

FRACTURE MECHANICS ANALYSIS ON VVER1000 RPV WITH DIFFERENT METHODOLOGIES

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Abstract

The main component that limits the operational life of the (Nuclear Power Plant) NPP is the Reactor pressure Vessel (RPV) because of the property of carbon steel material change during the operational life due to the different causes: high neutron flux in the welding region, thermal aging etc. This results in an increase of RPV embrittlement level that decreases the safety margin for the crack propagation in case of transients with fast cooling rate due to the emergency systems injection, or increase of secondary side heat exchange. This problem is known as Pressurized Thermal Shock (PTS) and constitutes a relevant problem for the safety of the NPP that are in operation from several years.

Nowadays, the scientific community is trying to change the approach to the PTS analysis toward a “Best Estimate” (BE) scheme with the aim to remove the excess of conservatism in each step of the analysis coming from the limited knowledge of the phenomena in the eighties when the problem has been considered in the safety analysis. This change has been pushed from the possibility to extend the operational life of some plants and this has been possible due to the availability of always more powerful computer and sophisticated computer codes that allows to the analyst to perform very detailed analysis with very high degree of precision of the mixing phenomena occurring at small scale in the down-comer and to calculate the stress intensity factor at crack tip with very refined mesh of millions of nodes.

This paper describes the main steps of a PTS analysis: system thermal-hydraulic calculation, CFD analysis, stress analysis and the Fracture Mechanics analysis for the RPV of a generic VVER1000. In particular the paper shows the comparison of the results of the fracture mechanics analysis performed with different methodology for the calculation of the stress intensity factor at crack tip (KI).

Keywords: PTS, CFD, Thermalhydraulics, safety, code validation, Fracture Mechanics.

1. Introduction

The present work deals with a MSLB transient for a the PTS analysis in a VVER-1000. The analysis has been conducted following a BE approach in the selection of the boundary conditions for the transient, and in all the steps of the analysis for the calculation of the stress intensity factor at crack tip.

The integrity of the reactor pressure vessel has to be maintained throughout the plant life since there are no feasible provisions which would mitigate a catastrophic vessel failure, therefore integrity is ensured by a margin between its load bearing capacity, given by vessel design and material properties and the acting loads, which could occur during the plant operation.

The degradation of material properties by neutron irradiation, thermal ageing and other mechanisms, reduce the resistance of the vessel against brittle fracture.

The loads to be considered in the vessel integrity assessment are mainly related to plant states leading to a pressurized thermal shock (PTS) events, characterized by rapid cool-down in the primary coolant system usually with high level of primary system pressure.

The PTS analysis is performed in several consequential steps following the methodology developed by UNIP, see ref. [1] and [2]. The analysis starts with the thermal hydraulic study of the NPP using the RELAP5-mod3.3 System Thermal-Hydraulic (SYS TH). RELAP5 provide the necessary boundary condition to be used in the following steps.

Because the transient evolves in single phase, a detailed analysis of the mixing phenomena occurring in the down-comer region is performed by mean of the CFD code ANSYS[®] CFX.

The result of this step is the time dependent temperature distribution inside the RPV structure.

The thermal load here calculated is applied to the FE model for the stress analysis using suitable MATLAB[®] functions developed for this purpose. Pressure and nodes temperature are the main loads of the 3rd analysis using the ANSYS[®] mechanical APDL software .

The objective of the RPV PTS analysis is to demonstrate by a deterministic analysis that there will be no initiation of a brittle fracture from the postulated defect. Various methods to calculate the stress intensity factor have been proposed in literature. In this paper two of those are presented and compared: the J-Integral (JINT) and the Weight Function (WF) methodology and the NASGRO software approach.

2. TH analysis

The TH analysis presented here consist in a MSLB transient simulated by means of the RELAP5-mod3.3 software code. The Input Deck nodalization has been validated in the framework of the agreement between IRR and DIMNP of the University of Pisa: activity performed to investigate the peculiarities and or unexpected behavior of the Temelin WWER-1000 NPP during the MSLB transient, see ref. [3].

The accident is originated by a MSLB occurring in one loop. The Scram occurs in a few seconds and the stop signal of the main coolant pump and of the isolation of the Steam Generator (SG) follow immediately. The Primary side pressure increases and a pressurizer relief valve is taken into operation. Due to the heat exchange between primary and secondary side, the SG pressure increases too, and the atmospheric steam dump valve valves are taken into operation. After 30' the 100 K/hr procedure starts and secondary side pressure starts to decrease. The emergency feed water in the intact SG is activated by the SG level signal. The depressurization of the SG improves the heat exchange between the primary and the secondary side preventing the power operated relief valve to open. After 40' the primary side feed and bleed procedure starts, and the primary side depressurizes up to the value of residual heat removal activation. The whole transient evolves without dry out phenomena reaching a stable condition after 4000 sec.

In this paper the first 1000 sec of the transient has been analyzed, examining the effect of the abrupt initial cool down on the structures. Fig. 1 shows the temperature and mass flow rate in the for Cold Legs (CL) calculated by RELAP5.

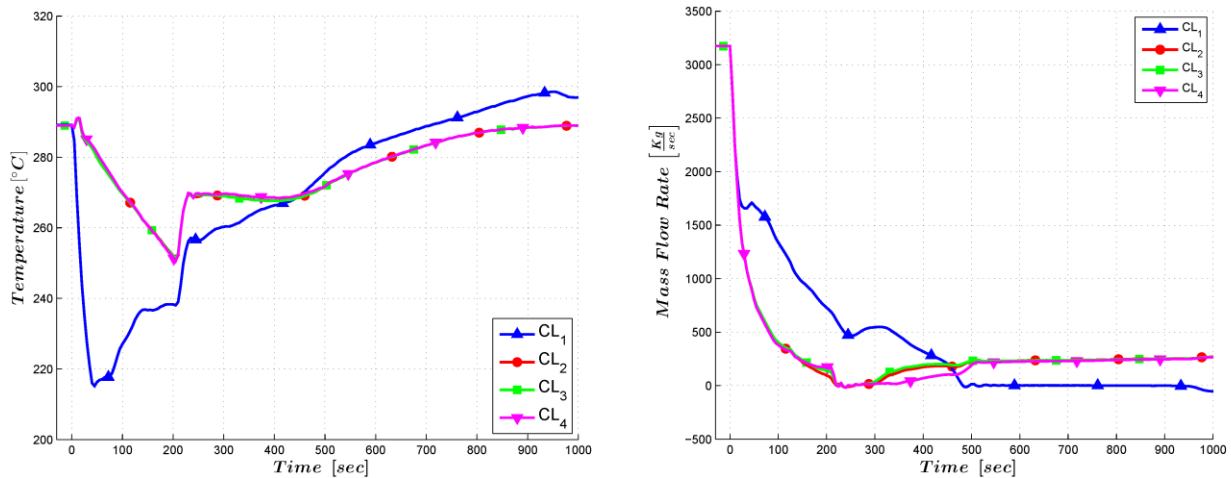


Fig. 1: Temperature and mass flow rate in cold legs

3. CFD analysis

The RELAP5-mod3.3 calculate the TH variables magnitude using 1-D nodalization described in ref. [3]. Because the transient evolves in single phase a detailed analysis of the mixing phenomena occurring in the down-comer region can be performed by mean of CFD codes. In this analysis a complete RPV WWER-1000 mesh has been developed using the ANSYS[®] Parametric Design Language (APDL) and imported into the CFX environment. The models is subdivided in two regions: a solid region representing the RPV structure, and a fluid region representing the downcomer flowing fluid. In fig. 2 the fluid region is represented in blue, emphasizing in yellow the cold legs inlet and in red the downcomer outlet surfaces. The two regions have been modeled using respectively about one and for millions of elements.



Fig. 2: WWER-1000 CFD model

The CFD model, has been set-up using the standard κ - ϵ turbulence model and the CHT model to calculate the temperature distribution inside the RPV structure illustrated in fig. 3.

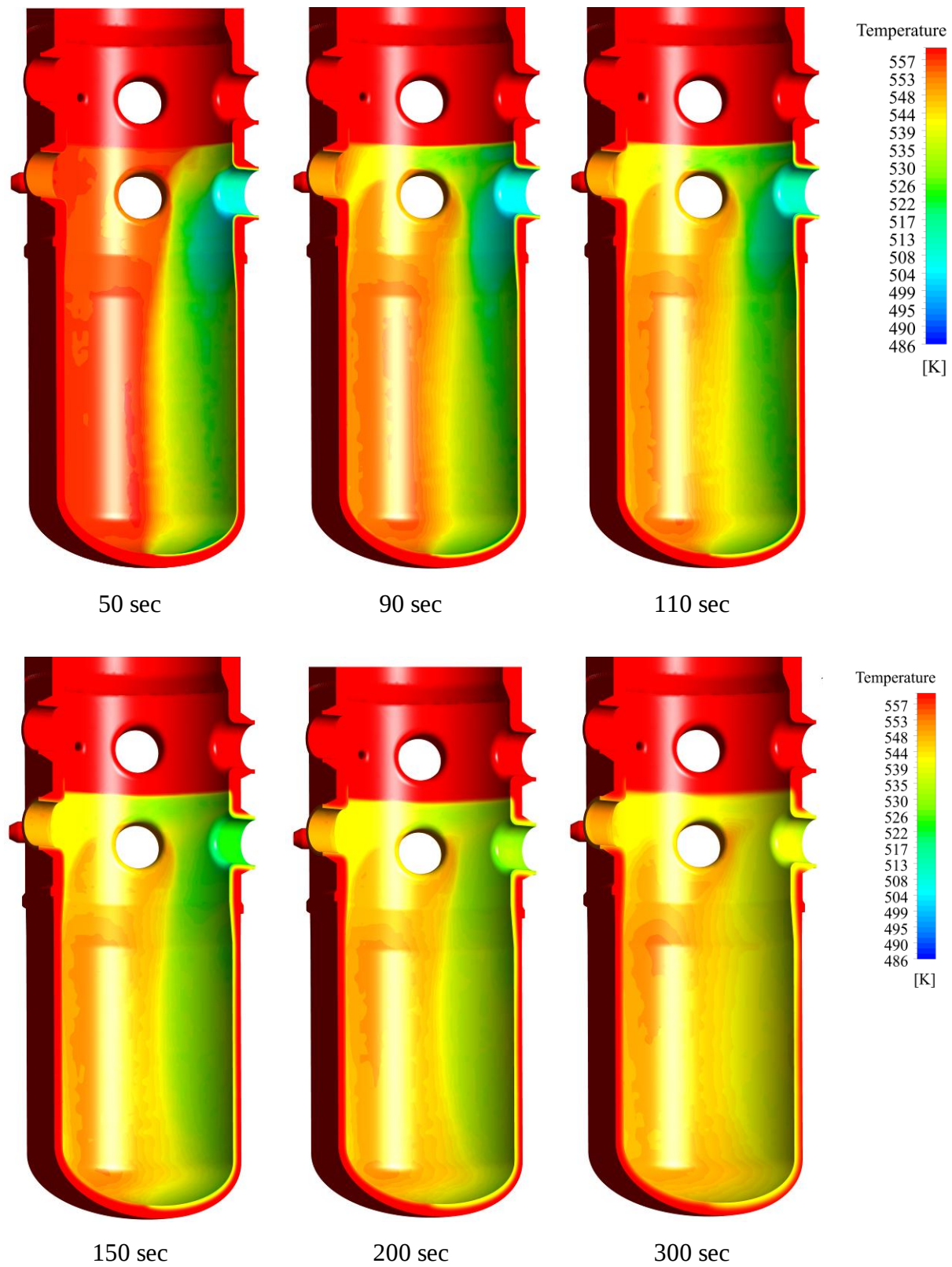


Fig. 3: Temperature distribution into the RPV structure

4. Structural analysis

The structural stress analysis has been performed within the ANSYS APDL environment using the same structural mesh developed for the CFD analysis has been used. The RPV structure has been meshed using mainly hexahedral elements. A linear growth factor has been imposed to the elements through the thickness to calculate accurately the temperature and stress profile, see fig. 4. Two material properties has been used modelling the structure: the clad, the thin internal RPV layer of austenitic steel with good ductility and toughness and the base material and the base material, in accordance with ref. [1].

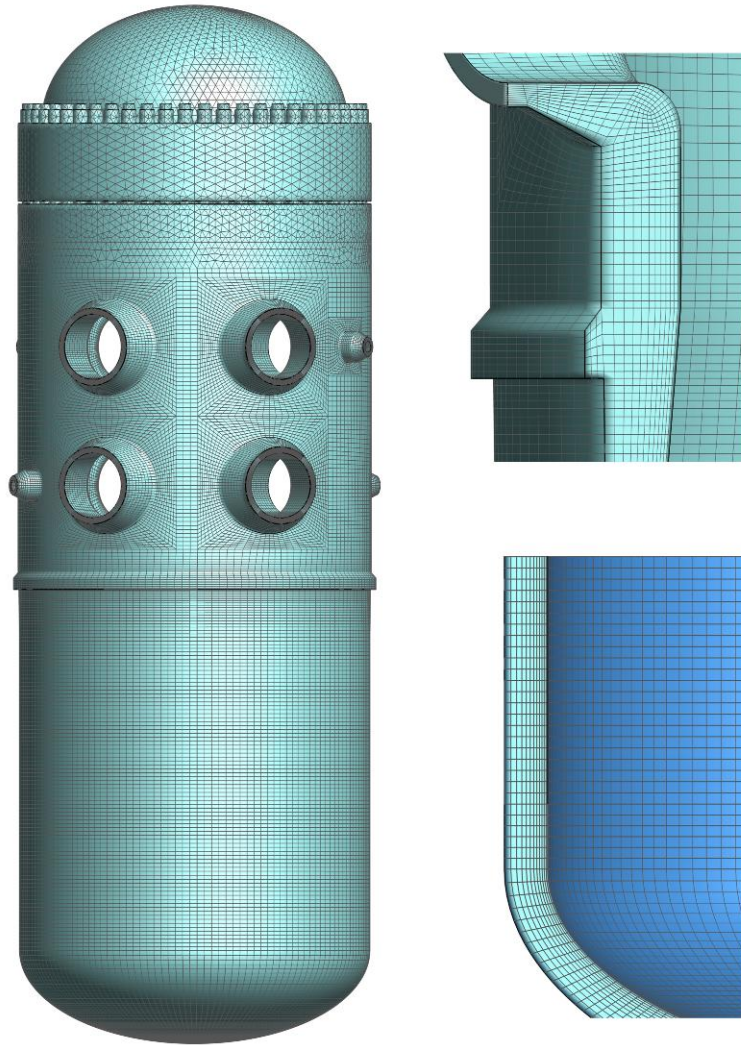


Fig. 4: ANSYS® structural mesh model

The node temperature calculated by CFX at various instant of the transient has been imported as body loads into ANSYS® and several runs has been performed. Stresses due to thermal shock and internal pressure for two postulated flaw has been recorded and utilized in the successive fracture toughness analysis. Fig. 5 and fig. 7 shows the stresses magnitude respectively due to internal pressure and thermal shock after 90 sec. in the undamaged RPV structure at the location of the postulated defects indicated in fig. 6 as CRK_{circ} and CRK_{ax} .

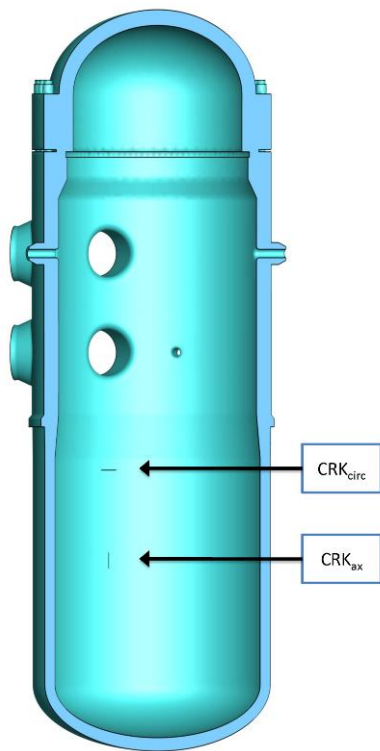


Fig. 6: Cracks location

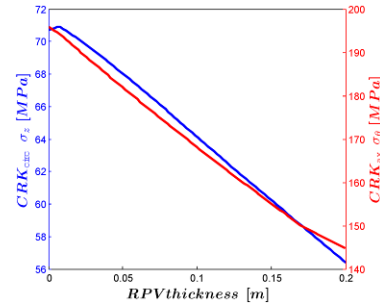


Fig. 5: Stresses due to pressure near the cracks

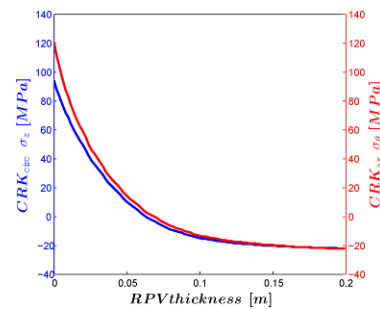


Fig. 7: Stresses due to thermal shock near the cracks at 90 sec

To perform the toughness assessment using the J-integral methodology a second RPV mesh has been developed. New volumes have been defined at the cracks locations and the cracks mesh has been developed following ref. [4]. The two cracks have been modeled as semi-elliptical surface cracks with depth to thickness ratio of $\frac{1}{4}$ and depth to length ratio of $\frac{1}{3}$. The CFX temperature transfer in this last case results more complicated because each structural node doesn't have a corresponding node with the CFX mesh used for the calculus of the temperature field. Suitable MATLAB[®] functions have been developed for this purpose performing for each ANSYS[®] node a trimap interpolation using the temperature values at the corner of each CFX hexahedral element, see fig. 8 and ref. [5]. Fig. 9 and fig. 10 show the equivalent Von Mises stresses due to the operating internal pressure of 16 MPa and the stresses near the two postulated flaws.

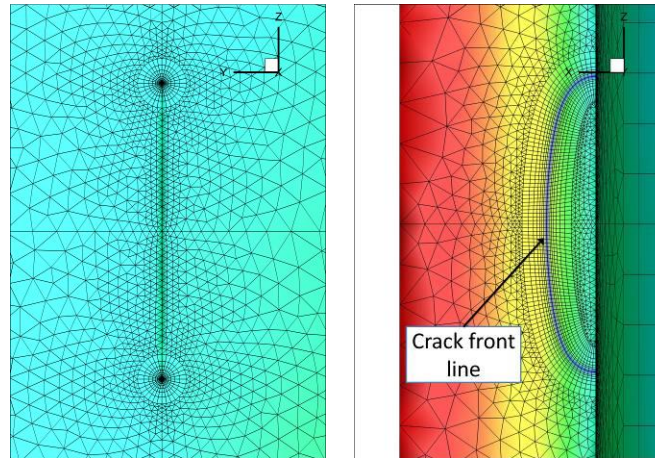


Fig. 8: Axial crack mesh and temperature transfer for the J-integral calculation

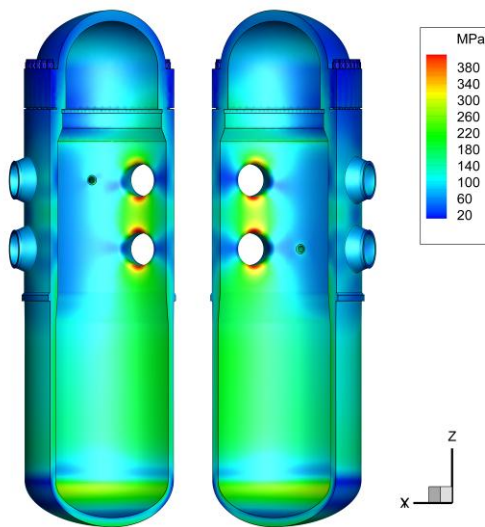


Fig. 9: Equivalent Von Mises stresses due to the internal pressure (16 MPa)

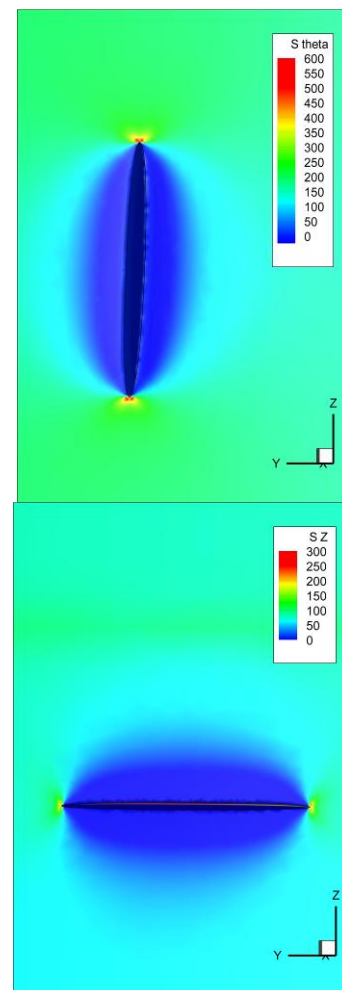


Fig. 10: Hoop and axial stresses due to internal pressure (16 MPa) near the cracks

5. Stress intensity factor evaluation

The Stress Intensity Factor (SIF) has been evaluated with three different methods:

1. J-integral
2. Weight Function method
3. NASGRO software database formula see ref. [6]

The J -integral, introduced by ref. [7] and [8], is defined as:

$$J_m = \lim_{\Gamma \rightarrow 0} \oint_{\Gamma_\epsilon} \left[(W + K)n_m - \sigma_{ij} n_j \frac{\partial u_i}{\partial x_m} \right] d\Gamma$$

- $W = \sigma_{ij} \cdot \epsilon_{ij}$ is the stress-work density
- $K = \frac{1}{2} \cdot \rho u_i u_i$ is the and kinetic energy density
- ρ is the density, σ_{ij} are stresses and ϵ_{ij} the strains
- u_i and $\frac{\partial u_i}{\partial x_m}$ are displacements and displacement gradients
- n_m are components of the unit normal vector to the J integral contour Γ

Γ integrals are performed along contours surrounding the crack tip. Ref. [8] shows that for small-scale yielding the stress energy release rate G is equal to the J and the SIF can be obtained by:

$$G = J = \frac{KI^2}{E^*} \quad KI = \sqrt{E^* J}$$

- $E^* = E$ for plane stress and $E^* = \frac{E}{1 - \nu^2}$ for plane strain

The J integral and related KI values is evaluated by ANSYS[®] by means of the CINT APDL function. In the ANSYS[®] calculation a plane strain condition has been assumed. Fig. 11 and fig. 12 illustrate the SIF due to thermal shock result at various time instant calculated with the J-Integral methodology respectively for the circumferential and axial crack.

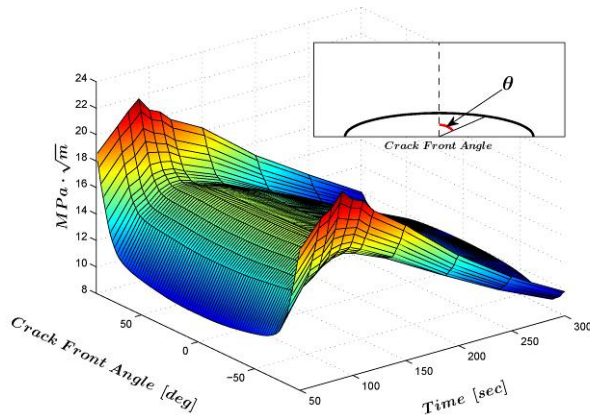


Fig. 11: Thermal KI results for the circumferential crack

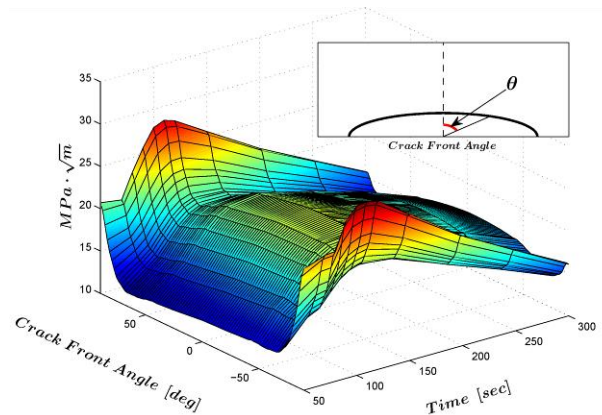


Fig. 12: Thermal KI results for the axial crack

Another classic approach discussed in this paper is the Weight Function method developed by Bueckner, it simplifies the determination of stress intensity factor considerably. A weight function exists for any crack problem specified by the geometry of the component and crack type. If this function, in the following defined h , is known, the stress intensity factor can be obtained by simply multiplying this function by the stress distribution of the un-cracked component and integrating it along the crack length a , as:

$$K_I = \int_0^a \sigma(x) \cdot h(x, a) dx$$

The integration in the previous formula has to be performed along the crack length from $x=0$ at the surface until $x=a$. The weight function $h(x, a)$ depends only on the geometry of the component.

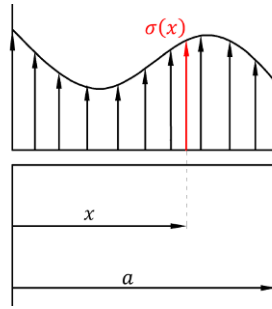


Fig. 13: Weight function integral

Ref.[9] express the weight function h taking into account tensile and bending stresses for a circumferential internal crack inside a cylinder as:

$$h = \sqrt{\frac{2}{\pi a}} \left[\frac{\rho}{\sqrt{1-\rho}} + \left(\frac{5}{4} \sqrt{\pi/2} \cdot Y - 1 \right) \sqrt{1-\rho} + \left(\frac{5}{12} \sqrt{\pi/2} \cdot Y - \frac{5}{3} \right) (1-\rho)^{3/2} \right]$$

- $\rho = \frac{x}{a}$

Where $Y(\alpha, \beta)$ is a geometric parameter obtained by:

$$Y(\alpha, \beta) = \frac{1}{\sqrt{1-\alpha}} \left[\frac{\alpha\sqrt{\pi}}{\sqrt{\pi^2-4}} (1+\beta) + 1.989(1-\alpha) + \alpha(1-\alpha) \sum_{v=0}^3 \sum_{\mu=0}^4 A_{\mu v} \alpha^\mu \beta^v \right]$$

- $A_{\mu v} = \begin{bmatrix} -13.779 & 56.546 & -83.814 & 41.688 \\ 79.931 & -397.34 & 656.81 & -339.45 \\ -211.20 & 1112.23 & -1927.36 & 1047.50 \\ 247.79 & -1325.67 & 2322.80 & -1267.64 \\ -105.96 & 565.64 & -990.34 & 537.86 \end{bmatrix}$

- $\alpha = \frac{a}{R-r} \quad \beta = \frac{r}{R}$

- a crack depth, r cylinder inner diameter and R cylinder outer diameter

In a similar way the weight function h for an axial internal crack inside a cylinder is obtained by:

$$h = \sqrt{\frac{2}{\pi a}} \left[\frac{\rho}{\sqrt{1-\rho}} + B_0 \sqrt{1-\rho} + B_1 (1-\rho)^{3/2} \right]$$

- $B_0 = -\frac{15}{4} \sqrt{\frac{\pi}{2}} \left(Y_0 - \frac{7}{2\alpha} Y_1 \right) - 9$
- $B_1 = \frac{35}{4} \sqrt{\frac{\pi}{2}} \left(Y_0 - \frac{5}{2\alpha} Y_1 \right) + \frac{35}{3}$

Where the geometric parameter $Y_n(\alpha, \beta)$ is obtained by:

$$Y_n = \frac{1}{(1-\alpha)^{3/2}} \sum A_{\mu\nu} (R/r)^\mu \alpha^{v+n}$$

- $A_{\mu\nu} = \begin{bmatrix} 2.2069 & 16.933 & -126.67 & 293.43 & -123.665 \\ -0.4700 & -38.366 & 276.042 & -604.97 & 239.28 \\ 0.3293 & 24.729 & -184.51 & 389.60 & -142.3 \\ -0.0765 & -5.431 & 40.716 & -83.399 & 28.584 \end{bmatrix} \quad n = 0$
- $A_{\mu\nu} = \begin{bmatrix} 1.1902 & 8.7853 & -65.067 & 145.041 & -70.304 \\ 0.0426 & -20.829 & 140.291 & -299.00 & 138.24 \\ -0.0296 & 13.643 & -93.90 & 193.80 & -84.69 \\ 0.0065 & -3.0148 & 20.716 & -41.575 & 17.312 \end{bmatrix} \quad n = 1$

Finally the NASGRO software database formula proposed in ref. [6] has been evaluated for the case of study. NASGRO[®] is a fracture mechanics and fatigue crack growth analysis software Originally developed at the NASA Johnson Space Center and now developed by the Southwest Research Institute[®] (SwRI[®]), San Antonio, Texas. It provides stress intensity factor equations and tables for the crack front angle of 0 and 90 deg for various type of cracks and loading cases in term of:

$$F_p = \frac{KI}{f_x \sigma_0 \sqrt{\pi \cdot a}}$$

- $f_x = \begin{cases} [1 + 1.464x^{1.65}]^{-\frac{1}{2}} & \text{for } x \leq 1 \\ [1 + 1.464x^{-1.65}]^{-\frac{1}{2}} & \text{for } x > 1 \end{cases}$
- $x = a/c$ crack depth to crack length ratio

Fig. 14 compare the KI calculated with the three methods before introduced vs. Time, while fig. 15 compare the KI values due to the internal pressure respectively for the axial and circumferential flaw.

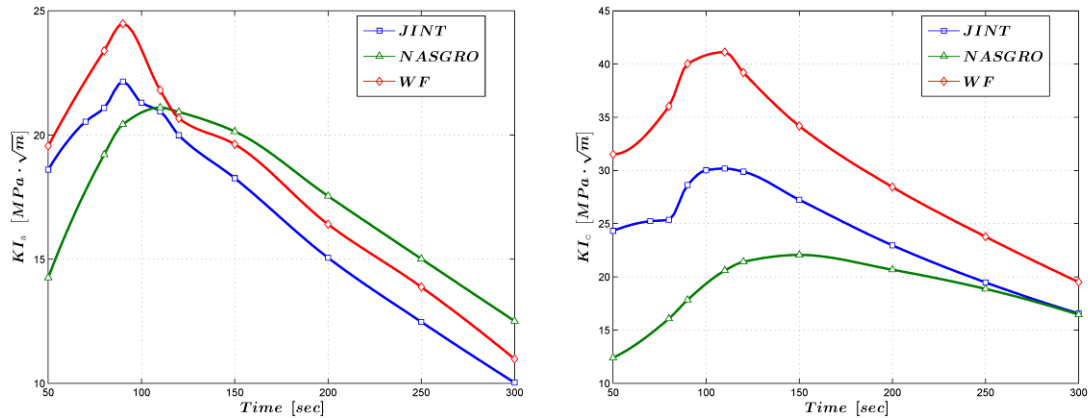


Fig. 14: Thermal shock SIF vs. Time for the axial and circumferential postulated defect

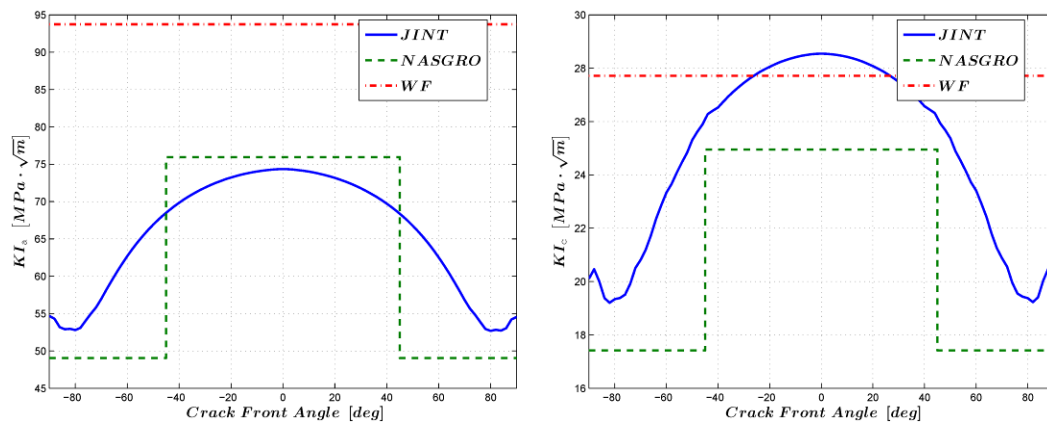


Fig. 15: SIF due to RPV internal pressure for the axial and the circumferential postulated defect

6. Conclusion

This paper describes all the steps needed to calculate the stress intensity factor in a PTS analysis: system thermal-hydraulic calculation, CFD analysis, stress analysis and the Fracture Mechanics analysis for the RPV of a generic VVER1000. In particular the paper has compared the results of the fracture mechanics analysis (KI) performed with three different methodology: J-integral, Weight Function and the NASGRO software database formula. Two semi-elliptical defect has been postulated: an axial and a circumferential flaw. The SIF due to the internal operating pressure of 16 MPa and to the thermal shock consequent a SMLB has been reported using three different methodology. A good agreement has been verified between the three different methodology for both pressure and thermal shock loading cases.

7. References

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