International Journal of Pressure Vessels and Piping 147 (2016) 55–63

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

Elastic-plastic Fracture Mechanics Assessment of nozzle corners submitted to thermal shock loading

S. Chapuliot[*], S. Marie

AREVA-NP, France

ARTICLE INFO

Article history:
Received 29 December 2015
Accepted 12 October 2016
Available online 13 October 2016

Keywords:
Stress intensity factor
Energy release rate
Nozzles
Thermal shock
Plasticity
Stress relaxation

ABSTRACT

This paper focuses on the development of a simplified analytical scheme for the elastic-plastic Fracture Mechanics Assessment of large nozzle corners. Within that frame, following the specific numerical effort performed for the definition of a Stress Intensity Factor compendium, complementary elastic-plastic developments are proposed here for the consideration of the thermal shock loading in the elastic-plastic domain: this type of loading is a major loading for massive structures such as nozzle corners of large components. Thus, an important numerical was performed in order to extend the applicability domain of existing analytical schemes to those complex geometries. The final formulation is a simple one, applicable to a large variety of materials and geometrical configurations as long as the structure is large and the defect remains small in comparison to the internal radius of the nozzle.

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 situations 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 (defect at the capability limits of the Non Destructive Examination used during manufacturing propagated by fatigue during the whole service life).

This assessment generally concerns class 1 components and in particular their welds where the probability of having a manufacturing defect is the highest (compared to the forged components where the possibility of manufacturing defects is very low). But for large cladded or cast components, the FMA of welds has to be completed by an evaluation of the most loaded areas. For those configurations, a FMA has to be performed for both Fast-Fracture (critical defect size determination) and Fatigue Crack Growth (End Of Life defect determination). This FMA has to consider mechanical loads as well as the thermal transient loadings which are significant due to the large thickness of those components.

FMA relies today on global approach parameters such as K_I, ΔK_I, J or G. Within those parameters, the Stress Intensity Factor (SIF) K_I being the starting point of all analytical schemes, a specific effort was performed in Ref. [1] in order to define solutions for Nozzle Corners.

Regarding the consideration of plasticity, following the huge work performed for the development of J analytical schemes of the RSE-M/5.4 appendix [2] and RCC-MRx/A16 appendix [3], it is well known that a specific treatment is needed for thermal loading associated to temperature gradients through the thickness of the components. In practice, those types of loading are corresponding to an imposed strain and, due to plasticity, the real stresses imposed to the component are lower than the one determined through an elastic assumption. A relaxation is then observed and it can be shown that the elastic evaluation of the thermal loading contribution overestimates the imposed loading.

For that reason, a specific formulation was developed within the Fracture-Mechanics dedicated appendixes [2] and [3] for PWR applications. Its main originality is that it provides a specific coefficient for the through thickness thermal loading (coefficient named k_{th} and representing the ratio between elastic-plastic K_J and elastic K_I of the thermal loading contribution). More details on the consideration of through-thickness thermal loading can be found in Ref. [4] and a detailed comparison of this formulation to the R6 rule

---

Abbreviations: BMM, BMC, Monotonic and Cyclic stainless-steel Base Metal; FMA, Fracture Mechanics Assessment; PWR, Pressurized Water Reactor; SIF, Stress Intensity Factor; WM, Stainless-steel Weld Metal.

[*] Corresponding author.

E-mail address: stephane.chapuliot@areva.com (S. Chapuliot).

http://dx.doi.org/10.1016/j.ijpvp.2016.10.002

Nomenclature

a, c	Crack depth and length of the postulated defect
G	Energy release rate
G_{FE}	G determined by F.E. modeling
$G_{FE\text{-}max}$, $G_{FE\text{-}mean}$	Max and mean values of G_{FE} along the crack front at a given time step
J	Rice integral
K_I, ΔK_I	Stress Intensity Factor and its variation
K_J	Elastic-plastic SIF derived from G
K	Normalized K_I
k_{th}	Attenuation coefficient for the through thickness thermal loadings
L_{th}	Loading parameter for through thickness thermal transient
P, $P_{t\text{-}max}$	Internal pressure, internal pressure at t_{max}
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)
t, t_{max}	Time during the transient and time corresponding to $G_{FE\text{-}max}$
t_c	Duration of the simplified temperature ramp
α, E	Thermal expansion coefficient and Young modulus
ξ	Normalized abscise along the crack front
ΔT, t_c	Amplitude and duration of the simplified temperature ramp
σ_{th}	Thermal stress
σ_y, $\Delta\sigma_y$	Yield stress of the material monotonic and cyclic curves

[5] is provided in Ref. [6].

However, today's applicability domain of this coefficient is limited to pipes, elbows and vessels. The nozzle corners are out of this scope. In addition, regarding the complexity of the problem, only few results are available in the open literature for the particular case of thermal loading: in recent publications, one can find the paper [7] dedicated to elastic modeling and the paper [8] dedicated to elastic-plastic modeling. Previously, the paper [9] has presented the same kind of application.

In all those publications, the investigated configurations are Reactor Pressure Vessels made of ferritic steel which encounter a high yield stress. In such a case, the effect of plasticity remains reduced. To answer design needs, it was then decided to complete those types of studies for nozzle corners made of low yield stress materials such as austenitic stainless steel. The final objective is to extend the field of application of the analytical schemes it in both Fast-Fracture and Fatigue Crack Growth assessments.

This paper presents this elastic-plastic numerical work performed on large nozzle corners. It is divided in two main parts:

- The description of the problematic then F.E. models used for the constitution of reference solutions;
- The interpretation of the obtained results and the definition of a specific envelope curve for nozzle corners.

2. Geometrical description of the problem

2.1. Definition of a simplified and an industrial configurations

We are considering in this work large components (more than 100 mm thick) with small surface defects (10–20 mm deep). Based on that principle, it can be postulated that the defect is very small in comparison to the structure geometry and thus is negligible regarding its global elastic-plastic behavior. A simplified model can then be developed at first approximation in order to make parametric analyses. This model is a simple ring model (see Fig. 1a and b) in which a defect is introduces at the internal corner. The dimensions of this simplified model are defined by:

- The internal radius is defined by R_{prin}.
- The other dimensions are supposed to be large enough in order to be negligible on the stress intensity factor: the coefficient C_o of Fig. 1 is $C_o = 2.5$ or 5 (quasi-semi-infinite model).

The radius of the beveled edge corner is defined by R (where R = 0 corresponds to the sharp corner configuration). For that simplified model, the defect is supposed to be semi-circular. Two dimensionless ratios are thus defining the geometry (in accordance with the SIF formula defined in Ref. [1]): R/a and a/R_{prin}. The F.E. code used for that first set of modeling is Cast3M [10]. More detail of the defect definition, in particular for the beveled edge configuration, could be found in Ref. [1].

2.2. Validation through an industrial configuration

For a validation in an industrial frame, a complete model of the EPR™ pump casing (including a crack at the flange corner – the most loaded area) was used (see Fig. 1b). The F.E. code used for that full model is SYSTUS [11].

3. Reference F.E. modeling

3.1. Geometry and boundary conditions

Fig. 2 gives an example of the simplified model used in modeling. In this model, the surfaces submitted to the thermal loading are the yellow and green surfaces.

Regarding the very small size of the defect in comparison to the structure dimensions, only ¼ of the ring is modelled. The boundary conditions imposed to that model are the following:

- Two symmetry planes (planes represented in black);
- The plane surface at the opposite of the green loaded surface remains plane (uniform normal displacement);
- The outside cylindrical cylinder remains a cylinder (uniform radial displacement).

Two types of simplified models were used for those elastic-plastic developments:

- In a first modeling phase (denoted phase I further), the adopted dimensions are consistent with the pump casing flange dimensions with $R_{prin} = 700$ mm and R = 0. In that case, only the stainless steel material is considered (monotonic and cyclic behaviors, base and weld metals);
- In a second modeling phase (denoted phase II), the parametric model used for the SIF compendium development [1] was used. In that case, a/R_{prin} varies from 0.02 to 0.4 and R/a from 0 to 10. Both austenitic and ferritic base metals were considered in this second phase.