Evaluation of the Integrity of Reactor Structural Components Using Fracture Mechanics Concepts

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Abstract

This paper deals with the evaluation of the integrity of Reactor Structural Components using fracture mechanics concepts. After describing the details of a general method of analysis, an illustrative example is presented which represents an exploratory analytical effort on a structural component of a future Fast Breedor Reactor.

1 - INTRODUCTION

The technical basis for the evaluation of the integrity of a reactor structural component could encompass several levels of which we shall mention two which provide protection against sudden failure.

- The first level is a basic evaluation of the compliance with the requirements of a given design code using hypothetical defects.
  Quite often, it represents a contractual framework. It provides protection against sudden failure of the component at the design stage.
- The second level is a special evaluation based on a mechanistic calculation of the critical and sub-critical crack growth, to demonstrate the admissibility of plausible defects at the fabrication stage or during the operation of the reactor.

The present study concentrates on the second level of evaluation although its eventual repercussions on the Design are not excluded.

2 - METHOD OF ANALYSIS

The general procedure of analysis is indicated in a schematic way in fig. 1. A preliminary stress analysis permits the localisation of the critical areas. Once these areas have been defined, the method consists of four steps :

2.1. Collection of material characteristics. The materials in each area are clearly identified along with presence or absence of welds. One then proceeds to collect all material data required in the stress analysis and to predict the crack behavior.

2.2. Stress Analysis

At this stage, a detailed stress analysis of the chosen areas is conducted to locate the critical zones, using appropriate models incorporating Finite-Element or analytical methods, and loadings corresponding to severe service limits (not only levels A and B but alos C and D).

2.3. Crack Analysis

Once the critical zones have been defined two types of analysis are conducted :

2.3.1. Instability behavior

The materials used in Fast Breedor Reactor components being ductile the prediction of the instability behavior generally requires the use of ductile fracture criterion. Here, the double criterion of the CEGB |1| is used, which requires the evaluation of :

. a parameter $K_R = K/K_{IC}$
  where K represents the stress-intensity-factor for the crack considered and K_{IC} the toughness of the material, and

. another parameter $S_R = S/S_L$
  where S represents the applied load and S_L the limit load of the structure.

The failure assessment line separating the stable and the unstable zone is give by

$$K_R = S_R \left\{ (8/\pi^2) \, \mathrm{Ln} \, \mathrm{Sec} \left(\pi/2 \cdot S_R \right) \right\}^{-1/2}$$

2.3.2. Sub-critical crack growth

Fatigue crack growth during the operational transients is analysed using the PARIS Law |2|

$$\frac{da}{dN} = C \; (\Delta Keff)^n$$

where $\frac{da}{dN}$ is the crack growth in each triensient

$\Delta Keff$ being the effective variation of the SIF, which integrates the effect of the mean-stress-level. In general, the walker model |3| is used which gives :

$$\Delta Keff = \Delta K/(1 - R)^{n_1}$$

where ΔK is the variation of the SIF during the transient and

R represents the ratio minimum SIF/maximum SIF

C, n and n_1 are material constants.

Where mixed mode situation exists, the following computation is made :

$$\Delta K = \langle \Delta K_I \rangle + |\Delta K_{II}| + |\Delta K_{III}|$$

where $\langle \; \rangle$ represents the positive value

and $| \; |$ represents the absolute value.

Where creep is present, one has also to compute the creep crack growth (ccg) This is generally done using C* integral in two steps :

- for the geometrical and the loading conditions the incubation period Ti is evaluated |4,5|.
  If Ti is greater than the time during which the transient occurs, no CCG is required,
- if a transient lasts longer than Ti, the crack growth da/dt is computed |4, 5, 6|

$$\frac{da}{dt} = \alpha (C^*)^{n_2}$$

where α, n_2 are material constants.

The instability analysis leads to critical crack lengths a_c, at the end of life (EOL) of the reactor. Using the sub-critical crack-growth, one comes to the critical crack length, a_o, at the beginning of life (BOL) of the reactor.

2.4. The final step concerns with a discussion on the margins available with respect to the failure of the structure. This is done in two ways :

- by reasoning on the improbability of having a_o in the BOL of the reactor,
- by defining certain plausible scenarios concerning the cracks which could exist during fabrication or operation of the reactor, analysing their growth during the life of the reactor and comparing the EOL crack length with the critical crack length, a_c.

If sufficiently large margins exist, the objective is attained. If only small margins are available, then

- either the design is reviewed,
- or the detectability of critical defects (either directly or through global consequences) is investigated.

If reliable means of detection are available, the objective is attained. If not, the design has to be reviewed.

3 - ILLUSTRATIVE EXAMPLE

The example presented here represents an exploratory analytical effort on a structural component of a future FBR. The component chosen is a support structure composed of two perforated base plates (upper and lower plates) bolted to each side of a vessel.

3.1. Definition of critical zones

A preliminary analysis revealed three zones to be retained for detailed analysis :

- the bolts,
- the perforated region of the vessel,
- the perforated region of the upper base plate.

3.2. Material characteristics

The materials used are

- a stainless steel (type 304) for the base plates and the vessel,
- a high strength material for the bolts.

Minimum properties are given in Table I (Creep being negligible, creep properties are not given). It should be noticed that the weld metal has a J_{IC} value of 120 KJ/m^2. In some cases, irradiation effects futher lower this value drastically. For reasons of space, many details are being omitted.

3.3. Stress analysis

1/ Analysis of Bolted area. The stress state in the bolted area is analysed using axisymmetric models in conjuction with an analytical model,

2/ Analysis of perforated base plate. This analysis is carried out using several models (local, global and some specific models) to take into account earthquake loading and stress-concentration effects in the ligament as well as due to some three-dimensional stress raisers which are a part of the fabricated component.

3.4. Crack analysis

An exhaustive fracture mechanics analysis was carried out in all the three critical zones, using various kinds of hypothetical cracks and different service limit levels. For illustration purposes, results given here are only for the case of major seismic event (level D service limit).

3.4.1. Bolts (fig. 2)

The results for the case of a hypothetical semi-circular crack at the surface are as follows :

- critical defect at the EOL = a_c = 8,0 mm
- critical defect at the BOL
  (before subcritical crack growth = a_o = 5,8 mm

3.4.2. Perforated region of the vessel (fig. 3)

In this case, the axial cracks are the most critical ones. With respect to a semi-circular crack at the inner surface of the vessel, the following results are obtained :

- critical defect at EOL = a_c = 14,5 mm
- critical defect at BOL = a_o = 13,0 mm.

3.4.3. Perforated region of the base plate

The analysis is conducted using the isolated part of the plate (fig. 4) as a beam. Three types of hypothetical cracks are considered as shown in the fig. 4 as I, II and III. Using minimum toughness values and an R-ratio of 0,25, the results are as follows :

- section I a_c = 10,48 mm (EOL)
  a_o = 10,00 mm (BOL)
- section II a_c = 15,1 mm (EOL)
  a_o = 8,85 mm (BOL)
- section III a_c = 8,75 mm (EOL)
  a_o = 4,55 mm (BOL)

4 - DISCUSSION OF RESULTS/CONCLUSION

4.1. Summary of results

Table II summarises the results for all the cases. One can notice that these cracks are too large to be left unobserved.

4.2. Analysis of plausible scenarios

In this part of the study a more realistic attitude is observed towards the existence of plausible cracks. In other words, initial semi-circular cracks of radii 1 mm - 1,5 mm are postulated in different zones (hatched cracks in fig. 2, 3 and 4), depending on certain geometrical/operating constraints. These cracks are propagated under the retained transients and the EOL cracks (a_f) are compared with the EOL critical crack lengths to appreciate the safety margins. Here are the results :

- bolts : initial crack of depth 1,5 mm grows to 1,65 mm (a_c = 8 mm);
- perforated region of the base plate. The maximum growth of initial cracks of depth 1 mm in the three sections analysed is about 0,2 mm. Thus a_f = 1,2 mm (minimum value of a_c = 8,75 mm),
- perforated region of the vessel initial crack of depth 1,5 mm grows to 1,6 mm (a_c = 14,5 mm).

From the above results and discussion, it is concluded that the component analysed will maintain its integrity during the whole lifetime of the reactor.

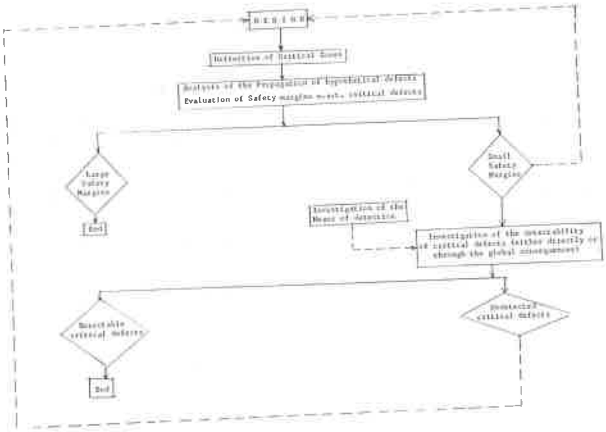

Fig. 1 - Schema of the General Procedure of Analysis

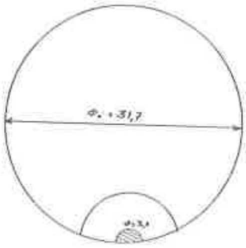

Fig. 2 – Postulated defects in Bolts

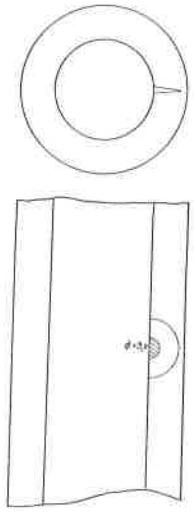

FIG. 3 – Postulated defects in the Perofrated regionof the Vessel

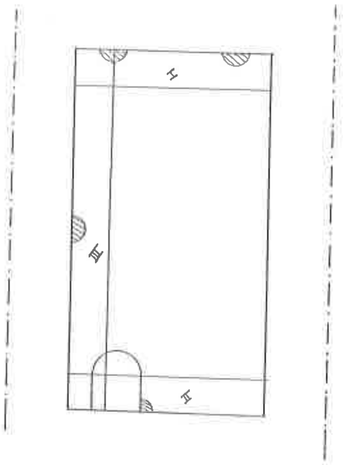

Fig. 4 – Postulated defects in the Perforated region of the Base Plate

TABLE I : Material characteristics

	Bolt Material	Vessel & Base Plate Material
σ_y N/mm²	670	141
σ_u N/mm²	924	403
J_{IC} KJ/m²	45	215

For FATIGUE Law n = 4, C = 2 × 10^{-9}

Zone/section		EOL (a_c)	BOL (a_0)
Bolts		8,0	5,8
Perforated region of Vessel		14,5	13,0
Perforated region of Base plate	I	10,48	10,0
	II	15,1	8,85
	III	8,75	4,55

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