Probabilistic Integrity Assessment of Reactor Pressure Circuits

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1 INTRODUCTION

Probabilistic structural assessment methods can provide benefits for both the safe and economic performance of nuclear plant. Three areas of potential application may be identified :-

i) as part of an overall plant safety analysis to substantiate a case for new plant or continued operation of old plant,
ii) as a guide to decisions on plant design or modification,
iii) as a guide to economic deployment of resources on maintenance, inspection and repair.

Whilst probabilistic structural assessment methods have been used by the U.K. nuclear industry in each of the above areas, generally structural integrity is handled by deterministic methods employing safety margins. Such approaches, whilst demonstrating the integrity of a specific component, cannot provide quantitative comparisons of risk between many components. Similarly they cannot provide an integrated assessment of the risk from a pressurised system containing many diverse components under a variety of loading conditions. Probabilistic methods provide the capability to compare and sum the risks thus forming an integral part of an overall plant safety assessment.

The main technical problems with probabilistic structural assessment techniques are the need for a knowledge of variability in loads, material properties, defect occurrence etc. and fast, efficient and flexible codes that can handle a variety of problems. The illustration described in this paper, uses the specific example of components in a Magnox reactor top duct but the overall project was mainly concerned with the development of probabilistic methods that could be widely used in the CEGB. The two classes of components considered are straight duct sections and fabricated welded 90° corner units (mitre bends). Both have an internal diameter of 2 m and wall thicknesses of between 28 and 50 mm.

2 METHOD OF ASSESSMENT

The probabilistic assessment of the integrity of each pressure circuit falls into five main activities.

i) Identification of the potential modes of failure for each component and development of appropriate fracture mechanics models.
ii) Quantitative assessment of the immediate consequences of each potential failure in terms of gas forces on internal or external components or the generation of external missiles.

iii) The creation of a computerised database containing details of the relevant welds (geometry, materials, operating history, and NDT history).

iv) Calculation of the failure probabilities for certain specified failure modes and operating conditions using the CEGB Probabilistic Fracture Mechanics computer codes STAR6 or PROF.

v) Calculations of the annual probability that particular consequences might occur. That is to say the probability that a consequence of at least the specified magnitude might occur during the year per circuit.

3 MODES OF FAILURE AND FRACTURE ASSESSMENTS

Failure modes are considered for all axial and circumfrential welds in the pressure envelope (Figure 1). Defects are assumed to occur only in the fabrication welds. These defects are taken to be long part-penetrating, surface breaking defects which are normal to the the component surface and have uniform depth. Should defect depth exceed the critical value for the materials properties and loading conditions failure of the the adjoining ligament will occur by fast fracture or plastic collapse. Similarly, if the resulting full penetration crack exceeds the critical length then failure of the structure will occur. Thus the distribution of defect sizes used in probabilistic assessments should include both defect depth and length.

Fracture assessments of the welds in the straight sections, are relatively straightforward for such defects. The geometry of mitre bends is more complex. It has therefore been necessary to carry out experimental investigations of failure pressures and critical crack lengths using scale models of the bends. These included components up to 2/3 rds full size. The results of this work have been extrapolated to full size units and a series of fracture models for the relevant parts of mitre bends have been proposed (Connors et al 1989).

4 CONSEQUENCES OF A FAILURE (RAREFACTION WAVES AND LARGE MISSILES)

The potential immediate consequences considered in the present work are :-

a) impulsive loadings on core internals caused by the rarefaction wave generated by a sudden rupture of the duct.

b) generation of missiles which may impact on external components.

Additional work has considered external blast waves and the quasi-steady over-pressurisation of core regions relative to the upper and side plenums.

All the above consequences are dependent, although to a different degree, on size and location of the breach in the duct. For the purposes of comparison it is necessary to choose an appropriate parameter(s) to quantify each type of consequence and devise suitable methods for their calculation.

If a break failure of the duct were to occur, depressurisation of the vessel would be initiated by a rarefaction wave which propagates from the point of rupture along the remaining length of intact duct and into the pressure vessel. A convenient parameter for comparing the likely effects of different rarefaction transients under the same geometries is a a non-dimensionalised rate of change of pressure with time quantity which following Baum and Butterfield (1979) will be denoted by $d\bar{p}/dz$. This effectively represents the rate of change of pressure with time in the initial linear portion of the wave and is a direct input to calculations of impulse loadings on internal components. Its value for a given duct geometry and pressure varies with breach opening rate.

Experimental investigations of $d\bar{p}/dz$ have been carried out at BNL for both axial and circumferential ruptures of pressurised pipes. In the case of ductile axial failures the value of $d\bar{p}/dz$ close to the break is typically 0.055 (Baum and

Butterfield 1979, Baum 1985, Private Communication). For circumferential failures Baum has given a simple model enabling $d\bar{p}/dz$ to be related to the rate of increase in the breach area which occurs as the duct sections are assumed to rotate about nearby bellows units. The CEGB mechanisms computer code AMP2D has been used to calculate the resulting motion. Once $d\bar{p}/dz$ local to the breach is known the reduced value of $d\bar{p}/dz$ at the vessel may be readily calculated by assuming a plane rarefaction wave propagates along the duct to the vessel.

The values of $d\bar{p}/dz$ at the pressure vessel for axial failures on the straight sections lie in the range 0.008 - 0.055. The results for mitre bend failures are in the range 0.008 - 0.036.

In order to assess the potential damage to other parts of the plant from missiles, data on geometry, mass and velocities are required. Guidelines for such calculations based on experimental and analytical work have been described by Baum (1988). These guidelines have been used to calculate upper limits for the energies of the different types of duct missile that might occur.

The largest calculated energy for a missile arising from the top duct is 11.7 MJ and corresponds to failure of an axial weld on a relatively long straight section of duct. The largest predicted missile energy arising from the failure of a top duct mitre bend is 6.6 MJ.

The results for the various consequences can be used to identify which types of failures give rise to the most severe consequences. These welds can then receive a higher priority in the failure probability calculations if resources are limited.

5 CALCULATION OF INDIVIDUAL WELD FAILURE PROBABILITIES

Many of the early probabilistic analyses developed by various workers have been based on Linear Elastic Fracture Mechanics (LEFM) or just plastic collapse. The present method (Gates et al 1989) uses an elastic plastic approach based on the CEGB failure avoidance diagram (R6) of Milne et al (1986). Two computer programs have been developed to carry out the required calculations. The code STAR6 (STAtistical R6) uses a combination of analytical and numerical integration over the probability distributions to evaluate failure probabilities. The second code PROF (PRobability Of Failure) employs Monte Carlo simulation with importance (or biased) sampling to carry out the integrations. Each program considers defect depth, fracture toughness and flow stress as the stochastic variables. STAR6 is limited to just these three variables but has the advantage that calculations are easily set up and relatively fast to run. The Monte Carlo code PROF can consider more variables, if necessary, but the very small calculated failure probabilities in this instance require that suitable importance weighting functions must first be determined if reliable results are to be obtained without excessive computing costs. Thus most of the results have been obtained with STAR6 and some cases repeated with PROF to verify the calculations.

The selection of defect size distribution to use in a probabilistic assessment is of major importance because of the great sensitivity of the calculated failure probabilities to the distributions form and magnitude. The distribution that has been used is a refinement of an earlier analysis by Stewart and Formby (1984). It is assumed that the variability of extreme defect depth and its aspect ratio in a given volume of weld metal (1 litre) can be represented by Gumbel Type II and Weibull distributions respectively. The resulting bivariate probability distribution function is given by

$$f(a,L) = \left(\frac{\beta A^B B}{\theta}\right) a^{-(B+1)} \left(\frac{z - \gamma}{\theta}\right)^{\beta-1} \exp- \left[\left(\frac{a}{A}\right)^{-B} + \left(\frac{z - \gamma}{\theta}\right)^{-\beta}\right] \qquad (1)$$

where a is defect depth, L is defect length, z is aspect ratio (= L/2a) and A, B, β, γ and θ are the relevant distribution constants. The programs take account of fatigue crack growth in service.

Typical distributions used to reflect the variability in the properties of the ferritic materials are defined as follows.

Yield Stress (Weibull Distribution) median = 208 MPa, 2.5 percentile = 170 MPa.
U.T.S. (Weibull Distribution) median = 421 MPa, 2.5 percentile = 393 MPa.
Fracture Toughness (Log-Normal Distribution) median = 180 MPA $m^{\frac{1}{2}}$, 2.5 percentile = 132 MPa $m^{\frac{1}{2}}$

Additional input to the programs includes structure geometry, loading stresses and critical crack lengths calculated using R6.

The stresses in the corner regions of the mitre bends can vary rapidly with both azimuthal and longitudinal position as shown by experiment and by finite element stress analysis (Connors et al 1989). In the present calculations, the peak stresses calculated for a given weld have been assumed for its entire length. However, the region where the stresses are comparable with the peak stress may be quite short and thus this approach is unduly pessimistic.

Three failure probabilities are calculated for each weld. The first is for 30 years of normal operation (P_{30}), the second for 35 years (P_{35}) and the third is also for 35 years but includes a fault overpressure transient (P^F_{35}). It is assumed that the probability of such a transient is once in 300 reactor years. The annual failure probability for the 5 year period of 30 - 35 years of operation is then taken to be

$$P_{annual} = \frac{P_{35} - P_{30}}{5} + \frac{P^F_{35} - P_{35}}{300} \qquad (2)$$

6 RESULTS AND DISCUSSION

Annual failure probabilities have been calculated for the welds in straight section and mitre bends in the top ductwork.

It is important that the results are not misused or misinterpreted and a number of observations will be made after the summary of results.

The annual failure probabilities for the axial welds on the straight duct sections lie in the range 1.3×10^{-10} to 7.3×10^{-9}. The results for circumferential defects are typically two orders of magnitude lower as might be expected with the lower stresses and critical crack lengths. The annual failure probabilities for an axial weld in the mitre bend leg, the circumferential weld on the bend corner and the axial weld on the inside of the bend are 5.7×10^{-10}, 8.6×10^{-7} and 2.0×10^{-7} respectively. However, it will be recalled that these are likely to be highly pessimistic as peak stress values have been used.

Combining the the failure probabilities with the consequence calculations, risk consequence curves can be plotted as shown generally in Figure 2. The vertical axis gives the calculated probability of exceeding a particular value of the consequence parameter shown on the horizontal axis. Figures 3 and 4 give the results for dp/dz and missile energy respectively. Each plot shows the results for straight duct sections and mitre bends both individually and combined. It can be seen that in each case the the largest consequences are associated with straight duct failures but the mitre bends dominate the total cumulative results for smaller values.

It should be emphasised that the failure probabilities for each component apply to the failure modes under the loading conditions considered. If an important potential failure mode has not been identified then of course its probability of occurring will not have been included in the calculations.

A second important consideration is the meaning of the absolute values of the failure probabilities. The numbers are based on a set of assumptions about failure models and the possible range of values of dependent parameters. Wherever possible 'best-estimate' data and models are used. Where necessary suitable pessimisms have been included. Thus it is reasonable to assume that the quoted results are likely to be upper bounds to the real failure probabilities of the components.

When the failure probabilities are used in a comparative rather than an absolute sense, greater confidence may be placed on identifying the higher risk locations. Thus the probabilistic methods are particularly valuable in making decisions on inspection and maintenance programmes by providing a relative risk. When the probabilities are associated with a particular consequence they provide an even more powerful means of making decisions on maintenance strategies.

7 CONCLUSIONS

A methodology has been described for the probabilistic assessment of the integrity of Magnox pressure circuits.

It has been illustrated by the example of straight sections and mitre bends in the top ductwork.

The work described shows clearly the potential of the methods in aiding safety cases, developing inspection and maintenance strategies and directing future research and development studies.

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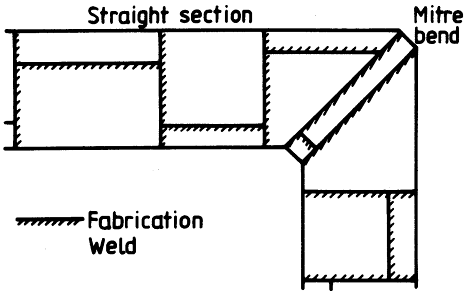

Fig. 1. Schematic Representation of Straight Section and Mitre Bend Ductwork.

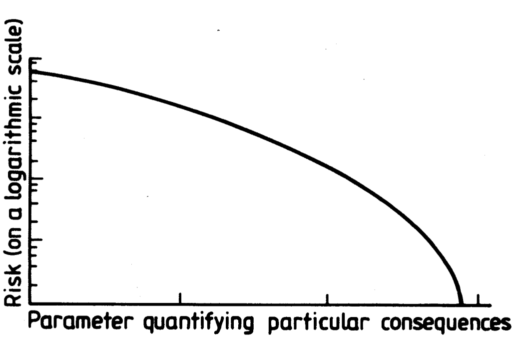

Fig. 2. Schematic Representation of Risk – Consequence Curve.

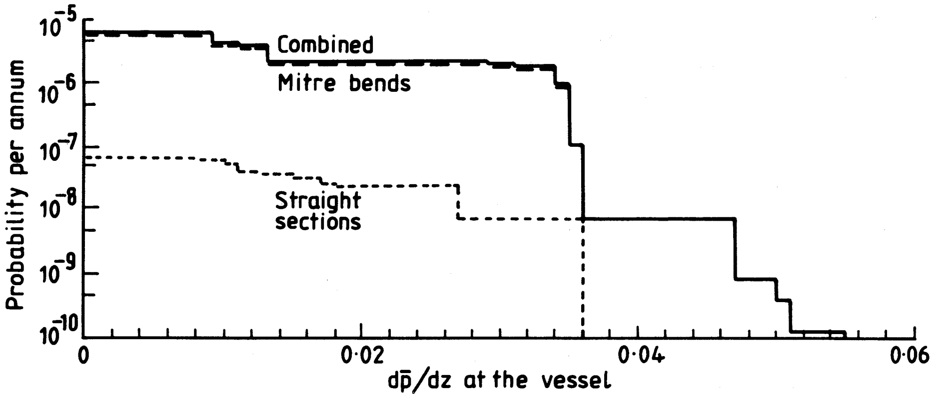

Fig.3. Plot Showing Annual Probability that a $d\bar{p}/dz$ of AT LEAST the Given Value Might Occur.

(For a Single Reactor Circuit. Top Duct–Straight Sections Bends and Combined)

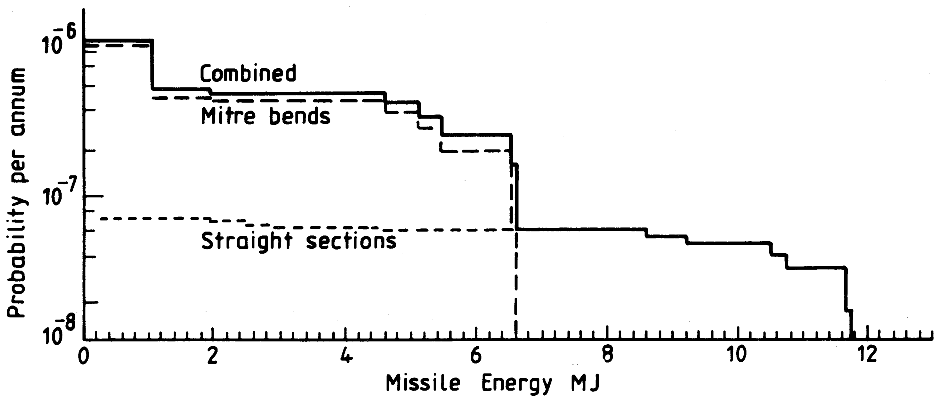

Fig. 4. Plot Showing Annual Probability that a Missile Energy of AT LEAST the Given Value Might Occur.

(For a Single Reactor Circuit. Top Duct–Straight Sections Bends and Combined)