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Fatigue Evaluation for the Socket Weld in Nuclear Power Plants

Young Hwan Choi, Sun Yeong Choi*, and Nam Soo Huh**

Korea Institute of Nuclear Safety, 19 Gusung, Yusung, Daejeon 305-338, Korea
**Korea Atomic Energy Research Institute, 150 Dukjin, Yusung, Daejeon, 305-353, Korea*
***School of Mechanical Engineering, Sungkyunkwan University, Suwon, Korea*

The operating experience showed that the fatigue is one of the major piping failure mechanisms in nuclear power plants (NPPs). The pressure and/or temperature loading transients, the vibration, and the mechanical cyclic loading during the plant operation may induce the fatigue failure in the nuclear piping. Recently, many fatigue piping failure occurred at the socket weld area have been widely reported. Many failure cases showed that the gap requirement between the pipe and fitting in the socket weld was not satisfied though the ASME Code Sec. III requires 1/16 inch gap in the socket weld. The ASME Code OM also limits the vibration level of the piping system, but some failure cases showed the limitation was not satisfied during the plant operation. In this paper, the fatigue behavior of the socket weld in the nuclear piping was estimated by using the three dimensional finite element method. The results are as follows. (1) The socket weld is susceptible to the vibration if the vibration levels exceed the requirement in the ASME Code OM. (2) The effect of the pressure or temperature transient load on the socket weld in NPPs is not significant because of the very low frequency of the transient during the plant lifetime operation. (3) 'No gap' is very risky to the socket weld integrity for the specific systems having the vibration condition to exceed the requirement in the ASME OM Code and/or the transient loading condition. (4) The reduction of the weld leg size from $1.09*t_1$ to $0.75*t_1$ can affect severely on the socket weld integrity.

Keywords : *nuclear power plant, piping, socket weld, fatigue, integrity*

1. Introduction

The fatigue is one of the major piping failure mechanisms in nuclear power plants (NPPs).[1)~6)] The pressure and/or temperature loading transients, the vibration, and the mechanical cyclic loading during the plant operation may induce the fatigue failure in the nuclear piping. OPDE (OECD Piping Failure Data Exchange) database(rev.0.a) lists 843 fatigue failures among 2,399 nuclear piping failure cases during 1970 to 2001.[1)] The OPDE database also shows 688 piping failures due to corrosion, 341 failures due to flow accelerated corrosion (FAC), 233 failures due to human errors, 136 failures due to overloading, and 158 failures due to other root causes. In special, many fatigue failures occurred at the location with geometric discontinuities such as the socket weld area. The OPDE database lists 108 socket weld failures among 2,399 nuclear piping failure cases. Six failures in the socket weld were also reported in Korean NPPs.[7)]

There are usually about 40,000 socket welds in one typical 1000 MWe pressurized water reactor (PWR) plant. The ASME B & PV Code Sec. III allows the socket weld for nuclear piping with a special condition that they should not be used in service where crevice corrosion between the pipe and fitting may occur.[8)] Using the socket weld is also limited to the pipes which has the size less than the nominal pipe size (NPS) of 2 inch for the ASME Class 1 & 2 piping and less than the NPS of 4 inch for ASME Class 2 drain or bypass piping in NPPs.[8)]

The purposes of this paper are to evaluate the integrity of the socket weld in nuclear piping and prepare the technical basis for a new guideline on RT for the socket weld. The effects of the gap and weld leg size on the socket weld integrity were evaluated by using the finite element method in this paper.

2. Fatigue failure events in Korean NPPs

From 1999 to 2003, 10 piping failures due to the fatigue occurred in Korean NPPs. Table 1 represents the summary of the fatigue failure cases up to June 30, 2003 including failed system, pipe size, failure type and dimension, pipe material, and piping failure analysis results about root cause, impact on plant safety, corrective action (CA), and in-service inspection (ISI) history.[7)] The failed systems were the chemical and volume control system (CVCS) in

WH 3-loop plant, the primary sampling system (PSS) in Korean standard nuclear power plant (KSNP), and the purification system in CANDU 6 reactors. The root causes of the socket weld failures were analyzed to be vibration, thermal fatigue (TF), and/or improper weld joint. Pipe sizes of the failed piping ranged from the NPS of 3/8 inch to 4 inch, and the pipe materials were the stainless steel such as 304SS and 316SS and the carbon steel such as SA234 WPB. There was no pipe rupture in the above socket weld failures in spite of crack and leakage in the socket weld area.

Among the ten piping failures due to the fatigue, six piping failures occurred at the socket weld area in the CVCS and PSS as follows.

2.1 Socket weld failure in CVCS

Five (5) socket welds in CVCS of one Korean NPP were successively failed during about 3 months. Leak rate from the failed socket welds was approximately estimated as about 0.043 gpm to 0.09 gpm, which was the limitation of one (1) gpm in the plant Technical Specification (Tech. Spec.).

The cracking in the socket weld in CVCS was analyzed to be flow induced vibration. The vibration was induced from the unstable flow in one CVCS orifice which flow hole was damaged by cavitations.

The vibration deflection and velocity near the failed socket weld during operation were measured as 110 μm and 30 mm/sec, respectively. The ASME Code OM Part 3 gives requirements on allowable vibration deflection (δ_{allow}) and allowable vibration velocity (V_{allow}).[9] From these requirements, the values of δ_{allow} and V_{allow} near the failed socket weld under events were calculated as 18 μm and 20 mm/sec, respectively. These results show that the vibration level near the failed socket weld was higher than the limitations required in the ASME Code OM Part 3 by factors of 6.1 and 1.5 in deflection and velocity, respectively. After repairing the failed area, the vibration levels were measured as about 2~3 μm and 2.2~2.4 mm/sec in deflection and velocity, respectively.

The crack was initiated from the socket weld root and was propagated along the center of the socket weld due to the fatigue loading. The lengths of the through-wall cracks (TWC) were ranged from 2% to 48% of the pipe circumference.

By using both the number of welds in CVCS and operating years, the piping failure frequencies were estimated as 4.86E-05/Rx-Yr and 9.04E-05/Rx-Yr for the NPS of 3/4 inch and 2 inch, respectively.[7]

2.2 Socket weld failure in primary sampling system

During full power operation of one KSNP, the increase of normal sump level was alarmed at the main control room and operators identified the leakage at the socket weld between the tube and union in primary sampling system. The failed tube was temporally repaired with a mechanical coupling during power operation. The failed tube was made of 316 stainless steel with the NPS of 3/8 inch. There was about 0.01 gpm leakage from the failed socket weld. The length of the through-wall crack was about 4mm that is about 14% of the pipe circumference. All piping of the primary sampling system was replaced

Table 1. Summary of Socket Weld Failures in Korean NPPs[7]

ID	Failed System		Pipe Size		Failure		Piping Material	Piping Failure Analysis			
	Rx Type	System	Nominal Diameter (in)	Schedule (Thickness)	Failure Type	Failed Depth/ Crack Length		Root Cause	Impact on Plant Safety	Corrective Action	ISI History
1	WH-3	CVCS	2	160	crack/leak	TWC/unknown	340SS	Vibration	Line Isolation	repair	Out of Scope
2	WH-3	CVCS	2	160		TWC/4mm					
3	WH-3	CVCS	3/4	160		TWC/40mm					
4	WH-3	CVCS	3/4	40		TWC/25mm					
5	WH-3	CVCS	2	160		TWC/40mm					
6	KSNP	PSS	3/8	N/A (1.65mm)	crack/leak	TWC/4mm	316SS	TF	Line Isolation	repair	Out of Scope
7	CANDU	PS	4	80	crack/leak	TWC/16mm	SA234 WPB	TF	Plant Shutdown	replaceme nt	Out of Scope
8	CANDU	PS	4	80		TWC/24mm					
9	CANDU	PS	4	80		TWC/50mm			No (O/H)	repair	Out of Scope
10	CANDU	PS	4	80		TWC/unknown					

with new tubes and unions in the next O/H.

The root cause of the failure in the primary sampling system was analyzed to be the thermal fatigue (TF) due to operational condition and the improper weld joint. There was 'no gap' between the tube and union in the failed socket weld. Such weld geometry can induce a high thermal stress at the socket weld area because the thermal expansion of the tube was constrained. Operation procedure for the primary sampling system shows that the sampling time of the primary coolant is about 20 minutes and then the line was isolated and cooled-down by natural convection.[10] It means that the primary sampling system experiences the severe transient loading from P = 0 and T = 25℃ to P = 15.51 MPa and T = 288℃, which P and T are the pressure and temperature, respectively. In addition, operational record showed that operators had sampled the primary coolant every day though the plant Tech. Spec. requires primary coolant sampling every 3 days. The frequent surveillance may contribute the socket weld failure by fatigue.

By using both the number of welds in the primary sampling system and operating years, the piping failure frequency of the primary sampling system was estimated as 2.54E-04/Rx-Yr.[7]

3. Fatigue evaluation of socket weld by using fem

3.1 Socket weld geometry

Fig. 1 shows the schematic diagram of the socket weld between the pipe and fitting such as valve, union, tee, orifice, or elbow. The ASME Code Sec. III requires about 1/16 inch gap(g) between the pipe and fitting in the socket weld and the minimum of 1.09*t_l for the weld leg (WL), where t1 is the pipe thickness as shown in the Fig. 1. Some cases, however, showed that the requirements on the gap were not satisfied.

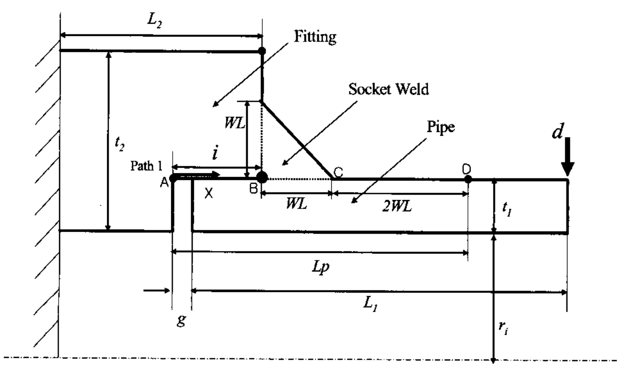

Fig. 1. Geometry of Socket Weld with Pipe and Fitting

The ASME Code also requires non-destructive examination (NDE) such as magnetic particle examination (MT) or liquid penetration examination (PT) on the socket weld area, but not radiographic examination (RT).

It means that it is not easy to examine the 1/16 inch gap by using the NDE methods currently required in the Code.

3.2 FEM modelling for socket weld

The socket weld integrity was evaluated by finite element method (FEM) with the well-known ABAQUS program. 20-nodes isoparmetric brick reduced integration element (C3D20R in ABAQUS) was used for the modelling as shown in Fig. 2 The surface between the outer side of pipe and the inner side of fitting was assumed as a crack for conservatism. The crack tip is located at the socket weld root that is the Point B in the Fig. 1. The numbers of element and node were 4,321 and 19,932, respectively. Two types of failure mode such as open mode and close mode were considered in the vibration analysis.

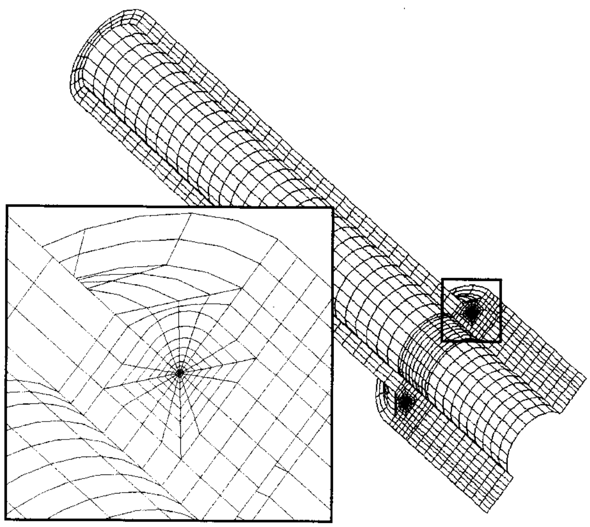

Fig. 2. 3 Dimensional FEM Modelling for Socket Weld Analysis

The dimensions of the pipe and fitting shown in the Fig. 1 are as follows; pipe inner radius (r_i) is 21.41 mm, pipe thickness (t_1) is 8.738 mm, pipe total length (L_1) is 310.5 mm, fitting thickness (t_2) is 23.70 mm, fitting length (L_2) is 86.00 mm, and i=16.00 mm. For comparison, reference problem is defined in this study with the conditions that weld leg (WL) is 9.525 mm, gap (g) is 1.588 mm (1/16 inch), deflection (d) is 1.016 mm, reference temperature is 25℃, and no pressure inside the pipe.

3.3. Fatigue crack growth curve

The appendix C in the ASME Code Sec. XI gives the

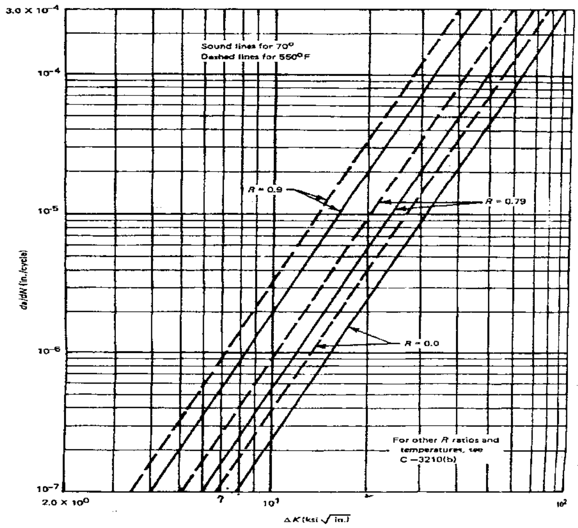

Fig. 3. Fatigue Crack Growth Curve for Stainless Steel

fatigue crack growth curve as

$$da/dN = Co\ (\Delta K)^n \quad (1)$$

where n = 3.3 and C_o is the function of temperature and R ratio (K_{min}/K_{max}).[11] Fig. 3 shows the fatigue crack growth curve for the stainless steel.

4. Results and discussions

4.1 Effect of loading condition

We considered three types of loading conditions as follows; (1) the deflection due to vibration, (2) the pressure transient load from P = 0 to 15.51 MPa, and (3) the thermal transient load from T = 25 ℃ to 288 ℃.

4.1.1 Deflection due to vibration

Vibration is known as one major root cause of the small bore piping failure. We modelled the vibration in piping system as the deflection type load (d) as shown in the Fig. 1. We used the stress intensity factor (K) as a measure of the socket weld integrity. Fig. 4 shows the effect of deflection (d) on the socket weld. The values of K were normalized as K_{ref} of 289 MPa√(mm) for the above reference problem. As shown in the figure, the stress intensity factor linearly increases as the deflection increases. The difference of the stress intensity factor between the open mode and close mode (ΔK) can be considered as the fatigue loading due to vibration. The value of ΔK at the deflection of 0.73 mm, which is the measured vibration level in the failed socket weld of HV3 in CVCS, is about 135.3 MPa√(mm). By using this fatigue growth curve with the ΔK value of 135.3 MPa√(mm), the fatigue crack growth rate (da/dN) can be obtained as

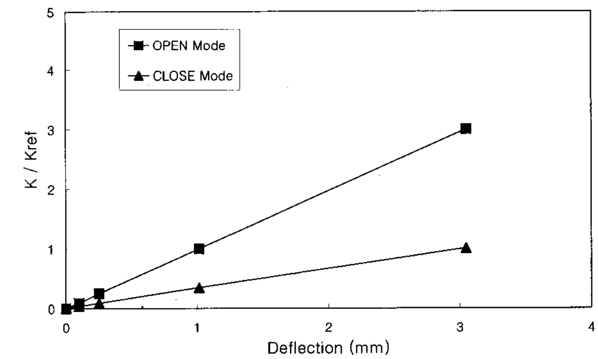

Fig. 4. Deflection Effect on Stress Intensity Factor(K) normalized as K_{ref} = 289 MPa√(mm).

4.05×10^{-7} mm/cycle. If the vibration frequency of the failed piping in CVCS is assumed as 33Hz, which is the design limit required in ASME Code OM,[9] it takes only about 8.25 days to penetrate the weld leg(9.525 mm). The result shows that socket weld is susceptible to the vibration if the vibration levels exceed the requirement in the ASME Code OM.

4.1.2 Pressure transient load

Fig. 5 shows the pressure effect on the stress intensity factor for the reference problem with no deflection. The stress intensity factor for the normal operation pressure (15.51 MPa) is calculated as 535.4 MPa√(mm). There was no pressure transient in CVCS during the normal operation, so the K value of 535.4 MPa√mm affects the R ratio. The R ratio changes from 0.394 to 0.818 if the pressure is considered in the fatigue analysis.

If the pressure transient from zero to the normal operation pressure(15.51 MPa) is considered as loading condition as PSS, the K value of 535.4 MPa√(mm) can be applied as the fatigue loading of ΔK = 535.4 MPa√(mm). By using the Eq. (1) with this ΔK, the fatigue crack growth rate (da/dN) can be obtained as 2.33×10^{-5} mm/cycle. It means that it takes 409,040 cycles of pressure

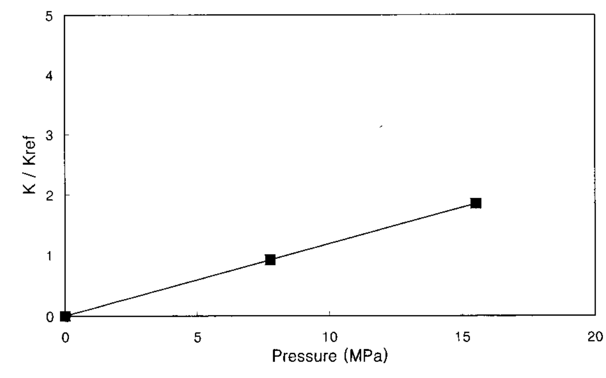

Fig. 5. Pressure Effect on Stress Intensity Factor(K) normalized as K_{ref} = 289 MPa√(mm).

transients for a crack to penetrate the weld leg(9.525mm). This result shows that the effect of the pressure transient load on the socket weld in CVCS and PSS is not significant because of the very low frequency of the pressure transient during the plant lifetime operation.

4.1.3 Thermal transient load

Fig. 6 shows the stress intensity factor for the reference problem with no deflection under the thermal transient loading condition of $\Delta T = 0$, 100, 200, and 263℃. The stress intensity factor at the normal operating temperature (288 ℃) is estimated as 542.9 MPa$\sqrt{\text{mm}}$. By using the Eq. (1) with this ΔK, the fatigue crack growth rate (da/dN) can be obtained as 4.07×10^{-5} mm/cycle. It takes 233,890 cycles of thermal transients for a crack to penetrate the weld leg(9.525 mm). As similar to the above pressure effect, this result shows that the effect of the thermal transient load on the socket weld in CVCS and PSS is not significant because of the very low frequency of the thermal transient during the plant lifetime operation.

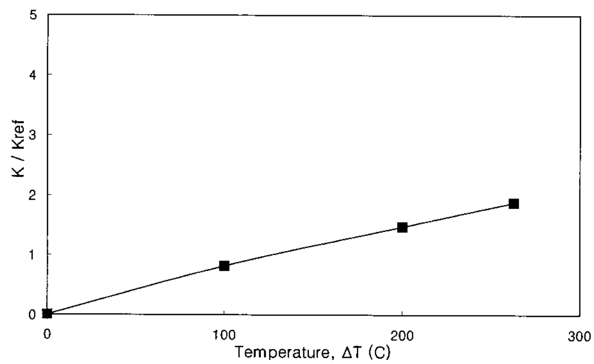

Fig. 6. Temperature Effect on Stress Intensity Factor(K) normalized as Kref = 289 MPa$\sqrt{\text{(mm)}}$.

4.2 Effect of gap

The ASME Code requires 1/16in gap between the pipe and fitting in the socket weld. However, socket welds with 'no gap' (g = 0) between the pipe and fitting were found in some failure cases. If there is 'no gap' in the socket weld, the thermal stress will be applied to the socket weld because of the constraint against the thermal expansion.

Fig. 7 shows the stress intensity factor as a function of gap for the reference problem under the deflection due to vibration. As the gap decreases to zero, the stress intensity factor in the close mode decreases, while that in the open mode very slightly increases as shown in the Fig. 7. It means that the ΔK increases as the gap decreases in the socket weld. The value of ΔK under 'no gap' condition is calculated as 273.4 MPa$\sqrt{\text{(mm)}}$. By using the Eq. (1) with this ΔK, the fatigue crack growth rate (da/dN) can be obtained as 4.73×10^{-6} mm/cycle. If the frequency of the failed CVCS is assumed as 33Hz, which is the design limit required in the ASME OM Code,[9] it takes only about 17 hours to penetrate the weld leg under the vibration condition of CVCS. It means that the socket weld is very susceptible to vibration if there is 'no gap' in the socket weld.

Fig. 8 shows the gap (g) effect under the thermal transient loading for the values of g = 0 and g = 1.5875 mm(1/16 inch). The gap of 1.588 mm(1/16 inch) is sufficient to protect the contact because there is only 0.069 mm thermal expansion of the pipe inside the fitting under the thermal transient of ΔT= 263℃. The difference between the two cases represents the gap effect excluding the thermal transient effect. The stress intensity factor at the normal operating temperature(288℃) is estimated as 1182.7 MPa$\sqrt{\text{(mm)}}$.

If the transient loading from P = 0 and T = 25 ℃ to P=15.51 MPa and T=288 ℃ is considered in the analysis, the stress intensity factor is estimated as 1,811.6 MPa$\sqrt{\text{(mm)}}$. Under this transient loading condition, the fatigue crack growth rate (da/dN) is calculated as 2.18×10^{-3}

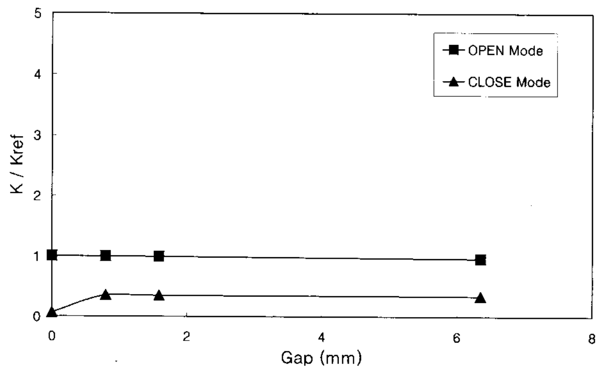

Fig. 7. Gap Effect on Stress Intensity Factor(K) normalized as K_{ref} = 289 MPa$\sqrt{\text{(mm)}}$ under Deflection Load.

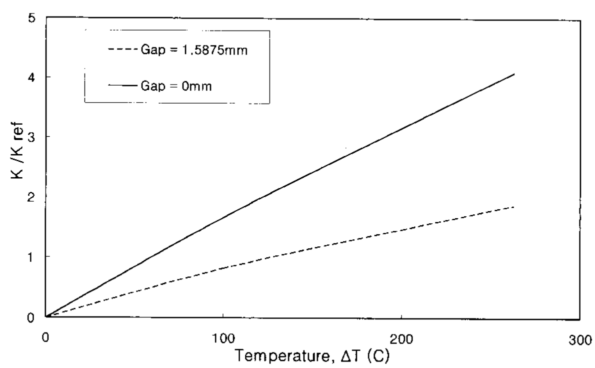

Fig. 8. Gap Effect on Stress Intensity Factor(K) normalized as K_{ref} = 289 MPa$\sqrt{\text{(mm)}}$ as a function of Temperature.

mm/cycle. It means that it takes about 4370 cycles to penetrate the weld leg(9.525 mm). If such transient load is applied to the socket weld ever day, the socket weld will be failed within 7.3 years. The results show that 'no gap' is very risky to the socket weld integrity for the specific systems having the vibration condition to exceed the requirement in the ASME Code OM and/or the transient loading condition from P = 0 and T = 25 ℃ to P = 15.51 MPa and T = 288 ℃. To such systems, RT to examine the gap during construction stage is strongly recommended.

4.3 Effect of weld leg

The industrial guideline for the weld leg size has been relieved from $1.25*t_l$ in 1989 Edition to $0.75*t_l$ in 1992 Edition of the ASME Code Sec. III, where t_l is the pipe thickness. However, the current requirement on the weld leg size in the socket weld of the nuclear piping is $1.09*t_l$ based on the ASME Code Case N-316.

The results show that K_{open} and ΔK increase as the size of the weld leg decreases. Compared with the case of WL = $1.09*t_l$, the values of K and ΔK for WL = $0.75*t_l$ increase by a factor of 1.5. It means that the reduction of the weld leg size to $0.75*t_l$ from $1.09*t_l$ can affect on the socket weld integrity by a factor of 1.5.The value of ΔK under the deflection load with the weld leg size of $0.75*t_l$ (6.554 mm) is estimated as 273.4 MPa$\sqrt{mm}$. By using Eq. (1) and this ΔK value, the fatigue crack growth rate (da/dN) can be obtained as 4.72×10^{-6} mm/cycle. If the vibration frequency of the failed piping in CVCS is assumed as 33Hz,[9] it takes only 11.7 hours to penetrate the weld leg(6.554 mm). The result shows that the reduction of the weld leg size from $1.09*t_l$ to $0.75*t_l$ can affect severely the socket weld integrity.

5. Conclusions

Six piping failures in socket weld in Korean NPPs were investigated in this paper. The root causes of the socket weld failures in the CVCS and the PSS were analyzed to be fatigue loadings such as vibration or thermal fatigue with improper weld joint during construction.

The effects of the requirements in the ASME Code Sec. III on the socket weld integrity were evaluated by using the three dimensional finite element method. The results are as follows; (1) The socket weld is susceptible to the vibration if the vibration levels exceed the requirement in the ASME Code OM. (2) The effect of the pressure or temperature transient load on the socket weld in CVCS and PSS is not significant because of the very low frequency of the transient during the plant lifetime operation. (3) 'No gap' is very risky to the socket weld integrity for the specific systems having the vibration condition to exceed the requirement in the ASME OM Code and/or the transient loading condition from P = 0 and T=25 ℃ to P = 15.51 MPa and T = 288 ℃. To such systems, RT to examine the gap during construction stage is strongly recommended. (4) The reduction of the weld leg size from $1.09*t_l$ to $0.75*t_l$ can affect severely on the socket weld integrity.

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