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ESTIMATION OF STRESS INTENSITY FACTORS FOR NOZZLE CORNER CRACKS UNDER COMPLEX LOADING USING WEIGHT FUNCTION METHOD

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Abstract

The nozzle region of a reactor pressure vessel (RPV) is subjected to higher and more complex stresses compared to the remaining portions. The presence of nozzle corner cracks at the intersection of RPV nozzles has been a longstanding issue. The fracture analysis of these nozzle corner cracks is of paramount importance and critical for the effective design and assessment of RPV structural integrity. To evaluate the integrity of nozzle structures with cracks under combined loading conditions, accurate determination of the stress intensity factors along the crack front is required. This study employs the standardized analytical weight function method based on crack opening displacements (CODs) proposed by Wu-Carlsson, combined with finite element analysis, to obtain the weight function along the front of nozzle corner crack. The effectiveness of the weight function is validated by comparing the stress intensity factor calculation results obtained using the weight function method and finite element method under complex loading.

Introduction

After long-term operation, the reactor pressure vessel (RPV) in nuclear power plants is subjected to significant irradiation embrittlement aging effects, which pose a critical challenge to the plant's service life. Due to the localized structural inconsistencies, the local stress levels in the corner region of the nozzle can be extremely high. Under potential thermal transient loading, fatigue cracks are prone to initiate and propagate in this region. Fracture mechanics methods are commonly employed to analyze the potential effects of cracks located in the inner corner of the nozzle and assess the structural integrity of the RPV. Within the framework of structural integrity assessment for pressure vessels, the stress intensity factor (SIF), denoted as K, is one of the key parameters in fracture mechanics.

Many scholars have analyzed the stress intensity factor calculation methods for corner cracks in nozzles. Some researchers directly computed the stress intensity factor at the front of the corner crack using the finite element method. Nagai et al.(2015) employed the influence function method to calculate the stress intensity factor of surface cracks with arbitrary stress distributions and compared the results with finite element analysis for validation. Jin et al.(2021), within the framework of linear superposition technique, proposed a method to solve the stress field by fitting the stress on the crack surface using the response surface method.

The weight function method is a powerful tool for determining stress intensity factors. The weight function separates the consideration of load conditions and geometric conditions, focusing solely on the geometric characteristics of the crack body and remaining unaffected by the applied loads. Once the weight function is determined, it can be used without limitations to calculate the stress intensity factors under any loading conditions. The geometric conditions of nozzle corner cracks at the intersection between RPV nozzles and the cylindrical body are relatively complex. Currently, three-dimensional weight function methods such as Zhao's Slice Synthesis Weight Function Method (1989b, 1989a) and Orynyak's Point Load Weight Function Method (1994) are challenging to solve. Shen-Glinka (1991) proposed a weight function method based on their two-dimensional crack general weight function

approach, which is used to calculate stress intensity factors at the deepest and surface points of surface cracks and corner cracks but does not provide a solution for the entire crack front. Regarding the stress fitting of nozzle corner crack surfaces, the stress fitting is often one-dimensional (1990).

This study proposes a weight function for nozzle corner cracks based on the two-dimensional analytical weight function method by Wu-Carlsson(2022). By fitting the stress on the crack surface, the stress intensity factors at the crack front are calculated.

Weight Function Method

The weight function method is a highly efficient and accurate approach for calculating stress intensity factors, known for its ease of application. It is particularly suitable for rapidly determining stress intensity factors under various complex loading conditions. This method separates the geometric and loading factors that influence the stress intensity factor K, allowing for the integration of the product of the weight function of the crack body and the stress at the hypothetical crack position in the absence of a crack. This results in computational efficiency several orders of magnitude higher than that of finite element methods, providing high-precision values of K and other mechanical parameters for any crack length under arbitrary complex loading conditions within the applicable range of the weight function. The fundamental theory of the weight function method was initially proposed by Bueckner (1970) and Rice (1972) in the early 1970s, as shown in Equation 1.

$$\begin{aligned} \alpha &= a / W \\ \xi &= x / W \\ K &= f\sigma_0\sqrt{\pi\alpha} \\ f &= \int_0^{\alpha} \frac{\sigma(\xi)}{\sigma_0} \frac{m(\alpha, \xi/\alpha)}{\sqrt{\pi\alpha}} \sigma(x) d\xi \end{aligned} \tag{1}$$

Where α and ξ represent the dimensionless crack length and coordinate (a and x represent the actual crack length and coordinate, respectively), W is the characteristic size of the crack body. $\sigma(\xi)$ denotes the stress at the hypothetical crack position in the absence of an actual crack, and $m(\alpha, \xi/\alpha)$ represents the weight function of the considered crack body.

Wu-Carlsson developed a standardized analytical weight function method based on crack surface displacements. They proposed normalized series expansion expressions for the crack surface displacements of a crack under a reference loading condition. By utilizing the characteristics of the crack tip field, self-consistent conditions, crack mouth opening displacements (CMODs), and reasonable geometric conditions in various combinations, the relevant functions for the displacement series are derived. The coefficients $\beta_i(\alpha)$ in the crack weight function $m(\alpha, \xi/\alpha)$ are determined by taking the partial derivatives of the crack surface displacements with respect to the crack length. For an edge crack, the general formula for this analytical weight function is:

$$m\left(\alpha, \xi/\alpha\right) = \frac{1}{\sqrt{2\pi\alpha}} \sum_{i=1}^{J+1} \beta_i(\alpha) \cdot \left(1 - \frac{\xi}{\alpha}\right)^{i-3/2} \tag{2}$$

$$\beta_i(\alpha) = \left\{ \alpha \cdot \frac{\mathrm{d}F_{i-1}\left(\alpha\right)}{\mathrm{d}\alpha} + \frac{1}{2}\left[\left(2i-1\right) \cdot F_i\left(\alpha\right) - \left(2i-5\right) \cdot F_{\mathrm{i\text{-}1}}\left(\alpha\right)\right] \right\} \Big/ f_r\left(\alpha\right) \tag{3}$$

Where $F_i(\alpha)$ represents the coefficients of the series expansion of crack surface displacements. These coefficients are determined for an edge crack using a normalized analytical method based on various combinations of solution conditions.

By employing four solution conditions, and considering a reference loading condition where $\sigma_r(\xi)/\sigma_0 = 1$, the coefficients $F_i(\alpha)$ can be obtained from the following equation:

$$
\begin{aligned}
F_1(\alpha) &= 4 f_r(\alpha) \\
F_2(\alpha) &= \frac{1}{12\sqrt{2}}\left[315\pi\phi(\alpha) - 105V_r(\alpha) - 208\sqrt{2} f_r(\alpha)\right] \\
F_3(\alpha) &= \frac{1}{30\sqrt{2}}\left[-1260\pi\phi(\alpha) + 525V_r(\alpha) + 616\sqrt{2} f_r(\alpha)\right] \\
F_4(\alpha) &= \sqrt{2}V_r(\alpha) - \left[F_1(\alpha) + F_2(\alpha) + F_3(\alpha)\right] = \\
&\frac{1}{20\sqrt{2}}[315\pi\phi(\alpha) - 135V_r(\alpha) - 144\sqrt{2} f_r(\alpha)] \\
\phi(\alpha) &= \frac{1}{\alpha^2}\int_0^\alpha s \cdot \left[f_r(s)\right]^2 \mathrm{d}s
\end{aligned}
\tag{4}
$$

Where the variables f_r and V_r can be fitted using the following polynomial equation.

$$
\begin{aligned}
f_r(\alpha) &= \sum_{n=0}^{N} \lambda_n \alpha^n \\
V_r(\alpha) &= \sum_{n=0}^{N} \gamma_n \alpha^n
\end{aligned}
\tag{5}
$$

To obtain the weight function, it is necessary to first determine the dimensionless SIF f_r and CMOD V_r under the reference loading condition. From there, the coefficients β_i can be calculated, and ultimately, the weight function $m(\alpha, \xi/\alpha)$ can be determined.

PROPOSAL METHOD FOR THE NEW SIF SOLUTION

Geometrical and Load Description of the Problem

In general, the structure of a nozzle corner is highly complex. Therefore, this study focuses specifically on nozzle corner cracks. For the analysis, a simplified geometric structure of the vessel nozzle corner is chosen, as depicted in FIGURE 1. This structure includes a surface crack in the nozzle corner.

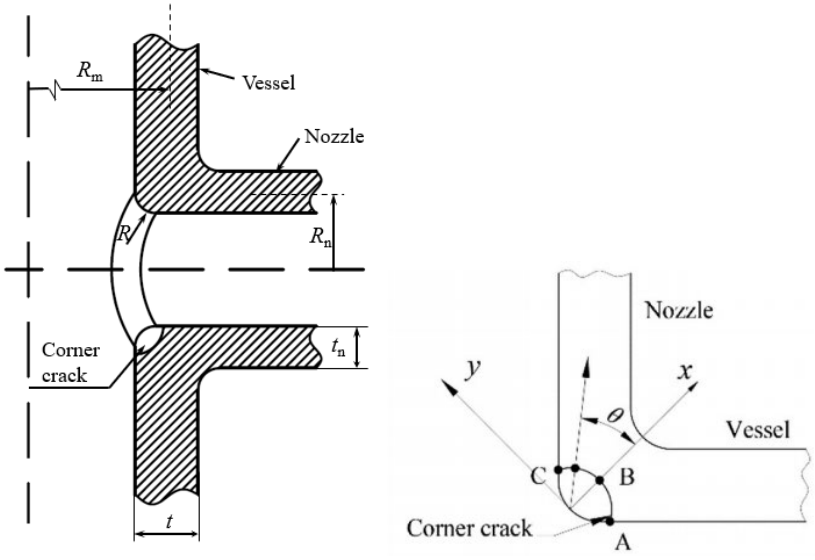
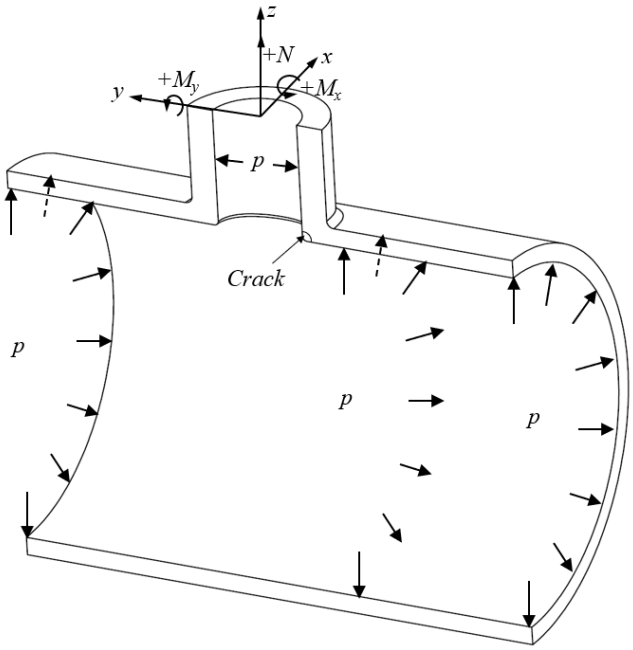


FIGURE 1 Geometry of the nozzle corner with surface crack.

In the given context, R_m and R_i represent the average radius and inner radius of the cylinder, while r_m and r_i represent the average radius and inner radius of the nozzle. t and t_n denote the wall thickness of the cylinder and nozzle, respectively. a represents the depth of the semi-elliptical crack, c denotes the crack length, and R represents the corner radius. The dimensions mentioned above are measured in millimetres (mm). In this study, a non-dimensional approach is applied to the geometric structure. The non-dimensional depth of the crack α, crack shape ratio φ, cylinder-nozzle average diameter ratio γ, and wall thickness ratio δ are defined as follows:

$$\alpha=\frac{a}{t},\quad \varphi=\frac{a}{c},\quad \gamma=\frac{d_n}{2R_m},\quad \delta=\frac{t}{t_n},\quad \kappa=\frac{t}{R_m} \tag{6}$$

Considering internal pressure as a common loading condition in pressure vessels, when the vessel is subjected to internal pressure, the nozzle end typically experiences axial loads and bending moments due to factors such as expansion of the vessel and piping, weight of the connecting components or equipment. Therefore, it is important to consider the combined effects of internal pressure and external loads (axial force and bending moment at the nozzle end) on the nozzle corner crack component. FIGURE 2 illustrates the complex loading conditions imposed on the analyzed structure.



FIGIRE2 Load conditions of nozzle with corner cracks.

In the case of complex loading conditions, this study refers to the definition of load ratio for combined loading effects on pipe components proposed by Lei (2014). The study defines the load ratio between internal pressure P, axial force N, and bending moment M applied to the nozzle corner crack component as follows:

$$\lambda_1=\frac{N}{\pi r_i^2 p}$$
$$\lambda_2=\frac{M}{r_m\left(|N|+\pi r_i^2 p\right)} \tag{7}$$

Where the loadings shown in FIGURE 2 include the pressure P acting on the inner wall of the vessel, the bending moment M applied to the nozzle end, and the axial load N. The directions of the loadings are defined in the figure.

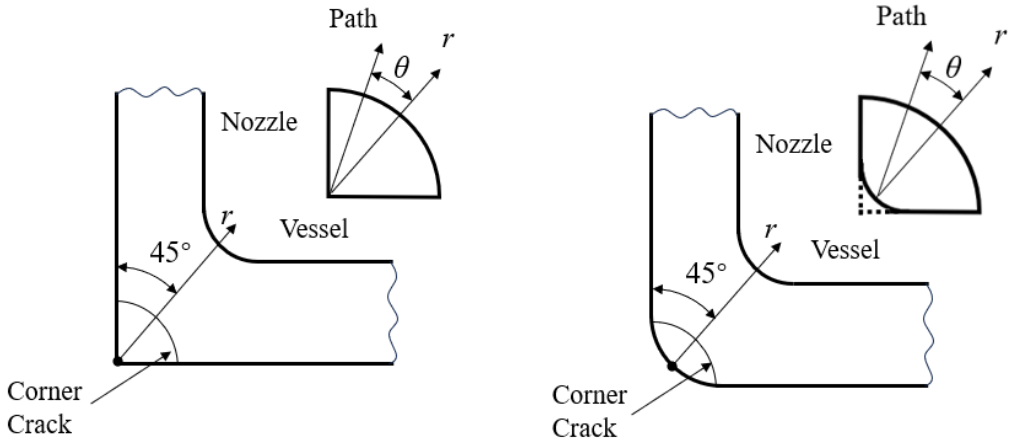
Three Dimensional Development of Wu-Carlsson Weight Function for Nozzle Corner Cracks

In this study, a method is proposed to directly apply the two-dimensional weight function by Wu-Carlsson on the crack surface, with the midpoint of the crack surface corner as the origin and pointing towards the direction of the wall thickness, as illustrated in FIGURE 3. This path can be considered as a two-dimensional edge crack. A reference loading of 1MPa stress is applied throughout the crack surface as the reference load. The non-dimensional stress intensity factor f_r and CMOD V_r (with the CMOD taken as the normal displacement of the crack surface at the origin) are obtained for different crack lengths under the reference loading condition using the finite element method. Consequently, the coefficients β_i for each crack length along the individual path can be determined. By extracting the stress along the path without a crack, the stress intensity factor K can be calculated.

As shown in FIGURE 3, a polar coordinate system is established with the midpoint of the nozzle corner as the origin and the direction pointing 45° towards the wall thickness as 0°. Eleven paths are evenly distributed from the inner surface of the nozzle to the inner surface of the cylinder, with the crack surface corner midpoint as the origin. The coefficients β_i are computed along these 11 paths, resulting in β_i values for different crack lengths and discrete points at different angles on the crack surface. A two-dimensional polynomial fitting is performed on the crack surface to obtain the β_i values. The same method is applied for stress fitting on the crack surface.

$$\begin{aligned}\beta_i(\xi,\theta) = {} & b_{i00} + b_{i10}\xi + b_{i01}\theta + b_{i20}\xi^2 + b_{i11}\xi\theta + b_{i02}\theta^2 + b_{i30}\xi^3 + b_{i21}\xi^2\theta \\ & + b_{i12}\xi\theta^2 + b_{i03}\theta^3 + b_{i40}\xi^4 + b_{i31}\xi^3\theta + b_{i22}\xi^2\theta^2 + b_{i13}\xi\theta^3 + b_{i04}\theta^4 \\ & + b_{i50}\xi^5 + b_{i41}\xi^4\theta + b_{i32}\xi^3\theta^2 + b_{i23}\xi^2\theta^3 + b_{i14}\xi\theta^4 + b_{i05}\theta^5\end{aligned} \tag{8}$$

$$\begin{aligned}\sigma(\xi,\theta)/\sigma_0 = {} & S_{00} + S_{10}\xi + S_{01}\theta + S_{20}\xi^2 + S_{11}\xi\theta + S_{02}\theta^2 + S_{30}\xi^3 + S_{21}\xi^2\theta \\ & + S_{12}\xi\theta^2 + S_{03}\theta^3 + S_{40}\xi^4 + S_{31}\xi^3\theta + S_{22}\xi^2\theta^2 + S_{13}\xi\theta^3 + S_{04}\theta^4\end{aligned} \tag{9}$$



(a) R = 0mm (b) R = 20mm

FIGURE 3 Two-dimensional weight function application path.

FINITE ELEMENT ANALYSIS AND NEW SOLUTION VERIFICATION

Based on the geometric parameters provided in Table 1, a finite element mesh model is established for the structure with an angled crack. Assuming R_m = 2130 mm, other geometric parameters can be calculated based on the non-dimensional parameters given in Table 1. The elastic modulus E is 204GPa, and the Poisson's ratio μ is 0.3. With these values, the finite element mesh model can be constructed for further analysis.

TABLE 1 Geometrical parameters of the model.

Geometrical parameters	Value	Definition of Parameters.
κ	0.0705	The ratio of cylinder wall thickness (t) to cylinder radius (R_m)
δ	1.5	The ratio of cylinder wall thickness (t) to nozzle wall thickness (t_n)
γ	0.1	The ratio of nozzle radius (R_n) to cylinder radius (R_m)
α	0.02/0.05/0.1/0.2/0.3/0.4	The ratio of defect depth (a) to cylinder wall thickness (t)
Φ	0.4	The ratio of defect depth (a) to defect length (c)
R	1.0	Radius of curvature of the corner inside the nozzle

Based on these geometric parameters, the analysis can be conducted using the 3D finite element software ABAQUS. The C3D8R finite element type can be used. Considering the symmetry of the structure and loading conditions, a 1/4 model can be created for the case with internal pressure and axial load, while a 1/2 model can be used for the case with overall bending moment. Both the models should consider the presence and absence of a crack. The stress distribution and Stress Intensity Factors (SIFs) can be obtained. The typical finite element mesh models for the crack and no-crack cases are shown in the figure. The stress field can be obtained using the no-crack model, while the SIFs can be calculated using the crack model.

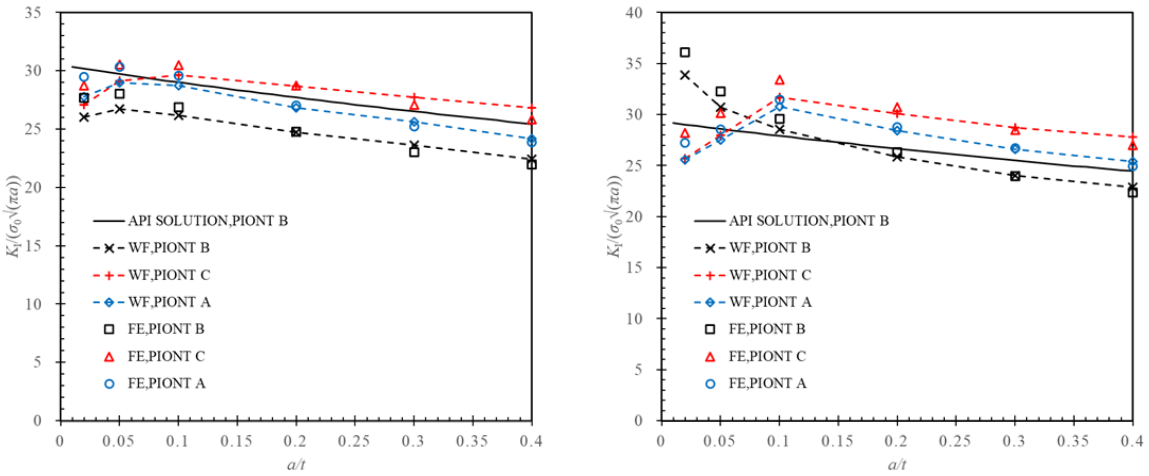
The Stress Intensity Factors (SIFs) under combined loading conditions can be determined using the weight function method based on the non-dimensional stress intensity factor f_r, crack mouth displacement V_r, and the stress distribution of the no-crack model obtained from the reference loading. The finite element results can be utilized to validate the solutions obtained from the weight function method. API 579 (2016) also provides an estimation method for SIFs of nozzle corner cracks under internal pressure. API 579 simplifies the stress distribution at the nozzle corner as a symmetric distribution and represents the stress distribution along the 45° line with a third-order polynomial. Based on the polynomial stress distribution, API 579 provides an estimation formula for the SIF at the deepest point of the crack.

$$K_I = \left[0.706A_0 + 0.537\left(\frac{2a}{\pi}\right)A_1 + 0.448\left(\frac{a^2}{2}\right)A_2 + 0.393\left(\frac{4a^3}{3\pi}\right)A_3 \right]\sqrt{\pi a} \tag{10}$$

Where the coefficients A_0-A_3 represent the fitting coefficients of the stress distribution polynomial.

Additionally, the SIFs can be calculated using the weight function method along a single path. FIGURE 4 demonstrates a comparison of the deepest point SIFs obtained using two methods for a typical model under internal pressure loading. It can be observed that the two-dimensional weight function method provides SIFs along a single path, while the API 579 solution tends to be more

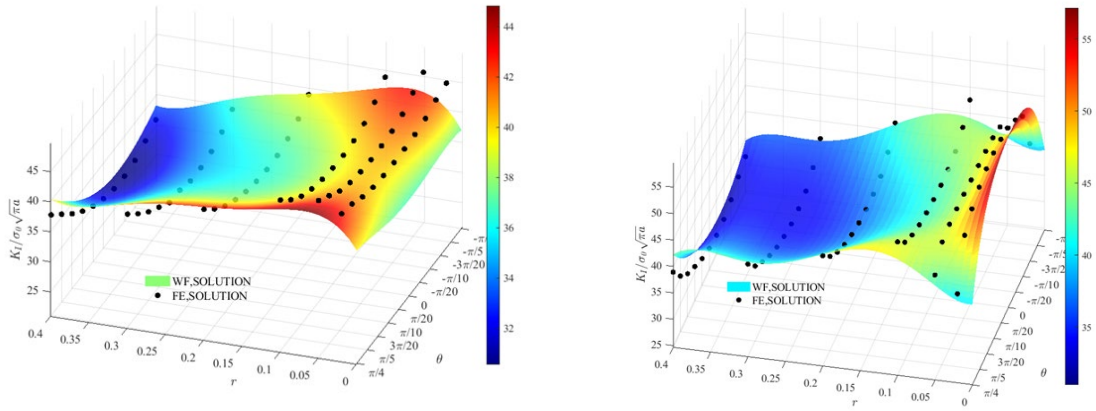
conservative compared to the finite element solutions. At R = 20mm, there is a significant discrepancy between the finite element solutions and API 579 solutions, which could be attributed to the reduction of stress concentration due to the presence of fillets or rounded edges.



(a) R = 0 mm (b) R = 20 mm

FIGURE 4 Comparison of SIF results obtained using different methods under internal pressure loading.

In addition, based on the weight function method, the fitting coefficients of the weight function βi and the stress fitting coefficients under combined loading were derived. The fitting coefficients are provided in the appendix. The comparison of the stress intensity factors (SIFs) for corner cracks under combined loading with finite element results is shown in FIGURE 5. It can be observed that the SIFs calculated using this method under combined loading show good agreement with the finite element results, with a maximum error of approximately -9.88%.



(a) R = 0 mm, $\lambda_1 = 1$, $\lambda_2 = 1$ (b) R = 20 mm, $\lambda_1 = 1$, $\lambda_2 = 1$

FIGURE 5 Comparison of SIF results under combined loading conditions.

CONCLUSION

In this study, the analytical weight function method based on crack surface displacements was employed to estimate the SIFs at the front edge of the complex nozzle corner crack under various loading conditions. By fitting polynomials to represent the stress field on the crack surface and the coefficients of the weight function, the SIFs at the crack front were obtained.

The comparison between the API 579 solution under internal pressure and the finite element analysis demonstrates the consistency of the two approaches, validating the accuracy of the finite element results. The comparison between the new solution along a single path and the finite element analysis confirms the correctness of the single path method. After three-dimensional fitting, the new weight function method for SIFs shows an error of less than 10% compared to the finite element results, further confirming the accuracy of the new weight function solution.

Different loading conditions have varying influences on the SIFs at the front edge of the nozzle corner crack. The API 579 standard is suitable for estimating the stress intensity factors under internal pressure only, while the proposed method in this study is applicable not only to complex loading conditions but also to internal pressure. Future work will consider analysing a wider range of crack sizes and combined loading conditions to further enhance the understanding of the influence factors for engineering applications.

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Appendix A

Table A1 Coefficients for $R = 0mm$

β_i coefficients					σ coefficients	
b_i	i =2	i =3	i =4	i =5	S	σ
b_{i00}	-16.5256	47.8959	-44.6555	14.3891	S_{i00}	63.5448
b_{i10}	1.1326	-3.7049	3.7437	-1.2545	S_{i10}	-1.2873
b_{i01}	-250.3558	1013.5657	-1077.3850	367.7063	S_{i01}	-72.6661
b_{i20}	4.5142	-15.0106	15.1870	-5.0931	S_{i20}	4.7587
b_{i11}	-12.5720	37.2024	-35.3098	11.5848	S_{i11}	29.1849
b_{i02}	3722.6059	-14920.4666	15820.6121	-5395.0050	S_{i02}	7.7023
b_{i30}	0.9085	-2.9735	3.0365	-1.0205	S_{i30}	2.8109
b_{i21}	62.6525	-201.3580	204.4702	-68.5807	S_{i21}	29.7278
b_{i12}	94.1175	-273.6751	259.5090	-85.0712	S_{i12}	9.6529
b_{i03}	-22694.3032	93327.9110	-101506.9119	34855.0184	S_{i03}	19.8441
b_{i40}	-3.0549	12.1830	-13.8077	4.7860	S_{i40}	-8.0838
b_{i31}	-5.0037	14.5265	-13.2536	4.2920	S_{i31}	-19.7388
b_{i22}	-298.5955	930.2000	-929.8903	310.2617	S_{i22}	11.1959
b_{i13}	-259.4891	788.2421	-786.5790	262.1277	S_{i13}	-7.5297
b_{i04}	60845.2903	-259478.0367	291313.4194	-100869.1969	S_{i04}	-15.0376
b_{i50}	-0.4582	1.4638	-1.4813	0.4963		
b_{i41}	18.7223	-67.5036	72.9523	-24.9443		
b_{i32}	5.2975	-10.0370	4.6042	-0.9616		
b_{i23}	353.9669	-1072.2613	1064.7349	-354.2935		
b_{i14}	260.4927	-860.0361	922.5011	-314.1976		
b_{i05}	-59009.3542	261469.6861	-302651.9633	105610.3153		

Table A2 Coefficients for $R = 20mm$

β_i coefficients					σ coefficients	
b_i	i =2	i =3	i =4	i =5	S	σ
b_{i00}	-9.8830	37.8201	-39.6731	13.3072	S_{i00}	60.9732
b_{i10}	-0.0470	0.2515	-0.3212	0.1148	S_{i10}	-1.9830
b_{i01}	-1.2010	-312.5433	503.0107	-188.8209	S_{i01}	-83.9026
b_{i20}	-15.3935	46.7079	-44.9711	14.8300	S_{i20}	4.3495
b_{i11}	8.6637	-29.6886	31.1651	-10.5642	S_{i11}	33.1544
b_{i02}	-1197.1265	8995.3886	-12287.3102	4460.7532	S_{i02}	55.0387
b_{i30}	0.0826	0.1590	-0.4739	0.1918	S_{i30}	3.9225
b_{i21}	433.6740	-1270.7329	1183.0518	-385.7116	S_{i21}	32.7179
b_{i12}	-35.3479	110.2156	-109.9768	36.6759	S_{i12}	9.6393
b_{i03}	9611.9713	-65073.9003	87474.1109	-31636.5140	S_{i03}	-47.9251
b_{i40}	-40.3637	145.5587	-156.4269	53.4104	S_{i40}	-6.3976
b_{i31}	-1.5162	14.8672	-21.6313	7.9529	S_{i31}	-22.7933

b_{i22}	-1828.5201	5047.9169	-4447.8798	1421.3122	S_{i22}	10.2885
b_{i13}	99.5237	-273.9801	251.7073	-81.5470	S_{i13}	-8.9437
b_{i04}	-27617.3507	186528.4021	-251743.0294	91112.6538	S_{i04}	16.6664
b_{i50}	-0.3912	0.0564	0.7840	-0.3520		
b_{i41}	135.7749	-475.6083	502.6154	-170.7609		
b_{i32}	5.7785	-44.0633	61.7140	-22.5069		
b_{i23}	2057.0319	-5223.6427	4215.0017	-1299.9162		
b_{i14}	-121.6834	341.0209	-320.7690	104.7654		
b_{i05}	27224.1826	-187284.7094	254858.3112	-92394.1816		