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Structural and Component Integrity

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ABSTRACT

A structure or a component is expected to perform specific functions for a minimum specified period of time. If it ceases to do so, it is said to have failed. The consequence of service failure can be tragic and expensive. There are innumerable cases of engineering disasters resulting in loss of life and property. Therefore, utmost care and attention are required to be given to critical structures / components to ensure that such incidents do not take place. Integrity evaluation performed at regular intervals is a means to ensure absence of such tragic service failure. It also gives us an estimate of its remaining life which is essential to plan future course of action so that it could be used till the very end of its real life. Recent development of powerful non-destructive techniques and availability of modern computational facility at affordable cost has made this a routine exercise for many critical applications. This paper describes the basic principles behind structural and component integrity evaluation and also presents some of our recent experiences.

Keywords *: Remaining life, Creep, Fatigue, Fracture, Corrosion, Failure analysis.*

INTRODUCTION

Although engineering structures and components are designed to last for a specified period, premature failure does take place for a variety of reasons viz., design deficiencies (lack of knowledge), material selection deficiencies, processing deficiencies, assembly and installation error, operational and maintenance error, and environmental impact. In addition one must realise that every design has a probability of failure. This is because both the material property and the loading are random variables having a mean and a standard deviation. Therefore, inspite of the best effort there would always be a few incidents when the loading may exceed the critical value or the material used may have inferior property. However, depending on the level of factor of safety used, the probability of failure is always very low (10^{-6} / 10^{-7}), but it increases with prolonged

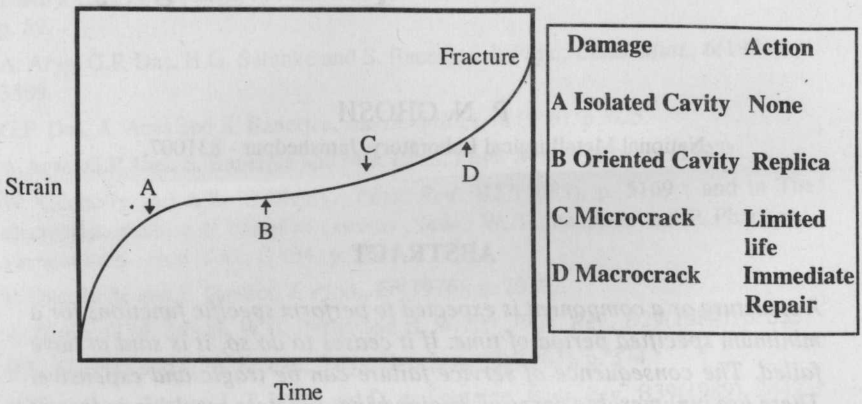

Fig. 1 : A schematic diagram showing a relationship between the nature of defects that develop at various stages of creep strain accumulation and actions required.

service. Old components are likely to be more prone to failure primarily due to the natural process of ageing and also due to the fact that so far no failure has taken place; a characteristic of any stochastic process. There are several natural processes of ageing of structural materials *e.g.*, corrosion, fatigue, wear, creep, shock loading *etc.* Microstructural damages keep on accumulating in the component due to any one or a combination of the above factors. As a result its load bearing capacity continues to decrease. Failure takes place when it falls below a critical level determined by the component geometry and loading. Fig. 1 gives a typical illustration of the nature of defects that develop at various stages of the life of a creep test specimen subjected to a given load and temperature. It is evident that even after certain types of defects are seen to have nucleated, the specimen does still have a significant amount of life. Past experience has shown that this analogy also holds good for components as well [1-3]. Careful non-destructive evaluation carried out at various stages can indeed help us extract the full service potential of an expensive component without any compromise on safety. This type of exercise which helps us in estimating the remaining life of a component is known as component integrity evaluation.

The consequence of failure of engineering structures / components can be tragic and expensive. Therefore, all such cases are critically examined to provide valuable inputs for future developments. The analysis carried out on Comet aircraft accident is a classic example [4]. This did provide powerful insight into the actual problem and was in some way responsible in making air travel one of the safest mode of public transport. Integrity assessment is however performed much before a failure is likely to occur. Its main objective is failure prevention. In addition it helps us delay failure through timely action *e.g.*, if some abnormality is detected, it is repaired before being put into service again and thus use the component till the very end of its life. In view of the ever growing cost of setting up new plants and equipment, the current trend now is to refurbish and extend the life of the existing units. Integrity assessment is the first major step in this exercise. Whenever such an exercise is taken up, one of the objectives is to estimate remaining life so as to suggest when the next inspection should be conducted. This paper describes the basic concepts of such studies and examines the scope and limitation of structural and component integrity evaluation.

WHY DO COMPONENTS HAVE REMAINING LIVES ?

Design of components always aims at absence of failure. Therefore its size or dimension is estimated on the basis of the minimum specified material properties, whereas in reality it may have been made of materials having superior properties. Consequently re–evaluation would indicate that the component has significant built–in remaining life.

Life estimation of a component often requires long term properties which may not be available at the time of design. Under such a situation the designer extrapolates short term material data to satisfy his requirement. Subsequently, as long term data are generated, recalculation may exhibit availability of additional life. Design of power plant components subjected to creep condition during the sixties were based mostly on 100,000 hrs stress rupture tests. In view of the importance of long term creep data in estimating the life of critical components, many costly multi-laboratory test programs were concurrently undertaken to generate long term data. Presently, for many grades of steels, stress rupture data for periods upto 250,000 hrs are available. Re–evaluation of the life of many such components in the light of the newly acquired data often suggests that these could be used far beyond the recommended design life. Past operating experience also supports that service lives considerably longer than design expectations are usually achieved in practice. In fact a survey carried out by EPRI, USA indicate that during the mid eighties about 93,000 MW of power was being generated by plants which have been in operation for more than 50 years [5].

Engineering components are designed on the assumption that they will experience, to some extent, higher than normal operating conditions, whereas in reality that may not have happened. Therefore, it is worthwhile to re–estimate the life of an ageing plant based on its actual operating data collected over its entire period of service life.

Over the years there has been significant development in the area of non-destructive evaluation of engineering components. Modern non-destructive testing (NDT) tools are capable of detecting much smaller defects with greater reliability. Therefore periodic NDT studies carried out on critical components can help us to use them until the very end of their useful life.

INTEGRITY EVALUATION TECHNIQUES

Component integrity evaluation technique would depend on the nature of damage or defects that may have accumulated during service. Therefore careful non-destructive evaluation is the first step in any integrity evaluation activity. Modern non-destructive tools can not only detect fine defects / cracks but also provide an estimate of material properties. The defect size determines the approach which would be most applicable, *e.g.,* for steel, if it is less than 1 mm (*i.e.,* microscopic), one should use damage mechanics approach; whereas if it is greater than 1mm, fracture mechanics based method would be more appropriate[6,7].

The basic difference between the two methods are described in Figs. 2 and 3. In damage mechanics the failure criterion generally is:

$$\sigma > \sigma_y \qquad \cdots \quad 1$$

where σ is the applied stress σ_y is the yield strength. The applied stress being a function of geometry, size and loading is likely to change with service exposure as more numbers of defects accumulate. Likewise the yield strength may also change, particularly in cases where the component is subjected to elevated temperature. Therefore, life assessment of a component, using this approach, would require development of models that would describe evolution laws for

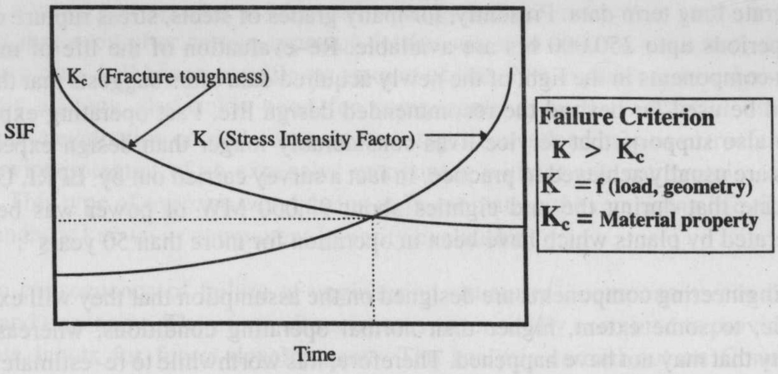

Fig. 2 : A schematic diagram showing the basic principle behind damage mechanics based integrity assessment.

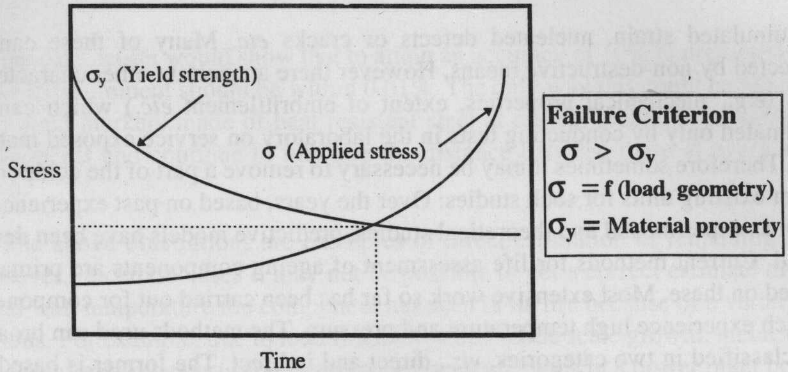

Fig. 3 : A schematic diagram showing the basic principle behind fracture mechanics based integrity assessment.

both σ and σ_y. The point of intersection of the two gives the expected life of the component. The component must therefore be inspected before it reaches this state to avoid service failure.

Fracture mechanics based approach uses unstable crack extension as the failure criterion, instead of plastic deformation (or yielding). The basic principle involved is shown in Fig. 3. The condition for such a crack growth is defined in terms of a parameter called stress intensity factor (K). When K exceeds a critical value (K_c) failure takes place [8]. Stress intensity factor K gives the amplitude of the stress distribution at the tip of a crack. It is a function of applied stress (σ), crack length (a), and component geometry. It is commonly expressed as:

$$K = \sigma (\pi a)^{0.5} f(a/W) \quad \ldots \quad 2$$

where W is the component thickness through which the crack is likely to propagate and $f(a/W)$ is a function dependent on the geometry and the type of loading. K_c which is commonly known as fracture toughness, is a material property. As the crack grows in service under the influence of the applied stress, K continues to increase. Likewise depending on the environment to which the component is subjected, K_c may also change. Therefore, here also there is a need to establish laws governing evolution of K as well as K_c. The point of intersection of the two is the safe operating life. The inspection interval for component integrity evaluation should therefore be selected accordingly.

Damage Mechanics Based Approach

Service exposure often leaves permanent marks on components being investigated. These may be in the forms of microstructural/dimensional changes, accumulated strain, nucleated defects or cracks *etc.* Many of these can be detected by non-destructive means. However there are certain other characteristics (*e.g.,* mechanical properties, extent of embrittlement *etc.*) which can be estimated only by conducting tests in the laboratory on service exposed materials. Therefore sometimes it may be necessary to remove a part of the component from existing units for such studies. Over the years, based on past experience as well as experimental and theoretical studies, predictive models have been developed. Current methods for life assessment of ageing components are primarily based on these. Most extensive work so far has been carried out for components which experience high temperature and pressure. The methods used can broadly be classified in two categories, *viz.,* direct and indirect. The former is based on direct estimation of life from the present condition of the unit, *e.g.,* dimensional / microstructural changes, extent of cavitation *etc.* [8]. Whereas the latter uses measurements like oxide scale thickness, hardness, *etc.,* to calculate the average metal wall temperature which, in conjunction with the operating pressure and the master rupture plot of the material, gives an estimate of the life [2]. The following examples illustrate the basic approach being followed at present.

Creep cavitation is a common failure mechanism for HAZ in welded super heater/reheater tubes or steam pipes [1,2]. Evolution of cavities could be followed by *in–situ* metallographic examination using plastic replication technique or direct examination under a portable microscope during the shut down. Fig. 1 shows the nature and the distribution of cavities at various stages of the life of a component. Based on past experience and laboratory tests a number of thumb rules have been devised for life estimation. For example the detection of macro cracks formed due to coalescence of cavities would require immediate repair and/or replacement of the component. Established empirical models are also used to arrive at a more direct estimate. One of these relates a cavitation parameter (A), defined as the fraction of grain boundaries containing cavities, with the life fraction used up (t/t_r) as follows [1,2]:

$$A = 0.51\,(t/t_r) - 0.095 \qquad \dots \quad 3$$

Using the concept of damage mechanics and laws governing the evolution of creep strain, a simple expression relating remaining life fraction (RLF) with the accumulated strain can be derived. One of these is as follows :

$$\ln(\mathrm{RLF}) = \ln(1 - t/t_r) = (\varepsilon_r/\varepsilon_s)\,\ln(1 - \varepsilon/\varepsilon_r) \qquad \dots \quad 4$$

where t_r is the rupture life, ε_r = rupture strain (~10%), ε_s = a material constant (~3%) ε = accumulated creep strain at a time t [8]. The above expression could directly be used to calculate the remaining life from strain measurement. A simple calculation would show that to attain an accuracy of 10% in predicted life strain measurement should be within 0.01%. The only way this could be attained is to weld markers made of heat resistant steel at critical locations on selected components and continue to measure the distance between these at every shut down.

The above illustrations are examples of direct estimation of remaining life. However, in certain cases it may not be possible to get a correct estimate of the metal wall temperature the component has seen in its life because of a variety of reasons. For example, due to load fluctuation and oxide scale growth, metal wall temperature of reheater/ superheater tubes or steam pipes in a power plant boiler is unlikely to remain constant. In such cases indirect methods are used to get an approximate estimate of the same from a set of simple non-destructive tests. Microstructural examination, hardness and oxide scale thickness measurements provide valuable inputs for such studies. Each one of these is a function of both time and temperature of exposure. Master plots are now available for describing the expected variations in either microstructure, hardness or scale thickness as functions of both time and temperature. Using these and the total length of service, the average metal wall temperature can be calculated. Subsequently on the basis of the operating pressure or the stress the unit is likely to experience in future, the remaining life can be estimated from the master rupture plot of the material the component is made of [5].

Methods described above essentially depend on information collected from non-destructive tests. In view of the importance of integrity assessment of ageing high temperature components extensive destructive tests (*e.g.*, creep) have been carried out on samples removed from components such as steam pipes turbine discs *etc.* Analysis of these data indicates that matching of the shape of the creep curves of a service exposed material with that of the virgin could be quite dependable. There are two basic approaches. The one developed by Wilshire *et al.*[9], commonly known as θ projection, is purely empirical in nature. It uses a specific algebraic equation to represent creep strain as function of time. The material constants are evaluated from experimental data on the virgin material and their dependence on stress and temperature is also established experimentally. Material constants are now available for several grades of low alloy steels used in power plants. Using these, creep curves at any stress and temperature can be generated. Fig. 4 indicates a typical plot at a relatively higher temperature (T_{exp}) and stress (σ_{exp}) so that it takes reasonably short time to conduct the test. On this an actual experimental plot obtained from the service exposed material has been superimposed. The creep strain from which the matching appears to be satisfactory is a measure of the damage that has accumulated in the material because of service exposure. This is projected on to the estimated creep curve

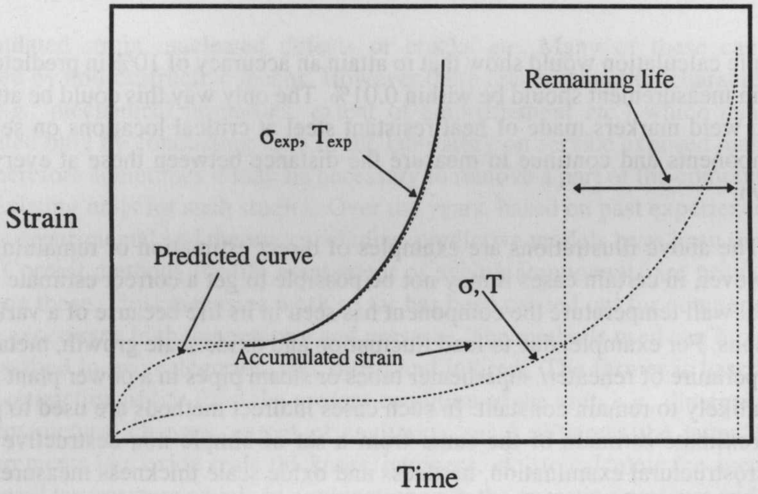

Fig. 4 : A schematic diagram showing the principle of remaining life assessment based on a creep test performed on a service exposed material.

under the actual operating condition (σ, *T*) as shown in the Fig. 4 to estimate the remaining life.

The method suggested by the high temperature materials group at NPL, Teddington uses a set of coupled differential equations to represent simultaneous evolution of creep strain and microstructural damages. These have been built on our current understanding of the underlying principle of high temperature deformation. The procedure has been implemented in the form of a computer based design aid called CRISPEN [10]. The approach being model based, it has been possible to extend its scope to describe behaviour of anisotropic material [11], the effect of complex loading conditions[12] and the influence of environmental interaction [13]. Even though in principle this approach could also be applied to estimating remaining life of engineering components subjected to creep, it has so far not been explored as extensively as the θ projection. One of the reasons is that the present form of CRISPEN primarily deals with materials that exhibit strain softening whereas most engineering structures are made of steel whose creep behaviour is best described by time softening model [14].

Fracture Mechanics Based Approach

Unlike damage mechanics, here a specific macroscopic defect of known size and geometry determines the life of a component. Therefore its growth characteristics under the given condition of loading is required to be followed. Under sustained loading in neutral environment, unstable crack growth takes place only if the dimension of a pre–existing defect is greater than a_c (critical crack length).

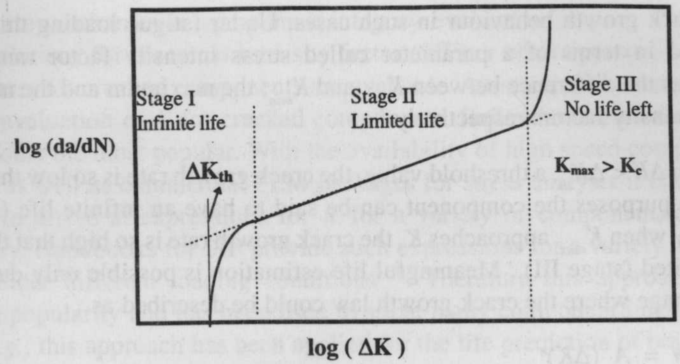

Fig. 5 : An approach to fracture mechanics based integrity assessment for components subjected to fatigue loading.

For a given loading condition a_c is estimated by substituting the value of material toughness in place K in eqn. (2). The major challenge before NDE is therefore to ensure that any crack exceeding a_c does not go undetected. The choice of NDE technique to be employed would depend on material toughness. Lower the toughness, shorter is the critical crack length. Such material would therefore demand for more sensitive equipment to be employed. Past experiences reveal that prolonged service exposure leads to embrittlement or loss of toughness. Therefore old/ageing components are required to be evaluated more carefully.

Subcritical cracks in a component can grow in service either due to fatigue loading or due to prolonged exposure to corrosive environment. Figs. 5 and 6

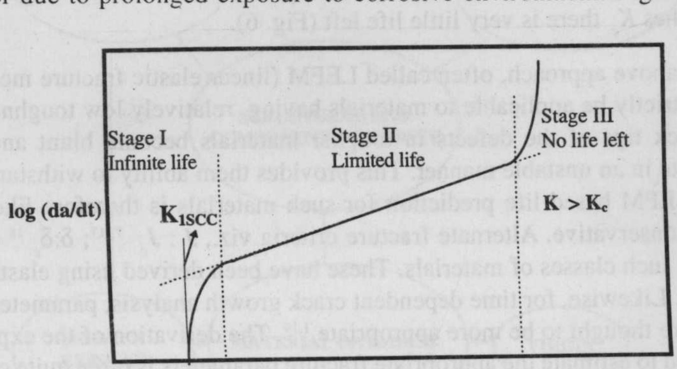

Fig. 6 : An approach to fracture mechanics based integrity assessment for components subjected to sustained loading in corrosive environment

show crack growth behaviour in such cases. Under fatigue loading this is best described in terms of a parameter called stress intensity factor range (ΔK) defined as the difference between K_{max} and K_{min}; the maximum and the minimum stress intensity factors respectively [7].

When $\Delta K < \Delta K_{th}$, a threshold value, the crack growth rate is so low that for all practical purposes the component can be said to have an infinite life (stage I). Similarly when K_{max} approaches K_c the crack growth rate is so high that the life is very limited (stage III). Meaningful life estimation is possible only during the second stage where the crack growth law could be described as

$$da/dN = A\ (\Delta K)^n \qquad \ldots \qquad 5$$

where N is the number of cycles, A and n are material parameters. Since ΔK is a function of crack length, a numerical integration scheme is required to estimate life. In cases where amplitude of loading varies, integration should be performed in units of sub-blocks consisting of constant amplitude loading [7,15].

Life estimation procedure under sustained loading is also very much the same. Crack growth law during the second stage in this case is given by

$$da/dt = A\ K^n \qquad \ldots \qquad 6$$

where A and n are material constants. The time it takes for the crack to grow from a to a_c is the useful life of the component. K being a function of crack length here as well, numerical integration will be required. As in fatigue here also there is a threshold stress intensity factor, K_{ISCC} such that when $K < K_{ISCC}$ there is no crack growth and the component has an infinite life. Likewise in stage III as K approaches K_c there is very little life left (Fig. 6).

The above approach, often called LEFM (linear elastic fracture mechanics), would strictly be applicable to materials having relatively low toughnesses [7,16]. The crack tips of the defects in tougher materials become blunt and do not propagate in an unstable manner. This provides them ability to withstand higher loads. LEFM based life prediction for such materials is therefore likely to be highly conservative. Alternate fracture criteria viz., $J : J_c$ [7,17]; $\delta:\delta_c$ [18] could be used for such classes of materials. These have been derived using elasto-plastic analysis. Likewise, for time dependent crack growth analysis, parameters like C andC^* are thought to be more appropriate [1,19]. The derivation of the expressions to be used to estimate the appropriate fracture parameters is often quite complex. It may require the use of high speed computers. This is the reason why the application of fracture mechanics based concept for integrity assessment of engineering components is of rather recent origin. Application of the principles of fracture mechanics in component integrity evaluation is quite simple, provided solutions for the stress intensity factor (SIF) or other appropriate fracture parameters for cracked components are available. Amongst the various methods for the evaluation of *K* for cracked components, finite element method (FEM) has become the most popular. With the availability of high speed computational facility as well as commercial FEM packages for stress analysis it is now quite simple to arrive at expressions for *K* for a variety of component, and crack geometry. Handbooks for SIF provide such expressions for a variety of components under different loading conditions [20]. Therefore this approach is now gaining popularity and has been used to solve many component integrity problems, *e.g.*, this approach has been applied for the life prediction of boiler drums exhibiting ligament cracking[1].

ROLE OF NON-DESTRUCTIVE TESTING

In the light of the above background, it is now possible to illustrate the role that NDT is expected to play. This has been presented in the form of a schematic diagram (Fig. 7). There are broadly two kinds of expectations *viz.*, current physical dimensions and material properties. The former helps us estimate the stress (or SIF) the component is likely to experience and the latter provides a value of material strength (or toughness) to test whether it is still safe to use. Varieties of simple, easy to use tools are now available for the measurement of

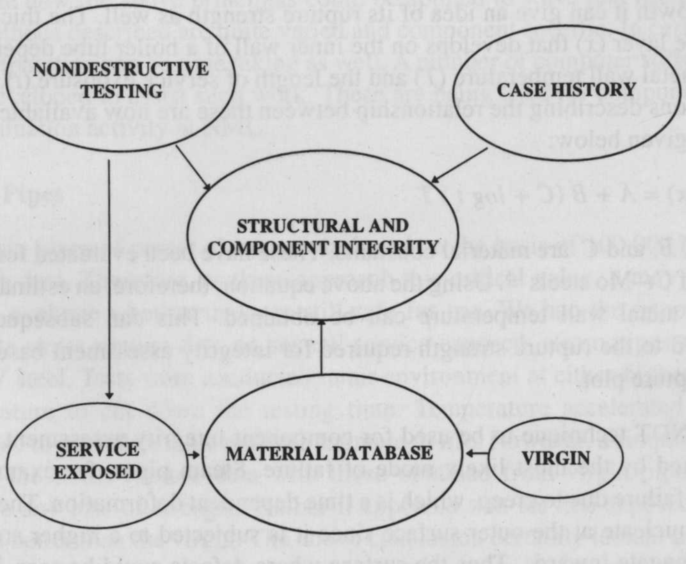

Fig. 7 : A schematic representation of the role of NDT in component integrity evaluation

physical dimensions *e.g.*, ultrasonic gauges are regularly used for thickness measurement of pressure vessels. Service exposure leads to loss of section thickness due to interaction with environment. Therefore old vessels are likely to experience higher stresses which can be estimated from such measurements. However to assess its integrity we need to compare it with the current material strength which may have changed because of service induced embrittlement. This indeed is a difficult task. In the absence of suitable non-destructive techniques the practice currently followed is to carry out WFMPI (wet fluorescent magnetic particle inspection) on the surface which is exposed to the corrosive environment. Detection of a crack is considered to be a sign of embrittlement. The decision to repair or retire the vessel is based primarily on the nature and the extent of the defects. Sometimes an acoustic emission test may also be conducted to check whether the defects are likely to grow during service. However such a test might be very expensive as it needs the use of a costly microprocessor based equipment available only in a few organisations in India. Nevertheless non-destructive evaluation of material property still remains a major problem to be solved for reliable integrity assessment of ageing components.

In certain areas some novel techniques are being attempted to estimate the material property. Integrity assessment of boiler tubes based on oxide scale thickness measurement using special ultrasonic probes is an example worth looking at. It may appear that such a measurement would give an idea of the stress the tube is subjected to, but if this is connected with the kinetics of oxide scale growth it can give an idea of its rupture strength as well. The thickness of the oxide layer (x) that develops on the inner wall of a boiler tube depends both on the metal wall temperature (T) and the length of service exposure (t). Several expressions describing the relationship between these are now available. One of these is given below:

$$\log(x) = A + B\,(C + \log t)\,T \qquad \ldots \qquad 7$$

where A, B, and C are material constants. These have been evaluated for several grades of Cr–Mo steels [1,5]. Using the above equation, therefore, an estimate of the average metal wall temperature can be obtained. This can subsequently be converted to the rupture strength required for integrity assessment based on its stress rupture plot.

The NDT technique to be used for component integrity assessment is often determined by the most likely mode of failure. Steam pipes, for example, are prone to failure due to creep, which is a time dependent deformation. The defects usually nucleate at the outer surface since it is subjected to a higher stress and they propagate inwards. Thus the surface where defects could be seen is easily accessible. *In–situ* metallography is therefore the best technique to be used. It can detect defects much before they attain the critical size in comparison to other methods [1].

Likewise, the limitations of current NDT techniques to detect cracks/defects may lead to premature failure of components. Fatigue failure of Comet aircraft is an excellent example. Later analysis has shown that the critical crack size for the material of which the aircraft was made was smaller than the diameter of the bolt head [7]. Therefore, visual examination could not detect them. Development of materials having higher critical crack length (fracture toughness) and better joining techniques were needed to overcome such failures.

CASE STUDIES

Ever since the establishment of creep testing facility at the National Metallurgical Laboratory (NML) in 1974, a number of its scientists had the opportunity to look at various problems related to integrity assessment of power plant components. The major emphasis initially has been on components subjected to high temperature and pressure. In view of the growing importance of the topic, a multi-sponsor thrust area project called Component Integrity Evaluation Programme (CIEP) was initiated primarily to augment facility and expertise to undertake such work on a much larger scale. The first phase of this programme has just been completed. A few of the recent case studies included would illustrate how the above principles could be applied to solve real life problems. The methods described are quite varied and component specific. In certain cases the computation can be time taking as well. A number of computer softwares has been developed to assist such work. These are being used for component integrity evaluation activity at NML.

Steam Pipes

Steam pipes of power plants are designed on the basis of 100,000 hr rupture strength data. Therefore, as these approach this critical value, it may be necessary to evaluate whether they are still safe for use. We had the opportunity to generate stress rupture data on several service exposed steam pipes made of a CrMoV steel. Tests were conducted in air environment at either higher stress or temperature to cut down the testing time. Temperature accelerated tests are supposed to provide a more realistic estimate of life. However, a simple comparison of the stress rupture data with those obtained from virgin pipes did not indicate any loss of strength. Rather it appeared that service exposed material may be better than the virgin. The above conclusion certainly looked unrealistic. Later, a more rigorous analysis was carried out using a computer software

(CLIP), that provides a frame work for Creep Life Prediction of engineering materials with the help of three commonly used time temperature parameters *viz.* Larson-Miller (LMP); Sherby-Dorn (SDP) and Manson-Haferd (MHP) parameters [21]. Table 1 gives a summary of the analysis. Both rupture life at 550°C and 64 MPa and 100,000 hr rupture strength at 550°C were estimated for virgin as well as service exposed pipes.

It is revealed that while the rupture strength decreases with time, the estimates of remaining life has no correlation with service exposure. This is primarily because in case of the latter an attempt has been made to extrapolate the data beyond its domain of validity. Therefore it is important to know the limits of extrapolation. It would be more rational to use rupture strength as the criterien for integrity assessment rather than to estimate its remaining life [22].

Table 1. Remaining life and 100,000 hr rupture strength of steam pipe material at 550°C as function of service exposure

Service Exposure (hr)	Remaining life (hr)			Rupture Strength (MPa)		
	LMP	SDP	MHP	LMP	SDP	MHP
0(Virgin)	161000	164000	98000	97	97	102
56000	184000	199000	105000	73	73	67
100,000	91000	97000	89000	68	67	60

A more detailed analysis did show that prolonged service exposure had changed the microstructure significantly [23] and it has a definite correlation with the minimum creep rate. This has been established through the measurement of a parameter called threshold stress whose magnitude, in relation to the applied stress may give an idea of the condition of the pipes. It has been reported that it decreases with service exposure like the rupture strength [24]. This too supports the above observation.

Heater Tubes

Heater tubes are used in Coking/Visbreaking units of petroleum refineries to raise the temperature of reduced crude oil (RCO) to 500°C. These are made of CrMo steel and are required to withstand high temperature and pressure. During the heating stage, coke deposition takes place on the inner wall of the tube. Consequently the metal wall temperature is required to be raised to maintain the same level of heat flux to bring down the viscosity of RCO. Besides, the reduced cross sectional area due to coke deposition would demand higher pressure drop to maintain the flow rate. Therefore, it is of utmost importance to monitor skin temperature and pressure drop across the tube length. Whenever these go beyond a specified limit, the unit is shut down for cleaning. Usual length of a normal coking cycle varies between 150-240 days. During shut down, the furnace tubes are cleaned either by mechanical means with the help of a mandrel or by steam air decoking. Since the latter process is more efficient and provides cleaner surface, it is being practised in most of the units. Necessary steps are taken to ensure that the temperature does not go beyond 700°C during the decoking cycle[25].

These tubes are designed based on their 100,000 hr rupture strength. Many of these are in use for the past 20 - 25 years. Few of these were removed from service to carry out a detailed life assessment exercise. The study revealed that although no significant change in the strength of these tubes were detected there was a considerable loss of toughness and rupture ductility as a result of prolonged exposure. Carburization at the inner wall of the tube where coke deposition takes place during normal operation was identified as the main cause of this degradation[25]. This is also likely to impair weldability of tubes making weld repair more difficult and susceptible to cracking. Therefore it is of considerable relevance to evolve a strategy of tube replacement based on material degradation so far detected. Since there is an evidence of embrittlement, a fracture mechanism based integrity assessment was thought to be more appropriate. Fig. 8 gives an idea of the kinetics of the growth of the carburized layer. This layer is expected to be brittle and the unit is likely to experience thermal shock during the normal coking and decoking cycle. Therefore it may be justified to assume that cracks of length equal to the depth of carburization do exist in the component. Consequently it is expected that an integrity assessment exercise would provide

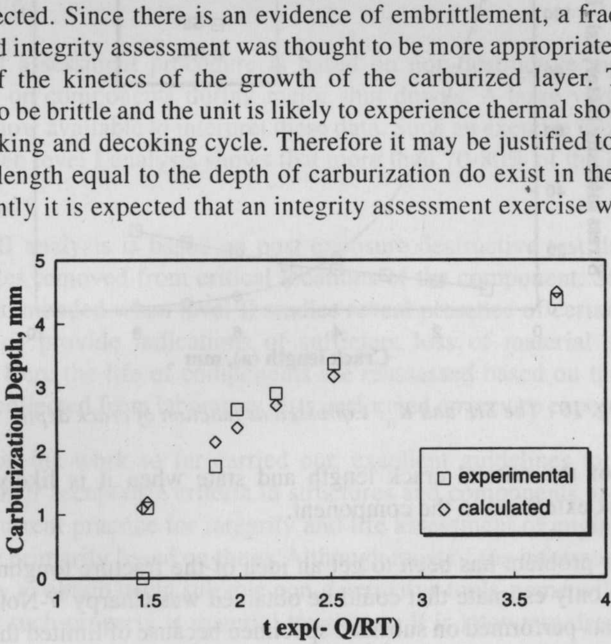

Fig. 8 : The observed depth of carburization expressed as function of temperature (T) compensated time (t). Q is the apparent activation energy of the process and R is the universal gas constant.

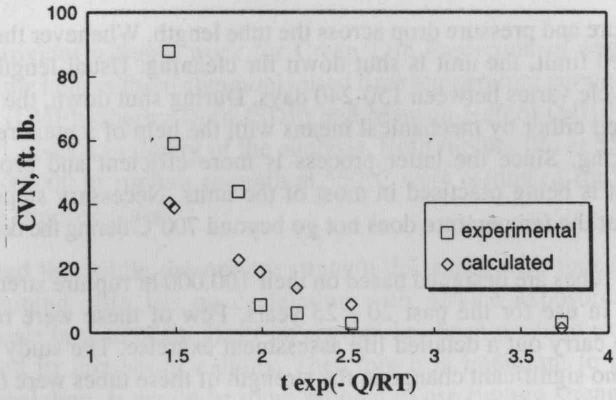

Fig. 9 : The observed Charpy impact value (CVN) expressed as function of temperature (T) compensated time (t). Q is the apparent activation energy of the process and R is the universal gas constant.

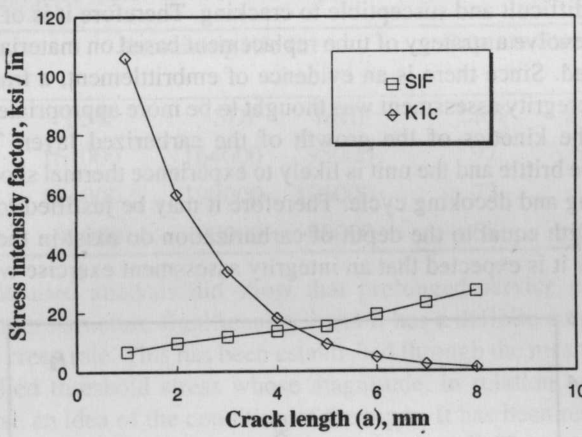

Fig. 10 : The SIF and K_{1C} expressed as function of crack depth.

an estimate of the critical crack length and state when it is likely to cause unstable crack extension in the component.

The major problem has been to get an idea of the fracture toughness of the material. The only estimate that could be obtained was Charpy V-Notch (CVN) value from tests performed on subsized specimen because of limited thickness of the tube. Therefore the use of standard expression available in the literature to convert the same to K_{Ic} [1] is the only alternative. With the assumption that such relationships are valid, here also the LEFM approach could be used to generate plots of the type given in Fig. 3. The effect of service exposure on the CVN value for the heater tube material is given in Fig. 9. Using the data presented in Figs. 8 and 9 and the eq. (2), a plot of the type given in Fig. 3 has been generated. This is given in Fig. 10. This gives us an idea about the depth of carburization that can be tolerated. Failure due to poor toughness of the service exposed tube may take place only during the mandatory hydrotests performed just before putting these back to service after steam air decoking. Integrity assessment provides valuable input to take correct decision to avoid failure at this critical stage.

CONCLUDING REMARKS

A broad overview of two distinct approaches for component integrity evaluation has been presented. A complete integrity assessment exercise on any equipment is no doubt going to be expensive and time taking. Therefore, for convenience the entire exercise is divided into three levels [1]. Level I looks at the past operating conditions in the light of the minimum specified material property data currently available. As mentioned earlier, often the design is based on a relatively short term material database. Reassessment may therefore exhibit additional remaining life.

Level II assessment procedure is based on non-destructive measurements carried out on components during major shut downs. A large variety of techniques are now available to interpret these data. Such an exercise is usually taken up only when level I analysis shows that more than 70-80% of the life has been used up.

Level III analysis is based on post exposure destructive test data obtained from samples removed from critical locations of the component. Such an exercise is recommended when level II studies reveal presence of certain categories of defects or provide indications of sufficient loss of material strength and toughness. Here the life of components are reassessed based on the short term properties collected from laboratory tests performed on service exposed materials.

Based on the work so far carried out, excellent guidelines to characterise flaws and their acceptance criteria in structures and components are now available [26,27]. Current practice for integrity and life assessment of engineering components are primarily based on these. Although most of the information required may be easy to obtain using suitable non-destructive tools, some will be difficult to get. One such property is material toughness. It is known to deteriorate with service exposure. This has been established from tests carried out on service exposed material. Mostly these are either simulated laboratory tests or studies conducted on miniature test samples removed from actual components. However, such data are very limited. At present there is no established non-destructive technique which could give an idea about the toughness of a material. In addition, often due to the limitation of the size and geometry of the component, it becomes difficult to conduct valid fracture mechanics tests on service exposed material. Keeping in view the importance of cylindrical pressure vessels and piping there is need to explore the possibility of using arc bend type specimens [28] for testing and derive expressions for SIFs [29] for various crack geometries so that more reliable fracture mechanics based integrity assessment can be carried out. Concurrently, more efforts are required for non-destructive detection, sizing and classification of defects. Recent work has shown that the measurement of certain magnetic characteristics of service exposed material can provide information on structural degradation of components made of steel [30]. Certainly there are many unexplored possibilities for non-destructive testing. Clearly these are the areas where more attention is required to fully exploit the capabilities of critical structures and components

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