# PRACTICAL METHODS FOR ASSESSING DEFECTS IN COMPONENTS

**C. H. A. Townley**

*Central Electricity Generating Board, Berkeley Nuclear Laboratories, Berkeley, Glos., England*

ABSTRACT

The paper traces the developments which have taken place within the CEGB, to provide a rational aproach to the assessment of crack like defects in power station plant. The aim has been to provide methods which are simple to use, can be applied to components of complext geometry and ensure the desired degree of prediction against plant failure.

KEYWORDS

Defect assessment; power plant components; ductile fracture; plant integrity; fracture mechanics.

## INTRODUCTION

Ultrasonic inspection, particularly when applied to old plant which has only been subjected to radiography and dye-penetrant or magnetic particle inspection during manufacture, reveals many small defects, and some-times a few larger ones. An important factor in the economics of power production is the reduction of outage time. There is therefore, a strong incentive to assess the significance of such defects as rapidly as possible, consistent with reaching sound decisions on all matters affecting safety.

Many of the small defects which are revealed by ultrasonic examinations are of no consequence whatsoever in terms of plant integrity. Nevertheless, it is important to demonstrate that this is so before plant is returned to service. Equally, it is important to identify as rapidly as possible those defects which require remedial action, such as removal by grinding or repair by welding. It is clear that a full numerical analysis of every defect discovered by NDT could not be contemplated. The aim has, therefore, been to provide methods of assessment which have general applicability, which can be used quickly in an obviously conservative mode to clear innocuous defects, and which, at the same time, can be used more rigourously when circumstances require a detailed safety analysis.

Real power plant components differ significantly from the idealised test specimens which are used in the laboratory to obtain materials data. They are generally of complex shape, containing stress concentrations and stress gradients. Materials properties may vary from place to place in the component, particularly in the vicinity of welds. The loadings applied in service often cannot be defined precisely. The fracture analysis of components cannot, therefore, be carried out with the same precision that can be applied to a laboratory test specimen. However, this does not mean that the methods developed for the analysis of power plant structures are founded on empiricism. They take as their starting point the scientific laws governing fracture phenomena and adapt them to meet the needs of component assessment.

## THE TWO CRITERIA APPROACH TO FAILURE INITIATION

The two criteria method, proposed by Dowling and Townley (1975), represented the first stage within the CEGB towards providing a method of assessing the safety of structures containing defects, making allowance for ductile behaviour. It had long been recognised that linear elastic fracture mechanics was inappropriate for many power plant components, made of relatively thin material, with high fracture toughness and operating at temperatures well above the ductile/brittle transition.

J contour integrals and crack opening displacement provide means of describing the behaviour of simple shapes in the post yield regime. At that time there was no satisfactory method of calculating the values of J or COD in complex three-dimensional geometries with stress concentration and stress gradient regions, and this is still the case today. Dowling and Townley therefore turned their attention to evaluating the load which the structure could sustain without failure. Margins of safety could then be established in relation to the loads actually applied to the structure in service.

An analysis of the available experimental data showed that there were two extremes of behaviour. These were not necessarily associated with brittleness or ductility of the material in the usually accepted sense. They were more related to the overall behaviour of the structure. At one extreme, failure occurred when the crack tip stress intensity factor reached the critical value, $K_{1c}$. Failure loads could be determined by linear elastic fracture mechanics, and were sufficiently low that the bulk of the structure behaved elastically. At the other extreme, significant plasticity had to be induced in the component before a sufficiently large crack opening displacement was achieved to cause failure. In the limit, the load carrying capacity could be determined from plastic collapse considerations, and failure was effectively governed by net section events.

Between these two extremes of behaviour there was a transition region which could be adequately described by an adaptation of the Heald, Spink and Worthington (1972) equation in terms of loads rather than stresses.

$$\frac{L_f}{L_u} = \frac{2}{\pi} \cos^{-1} \left[\exp - (\pi^2 L_k{}^2 / 8 L_u{}^2)\right] \qquad (1)$$

where $L_f$ is the failure load of the structure
$L_k$ is the failure load calculated by linear elastic fracture mechanics
$L_u$ is the collapse load of the structure determined from the limit analysis considerations.



The simplicity of the approach is self evident. The important aspect is that the two limiting failure criteria – LEFM and plastic collapse – are sufficiently well understood that scaling and application to complex structures can be achieved. Equation (1) provides an interpolation between these two extremes which is known to be accurate for test specimen geometries and which is a reasonable and convenient description of the experimental data for complex geometries.

## CEGB R6 ASSESSMENT PROCEDURE

The principles put forward by Dowling and Townley provided the basis for what has come to be known as the R6 procedure, which is now widely adopted for the assessment of components containing defects. The formalism of this assessment method was originally set out in the report by Harrison, Loosemore and Milne (1976). The guidelines provided for the R6 procedure have been updated from time to time. The most recently published version of the procedure is given in the report by Harrison and co-workers (1980).

The basis of the R6 procedure is the failure assessment diagram, reproduced in Fig. 1. The curve is derived from equation 1, but is plotted in terms of variables $K_r$ and $S_r$, rather than $L_f/L_u$ and $L_k/L_u$. This provides a diagram which is simpler to use in practice.

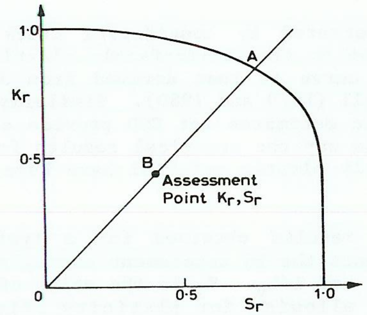


Fig. 1. The Failure Assessment Diagram

To carry out an assessment of a defective component, two calculations are required, which make use of linear elastic fracture mechanics and limit analysis. The linear elastic stress intensity factor K is calculated for the service loads on the component. Knowing $K_{1c}$, the fracture toughness of the material, the value of $K_r = K_1/K_{1c}$ can thus be established.

$S_r$ is defined as the most onerous load encountered in service divided by the load to cause plastic collapse. It is often sufficient to perform a classical lower bound limit analysis, using a rigid plastic material model, in which the yield stress of the model material is taken equal to the average of the yield and ultimate tensile strength of the real material.

The point $K_r$, $S_r$ is plotted on the diagram. If the point lies within the curve, initiation of fracture will not occur. The margin of safety with respect to load is the ratio oA/oB in Fig. 1.

The calculations of $K_r$ and $S_r$ can be as approximate or precise as the situation demands. There are many occasions when an immediate check of integrity is needed, so that the plant can be put back into production without delay. It is often possible to make simple but pessimistic assumptions about material properties and service loads, about crack sizes and shapes, about stress intensity factors and limit loads, and show that large margins exist against failure.

In other circumstances, where it is important to estimate the true margins, for example where risk of failure has significant economic and safety implications, more precise estimates may be needed. Thus, 3-dimensional finite element calculations can be undertaken to determine $K_r$, and special limit analysis solutions or model tests employed to estimate $S_r$. In addition the more precise investigations may require extensive material testing to determine the fracture toughness and tensile properties of the material, and a full exploration of the loads applied to the component in service, possibly including plant measurements.

## CORRELATION OF THE R6 CURVE WITH COD AND J INTEGRAL ESTIMATIONS; MODIFICATION OF THE R6 CURVE FOR STRONGLY STRAIN HARDENING MATERIALS

It is important to appreciate that the principles underlying the R6 procedure are consistent with a J integral approach, which in turn is consistent with an assessment based on COD. All three represent different ways of describing the same phenomena.

This is best illustrated by considering crack initiation in a series of components made from an elastic-perfectly plastic material. The equivalence of the R6 failure curve to that derived from J contour integrals has been demonstrated by Chell (1979 and 1980). Similarly, Ainsworth (1981) has shown that elastic-plastic estimates for COD provide a failure curve equivalent to that of R6. In this way the numerical results for a wide range of geometries for elastic-perfectly plastic material have been shown to be consistent with the R6 approach.

Fig. 2 shows the results obtained for a typical structure containing a defect. It represents the R6 assessment curve, replotted in terms of the new variables $K_1/K_{1el}$ and $L/L_y$. $K_1$ is the value of the stress intensity factor at the crack tip, allowing for platicity effects. $K_{1el}$ is the value of stress intensity factor which would be predicted from linear elastic fracture mechanics calculations. L is the load applied to the structure and $L_y$ is the collapse load.

The ordinate also represents $(J_1/J_{1el})^{1/2}$ and $(\delta/\delta_{el})^{1/2}$, since these are equivalent to $K_1/K_{1el}$. $J_1$ and $\delta$ are defined as the values of the J contour integral and of the COD respectively, derived from elastic-plastic calculations. $J_{1el}$ and $\delta_{el}$ are the values of the J contour integral and the COD which would be predicted from linear elastic fracture mechanics calculations.

The two extremes of behaviour are immediately obvious from the figure. The horizontal line at the unit value of $K_1/K_{1el}$, $(J_1/J_{1el})^{1/2}$ and $(\delta/\delta_{el})^{1/2}$ represents the extreme of behaviour, where load carrying capacity is governed by crack tip events and is determined from LEFM calculations. The vertical asymptote at the unit value of $L/L_y$ represents the other extreme of behaviour. Here, the failure is governed by net section events, and the failure load is determined from collapse considerations.

Recently the assumption of elastic-perfectly plastic behaviour, implicit in the R6 analysis, and explicit in many J integral and COD computations, has been called into question. The point at issue is whether this assumption, in



conjunction with the use of a flow stress to represent the tensile properties of the material, provides an adequate description of structures made from strongly strain hardening materials, and which fail at loads approaching collapse load. It is particularly relevant to the assessment of components made from austenitic steels.

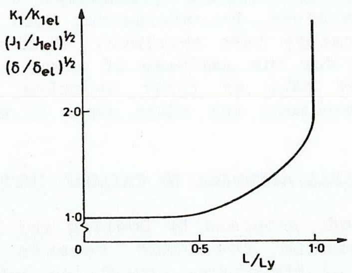


Fig. 2. Schematic Representation of Elastic Plastic Fracture Behaviour

Attention was first drawn to the problem by Bloom (1980) and Milne, (1983) who suggested ways of modifying the R6 diagram. Further investigations have been carried out by Akhurst and Milne (1983), Bradford et al (1983) and by Ainsworth (1983).

Ainsworth used a J estimation procedure, in conjunction with reference stress methods, to derive a geometry independent curve. Akhurst and Milne (1983) have demonstrated the validity of this approach for an austenitic steel by testing specimens of various geometries with a range of crack depths. It is intended to use a curve such as that shown in Fig. 3 in place of the original R6 assessment curve when investigating components made from materials such as stainless steel.

It is clear that similar considerations apply when making fracture assessments using J contour integrals or COD, because of the equivalence between the three methods which was noted above.

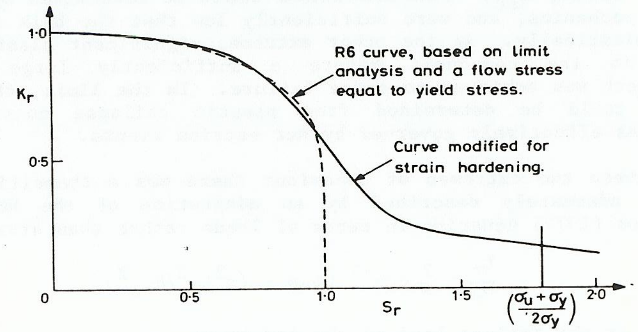


Fig. 3. Modified Failure Assessment Curve for Strain Hardening

Where direct calculation of the J contour integral is undertaken on simple components, elastic-perfectly plastic materials behaviour is often assumed to reduce computer costs. It is clear that an elastic-perfectly plastic analysis using the real yield stress of the material would lead to highly pessimistic conclusions in ductile situations. The use of a flow stress, derived from yield and ultimate tensile stress, would lead to the same discrepancies as arise from the use of the R6 assessment diagram, and would underestimate the load carrying capacity in ductile situations. A more precise analysis can only be obtained if the full stress-strain curve of the material is used as input data, and this may not be possible with some of the computer programs which are currently available.

## EXTENSION OF THE R6 METHOD TO INCLUDE STABLE TEARING

Most ferritic steels used in the construction of power plant can fail at the crack tip either by cleavage or by microvoid coalescence. The former occurs at low temperatures, the latter is associated with the upper shelf, above the ductile/brittle transition temperature . In the cleavage regime, components loaded by pressure or by external forces can, for all practical purposes, be assumed to fail when the critical conditions for crack initiation are attained at the crack tip. It should be noted that this does not automatically mean that a component will fail at the load predicted by LEFM: in thin components, considerable plasticity may occur in the body of the structure before critical conditions of cleavage are attained at the crack tip.

In the microvoid coalescence regime, the material can tear in a stable manner after the material at the crack tip has begun to disintegrate. This stable tearing is accompanied by an increase in load carrying capacity, as represented in the familiar J-resistance curves. This increase in load carrying capacity provides additional margins of safety, beyond those calculated from the crack initiation criteria described above.

Means of establishing the tearing resistance of components by superimposing curves of structural behaviour on the J-resistance curve of the material have been described by Hutchinson and Paris (1979). The procedure requires an elastic-plastic evaluation of the J integral at a series of crack lengths. As such it is difficult to apply to components of complex shape and is essentially limited to simple structures or simple idealisations of complex components.

Chell and Milne (1979) have shown that stable tearing in complex shapes can be dealt with by an extension to the R6 procedure, and this is now incorporated in the latest version of the documentation. The principles of the method are illustrated in Fig. 4.

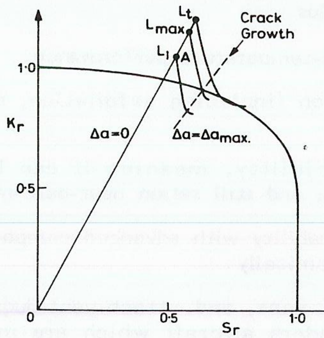


Fig. 4. Stable Tearing Included in the R6 Diagram



For any given load and initial crack size it is possible to postulate an amount of crack extension. The assessment point is then obtained by evaluating $K_r$ and $S_r$ as before, but with the stress intensity factor and limit load calculated for the extended crack, and with the fracture toughness replaced by the toughness derived from the point on the J resistance curve at the postulated crack extension. In this way a locus of assessment points as a function of crack extension may be constructed as shown in Fig. 4. For example, a load $L_1$ which initially leads to the point A outside the assessment curve would be unacceptable on initiation arguments; but allowing stable crack growth brings the assessment point within the curve and the load can, therefore, be tolerated. If, on the other hand, the crack growth locus had not intersected the curve, but had always been outside it, the load would have been unacceptable. For a given crack size, the maximum tolerable load is that which leads to a crack growth locus which is just tangential to the curve as indicated for the load $L_t$ in Fig. 5. In practice, crack extensions outside the validity limits of the J-resistance data are not permitted and this may limit the maximum load carrying capacity below $L_t$ to the load for which the locus intersects the curve at the maximum crack extension allowed (e.g. load $L_{max}$ in Fig. 5).

## CONCLUDING REMARKS

It is a truism that research is never complete, and every investigation reveals further aspects that need to be explored. It is also a truism that no two research workers have precisely the same view about the nature of the phenomena which are observed, and their theoretical explanation. Even in such an apparently well defined area as materials testing, individual interpretation of test results can lead to significant differences in the values ascribed to materials properties.

Because of the divergent views expressed by scientists in the fracture field, the engineer faced with the need to make decisions today, finds considerable difficulty in knowing how to proceed. The methods described in this paper are intended to resolve that difficulty. There must necessarily be an element of pragmatism. At the same time, the procedures must not be in conflict with current theoretical understanding of the underlying phenomena.

The methods described in the paper are not the only ones which can be developed from existing scientific knowledge. They are particularly well suited to the assessments which have to be carried out within CEGB, and are being used extensively in a wide range of applications on nuclear and fossil fuelled plant. That does not mean that other methods, founded on the same scientific facts, would not be better suited in other circumstances.

No assessment procedure can ever be regarded as fully developed. There will always be need to incorporate new ideas as further research is completed and new facts come to light. Some further simplification may also be possible, such as that proposed by Crossley and Townley (1984) which provides a rapid, although pessimistic, method of establishing critical defect sizes in pressure vessels design and manufactured to certain Standards.

## ACKNOWLEDGEMENTS

This paper is published by permission of the Central Electricity Generating Board.

The author wishes to acknowledge the assistance he has received from his colleagues, Dr. R.A. Ainsworth, Mr. M. Crossley, Dr. I. Milne and Dr. B.K. Neale, in the preparation of the paper.

REFERENCES

Ainsworth, R.A. (1981). Some aspects of fracture assessment diagrams, plastic zone size corrections and contour integrals in post-yield fracture mechanics, CEGB report RD/B/5043N81.

Ainsworth, R.A. (1983). The assessment of defects in structures of strain hardening material, Engng Fract. Mech. 19, 633-642.

Akhurst, K.N. and Milne, I. (1983). Failure assessment diagrams and estimate: validation for an austenitic steel. Int. Conf on Application of Fracture Mechanics to Materials and Structures, Freiburg, W. Germany.

Bloom, J.M. (1980). Prediction of ductile tearing using a proposed strain hardening failure assessment diagram, Int. J. Fracture, 16, R73.

Bradford, R., Gates, R.S., Green, G. and Williams, D.C., (1983). Integrity assessment diagrams for mild steel CT specimens: some theoretical and experimental results, CEGB report SSD/SW/R417.

Chell, G.G. (1980). Elastic-Plastic Fracture Mechanics. In G.G. Chell (Ed.), Developments in Fracture Mechanics, Applied Science, London.

Chell, G.G. (1979). A Procedure for incorporating thermal and residual stresses into the concept of a failure assessment diagram, in ASTM STP 668, 581.

Chell, G.G. and Milne, I. (1979). A simple practical method for determining the ductile instability of cracked structures, CEGB report RD/L/N87/79.

Crossley, M.R. and Townley, C.H.A. (1984). Minimum critical crack depths in pressure vessels - guidelines for non-destructive testing. To be published in Intl. Jnl of Pressure Vessels and Piping.

Dowling, A.R. and Townley, C.H.A. (1975). The effects of defects on structural failure: a two-criteria approach, Int. J. Pres. Ves. Piping 3, 77.

Harrison, R.P., Loosemore, K. and Milne, I. (1976). Assessment of the Integrity of Structures Containing Defects, CEGB Report R/H/R6.

Harrison, R.P., Loosemore, K., Milne, I. and Dowling, A.R. (1980). Assessment of the Integrity of Structures Containing Defects, CEGB Report R/H/R6-Rev 2.

Heald, P.T., Spink, G.M., and Worthington, P.J. (1972). Post yield fracture mechanics. Mater. Sci. Eng., 10, 129.

Hutchinson, J.W. and Paris, P.C., (1979). The theory of stability analysis of J-controlled growth, ASTM STP 668, 37.

Milne, I. (1983). Failure assessment diagrams and J estimates: a comparison for ferritic and austenitic steels. Int. J. Pres. Ves. Piping. 13, 107.