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A Procedure for Safety Assessment of Components with Cracks

M. BERGMAN , B. BRICKSTAD, L. DAHLBERG, I. SATTARI-FAR
The Swedish Plant Inspectorate, Stockholm, Sweden
F. NILSSON
Royal Institute of Technology, Stockholm, Sweden

ABSTRACT

A high safety level of nuclear power plants requires rational and simple assessments of defects found during inservice inspections. For this reason a safety assessment procedure documented in a handbook has been developed for cracks and crack like defects in components. The main objective was to develop a procedure for operative use. The handbook therefore has to be self-contained and easy to use. The procedure is based on the R6-method, option 1 and category 1, which ensures uniqueness of the assessments.

A number of solutions of the stress intensity factor and the plastic limit load for cracks in plates, cylinders, spheres, holes and nozzles are included in the handbook. The handbook also contains rules for defect characterization, recommendations for estimation of residual stresses, material data for nuclear applications, recommendations for calculation of subcritical crack growth and a safety evaluation system.

The procedure has been validated by comparing predictions based on the procedure with the results from 30 full scale experiments reported in the literature.

INTRODUCTION

During the last decade there has been a growing demand for fracture mechanics evaluations of structural components in the nuclear industry. The need of routines for such assessments have been accentuated during the last years because of the increasing age of the plants and the thereby larger risk of occurrence of service induced cracks. But also because of the increasing number of detected fabrication induced defects caused by the increasing sensitivity of the applied nondestructive testing methods. For this reason a safety assessment procedure documented in a handbook (Bergman et al. 1991) has been developed for cracks and crack like defects. The main objective has been to develop a procedure for operative use. The following requirements should be fulfilled by the procedure and the handbook.

i) The procedure should be able to handle both linear and nonlinear cases without any a priori division.

ii) The procedure should ensure uniqueness of the assessments.

iii) The procedure should be easy to use.

iv) The handbook should be as self-contained as possible, i.e. most assessments should be possible to carry out without access to any other literature in fracture mechanics.

v) The procedure should be well validated.

An obvious candidate which fulfilles the first and the last requirement is the R6-method (Milne et al. 1988a). The other requirements are however only partly fulfilled by this method. The procedure developed is based on the R6-method, but to ensure uniqueness of the assessment result and to consider the requirement of easy to use, only the option 1 and category 1 type of R6-analysis is employed. To meet the requirement of a self-contained handbook, a number of solutions of the stress intensity factor and the plastic limit load for cracks in plates, cylinders, spheres, holes and nozzles are included in the handbook. It also contains rules for defect characterization, material data for nuclear applications, recommendations for estimation of residual stresses, recommendations for calculation of subcritical crack growth due to fatigue or stress corrosion and a safety evaluation system.

THE PROCEDURE

There are two extremes of the behaviour of failure for a structure containing cracks, brittle fracture and plastic collapse. Initiation of crack growth and brittle fracture will not occur if the stress intensity factor of the crack is smaller than the fracture toughness of the material. The plasticity effects at this extreme is none or small. The other extreme, plastic collapse, will for a material without strainhardening not occur if the load that contributes to plastic collapse of the structure is smaller than the plastic limit load of the structure. Introducing non-dimensional variables, the two conditions for non-failure can be written as

$$K_R=K_I/K_{Ic}<1, \tag{1}$$

$$L_R=P/P_L<1. \tag{2}$$

These conditions define an allowable region corresponding to a unit square in the L_RK_R-plane. In structural materials, however, there is an interaction between brittle fracture and plastic collapse which requires an interpolation. By examining a number of materials a conservative estimate of this interaction has been derived (Milne et al. 1988b). Failure is assumed not to occur if

$$K_R < (1-0.14L_R^2)[0.3+0.7\exp(-0.65L_R^6)]. \tag{3}$$

Also real materials show strainhardening, why the allowable region can be extended outside $L_R=1$ to $L_R = L_R^{max}$. In the present procedure $L_R^{max} = 1$ is applied for materials with a yield plateau or when an acceptance assessment against code requirements is performed, otherwise $L_R^{max} = (\sigma_Y + \sigma_u)/2\sigma_Y$. σ_Y and σ_u are the yield strength and the ultimate tensile strength respectively.

Eqs. (3) and L_R^{max} give the locus for failure of the structure, the failure assessment line (FAL), see Fig. 1. Assessment points located within the FAL are considered safe.

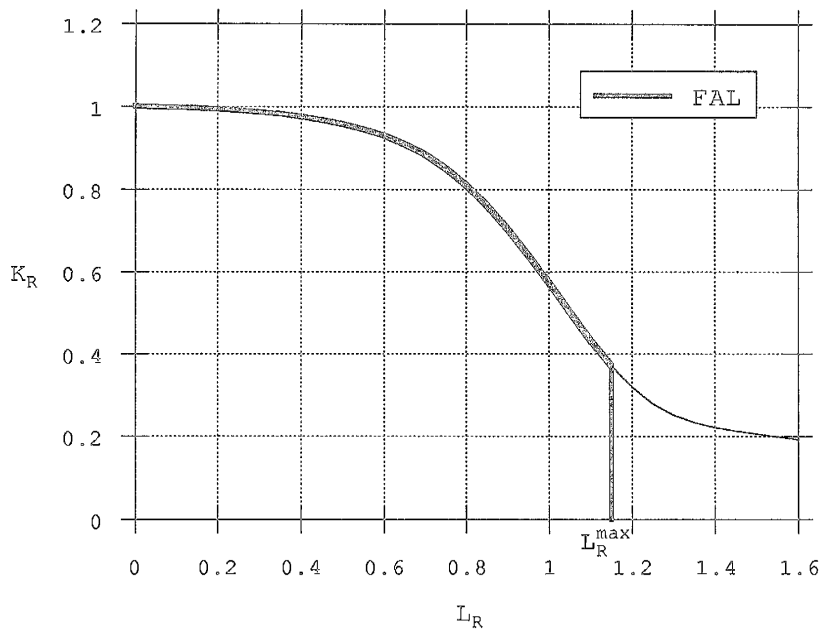

Figure 1. The Failure Assessment Diagram (FAD).

In an assessment, stresses are categorised as primary σ^p or secondary σ^s depending on whether or not they contribute to plastic collapse. Therefore secondary stresses are not included in the calculation of L_R. However, interaction effects between primary and secondary stresses may contribute to crack growth initiation. This is considered by adding a term ρ in the calculation of K_R, i.e.

$$K_R = \frac{K_I^p + K_I^s}{K_{Ic}} + \rho. \tag{4}$$

The definition of ρ used in the R6-method (Milne et al. 1988a) is slightly modified in the present procedure to enable assessment of cases involving purely secondary stresses.

THE HANDBOOK

The handbook consists of a main body and a number of appendices. In the main body, the procedure is described in a logical order. For many assessments all necessary information is available in the appendices. These consists of:

a) Rules for defect characterisation.

b) Recommendations for estimation of residual stresses.

c) Solutions for the stress intensity factor.

d) Solutions for the plastic limit load.

e) Material data for nuclear applications.

f) Partial coefficients for nuclear applications.

The rules given for defect characterisation are based on the rules given in ASME XI (1989) and in BS PD6493 (1980).

The recommendations for estimation of residual stresses are given for butt and fillet welded joints.

Solutions for the stress intensity factor and the plastic limit load have been compiled for a number of crack geometries of interest for pressure vessel applications. At present the geometries included are:

1) Cracks in a flat plate; semi-elliptical surface cracks, through thickness cracks and elliptical embedded cracks.

2) Axial cracks in a cylindrical shell; semi-elliptical inside and outside surface cracks and through thickness cracks.

3) Circumferential cracks in a cylindrical shell; semi-elliptical inside surface cracks and through thickness cracks.

4) Cracks in a spherical shell; through thickness cracks.

5) Cracks at a hole; corner cracks.

6) Cracks at a nozzle; corner cracks.

The solutions used are the most accurate and complete ones found in the literature. In some cases, when accurate solutions have not been found or in order to complete the range of applicability, analytical or FEM derived solutions have been determined. The solutions are given for membrane and bending stresses. An arbitrary stress field is linearized under the conditions of preserved equilibrium.

For through thickness cracks, the solutions of the stress intensity factor can be based on two forms of shell theory, classical and shear deformation theory. By comparisons, solutions based on classical theory seem to give more conservative and consistent results. Hence, all solutions used in the handbook for this crack geometry are based on the classical theory. In general, accurate and complete solutions for the stress intensity factor are easy to find in the literature. This is not the case for solutions of the plastic limit load which are rare in the literature and in comparison give non-accurate results. The plastic limit load used in the present handbook is the "local" limit load. The "local" limit load is the load required to cause plasticity at the remaining ligament whereas the "global" limit load is the load required to cause plasticity over the whole net section. For some crack and structural geometries the "local" limit load coincide with the "global" limit load.

The material data given are for ferritic and austenitic stainless steels common in nuclear applications. Both base material, weld material and HAZ are included. Here, data for subcritical crack growth, i.e. crack growth due to fatigue and stress corrosion, are also given.

In the procedure a safety evaluation system based on partial coefficients is introduced. With such a system the safety level of different variables may be differentiated due to their specific uncertainties. By assigning numerical values to the partial factors, γ-factors, the safety margin desired for the actual application can be obtained. For nuclear applications a particular set of partial factors is suggested in the handbook. By design the safety level given by this set is roughly comparable to the safety level given in ASME XI (1989). The factors have been derived so that the safety level for the present procedure and ASME XI (1989) agree at brittle fracture (L_R=0) and at plastic collapse (L_R=1). Between these extremes, the result of the procedure with these factors will be slightly more conservative than ASME XI (1989). This is due to the form of the failure assessment line and the factor ρ for interaction between primary and secondary stresses.

A PC-program has also been developed for the procedure. The program provides fast and easy calculations of acceptable and critical crack and load sizes. It also provides calculations of crack growth due to stress corrosion and fatigue. All the geometries considered in the handbook are implemented in the program.

THE VALIDATION

An important part in developing a practical procedure is to ensure a reliably conservative assessment.

The procedure was applied to 30 full scale experiments reported in the literature. Only surface cracks in plates and cylindrical shells, axially and circumferentially oriented, were considered. L_R and K_R were evaluated at a load level estimated to correspond to initiation of crack growth and plotted in the FAD-diagram. Here, large difficulties were encountered in determining a relevant value of the fracture toughness. The values used were the most unfavourable ones, i.e. the highest possible ones for the actual experiment. The results are shown in Fig. 2. The procedure gives a conservative result in all cases. The large conservatism in some cases is partly due to uncertainty in material properties. But it is believed that the main conservatism of the procedure stems from the used solution for the plastic limit load.

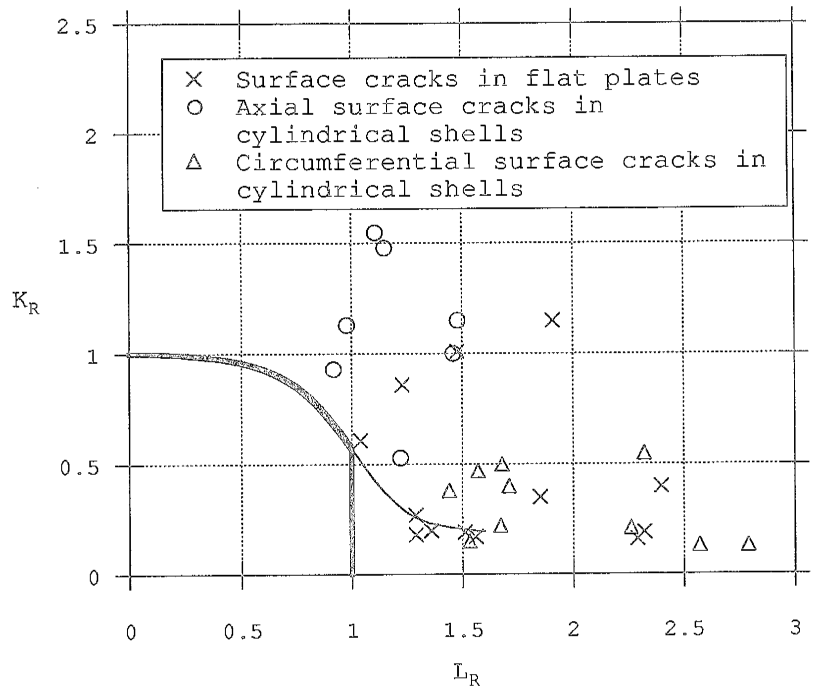

Figure 2. The result of the experimental validation.

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