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Modification of the ASME Code Z-Factor for Circumferential Surface Crack in Nuclear Ferritic Pipings

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원전 페라이트 배관내의 원주방향 표면균열에 대한 ASME Code Z-Factor의 수정

최영환 · 정연기 · 고완영 · 이정배
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Abstract

The purpose of this paper is to modify the ASME Code Z-Factor, which is used in the evaluation of circumferential surface crack in nuclear ferritic pipings. The ASME Code Z-Factor is a load multiplier to compensate plastic load with elasto-plastic load. The current ASME Code Z-Factor underestimates pipe maximum load. In this study, the original SC. TNP method is modified first because the original SC. TNP method has a problem that the maximum allowable load predicted from the original SC. TNP method is slightly higher than that measured from the experiment. Then the new Z-Factor is developed using the modified SC. TNP method. The desirability of both the modified SC. TNP method and the new Z-Factor is examined using the experimental results for the circumferential surface crack in pipings. The results show that (1) the modified SC. TNP method is good for predicting the circumferential surface crack behavior in pipings, and (2) the Z-Factor obtained from the modified SC. TNP method well predicts the behavior of circumferential surface crack in ferritic pipings.

요 약

이 연구의 목적은 원자력발전소 페라이트 배관에 존재하는 원주방향 표면균열을 평가하는데 사용되는 ASME Code Z-Factor를 수정하는데 있다. ASME Code Z-Factor는 소성하중을 탄소성하중으로 보정하는 하중 보정계수로서, 현재 사용되는 ASME Code Z-Factor는 최대하중을 과소평가하는 문제점이 있다. 이 연구에서는 먼저 기존의 SC. TNP 방법이 수정되었으며, 그 이유는 기존의 SC. TNP 방법으로 예측된 최대허용하중이 실험에서 측정된 방법보다 약간 큰 결과를 주는 문제가 있기 때문이다. 이 수정된 SC. TNP 방법을 사용하여 페라이트 배관에 대한 새로운 Z-Factor를 개발하였다. 수정된 SC. TNP 방법의 타당성과 새로 개발된 Z-Factor의 타당성을 원주방향 표면균열을 갖는 배관에 대한 실험 결과를 통해 조사하였다. 평가결과는 수정된 SC. TNP 방법은 페라이트 및 오스테나이트 배관의 원주

방향 표면균열의 거동을 잘 예측할 수 있음을 보여 주며, 또한 수정된 SC. TNP 방법으로 구한 새로운 Z-Factor는 페라이트 배관에 존재하는 원주방향 표면균열의 거동을 잘 예측할 수 있음을 보여준다.

1. Introduction

In the design stage of nuclear pipings, it is assumed that there is no crack in the pipings.[1] There, however, are many micro-cracks in nuclear pipings because of material inhomogeneity and welding process problems. During plant operation, some micro-cracks may grow into surface cracks or throughwall cracks, which give adverse effect on the piping integrity.

ASME Boiler & Pressure Vessel Code Sec. XI "Rules for Inservice Inspection of Nuclear Power Plant Components" (hereafter we denote this code as ASME Code.) requires the evaluation of cracks which are detected during in-service inspection.[2-4] The Z-Factor method is one of the ASME Code's recommendations to evaluate circumferential surface crack in pipings. The Z-Factor is a load multiplier to compensate plastic load with elasto-plastic load. This method can be applied to the circumferential surface cracks under elasto-plastic condition. It is known that the current ASME Code Z-Factor for ferritic pipings underestimates the maximum allowable load of ferritic pipings with circumferential surface crack.[5-7]

The purpose of this paper is to modify the ASME Code Z-Factor to evaluate the circumferential surface crack in both ferritic base metal pipings and ferritic Submerged Arc Welding (SAW) weld metal pipings.

In order to develop new Z-Factor, a crack evaluation method, which can exactly predict the behavior of the circumferential surface crack in pipings under elasto-plastic condition, has to be determined first. Many methods such as J integral method[5-7, 11-30], R6 method[8], and DPFAD method[9-10] have been proposed to evaluate the circumferential surface crack in pipings. Specially the SC. TNP method, which is based on J integral GE/EPRI method [13], has been known to well predict the circumferential surface crack behavior in ferritic pipings compared to other methods. [14-16] However, the SC. TNP method has a problem in that it gives slightly non-conservative results[14-16]. This means that the maximum load obtained from the original SC. TNP method is larger than that from experiments. This result is not desirable from the viewpoint of nuclear safety.

In this paper, the original SC. TNP method is modified first, and then the new Z-Factor for ferritic pipings is developed using the modified SC. TNP method. The desirability of both the modified SC. TNP method and the new Z-Factors will be examined using the experimental results for the circumferential surface crack in both ferritic base metal pipings and ferritic SAW weld metal pipings.[5-7]

2. Modification of SC. TNP Method

As mentioned above, many methods such as the J integral method [5-7, 11-30], R6 method[8], and DPFAD method[9-10] have been proposed to describe the surface crack behavior in pipings under elasto-plastic condition. The GE/EPRI method based on J integral stress field has been widely used for cracks in nuclear pipings. In the GE/EPRI method, J is divided into elastic component of J (Je) and plastic component of J (Jp). For the piping with circumferential surface crack as shown in Fig. 1, the Jp is expressed as[13]

$$J_p = \alpha \cdot \varepsilon_0 \cdot \sigma_0 \cdot \left(1-\frac{a}{t}\right) \cdot a \cdot h_1 \cdot \left[\frac{\sqrt{3}}{2}\frac{t}{b}\frac{\sigma}{\sigma_0}\right]^{n+1} \tag{1}$$

In Eq.(1), a, t, and b are the crack depth, the piping thickness, and the uncracked ligament respectively, and h_1 is the GE/EPRI coefficient given in the GE/EPRI Handbook[13]. Eq.(1) is based on the fol-

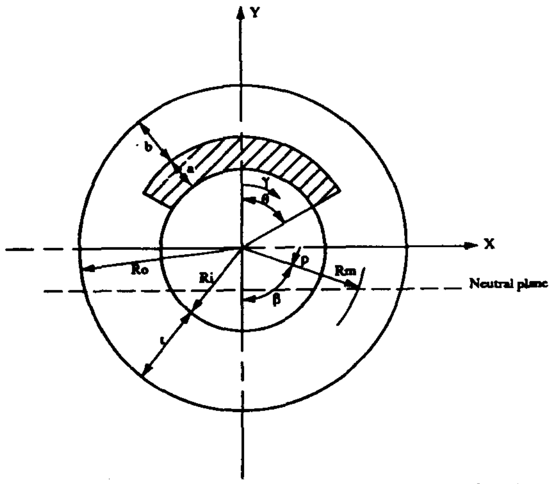

Fig. 1. Geometry of Circumferential Surface Crack

lowing stress-strain relationship.

$$\frac{\varepsilon}{\varepsilon_o} = \alpha\left(\frac{\sigma}{\sigma_0}\right)^n, \qquad (2)$$

where ε_0 and σ_0 are the reference strain and the reference stress respectively, and α and n are the material constant and the strain hardening exponent respectively. Under the applied moment M, the stress σ in Eq.(1) can be expressed as[14-16]

$$\sigma = \left(\frac{M}{4\cdot R_m^2\cdot t\cdot H_n}\right)\left[\frac{\sin\rho+\cos\gamma}{1+\left(\frac{a\cdot h_3}{2L}\right)\left(\frac{\sqrt{3}}{2}\frac{t}{b}\right)^n}\right]^{\frac{1}{n}}. \qquad (3)$$

In Eq.(3), ρ is the angle from x-axis to neutral plane, and γ is the angle from y-axis to the J estimation point as shown in the Fig. 1. Hn and h_3 are given in reference [15] and the GE/EPRI Handbook[13] respectively. L is the characteristic length, which is large enough such that the stress σ(R) acting at the ends is equal to the remote stress σ_r in the pipe wall caused by the applied moment M as shown in Fig. 2.

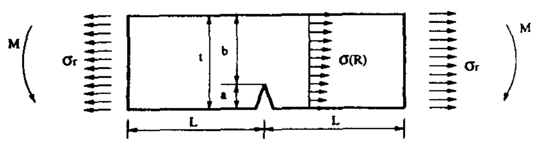

Fig. 2. Cross Section of Pipe Wall Under Bending Load

The method to estimate J integral using Eqs.(1) and (3) is called the SC. TNP method(Surface Crack for ThiN Pipe).[14-16] In the original SC. TNP method, the following relation is used under the assumption that n≫1.

$$L = t \qquad (n \gg 1) \qquad (4)$$

However, this assumption is not exact because the n values measured from experiment range from 3.368 to 8.263 as seen in Table 2.

In this study, L value in the original SC. TNP method is approximately modified as follows.[Hereafter we call this modified method the modified SC. TNP method.]

The SC. TNP method gives the relation between σ and L as [14-16]

$$\sigma \approx L^{\frac{1}{n}}. \qquad (5)$$

Based on the approximation of force equilibrium of the piping system in Fig. 2, the following relation may be obtained.

$$\int_0^L \sigma \, dL = \sigma_r \cdot t \qquad (6)$$

Substituting Eq.(5) into Eq.(6), the relation can be obtained as

$$L = \frac{n+1}{n}t. \qquad (7)$$

If n≫1 (assumption in the original SC. TNP method), the L value in Eq.(7) converges into the pipe thickness t.

Using the Eqs.(1), (3), and (7), and J-R curve of piping material, the moment-rotation relation can be obtained.

3. Modification of ASME Code Z-Factor for Ferritic Pipings

3.1. ASME Code Z-Factor

In the ASME Code, the following criterion is specified for the circumferential surface crack in pipings.

$$P_b \leq S_c \quad , \tag{8}$$

where

P_b = applied bending stress

S_c = allowable stress.

The Sc is a function of fracture parameters such as the pipe material properties, the crack length, the crack depth, the pipe failure mode, the required safety factor, and the actual pipe stresses. The ASME Code gives Sc as

$$Sc = \frac{1}{(SF)}\left(\frac{P'_b}{Z} - P_e\right) - P_m\left(1 - \frac{1}{Z(SF)}\right) \quad , \tag{9}$$

where

P'_b = bending stress at incipient plastic collapse

P_e = thermal stress

P_m = membrane stress

(SF) = safety factor

= 2.77 for normal operating(including upset and test) conditions

= 1.39 for emergency and faulted conditions.

The Z-Factor in Eq.(9) is defined as (Hereafter we denote Z_{ASME} for the Z-Factor given in the ASME Code)

$$Z_{ASME-1} = 1.20\ [1 + 0.021 \cdot A \cdot (OD - 4)] \quad : \text{base metal} \tag{10}$$

$$Z_{ASME-2} = 1.35\ [1 + 0.0184 \cdot A \cdot (OD - 4)] \quad : \text{SAW weld metal,} \tag{11}$$

where

Z_{ASME-1} = Z-Factor for ferritic base metal

Z_{ASME-2} = Z-Factor for ferritic SAW weld metal

OD = outside diameter (inches).

The A in Eqs.(10) and (11) is given as (hereafter we denote A_{ASME} for the A value given in the ASME Code)

$$A_{ASME} = [0.125\left(\frac{R_m}{t}\right) - 0.25]^{0.25} \quad : \quad 5 \leq \left(\frac{R_m}{t}\right) \leq 10$$

$$= [0.4\left(\frac{R_m}{t}\right) - 3.0]^{0.25} \quad : \quad 10 \leq \left(\frac{R_m}{t}\right) \leq 20 \quad . \tag{12}$$

The Z_{ASME} in Eqs.(10) and (11) were obtained using the low bound values of ferritic pipe material properties. Table 1 represents the reference tensile properties of ferritic pipe base metal used in ASME Code.[7] These tensile properties were also used for ferritic SAW weld metal because this provides a conservative result. Fig. 3 shows the J-R curves for ferritic base metal and the ferritic SAW weld metal used in the ASME Code Z-Factor calculation.[7]

Table 1. Reference Tensile Properties of Ferritic Pipings

σ_y (MPa)	σ_u (MPa)	σ_f (MPa)	ε_o	α	n
186.84	411.62	229.23	0.0010423	2.51	4.2

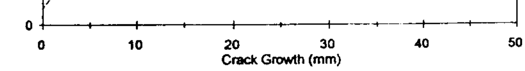

Fig. 3. Reference J-R Curves for Ferritic Base Metal and Ferritic SAW Weld Metal

3.2. Development of New Z-Factor for Ferritic Pipings

3.2.1. Definition of Z-Factor

The Z-Factor as a load multiplier is defined as

$$Z = \frac{M_L}{M_{EP-\max}} \quad , \tag{13}$$

where

M_L = limit moment

$M_{EP\text{-}max}$ = maximum moment under elasto-plastic condition.

The limit moment of circumferential surface crack (M_L) is given as [2]

(1) $\theta+\beta\le\pi$

$$M_L = 2\,\sigma_f R_m^2\, t\left\{2\sin\beta-\left(\frac{a}{t}\right)\sin\theta\right\} \tag{14}$$

$$\beta=\left\{\pi-\left(\frac{a}{t}\right)\theta-\pi\left(\frac{P_m}{\sigma_f}\right)\right\} \tag{15}$$

(2) $\theta+\beta>\pi$

$$M_L = 2\,\sigma_f R_m^2\, t\left\{2-\frac{a}{t}\right\}\sin\theta \tag{16}$$

$$\beta=\frac{\pi}{2-\frac{a}{t}}\left\{1-\frac{a}{t}-\frac{P_m}{\sigma_f}\right\},$$

where Rm is the mean radius and σ_f is the flow stress, which is defined as the average of yield stress(σ_y) and ultimate tensile stress(σ_u). Pm is given by

$$P_m = p\,\frac{R_i^2}{(R_o^2-R_i^2)}, \tag{18}$$

where p is the pipe internal pressure.

As previous stated, the maximum moment under elasto-plastic condition ($M_{EP\text{-}max}$) is calculated from the modified SC. TNP method in this study.

3.2.2. New Z-Factor for Ferritic Base Metal ($Z_{NEW\text{-}1}$)

The effect of pipe diameter on the new Z-Factor is investigated for 3 cases of pipe outside diameters (OD=4.5, 16, 42 inches) with Rm/t=10. And also Rm/t effect on the new Z-Factor is investigated for 3 cases of Rm/t (Rm/t=5, 10, and 20) with OD=42 inches. For each of the above cases, 4 cases of crack depth (a/t=0.1, 0.3, 0.5, 0.75) and 4 cases of crack length (θ/π=0.1, 0.25, 0.5, 1) are considered in order to investigate the effect of both the crack depth and the crack length on the new Z-Factors.

Figs. 4 and 5 show the limit moment obtained from Eqs.(14)−(17) and the maximum moment obtained from the modified SC. TNP method for OD=16 inches case with Rm/t=10 respectively. Using the data shown in Fig. 4 and Fig. 5, the Z-Factor can be easily obtained from Eq.(13). The Z-Factor is shown in Fig. 6. As shown in the figure, the ASME Code Z-Factor has a constant value because the ASME Code Z-Factor is not a function of crack depth or crack length. It is meaningful that the new Z-Factor is not sensitive to either the crack depth or the crack length as shown in Fig. 6. We define the maximum Z value among 16 cases in the figure as the new Z-Factor corresponding to the given pipe outside diameter and Rm/t.

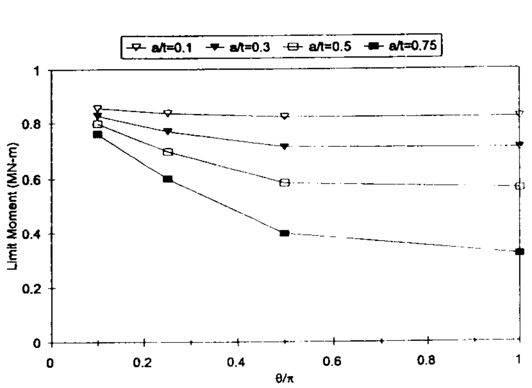

Fig. 4. Limit Moment for Ferritic Base Metal With OD=16 inches (Rm/t=10)

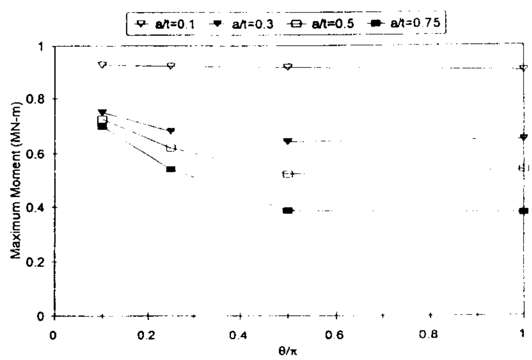

Fig. 5. Maximum Moment for Ferritic Base Metal With OD=16 inches (Rm/t=10)

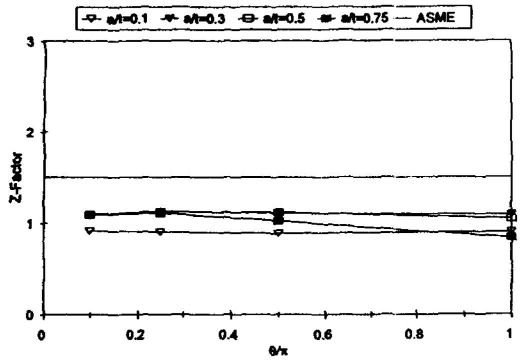

Fig. 6. Z-Factors for Ferritic Base Metal With OD=16 inches (Rm/t=10)

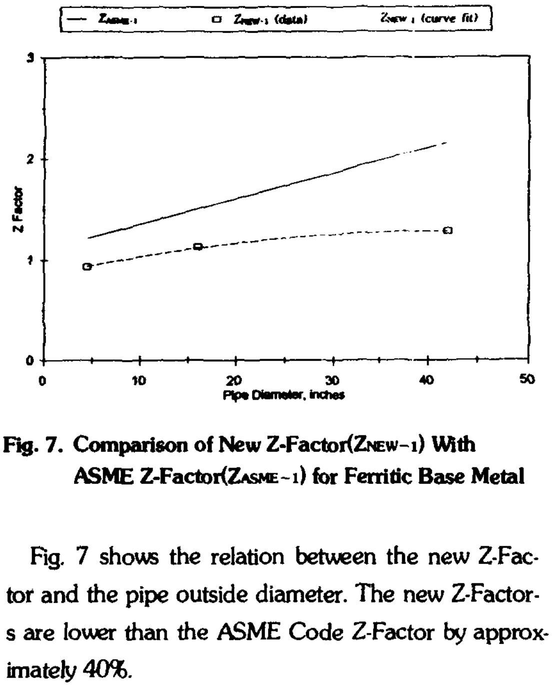

Fig. 7. Comparison of New Z-Factor(Z_{NEW-1}) With ASME Z-Factor(Z_{ASME-1}) for Ferritic Base Metal

Fig. 7 shows the relation between the new Z-Factor and the pipe outside diameter. The new Z-Factors are lower than the ASME Code Z-Factor by approximately 40%.

The new Z-Factor for ferritic base metal (Z_{NEW-1}) can be fitted as (hereafter we denote Z_{NEW} for the new Z-Factor)

$$Z_{NEW-1} = 1.2[0.744 + 0.0152A_{NEW-1}$$

$$(OD-4) - 0.0002A_{NEW-1} \cdot (OD-4)^2] \quad (19)$$

where A_{NEW-1} is a new A value for ferritic base metal, which can be obtained from the relation between A_{NEW-1} and Rm/t as shown in Fig. 8. The A_{NEW-1}

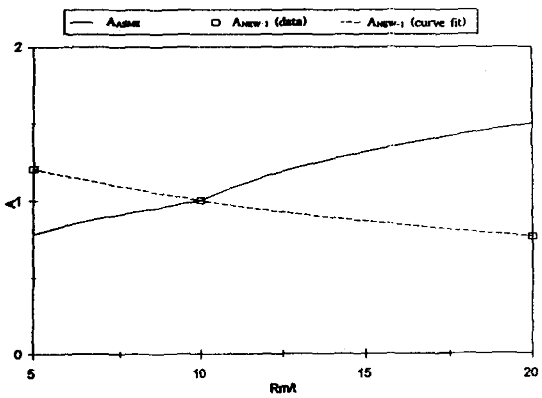

Fig. 8. Comparison of New A Value(A_{NEW-1}) With ASME A Value(A_{ASME}) for Ferritic Base Metal

values decrease as the Rm/t values increase. A_{NEW-1} can be fitted as

$$A_{NEW-1} = [0.0125\left(\frac{R_m}{t}\right) + 0.875]^{-2.791}$$

$$: \quad 5 \le \frac{R_m}{t} \le 20 \quad (20)$$

3.2.3. New Z-Factor for Ferritic SAW Weld Metal (Z_{NEW-2})

New Z-Factor for ferritic SAW weld metal (Z_{NEW-2}) can be obtained through similar methods used in the calculation of Z_{NEW-1}. The effects of crack depth(a/t = 0.1, 0.3, 0.5, 0.75), crack length (θ/π = 0.1, 0.25, 0.5, 1), pipe outside diameter(OD = 4.5, 16, 42 inches with Rm/t = 10), and Rm/t(Rm/t = 5, 10, 20 with OD = 42 inches) on Z_{NEW-2} are also investigated. investigated.

Fig. 9 shows the relation between Z_{NEW-2} and pipe outside diameter, which can be fitted as

$$Z_{NEW-2} = 1.35[0.742 + 0.0134A_{NEW-2} \cdot (OD-4)$$

$$- 0.000176A_{NEW-2} \cdot (OD-4)^2] \quad (21)$$

where A_{NEW-2} is a new A value for the ferritic SAW weld metal, which can be fitted as

$$A_{NEW-2} = [0.1161\left(\frac{R_m}{t}\right) + 0.161]^{-0.383}$$

$$: \quad 5 \le \frac{R_m}{t} \le 20 \tag{22}$$

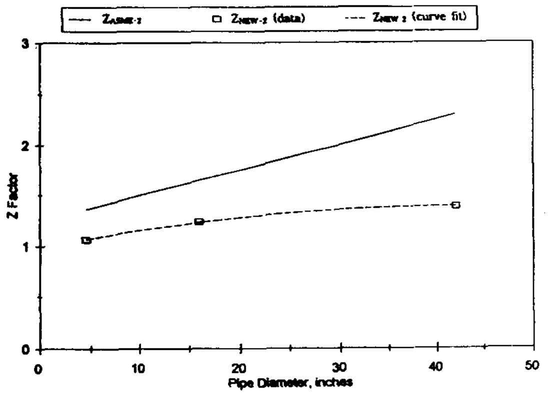

Fig. 9. Comparison of New Z-Factor(Z_{NEW-2}) With ASME Z-Factor(Z_{ASME-2}) for Ferritic Base Metal

4. Results and Discussions

4.1. Pipings Fracture Experiments

Many pipe fracture experiments had been performed for nuclear pipings with surface/throughwall crack as a part of the Degraded Piping Program, IPIRG(International Piping Integrity Research Group) Program, and Short Crack Program.[5-7]

Table 2 is a summary of experimental results obtained from the above Programs. Eight surface crack experiments for ferritic base metal, 2 for ferritic SAW weld metal, and 16 for austenitic base metal are shown in the table. Experiment number, material specification, pipe outside diameter(OD), thickness(t), crack length(θ/π, %), crack depth(a/t, %), yield stress(σ_y), ultimate tensile stress(σ_u), reference strain(ε_0), strain hardening coefficient(α), strain hardening exponent(n), pipe internal pressure(p), and maximum moment measured from the pipe fracture experiments(M_{exp}) are given in Table 2.

The pipe fracture experiments were performed at 288°C under the 4 points bending loading. The potential drop method was used to determine the crack growth amount. Detailed contents including experimental facilities, experimental methods, data processing, and crack evaluation methods are provided in references [5] and [6].

4.2. Desirability of the Modified SC. TNP Method

The maximum moments and fracture ratios obtained from the modified SC. TNP method, the original SC. TNP method[14-16], the R6 method[8], and DPFAD method[9-10] are given in Tables 3 and 4 for ferritic and austenitic pipings respectively. The fracture ratio is defined as

$$FR = \frac{(\sigma_{exp} + \sigma_p)}{(\sigma_{pred} + \sigma_p)} \tag{23}$$

The σ_{exp} and σ_p are the measured stress from experiments and the calculated stress induced by pipe internal pressure respectively. The σ_{pred} is the predicted stress obtained from the modified SC. TNP method, the original SC. TNP method, the R6 method, or the DPFAD method. The σ_{exp}, σ_{pred}, and σ_p are given as

$$\sigma_{exp} = \frac{M_{exp}\ R_m}{I} \tag{24}$$

$$\sigma_{pred} = \frac{M_{EP-\max} R_m}{I} \tag{25}$$

$$\sigma_p = p\ \frac{R_i^2}{(R_o^2 - R_i^2)} \tag{26}$$

The I is the moment of inertia given by

$$I = \left(\frac{\pi}{4}\right)\{R_o^4 - R_i^4\} \tag{27}$$

For the ferritic material given in Table 3, the average fracture ratio of the modified SC. TNP method is 1.008, while the average fracture ratios of the original SC. TNP method, the R6 method, and the DPFAD method are 0.969, 1.401, and 1.427 respectively. For the austenitic pipings, the average fracture ratios of the modified SC. TNP method, the original SC. TNP method, the R6 method, and the DPFAD method are 1.012, 0.976, 1.223, and 1.262 respectively. As shown in the Table, the average fracture ratio of

Table 2. Test Matrix of Surface Crack Experiments in Ferritic and Austenitic Pipings

Exp. No	Material Specication		OD (in)	t (in)	a/t (%)	θ/π (%)	σ_y (MPa)	σ_u (MPa)	ε_0	α	n	p (MPa)	Mexp (MN-m)
1	Ferritic Piping	A 106	169.3	7.44	50.80	63.10	212.4	467.5	0.00110	0.499	7.222	0.00	0.0380
2			167.5	14.78	50.30	68.00	319.9	620.5	0.00152	1.970	5.366	0.00	0.0801
3			168.2	21.46	52.60	63.30	258.6	570.2	0.00134	0.171	8.263	0.00	0.1174
4			402.6	26.42	53.20	66.20	237.2	610.2	0.00124	2.189	3.729	0.00	0.7484
5			404.9	12.70	53.50	66.20	262.0	611.6	0.00138	2.972	3.998	0.00	0.3656
6			167.5	13.49	43.20	64.70	319.9	620.5	0.00152	1.970	5.366	15.51	0.0772
7			167.4	14.02	41.90	72.00	319.9	620.5	0.00152	1.970	5.366	15.51	0.0616
8		A516	711.2	22.68	25.00	50.00	231.0	544.0	0.00119	1.382	5.644	9.56	2.1899
9		A106 SAW	403.2	25.37	50.00	67.00	237.2	610.2	0.00124	2.189	3.729	15.49	0.5946
10			609.6	42.67	25.00	60.50	234.4	541.9	0.00114	3.206	3.410	15.51	2.5753
11	Austenitic Piping	TP316	405.1	9.80	51.10	65.80	166.9	470.2	0.00095	5.164	4.344	0.00	0.2303
12			406.7	9.47	25.00	47.60	224.1	508.8	0.00108	5.012	4.946	1.55	0.3564
13		TP304	167.4	7.01	50.20	63.40	146.9	448.9	0.00080	8.658	3.368	0.00	0.0295
14			168.6	13.61	51.80	65.90	138.6	449.5	0.00076	11.230	3.565	0.00	0.0596
15			168.3	22.48	44.20	65.30	150.3	477.1	0.00082	3.722	4.181	0.00	0.1009
16			114.3	8.89	50.00	38.00	246.8	629.5	0.00138	2.558	5.500	0.00	0.0411
17			114.3	9.02	50.00	59.40	246.8	629.5	0.00138	2.556	5.500	0.00	0.0330
18			114.3	8.53	25.00	38.70	246.8	629.5	0.00138	2.556	5.500	0.00	0.0377
19			114.3	8.81	25.00	60.80	246.8	629.5	0.00138	2.556	5.500	0.00	0.0336
20			114.3	8.79	75.00	41.30	246.8	629.5	0.00138	2.556	5.500	0.00	0.0375
21			114.3	8.51	75.00	64.50	246.8	629.5	0.00138	2.556	5.500	0.00	0.0303
22			114.3	9.27	50.00	57.50	246.8	629.5	0.00138	2.556	5.500	0.00	0.0323
23		SA333	265.2	17.27	42.00	70.00	239.2	527.5	0.00124	2.134	5.583	0.00	0.2211
24			272.0	17.12	43.00	71.00	239.2	527.5	0.00124	2.134	5.583	0.00	0.2342
25			270.6	15.06	48.00	67.80	239.2	527.5	0.00124	2.134	5.583	0.00	0.1951
26			272.8	16.61	52.50	65.90	239.2	527.5	0.00124	2.134	5.583	18.27	0.1600

the original SC. TNP method gives non-conservative results by 3-4%, while those of the modified SC. TNP method show conservative results within 1-2%. The well known R6 and DPFFAD method give too conservative results by 20-50%.

Fig. 11 and 12 show the fracture ratios for ferritic pipings and austenitic pipings respectively. The x-axis represents the experiment number.

4.3. Desirability of New Z-Factor for Ferritic Pipings

The ASME Code specifies that the safety margins of 2.77 and 1.39 should be applied to Eq.(9) for normal operating condition and emergency/faulted conditions respectively. In this study, however, the safety margin is considered as 1 in order to compare the predicted results with the experimental results.

Table 3. Predicted Maximum Moments and Fracture Ratio from Modified SC. TNP Method, Original SC. TNP Method, R6 Method, and DPFAD Method for Ferritic Pipings

Exp. No	Mexp (MN-m)	mod. SC. TNP (MN-m)	org. SC. TNP (MN-m)	R6 (MN-m)	DPFAD (MN-m)	FR mod. SC. TNP	FR org. SC. TNP	FR R6	FR DPFAD
1	0.0380	0.0467	0.0476	0.0312	0.0339	0.813	0.799	1,217	1.120
2	0.0801	0.0773	0.0787	0.0577	0.0541	1.036	1.018	1.388	1.480
3	0.1174	0.1160	0.1176	0.0716	0.0652	1.012	0.998	1.639	1.800
4	0.7484	0.6821	0.7250	0.4840	0.4724	1.097	1.032	1.546	1.584
5	0.3656	0.3822	0.4036	0.2943	0.2973	0.956	0.906	1.242	1.230
6	0.0772	0.0694	0.0720	0.0514	0.0495	1.100	1.065	1.429	1.478
7	0.0616	0.0655	0.0679	0.0473	0.0465	0.947	0.917	1.257	1.275
8	2.1899	2.5824	2.6685	1.7065	1.7891	0.875	0.852	1.214	1.171
9	0.5946	0.4406	0.4797	0.2698	0.3010	1.268	1.187	1.804	1.674
10	2.5753	2.6355	2.8616	1.9276	1.6256	0.980	0.913	1.273	1.459
					Average	1.008	0.969	1.401	1.427

Table 4. Predicted Maximum Moments and Fracture Ratio from Modified SC. TNP Method, Original SC. TNP Method, R6 Method, and DPFAD Method for Austenitic Pipings

Exp. No	Mexp (MN-m)	mod. SC. TNP (MN-m)	org. SC. TNP (MN-m)	R6 (MN-m)	DPFAD (MN-m)	FR mod. SC. TNP	FR org. SC. TNP	FR R6	FR DPFAD
11	0.2303	0.2511	0.2630	0.2056	0.2429	0.917	0.876	1.120	0.948
12	0.3564	0.4486	0.4654	0.4082	0.3670	0.802	0.774	0.787	0.972
13	0.0295	0.0367	0.0394	0.0297	0.0289	0.804	0.749	0.993	1.021
14	0.0596	0.0471	0.0502	0.0416	0.0465	1.265	1.187	1.431	1.281
15	0.1009	0.0839	0.0882	0.0643	0.0704	1.202	1.143	1.569	1.434
16	0.0411	0.0391	0.0400	0.0366	0.0308	1.051	1.027	1.122	1.334
17	0.0330	0.0322	0.0331	0.0268	0.0242	1.026	0.996	1.231	1.362
18	0.0377	0.0405	0.0414	0.0392	0.0332	0.932	0.911	0.962	1.137
19	0.0366	0.0375	0.0386	0.0318	0.0302	0.895	0.869	1.057	1.110
20	0.0375	0.0375	0.0385	0.0339	0.0290	0.999	0.975	1.105	1.292
21	0.0303	0.0287	0.0296	0.0217	0.0193	1.053	1.023	1.396	1.568
22	0.0323	0.0336	0.0346	0.0281	0.0254	0.963	0.935	1.149	1.272
23	0.2211	0.2022	0.2083	0.1534	0.1571	1.093	1.062	1.441	1.407
24	0.2342	0.2069	0.2130	0.1567	0.1619	1.132	1.099	1.495	1.447
25	0.1951	0.1866	0.1921	0.1403	0.1451	1.046	1.016	1.391	1.345
26	0.1600	0.1387	0.1448	0.0773	0.1092	1.113	1.078	1.651	1.320
					Average	1.012	0.976	1.223	1.262

The maximum moments measured from the experiments (M_{exp}), the predicted maximum moment using the ASME Code Z-Factor (M_{pred}(ASME)), and the predicted maximum moment using the new Z-Factor (M_{pred}(New)) are given in Table 5. The fracture ratios from the ASME Code Z-Factor (FR(ASME)) and those from the new Z-Factor (FR(New)) are also shown in Table 5. The average FR(new) value is 0. 980, while the average FR(ASME) is 1.308. This means that the Z-Factor method using the new Z-Factor well predicts the circumferential surface crack behavior in ferritic pipings within 2%, while the Z-Factor method using the ASME Code Z-Factor gives too conservative results by 30.8%. The standard devia-

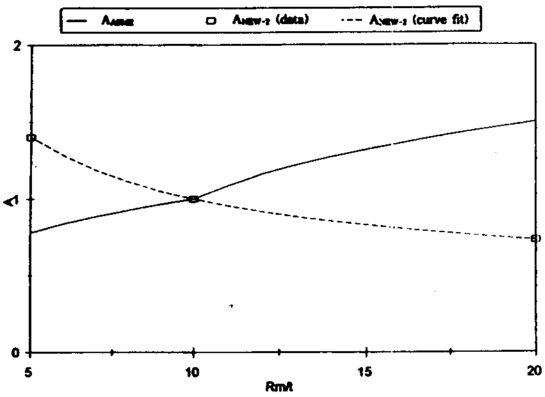

Fig. 10. Comparison of New A Value(A_{NEW-2}) With ASME A Value(A_{ASME}) for Ferritic SAW Weld Metal

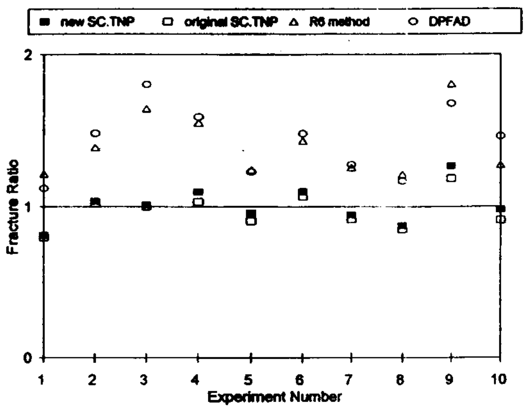

Fig. 11. Comparison of Fracture Ratio from Modified SC. TNP Method, Original SC. TNP Method, R6 Method, and DPFAD Method for Ferritic Pipings

tions of fracture ratios from the new Z-Factor and the ASME Code Z-Factor are 0.093 and 0.140 respectively. The standard deviation of fracture ratios from the new Z-Factor is reduced by 33.5% compared to those from the ASME Code Z-Factor.

The fracture ratio for ferritic pipings given in Table 4 are shown in Fig. 13.

This study is focused on the Z-Factor in the ferritic pipings. Further research is required for the ASME Code Z-Factor in austenitic pipings because the ASME Code Z-Factor for austenitic pipings also gives

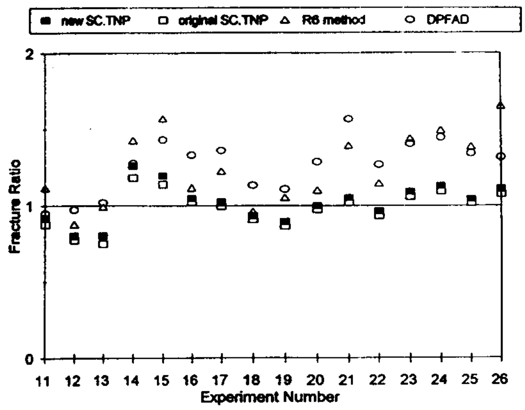

Fig. 12. Comparison of Fracture Ratio from Modified SC. TNP Method, Original SC. TNP Method, R6 Method, and DPFAD Method for Austenitic Pipings

Table 5. Predicted Maximum Moments and Fracture Ratio from ASME Code Z-Factor and New Z-Factor

Exp. No.	Mexp (MN-m)	Mpred(ASME) (MN-m)	Mpred(New) (MN-m)	FR(ASME)	FR(New)
1	0.038	0.029	0.038	1.298	0.998
2	0.080	0.068	0.086	1.180	0.931
3	0.117	0.087	0.108	1.355	1.082
4	0.748	0.566	0.730	1.323	1.025
5	0.366	0.277	0.407	1.318	0.898
6	0.077	0.062	0.082	1.210	0.952
7	0.062	0.058	0.076	1.049	0.826
8	2.190	1.202	2.405	1.556	0.928
9	0.595	0.347	0.487	1.504	1.171
10	2.575	1.894	2.605	1.287	0.990
			Average	1.308	0.980
			Diviation	0.140	0.093

an underestimation of the maximum moment of austenitic piping with circumferential surface crack[5-7].

5. Conclusions

In this study, the SC. TNP method, which is based on the J integral GE/EPRI method, is modified first and then new Z-Factors are developed using the modified SC. TNP method. The desirabilities of both

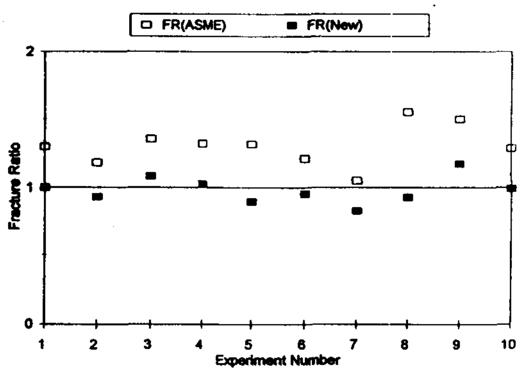

Fig. 13. Comparison of Fracture Ratio from ASME Z-Factor and New Z-Factor

the modified SC. TNP method and the new Z-Factor s are examined using the previous experimental results for the circumferential surface crack in ferritic pipings. The conclusions of this study are as follows :

(1) The modified SC. TNP method is good for describing the circumferential surface crack behavior in ferritic and austenitic pipings.

(2) The new Z-Factor obtained from the modified SC. TNP method well predicts the behavior of circumferential surface crack in both ferritic base metal pipings and ferritic SAW weld metal pipings within 2%.

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