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Development of Computational Macros for Complete Fast Fracture Analyses

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ABSTRACT

A complete set of calculation macros using ANSYS® Parametric Design Language were developed for the fast fracture analyses in compliance with the Appendix ZG rules of the RCC-M Code. The stress intensity factors are calculated by the method of the influence coefficients, which are obtained from the tables in Appendix 5.4 of the RSE-M Code based on the flaw characteristics and component geometry. To automate the calculations, the RSE-M tables are digitized and provided in text files that are read directly by the macros such that the stress intensity factors for different flaw shapes, locations and sizes can be immediately obtained in one analysis run. Through many benchmarking cases, the capability and efficiency of the developed macros can be assured for evaluating the fast fracture risks.

INTRODUCTION

Assurance for structural integrity of pressure-retaining vessels is vitally important to prevent catastrophic failure and thus ensure safe operation of the nuclear power plants. One of the possible failures, known as fast fracture or non-ductile failure, is due to the presence of defects and then an abrupt crack growth to a critical size under operating conditions. The fundamental engineering principle for preventing such structural failures is to postulate a defect in the area of interest, determine the stress intensity factor (K_I) at the defect, and then compare it with the material fracture toughness with some safety margins to preclude the onset of the crack growth.

The paper presents our recent efforts in improving a prior study (Ching et al., 2015) for fast fracture analyses by utilizing the Appendix ZG rules in French RCC-M Code (2012). In Ching et al. (2015), the *J*-integral method combined with a local model approach was proposed to evaluate fast fracture risks at the tubesheet junctions in a steam generator. While this approach was deemed accurate in computing the stress intensity factors through the application of *J*-integral such as the studies by Ching and Batra (2001) and Ching et al. (2004), just to name a few, it required creating different local cracked models pending the types (e.g., circumferential or longitudinal crack) and locations (insider or outside surface) of the flaws. This inevitably makes this computational scheme time-consuming in complying with all the regulatory code requirements. The purpose of this paper is to develop ANSYS® APDL (ANSYS Parametric Design Language, 2017) macros that can perform and automate fast fracture computations for longitudinal and circumferential types of flaws on both inside and outside surfaces of shell or nozzle by using the influence coefficients from Appendix 5.4 of RSE-M Code (2016) and EPRI method (1978) in order to comply with the Appendix ZG rules in French RCC-M Code (2012).

DEVELOPMENT OF FAST FRACTURE ANALYSIS MACROS

Figure 1 presents a flowchart listing the major steps for completing the fast fracture analysis. In general, the complete set of macros includes two major analysis macros, namely, *post.mac* and *kcal.mac*. The macro of "*post.mac*" is to extract the opening stresses at each time step throughout the entire duration of a transient. Then, the opening stresses are combined with those obtained by the most limiting mechanical loads. The macro also extracts the temperature and yield strength at the crack tip. The macro of "*kcal.mac*" calculates the stress intensity factors at each time step using the influence coefficient method. The calculated stress intensity factors are further adjusted considering the plastic zone at the defect tip. Finally, the corrected stress intensity factor is compared with the material fracture toughness in compliance with the RCC-M Code (2012). Details of the major calculations are discussed as follows:

Time history of crack opening stress

In a 2D/3D global Finite Element Model (FEM), thermal and structural analyses are available for the transients of the 2nd, 3rd and 4th categories and the primary and secondary in-shop and on-site Hydrotests (HTs). For each postulated crack, the opening stress along the defect depth is extracted for each external mechanical load (e.g., piping load, support loads. pressure boundary loads...). For each type of mechanical load, the average opening stress along the crack is evaluated for all combinations of the mechanical load components (Fx, Fy, Fz, Mx, My, Mz) and the Most Limiting Mechanical Load (MLML) combination is identified for each crack (longitudinal or circumferential; inside or outside; for every angle around the axis (2D model). The stresses from the identified MLML for all load types (e.g., piping, stops, legs, pressure boundary,…) are combined for each crack (using ANSYS load cases combination capability) with the pressure and thermal stresses from each load steps of the thermo-mechanical runs. The thermal stresses are read directly into the ANSYS result file. The pressure stresses are obtained by factorization of the unit pressure load case according to the transient pressure. The through-the-thickness opening stress distribution is obtained for each crack, at each time instant and in longitudinal and circumferential directions.

Stress intensity factor calculation

The stress intensity factors are then calculated for a situation at all the time steps following the influence coefficients method described in Appendix ZG 5120 of the RCC-M Code (2012). Regarding the type of crack (longitudinal or circumferential orientation), localization (on inside or outside shell surface) and the stress intensity factor calculation point (crack tip A or crack surface B), the influence coefficients are calculated from tables in the appendix 5.4 of the RSE-M Code (2016). For inside longitudinal crack in knuckle area only, the influence coefficients are provided by the EPRI document of NP-719-SR (1978). Note that The RSE-M tables are digitized and provided in text files that are read by the macros. The tables are also provided in EXCEL files (.xlsx) for convenience. Each file has the name corresponding to the table number in RSE-M Code (2016).

The calculation steps using the influence coefficients method are coded in the macro and introduced as follows:

1. Read the time-history of through-the-thickness stress distribution stored in the results files.
2. For each time step, perform the polynomial interpolation of the through-the-thickness opening stress and compute the polynomial coefficients A_0, A_1, A_2 and A_3.
3. From the crack depth *a*, the shell surface radius *R*, the shell thickness *t*, obtain the influence coefficients i_0, i_1, i_2 and i_3.
4. Compute the stress intensity factor by the influence coefficients method using the following equation:

$$K_I = \sqrt{\pi \cdot a} \cdot \left[i_0 \cdot A_0 + i_1 \cdot A_1 \cdot \left(\frac{a}{t}\right) + i_2 \cdot A_2 \cdot \left(\frac{a}{t}\right)^2 + i_3 \cdot A_3 \cdot \left(\frac{a}{t}\right)^3 \right]$$

For the EPRI method (1978), the following equation is used

$$K_I = \sqrt{\pi \cdot a} \cdot \left[0{,}706 \cdot A_0 + 0{,}537 \cdot \left(\frac{2a}{\pi}\right) \cdot A_1 + 0{,}448 \cdot \left(\frac{a^2}{2}\right) \cdot A_2 + 0{,}393 \cdot \left(\frac{4a^3}{3\pi}\right) \cdot A_3\right]$$

5. Create an array containing the stress intensity factors for all time steps.

Adjustment of stress intensity factor

In order to take into account the plastic zone at the crack front, the stress intensity factor with plastic correction K_{CP} is calculated according to the Appendix ZG 5000 of the RCC-M Code (2012). Plastic zone correction must be applied to the stress intensity factor according to the following procedure:

- determine the plastic zone radius r_y at the defect tip (point A or B on Figure 2), as follows:

$$r_y = \frac{1}{6\pi}\left(\frac{K_I}{R_P}\right)^2$$

where R_p is the yield strength value for the material at the crack front and at the temperature at the point at the time considered. R_p value is given in the Appendix ZI of the RCC-M Code (2012), and K_I is the stress intensity factor at the crack front.

- determine the corrected value of the intensity factor K_{CP} as follows:

$$K_{CP} = \alpha K_I \sqrt{\frac{a + r_y}{a}}$$

where K_I is the stress intensity factor determined at the tip of the defect considered, and the value of α is determined as follows:

  - if $r_y \leq 0.05(t-a)$ $\quad \alpha = 1$
  - if $0.05(t-a) < r_y \leq 0.12(t-a)$ $\quad \alpha = 1 + 0.15\left[\frac{r_y - 0.05(t-a)}{0.035(t-a)}\right]^2$
  - if $r_y > 0.12(t-a)$ $\quad \alpha = 1.6$

where *t* is the wall thickness at the analyzed section and *a* is the crack depth.

Then K_{CP} is compared to the allowable (K_{IC} or K_{JC}) depending on the situation studied.

Acceptance Criteria

Margins against brittle fracture and ductile tearing resistance are expressed in the ratios of K_{IC}/K_{CP} and K_{JC}/K_{CP}, respectively.

The safety coefficient Cs is defined as:

$$\text{Cs} = \frac{K_{IC} \text{ or } K_{JC} \text{ (toughness)}}{K_{CP} \text{ (stress intensity factor with plasticity correction)}}$$

The criterion is Cs ≥ Csr where Csr is the required safety coefficient. The required safety coefficient depends on the transient category and can be found in Table ZG 3230 of the RCC-M Code (2012).

For the brittle fracture which is subject to the temperature range of $T - RT_{NDT} \leq 60$°C, the analytical expression of the static toughness K_{IC}, is

$$K_{IC} = 40 + 0.09(T - RT_{NDT}) + 20e^{0.038(T - RT_{NDT})}$$

where K_{IC} is expressed in $MPa.m^{1/2}$. T and RT_{NDT} are expressed in °C, and are the temperature and reference transition temperature of the analyzed defect location, respectively.

For the ductile tearing fracture, the resistance to the onset of crack-extension can be expressed by the values of K_{JC}. Table ZG 6141 of the RCC-M Code (2012), as also shown in Table 1, gives the values of K_{JC} applicable to all low-alloy manganese-nickel-molybdenum steels.

TEST CASES

In this study, two test cases are presented to demonstrate the applicability and validity of the developed macros for the fast fracture risk evaluations.

SG Upper Tubesheet Junction under In-Shop Secondary Hydrotest (Brittle Facture)

The first case tested by the developed macros is the SG upper tubesheet junction to secondary shell under in-shop secondary hydrotest. Figure 3 depicts a 3D finite element model with a postulated defect at the SG upper junction. The hydrotest temperature (T) and the reference transition temperature (RT_{NDT}) are 18°C and -21°C, respectively. Only the evaluation for the brittle fracture is required as $T - RT_{NDT} \leq 60$°C. By using the developed macros, Table 2 lists the fast fracture analysis results for the brittle failure with all the possible flaw orientations, locations and surface points. Results show excellent agreement between the results computed by the macros and those by the hand calculations. Note that the maximum ratio of Csr/Cs is 0.86, thus indicating that the acceptance criterion is met. For the purpose of validation, Figure 4 delineates the curve fit for the through-thickness opening stresses. In the figure, it is shown that the third order polynomial coefficients can be obtained accordingly. According to the flaw geometry properties (e.g., radius and thickness of the vessel, the flaw depth, and flaw length), the influence coefficients are calculated in Table 3. The stress intensity factors can be calculated, and thus the fast fracture risk is evaluated. Table 4 summarizes the hand calculations for the RCC-M fast fracture analyses.

SG Steam Outlet Nozzle under a Category 4 Transient Condition (Ductile Facture)

The second case is to evaluate the fast fracture risks at the knuckle region of the SG steam outlet nozzle under a Category 4 transient. Figure 5 shows a 2D finite element model with a postulated defect at the knuckle region of the nozzle. It is known that high stresses occur at the knuckle region especially when a faulted condition transient is loaded. Upon the review of the temperature range through the entire transient history, the difference of $T - RT_{NDT}$ is larger than 40°C where RT_{NDT} = -6°C. Note that the aging effects have been taken into account in determining the RT_{NDT} value. In the study, the shift of the reference temperature is set equal to -15°C per RCC-M Code. By using the developed macros, Table 6 lists the fast fracture analysis results for the ductile failure with all possible flaw orientations, locations and surface points. The comparisons in Table 5 shows a good match between the results computed by the macros and those calculated by hand. The maximum divergence is 2.13% for outside longitudinal crack on the surface (point B).

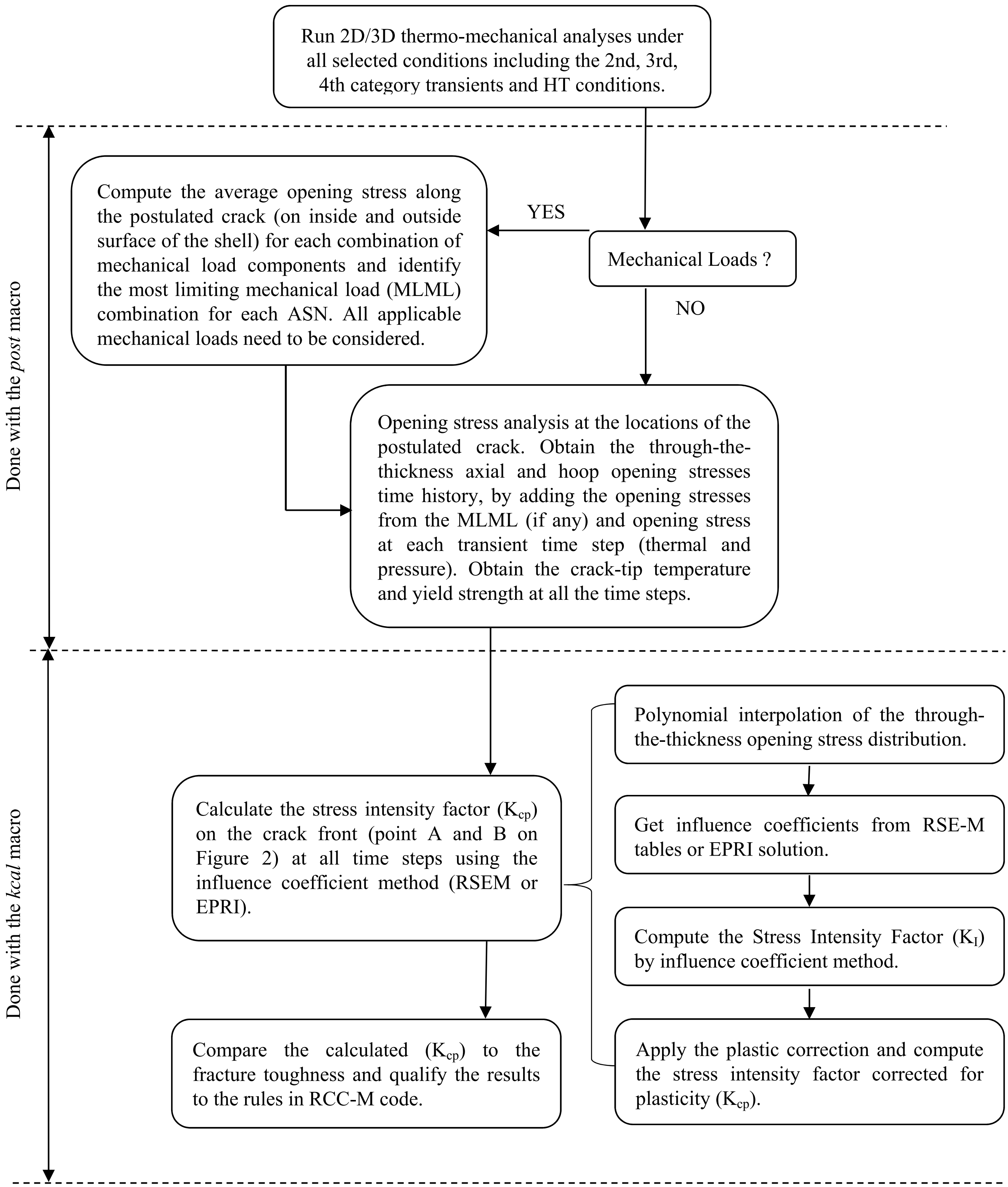

Figure 1: Flowchart of the Major Steps for the Fast Fracture Analysis with the Macros

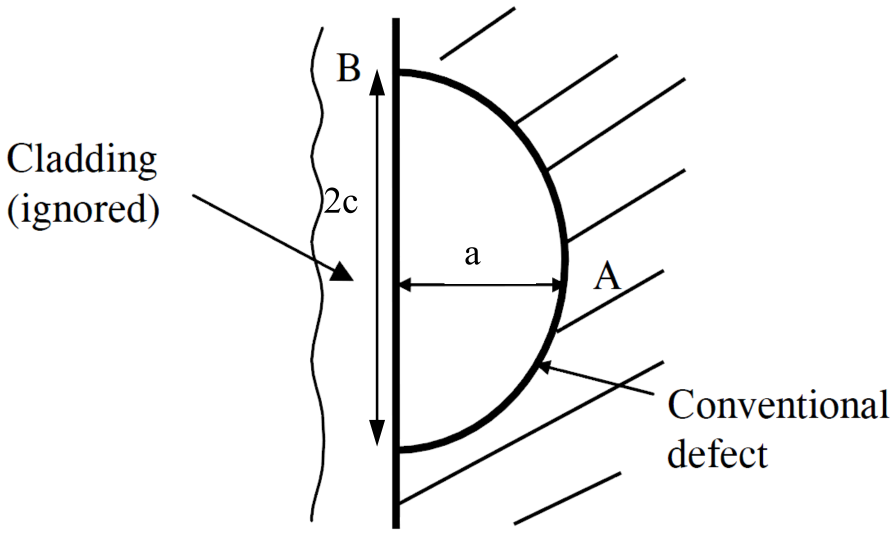

Figure 2: Conventional Reference Defect

Table 1: Values of Ductile Tearing Toughness

Temperature Range [(2)]	Material [(1)]		K_{JC} ($MPa.m^{1/2}$)
T ≥ 200°C	Base metal, function of sulfur content (%)	S ≤ 0.005	200
		0.005 < S ≤ 0.008	170
		0.008 < S ≤ 0.011	155
		0.011 < S ≤ 0.015	135
	Welded joints		170
T ≤ 50°C	Base metal, function of sulfur content (%)	S ≤ 0.005	245
		0.005 < S ≤ 0.008	205
		0.008 < S ≤ 0.011	190
		0.011 < S ≤ 0.015	175
	Welded joints		205

Note(s):

1. Values of K_{JC} for materials covered under M2110 and M2120 in the RCC-M Code (2012) and related welded joints.
2. Toughness values for intermediate temperatures between 50°C and 200°C are determined by linear interpolation.

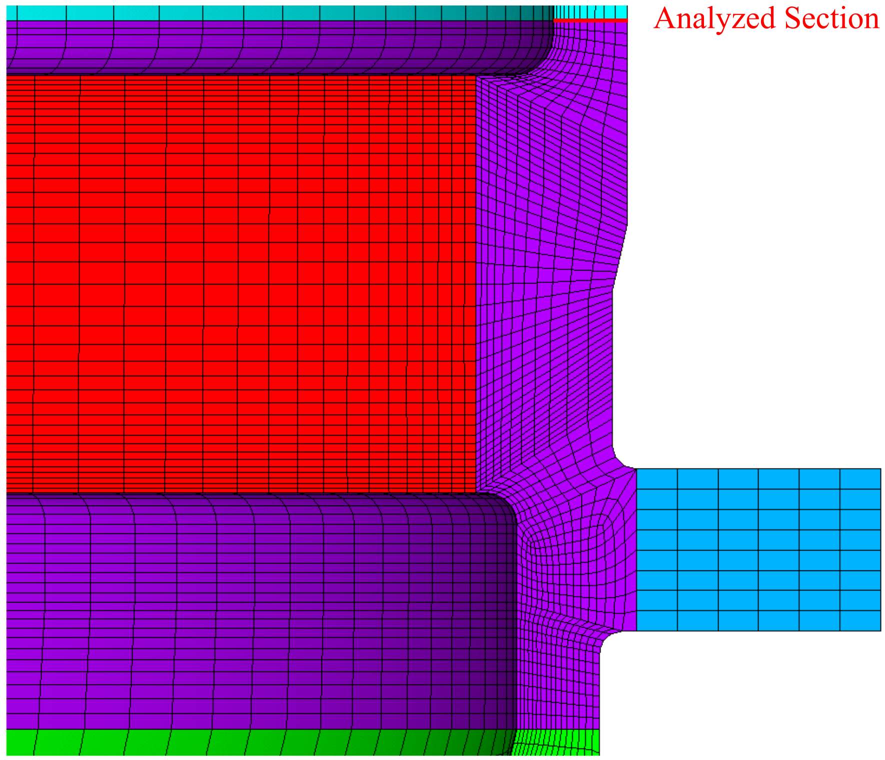

Figure 3: Postulated Defects at the SG Tubesheet Weld Junction on the Secondary Side

Table 2: Fast Fracture Risk Evaluation for TS Weld Junction under In-Shop Secondary Hydrotest

Flaw Orientation	Shell Surface	Point on Flaw	Csr/Cs From Macros	Csr/Cs Manually calculated	Difference
Longitudinal	Inside	A	0.21425	0.21426	0.00%
Longitudinal	Inside	B	0.15750	0.15750	0.00%
Circumferential	Inside	A	0.85914	0.85914	0.00%
Circumferential	Inside	B	0.61831	0.61831	0.00%
Longitudinal	Outside	A	No Risk of fracture as the stresses normal to the crack plane are compressive at outside		
Longitudinal	Outside	B			
Circumferential	Outside	A			
Circumferential	Outside	B			

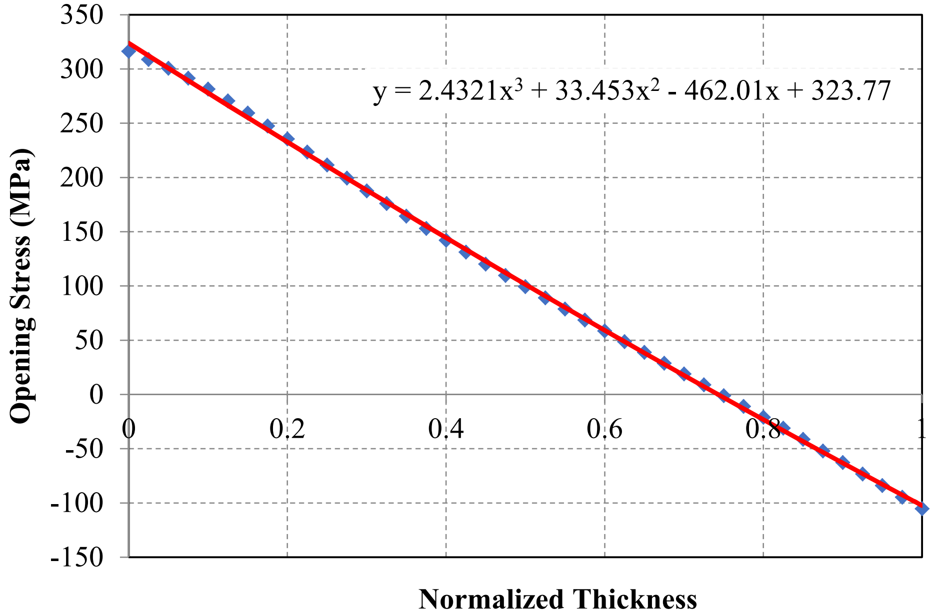

Figure 4: Curve Fitting of Through-the-Thickness Opening Stress at the SG Tubesheet Upper Junction under In-Shop HT

Table 3: Influence Coefficients (Calculated by Hand)

Influence Coefficients	Values
i_0	0.9949
i_1	0.6160
i_2	0.4782
i_3	0.4036

Table 4: Fracture Mechanics Calculations (by Hand)

Parameters	Calculated Values	Units
Stress Intensity Factor K_I	0.45	(1)
Temperature at Crack Front T	18	°C
RT_{ndt}	-21	°C
$T-RT_{ndt}$	39	°C
Plastic Zone Radius r_y	0.00106	(2)
Plastic Correction Factor α	1	-
Stress Intensity Factor Corrected for Plasticity K_{cp}	0.46	(1)
Material Toughness K_{IC}	132	MPa.√m
Cs	1.86	-
Csr	1.6	-
Csr/Cs	0.86	-

Note(s):

1. The stress intensity factor is normalized by $Rp\sqrt{t}$ where Rp is the material yield strength and t the wall thickness.
2. The plastic zone radius is normalized by $\sqrt{t}$ where t is the wall thickness.

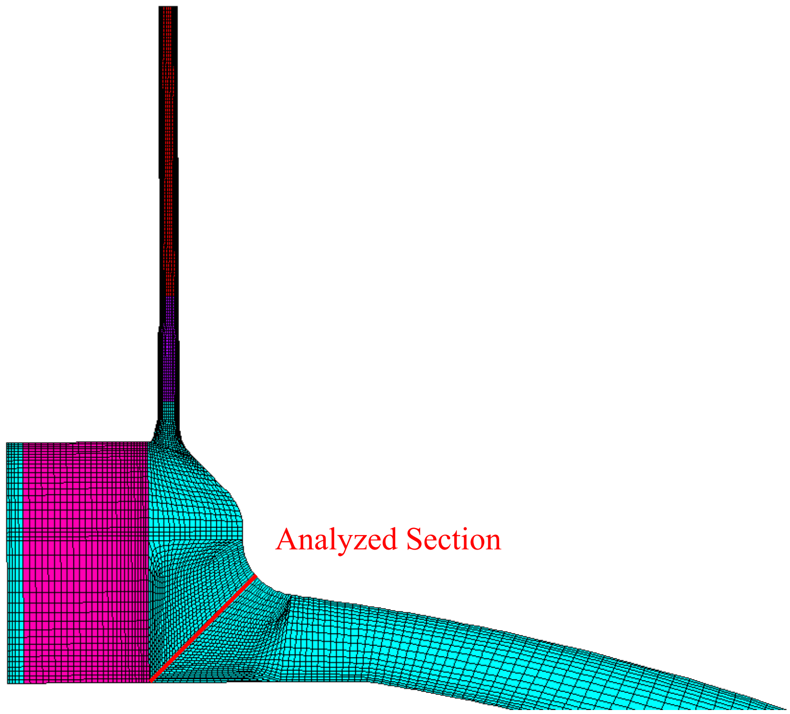

Figure 5: Postulated Defects at the SG Steam Outlet Knuckle Region

Table 5: Fast Fracture Risk Evaluation at the Steam Outlet Knuckle Region under a Category 4 Transient

Flaw Orientation	Shell Surface	Point on Flaw	Csr/Cs From Macros	Csr/Cs Manually calculated	Difference
Longitudinal	Inside	A	0.21	0.21266	1.27%
Longitudinal	Inside	B	0.22049	0.22049	0.00%
Circumferential	Inside	A	0.00794	0.00794	0.05%
Circumferential	Inside	B	0.00752	0.00752	0.07%
Longitudinal	Outside	A	0.15042	0.14928	-0.76%
Longitudinal	Outside	B	0.17463	0.17092	-2.13%
Circumferential	Outside	A	0.14283	0.14273	-0.07%
Circumferential	Outside	B	0.19113	0.19081	-0.17%

CONCLUSION

A complete set of calculation macros using the ANSYS® APDL (2017) are developed for the fast fracture analyses in compliance with the Appendix ZG rules of the RCC-M Code (2012). To demonstrate the capability and validity of the developed macros, two benchmarking cases are presented: one is the brittle fracture analysis for the SG upper tubesheet junction to secondary shell under in-shop secondary hydrotest; the other is the ductile tearing risk analysis at the knuckle region of the SG steam outlet nozzle under a Category 4 transient. The benchmarking results show excellent agreements with those obtained from the hand calculation, thus indicating that the developed macros are validated and can be utilized to evaluate the RCC-M fast fracture risks with assurance. Additionally, the developed macros provide an efficient computational tool for fast fracture analyses especially in the need of production work. All the RSE-M tables (2016) are digitized and provided in text files that are read directly by the macros such that the stress intensity factors for different flaw shapes, locations and sizes can be immediately obtained in a single analysis analysis run. This thus makes these developed macros suitable for the production work of fast fracture analyses per the regulatory code requirements.

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