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Enhancement of *J* estimation for typical nuclear pipes with a circumferential surface crack under tensile load

Doo Ho Cho[1], Seung Wan Woo[1], Yoon-Suk Chang[2], Jae-Boong Choi[1], Young-Jin Kim[1,*]
Myung Jo Jhung[3] and Young Hwan Choi[3]

[1] *School of Mechanical Engineering, Sungkyunkwan Univ., 300 Chunchun-dong, Jangan-gu, Suwon, Kyonggi-do 440-746, Korea*
[2] *Department of Nuclear Engineering, Kyung Hee University, 1 Seocheon-dong, Gilleung, Yongin, Kyonggi, 446-701, Korea*
[3] *Korea Institute of Nuclear Safety 19 Guseong-dong, Yuseong-gu, Daejeon 305-338, Korea*

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Abstract

This paper is to report enhancement of engineering *J* estimation for semi-elliptical surface cracks under tensile load. Firstly, limitation of the sole solution suggested by Zahoor is shown for reliable structural integrity assessment of thin-walled nuclear pipes. An improved solution is then developed based on extensive 3D FE analyses employing deformation plasticity theory for typical nuclear piping materials. It takes over the structure of the existing solution but provides new tabulated plastic influence functions to cover a wide range of pipe geometry and crack shape. Furthermore, to facilitate easy prediction of the plastic influence function, an alternative simple equation is also developed by using a statistical response surface method. The proposed H_1 values can be used for elastic-plastic fracture analyses of thin-walled pipes with a circumferential surface crack subjected to tensile loading.

Keywords: *J*-integral; Plastic influence function; Response surface method; Stress intensity factor; Thin-walled nuclear pipe

1. Introduction

Recently, integrity assurance of secondary system components becomes an important issue relating to impacts on large and early release frequency (LERF) as well as core damage frequency (CDF) due to piping failures in nuclear power plant. The secondary system piping has relatively thin thickness and higher mean radius to thickness ratio (R_m/t) of the pipe, as distinguished from primary piping of reactor coolant system, which may cause impossibility for applying well-known elastic-plastic *J* solutions [1-4] basically derived from thick-walled pipes.

Battelle Integrity of Nuclear Piping (BINP) project [5] has dealt with the problem as one of several research items. Thereby, a method which is applicable to thin-walled pipes was proposed by adopting a concept of correction coefficient for the existing solutions [2, 3], based on two-dimensional finite element (2D FE) analysis results. Despite its sound results, the BINP method also has some limitations. Although effectiveness of shell and line spring model already has been proven, it is inherently less accurate than 3D FE analysis in use of solid elements. Also, for loading conditions, bending and internal pressure were taken into account but tensile loading was not considered.

The present research provides an enhanced engineering *J* estimation for typical nuclear pipes with a circumferential surface crack subject to tensile loading. In this context, the remainder of paper is organized as follows: In section 2, preliminary FE analyses are carried out to show limitation of current *J* estimates. Then, detailed analysis method, extensive 3D elastic-plastic FE models and their results are described in section 3. In section 4, improved *J* estimates are developed based on Zahoor's solution with modified plastic influence functions both in tabulated and simple equation forms, which are followed by the last section where conclusions are drawn.

2. Limitation of current *J* estimates

2.1 R_m/t ratio

Table 1 shows existing elastic-plastic *J* solutions for pipe with a circumferential surface crack and it can be pointed out that currently applicable R_m/t is equal or less than 20 except for aforementioned BINP method. Also, with regard to tensile load condition, there exists sole solution suggested by Zahoor [6], of which applicability is restricted only to R_m/t =10.

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*Corresponding author. Tel.: +82 31 290 5274, Fax.: +82 31 290 5276
E-mail address: yjkim50@skku.edu

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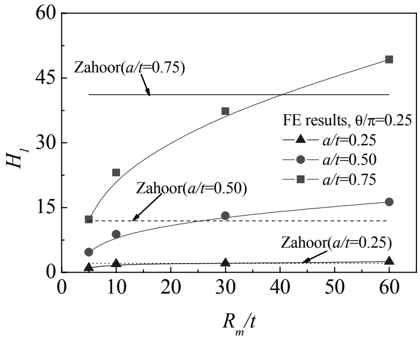
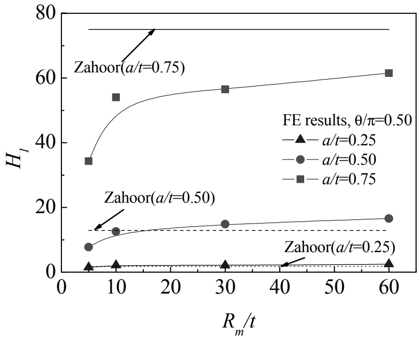
Table 1. Applicable J solutions for pipes with a circumferential surface crack.

Loading type	Applicable R_m/t	Solution
Tension	10	Zahoor (1990) [6]
Bending	5-20	Kim et al. (2002) [7]
	7.5	NUREG (1995) [2]
	5-60	BINP (2002) [5]
Internal pressure	5-20	Kim et al. (2002) [7]
	5-15	NUREG (1995) [3]
	5-60	BINP (2002) [5]



(a) θ/π=0.25



(b) θ/π=0.50

Fig. 1. Comparison of H_1 values for different pipe geometry and crack shape.

2.2 Preliminary FE analysis

The structure of J solution for tensile loaded thin-walled pipes takes over Zahoor's one as follows:

$$J^{FE} = J_e + J_p \tag{1}$$

$$J_e = f_t \cdot P^2 / (4 \cdot \pi \cdot R^2 \cdot t \cdot E') \tag{2}$$

$$J_p = \alpha \cdot \sigma_o \cdot \varepsilon_o \cdot t \cdot H_1 \cdot (\sigma_t / \sigma_o)^{n+1} \tag{3}$$

where H_1 is the plastic influence function dependent upon θ/π, a/t, n and R_m/t.

Table 2. FE analysis matrix.

R_m/t	a/t	θ/π
5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60	0.25, 0.50, 0.75	0.25, 0.50

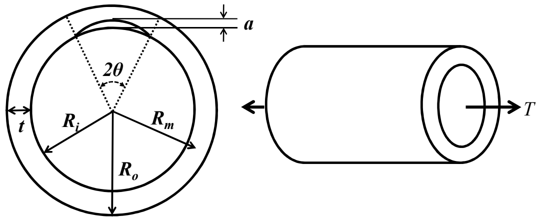


Fig. 2. Schematic illustration of circumferential surface cracked pipe under tensile loading.

To confirm limitation of the existing solution, plastic influence functions obtained from preliminary FE analyses and Zahoor's solution were compared. The FE-based H_1 values were determined from Eq. (3), here, the fully plastic part of J_p was obtained by subtracting elastic part of J_e from elastic-plastic FE analysis results. As depicted in Fig. 1, first of all, FE-based H_1 values increased with the increase of R_m/t while Zahoor's H_1 values were constants. Also, H_1 values obtained from both methods affected by varying normalized crack depth (a/t) and normalized crack length (θ/π), and effect of a/t was relatively bigger than that of θ/π. In other words, as the increase of a/t, the difference of two types of H_1 values was rapidly increased. Additionally, a side observation was taken from these preliminary FE analyses that the maximum difference between two methods was over than two times when R_m/t=5 while its difference was less than 80% at R_m/t=60. Hence, to develop an enhanced J solution, parametric FE analyses are required not only for varying R_m/t but also for diverse a/t and θ/π.

3. Detailed FE analysis

3.1 Geometry and material

Fig. 2 represents the schematic illustration of circumferential surface cracked pipe subjected to tensile load, T. Since three variables such as R_m/t, a/t and θ/π affects to J-integral values as mentioned in the previous section, to cover practical ranges of these variables, seventy-two cases were considered in the present work as summarized in Table 2; twelve values of R_m/t ranging from 5 to 60, three values of a/t ranging from 0.25 to 0.75, and two values of θ/π as 0.25 and 0.50.

Table 3 lists four representative nuclear piping materials taken into account for the FE analyses and their mechanical properties were retrieved from a massive database [8]. All of the materials assumed to follow Ramberg-Osgood (R-O) relationship:

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha\left(\frac{\sigma}{\sigma_o}\right)^n \tag{4}$$

where σ_y denotes the 0.2% proof (yield) stress, $\varepsilon_o = \sigma_y/E$ is the reference strain, E is the Young's modulus, and α and n are the R-O parameters, respectively. Poisson's ratio is fixed as ν=0.3.

3.2 Analysis method

A series of detailed FE analyses were performed based on deformation plasticity using the R-O parameters. Materials were modeled to depict isotropic elastic-plastic behaviors that obey J_2 flow theory, and a small geometry change continuum FE model was employed. The J-integral values were extracted from general-purpose FE program, ABAQUS [9], using a domain integral technique as a function of the applied tensile load.

3.3 FE model

Fig. 3 depicts a typical 3D FE mesh used in the analysis. Due to symmetry condition, a quarter models was generated by using the reduced integration 20-node bricks (type C3D20R in ABAQUS element library). Especially, the crack tip was designed with focused elements and wedge-shaped elements were used in the crack-tip region as shown in the enlarged area. Confidence of the FE models was obtained by checking the path independence of J values. While the overall deviation of J values calculated from ten contours was lower than a few percents, the J values were finally defined as the mean value of 2nd-8th contours after discarding the closest and furthest ones to the crack front. Further verification of the model was conducted by comparing the FE stress intensity factor (K_I) with the corresponding one obtained from existing elastic solution [6] of which applicability is for $5 \le R_m/t \le 160$. In case of FE K_I, the J-integral can be easily converted to it by using Eq. (5).

$$K_I = \sqrt{E' J_e} \tag{5}$$

where $E'=E$ for plane stress condition and $E'=E/(1-\nu^2)$ for plane strain condition.

Table 3. Mechanical properties of representative nuclear piping materials.

Type	E (GPa)	σ_y (MPa)	α	n
SA106 Gr.B	190	222	1.64	4.51
SA106 Gr.C	186	186	1.56	3.75
TP304	186	184	6.68	3.31
TP316	186	168	5.87	3.68

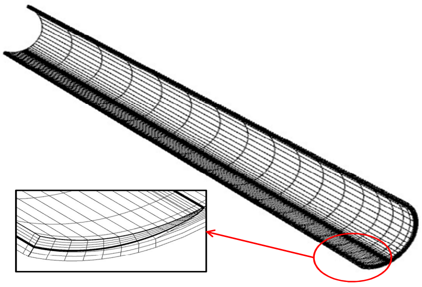


Fig. 3. Typical FE mesh used in the present work.

On the other hand, the corresponding engineering K_I was calculated by using the existing solution expressed as:

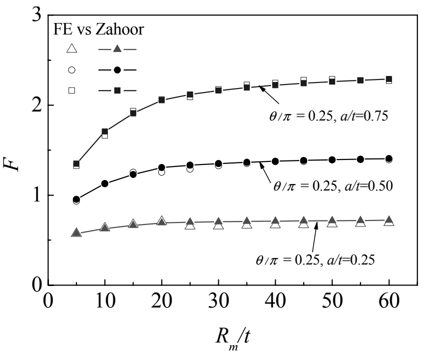
$$K_I = \sigma_t (\pi t)^{0.5} \cdot F \tag{6}$$

where σ_t denotes the applied stress due to axial loading and F is the shape factor dependent upon a/c and a/t as well as R_m/t. Fig. 4 shows comparison of K values obtained from the detailed FE analyses and the existing solution, in which maximum difference was just 4% in all cases. This means that validity of FE models was proven sufficiently and it is possible to use them for main fracture mechanics analyses.

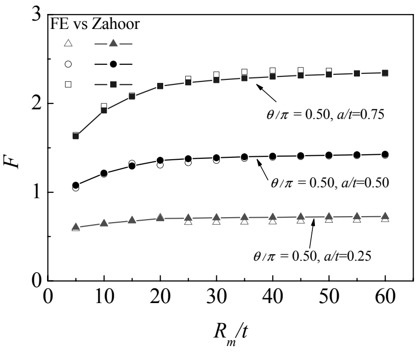
3.4 FE results

Based on elastic-plastic FE analyses results, values of H_1 can be determined through Eq. (3). However, since the H_1 was dependent on load magnitudes, it should be cautiously determined. As shown in Fig. 5, the variation of H_1 was getting flat and becomes almost constants at sufficiently high load. These converged constants were taken as specific H_1 values at a given analysis condition.

Meanwhile, the H_1^{FE} values were divided by H_1^{Zahoor} from the existing solution and provided in Fig. 6. Note that these values were determined at the deepest point of surface crack. Even if R_m/t was set to 10 that is the reference case, the normalized H_1 values were sensitive to θ/π, a/t and material rep-

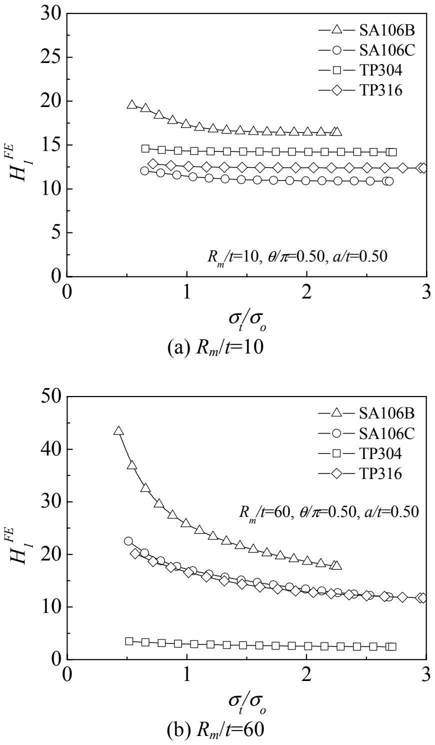


(a) θ/π=0.25



(b) θ/π=0.50

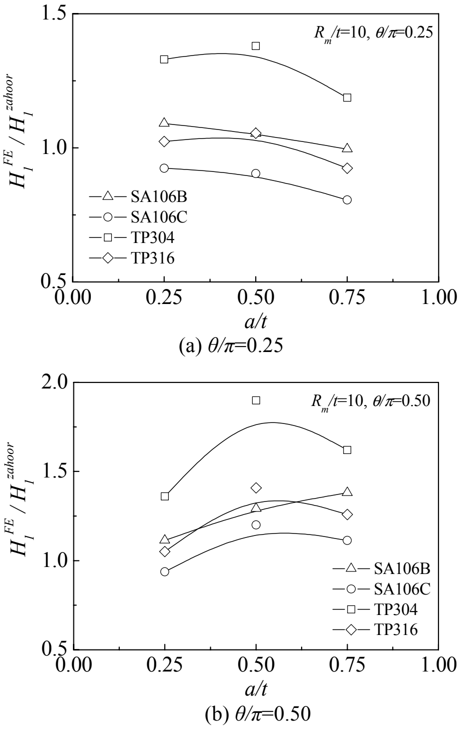
Fig. 4. Comparison of elastic shape factors, F, from the present FE analysis and existing solution.



(a) R_m/t=10

(b) R_m/t=60

Fig. 5. Variation of H_1 values according to load levels.



(a) θ/π=0.25

(b) θ/π=0.50

Fig. 6. Normalized H_1 values for different a/t when R_m/t=10.

Table 4. Values of the plastic influence functions, H_1, ranging from 5 to 30.

R_m/t	θ/π	a/t	n			
			4.51	3.75	3.31	3.68
5	0.25	0.25	1.42	1.11	1.55	1.25
		0.50	5.32	3.96	5.44	4.48
		0.75	16.59	10.89	14.50	12.72
	0.50	0.25	1.59	1.23	1.68	1.37
		0.50	10.07	6.85	9.19	7.97
		0.75	55.45	30.66	36.48	34.85
10	0.25	0.25	2.02	1.57	2.13	1.72
		0.50	10.75	7.68	10.45	8.81
		0.75	30.39	19.91	25.66	22.36
	0.50	0.25	2.24	1.71	2.34	1.90
		0.50	16.38	10.88	14.18	12.37
		0.75	83.03	46.02	53.19	50.21
15	0.25	0.25	2.48	1.89	2.56	2.08
		0.50	14.53	10.23	13.54	11.54
		0.75	43.90	27.63	34.77	30.95
	0.50	0.25	2.70	2.04	2.77	2.26
		0.50	21.86	14.47	18.59	16.2
		0.75	69.79	38.95	43.41	41.95
20	0.25	0.25	2.96	2.24	3.01	2.46
		0.50	14.69	10.29	13.63	11.63
		0.75	46.02	29.65	37.78	33.32
	0.50	0.25	3.20	2.39	3.23	2.65
		0.50	18.65	11.40	13.77	12.98
		0.75	79.75	47.52	57.57	52.79
25	0.25	0.25	2.28	1.76	2.41	1.96
		0.50	14.87	10.39	13.79	11.78
		0.75	44.69	29.79	38.48	33.51
	0.50	0.25	2.37	1.81	2.47	2.01
		0.50	18.21	11.64	14.16	12.93
		0.75	77.63	42.47	49.89	48.85
30	0.25	0.25	2.12	1.65	2.30	1.87
		0.50	15.27	10.21	12.66	11.27
		0.75	46.17	28.33	35.33	32.70
	0.50	0.25	2.02	1.56	2.06	1.67
		0.50	18.76	12.03	14.49	13.18
		0.75	78.65	44.21	52.11	50.11

resented by different R-O parameter n, especially for TP304 steel. The normalized H_1 values were varied between 0.8 and 1.92. It seems that the deviation of H_1^{FE} and H_1^{Zahoor} values was caused by disparity of FE details or coarse interpolation/extrapolation processing, which implies necessity for enhancement of the existing solution.

4. Development of improved *J* estimates

4.1 New plastic influence function (H_1)

As mentioned in chapter 2, the existing solution has limitations both in accuracy and usefulness for structural integrity assessment of thin-walled pipes. To overcome these problems, modified H_1 values were determined based on parametric 3D FE analyses results from chapter 3. Note that the modified H_1 values were calculated by using Eq. (3) in the present research to easily use the proposed plastic influence function. That is, the frame of Zahoor's solution was adopted instead of addressing a new estimation scheme in which these values were determined at the deepest point of surface crack. The newly developed H_1 values are summarized in Table 4 for $5 \le R_m/t \le 30$ and in Table 5 for $35 \le R_m/t \le 60$, respectively. It can be used for calculating the plastic J value ranging wider R_m/t in which is not covered by the existing solution.

4.2 Alternative H_1 equation of by using RSM

The response surface method (RSM) has been widely utilized for solving engineering problems and optimizing processes due to its practical and economical features [10]. In this clause, to facilitate easy prediction of the plastic influence function, a relatively simple alternative equation is also developed by using the RSM. H_1 values represented in Tables 4 and 5 were used to build a mathematical model so that the following equation was derived incorporating key parameters of R_m/t, a/t, θ/π and n:

$$H_1 = \gamma_1 n(\theta/\pi)(t/R_m)^2 + \gamma_2 n(\theta/\pi) + \beta_0 \tag{7}$$

$$\gamma_1 = \beta_1 (a/t)^2 \tag{8}$$

$$\gamma_2 = \beta_2 (a/t)^2 + \beta_3 (a/t) + \beta_4 \tag{9}$$

Validity of the coefficients, β_i (i=0, 1, 2, 3 and 4), were confirmed by t- and p-values [11]. Criteria used for the validity check were summarized in Table 6. Additionally, its statistical validity was also confirmed in terms of adjusted coefficient of determination (CD). The calculated CD of 0.926 is reasonably sufficient. Fig. 7 compares J-integrals derived from two types of H_1 values, which represents effectiveness of the alternative equation.

4.3 Discussion

Although the newly proposed H_1 tables and alternative equation successfully applied to predict comparable J-integrals, since the RSM is inherently based on regression analysis [12, 13], we recommended the newly proposed H_1 tables for accurate estimation.

Noting that, despite two hundred and eighty-eight FE analyses were performed in this research, the suggested J solution is restricted to pipes made of typical nuclear materials under tensile loading. In order to expand its applicability such as to other geometry, loading type and material, further huge amount of analyses are being carried out. Besides, to reduce the material dependency affecting on the solution, another approach, for instance, the reference stress method is being considered.

Table 5. Values of the plastic influence functions, H_1, ranging from 35 to 60.

R_m/t	θ/π	a/t	n			
			4.51	3.75	3.31	3.68
35	0.25	0.25	2.20	1.71	2.36	1.91
		0.50	16.70	11.70	14.77	12.64
		0.75	51.79	34.78	44.21	38.56
	0.50	0.25	2.24	1.74	2.40	1.95
		0.50	19.97	13.48	16.66	14.51
		0.75	78.65	45.35	53.30	50.64
40	0.25	0.25	2.15	1.69	2.33	1.88
		0.50	16.96	11.96	14.88	12.67
		0.75	54.52	36.74	46.59	40.61
	0.50	0.25	2.18	1.70	2.35	1.90
		0.50	19.74	13.46	16.41	14.20
		0.75	78.35	45.93	53.75	50.73
45	0.25	0.25	2.16	1.70	2.32	1.87
		0.50	17.02	12.13	15.00	12.67
		0.75	53.88	34.08	41.67	37.92
	0.50	0.25	2.06	1.62	2.09	1.67
		0.50	18.49	12.06	14.17	12.69
		0.75	77.46	46.14	53.69	50.34
50	0.25	0.25	2.22	1.76	2.36	1.88
		0.50	16.54	11.90	14.61	12.27
		0.75	55.16	35.23	42.66	38.68
	0.50	0.25	2.28	1.80	2.40	1.92
		0.50	17.51	11.61	13.61	12.11
		0.75	76.02	45.88	52.93	49.39
55	0.25	0.25	2.28	1.81	2.38	1.89
		0.50	17.00	12.13	14.64	12.29
		0.75	58.36	39.47	49.16	42.82
	0.50	0.25	2.31	1.83	2.40	1.91
		0.50	17.86	11.92	13.71	12.07
		0.75	77.95	49.84	59.66	53.36
60	0.25	0.25	2.36	1.88	2.42	1.92
		0.50	16.96	12.21	14.49	12.08
		0.75	57.27	38.86	48.24	42.05
	0.50	0.25	2.37	1.88	2.42	1.92
		0.50	17.67	11.92	13.42	11.71
		0.75	74.12	47.96	57.29	51.02

Table 6. Coefficient of equation of plastic influence function.

Coefficient	t-value	p-value	Remarks
$\beta_0 = 7.072$	7.31	2.7E-12	Values are meaningful when $t \neq 2$ and $p < 0.05$
$\beta_1 = -560.993$	-10.18	6.3E-21	
$\beta_2 = 121.951$	16.85	1.4E-44	
$\beta_3 = -61.299$	-8.39	2.4E-15	
$\beta_4 = 4.702$	2.74	6.5E-03	

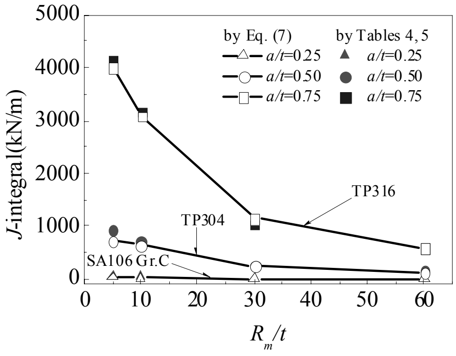


Fig. 7. Estimated J values for different R_m/t when θ/π=0.50.

5. Concluding remarks

This work is to report enhancement of J estimation for thin-walled pipes with a semi-elliptical surface crack under tensile loading. To make the solution, a series of 3D FE analyses employing the deformation plastic theory were carried out. It took over the structure of the existing Zahoor's solution but provided newly, tabulated plastic influence functions to cover a wide range of pipe geometry and crack shape. Moreover, an alternative equation was also developed to facilitate easy prediction of the plastic influence function based on RSM and its effectiveness was proven.

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Doo-Ho Cho received his B.S. and M.S. in the school of Mechanical Engineering from Sungkyunkwan University, Korea, in 2007 and 2009, respectively. He is currently a Ph.D. Candidate in Sungkyunkwan University. His research interests include computational mechanics and fracture mechanics.

Young-Jin Kim received his Ph.D. from the Department of Mechanical Engineering in 1982 at University of Manitoba in Canada. Currently, he is a Professor in the School of Mechanical Engineering at Sungkyunkwan University. He is also director at Safety and Structural Integrity (SAFE) Research Center in Sungkyunkwan University. His current research interests are fracture mechanics and nano mechanics.