CHAPTER - V

COMPONENT INTEGRITY EVALUATION

Dr. S. Tarafdar & Dr. S. Sivaprasad

5.1 INTRODUCTION

The increasing demand for higher output efficiency coupled with rising material costs have forced man-made structures to be very critically designed. Components are now pushed to their limits, having to operate at higher stress levels and in more severe environments. Moreover, the consequences at stake should a component fail are now greater than ever. Hence their design has to conform to the higher standards of safety demanded.

One of the newer concepts that has played a significant role in the design of critical components and the assessment of their safe continual service is *fracture mechanics*. The science of fracture mechanics is built upon recognition of the fact that all material contain crack-like flaws. These flaws may grow under the conjoint action of stress and the environment during service, and ultimately lead to the failure of the component. Fracture mechanics thus is especially suitable for assessing the integrity of components that are in service. Fracture mechanics is also the cornerstone of *damage tolerant* design philosophy, wherein the presence of crack-like defect does not necessarily mean that a structural component is at, or even near, the end of its useful life. The cost of repair and replacement can therefore be balanced against the possibility that continued service could lead to failure.

This paper attempts to describe the usage of fracture mechanics concepts in assessing the integrity of components.

5.2 FAILURE OF STRUCTURES

Strength failures of load-bearing structures are usually of two types, *viz.* yielding dominant and fracture dominant. Failures may also take place through elastic processes, like buckling due to elastic instability and jamming through excessively large elastic deformations; however such failures are easily prevented by basic design practice and serious engineering failures of this type may generally be ruled out. The characteristic features of yielding dominant and fracture dominant failures are listed in Table 1. The most significant difference between the two is the presence of a dominant, apparently *brittle*, crack surface in the latter, as opposed to the manifestation of gross plasticity through substantial material volume and the presence of a fibrous *ductile* failure surface in the former. It may be pointed out that at the microscopic level, the apparently brittle fracture dominant failures may also exhibit ductile flow. However such ductile deformations are highly localized and restricted to the vicinity of the crack.

Table 1 : Characteristics of Failure Modes

Yielding dominant	Fracture dominant
• General Plasticity	• Highly Localised Plasticity
• Significant defects are those controlling resistance to plastic flow; eg : intertitials, grain boundaries, precipitates, dislocation networks	• Significant defects are essentially macroscopic; eg : weld flaws, porosity, forging laps, fatigue cracks, stress corrosion cracks
• Failure surface is usually non-planar, highly distorted, ductility exhausted, shear type	• Failure surace is usually planar, often *brittle* in appearance, arising from cracks
• Failure is generally "slow and stable"	• Failure is often "catastrophic

While engineering failures through yielding do occur, the majority of structural failures that have become "memorable" due to the scale of destruction and the abruptness of the catastrophe, are of the fracture dominant type. The following are some examples of such failures. Atallah [1] has described the devastating rupture of a liquefied natural gas (LNG) storage tank at Cleveland in 1944 which resulted in property damage estimated at over 6 million US dollars and killed 130 people. The failure was attributed to welding defects from which fatigue cracks grew under vibrations and shocks emanating from heavy railway traffic and stamping mills in the neighbourhood. The problem of brittle fracture begun to be appreciated with the large number of failure of ships of welded construction during World War II. Out of the 2580 Liberty ships built during the period, 145 broke into two halves, while another 700 experienced serious failures. Of the approximately 5000 merchant ships constructed, over 1000 had developed cracks of considerable size by 1946. These failures were though to occur due to design deficiencies (e.g. square hatch corners) in many of the cases; but for the majority, the quality of the steel used was at fault [2]. One of the earliest catastrophic failure in aviation engineering occurred in the mid-1950s, when two Comet aircrafts failed while at high altitudes (one over Calcutta) [3] due to fatigue cracks originating from rivet holes in the fuselage.

In spite of the concerted research and development of codes of practice to counter the occurrence of fracture dominant failures, such failures continue to occur. Cracks were observed in British nuclear submarines in 1990 [4]. Forty-four years after the Cleveland LNG tank disaster, a diesel fuel oil tank fractured vertically while being filled in Pennsylvania in 1988 [5]. Through 1993-94, a series of supersonic fighter aircrafts of the Indian Airforce were destroyed due to fatigue cracks growing in Ti-alloy compressor discs of their engines [6]. With the development of newer materials and advanced construction methodology, the requirement for preventing fracture dominant failures thus remains as forceful as ever.

5.3 Strength of Materials *vis-a-vis* Fracture Mechanics

The adoption of strength of materials based design procedures can effectively deter failures through the yielding dominant mode. Such design methodology essentially strives to provide sufficient section area to prevent the onset of plastic yielding of the material throughout the component. With the high degree of sophistication available in engineering design practice, concentration of stresses at changes in sections, notches and radii can be effectively calculated and designed against exceeding a safe stress level.

When cracks are present in structures, if it is assumed that the sole effect of a crack is through the reduction in the net section available to resist deformation, then the maximum stress that can be tolerated will be inversely proportional to the crack length, as per the strength of materials approach. In reality, the stress at which a structure fails is conspicuously lower, as shown schematically in Fig.1. This discrepancy arises from the nature of stress intensification induced by cracks. For a stressed linear elastic material containing a crack, a singularity is exhibited by the stress profile ahead of the crack tip, as shown in Fig.2(a). In comparison, the stresses ahead of a notch, illustrated in Fig.2(b), are of finite magnitude. The strength of materials approach can therefore be applied to the latter case, but not for the former. It may be mentioned that "real" materials have elastic-plastic stress-strain response and hence infinite stresses in the vicinity of the crack tip, as in Fig.2(a), cannot be sustained. These high stresses are consequently relaxed through plastic yielding. However, the strength of materials methodology still cannot be applied as under this design philosophy yielding is not permitted.

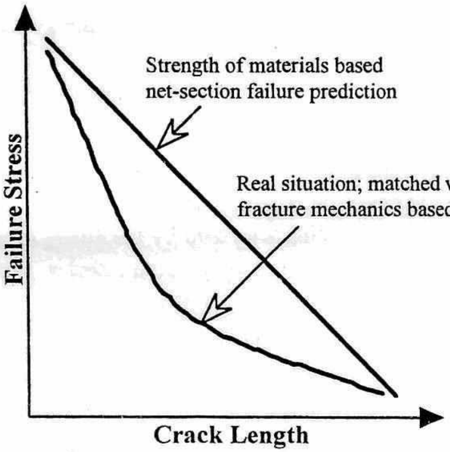

***Fig.1** : Failure stress of a structure with respect to the crack length contained in it*

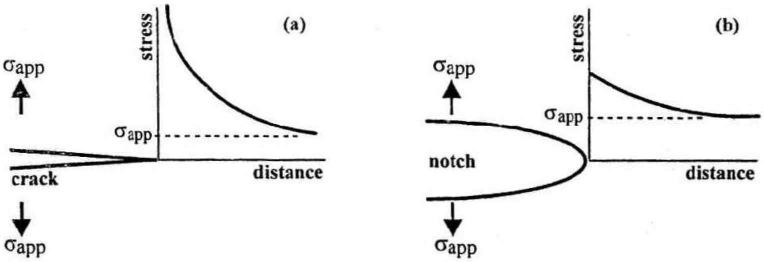

Fig.2 : The stress ahead of a (a) crack and (b) notch

5.4 Fracture Mechanics Methodology

Consider a structure containing pre-existing flaws, or in which cracks have initiated in service. The cracks may grow with time due to the operation of mechanisms such as fatigue, stress corrosion or creep, and will generally grow progressively faster. As noted earlier, with the increase of crack length, the residual strength of the structure would decrease. The situation is schematically depicted in Fig.3. With reference to the figure, in order to assess the integrity of the structure, the following queries will have to be answered :

a) What is the residual strength as a function of the crack size ?
b) What is the maximum permissible crack size under the service loading conditions ?
c) What is the service lifetime of the structure ?
d) What size of pre-existing flaws may be permitted at start of service in order to ensure a minimum lifetime ?
e) At what intervals should the structure be inspected for monitoring cracks ?

In order to provide quantitative answers to the above questions, fracture mechanics relies on a few essential basics. The strength of the singularity in the stress field at the crack tip is characterized by the stress intensity factor (SIF), K. The SIF can also be employed to characterize the embedded plasticity, or any other *failure process zone*, at the crack tip in real materials. The SIF can be expressed as a function of the applied stress, s, and the crack length, a, through relations of the form

$$K = \sigma\sqrt{\pi a}\ Y \qquad \dots (1)$$

where Y is a geometric function dependent on the component configuration and the crack length. Further, it has been experimentally proven that for all materials a critical value of the SIF, K_{crit}, exists beyond which the stability of cracks contained in them cannot be ensured. Hence K_{crit} can be taken as the limit up to which an applied SIF may be tolerated without compromising the integrity of a structure.

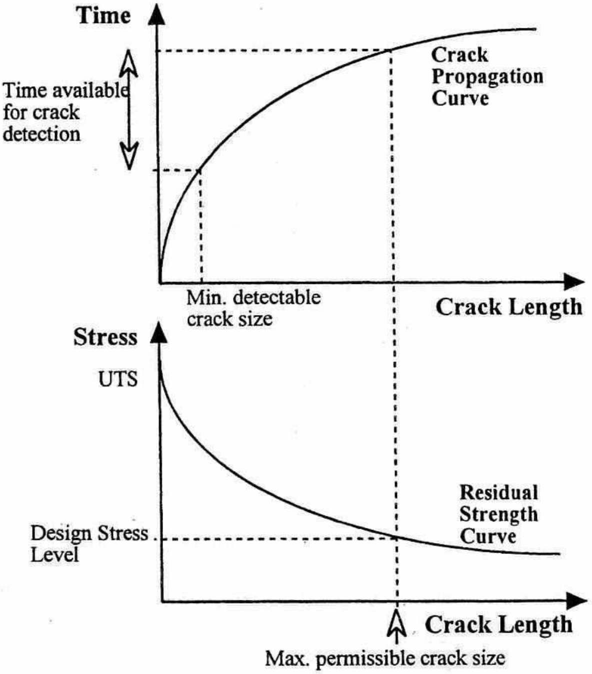

***Fig. 3** : Crack growth in and residual strength of structures*

Substituting K_{crit} for K, for a range of crack lengths, the maximum stress that can be endured by a component can be obtained from eq.(1) in response to query (a) above. It must be pointed out that this will require knowledge of the geometric function Y in eq.(1) for the given crack configuration of the component. Similarly, to obtain the maximum permissible crack size (query (b), K_{crit} and the service stress can be substituted into eq.(1).

To obtain informations on the lifetime of a structure, the time dependence of the crack growth process has to be characterized. Generally, in engineering situations, crack growth will occur through mechanisms such as fatigue, stress corrosion or localized creep at the crack tip. A combination of mechanisms, as during corrosion fatigue crack growth, may also be operative. Fracture mechanics provides correlative parameters for such processes. By way of example, for crack growth through fatigue, which is one of the most common mechanism responsible for structural failures, the crack growth per stress cycle, d*a*/d*N*, can be related to *DK* (obtained by using *Ds* instead of *s* in eq.(1)) through equations of the form

$$\frac{da}{dN} = C\,\Delta K^{m} \qquad \text{... (2)}$$

where *C* and *m* are constants. Such equations can be rearranged and integrated to provide predictions of the crack growth behaviour in terms of *a* versus *N* curve. Responses to queries (c), (d) and (e) can be advanced on the basis of this behaviour. Similar formalisms are available in fracture mechanics for stress corrosion cracking, creep-fatigue interactive crack growth, corrosion fatigue crack growth and various other material specific and situation specific processes. Some of the parameters used in fracture mechanics to characterize the various types of fracture processes are listed in Table 2.

Table 2 : Parameters used in Fracture Mechanics

Type of Fracture	Fracture Mechanics	
	Parameter	Condition
• Initiation of unstable crack growth	K_{Ic}, K_c	LEFM
• Slow stable tearing	J_{Ic}, CTOD K_R *R*-curve, *T*	EPFM LEFM EPFM
• Fatigue crack growth	ΔK, ΔK_{th} ΔJ	LEFM EPFM
• Stress corrosion cracking	K_{ISCC}	LEFM
• Crack growth under creeping conditions	C^*	TDPFM
• Dynamic fracture	K_{Id}	LEFM

With reference to Table 2, it may be clarified that conditions under which fracture processes take place refer to the extent of plasticity attending the crack tip. The SIF, discussed above, is applicable only for linear elastic fracture mechanics (LEFM) conditions in which the plastic zone ahead of the crack tip is absent or insignificant in comparison to the remaining ligament. In ductile materials, it is possible to apply substantially larger stresses approaching the yield strength on a cracked body without K_{crit} being exceeded. Under such circumstances, when the applied SIF, K_{app} is a large fraction of K_{crit}, elastic plastic fracture mechanics (EPFM) conditions are said to prevail. The plastic zone is still contained within the remaining ligament, but is much larger than in LEFM. The preferred parameter to characterize ductile fracture under EPFM conditions is the *J*-integral, which is actually an energy parameter. For very ductile materials in thin sections, it is possible that through extensive blunting of the crack tip due to excessive yielding of the entire remaining ligament, the intensification of stresses by the crack is totally annulled. The situation approaches that for a notch and failure is governed by general yield. The interrelations between the various regimes of fracture mechanics is depicted in Fig.4.

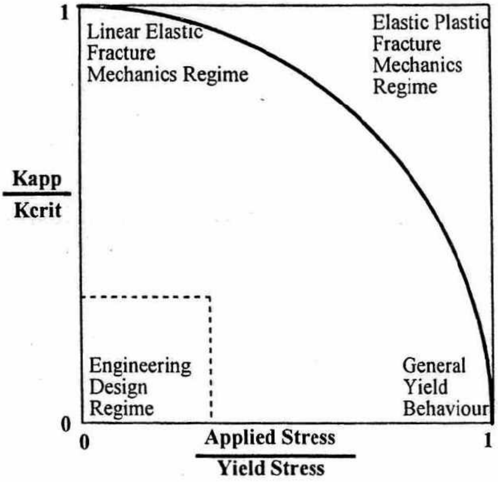

***Fig.4** : Interrelations between the various regimes of fracture mechanics*

5.5 Activities for Life Assessment

Based on fracture mechanics concepts, the various activities that are involved in assessing the integrity of components that are in service, and the interactions between such activities, are shown in Fig.5.

The basic inputs (dark arrows) that are to be obtained from the component for life assessment activities are informations regarding :

- the material from which the component is made and its microstructural state
- the size and orientations of cracks or defects contained in it
- the stresses the component is subjected to
- the environment in which the component operates

Specifications of components usually contain informations on the material. However, materials may *degrade* with time, temperature and stress, and often the current state of the material has to be ascertained. For this *in situ* metallographic techniques may be used. For detecting and sizing of cracks, a number of NDT methods are available. In recent times considerable advancements have been made and continual developments are in progress in potential drop and ultrasonic scanning techniques, automated detection of cracks and use of neural networks for signal analysis. The resolution offered by NDT methods are being bettered continuously so that the limiting size for detectable defects is being decreased. For stress analysis of components, numerical methods like the FEM and BEM have become quite popular and affordable.

For fracture mechanics based assessment of component integrity, the fracture resistance data of the material pertinent to the dominant mode of failure has to be obtained. The dominant mode of failure is governed by the stress situation and the environment the component is exposed to. For example, for a component which is subjected to cyclic loading of sufficient magnitude, the fatigue crack growth rate data for the material is necessary; whereas if a similar component is operating in a marine environment, the corrosion fatigue crack growth rate data, which can be distinctly different, have to be obtained. Previous experience with failure behaviour of similar component is often helpful in deciding on the type of data that may be required. Fracture resistance data for a large variety of materials are available in the literature. Hudson and Seward [7] have published a compendium of sources of fracture toughness and fatigue crack growth data for metallic materials. Databases of material properties, such as the database on toughness of steel containing about 30000 test results on more than 80 steels prepared by EPRI [8], are also available. More often than not, for specific microstructural condition of a component and for particular environments, the relevant data is not available in the literature. In such cases, data have to be obtained through experimentation in the laboratory. Experimental determination of fracture resistance data is a key aspect to successful application of fracture mechanics for integrity assessment. In India, within the CSIR setup, a great amount of emphasis has been laid on this aspect, with NAL, Bangalore, and SERC, Madras, operating facilities for conducting failure tests on structural components, and NML, Jamshedpur, setting up large scale facility for fracture mechanics based testing of materials.

One of the key requirements for fracture mechanics based integrity assessment is the availability of fracture mechanics expressions for the cracked configuration of the component under analysis. For LEFM conditions this essentially entails obtaining the geometric function Y of eq.(1). Fairly extensive collections of such functions are available in handbooks of stress intensity factors compiled by Tada, Paris and Irwin [9], Sih [10] and Rooke and Cartwright [11]. Whenever Y-functions are not available, they must be derived using numerical methods like the boundary collocation technique, FEM *etc*. In EPFM conditions, engineering approximations of the J-integral are required. A limited set of such approximations have been developed using FEM by EPRI for common crack growth configurations [12].

Armed with informations on the size and orientation of cracks, the magnitude of stresses experienced, fracture resistance data for the material and appropriate fracture mechanics expression for a cracked component, the integrity of such components may be estimated in much the same way as discussed under *Fracture Mechanics Methodology* . This is best done using a software, and to this end a number of commercial software packages are available. However most of such softwares are specific to a few component configurations and may not provide a platform for the current need in totality. Hence the intensive user of fracture mechanics technology often finds it more productive to develop custom-made software for specific use. For integrity assessment under EPFM conditions, the procedures followed are somewhat more involved than that discussed in this paper. Kumar *et al.* [12] gives a detailed discussion the methods applicable.

5.6 Concluding Remarks

An overview of the need, methodology and the activities for fracture mechanics based integrity assessment of components has been presented in this paper. More rigorous guidelines have been developed by professional institutions, noteworthy amongst which is the BSI document for engineering criticality assessment (ECA), PD 6493 [13]. The ASME Boiler and Pressure Vessel Code [see 14], particularly Section III, Appendix G and Section XI, also provide guidelines for fracture mechanics based design procedures.
The assessment of integrity of components has to be viewed in the totality of the scenario of their operation and environment, and their probable failure. While the use of fracture mechanics concepts does indeed provide a definite advantage in most situations, there are occasions when processes not characterizable by fracture mechanics play important parts. The operation of creep and general corrosion are such processes that may lead to failure. Similarly, the health of a component in service may be revealed by signatures on the material which are not necessarily cracks. Studies of such signatures, as in microstructure based integrity evaluation, should therefore form a part of any exercise in integrity evaluation. With these objectives in mind, NML has launched the "Component Integrity Evaluation Programme", encompassing the whole gamut of activities that may be necessary to provide a one-window service.

FURTHER READING

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