Development of a Leak–Before–Break Procedure for Pressurised Components

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ABSTRACT

For pressurised components there is an increasing interest in the use of leak-before-break arguments to show that defects will behave in a "failsafe" manner by growing in such a way as to cause a detectable leak before a disruptive failure of the pressure boundary can occur.

The CEGB operates a wide variety of plant and has recognised the need for a flexible leak-before-break procedure which can be applied in a variety of different situations rather than the more rigid code approach adopted for LWR piping for example in NUREG-1061.

This paper describes the development of such a procedure and discusses some of the key aspects of the leak-before-break procedure.

1. INTRODUCTION

The CEGB operates a variety of plant under a wide range of operating conditions and involving a variety of different materials. In order to maximise the potential benefits of leak-before-break the CEGB has recognised the need for a flexible yet consistent approach to leak-before-break that can be applied to a variety of pressurised components. An important aspect of the approach is the need to be able to assess the behaviour of part-through defects that might be revealed by in-service inspection. This means that existing approaches such as that of NUREG-1061 (1) based on postulating through-wall, leaking cracks are not suitable.

The approach chosen was to develop a leak-before-break methodology to incorporate into the existing CEGB defect assessment procedure R6 (2). The R6 procedures developed by the CEGB have gained wide acceptance as a reliable means of assessing the integrity of structures containing defects and already contain much of the methodology needed to make leak-before-break cases. Methods for assessing sub-critical crack growth, ligament failure and limiting crack lengths for example are already included in R6. Methods have also been developed in areas such as predicting crack-opening areas and calculating leakage rates from through-wall defects.

This paper outlines the main elements of the leak-before-break procedure and discusses in more detail some aspects of the fracture mechanics, crack-opening area and leak rate calculations required by the procedure. New or improved methods are highlighted and areas where further work is planned or underway described. Finally brief descriptions of some applications illustrating the use of the procedure on operating plant are given.

2. THE LEAK-BEFORE-BREAK PROCEDURE

2.1 Outline of Procedure

The main aims of a leak-before-break procedure should be

(i) to demonstrate that a defect will penetrate the pressure boundary before it can lead to a disruptive failure.

(ii) to demonstrate that the resulting through-wall defect will leak at a sufficient rate to ensure its detection before it can grow to a critical length at which disruptive failure could occur.

Several steps are involved in establishing these objectives and making a satisfactory leak-before-break case. First the defect must be characterised and the mechanisms by which it can grow identified. The next step is to calculate the length of the through-wall defect formed as the initial defect penetrates the pressure boundary and compare this with the critical length. It is then necessary to estimate the crack-opening area, the rate at which fluid will leak from the crack, and finally whether or not the leak will be detected before the crack can grow to a critical length. These steps form the basis of the proposed leak-before-break procedure for R6 and are set out in the form of a flow-chart in Figure 1. The major aspects of the procedure are now discussed in more detail.

2.2 Fracture Mechanics Calculations

In order to make a leak-before-break case it is necessary to show that a defect will grow in such a way as to penetrate the pressure boundary before it reaches the critical length at which sudden disruptive failure would occur. The critical length and the defect size at which breakthrough or ligament failure occurs can both be determined using R6. However, since leak-before-break procedures are concerned with failure prediction and the R6 procedures were written to ensure failure avoidance the pessimistic use of upper-bound stress-intensity factor solutions together with lower-bound material properties and collapse solutions, as recommended in R6, is not appropriate for a leak-before-break case. Although these bounding values provide conservative estimates of critical crack length they minimise the defect length at breakthrough and maximise the crack-opening width, both of which are non-conservative when making a leak-before-break case. Best-estimate values are therefore used and calculations performed to assess the sensitivity of the results to likely variations in material properties and other input data.

Since the defect length at breakthrough determines whether the initial failure results in a leak or a break it is important to correctly predict the crack shape development as it grows to penetration. For the time being a conservative approach has been adopted; this involves allowing the defect to grow until it reaches a size at which ligament failure is predicted to occur and then re-characterising the defect as a uniform, through-wall defect in accordance with the guidance in R6. Methods for evaluating crack growth due to fatigue or environmentally-assisted cracking, estimating the size at which ligament failure occurs and re-characterisation are all included in R6.

For defects growing by fatigue work within the CEGB has examined the shape development of surface flaws in plates and cylinders. A simple method for predicting the two-dimensional growth of semi-elliptical, surface flaws in plates has been developed (3) from the stress-intensity factor calculations of Newman and Raju (4) and extended to model the shape development of surface flaws in cylindrical geometries. The model was compared with experimental results from cracks grown under tension and bending and reasonable agreement found. An important observation was that the aspect ratio at breakthrough (defect depth divided by half-length) tended towards a constant value around 0.7 for growth predominantly under tension but around 0.1 when bending loads were dominant; successful leak-before-break cases would therefore be less likely under the latter circumstance. Further work is planned to study defect behaviour close to breakthrough and the CEGB is funding wide-plate tests to provide data on the effects of tearing-fatigue interaction prior to breakthrough, crack shape development and leakage flow rates following breakthrough.

2.3 Crack-opening Area Calculations

The method for calculating the crack-opening area depends on the stress distribution normal to the plane of the crack. If membrane stresses dominate the simple LEFM-based expressions of Wuthrich (5) provide conservative estimates of crack-opening area of the form

$$A = \alpha(\lambda) \frac{2\pi\sigma c^2}{E'} (1 + \sigma^2/\beta\sigma_F^2)$$

for a through-wall defect of length 2c subjected to a uniform tensile stress σ. The factor $\alpha(\lambda)$ represents a bulging correction in terms of the shell parameter λ and the term in brackets a first-order plasticity correction. The expressions were derived using shallow-shell theory and are strictly only valid for crack lengths less than the least radius of curvature of the shell and radius to thickness ratios of $R/t > 10$. The method of derivation is more general however and alternative expressions for crack-opening area can be derived if appropriate crack-tip stress-intensity factors are known.

If a significant through-wall bending stress is present crack face rotation can occur causing either the inner or outer crack surface to close up reducing the effective crack-opening area. To ensure that predicted crack-opening areas are conservative it is necessary to allow for this effect. It can be calculated by finite-element methods but as these can be costly an approximate analytical method has been developed within the CEGB. The method is based on the elastic crack-opening displacements and rotations derived by Miller (6). The crack opening area in the mid-plane of the wall is given by

$$A = (\pi c^2/E)\ (C_{mm}\sigma_m + C_{mb}\sigma_b)$$

and in the inner and outer crack surfaces as $A \pm A'$ where A' measures the effect of crack face rotation and is given by

$$A' = (3\pi c^2/E)\ (C_{bm}\sigma_m + C_{bb}\sigma_b)$$

The C_{ij} are dimensionless elastic compliance factors defined in (6) for axial and circumferential cracks in cylinders and meridional cracks in spheres, so for these geometries the significance of any crack closure effects can be readily estimated.

2.4 Leak Rate Calculations

The need to calculate leakage flow rates through cracks has led to the development of several models for both two-phase and single-phase fluid flow. For two-phase fluids computer codes such as PICEP (7) and SQUIRT (8) have been developed. The codes are easy to use but the extent of their validation against real cracks is limited, as is their ability to model friction effects on flow.

For single-phase fluids such as dry steam or the CO_2 gas used in the CEGB's gas-cooled reactors the CEGB has developed its own models. Based on the work of Button, Grogan, Chivers and Manning (9) a computer code DAFTCAT has been written to predict leakage flows of gases or liquids through cracks. The code includes a detailed treatment of the effects of friction due to wall roughness and has been extensively validated against experiment. In addition Ewing has derived simple approximate solutions for isothermal and polytropic flow of gases (10) in the form

$$Q = C_D (P\rho)^{\frac{1}{2}} WL$$

where Q is the mass flow, P and ρ are the pressure and density of the fluid and W and L are the mean width and length of the leaking crack. Friction effects due to both wall roughness and the leakage path tortuosity are included through a variable discharge coefficient C_D, a function of the flow regime.

2.5 Leak Detection and Crack Stability following Breakthrough

The final step in any leak-before-break procedure is to show that the leaking crack remains stable for a sufficient time to allow the leak to be detected. The stability of the leaking crack can be assessed in terms of the margins to criticality. If no potential for further crack growth exists then a margin on crack length will suffice but if further time-dependent crack growth can occur then margins on length and time to failure need to be demonstrated. The time required to detect the leak must be judged by comparing the detection sensitivity with the predicted leak rate.

Various methods exist for detecting the leaking fluid and appropriate systems can be engineered for specific applications. The CEGB makes use of global and local leak detection systems in making leak-before-break cases. Part of the safety case for its Magnox reactor pressure vessels for example is based on a leak-before-break case sustained by a global detection system for reactor coolant gas leakage. In another example involving cracking of a steam pipe weld a highly localised system was designed and built to sheathe the weld and channel any leaking steam to a nearby thermocouple permitting steam leaks as small as 0.5 grammes/second to be detected. A technique of current interest to the CEGB is acoustic emission monitoring or acoustic leak detection. Studies are underway to assess the potential of both airborne systems, using conventional microphones, and structure-borne systems, using acoustic emission transducers and solidly-mounted waveguides. These systems offer the potential benefits of localised leak detection using a relatively small number of transducers but further work is needed to reliably discriminate between leakage from cracks and background noise.

3. CONCLUSIONS

A leak-before-break procedure for use within the CEGB defect assessment procedure R6 has been outlined and some of the fracture mechanics, crack-opening area and leak rate calculations described in more detail.

New or improved methods have been highlighted and areas where further work is planned or underway described. An important feature of the procedure is its ability to assess the leak-before-break behaviour of part-through defects.

The complete procedure is intended to be published as an Appendix to the R6 procedures.

4. ACKNOWLEDGEMENT

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5. REFERENCES

(1) US Nuclear Regulatory Commission, NUREG-1061, Report of the US Nuclear Regulatory Commission Piping Review Committee, Volume 3 Evaluation of potential for pipe breaks, November 1984.

(2) I Milne, R A Ainsworth, A R Dowling and A T Stewart, Assessment of the Integrity of Structures Containing Defects, CEGB Report R/H/R6 Revision 3, May 1986, also publised in Int. J. Pres. Ves. and Piping, 32 (1988) pp. 3-104.

(3) D C Connors, The Shape Development of Surface Defects in Plates and Cylinders under Cyclic Loads, CEGB Report TPRD/B/0469/N84, August 1984.

(4) J C Newman and I S Raju, Analyses of Surface Cracks in Finite Plates under Tension and Bending Loads, NASA Technical Paper 1578, 1979.

(5) C Wuthrich, Crack Opening Areas in Pressure Vessels and Pipes, Engrg. Fracture Mech. 18, p. 1049, 1983.

(6) A G Miller, Elastic Crack Opening Displacements and Rotations in Through-cracks in Spheres and Cylinders under Membrane and Bending Loading, Engrg. Fracture Mech. 23, p. 631, 1986.

(7) D M Norris and B Chexal, PICEP: Pipe Crack Evaluation Programme (Revision 1), EPRI Report NP-3696-SR Revision 1, 1987.

(8) D D Paul, J Ahmad, P M Scott, L F Flanigan and G M Wilkowski, Evaluation and Refinement of Leak-rate Estimation Models: Topical Report, NUREG/CR-5128 (Draft Report, March 1988).

(9) B L Button, A F Grogan, T C Chivers and P T Manning, Gas Flow Through Cracks, J. Fluids Engineering, 100, p. 453, December 1978.

(10) D J F Ewing, Simple Methods for Predicting Gas Leakage Flows Through Cracks, CEGB Report RD/L/3387/R88, also published as Paper C376/047 in Proceedings of Int. Conf. on Pipework Engineering and Operation, I. Mech. E, 21-22 February 1989, London.

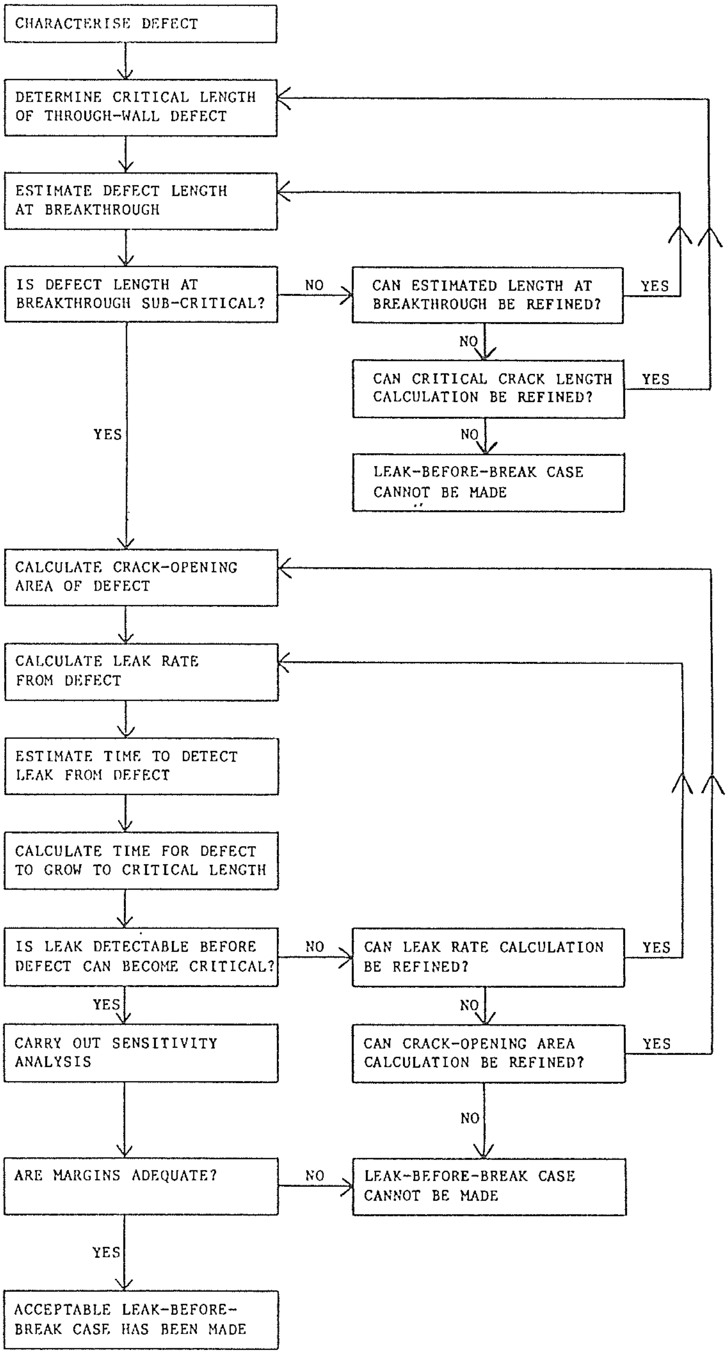

FIGURE 1 : FLOW-CHART FOR LEAK-BEFORE-BREAK PROCEDURE