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The assessment of partial safety factors for fast fracture analysis in power plant components

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ABSTRACT

Fast fracture is a physical process in which the dispersion of different parameters plays an important rôle. The fast fracture risk must be analysed by probabilistic methods able to take into account this dispersion ; among them, the method of partial safety factors may be used for many components ; it appears to be usually more appropriate than the direct method.

1. INTRODUCTION

Fast fracture analyses are performed for nuclear power plant components, at the design stage, and during the life of the power plant. The aim of the analyses is to demonstrate that leakage or breaking of components cannot be expected. The analyses are based on Fracture Mechanics methods. They require extensive data concerning the possible defect sizes, the loads and the material properties. In practice, these data are scattered and deterministic Fracture Mechanics is not appropriate for performing these analyses.

Some methods of structural reliability may be used. They can be divided into direct methods and partial safety factors method. The direct methods allow a direct calculation of the failure probability. The partial safety factors method allows the demonstration that the failure probability is smaller than an arbitrary threshold. It can be easily applicable in the same way to many similar components and has been widely used in other industrial applications.

The aim of this paper is to show how these methods can be used in fast fracture assessment of nuclear power plant components.

2. SAFETY OBJECTIVE IN FAST FRACTURE ASSESSMENT OF NUCLEAR POWER PLANT COMPONENTS

2.1. Global safety objective

The safety rules require it to be demonstrated that the probability of a significant release of radioactive products in the environment is lower than a given threshold, P_t, for instance 10^{-6} per year. The demonstration is performed through so-called Probabilistic Safety Analyses (P.S.A.). P.S.A. consider several modes of failure among which is the fast fracture of the components. This paper is mainly devoted to evaluating the risk of fast fracture. The probability of failure by fast fracture, P_{FF}, must be much lower than P_t. It is possible to use one tenth of P_t as an objective for P_{FF} .

$$P_{FF} < \frac{1}{10} P_t \qquad \text{Inequation (2.1.)}$$

2.2. Safety objective for each component during every loading condition

The power plant can be subjected to various loading conditions. The frequent conditions are classified as normal and upset. The infrequent conditions are classified as emergency conditions. Very infrequent conditions are classified as faulted conditions.

The reliability of the components is required to be greater in normal and upset conditions than in emergency ones. Similarly, it is required to be greater in emergency conditions than in faulted conditions. The stresses in the components are limited by the design limits. Three types of design limit are defined, level O design limits, level C design limits, level D design limits. For many components, level O, level C and level D design limits are required, respectively, in normal + upset, emergency and faulted conditions. But some specific systems are only actuated in infrequent conditions and their reliability must be better than the reliability of common components. In the components of such a system, level O design limits are often required for emergency conditions and level C design limits for faulted conditions.

Let P_{FF}, i, j be the probability of failure of the ith component during the jth loading condition, and P_t, i, j, the allowable global probability of failure determined by the P.S.A. for the ith component in the jth load.

$$P_{FF} = \Sigma i\ \Sigma j\ P_{FF}, i, j \qquad \text{Equation (2.2.)}$$

$$Pt = \Sigma i\ \Sigma j\ P_t, i, j \qquad \text{Equation (2.3.)}$$

If :

$$P_{FF}, i, j < \frac{1}{10} P_t, i, j \qquad \text{Inequation (2.4.)}$$

for each component and each load

then

$$P_{FF} = \Sigma i\ \Sigma j\ P_{FF}, i, j < \frac{1}{10} \Sigma i\ \Sigma j\ P_t, i, j \qquad \text{Equation (2.5.)}$$

$$P_{FF} < \frac{1}{10} P_t \qquad \text{Inequation (2.6.)}$$

The condition (2.4.) is similar to the condition (2.1.), but is applied to a given component during a given loading condition. If it is verified for each component during each loading condition, the equation (2.1.) is verified.

The condition (2.4.) provides a very simple method for defining a maximum allowable fast fracture probability for each component during each loading condition.

2.3. Reliability and design limit

In many components, the required reliability for fast fracture can be considered as component-independent and as depending only on the level of the design limit specified for the component and for the loading condition. It is generally 10^{-5} per year when level O design limits are applicable, 10^{-4} when level C design limits are applicable and 10^{-3} when level D design limits are applicable.

3. DETERMINISTIC FAST FRACTURE ANALYSIS OF NUCLEAR POWER PLANT COMPONENTS

Consider a cracked structure subjected to several loading conditions, such as pressure, loads and thermal gradients. The condition for crack stability is :

$J\ (a, c, L_1, L_2, L_3) < J_t$ Inequation (3.1.)

a, c being the crack dimensions and L_1, L_2, L_3, the loading conditions

J and J_t are respectively Rice's integral and its maximum allowable value.

In usual conditions, J_t is determined with reference to crack initiation threshold $J_{0,2}$; in exceptional conditions, a small amount of stable crack growth Δa can be allowed and J_t is determined with reference to $J_{\Delta a}$.

For a given material and a given temperature, J_t can be considered as depending only on the level of the design limits.

4. STATISTICAL ASPECT OF THE DATA FOR FAST FRACTURE ANALYSIS OF NUCLEAR POWER PLANT COMPONENTS

The inequation (2.1.) can be directly used when parameters a, c, L_1, L_2, L_3 and J_t are accurately known. Unfortunately, this is generally not the case. Only some information is available :

a, c are actual or postulated defect dimensions. Actual defect dimensions can be measured and characterized by conservative bounds or statistical distributions. To characterize postulated defects, it is necessary to measure many actual defects, and to define statistical distributions to characterize them [1].

Some loads are deterministic, other loads are random and can be characterized by statistical distributions.

J_t is a scattered quantity, and is experimentally defined ; data set, and correlation with temperature and/or aging time, are available.

Statistical formulation is the most appropriate method for defining J_t.

The methods for defining statistical distributions will be examined in paragraph 6.

5. PROBABILISTIC APPROACH FOR FAST FRACTURE ANALYSIS OF NUCLEAR POWER PLANT COMPONENTS

In equation (3.1.), most of the parameters are characterized by random variables ; the realistic safety requirement consists in demonstrating through any probabilistic method, that the probability of failure is lower than the limit value considered in § 2 :

$$\mathcal{P}_{i,j}\,[J\,(a,\, c,\, L_1,\, L_2,\, L_3) \geq J_t] < \frac{1}{10}\, P_{t,\,i,\,j} \qquad \text{Inequation (5.1.)}$$

To directly solve this problem, it is first necessary to use a specific method for calculating the probability $\mathcal{P}_{i,j}$ of equation 5.1. Among the available methods are Monte Carlo simulation, FORM, SORM, or directional simulation, [2.7.]. The FORM and SORM methods can be easily used and are often sufficiently accurate for structural reliability analyses.

The simulation methods [4, 7] are very appropriate when the probability must be accurately calculated.

Each point of the space of random variables corresponds to a definite value of all the parameters a, c, L_1, L_2, L_3, J_t. The condition (3.1.) separates the space of random variables into two half-spaces : the safe domain where it is verified, and the unsafe domain where it is not verified (Figure 1). The limit surface C is the limit domain of failure.

The First Order Reliability Method (F.O.R.M.) is based on the assumption that the random variables are transformed and that they are characterized by normal and independent distributions of special basic variables. The Barenblatt transform or Nataf transform may always be used to respect this condition. In the space of the normal random variables, each point corresponds to a specific occurrence of all the random variables and the density of the occurrence only depends on the distance D of the point to the origin O of the axes (figure 1). The density decreases very quickly when the distance D increases.

The FORM method consists in finding the point I of the surface C where the distance d to the origin O is minimum (Figure 1), and in replacing the surface (C) by the hyperplane which is tangent in I to C. And in the case of a hyperplane limit surface, the probability is given by : $P = \phi\,(-d)$

Where ϕ is the normal distribution function.

The larger the value of d, the smaller the probability.

Let d_1, d_2, ... dn be the components of d on the different axes ; d_i defines the normal random variable of the ith random distribution, it is the value where the density of the ith random variable has a maximum influence on the probability of failure. This means that the uncertainty in the density function, at this point must be limited. For instance, the probability that the error in the density function is larger than 50 % must be lower than 10 %.

6. MODELISATION OF THE RANDOM DATA BY STATISTICAL DISTRIBUTIONS

In order to take into account the random aspect of the data, they can be characterized by statistical distributions. Two approaches are possible.

The first approach consists in using current methods to characterize the statistical distributions. The mathematical model of the distribution must be carefully selected for the statistical distribution to be representative of the physical problem, in the domain where the density of the distribution has a large importance : when the FORM method is used for calculating the probability of failure, this domain is accurately known if the probability density functions is accurately known. The amount of actual statistical data in the domain used for determining the probability density function must be significant and not very different from that predicted by the distribution.

The second approach consists in analysing only the statistical data existing in the tail and in seeking a distribution giving a good representation of the tail even if it does not give a good modelisation of the global distribution.

From our experience, most of the random distributions can be modelized by log normal models (defect distribution, random stresses, J_t)..

7. THE METHOD OF PARTIAL SAFETY FACTORS

The direct methods for calculating the probability of failure have been presented in § 5. They require special care and a substantial amount of time to obtain the probability of failure. They can only be used for those components for which safety considerations are the most crucial.

The method of partial safety factors is better suited when many similar structural reliability analyses are required. It has been extensively used in many industrial applications [8, 9].

The inequation (3.1.) is the stability condition of a defect when all the physical variables of a problem are known :

$$J\ (a, c, L_1, L_2, L_3) < Jt \qquad \text{Inequation (3.1.)}$$

In practice, the inequation [5.1.] is to be used in lieu of (3.1.), because some physical variables are random variables and are not exactly known.

$$\mathcal{P}_{i,j}\ [J\ (a,\ c,\ L_1,\ L_2,\ L_3) \geq J_t] < \frac{1}{10}\, P_{t,\ i,\ j} \qquad \text{Inequation (5.1.)}$$

When using the method of partial safety factors, inequation (5.1.) is replaced by an inequation similar to (3.1.) and easier to solve :

a) firstly, it consists in defining a reference value for each random variable. Reference values are values more pessimistic than the mean values and directly deduced from the distribution. They can be a quantile of the random variables. Let a_o, c_o, L_{10}, L_{20}, L_{30}, J_{to} be the reference values of the random variable of equation (3.1.).

b) secondly, for each random variable is defined a safety factor γ and equation (3.1.) is replaced by :

$$J\ (\gamma a.a_o,\ \gamma c.c_o,\ \gamma L_1.L_1,\ \gamma L_2.L_2,\ \gamma L_3.L_3) < \gamma t.J_t \qquad \text{Inequation (7.1.)}$$

c) thirdly, the safety factors γ are determined in such a way that inequation (7.1.) is almost equivalent to inequation (5.1.).

Other conditions may be imposed on safety factors γ [10].

8. PARTIAL SAFETY FACTOR DERIVED FROM THE DESIGN POINT

When partial safety factors are fixed and when inequation (7.1.) is verified, it can be conservatively assumed that inequation (7.1.) is just verified.

$$J\,(\gamma a.a_o,\ \gamma c.c_o,\ \gamma L_1.L_1,\ \gamma L_2.L_2,\ \gamma L_3.L_3) = \gamma t.J_t \qquad \text{Equation (8.1.)}$$

It has some consequences for the solution of the inequation (5.1.) by FORM. The curve C depends on the safety factors γ, and the larger the factors γ are, the farther C from origin O is and the smaller the failure probability is.

The FORM equation permits the determination of a relation between the γ factors and the failure probability. It can be used to determine the "optimized set of γ". If these safety factors are imposed in equation (8.1.) and if some parameters are slightly changed, the design point I can change but remains in the same direction (Figure 2).

9. CONCLUSION

Fast fracture must be prevented in nuclear power plant components and the probability of failure must be limited for each component to a low threshold. Those thresholds can be deduced from the Probabilistic Safety Analyses (P.S.A.).

The stability of the cracks may be analysed, but requires a certain amount of physical data to be determined : crack dimensions, loads, material properties. When some samples of these data are known, it can be seen that many of them are scattered. They have to be analysed by statistical methods. The methods must be appropriate to the application of fracture model.

The failure risk can be assessed if probabilistic methods are used. Direct probabilistic methods require much careful work and are reserved for a few typical components. The partial safety factors method seems to be the most appropriate for many components. It can demonstrate that the failure probability is smaller than a given arbitrary threshold.

In France, several analyses using this method have been undertaken. They will contribute to a more through knowledge of the safety level of nuclear power plants and indicate if an improvement is ncessary.

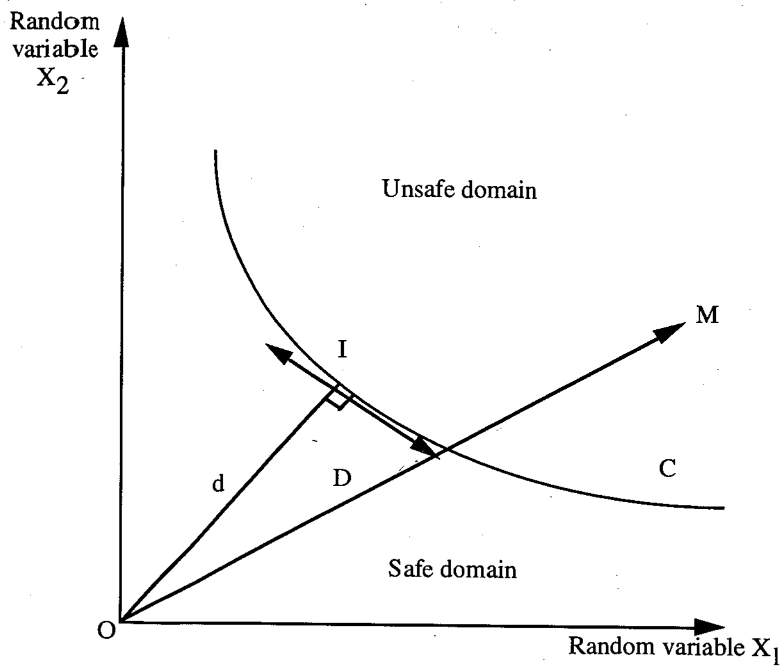

Figure 1 : domain of the random variables and FORM method.

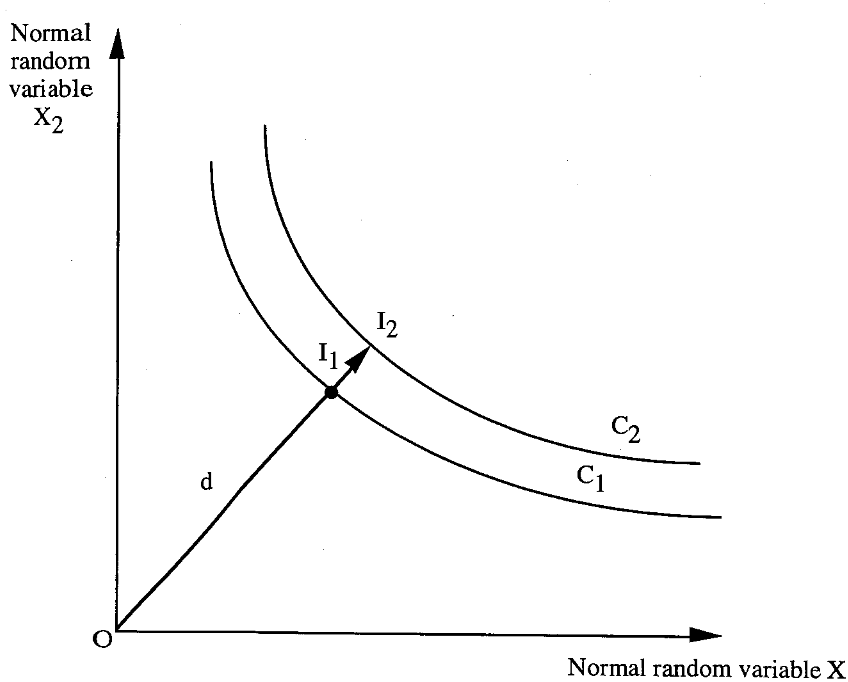

Figure 2 : use of FORM for determining optimum safety factors.

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