Probabilistic fracture mechanics analysis of reactor pressure vessel with underclad and through-clad cracks under pressurised thermal shock transient

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Abstract: Semi-elliptical underclad cracks resulting from the fabrication process of a reactor pressure vessel (RPV) were able to be detected by non-destructive testing method. Meanwhile, after long-term operation under severe conditions, such as high temperature, high pressure, and irradiation, the RPV becomes brittle and susceptible to damage, especially when subjected to pressurised thermal shocks (PTS). Therefore, the probabilistic fracture mechanics (PFM) analysis of RPV with the crack should be applied to evaluate the operation safety. To the best of the authors’ knowledge, few studies or computer codes have applied PFM analysis for such cracks. Therefore, this study conducts PFM analysis for cracks by modifying the calculation procedure of FAVOR 12.1 computer code. The results show that during the

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lifetime of a nuclear power plant, such cracks will not threaten the RPV’s safety. Additionally, three methods were proposed to improve FAVOR 12.1’s ability to perform PFM analysis for axial through-clad cracking.

**Keywords:** stress intensity factor; reactor pressure vessel; probabilistic fracture mechanics; pressurised thermal shock.


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Kuen Ting, Vice President and Professor of Lunghwa University of Science and Technology, has expertise in the field of nuclear engineering applications (risk analysis, solid mechanics, and probabilistic fracture mechanics). In addition, his research fields include nano-characterisation (AFM, nanoindentation and ellipsometer), plasma applications (fruit freshness maintenance, sterilisation, DLC, TCO, and AP), Biomedical engineering (cosmic surgery heat transfer, Doppler blood flow measurements, and IR), and heavy computations (parallel computations, molecular dynamics, FEM and meshless).

Anh Tuan Nguyen is PhD candidate of National Chung Hsing University. His major study focuses on probabilistic fracture mechanics, particularly for reactor pressure vessels under pressurised thermal shock transients.

Lihua Wang, PhD, Deputy Division Director and Research Supervisor at the Industrial Technology Research Institute, has expertise in the fields of nuclear energy and material science engineering.

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1 **Introduction**

Reactor pressure vessels (RPVs), the most important component of pressurised water reactors (PWRs), become brittle after long-term operation under severe conditions (e.g., neutron radiation, high pressure, and high temperature), especially in the beltline region. Pressurised thermal shock (PTS) transients, a potential threat to the structural integrity of the RPV, should be carefully considered during the plant’s operating life and have been studied for more than 30 years (Qian and Niffenegger, 2013; Jhung et al., 2010).
During transient loading, the existence of cracks threatens the structural integrity of the RPV. The critical crack size has been analysed through fracture mechanics calculations for some well-known types of cracks such as through-clad cracks, semi-elliptical underclad cracks, and fully elliptical underclad cracks (Jhung et al., 2007). Through-clad cracking has been widely considered in many studies, including round robin studies, on the structural integrity of RPVs through both deterministic (Jhung et al., 2009) and probabilistic fracture mechanics analysis (Chen et al., 2015). The effect of postulated cracks on the structural integrity of a PWR RPV was analysed by a deterministic method (Jhung et al., 2007) and fracture mechanical analysis for a Water Water Energetic Reactor (WWER) RPV under a thermal shock transient (Abendroth and Alststadt, 2007). In addition, probabilistic fracture mechanics analysis of VVER was performed for several PTS loading transients with the appearance of through-clad cracking (Pistora et al., 2014). The behaviour of the crack and the effects of the crack distribution on the failure probability were investigated (Qian et al., 2014). However, this type of cracking has not been found in the cladding of a real RPV (IAEA, 2010). Moreover, because of the increasing role of probabilistic analyses in safety assessments for nuclear power plants in the USA (Pugh et al., 2007), several specially designed computer codes, such as VISA (Stevens et al., 1983), OCA-P (Chauveton and Ball, 1984), PASCAL2 (Onizawa et al., 2010), and FAVOR (Dickson et al., 2012), have been developed to conduct probabilistic fracture mechanics analysis for RPVs. In these codes, through-clad cracks are mainly considered, and full-elliptical underclad cracks (full-elliptical embedded cracks) are additionally considered in FAVOR 12.1. On the other hand, few studies have considered the effect of semi-elliptical underclad cracking on RPV integrity through deterministic and probabilistic analysis for RPVs. However, in practice, this crack has been the consequence of the welding process (USNRC, 2011) and was able to be detected inside the wall thickness of a real cladded RPV in 1986 (Gruber et al., 1986).

From deterministic analysis results, the stress intensity factors in underclad cracking are two-times smaller than those of through-clad cracking and are almost negligible at the deepest point (Jhung et al., 2007). However, after long-time operation of an RPV under severe conditions, there is nothing to ensure that cracking does not threaten the structural integrity of an RPV. Following state-of-the-art structural integrity analysis trends and with the aim of evaluating the safe operation of an RPV, greater details on an assumed crack are achieved, and more precise results for safety assessment are obtained. It has been acknowledged that probabilistic fracture mechanics analysis should be applied for this type of cracking. Therefore, in this study, based on an influence method with shape factors (Marie and Chapuliot, 2005, 2008), the stress intensity factors are estimated, and PFM analyses are conducted by FAVOR 12.1, a computer code specifically designed to perform PFM analysis for RPV under PTS transients by National Oak Ridge Laboratory, for both crack types; in particular, the conditional probabilities of crack initiation are calculated. For through-clad semi-elliptical cracks, the stress intensity factor and the conditional probability of crack initiation (CPI) are compared with the results from other participants (IAEA, 2010; Jhung et al., 2005; NEA, 2016) to confirm the modified procedure. Then, those parameters of semi-elliptical underclad cracking are evaluated in consideration of nuclear power plant safety. In addition, axial semi-elliptical through-clad cracking (axial inner-surface cracking) is not modelled in the PFM module of FAVOR 12.1; this paper proposes three simple methods to evaluate the CPI of a postulated axial semi-elliptical through-clad crack to improve the capabilities of FAVOR 12.1.
2 Analysis method

2.1 Deterministic and probabilistic fracture mechanics analysis

The flowchart of the computation model and the data stream of FAVOR 12.1, as in Figure 1, shows the procedure for conducting PFM analysis for RPVs. The deterministic fracture mechanics analysis performed by the Load Generator FAVLoad (DFM module) includes the RPV geometry, cladding, base metal properties, and temperature history, pressure, and heat transfer coefficient of the coolant as input data. In the DFM module, the temperature, axial stress, and circumferential stress histories along with the wall thickness are calculated using a 1-D finite element model. In addition, the stress intensity factor ($SIF$) of the postulated crack is estimated based on the stress variations and shape factors. Hence, the deterministic result consists of the distributions of temperature, stress and SIF with the wall thickness during the transient event.

Figure 1 Modified procedure to conduct PFM analysis for RPV with axial through-clad crack and semi-elliptical axial underclad crack
In FAVOR 12.1, the probabilistic fracture mechanics analysis performed by the Probabilistic Fracture Mechanics Module FAVPFM (PFM module) uses the Monte Carlo method to estimate the conditional probability of crack initiation (CPI) and the conditional probability of vessel failure (CPF). The input of the PFM includes three main parts. The first part is the RPV material characteristics such as the Cu, Ni, and P contents; the chemistry factor; and the neutron fluence in the beltline region. The second part is the deterministic results involving the temperature, stress, and SIF distributions calculated by the finite element method in the previous step for postulated cracks at the wall thickness with time. The last part consists of crack properties, such as the crack depths, aspect ratios and crack densities of surface cracks, embedded cracks in welds, and the plate, based on three crack characteristic files. The beltline region is the main focus of the conducted analysis, and the SIF $K_I$ is estimated by the influence function method and compared with the fracture toughness $K_{Ic}$ at each transient step. If $K_I < K_{Ic}$, cracking is not initiated; if $K_I > K_{Ic}$, then crack initiation will occur, and the crack is assumed to become of infinite length, where the CPI is $P(K_{Ic} < K_I)$, expressed in equation (1). The crack will propagate and be arrested when $K_I < K_{Ia}$, and the analysis jumps to the next simulation step. The process continues until the vessel fails (crack propagation up to 90% of the wall thickness) or until the transient time has passed (William et al., 2012).

$$
P(K_{Ic} \leq K_I) = \begin{cases} 
0; & K_I \leq aK \\
1 - \exp\left\{\left(-\frac{K_I}{K_{Ia}}\right)^4\right\}; & K_I > aK
\end{cases} 
$$

(1)

$$
a_K = 19.35 + 8.335 \exp(0.02254(T - RT_{SDF})) \tag{2}
$$

$$
b_K = 15.61 + 50.132 \exp(0.008(T - RT_{SDF})) \tag{3}
$$

2.2 Three methods to perform probabilistic analysis for axial through-clad cracks

In several round robin projects, such as PROSIR (NEA, 2016), IAEA (IAEA, 2010), and international PFM round robin analyses among Asian countries on RPV integrity during pressurised thermal shocks (Kanto et al., 2012), the safe operation of RPVs under PTS shown in Figure 2 was evaluated by PFM analysis assuming axial through-clad cracking or the so-called axial inner-surface-breaking cracking. The crack is presented in Figure 3 with shape 2. Because of the non-destructive experts’ ideas in the PFM analysis of FAVOR 12.1, all the through-clad cracks are assumed to be circumferentially oriented (Dickson et al., 2012); hence, only the SIFs of circumferential cracks are chosen for comparison with fracture toughness at the crack tip. To conduct PFM for RPVs with axial through-clad cracking, the procedure, i.e., the source code, has to be modified. The basic principle in modifying the procedure, in this case, is to postulate an axial crack by replacing the SIF values of circumferential cracks by those of axial cracks. In accordance with this principle, three different methods were developed to model axial cracking in the PFM module. Each method is applied at different stages of the procedure. Using one of the three methods is sufficient to perform PFM analysis for an axial crack.
Figure 2  The scheme for reactor pressure vessel under pressurised thermal shock transient

![Figure 2: Reactor Pressure Vessel](image)

Figure 3  Postulated through-clad crack geometries

![Figure 3: Clad Crack](image)

The first method (Method 1) is a trial-and-error method that is applied to the input of the deterministic analysis by changing the pressure history of the input parameters to make the distributions of the new axial stress equal that of the original hoop stress and the SIF of the new circumferential crack equal to the SIF of the original axial crack. In this study, the input pressure is changed and shown in Figure 6a; from 0 to 7200 seconds, the new pressure is 2.2 times the original pressure, and from 7200 to 15000 seconds, the new pressure is twice the original pressure. Then, when conducting PFM analysis, the SIF of the original axial through-clad cracking will be used for comparison with the fracture toughness at the crack tip, and the CPI of the axial through-clad crack will be estimated.

The next method is Method 2, in which the deterministic result consists of the temperature, stress and SIF histories of both axial and circumferential through-clad cracking with the wall thickness during the transient time. Method 2 manually replaces the SIF values of the circumferential crack with the SIF values of the axial cracks in the deterministic results. Using this method, the SIF values of the axial crack will be utilised to estimate the CPI of the RPV. The last method is Method 3, which is applied during the calculation process of the PFM module. In the original source code of the PFM module, only the SIFs of circumferential through-clad cracks are chosen from the deterministic
results for comparison with the fracture toughness at the crack tip. Hence, the source code of the PFM module was modified to collect the SIFs of the axial cracks for comparison with the fracture toughness to able to perform probabilistic analysis for axial through-clad crack.

2.3 Procedure to conduct probabilistic analysis for through-clad cracks and semi-elliptical underclad cracks

By applying Method 1, Method 2 or Method 3 of the previous section, FAVOR 12.1 can perform PFM analysis of axial through-clad cracks with crack shape 2. However, a limitation lies in the aspect ratios, whereby only cracks with aspect ratios of the crack length over the crack depth \(c/a\) equal to 1, 3, 5 and infinity are able to be analysed. In addition, FAVOR 12.1 is unable to perform analysis for semi-elliptical underclad cracks, as shown as in Figure 4, because the cracks are not considered in the deterministic analysis. In this study, the procedure for performing PFM analysis of FAVOR 12.1 is modified to be capable of increasing the number of aspect ratios of the evaluated through-clad cracks and to estimate the CPI for the postulated semi-elliptical underclad cracking. The modified procedure for performing PFM analysis for axial through-clad (with crack shape 1 in Figure 3) and axial semi-elliptical underclad cracks for a wider range of aspect ratios, i.e., crack length to the crack depth \(c/a\) of 1 to 16 and infinity, and for ratios of the crack depth to the cladding thickness \(a/r\) from 0 to 4 is shown in Figure 1. From the fracture mechanics results (deterministic result) given by FAVOR 12.1, the stress distributions are analysed as given in equations (4), (5), (6) to calculate the polynomial stress description of the uncracked wall thickness during each time step, as shown Figure 5 (Marie and Chapuliot, 2008). Then, the shape factors and stress descriptions are incorporated to estimate \(K_I\) at the crack tip of axial through-clad cracks or axial semi-elliptical underclad cracks, as presented in equations (7) and (8).

\[
\sigma_r = \sigma_f + \sigma_r \\
\sigma_f = \sigma_0 + \sigma_f \left( \frac{u}{h+r} \right) \quad \text{If } u < r \\
\sigma = \sigma_f + \sigma_r \\
\sigma_f: \text{stress in base metal} \\
\sigma_r: \text{stress in clad} \\
\sigma_c: \text{opening stress in the cracked section} \\
u: \text{radial distance to inner surface}
\]

The expression used to calculate the SIF of a through-clad crack of shape 1 is

\[
K_I = \left[ \sum_{j=0}^{i} \sigma_j \left( \frac{a+r}{h+r} \right)^j + \sum_{j=0}^{i} \sigma_j \left( \frac{a+r}{h+r} \right)^j \right] \sqrt{\pi (a+r)}
\]
The expression to calculate the SIF of a semi-elliptical underclad crack is

\[
K_I = \sum_{i=0}^{\infty} \sigma_i j_i \left( \frac{a + r}{h + r} \right)^{\frac{1}{2}} \sqrt{\pi a}
\]  

(8)

\(a\): crack depth in the ferritic metal

\(h\): wall thickness

\(u\): radial distance to inner wall

\(\sigma_0 - \sigma_4, \sigma_{0r}, \sigma_{1r}\): stress components

\(i_0 - i_4, i_{0r}, i_{1r}\): shape factors (influence coefficients)

The loop used to calculate \(K_I\) is repeated iteratively until the transient time has passed. In the deterministic result of FAVOR, the stress intensity factors are estimated at nine defined points from the inner surface to the middle of the wall thickness at every transient time step. To conduct PFM analysis of an axial through-clad crack of shape 1 or an axial semi-elliptical under-clad crack, the SIF values of those cracks evaluated at the nine points using S. Marie shape factors have to be replaced in the deterministic result before performing PFM analysis. Then, in the PFM analysis, with the input crack properties, the SIFs at the crack tip will be determined by interpolating the SIF values of the nine points and compared with the fracture toughness at the deepest point to estimate the CPI. In this case, the nine points are at 0, 2.08, 3.818, 10.376, 15.564, 20.752, 41.506, 62.255, and 103.759 mm of wall thickness from the inner surface. Before doing this, a very important step is to verify whether this modified procedure is correct. In Section 2.1, the SIFs and CPIs of an axial through-clad crack of shape 2 calculated by FAVOR 12.1 and participants are compared. Therefore, in this step, the SIFs and CPIs of an axial through-clad crack of shape 1 estimated using S. Marie’s shape factors and the above procedure are compared with the results of the through clad-crack of shape 2 to verify the procedure. Then, the procedure is applied to facilitate PFM analysis of an axial semi-elliptical underclad crack.

**Figure 4** Postulated underclad crack geometries
3 RPV geometries, material properties, crack types and loading transient

3.1 RPV geometry

A pressure vessel with an inner radius $R_i$ of 1994 mm, a thickness of the base metal $h$ of 200 mm, and a thickness $r$ of 7.5 mm for the cladding subjected to a PTS transient was chosen for evaluation.

3.2 Material and mechanical properties

To satisfy the requirements of a PWR RPV in terms of strength, toughness, weldability, ductility, and corrosion resistance, the RPV wall was manufactured with two layers. The base metal is made of ferritic low alloy steel, and the cladding is made of austenitic stainless steel. The temperature-dependent thermal and mechanical properties of the base metal, welds and cladding are presented in Table 1 (IAEA, 2010). Moreover, the chemical compositions in terms of Cu and Ni are essential variables for neutron irradiation embrittlement, along with initial RTNDT, shown in Table 2 (NEA, 2016), and are input parameters for the probabilistic analysis.

Table 1 Thermal and mechanical properties of base metal, welds and cladding of the RPV

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Base metal &amp; welds</th>
<th>Cladding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal expansion $\alpha$ ($10^{-6}$°C$^{-1}$)</td>
<td>20</td>
<td>10.9</td>
</tr>
<tr>
<td>300</td>
<td>12.9</td>
<td>17.7</td>
</tr>
<tr>
<td>Conductivity $\lambda$ (W.m$^{-1}$.°C$^{-1}$)</td>
<td>20</td>
<td>54.6</td>
</tr>
<tr>
<td>300</td>
<td>45.8</td>
<td>18.6</td>
</tr>
<tr>
<td>Thermal diffusivity $\lambda/\rho C_p$ ($10^{-6}.m^2.s^{-1}$)</td>
<td>20</td>
<td>14.7</td>
</tr>
<tr>
<td>300</td>
<td>10.6</td>
<td>4.3</td>
</tr>
<tr>
<td>Density $\rho$ (kg/m$^3$)</td>
<td>20-300</td>
<td>7.6</td>
</tr>
<tr>
<td>Yield strength $S_y$ (Rp0.002)</td>
<td>20</td>
<td>588 / 646</td>
</tr>
<tr>
<td>300</td>
<td>517 / 563</td>
<td>270</td>
</tr>
<tr>
<td>Young modulus $E$ (GPa)</td>
<td>20</td>
<td>204</td>
</tr>
<tr>
<td>300</td>
<td>185</td>
<td>176.5</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu$</td>
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Table 2  Chemical composition and initial $RT_{NDT}$

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<th></th>
<th>$RT_{NDT}$</th>
<th>% Copper (Cu)</th>
<th>% Phosphorus (P)</th>
<th>% Nickel (Ni)</th>
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<tr>
<td></td>
<td>Mean 1SD</td>
<td>Mean 2SD</td>
<td>Mean 1SD</td>
<td>Mean 2SD</td>
</tr>
<tr>
<td>Base metal</td>
<td>–20°C 9°C</td>
<td>0.086 0.02</td>
<td>0.0137 0.002</td>
<td>0.72 0.1</td>
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<tr>
<td>Weld</td>
<td>–30°C 16°C</td>
<td>0.120 0.02</td>
<td>0.0180 0.002</td>
<td>0.17 0.1</td>
</tr>
</tbody>
</table>

3.3 Type and geometry of crack

An axial through-clad crack with two crack shapes, shown as in Figure 3, with a crack depth $a'$ (depth in both the cladding and base metal) of 19 mm and a crack length $2c$ of 117 mm, was postulated in the ferritic wall at the weld and base metal of the PWR RPV. An axial semi-elliptical underclad crack, shown as in Figure 4, with a crack depth $a$ of 12 mm (depth in the base metal only) and a crack length $2c$ of 117 mm, was postulated in the ferritic wall of the RPV. In this study, the $K_I$s at the deepest points of an axial through-clad crack of shape 1 and an axial semi-elliptical underclad crack were evaluated by the influence method with the shape factor from (Marie and Chapuliot, 2008), and the $K_I$ at the deepest point of the axial through-clad crack of shape 2 was evaluated by FAVOR 12.1.

3.4 Loading transient and participants

A typical PTS transient called TR3 was considered in this study. The variations in the inner pressure, fluid temperature and heat transfer coefficient during the transient time are shown as in Figure 6. The repressurisation and increasing of the temperature occurred at approximately 7200 s of the transient; hence, the deterministic analysis would be focused on that time to determine the temperature and stress variations with the wall thickness. In this transient, the pressure was presumed to be the dominant factor because of its rapid increase (Jhung et al., 2005). The participants and their methods are presented in Table 3.

Figure 6  (a) Inner pressure and fluid temperature transient histories and (b) heat exchange coefficient transient history
Figure 6  (a) Inner pressure and fluid temperature transient histories and (b) heat exchange coefficient transient history (continued)

![Heat Exchange Coefficient](image)

Table 3  Participants and computer codes

<table>
<thead>
<tr>
<th>Participant</th>
<th>Organisation</th>
<th>Deterministic analysis</th>
<th>Probabilistic analysis</th>
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<tr>
<td>P1</td>
<td>Korea Power Engineering Company (KOPEC)</td>
<td>PREVIAS</td>
<td>PREVIAS</td>
</tr>
<tr>
<td>P2</td>
<td>Korea Power Engineering Company (KOPEC)</td>
<td>ABAQUS V. 5.8 &amp; Influence Function Method</td>
<td>Fortran</td>
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<tr>
<td>P3</td>
<td>Korea Atomic Energy Research Institute (KAERI)</td>
<td>ABAQUS V. 6.3 Influence Function Method</td>
<td>PFAP Version 1.0</td>
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<td>Korea Atomic Energy Research Institute (KAERI)</td>
<td>ABAQUS V. 6.3 Influence Function Method</td>
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<tr>
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<td>Korea Institute of Nuclear Safety (KINS)</td>
<td>PROBie-Rx</td>
<td>PROBie-Rx</td>
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<tr>
<td>P6</td>
<td>Korea Institute of Nuclear Safety (KINS)</td>
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<td>Origin</td>
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<td>P7</td>
<td>Present Study</td>
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<td>TECNATOM</td>
<td>Spain</td>
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4 Results and discussion

4.1 Deterministic results

In the deterministic analysis, temperature and hoop stress variations with the wall thickness were expressed using thermal and mechanical properties, as in Table 1, and the 1-D finite element model in the FAVOR code. The temperature and hoop stress distributions at 7200 seconds are shown in Figure 7a, 7b. It is observed in Figure 7a that because of the significantly lower thermal conductivity of the cladding material, the temperature gradients in the cladding are steeper than those in the base metal (IAEA, 2010). Accordingly, because of the different thermal expansion coefficients between the base metal and the cladding, the stresses in the cladding are much higher than those in the base metal, as shown in Figure 7b (IAEA, 2010). Additionally, the temperature histories at crack tip are compared in Figure 8a. This study’s temperature and hoop stress variations with the wall thickness and the temperature histories at the crack tip show good agreement with the results from other participants. Therefore, it is important to continue to the next step to calculate the SIFs by the influence method and perform a comparison with other results.

Figure 7 Comparison of (a) temperature and (b) hoop stress distributions with wall thickness at 7200 s
The SIFs of axial through-clad cracks of crack shape 1 and 2 are estimated and shown in Figure 8b. Three results of this study in Figure 8b are the following: Present Study 1, calculated by the S. Marie shape factors; Present Study 2, calculated from deterministic analysis of FAVOR 12.1; and New Axial Crack, calculated by Method 1. The New Axial Crack SIFs are almost identical and only slightly higher than those of the other two methods’ results from 500 s to 4500 s and at the critical time (7200 s) because of the new
higher input pressure. There are small differences in the SIFs among the results of other participants. There are two reasons for this result. The first reason is the crack geometries: participants P4 and P6 as well as Present Study 1 used cracks of shape 1, and participants P1-P3 and P5, Present Study 2, and New Axial Crack used cracks of shape 2. However, the SIF evaluated here is at the deepest point, and thus, the influence of the crack shape on the SIF value is negligible, as proved by the IAEA report (IAEA, 2010). The second reason, which is also the main reason, is the different calculation methods. Participants P4 and P6 used a 3D finite element model to directly determine the J-integral, and participants P1-P3 and P5, Present Study 1 and 2, and New Axial Crack used the influence function method with different shape factors (IAEA, 2010). All the SIF values of this study in Figure 8b show good agreement with the results of the other participants. This demonstrates that the $K_I$ of axial through-clad cracks of shape 2 estimated by Method 1 and the $K_I$ of axial through-clad cracks of shape 1 estimated by the influence method with the shape factors of Marie and Chapuliot (2008) are acceptable. This represents the foundation for continuing onto the probabilistic analysis for RPVs.

4.2 Probabilistic fracture mechanics results of axial through-clad cracks of crack shape 2 calculated with three methods

From Section 2.2, Methods 1, 2, and 3 are shown in detail, and from Section 4.1, Method 1 is shown to be suitable for PFM analysis for axial through-clad cracks of shape 2. The CPI results for the weld and base metal estimated by the three methods are shown and compared with results from the other participants in Figures 9a, 9b. The CPI results estimated by Method 1 are slightly higher than those of Method 2 and Method 3 because the SIF results from the first method are higher than the SIF results of the remaining methods. The CPI values from participant P4 are the lowest among those from the participants, but when the fluence values increase, the CPI values from participant P4 also converge with those of the other methods. Because the SIF values of participant P3 are the highest values in Figure 8b, the CPI values from that participant are higher than the CPI values from all participants. The results of this study (Method 1, Method 2, and Method 3) are in good agreement with the results from the other participants and are strongly dependent on the fluence levels.

Among the results of the three methods, Method 1 only gives approximate results because the SIFs are drawn from a trial-and-error method. Methods 2 and 3 give the same results because they used exact SIFs of the axial cracks in comparison with the fracture toughness at the crack tip. Generally, the above methods present various strengths and weaknesses. Method 1 is easy to apply but is time consuming and inexact. Because of the use of the trial-and-error method and because the input pressure has to be changed, this method cannot simultaneously compute other cracks such as outer surface-breaking cracks or embedded cracks (full elliptical underclad cracks). Method 2 is not difficult to use and gives exact results. Method 3 is slightly complicated because the source code has to be changed. Therefore, it can be assumed that Method 2 is the easiest and most exact method for calculating the PFM of RPV's with axial through-clad cracks using FAVOR 12.1. Nonetheless, it is also acknowledged that all three methods can be applied to improve FAVOR 12.1 for conducting PFM analysis on axial through-clad cracks of shape 2.
4.3 Probabilistic fracture mechanics results of axial semi-elliptical underclad cracks calculated with S. Marie shape factor data

To the best of the authors’ knowledge, there is minimal research considering PFM analysis for semi-elliptical underclad cracks; therefore, the main objective of this section is to evaluate the probabilistic analysis of an RPV with an axial semi-elliptical underclad crack generated by a typical pressurised thermal shock. In this study, the influence method with shape factors from Marie and Chapuliot (2008) are used to estimate $K_I$ at the...
As presented in Section 2.2, first, the $K_i$s at the deepest point of an axial through-clad crack of shape 1 are computed by the influence method with the shape factors from S. Marie to verify the modified procedure. This has been done in Section 4.1, and the calculated $K_i$s of the axial through-clad cracks of shape 1 show good agreement with the results of the axial through-clad cracks of shape 2 in Figure 8b. The $K_i$s at the nine points are calculated then applied to the deterministic results in the defined order as the method shown in Section 2.3 to estimate CPI of the axial through-clad cracks of shape 1. The CPI values of through-clad cracks of shape 1 (S. Marie) and those of through-clad cracks of shape 2 (FAVOR 12.1) at the weld and base metal with varying neutron fluences are shown in Figures. 11a and 11b. The values show very good agreement with each other, proving that the different crack shapes do not affect the probabilistic results, and the $K_i$s of through-clad cracks of shape 1 given by the influence method with S. Marie’s shape factors can completely replace $K_i$s of the cracks of shape 2 given by the FAVOR 12.1 deterministic analysis. The verifications also prove that the modified procedure of the PFM module is capable of facilitating PFM analysis for through-clad cracks of shape 1.

Based on the successful application of S. Marie’s shape factors for axial through-clad cracks, axial semi-elliptical underclad cracks are analysed. Figure 10a shows and compares $K_i$ variations characterising axial semi-elliptical underclad cracks with temperature at the crack tip between the present study’s results estimated by the influence method with S. Marie’s shape factors and Jhung’s results. The transient, RPV properties and axial semi-elliptical under-clad cracks from Jhung’s research are the same as those of this study (Jhung et al., 2007). The comparison shows a fair agreement between the results. There is small difference from 260°C to 300°C because the time steps in this study are not as fine as in the reference. In addition, Figure 10b shows the comparison of the $K_i$s of the through-clad and underclad cracks, calculated by the influence method with S. Marie’s shape factors. Apparently, the trends characterising the $K_i$ variations with the transient time of the two crack types are quite similar, but the $K_i$s values of the through-clad cracks are almost double the $K_i$s values of the underclad cracks. Evidently, in this case, the crack type difference causes the disparity. The $K_i$s values at the nine points are computed then applied to the deterministic results in the defined order as the method shown in Section 2.3 to estimate CPI of the axial semi-elliptical underclad crack. The comparison of the CPI of different crack types in Figures 11a and 11b shows that the trends of the CPI variations with neutron fluence of the two crack types are very similar, but the values of the through-clad cracks are approximately five orders of magnitude higher than those of the semi-elliptical underclad cracks. Those results are consistent with the SIF results and show that the crack type obviously affects the CPI. Given that the CPI values are less than $5 \times 10^{-6}$ (the acceptable probability for US regulatory bodies), it is proved that underclad cracking does not affect the structural integrity of RPVs after long-time operation under PTS events. Additionally, the application of the influence method with S. Marie’s shape factors can estimate $K_i$ for both through-clad cracks of shape 1 and semi-elliptical under-clad cracks in the circumferential direction (Marie and Chapuliot, 2008). Thus, the results prove that the application of S. Marie’s shape factors improves FAVOR 12.1’s ability to evaluate the CPIs of semi-elliptical underclad cracks and the CPIs of through-clad cracks of greater size.
Figure 10 (a) Comparison of $K_I$ distributions with temperature at crack tip of axial semi-elliptical underclad crack between this study and reference results; (b) comparison of $K_I$ of axial through-clad crack and axial semi-elliptical underclad crack with the same crack depth of 12 mm in base metal.
Figure 11 Comparison of the distribution of the conditional probability of crack initiation of different crack types at (a) weld and (b) base metal

5 Conclusion

In this study, three methods of PFM analysis for axial through-clad cracks and one method of PFM analysis for axial semi-elliptical underclad cracks are introduced to FAVOR to improve the code’s capabilities. The following conclusions are drawn.

- Among the above three methods, Method 2 is the simplest and most exact method. Using this method, the probabilistic analysis of axial through-clad cracking can be achieved by FAVOR 12.1.
• Given the same crack depth in the base metal, at the deepest point, the SIF of axial through-clad cracks is almost two times that of axial semi-elliptical underclad cracks, and the CPI of axial through-clad cracks is five orders of magnitude higher than that of axial semi-elliptical underclad cracks. Therefore, the impact of through-clad cracks on the integrity of RPVs is also much higher than that of underclad cracks. In addition, underclad cracks do not affect the structural integrity of RPVs during long-term operation.

• This study improves FAVOR 12.1 by allowing it to calculate a PFM for a wider range of through-clad cracks in the axial directions, with aspect ratios of the crack length to the crack depth ($c/a$) from 1 to 16 and infinity and ratios of the crack depth to the cladding thickness ($a/r$) from 0 to 4.

• This study improves FAVOR 12.1 by allowing it to perform PFM analysis for axial semi-elliptical underclad cracks with aspect ratios of the crack length to the crack depth ($c/a$) from 1 to 16 and infinity and ratios of the crack depth to the cladding thickness ($a/r$) from 0 to 4.

In summary, the new methods presented above improve FAVOR 12.1’s capabilities to conduct PFM analysis for both through-clad cracking and semi-elliptical underclad cracking in the axial direction for broader ranges of crack sizes. Based on those improvements, PFM analyses conducted for RPVs become more realistic, with additional types and sizes of cracks able to be considered.

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References


Abbreviations

- $a$: Crack depth in the ferritic material (mm)
- $a'$: Crack depth including cladding thickness and the ferritic material (mm)
- $c$: Crack length (mm)
- $h$: Wall thickness (mm)
- $i_0$, $i_1$, $i_0^r$, $i_1^r$: Shape factors (influence coefficients)
- $K_{II}$ and $K_{IIa}$: Material initiation and arrest fracture toughness (MPa m0.5)
- $K_I$: Stress intensity factor (MPa m0.5)
- $r$: Cladding thickness (mm)
- $u$: Radial distance to inner wall (mm)
- $\sigma_f$: Stress in base metal (MPa)
- $\sigma_v$: Stress in cladding (MPa)
- $\sigma_0$, $\sigma_1$, $\sigma_0^r$, $\sigma_1^r$: Stress components

CPF: Conditional Probability of vessel Failure

CPI: Conditional Probability of crack Initiation

DFM: Deterministic Fracture Mechanics

PFM: Probabilistic Fracture Mechanics

PTS: Pressurised Thermal Shock

PWR: Pressurised Water Reactor

RPV: Reactor Pressure Vessel

SIF: Stress Intensity Factor

WWER: Water Water Energetic Reactor