk of failure. Like all methods, their applicability depends upon the relevance and quality of the data base, and the best they can do is provide an indication of the structure's integrity relative to others.

Uses of simplified fracture analysis methods

Conventional uses

There are many examples where fracture mechanics is used as the basis for defect acceptance criteria, for design, construction, and in-service inspection of specified components. The ASME III and ASME XI codes **(2)** have been in existence for some time for use with welded pressure vessels, as has BS 5500 **(7)**.

Similar codes exist for gas pipelines, and these have been critically reviewed by Hopkins **(8)**. Being laid under public land, gas pipelines often suffer denting damage, and for in-service analysis, the effects of such damage has to be taken into account **(9)**. These code routines base their fracture mechanics analysis on LEFM, or the older versions of PD6493 **(10)** and R6 **(11)**.

For most situations, however, fracture mechanics is used as an adjunct to design codes, or to identify fitness for purpose for situations of components not covered by such a code. On one special instance, fracture mechanics was used to provide an independent, exhaustive, scrutiny of the fitness for purpose of the PWR pressure vessel design to be used for Sizewell B **(12)**. It is notable that the design of the vessel was so robust as to withstand such modern scrutiny, despite being based upon old design rules.

Fracture mechanics can also be used to help in material's selection. In the electricity supply industry in the UK, it was used to design and select the material for the inlet pipes and penstocks of the Dinorwig pump storage power station **(13)**. In this case, there was a strong initial desire to fabricate these components using a high strength quenched and tempered low alloy steel to save weight, allow shop fabrication and potentially produce a higher quality and cheaper component than would be obtained using conventional C–Mn steels. The fracture mechanics analysis identified fatigue as the most likely source of component degradation, caused by an unusually high loading amplitude because of the 600 m head of water, and a high frequency, caused by the design need to change from generating to pumping mode 15 000 times per year, compounded by the six turbines being fed by a parallel linked pipework system. This fatigue loading could only be contained by using a relatively low stress amplitude obtained from using thick pipes. Pipes of the appropriate thickness could only be obtained in C–Mn steel. Techniques were developed for shop fabrication of these thicker pipes so that the high quality was maintained, and a defect inspection strategy was developed.

Worldwide the electricity supply industry finds that fracture mechanics is especially useful in diagnosing the causes and progress of fatigue and environmental cracking in tubo-generator rotor steels. This is important as the development of cracks during service remains one of the major risks to the integrity of operating turbo-generators, and when a failure occurs, as significant and costly loss of generating capacity ensues. Not only can fracture mechanics help identify the initial cause of the problem, but it can also be used, in conjunction with an analysis of the topography of the crack, to trace individual loading events and identify their contribution to the progress of the crack growth **(3)**. Thus, the effect of load history on crack growth is becoming better understood to help provide a more exact prediction of plant performance, and allows planning and better utilisation of similar components.

More strategic uses for fracture mechanics

A major factor in the costs of any complex item of plant is its availability for use, and the extent to which this can be influenced. The facility to plan repair and maintenance schedules for periods of low demand, and to minimise downtime, has major commercial implications. Without a rational means of establishing such a plan the operator is faced with judging between two alternatives:

- a potentially, unnecessarily frequent, repair/maintenance or replacement schedule;
- a potentially, dangerously infrequent, repair/maintenance schedule.

The risks of the latter are manifold, ranging from the safety implications to the commercial. In commercial terms a failure could lead to consequential damage in other components and extensive outages caused by long lead times for remanufacturing. Fracture mechanics provides a rational basis for influencing decisions about repair, maintenance, and replacement strategies, such that the relative risks can be appropriately assessed. Some areas of plant operation which can benefit from this are identified below.

(*a*) *Optimization of planned outage time*

Inspection information from a previous outage, or from a similar component, which has a comparable operating history, can provide a valuable basis for optimizing outage schedules. Where defects are well defined, growth rates can be calculated with some degree of accuracy such that the timing of the next outage can be optimized. Judgement can be made using different strategic criteria so that a total assessment of the relative costs, benefits, and risks can be established.

For example, suppose at a given manufacturing outage, an item of complex equipment was found to contain a crack-like defect. A decision needs to be made as to whether to repair during this outage (it would be an unscheduled repair, so possibly extend the outage considerably) or leave the repair until later. Leaving till later allows proper assessment of the appropriate repair techniques, planning of the repair schedules, and provides the necessary lead time to manage the project optimally. The repair could be scheduled during a period of low demand, or when alternative equipment can be brought into service.

The two important criteria are the limiting size of the defect for failure and the limiting size of defect which allows a successful repair. The fracture mechanics analysis can evaluate explicitly for the first of these, and can determine the time taken to reach both. If an acceptable situation is not demonstrated, the analysis can also be used to define operating conditions which would produce an acceptable situation.

(*b*) *Minimization of outage periods*

For the repair requirements alluded to above, the potential for turning an unplanned event during an outage into a planned and optimally managed repair project, will automatically minimize the outage time for that repair. There are, however, other situations where fracture mechanics can be used beneficially for minimizing outage periods, principally in the field on non-destructive examination.

The benefits here can be derived from the use of fracture mechanics to devise an inspection strategy. This requires an analysis of all locations vulnerable to crack-like defects, taking into account welds and geometrical factors, and where possible, the likely driving mechanisms for defect growth (e.g. aqueous environmentally assisted cracking mechanisms may only occur when the component is wet). From this the high risk areas of the plant can be determined and the inspection strategy developed to focus on these. The strategy must, of course, take account of the chances of having defects prior to operation, as well as defects which may grow during operation.

The advantages of such a strategy are two-fold. First, focusing on the high risk areas reduces the overall inspection requirements, hence the time and cost. This is especially so for high temperature plant, where lagging must be stripped prior to inspection (and reinstated afterwards) or for complex structures where inspection may be difficult without dismantling of the plant. Second, because of this, a more thorough inspection of the high risk areas will be possible, rendering the overall examination more effective. It may be decided that parts of the plant considered to be of low risk may still need inspecting, but the need would not be for such a thorough inspection, or for so frequent a one.

(*c*) *Reducing repair costs*

There are two issues here, the need for the repair, and the repair programme itself. Repairs of complex plant containing crack-like defects can take 3 forms. In order of cost and complexity, these are:

- grind the defect out and smooth the remaining profile to reduce the consequential stress concentration effects;
- grind the defect out and reprofile the component by welding;
- replace the defective component.

There is seldom any virtue in embarking on a repair for a defect which does not imperil the plant. Therefore the first requirement on finding a defect is to perform a fitness for purpose analysis to assess for the significance of the defect. This is important, since grinding and weld repairing are not only difficult exercises, but can pose a further risk to the plant by changing the geometry, degrading the material properties and creating residual stresses. A benign defect, or one which can be made to be benign by modifying plant operation, is often the more secure, and certainly the cheaper option. To assess for this, the fracture analysis must not only evaluate for the significance of the found defect, but also for the likelihood of a defect growing in the region after repair, and the risks which this would produce.

When a decision is made to repair, the assessment of the repair is extremely important, especially if a weld is involved.

For ferritic materials it is normal to stress relieve by post weld heat treating (PWHT). For large components this can be done by heat treating only the affected area. The heat treatment runs the risk of being only partially effective, and also of inducing residual stresses elsewhere. For austenitic materials, stress relieving may not be considered necessary, as such materials are often considered to be insensitive to residual stresses from a fracture viewpoint. However, especially for high carbon austenitic components, the coarse grained heat affected zone may be sensitised to grain boundary attack. In such cases a post weld heat treatment to desensitise the affected area may be necessary. This also runs the risk of inducing sensitisation elsewhere, so this has to be considered in the design of the PWHT programme.

Post weld heat treatment of a repair weld therefore is not only costly and technically difficult, but can also create further risks for the plant. In many cases, however, high residual stresses can be tolerated so that this step in the repair can be eliminated. Such cases occur when the material is highly ductile, and therefore innately defect tolerant **(14)**, and where forms of crack growth other than by fast fracture can be avoided. A fracture mechanics analysis of the repair containing postulated defects can evaluate for this.

(*d*) *Extending plant life*
It is axiomatic of any complete fracture analysis to evaluate for useful plant life, and this is implied in all of the three uses outlined above. Plant life extension can of course be the sole purpose of the analysis. As for other purposes, the desired outcome can often be achieved by modifying the plant operating regime.

Basic requirements

In developing a strategy for determining the cost/benefits of a potential repair to a component found to contain a defect, a number of key steps need to be evaluated. Some of these are the province of the fracture expert, and some the province of others. Some of the main ones are defined below.

(*a*) *Nature of defect*
This is the province of the NDE expert or the investigating metallurgist. It has an important bearing on the applicability and validity of the analysis. The main questions are: is the defect volumetric, a surface network or planar and crack-like, and why is it present

(*b*) *Significance of failure*
This is the province of the operator.

(*c*) *Significance of the defect*
Here, the fracture expert is important. He must call upon the stress analyst, experts in welding and residual stresses, and metallurgists in order to derive his input data. He will need to perform an elastic–plastic analysis over a range of these variables to determine the sensitivity of the result to different values of them, taking into account the differences between the different types of defect. This will tell him under what conditions failure can be expected, how it might occur and whether it could be benign (e.g. a detectable leak in a pipe) or catastrophic (e.g. fast brittle fracture). A knowledge of the various combinations of input which could cause failure provides a valuable insight into its likelihood.

(*d*) *What is the most likely route to failure?*
If defect growth is needed, how can it occur? Can growth rate be reduced? These questions can be addressed by the fatigue or the environmentally assisted cracking expert, who can also advise or palliative measures which can reduce or eliminate growth. If a fault load is needed to cause failure, can further safeguards be incorporated to eliminate such faults?

(*e*) *What is the period remaining for safe operation?*
This important question follows from (*d*) and is dependent upon the various palliative measures which can be invoked.

(*f*) *The repair options*
The 3 basic options, grinding, grinding and welding, and component replacement should each be assessed against the key questions, to ensure that the chosen option will not introduce further problems.

As an example, surface intergranular attack (IGA) on austenitic components can be remedied by grinding out the affected area. However, often it can be shown that in a region of low stress, blocking of an IGA network by corrosion products restricts it to the surface few millimetres, and it does not develop into a stress corrosion crack. In such circumstances the IGA produces the same effect as a local thinning of the structure. The grinding produces the same mechanical effect, but with a fresh surface which can be susceptible to further intergranular attack, hence reinitiating the degradation cycle. Grinding out the area affected by IGA would therefore increase the risk of failure not reduce it. There may, of course, be good reasons for grinding out such defects, but the reasons and effects should all be evaluated carefully.

This illuminates the importance of understanding the initial cause of the defects. Even a replacement of the component may not solve the problem without a modification of the operating conditions.

(*g*) *Evaluate the costs and benefits of the different options*
This is the optimization phase of the assessment, where attention can be focused on the timing and planning of any necessary repair, and in minimizing the consequential risks.

Concluding comments

The main advantage in using fracture mechanics rather than empirical methods for assessing plant lies in its predictive capability. This comes from its sound theoretical base, which has been underwritten by a considerable amount of experimental and numerical validation, and makes it applicable to new problems and new variations of old problems without the need for further testing. For maximum benefit, the method used must be cheap and flexible. It is worth noting that a high level of accuracy is unlikely, because of the large range and number of uncertainties in the input to any analysis. The cheapness is therefore important, as for strategic use and to cater for these uncertainties, it is necessary to evaluate a matrix of conditions (load cases, defect sizes, locations, etc.), which at times can be large. Numerical methods of analysis would normally be prohibitive for this purpose, and model or real structure testing would not be able to meet the range of conditions of interest.

For the analysis to be successful, all potential sources of defect propagation and failure must be considered. This includes degradation due to non-crack degradation mechanisms (such as erosion–corrosion) as well as all crack-like mechanisms. Pitting, intergranular attack, stress corrosion cracking, corrosion fatigue, fretting fatigue, and all combinations of these mechanisms need to be considered. This does not make the problem intractable, of course, since, in most cases, most of these mechanisms can be shown to be absent. For those that can't be shown to be absent, pessimistic assessment of defect growth can often be made quite readily.

In many cases, the fracture analysis will show that a structure is not safe to operate at all: indeed it is not unknown for failure to be 'predicted' under conditions which the plant has already survived. Such cases provide a good illustration that the outcome of the analysis depends upon the quality of the input. Where this is uncertain, an uncertain result will be obtained. Thus, fracture mechanics cannot replace the need for judgement. It does, however, provide the mechanism for focusing attention on the key issues so that the judgement is not clouded by issues of peripheral interest.

Finally, it is worth observing that, except in very rare circumstances, and for the obvious situation of defect growth by fatigue, fracture analyses are performed under the assumption that the load of interest is applied only once. Since, outside of the linear-elastic fatigue regime, plastic zones develop at the tips of defects on first loading, load history could have a significant effect on the performance of the structure. This effect can be beneficial in ferritic steels where warm prestressing may occur **(15)**. It may also be beneficial in highly ductile steels in regions of high tensile residual stress, or high stress concentrations. Evaluation of such effects may well prove fruitful in the future.

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