APPLICATION OF FRACTURE MECHANICS IN THE DESIGN AND OPERATION OF NUCLEAR PWR IN FRANCE

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Fracture Mechanics techniques are used to evaluate the risks associated with material aging, the occurence of fabrication defects or stress corrosion cracks, and also to determine the margins with respect to fast fracture resulting from the design and manufacturing practices.

Important programs are underway to improve the accuracy and domain of validity of the fracture mechanics methods.

INTRODUCTION

Nuclear energy furnishes more than 75% of the electricity used in France. It is therefore natural that France be among the nations which are contributing to the development of Fracture Mechanics in support of design and operation of commercial nuclear reactors.

The basic flow diagram of a Pressurized Water Reactor (PWR) nuclear power station is given in figure 1. For safety reasons, a particular attention is paid to the integrity of the pressurized primary circuit (155 bar, 300°C approxi.) which comprises mainly the Vessel and the primary side of the Steam Generator with its tubing and the primary piping with the parts of the Auxiliary pipes up to the isolation valves, and to the integrity of the secondary circuit (Steam line, Feed water line) up to the isolation valves which cuts circulation in case of contamination of these circuits.

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The demand for a high safety level has led to strict regulatory requirements for the verification of integrity at design stage and during operation, which are based on deterministic analyses with safety factors.

The plant safety analyses are conducted by attributing to the components failure probabilities which are obtained by experience. Computations of failure probability are undertaken in some special cases to support the basic hypotheses.

PRINCIPAL FRACTURE MECHANICS APPLICATIONS ON FRENCH P W R 'S

Ageing Effects

The ageing behaviour considered are essentially of two types:
-irradiation embrittlement of the reactor part near the core (1), which is examined in the frame of In-Service Surveillance program (2), and
-the thermal ageing of the duplex austeno-ferritic components of the primary loop (3).

For the analyses, the defects considered are conventional defects established from experience of fabrication processes and of non-destructive examinations.

Defect Behaviour

Analysis of defects followed by in-service inspection are codified by EDF within the RSEM code (4).

In order to evaluate the behaviour of certain category of defects, adjustments were made in the analysis methods to account for their mechanical particularities. An example is, for the under-clad defects, the account of plastic deformation of the ligament through the cladding (5).

Stress-Corrosion-Cracking of Inconel 600

The strategy with respect to the In-Service-Inspection and the maintenance of alloy 600 components affected by stress-corrosion-cracking (Steam Generator tubes (6), Control Rod Drive Mechanism (CRDM) Penetrations (7)), is elaborated by integrating the crack propagation estimates and the leak-before break (LBB) considerations.

Quality of Design and Fabrication Requirements

In response to the Regulatory requirements (8) concerning the verification of Fast Fracture resistance of the Primary circuit, appendix ZG of the RCC-M code (9) was established for the specific analysis of the vessel. Later on, safety margins were evaluated with respect to initiation and instability of a conventional defect on 1300 and N4 plants for the primary and secondary circuit components and for all category of design loading. These results will serve as a basis for adjusting the In-service Inspection plans and for the design and fabrication of future plants.

Leak-Before-Break concepts are implemented as a design basis for the EPR future plant (10) or as an element of Defense-in-Depth in the treatment of integrity problems on operating plants (11).

Probabilistic Analysis

Probabilistic analysis is used as a complementary tool in the two areas of:

- Predictive maintenance, and
- Integrity analysis for adjusting safety margins

In the first area for example, stochastic modelling of Inconel 600 stress-corrosion cracking has been used to extrapolate the experience on the rate of development of cracking in CRDM tubes (12) and in Steam Generator tubes (13). The predictions of the overall degradation rates for the different PWR series are used when considering their repair strategies.

In the second area, EDF is leading a program to better adjust the effective safety margins of the deterministic analysis in the RSEM code ; probabilistic fracture mechanics analysis is used to compare the overall level of safety achieved in the deterministic analyses with respect to options taken in choosing the values of the parameters and the safety coefficients (14).

DEVELOPMENT OF THE FRACTURE MECHANICS METHODS

Context of these developments

These developments reply to the specific needs of analyses of PWR components. Strict validations of methods are required by the Administration.

For these developments, Framatome, EDF and CEA are associated in the frame of a general agreement in R & D studies, in support of operation and development of PWR's, and collaborate with several European Institutions.

The international adjustement of the fracture mechanics methods is organised through the coordinated programs such as :

- the IPIRG program on LBB, organised by the NRC and the Battelle institute in USA,
- the FALSIRE program, coordinated by the OECD/CSNI and the GRS in Germany, and
- the NESC network coordinated by the JRC of Petten for the European Union

"Shallow Flaw" effect in the Analysis of the Vessel Core Region

The defects which contribute most to the risk in the vessel core region are under-clad cracks (15). The dimensions of the reference under-clad defects considered are small, from 4 to 12 mm of depth. The most severe loadings are associated with the thermal shock of the Safety Injection.

The theoretical study of the "shallow flaw" effect was undertaken through numerical computations using local approach of fracture in cleavage (16). For each defect, the numerical analysis gives all along the transient the relation between KI and the "Weibull stress" σ_W which characterises the crack tip loading with respect to risk of cleavage fracture in the local approach. The conditions for a rigorous application of the local approach for cleavage have been examined between EDF, Framatome, CEA and AEA Technology in U.K (17). In particular the necessity for a very refined mesh at the crack tip (50µmX50µm square mesh) was established.

Fig. 2 (from ref. 16) compares the relative variations of KI and σ_W computed on a CT-specimen, and during a thermal shock transient on under-clad cracks of 6 and 12 mm respectively. The "shallow flaw" effect is comparable to that observed on bars under bending with surface flaws of same crack-depth to width ratio.

The safety factor for an under-clad crack can be obtained by searching for the value of KI on the CT-specimen, corresponding to the maximum computed value of σ_W on the underclad crack, and comparing it with the reference value of KIC at the considered temperature.

An experimental prolongation of this theoretical study will be engaged to confirm the validity of these results.

Industrial Applications of the Numerical Elasto-Plastic Computation of J

This approach is necessary to determine the margins in the piping components subjected to accidental loadings whose values may exceed the yield limit load. The G-theta approach has been developped (18) in the finite-element codes of FRAMATOME, CEA and EDF as a general method to compute the deformation-theory J parameter in 2-D and 3-D for any type of loading including thermal shocks, body forces and pressure on the crack faces. Several benchmark exercices have validated the resolution (e.g. 19).

An essential feature for the industrial productivity lies in the abilities of the processors for meshing, for presenting the results and for checking the mechanical consistency. Meshing processors have been developped which comprise cracked blocks and programmed meshing procedures to insert them at any location and along any orientation in the overall mesh of the component. An example of insertion of a 35.5° inclined surface crack at the crown of an elbow is shown in fig. 3. These abilities in EPFM computations make it now possible to consider realistic loading sequences; but the mechanical significance of such analyses becomes uncertain when the non-proportional loading effects become predominant. The safety evaluations therefore, consider essentially the monotonically increasing load combinations.

Simplified Approaches based on Elasto-Plastic Correction to the Elastic Analysis

The most general J-estimation scheme is that of the R6/3-option 2 method (20) and of the GE-EPRI Handbook (21), in which the plasticity correction to derive J from the elastically computed KI value is related to the ratio of a reference stress to the yield stress.

Development of this mechanical scheme into reliable methods, when the component shape and the loading become complex, requires careful evaluation of the elastic-plastic deformation field, and the support of reference numerical elastic-plastic computations. Ihe mechanical effects which have to be understood and explicited are discussed in [22,23]. The problem is to account for local (on the cracked section) and global yielding interactions in the reference stress expression. This expression is related to those of the local and general yielding conditions. It is conditioned by the features of the mechanical relation occuring between the local and the general deformation fields.under increasing load.

For straight pipes and elbows, the local and general deformation fields are wholly interrelated (for elbows the overall deformation in bending results from the integration of the ovalization patterns) and accurate expressions of the reference stress for combined pressure and bending loadings have been derived (23) as shown in fig. 4.

For piping transitions and branches a unique expression of reference stress cannot be determined. The local yield expression can be used, but can become very conservative past general yield. An alternative approach for small cracks consists in calibrating elasto-plastic shape factors to use with the local shell resultant loads determined through an elasto-plastic numerical analysis of the uncracked component (24). This method is accurate for rather small defects and becomes unconservative for large defects.

The plasticity corrections of the simplified methods are basically derived for load-controlled loadings. When all or part of the loading is displacement-controlled, the plasticity correction is lowered. The problem is complex because the behaviour depends, for each case, on the particular features of the intraction between the spring effect and the load reduction by general yielding outside the cracked sections.

All approaches presented until now, such as (20, 25, 26, 27) are valid only in limited domains.

Mis-match effects in Austenitic Weldment and in Ferritic-Astenitic Bi-Metallic Welds

For the austenitic weldments, the mismatch weld to base metal yield stress ratio is of the order of 3. For the bi-metallic weld, the ferritic to austenitic mis-match ratio is of the order of 1.4.

For a crack within the weld metal, the strain hardening properties of the weld metal determine the strength of the stress-strain singularity at the crack tip, but the value of the overall limit load integrates the respective resistances of the base and weld material along the slip-line path. A simplified J-estimation scheme has been derived by implementing this behaviour in the GE-EPRI approach (28). For shallow cracks, the constraint conditions, according to the J-Q or the R/R0 local approach, are the same as they would be in a plain weld component when the crack tip plastic zone pattern has not completely crossed the weld. Lower triaxialities occur when the overall slip pattern is established (29).

CONCLUSION

In this paper, the emphasis has been placed on the development of the analysis methods undertaken to improve the accuracy in determining the safety margins. In addition, large efforts are be made to enlarge the material data bases, understand and measure the ageing effects, and determine the abilities of NDE in detection and sizing, which have not been detailed in this paper.

The approach for the analysis methods is to balance application of simplified methods, by which classifications of the risk can be made among the areas and loading conditions, and the EPFM numerical methods necessary to seize the safety margins with accuracy. The analyses are basically based on the J-EPFM criterion. Meanwhile, the influence of the constraint conditions is specially examined for the small near surface defects in the vessel and for the mis-match conditions in austenitic weldments and in bi-metallic welds.

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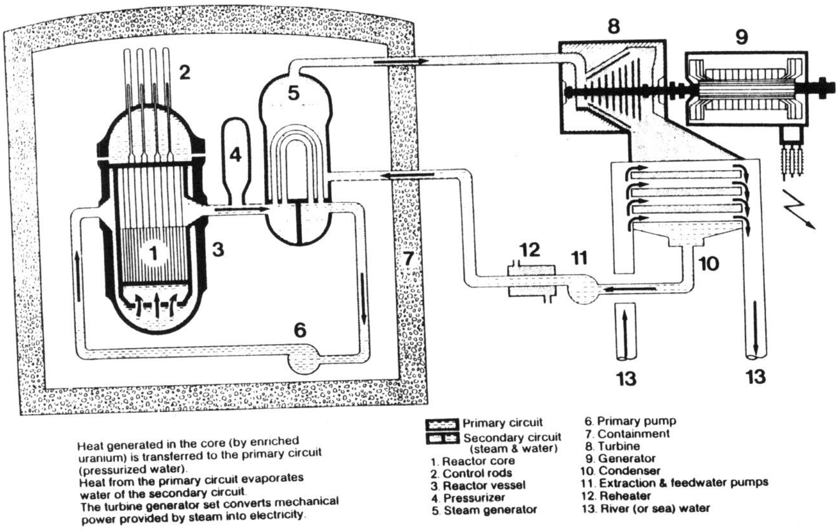

Figure 1 : PWR Nuclear Power Station (Basic Flow Diagram)

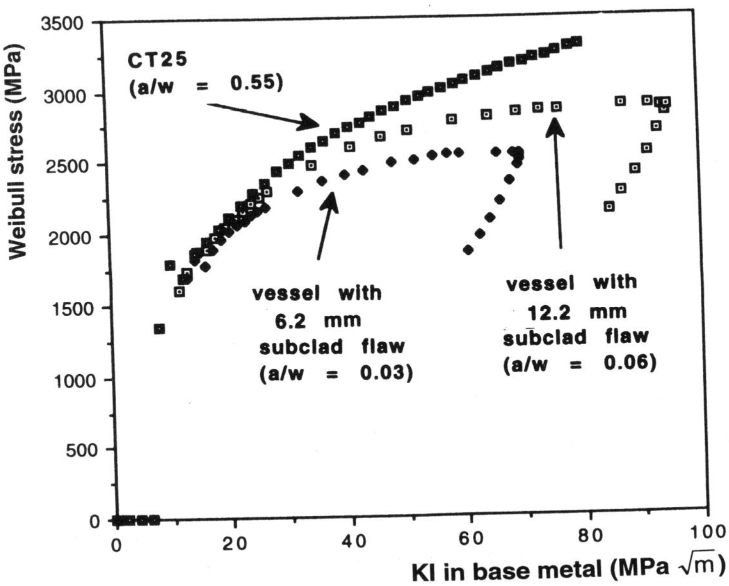

Figure 2 : Comparison between under-clad cracks and CT-specimen : σw-KI relationship

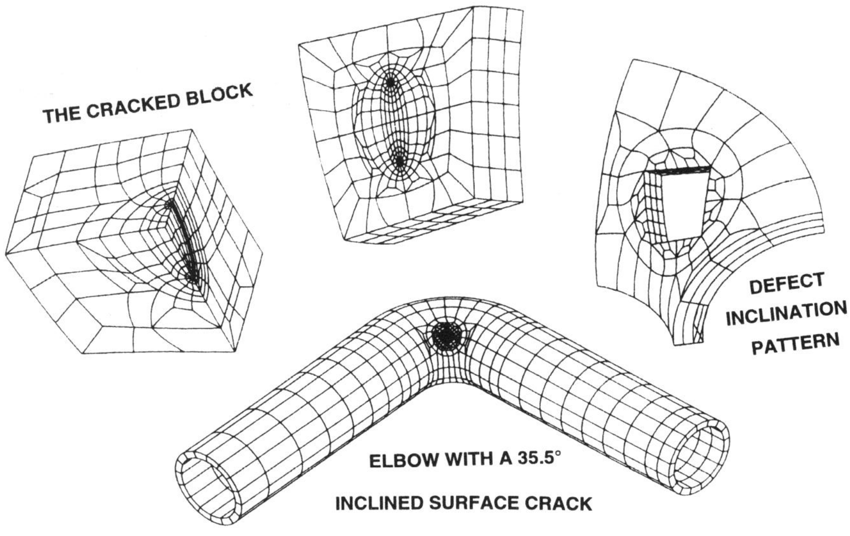

Figure 3 : Mesh of an elbow with a surface crack

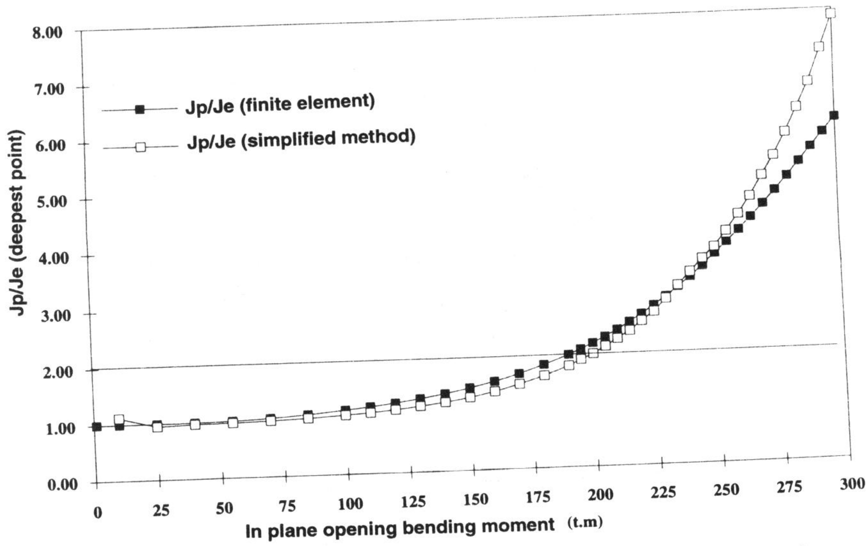

Figure 4 : Comparison of the simplified method and the numerical results elbow ($\lambda = 0.36$) with a large circumference surface crack,($a/t=0.5, \theta/\pi = 0.25$)