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Evaluation of Piping Integrity in Thinned Main Feedwater Pipes

Young Hwan Choi and Suk Chull Kang
Korea Institute of Nuclear Safety
19 Kusung-dong, Yusong-gu, Taejon, 305-338, Korea
k202cyh@kins.re.kr

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Abstract

Significant wall thinning due to flow accelerated corrosion(FAC) was recently reported in main feedwater pipes in 3 Korean pressurized water reactor(PWR) plants. The main feedwater pipes in one plant were repaired using overlay weld method at the outside of pipe, while those in 2 other plants were replaced with new pipes. In this study, the effect of the wall thinning in the main feedwater pipes on piping integrity was evaluated using finite element method. Especially, the effects of both the overlay weld repair and the stress concentration in notch-type thinned area on the piping integrity were investigated. The results are as follows ; (1) The piping load carrying capacity may significantly decrease due to FAC. In special, the load carrying capacity of the main feedwater pipe was reduced by about 40% during about 140 months operation in Korean PWR plants. (2) By performing overlay weld repair at the outside of pipe, the piping load carrying capacity can increase and the stress concentration level in the thinned area can be reduced.

Key Words : pipe wall thinning, flow accelerated corrosion(FAC), main feedwater pipe, piping integrity, load carrying capacity, stress concentration

1. Introduction

The total length of pipe in one typical 1000 MWe pressurized water reactors(PWR) plant is known to be about 100 km. Most of the nuclear pipes are made of carbon steel except some primary coolant pipes, which are made of stainless steel. It has been well known that the carbon steel pipe is susceptible to flow accelerated corrosion(FAC). During the last three decades, about 400 wall thinning and/or failure cases due to FAC have been reported in the world.[1,2,3] After some severe accidents in the USA in the mid-1980s, it was recognized that wall thinning in carbon steel pipe had a potential risk to nuclear safety. Substantial researches have been widely performed to determine the main factors that control FAC.[2] The researches show that such factors as alloy compositions of pipe, water chemistry, operating temperature, pipe design, and hydrodynamic conditions are important to control FAC. It, however, is still not

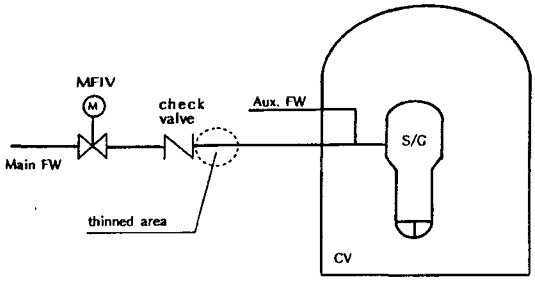


Fig. 1. Location of Thinned Area in Main Feedwater Pipe

easy to control FAC in operating plants in spite of some understanding for FAC. Hence, much emphasis have been put on the measurement and evaluation of pipe wall thinning in nuclear power plants.

The ASME Code Sec. XI IWA 2430 requires periodic inspection for nuclear safety class components.[4] However the measurement of pipe wall thinning is not required in the ASME Code Sec. XI. In USA, the measurement of pipe wall thinning for carbon steel pipe has been performed from 1989 according to some USNRC regulatory documents and NUMARC guideline.[2,5,6] In Korea, the measurement of pipe wall thinning has been also performed according to the same guideline from 1993. In 1999, significant wall thinning in main feedwater pipe was found in three Korean PWR plants. The thinned area was located between steam generator and check valve as shown in Fig. 1. The main feedwater pipe was designed as ASME Code Class 2 and was made of SA 333 Gr. 6 carbon steel with 457.2 mm(16 inches) outside diameter and Schedule 80.

ASME Code Sec. III NC 3324 gives an engineering approach to estimate the integrity of thinned pipe based on pipe minimum wall thickness,[4,7] while some ASME Code Cases give other approaches based on local thinning.[8-11] Some other engineering methods have been also proposed.[12-14] If the integrity of the thinned pipe is not verified, the thinned pipe should be repaired or replaced.

In this study, the effect of the wall thinning in the main feedwater pipes on piping integrity was evaluated using finite element method(FEM). The main feedwater pipe in one Korean PWR plant was repaired using overlay weld method at the outside of pipe, while those in the two other plants were replaced with new pipes. This overlay weld repair is 'Non-Code repair' because the ASME Code Sec. XI IWA 4000 requires that the repair should be performed at the flawed area, i.e., the inside of the thinned pipe.[4] However, the overlay weld repair may be allowed if it is verified that the piping load carrying capacity can be maintained after the overlay weld repair, considering stress concentration in the thinned area.[15] So this study focused on the effects of both the overlay weld repair and the stress concentration in notch-type thinned area on the piping integrity.

2. Wall Thinning in the Main Feedwater Pipes

2.1. The Shape of the Pipe Wall Thinning

Fig. 2 shows the cross section shape of thinned area in main feedwater pipe in one Korean PWR plant. The shape of the thinned area was obtained by replica technique using plaster. Severe wall thinning is shown at both check valve nozzle side and pipe wall side. However the thinning at the pipe wall side is more important to piping integrity because the wall thickness of this area is thinner than that of the check valve nozzle.

Fig. 3 shows the measured thickness of 3 main feedwater pipe lines(A, B, C) in circumferential direction at the location of 25 mm from the weld fusion line in the pipe wall side. The thickness was

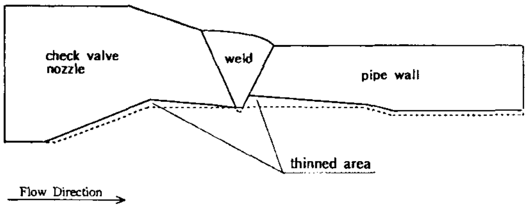


Fig. 2. Cross Section Shape of Thinned Area in Main Feedwater Pipe. The Dashed Line(…) Represents the Original Shape of the Main Feedwater Pipe

measured using ultrasonic(UT) method. As shown in the figure, wall thinning is more severe at the side of pipe(90° and 270°) than at the top and bottom(0° and 180°). The reason for the severe thinning at pipe side seems to be the structure of check valve. The nominal thickness(t_{nom}) of the main feedwater pipe is 23.83 mm, and the minimum thinned thickness(t_{thin}), which was measured at the location of 40° from the pipe top in line C, is 14.99 mm. It means that about 40% of pipe wall thickness have been thinned during about 140 months operation.

2.2. Minimum Wall Thickness in ASME Code Sec. III NC 3324

The ASME Code Sec. III requires that minimum wall thickness(t_{min}) should be maintained during plant operation. In the ASME Code Sec. III NC 3324, tmin is defined for class 2 piping as[7]

$$t_{min} = \frac{P \cdot D_0}{2(S + 0.4 \cdot P)} \quad (1)$$

, where P is the design pressure, D_o is the pipe outer diameter, and S is the maximum allowable stress. The value of tmin for the main feedwater pipe can be calculated as 17.50 mm from the values of P(= 8.17 MPa), D_o(= 457.2 mm), and S(= 103.42 MPa). This shows that the thinned

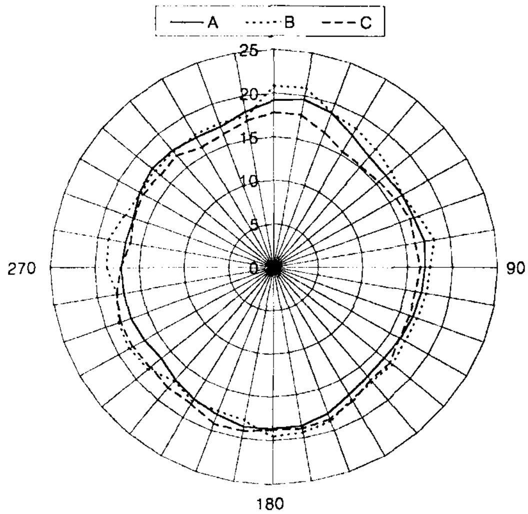


Fig. 3. Measured Thickness for 3 Main Feedwater Pipe Lines (A, B, C) in Circumferential Direction at the Distance of 25 mm from Weld Fusion Line Using UT Method. Radial Axis Represents the Pipe Wall Thickness

main feedwater pipe does not satisfy the minimum wall thickness requirement.

2.3. Allowable Thickness in ASME Code Case N-597

ASME Code Case N-597 gives a special estimation procedure for continued operation for the flawed components with a thickness less than the minimum wall thickness.[8] The ASME Code Case N-597 allows continuous operation if it is verified that predicted wall thickness(t_{pred}) at the next overhaul is larger than allowable thickness(t_{aloc}) based on local thinning.

The t_{pred} can be defined as

$$t_{pred} = t_{thin} - TR \cdot T_{no} \quad (2)$$

$$TR = \frac{(t_{nom} - t_{thin})}{T_0} \quad (3)$$

, where TR is the average wall thinning rate, T_{no} is the operation time to next overhaul, and T_o is the total operation time. With the data of t_{nom}(= 23.83 mm), t_{thin}(= 14.99 mm), T_{no}(= 15 months), and T_o(= 140.2 months), TR and t_{pred} for the main feedwater pipe can be obtained as 0.757 mm/year and 14.04 mm, respectively.

The ASME Code Case N-597 gives three cases of the local thinning as follows;

(1) 3622.2 Local Thinning - Limited Transverse Extent

(2) 3622.3 Local Thinning - Limited Axial and Transverse Extent

(3) 3622.4 Local Thinning - Unlimited Transverse Extent

Because the wall thinning of the main feedwater pipe has a shape of unlimited transverse extent as shown in Fig. 2 and Fig. 3, the criteria in N-597 3622.4 can be applied. Based on the measured data of $L_{m(a)}$(=164.73 mm) which is the maximum axial extent of local thinned area with wall thickness less than t_{min}, we can easily obtain the values of $L_m/\sqrt{(R_{min}t_{min})}$ as 2.66 with R_{min}(= 219.85 mm). From the Table 3622-1 in N-597, the value of t_{aloc}/t_{min} is 0.9, so the value of t_{aloc} is 15.75 mm. It shows that t_{aloc} is larger than t_{pred}. This result means that the thinned main feedwater pipe does not also satisfy the ASME Code Case N-597 requirement for continuous operation.

2.4. Repair and Replacement of Thinned Pipes

Since the requirements in both the ASME Code Sec. III and ASME Code Case N-597 are not satisfied, the thinned area should be replaced or repaired according to the ASME Code Sec. XI IWA 4000 or 5000.

Plant owners usually do not have alternating pipes to replace the thinned pipe in plants. It is also not easy to repair directly the thinned area because the thinned area is located inside the pipe. So it has been proposed to repair at the outside the thinned pipe using overlay weld method. The overlay weld repair is 'Non-Code repair' because the ASME Code Sec. XI IWA 4000 requires that the repair should be performed at the flawed area, i.e., the inside of the thinned pipe.[4] However, based on the cost-benefit approach, the temporary overlay weld repair is allowed if it is verified that the piping load carrying capacity can be maintained after the overlay weld repair, considering stress concentration in the thinned area.[15] Because one Korean PWR plant repaired the thinned main feedwater pipes using the overlay weld, this study focused on the effects of both the overlay weld repair and the stress concentration in the thinned area on the piping integrity.

3. Finite Element Modeling

The load carrying capacity of the main feedwater pipe was evaluated using finite element method in this study. In order to investigate the effects of both overlay weld repair and stress concentration in the thinned area on the piping integrity, following five cases are considered in the numerical analysis.

case 1 : Minimum Wall Thickness Case

case 2 : Nominal Thickness Case

case 3 : Thinned Case

case 4 : ASME Code Repair Case

case 5 : Overlay Weld Repair Case

Case 1 represents that the pipe has the minimum wall thickness(t_{min}) given in the ASME Code Sec. III NC-3324, while case 2 is for the initial status of pipe with the nominal thickness(t_{nom}). Case 3 is for the thinned pipe with the minimum measured thickness(t_{thin}). In case 4, the thinned section is assumed to be repaired at the inside of pipe with the weld thickness of 6 mm

Table 1. Pipe Outer Radius, Pipe Inner Radius, and Pipe Wall Thickness for Five Cases

	Cases	Outer Radius (mm)	Inner Radius (mm)	Wall Thickness (mm)	
1	Minimum Wall Thickness Case	228.60	211.10	t_{min}	17.50
2	Nominal thickness Case	228.60	204.77	t_{nom}	23.83
3	Thinned Case	228.60	213.61	t_{thin}	14.99
4	ASME Code Repair Case	228.60	207.61	t_{ASME}	20.99
5	Overlay Weld Repair Case	234.60	213.61	t_{over}	20.99

Table 2. Tensile Properties of Base Metal and Weld Metal Obtained from the Engineering Stress-strain Curves.[17-19]

	Yield Stress (MPa)	Tensile Strength (MPa)	Elongation (%)	Reduction of Area (%)
Base Metal	224	530	30.5	65.0
Weld Metal	325	670	28.0	45.8

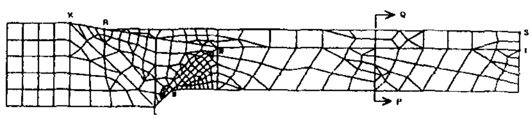


Fig. 4. Finite Element Modelling for the Overlay Weld Repair Case (case 5) Using ANSYS Program. The Boundary K-L-N Represents the Original Weld Area and the Boundary R-S-T-N Represents the Overlay Weld Area

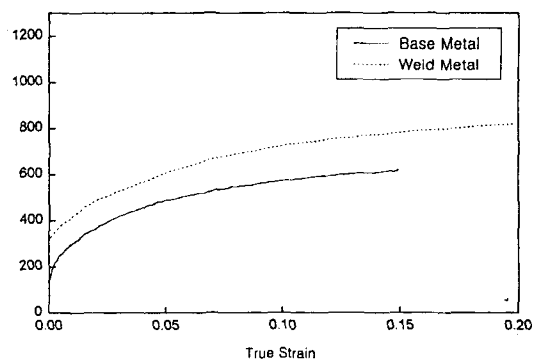


Fig. 5. True Stress-strain Curves for Base Metal and Weld Metal[17-19]

according to ASME Code Sec. XI IWA 4000. Case 5 is for the case that the thinned area is repaired at the outside of pipe using overlay weld with the weld thickness of 6 mm. The outer radius, the inner radius, and the wall thickness for five cases are shown in Table 1.

Fig. 4 shows the finite element modeling for the overlay weld repair case(case 5) using ANSYS program.[16] Axisymmetric structural solid element in ANSYS program was used in the modeling. In the overlay weld repair case, total 258 elements and 259 nodes were generated. The fine size element was used in the thinned area to examine the stress concentration effect. The boundary K-L-N represents the original weld area and the boundary R-S-T-N represents the overlay weld area. Points L, M, and N are the points along weld fusion line. It is assumed that the pipe wall side has the same thickness in both the circumferential direction and the axial direction as shown in Fig. 4.

Table 2 represents the tensile properties such as yield stress, tensile strength, elongation, and reduction of area for base metal and weld metal.[17-19] Fig. 5 shows the true stress vs.

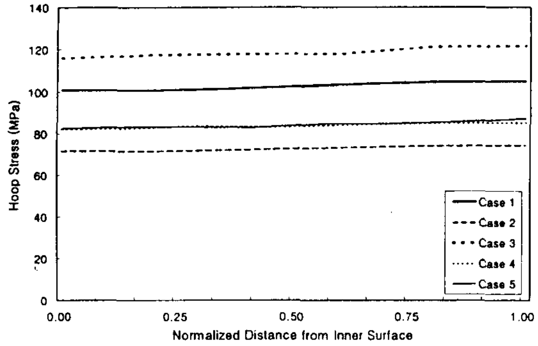


Fig. 6. Comparison of Hoop Stresses for Five Cases Obtained from FEM Results. The Hoop Stresses were Obtained Along the P-Q Cross Section Line Shown in Fig. 4

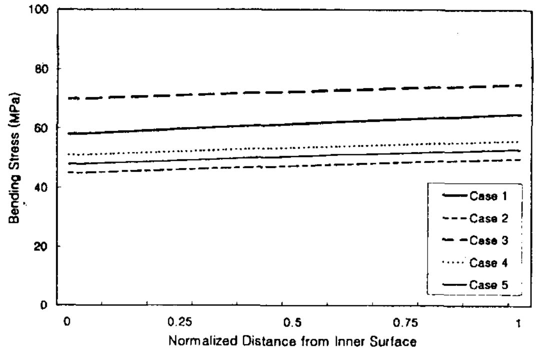


Fig. 7. Comparison of Bending Stresses for Five Cases Obtained from FEM Results. The Bending Stresses were Obtained Along the P-Q Cross Section Line Shown in Fig. 4

strain curve for base metal and weld metal.[17-19] The tensile properties of both the pipe wall and the check valve nozzle is assumed to be same. The tensile properties of both the original weld area and the overlay weld area(R-S-T-N) is also assumed to be same in FEM analyses.

There are usually two types of loading such as internal pressure and applied moment in piping system. The internal pressure and applied moment near the thinned area are given in design report as 8.17 MPa and 0.1673 MN-m, respectively. The applied moment is the absolute summation of moments due to dead weight, thermal transient, safe shutdown earthquake(SSE), and seismic anchor motion(SAM). The bending moment was applied to the pipe as a concentration load at the pipe end.

In this study, both the hoop stress and bending stress due to the internal pressure and the applied moment were used as measures of piping integrity. ANSYS program gives directly the hoop stress, radial stress, and axial stress as calculation results. The pressure-induced bending(PIB) stress may be applied to the pipe system by the internal pressure loading. For internal pressure loading, the axial stress represents the PIB stress because the ends of pipe are normally open. For the applied moment loading, the axial stress represents the bending stress.

4. Results and Discussion

4.1. Load Carrying Capacity

Fig. 6 and Fig. 7 show the hoop stress due to the internal pressure and the bending stress due to the moments for five cases, respectively. The hoop and bending stresses are obtained along the P-Q cross section line shown in Fig. 4. As shown in the figures, both the hoop stress and the bending stress of each case slightly increase to radial direction. The pressure-induced bending (PIB) stress may be applied to the piping system by the internal pressure. The PIB stress depends on the boundary condition of piping system. In this study, the check valve side is assumed as an anchor point because there are anchor supports between the check valve and the main feedwater isolation valve(MFIV). Fig. 8 shows the radial stress, axial stress, and hoop stress along the P-Q

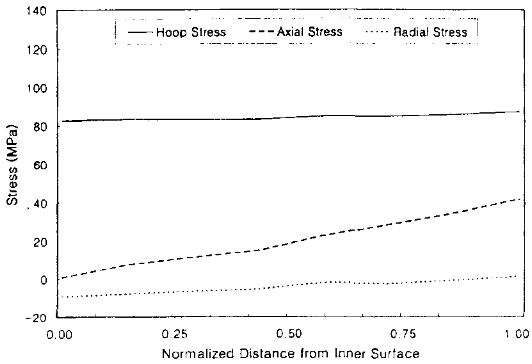


Fig. 8. Comparison of Radial Stress, Axial Stress, and Hoop Stress Bending Stresses for the Overlay Weld Repair Case(case 5) Obtained from FEM Results. The Stresses were Obtained Along the Cross Section of P-Q Shown in Fig. 4.

cross section line for the overlay weld repair case(case 5). In the figure, the axial stress due to the internal pressure represents the PIB stress. For case 5, the PIB stress is about 50% of the hoop stress at the outside of pipe. This PIB stress is also about 80% of the bending stress due to the moments at the outside of pipe. It implies that the PIB stress should be considered in bending stress calculation.

Table 3 represents the normalized hoop stress and bending stress for five cases. The hoop and bending stresses were normalized by those obtained from the minimum wall thickness case(case 1). The hoop and bending stresses at the outer surface of pipe are used for comparison in this study. The normalized bending stress considering the PIB stress is also listed in the table. The result shows that the PIB stress affects the result by about 5%. The normalized bending stress including the PIB stress is used in this study for comparison.

As listed in Table 3, the normalized hoop and

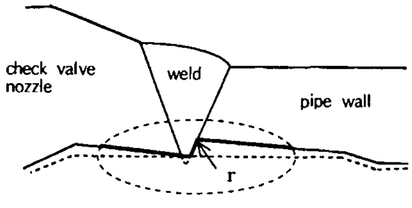
Table 3. Normalized Hoop Stress and Bending Stress at the Outside of Pipe for Five Cases. All Cases are Normalized by the Values from the Minimum Wall Thickness Case(case 1)

Cases	Normalized Hoop Stress	Normalized Bending Stress	
		M*	M+PIB**
1	1	1	1
2	0.71	0.77	0.81
3	1.16	1.15	1.22
4	0.81	0.86	0.88
5	0.83	0.82	0.87

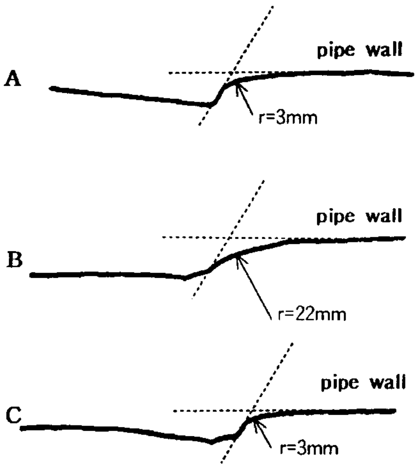
* M : Bending Stress due to Moments
** PIB : Pressure-Induced Bending Stress

bending stresses in the thinned case(case 3) are higher than those in the nominal thickness case(case 2) by 45% and 41%, respectively. This means that the main feedwater pipe had lost the load carrying capacity by about 40% during about 140 months operation, compared to initial status. It means that the piping load carrying capacity may significantly decrease due to FAC. The table also shows that the normalized hoop and bending stresses in the thinned case(case 3) are higher than those in the minimum wall thickness case(case 1) by 16% and 22%, respectively. This result implies that the piping integrity can not be assured if the thinned pipe is not repaired or replaced.

For ASME Code repair case(case 4), the normalized hoop and bending stresses are lower than those in the thinned case(case 3) by 35% and 34%, respectively. For the overlay weld repair case(case 5), the normalized hoop and bending stresses are lower than those in the thinned wall case(case 3) by 33% and 35%, respectively. These results show that the overlay weld repair can increases the load carrying capacity nearly up to the level of ASME Code repair.



(a) Replica location for the shape of thinned Area



(b) Shape of thinned area

Fig. 9. (a) Replica Location for the Shape of Thinned Area, and (b) Shapes of Thinned Area in the Three Main Feedwater Pipe Lines(A, B, C) Obtained from Replica

4.2. Stress Concentration in Thinned Area

Fig. 9 shows the thinned shape of the three main feedwater pipe lines(A, B, C) at the top of the pipes obtained by replica technique with plaster. As shown in Fig. 9, there is notch-type thinning between the weld fusion line and the pipe inner surface. The minimum roundness of the notch-type thinning is about 3~4 mm though the roundness varies at the measured point. So, it is assumed in the FEM modeling that the weld fusion line and the thinned pipe inner surface cross straightly at the point M as shown in Fig. 4.

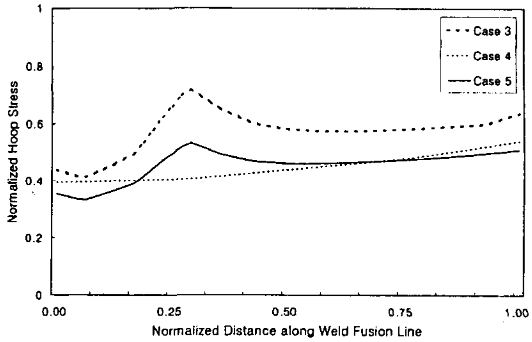


Fig. 10. Normalized Hoop Stress in Thinned Area Along Weld Fusion Line for Cases 3, 4, and 5. The Hoop Stress is Normalized by the Hoop Stress at the Outside of Piping Obtained from the Minimum Wall Thickness Case(case 1)

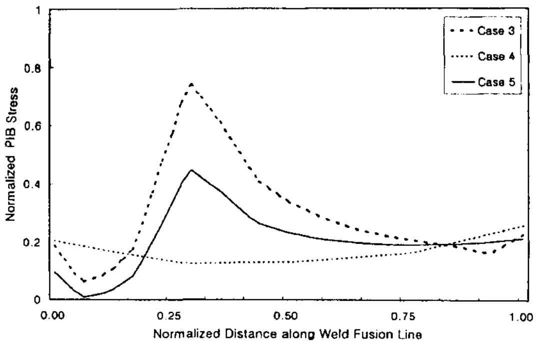


Fig. 11. Normalized Pressure Induced Bending (PIB) Stress in Thinned Area Along Weld Fusion Line for Cases 3, 4, and 5. The PIB Stress is Normalized by the Hoop Stress at the Outside of Pipe Obtained from the Minimum Wall Thickness Case(case 1)

Fig. 10 and Fig. 11 show the normalized hoop stress and the normalized PIB stress along the weld fusion line(Points L, M, and N in Fig. 4) for cases 3, 4, and 5, respectively. The hoop and PIB stresses are normalized by the hoop stress at the outside of pipe in the minimum wall thickness case(case 1). The figures show that there are stress concentration near the Point M in both the thinned case(case 3) and the overlay weld repair case(case 5). There, however, is no stress concentration in the ASME Code repair case(case 4) because it is assumed that the thinned area is directly repaired at the inside of pipe. The figures show that the stress concentration in PIB stress is more severe than in the hoop stress. As shown in the figure, the stress concentration level in the overlay weld case(case 5) was reduced by 26% in the hoop stress case and 40% in the PIB stress case, compared to the thinned case(case 3). This result shows that the stress concentration level may be reduced by the overlay weld repair though the overlay weld repair is performed at the outside of pipe. The reason for the reduction of the stress concentration level in case 5 is the wall thickening(6 mm) at the outside of pipe due to overlay weld.

4.3. Weakness of Overlay Weld

Although the overlay weld repair can increase the piping load carrying capacity and can reduce the stress concentration level, the overlay weld repair may give following two adverse effects on piping integrity. The first one is that the stress concentration still remains in the thinned area. Fig. 10 and Fig. 11 show that the normalized stresses in the overlay weld repair case(case 3) are higher than those of the ASME Code repair case(case 4) by 23% in the hoop stress and 71% in the PIB stress, respectively. It is obvious that the increase of stress level may reduce the fatigue life in S-N curve.[20] The increase of stress level may also accelerate the fatigue crack growth as represented in ASME Code Sec. XI App. A.[4] The second one is that the overlay weld repair can not protect FAC in the thinned area. The pipe wall thinning would be continued and accelerated in the thinned area. Because of the above adverse effects, it is recommended that the overlay weld repair is performed for temporary purpose. USNRC GL 90-05 also points out the overlay weld repair can be applicable until the next scheduled outage.

5. Conclusions

(1) The piping load carrying capacity may significantly decrease due to FAC. In special, the load carrying capacity of the main feedwater pipes was reduced by about 40% during about 140 months operation in Korean PWR plants.

(2) By performing the overlay weld repair at the outside of pipe, the piping load carrying capacity can increase up to the level in ASME Code repair at the thinned area and the stress concentration level in the thinned area can be also reduced.

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