Development of Acceptance Standards for Flaws Detected by In-Service Inspection of PWR Components

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French standard rules for inservice inspection of P.W.R. power plant components (R.S.E.M. code) describe ISI requirements and operations performed by E.D.F. in compliance with French regulation.

An important work performed by E.D.F. and FRAMATOME is in progress for the setting of acceptance standards appropriate for evaluating the results of nondestructive examinations of nuclear power plant components conducted during the service lifetime. This paper presents the development, technical basis and criteria that are proposed for establishing these standards.

1. INTRODUCTION

The construction codes, principally ASME and RCCM french code, specify nondestructive examination procedures and techniques with flaw detection capabilities well within the practical limits of acceptable workmanship and quality level for fabrication of the components. The acceptance standards applicable to theses examinations procedures encompass a spectrum of material and fabrication flaws whose presence in components has not impaired, during service, the safe and satisfactory performance in operating plants.

One objective of inservice examination is to assure that fabrication flaws are not growing in service. A second objective is to identify defects that may become unstable, in service so that improved inspection or corrective measures have to be defined.

The inservice examination requirements introduced the necessity to adopt new principles in evaluating the behavior of detected flaws in components under service loadings. As for fabrication, the detection threshold of examination methods must be considered, but new standards of acceptance are necessary to establish acceptability of components for continued service or the need for repairs. The principles of fracture mechanics provide the enginneering tool which formes the underlying basis for flaw acceptance standards (as reference [1]).

2. Approach for setting up the acceptance standards

The standards are set up and justified by several type of considerations :

- the detection threshold of examination methods employed,
- fracture mechanics principles,
- global and approximate methods,

- information derived from a large number of analyses of postulated cracks (more than 500) and some actual cracks. These analyses allow the evaluation of stress level, of critical crack size and of fatigue crack growth.

3. FRACTURE MECHANICS PRINCIPLES

Several phenomena play a role : crack initiation, fatigue crack growth, brittle fracture, ductile failure.

3.1. Fatigue initiation and growth

All the defects are conservatively assumed to be already initiated.

The presence of material and fabrication flaws, although not detrimental to the structural integrity of the newly constructed component, lead to the recognition that these flaws might grow in size as a consequence of the loadings imposed on the component during the service lifetime (référence [2]). Therefore fatigue crack growth is considered.

3.2. Stability

Brittle fracture is considered in irradiated parts of the reactor vessel. Crack initiation of ductile tearing has to be prevented in normal and upset conditions. A small amount of crack propagation due to ductile tearing could be allowed in faulted conditions.

4. METHOD FOR PREDICTING CRACK PROPAGATION

4.1. Definition of the propagation parameter P

The material is supposed to follow a Paris law

$$\frac{da}{dn} = C\left(\frac{K}{f(R)}\right)^n \qquad \text{with } R = \frac{k\ min}{K\ max}$$

The crack shape is assumed to be constant.

$K = F\ \sigma \sqrt{\pi a}$ with a = crack depth

a_i = a at time t (year)

a_f = a at time t + T

F is assumed to be independant of the crack size (small crack, constant stress). The fatigue crack growth during T years, is caracterized by the propagation parameter :

$$P = \frac{1}{T.F^n}\left[\frac{1}{a_i^{\left(\frac{n}{2}-1\right)}} - \frac{1}{a_f^{\left(\frac{n}{2}-1\right)}}\right]$$

P depends on the loadings imposed on the component ; P is independant of the crack shape and of the time interval.

We determine the value of P from every flaw analysis in every component ; the greatest value of P, Pmax for the component can often be considered as the maximum possible value of P.

4.2. Determination of the crack growth

The stability analysis gives a_0 the acceptable flaw size for 0 years more.

a_T is the acceptable flaw size for T years more :

$$a_T = \left[P.T.F.^n + \frac{1}{a_0^{\frac{n}{2}-1}} \right]^{\left(\frac{1}{1 - \frac{n}{2}} \right)}$$

5. STABILITY ANALYSIS

5.1. Principle of the crack stability assessment

The stability criterion is based on the crack driving force J. The requirement is J < J1c. In normal + upset conditions is tacken smaller than 1, so that crack initiation is surely prevented, and J is calculated from the primary plus secondary stress range (Pm + Pb + Q).
In faulted conditions, a small amount of crack initiation by ductile tearing is allowed and may be greater than 1.

5.2. Simplified method for calculating J integral

Previous works (reference [3], [4] and [5]) show that the crack driving force J (per unit of length) depends mainly on the nominal stress strain state.

FRAMATOME has developped a simplified method for assessing J associated to any small three dimensional crack configuration :

$$J = (1 - \nu^2)\, \gamma\, F^2\, \pi a\, \sigma nom\, \varepsilon nom$$

with
- ν poisson ratio
- F shape facter
- a crack deph
- σnom nominal stress level in the uncracked component
- εnom strain associated to the stress σnom on the stress-strain curve
- γ correction coefficient

The correction coefficient γ is equal to 1 in elasticity theory ; at higher stress level γ depends on a/t and a/c, slighthy on the nominal strain, on the material.

γ is evaluated from J computations in a cracked cylinder subjected to an internal pressure ; γ takes into account the effect of section reduction due to the crack.

Examples illustrating the verification of the above formula are given in reference 6. Figure N°1 shows the results of elastic-plastic finite-element computation for a cylinder with an internal circumferential crack under remote tension ($\frac{ri}{b} = 10$, $\frac{a}{b} = \frac{1}{4}$ and $\frac{1}{8}$, b is the thickness of the cylinder).

5.3. Stress level in normal and upset conditions

Pressure vessels

The primary and secondary stress intensity is limited by design code equations :

$\sigma nom < \Delta(Pm + Pb + Q) < 3Sm$

According to the Neuber rule, the product $\sigma nom \cdot \varepsilon nom$ is bounded by :

$$\sigma nom \cdot \varepsilon nom = \sigma el \; \varepsilon el < \frac{(3\ Sm)^2}{E}$$

Classe 1 piping

Worst stress state for classe 1 piping is determined using design code piping analysis equations (NB 3600 ASME, RCCM) and ratcheting rule (RCCM).

Primary and expansion elastic stresses are increased by using Neuber rule ; the secondary thermal stresses are supposed to be entirely relaxed. It has been demonstrated that

$$\sigma nom \cdot \varepsilon nom < \frac{(4,65\ Sm)^2}{E}$$

5.4. Maximum flaw sizes to prevent ductile failure in emergency and faulted conditions

Because of the limited primary stress in emergency and faulted conditions, and the difference in the safety margin, the normal and upset conditions appear to be generally more restrictive for pressure vessels. This is not the case for class 1 piping and for classe 2 piping the maximum flaw size in emergency and faulted conditions can be smaller or greater than in normal plus upset conditions.

For taking into account those conditions a set of critical flaw size tables has been worked out. They can take into account specific structure thickness, actual stress level and defect aspect ratio, they were set up for both ferritic and austenitic piping steel.

6. COMPARISON WITH ASME SECTION XI STANDARDS

The standards were compared to ASME Section XI standards. Some differences were found. They are associated to the type of material (ferritic or austenitic), to the component thickness, to the flaw shape, and to the fatigue damage level.

7. CONCLUSIONS

The flaw sizes of the French code RSEM standards will be based on fracture mechanics and toughness considerations, taking into account flaw detectability and consistency with other provisions of the RCCM Construction Code. Service-induced flaw growth by fatigue is considered, therefore acceptable flaw sizes depend on specified inspection intervals.

REFERENCES

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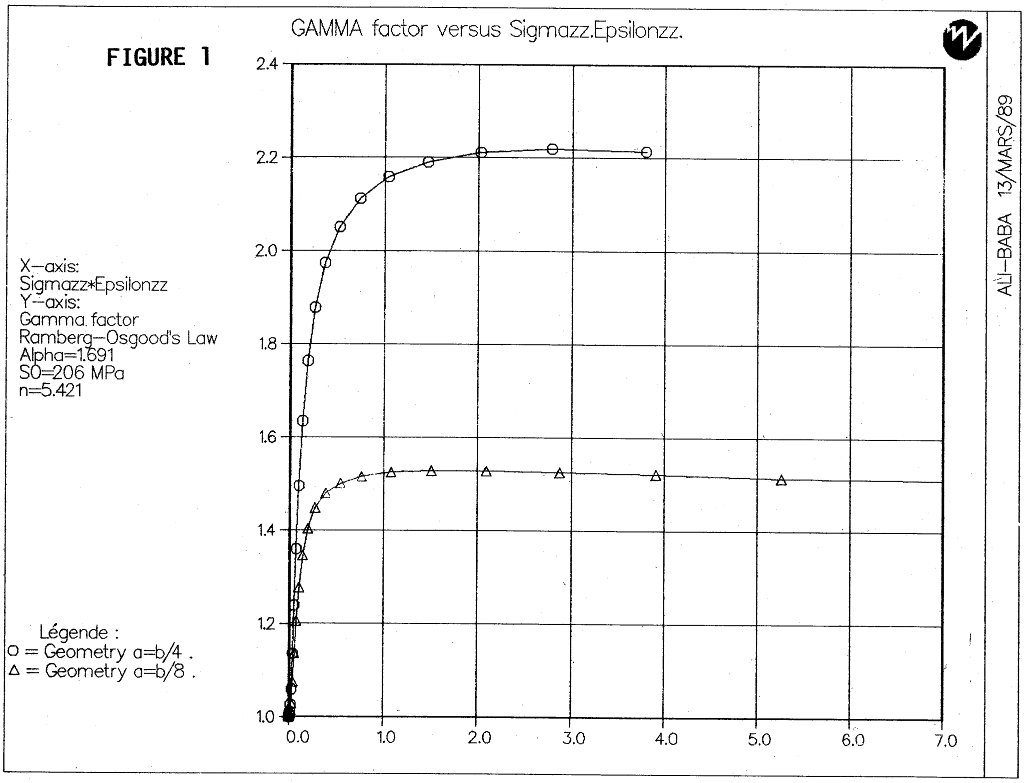
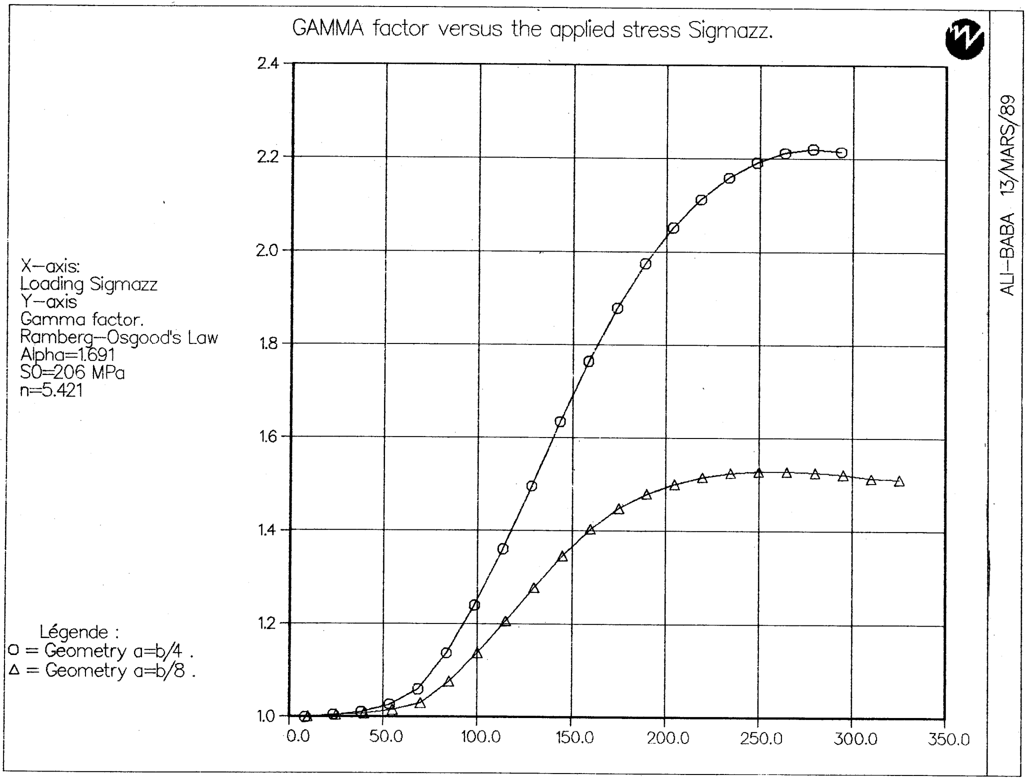
FIGURE 1


GAMMA factor versus Sigmazz.Epsilonzz.
X–axis:
Sigmazz*Epsilonzz
Y–axis:
Gamma factor
Ramberg–Osgood's Law
Alpha=1.691
S0=206 MPa
n=5.421
Légende :
O = Geometry a=b/4 .
Δ = Geometry a=b/8 .
ALI–BABA 13/MARS/89
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0


GAMMA factor versus the applied stress Sigmazz.
X–axis:
Loading Sigmazz
Y–axis
Gamma factor.
Ramberg–Osgood's Law
Alpha=1.691
S0=206 MPa
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Légende :
O = Geometry a=b/4 .
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ALI–BABA 13/MARS/89
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0