RECENT DEVELOPMENTS IN NUMERICAL FRACTURE METHODS WITHIN THE R6 PROCEDURE

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Recently, two new appendices have been added to the R6 defect assessment procedure. Appendix 17 deals with local approach methods and covers both cleavage and ductile fracture models. This appendix and work on extension of the models to predict coupled behaviour in the ductile-to-brittle transition region are described. Appendix 18 provides advice on finite element analyses which may be used to assist in the application of R6. These range from elastic analysis of the uncracked structure to inelastic analysis of the cracked structure to apply the local approach methods. The advice in Appendix 18 is summarised.

INTRODUCTION

The R6 procedures, Nuclear Electric (1), are well established and provide simplified, robust failure assessment diagram methods for defect assessment, Ainsworth (2). In addition to the main procedures, advice on a wide variety of aspects relating to defect assessment is provided in a number of appendices. These allow users to go beyond the basic R6 approach by including advice on aspects such as constraint, weld mismatch and probabilistic methods, for example.

Recently, new appendices 17 and 18 have been added to R6. Appendix 17 covers local approach methods while Appendix 18 describes finite-element analyses for defect assessment. In this paper, developments in these areas and the specific advice included in R6 are briefly described.

LOCAL APROACH METHODS

Local approach methods have been developed to obtain fracture toughness data for use in structural integrity assessments and to predict fracture behaviour under primary and

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secondary loading. These methods relate the conditions of stress and strain local to the crack-tip or stress concentrator to the critical conditions for fracture. This relationship is formulated through a micro-mechanical model of the fracture process which acknowledges microstructural characteristics such as grain size and inter-particle spacing. Material parameters, inherent to the model, are calibrated against laboratory test data and applied directly to predict structural behaviour.

Recent developments in the field of local approach have been focused primarily in two areas. First, the methodology associated with local approach calculations has been standardised in the form of an ESIS draft procedure (3) and as an appendix within the R6 defect assessment procedure, Appendix 17 (4). The ESIS draft procedure provides guidance on the testing and analysis of notched tensile specimens for the calibration of materials parameters. The R6 Appendix 17 provides more detailed guidance on both the calibration of parameters from standard fracture mechanics data and the application of the local approach method. Secondly, the approach has been developed by coupling the ductile and cleavage models to address fracture in the transition region. These two areas are discussed in the sub-sections below.

R6 Appendix 17-Guidance on Local Approach Methods

Guidance on the use of four local approach models is included in R6 Appendix 17:

the Beremin cleavage fracture model (5);
the Beremin ductile fracture model (6);
the Rousselier ductile damage mechanics model (7); and
the Gurson ductile damage mechanics model (8).

The steps in the Appendix 17 procedure are briefly as follows:

(i) obtain reference experimental data for the material and fracture mode of interest, preferably from pre-cracked specimens;
(ii) based on microstructural considerations and the reference data, estimate the parameters for the local approach model of interest;
(iii) perform finite element analyses of the reference experiments;
(iv) compare predicted and observed behaviour in the reference experiments;
(v) if the accuracy in (iv) is not acceptable, repeat steps (iii) and (iv);
(vi) use the model parameters in a finite element analysis of the structure to predict behaviour, or of a shallow cracked specimen to predict the effects of constraint on fracture toughness.

Guidance on application of these steps is given in the appendix, for the models listed above. Application of the approach to a case of combined cleavage/ductile response is given below.

Coupled Cleavage and Ductile Fracture Models

Models of cleavage and ductile fracture have been coupled to provide a methodology for predicting behaviour within the ductile-to-brittle transition temperature regime. Two kinds of coupled model have been developed: (i) Type I in which the chosen scale length (corresponding to the finite element mesh size) is set at a value which is intermediate between the appropriate scale lengths for ductile fracture and cleavage fracture; (ii) Type II in which an explicit acknowledgement is made within the finite element model for the different scale lengths associated with cleavage and ductile fracture processes.

The Type I model has been used to assess the influence of crack-tip constraint on ductile tearing behaviour and cleavage probability for small-scale specimens in the upper transition regime, Ruggieri and Dodds (9), and in a 3-D simulation of the NESC Spinning Cylinder test, Sherry et al (10). In this simulation, cleavage of the through-clad defect was predicted to occur after 190s into the thermo-mechanical transient. As illustrated in Figure 1, strain gauge data from the NESC experiment indicated an event, probably cleavage, occurred at 213s into the thermal transient. A small amount of ductile tearing prior to cleavage was predicted by the local approach analysis. It remains to be seen whether this is borne out by fractography when the test specimen is destructively examined later this year.

Koers, Krom and Bakker (11) also present a model which predicts cleavage fracture after some ductile tearing. This takes into account the competition between the nucleation of voids at second phase inclusions leading to ductile fracture and nucleation of unstable micro cracks initiated at second phase inclusions leading to cleavage fracture. As in (9, 10) the simulation takes into account the softening of the material in the process zone, due to damage, around a quasistatically ductile growing crack. However, it is also important to recognise that for cleavage fracture after some ductile tearing the nucleation criteria for cleavage and ductile tearing are competitive. Once a void has been nucleated at an inclusion, that inclusion can not contribute to the mechanism of cleavage fracture. A modification of the cleavage fracture models as given in (5) and Bakker and Koers (12) is proposed to take this phenomenon into account. It is assumed, for the two-parameter Weibull model that the cleavage probability P_f of a reference volume Vo stressed by a maximum normal stress σ is given by:

$$P_f(V_o;\sigma) = 1-(1-P_{void\ nucleation})\exp\left[-\left(\frac{\sigma}{\sigma_u}\right)^m\right] \qquad (1)$$

where m is the Weibull parameter, σ_u is the characteristic (63.2%) value of the distribution and $P_{void\ nucleation}$ is the probability of void nucleation in V_o. Since cleavage fracture is always preceded by some amount of plastic deformation only the plastically deformed part of the total volume has to be taken into account.

The model of eqn (1) to describe cleavage fracture after some ductile tearing has been used to predict cleavage fracture of 4 SENB specimens. The ductile crack growth simulation using the Gurson model was found to be in reasonable agreement with experimental data. The modified Gurson model was then input to the cleavage fracture analysis, using the probability of void nucleation as a function of loading at each material point in the finite-element mesh (11). The calculated probability of cleavage fracture as a function of the amount of ductile crack growth, together with the rank probability of the experimental data, is given in Figure 2 for both the two-parameter Weibull model of eqn (1) and the three-parameter Weibull model. As in (10) the model is promising for predicting behaviour in the complex ductile-brittle transition region.

R6 APPENDIX 18 - GUIDANCE ON FINITE ELEMENT METHODS

Finite element analysis may be used to assist in the application of R6. The complexity of the finite element analysis depends on the application involved and some uses of such analysis are as follows:

(i) Linear elastic analysis of the uncracked structure to provide the stress distribution at the position where a crack is to be assessed, for input to a weight function solution for calculation of the stress intensity factor or the T-stress for indexing crack-tip constraint .

(ii) Linear elastic analysis of the cracked structure to directly calculate the stress intensity factor, the T-stress, or the elastic compliance. Such analyses are more likely to be used for calculating stress intensity factors for complex secondary stresses or for mixed mode loadings, where there are fewer standard solutions available.

(iii) Inelastic analysis of the uncracked structure to calculate stress and strain distributions at the position where a crack is to be assessed, for input to a weight function solution for the stress intensity factors required in Appendix 4 which deals with secondary stresses.

(iv) Elastic or inelastic analysis of a pressurised structure containing a through-wall crack to evaluate the crack opening area as an input to a leak-before-break assessment.

(v) Elastic, inelastic or modified elastic modulus analysis of the cracked structure to evaluate the limit load. Such analyses are more likely for complex geometries or for structures with a strength mismatch, where there are fewer standard solutions available.

(vi) Inelastic analysis of the cracked structure to calculate J or a constraint parameter such as the Q-stress. Calculation of J, for example, may be used: to construct an Option 3 failure assessment curve; to demonstrate that the Option 1 or Option 2 failure assessment curves are relevant to a surface cracked component when used with a global limit load; or for direct use of J in an assessment to refine estimates of margins obtained using R6.

(vii) Inelastic analysis of the cracked structure to apply the local approach method of Appendix 17, either for direct assessment of the structure or to estimate a constraint enhanced toughness.

(viii) Inelastic analysis of the welding process to derive residual stresses and hence refine application of approaches in R6 Appendix 12. In order to use the finite element method satisfactorily, there are various general requirements in terms of material properties, the structure, boundary conditions, loadings and constraints. Guidance on these general aspects is given in the appendix.

In addition to this general guidance, more specific guidance is required depending on the use for which the finite element results are intended. For example, a relatively coarse finite element mesh may be adequate if only an estimation of compliance is required. However, a more refined mesh is necessary for the evaluation of K_I or J and the refinement needs to be greater still for the calculation of crack tip constraint parameters or for the application of local approach methods. Such specific guidance is also contained in the appendix.

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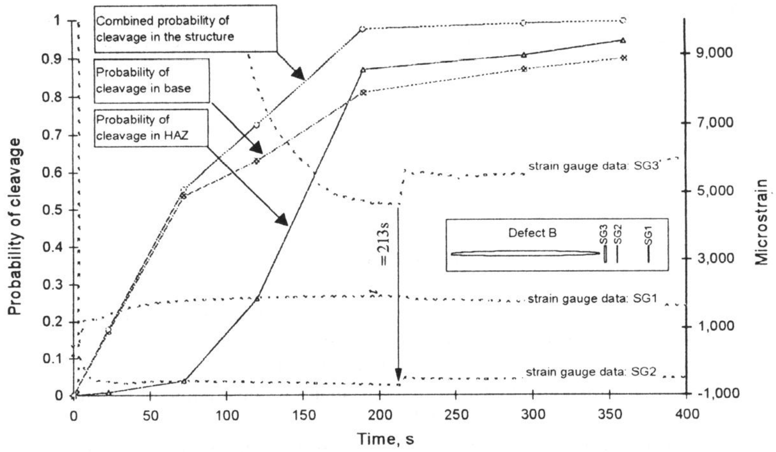

Figure 1: Predicted cleavage probability during NESC spinning cylinder experiment for through-clad defect 'B' and correlations with strain guage data (10)

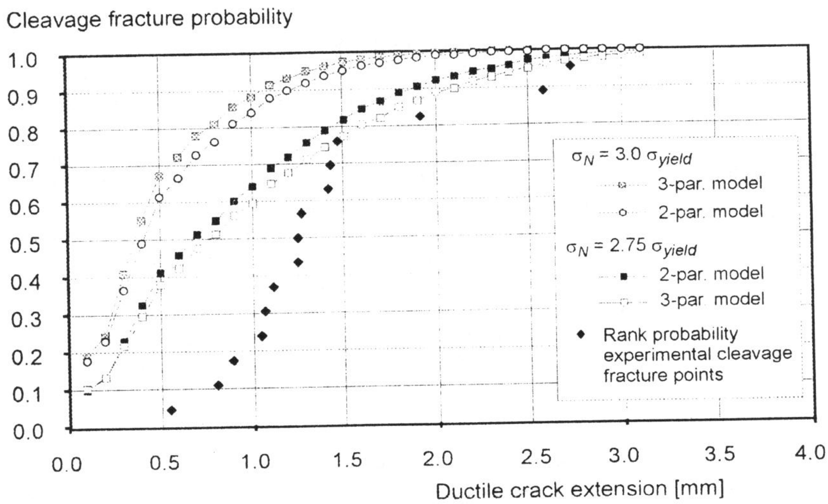

Figure 2: Predicted cleavage probability in SENB specimens as a function of the prior amount of tearing