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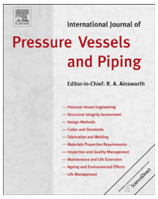

Stress intensity factor calculation in sharp and beveled edge nozzle corners

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ABSTRACT

This paper presents the work performed for the development of Stress Intensity Factor compendia for defects in nozzle corners. For that purpose, a large set Finite Element modeling were performed in order to cover the geometries, the defect sizes, the loading situations … encountered by large nuclear components. Then, based on that set of Finite Element modeling, an approximate solution relying on a fit of the stress field along the bisector line of the nozzle corner is proposed. This solution allows determining accurately the mean and maximum Stress Intensity Factor along the crack front for pressure loading and at the maximum of cold thermal shock loading. It is validated through a comparison to existing solutions or Finite Element modeling results.

1. Introduction – objectives

In the frame of Fracture Mechanics Assessment (FMA) of large nuclear components, defects are postulated then assessed against all the loading situations potentially encountered during the service life (from normal situation to accidental ones). The incredibility of failure is then demonstrated when a sufficient margin in size is shown between the critical defect (defect which becomes critical in terms of fracture under most loaded situations) and the End Of Life defect size (corresponding to the defect at the capability limits of the Non Destructive Examination (NDE) used during manufacturing), propagated by fatigue during the whole service life.

This assessment generally concerns components which are important for the safety (e.g. pressure boundaries), and in particular their welds where the probability of defect is the highest (compared to the forged components where the possibility of manufacturing defects is very low). But for large components, the FMA of welds has to be completed by an evaluation of the most loaded areas. Nozzle corners are included in this category with, for thick components, large stresses induced by thermal transients.

Regarding the objective of the Fracture Mechanics demonstration, two different evaluations are to be performed for the postulated defects:

- A fast-fracture analysis of the postulated defect: evaluation of the possible crack initiation for the most severe situations. This evaluation generally relies on a fracture criteria such as:

$$J(a,\ loading\ situation) < J_{IC}(material,\ temperature)$$

- A Fatigue Crack Growth (FCG) analysis for the component life: evaluation of the propagation of the defect at the Non Destructive Examination (NDE) capability limits. This evaluation relies on an integration of the Paris' law for the loading combinations postulated at design level:

$$\Delta a = \sum_i C.\Delta K^n(a_i, loading\ combination\ i),$$

where a_i is the crack size corresponding to the *i'th* loading cycle. In those two evaluations, the material characteristics J_{IC}, C and n are defined for the considered material in the appropriate conditions (temperature and environment).

For the determination of the loading parameters (ΔK and J), due to the large number of loading situations to consider, an important effort was performed in order to provide analytical solutions. Those solutions are codified in dedicated FMA appendixes such as RSE-M appendix 5.4 [1] in France or R6 rule [2] in the UK. They are covering the K_I calculation (Stress Intensity Factor associated to an elastic material behavior) as well as plastic corrections associated to the elastic-plastic material behavior. However, those documents

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Nomenclature

a, a_i, c	Crack depth, crack depth at the *i'th* loading cycle and half length of the defect
a', β	Effective semi-circular radius of the defect and angle defining the defect
Δa	Crack propagation under cyclic loading
K, ΔK	Stress Intensity Factor and its variation during cyclic loadings
K_I	Mode I Stress Intensity Factor
J, J_{IC}	Rice integral and material toughness
G_{FE}	Energy release rate determined through Finite Element modeling
C, n	Constants of the Paris' law
k_{max}	Amplification factor between mean K_I and max K_I along the crack front
R_{prin}, C_o	Principal radius and amplification coefficient defining the simplified model
R	Radius of the beveled edge corner ($R = 0$ for sharp corners)
H	Height of the simplified model
t	Thickness of the Newman's plate model
α, E, ν	Thermal expansion coefficient, Young's modulus and Poisson's ratio
T_c, T_f	Initial hot and final cold temperatures of the thermal transient
ΔT, t_c	Amplitude and duration of the simplified temperature ramp
i_j	Influence functions ($j = 0$ to 2)
p_j, q_j, p_{jk}, q_{jk}	Adjusted coefficients for k_{max} calculation ($j = 1$ or 2, $k = 1, 2$ or 3)
ζ, ξ	Abscise along the bisector line and curvilinear abscise along the crack front
L	Distance along the bisector line for the principal stress polynomial fit
FMA	Fracture Mechanics Assessment
FCG	Fatigue Crack Growth analysis
F.E.	Finite Element
NDE	Non Destructive Examination

dedicated to FMA are generally covering simple structures such as plates, pipes and vessels, but for complex geometrical configurations such nozzle corners, only few solutions exist and only in the elastic domain. As a consequence and for internal needs, AREVA-NP has launched an internal R&D program in order to develop specific solutions for that configuration. This effort focusses on Stress Intensity Factor calculation but also on the plasticity correction. The scope of this effort is large in terms of geometrical configurations as well as investigated loadings: internal pressure and thermal shock loadings are considered in the analysis. This choice was made in order to cover as many configurations as encountered in the design applications. With the same objective, two types of materials are investigated: the low alloy ferritic and the cast stainless steel used for the large component manufacturing.

The purpose of this article is to present the first part of this work devoted to the Stress Intensity Factor calculation, and in particular the methodology used for the development of specific compendia for K_I calculation in sharp and beveled edge nozzle corners. It describes successively the definition of the considered geometries (in terms of structures and investigated defects), the material and loading considered, then the post-treatment procedure used for the determination of the fitted coefficients. A validation of the proposed solutions then conclusions and perspectives for the continuation of this work are finally proposed.

2. Geometrical description of the problem

In the present paper, we are focusing on the FMA of nozzle corners of large nuclear Pressurized Water Reactor components. Those components are significantly thick in order to support high pressure. Most of them made of low alloy ferritic steel, but few of them, like the pump casing, are made of cast stainless steel. For that reason those two families of materials are investigated here.

Regarding the loading, as already mentioned, the pressure is an important loading to consider. But for those nozzles which are in general reinforced in comparison to the nominal thickness of the component, the worst loading situations are associated to thermal shocks, that is to say a sudden variation of the temperature on the inner skin of the component due to cold water injection. For that reason, in the following, those two types of loading are considered.

2.1. Defect geometry - simplifications and assumptions

The defects under consideration in FMA are to be larger in size than demonstrated NDE capabilities: the postulated defect sizes adopted for the analysis can be optimized to fit with NDE capabilities or are simple envelop values including both NDE capabilities and potential fatigue crack growth. This is the case for the conventional 20 mm defect size adopted by the appendix ZG of the RCC-M [3] design code.

Again conventionally, the postulated defect is supposed to be semi-circular (thus defined with only one parameter: its depth a), at surface of the component (which is the most loaded area for both pressure and thermal loading, and perpendicular to the principal stresses (perpendicular of the hoop stresses in the nozzle axes).

Regarding the defect size (20 mm or less) and because of the large thickness of the components, it is assumed in the following development that the defect has no impact on the nozzle behavior. In other words, the global geometry of the structure has no impact on the defect behavior and only the local geometry has to be taken into account in the calculation.

Following this assumption, the geometrical problem is defined by three parameters: the defect size a, the radius of the beveled edge corner (R on Fig. 1) and the internal radius of the nozzle (R_{prin} on Fig. 1). In a non-dimensional space, this can be reduced to two ratios: R/a, defining the relative size of the beveled edge and a/R_{prin} defining the relative defect size.

Regarding other dimensions, as explained previously, they are considered large enough to have no effect on the influence functions. As a consequence, for simplicity, we assume here the nozzle as a large ring (see Fig. 1) with a thickness H and an external radius significantly higher than the nozzle radius R_{prin} (the coefficient C_o is equal to 5 in the following).

2.2. Description of the F.E. models

As previously explained, the present work addresses the problematic of semi-circular defects. Additionally, for simplification purpose, we impose to the crack front to be perpendicular to the inner surface of the nozzle at surface point (point C on Fig. 1). As a consequence, because of the presence of a beveled edge, the center