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A comparison of the simplified probabilistic method in R6 with the partial safety factor approach

R. Wilson

Engineering & Technical Services, Magnox Electric Ltd., Oldbury Training Centre, Thornbury, South Gloucestershire, BS35 1RQ, UK

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Abstract

Probabilistic assessments are a useful aid to decision making in areas such as safety analysis, design studies and the deployment of resources on maintenance, inspection and repair. In principle, a full probabilistic assessment requires a complete knowledge of the relevant failure models and the distributions for each of the input quantities. However, in practice, these requirements cannot normally be met in full and it is necessary to employ various simplifying assumptions and approximations in order to make the analysis tractable. The partial factor method and the simplified approach in R6 provide two relatively simple and independent methods of assessing failure probabilities using R6.

The two methods have been applied to a set of test cases and the results compared. In the case of the partial safety factor method target reliabilities in the range 10^{-3}–10^{-5} were considered. Sets of partial safety factors for load, defect size, fracture toughness and yield stress were taken from BS 7910 and used for assessments covering different regions on the R6 failure assessment diagram. A calculation of the assessed failure probability was also carried out for each of these sets of conditions using a simplified probabilistic approach developed for the R6 procedure.

The assessed failure probabilities were compared with the corresponding target reliability assumed for the partial safety factor calculation. It was found that the partial safety factor assessments were generally conservative compared to the simplified approach. However, in many instances the assessed probabilities were several orders of magnitude smaller than the target reliabilities suggesting that the recommended values of partial safety factors in BS7910 were excessively conservative for some of these conditions.

Keywords: Probabilistic fracture mechanics; Partial safety factors; R6 assessment procedure

1. Introduction

Assessments of the structural integrity of Magnox reactor steel pressure vessels and pressure circuit components are currently undertaken using a deterministic approach. However, probabilistic assessments are a useful aid to decision making in areas such as safety analysis, design studies and developing maintenance, inspection and repair strategies [1–3]. In principle, a probabilistic assessment requires a complete knowledge of the relevant failure models and the distributions for each of the input quantities. However, in practice, these

E-mail address: ray.wilson@britishnucleargroup.com

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requirements cannot normally be met in full and it is necessary to employ various simplifying assumptions and approximation in order to make the analysis tractable.

Where the probabilistic analysis considers the full statistical distributions of the main input quantities this is commonly referred to as a Level 3 approach [4,5]. The assessments can be very complex and extremely time consuming to carry out and simplified Level 3 probabilistic approaches have therefore been developed [6,7] based on the well established R6 failure avoidance procedure for the assessment of the integrity of structures containing welding defects [8]. The method has the advantages that it is easy to apply and in most cases it provides an accurate estimate of the failure probability for very limited computational effort. It is therefore very useful for tasks where a large number of calculations are required and it has been used in the present work for this reason. A brief outline of the approach is given in Section 2.

Level 2 methods provide an alternative probabilistic assessment using only the mean and standard deviation of each input quantity. Examples are the first and second order reliability methods which are often referred to by the initials FORM and SORM, respectively [9,10]. Level 2 methods tend to be much easier to evaluate than Level 3 methods.

Level 1 calculations take the approximation for the distribution of input quantities a further stage and only employ a single value for each input quantity rather than use any form of distribution. Such calculations are often referred to as deterministic assessments. In some cases such as the calculations carried out for the assessment of Magnox reactor steel pressure vessels and pressure circuit components input quantities are particular quantiles of the distribution. Values such as the 5 or 95 percentile values are selected for the resistive and driving forces, respectively, to be conservative. The safety factor on a quantity such as load has to be applied to achieve a suitable reserve margin.

For design purposes, a Level 1 approach involves the application of a set of pre-defined partial safety factors on the different input quantities. Each set of partial safety factors is derived for a specified target reliability (i.e. maximum failure probability) and if the resulting overall safety factor exceeds unity then it may be claimed that the predicted notional failure probability will be less than this target maximum failure probability. However, the amount by which the assessed failure probability lies below the required maximum failure probability is not calculated as part of the assessment and so the method may produce unduly pessimistic results. Partial safety factors have been published in BS 7910 for the assessment of the acceptability of defects in fusion welded structures [11].

Thus the partial factor method and the simplified approach in R6 provide two relatively simple and independent methods of assessing failure probabilities using R6. However, neither method has been used extensively and consequently the limitations of the methods have not yet been fully established. In this paper results of the two approaches for a wide range of input values are compared. In Section 2 the simplified R6 approach is described and the corresponding partial safety factor approach is addressed in Section 3. The test cases used for the comparison are described in Section 4 and the results obtained by the two methods are also given in Section 4. A comparison of the results of the two methods is discussed in Section 5.

2. The simplified probabilistic approach in R6

In the R6 procedure the limiting condition of a structure is evaluated by reference to two criteria, fracture and plastic collapse. Variability in loadings and material properties, K_{IC} and σ_y, will cause corresponding variations in the R6 fracture and plastic collapse assessment parameters, K_r and L_r, respectively. Thus in a probabilistic R6 assessment, the failure probability, $P_f(a)$, for a defect of given size, a, and specified loading conditions and geometry is given by:

$$P_f(a) = \int\int_{A_{FAIL}} p(K_r, L_r)\,dK_r\,dL_r \quad (1)$$

where $p(K_r, L_r)$ is the bivariate probability density function that expresses the variability of K_r and L_r [4]. The integration is performed over A_{FAIL} that is the region outside the failure assessment line where failure is conceded according to the R6 criteria (see Fig. 1a).

In the earliest formulation of the simplified approach, [6] variability in only fracture toughness and yield stress is considered and $p_f(a)$ is approximated by summing the two relevant conditional failure probabilities.