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Structural Integrity Evaluation of Steam Generator Tube with Two Parallel Axial Through-Wall Cracks

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Abstract

It is commonly required that tubes with defects exceeding 40% of wall thickness in depth should be plugged; however, this criterion is too conservative for some locations and for some types of defects. Many studies have been done with the aim of developing an alternative plugging criteria, and these studies have shown that steam generator tubes with a certain range of axial through-wall cracks could remain in service without any safety or reliability problems. However, these studies have been limited, thus far, to consideration of single cracked tubes, necessitating a study on multiple cracks, which are commonly found.

A crack coalescence model applicable to steam generator tubes with two collinear axial through-wall cracks was proposed in the previous study. In this paper, the investigation is extended to the parallel axial cracks spaced in a circumferential direction, because parallel axial cracks are more frequently detected during in-service inspections than collinear axial cracks. Interaction effects between two parallel cracks are evaluated by performing elastic and elastic-plastic finite element analyses.

Key Words : coalescence criterion, interaction effect, steam generator tube, plastic collapse, plugging, rupture

1. Introduction

The steam generators in the pressurized water reactor (PWR) are huge heat exchangers that use the heat from the primary reactor coolant to make steam in the secondary-side drive turbine generators. The heat transfer area of steam generator tubes comprises well over 50% of the total primary pressure-retaining boundary. Rupture of the tubing can result in a release of fission products to the environment outside the reactor containment, via the pressure relief valves, the condenser off-gas, or other paths in the secondary system [1]. To prevent tube rupture, it is necessary that tubes with defects exceeding 40% of the wall thickness in depth be plugged [2, 3]. However, this criterion is considered to be too conservative for some locations and for some types of defects, and no criterion is currently available for a case involving multiple cracks [4-6].

Inspection of pulled out steam generator tubes and in-service inspection results show that the formation of multiple cracks is common, especially in the transition zone. There are several crack coalescence models available; however, all of these models are based on brittle fracture, whereas the failure of steam generator tubes is governed by plastic collapse. In the previous study, the conservatism of the present plugging criterion of steam generator tubes was reviewed, and a crack coalescence model was proposed as being applicable to steam generator tubes with two collinear axial through-wall cracks [7]. Since most of the cracks detected during in-service inspections are located around the roll transition zone and parallel axial cracks are more frequently detected in this area than collinear axial cracks [8, 9], the studies on parallel axial cracks spaced in a circumferential direction are necessary.

In this paper, 3D finite element analyses were carried out, and a new failure model of the steam generator tube with two parallel axial through-wall cracks was proposed. To explain the deformation behavior of cracked tubes, interaction effects between two adjacent cracks were investigated.

2. Multiple Collinear Axial Through-Wall Cracks

In the previous study, the conservatism of the present plugging criterion of steam generator tubes was reviewed, and a crack coalescence model was proposed as being applicable to steam generator tubes with two collinear axial through-wall cracks. It can be summarized as follows:

2.1. Conservatism of Present Plugging Criteria

Using R6 approach, it was proved that the failure mode of steam generator tubes is a plastic collapse. Limit load method was, therefore, adopted to estimate the collapse load of steam generator tubes. The pressure that is necessary to cause unstable ductile (plastic collapse) failure of tubes with an axial through-wall crack, P_{cr}, is calculated using Eq. (1) [10].

$$P_{cr} = \frac{\sigma_f t}{M_T R} \tag{1}$$

where σ_f is the flow stress, t is the wall thickness, R is the mean radius of the tube, and M_T is the bulging factor, expressed by Eq. (2).

$$M_T = 0.614 + 0.481\lambda + 0.386\exp(-1.25\lambda) \quad for\ 5 \le R/t \le 5 \tag{2}$$

$$\lambda = \left[12\left(1-\nu^2\right)\right]^{0.25}\left(c/\sqrt{Rt}\right) \tag{3}$$

where λ is the shell parameter, ν is Poisson' s ratio, and $2c$ is the axial crack length. For axial part-through cracks, the pressure required to fail the remaining ligament, P_{sc}, can be calculated from an empirical equation which was proposed by ANL (Argonne National Laboratory) to cover shallow and deep cracks, by modifying Kiefner' s equation [11, 12].

$$P_{sc} = \frac{\sigma_f t}{R}\frac{1\ \ a/t}{1\ \ \alpha a/M_T t} \tag{4}$$

where a is the crack depth and α is the parameter given by

$$\alpha = 1 + 0.9\left(\frac{a}{t}\right)^2\left(1 - \frac{1}{M_T}\right) \quad (5)$$

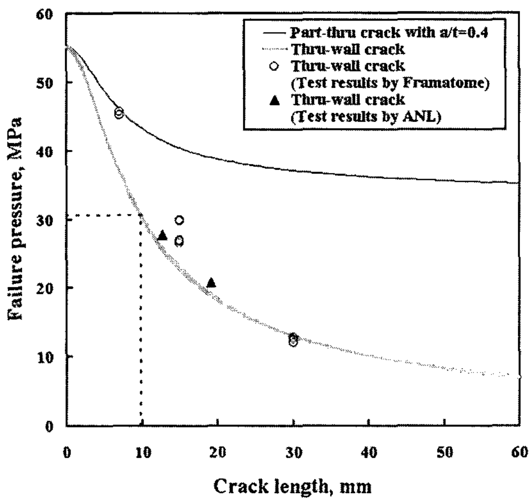


Fig. 1. Limit Load Solutions

Fig. 1 shows the failure pressures calculated by using Eq. (1) for through-wall cracked tubes and using Eq. (4) for surface-cracked tubes of a/t=0.4. The material properties, geometry, and operating conditions of the steam generator tubing were summarized in Table 1. The mean value between the yield strength and the tensile strength was used as the flow stress of the given material. The safety factors of 3 and 1.4 were considered for normal operation and accidential conditions, respectively, in accordance with the requirements of the Regulatory Guide 1.121 [2]. From this consideration, a pressure of 30.6 MPa is obtained as a limiting pressure. It is shown in Fig. 1 that the through-wall cracked tube fails at a crack length of 9.8 mm, whereas the surface-cracked tube never fails regardless of crack length. Therefore, there is no risk associated with steam generator tube integrity when the crack depth is less than 40% of the wall thickness. This means that the current plugging criterion based on 40% wall thickness can assure tube integrity, regardless of crack length.

With regard to crack type defects in steam generator tubes, the exact depth measurement can not be measured, so that the crack type defects are considered generally as through-wall defects, whatever depth they have, and all crack type defects are plugged. But this criterion is considered to be too conservative, especially for axial cracks of less than 9.8 mm in length, because the steam generator tube with a through-wall crack of less than 9.8 mm maintains its structural integrity in the event of the foregoing pressure as shown in Fig. 1. In addition, most of the detected cracks are located at the roll transition zone. In that case, the tube sheet constrains the deformation of the tube and shares

Table 1. Specification of Considered Steam Generator Tubes [7]

Outer Diameter	22.22mm
Thickness	1.27mm
Material	Inconel Alloy 600TT
Young' s Modulus at 300℃	199.8 GPa
Yield Strength at 300℃	256.0 MPa
Tensile Strength at 300℃	656.0 MPa
Flow Stress at 300℃	456.0 MPa
ΔP_{normal}	10.2 Mpa
$\Delta P_{accident}$	18.3 MPa

the applied loads. Thus, it is too conservative to apply the 40% of wall criterion to all cases, without considering the type, location, and length of the defect. It is, therefore, necessary to develop alternative plugging criteria based on SGDSM (Steam Generator Defect Specific Management) strategies. To accomplish this goal, many studies have been done [4-6]; however, these approaches have been limited to tubes with a single crack, despite the common occurrence of multiple cracks.

2.2. Coalescence Model of Multiple Collinear Axial Through-wall Cracks

Three coalescence models are available for multiple collinear axial through-wall cracks: ASME Sec. XI, BSI PD6493, and zero ligament length. It is known that the third shows a good agreement with experimental results [13-15]. This means that] two adjacent cracks come together when there is no remaining ligament between them. However, it is very difficult to predict when the ligament between two cracks fails without experimental observations, and this is not conservative in terms of safety. Since a credit could not be given to defect depth measurement at this time, it is assumed in this study that all the crack type defects are through-wall cracks. The basis of the previously proposed model is that the coalescence takes place when the ligament is subjected to fully yielding state and no longer sustains the applied loads.

Finite element analyses were performed to create a diagram that can be used to determine whether the adjacent cracks detected by NDE coalesce under a given pressure or not. For various crack lengths and distances between the cracks, we determined the applied pressures at which the ligament is subjected to fully yielding condition. The figure, called a coalescence evaluation diagram, was composed based on these results. The stress values were taken at the mid-thickness of the tube wall. It is assumed that the given material behaves in an elastic-perfectly plastic manner, with a flow stress of σ_f. Fig. 2 shows the coalescence evaluation diagram. Once the adjacent cracks come together, they are considered to be a single equivalent crack, i.e., $2c_{eq} = 2c + d + 2c$. When the limiting pressure is given with a consideration of the safety factor, the maximum allowable crack length, denoted by $2c_a$, can be determined from Fig. 1. If $2c_{eq}$ is greater than $2c_a$, it is unacceptable.

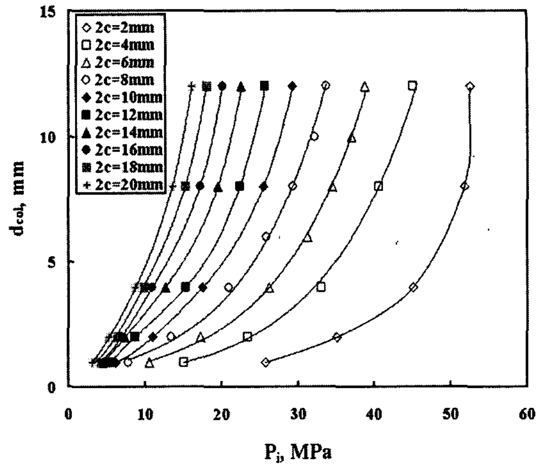


Fig. 2. Coalescence Evaluation Diagram

3. Two Parallel Axial Through-Wall Cracks

3.1. Interaction Effects of Two Parallel Axial Through-Wall Cracks

It is surmised that two cracks will behave independently when they are at a sufficient distance for no interaction between them to occur; however, two cracks will be more prone to fail if the distance between them becomes small enough for interaction effect to occur. Interaction effect

Table 2. Evaluation of Interaction Effect Based on K

Crack Size (mm)	K_S (MPa $\sqrt{m}$)	K_D (MPa $\sqrt{m}$)	K_{ratio}
2c=8, d=1	60.47	45.50	0.7524
2c=8, d=4		56.61	0.9362
2c=8, d=8		62.42	1.0322

can be observed under the development of plastic zones, so that 3D FEM analyses using ABAQUS were performed for various crack lengths and distances, to determine when the plastic zones come into contact with each other. The previously proposed coalescence model for two collinear axial through-wall cracks was modified to apply it to two parallel axial through-wall cracks. In the case of 2 axial through-wall cracks, plastic zones develop from the crack tips along the maximum shear stress plane, and they come into contact before the ligament between the two cracks is fully yielded. Therefore, it is assumed that the coalescence takes place when plastic zones that develop from crack tips come into contact with each other. The material properties and geometry are shown in Table 1. It is also assumed that the material behaves in an elastic-perfectly plastic manner, with a flow stress of σ_f.

Fig. 3 shows the finite element mesh used in this study. A quarter of the tube was modeled using the symmetry and isoparametric 20-node reduced-integration brick elements. Finite element analyses were carried out for the cases where the axial crack length, $2c$, is equal to 8 mm and the distance between two adjacent cracks, d, is equal to 1, 4, and 8 mm, respectively. As the pressure increases progressively, the changes in COD (Crack Opening Displacement) and the changes of the plastic zones were observed in the mid-thickness of the tube wall.

Fig. 4 shows the change of the plastic zone size for the case where $2c$ = 8 mm and d = 4 mm, as the applied pressure increases. It is observed that

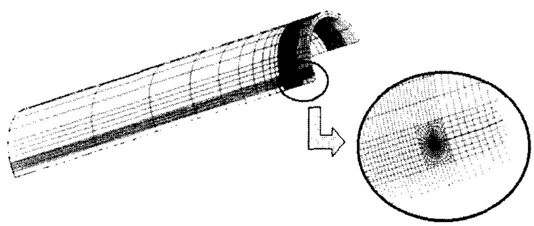
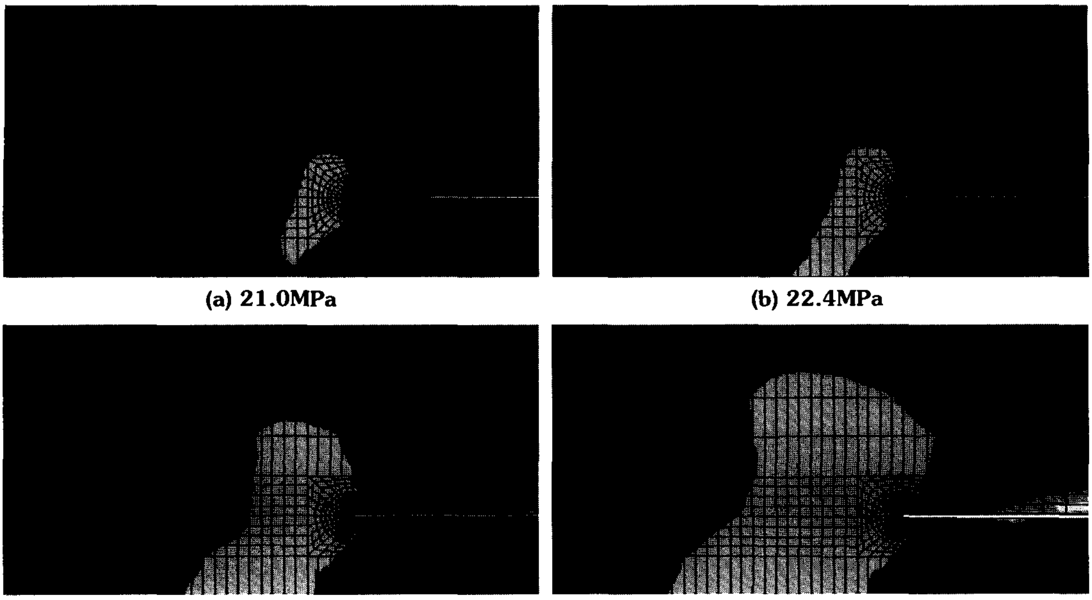


Fig. 3. Finite Element Mesh of Steam Generator Tube

the plastic zone, grow slowly for a pressure up to 21 MPa, and they come into contact at 22.4 MPa. After the contact of plastic zones takes place, their size increase rapidly with a small pressure increase. Larger plastic zones form in the inner section between the cracks than in the outer area, as expected, due to interaction effects.

Once the contact pressure was determined, an equivalent single crack length was calculated using Eq. (1). That is, a single crack length that fails at the contact pressure was determined. Even though the plastic zone contact does not reduce the load carrying capacity of the uncracked ligament to the level of the collinear cracked case, it is assumed that the two parallel axial cracks can be converted into a single equivalent crack, which is supposed to fail at contact pressure. The calculated crack length using the foregoing process, $2c_{eq}$, was shown in Fig. 5. The figure shows that the equivalent crack length curves consist of two linear sections, and all of the curves have an inflection point of about 3 to 4 mm in distance. When the distance is greater than 4 mm the slope is gradual and vice-versa. The equivalent crack length



(a) 21.0MPa **(b) 22.4MPa**

(c) 23.6MPa **(d) 29.7MPa**

Fig. 4. Changes in Plastic Zone Size as Pressure Increases

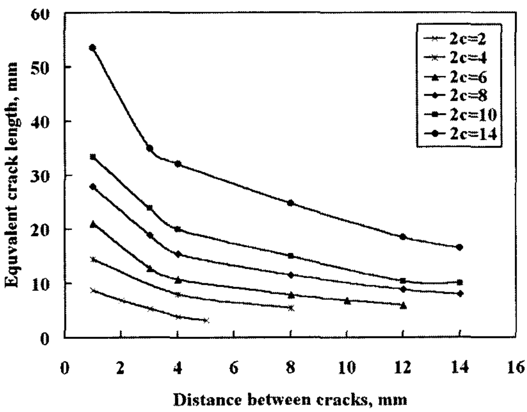


Fig. 5. Equivalent Crack Length of Two Parallel Cracks

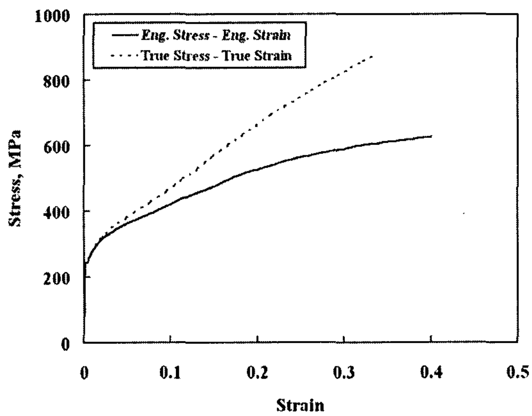


Fig. 6. Stress-strain Curve Used in the Analysis of Interaction Effects

approaches to the individual crack size when the distance between the two cracks is sufficient to neglect interaction effects. However, as two cracks come nearer to each other, the equivalent crack length increases more rapidly. This trend becomes more apparent as the crack length increases. It can be estimated that two cracks will merge into one crack as the two cracks approach each other and the distance between them decreases, so that the equivalent crack length in the case of very small separation should approach to a single crack length. In this regard, it seems that the proposed equivalent crack length overestimates interaction effects when cracks are closely spaced.

Since the proposed method overestimates the interaction effect for a case in which two cracks are closely spaced, an investigation on the conservatism of this model was conducted using elastic-plastic finite element analyses with a full stress-strain curve, given in Fig. 6 [7].

In this study, both elastic analyses based on K and elastic-plastic analyses based on *J*-integration were carried out. We defined the factors to explain the degree of interaction in the elastic analysis and the elastic-plastic analysis as K_{ratio} and J_{ratio} as follows:

$$K_{ratio} = \frac{K_D}{K_S} \tag{6}$$

$$J_{ratio} = \frac{J_D}{J_S} \tag{7}$$

where K_S and K_D are the stress intensity factors for a single crack and two parallel cracks, respectively, and J_S and J_D are *J*-integrations for a single crack and two parallel cracks, respectively.

Table 2 shows the values of K_{ratio} when $2c = 8$ mm and $d = 1$, 4, and 8 mm, respectively. It is shown in Table 2 that K_{ratio} increases as d increases. When K_D is less than K_S, the interaction produces a favorable effect and we call it a "beneficial interaction effect" (Kratio < 1). Such a negative interaction effect is getting more as the distance becomes smaller. These results are in a good agreement with Murakami' s study for two parallel through-wall cracks [16] and Cho' s study for two parallel surface cracks [17]. Table 3 shows the values of J_{ratio} when $2c = 8$ mm and $d = 1$, 4, and 8 mm, respectively. Like K_{ratio}, J_{ratio} also increases as d increases. Greater negative interaction effects are observed with smaller distances, and J_{ratio} shows greater negative interaction effects than those of K_{ratio} in all cases.

From these results, it can be said that longer and closer cracks produce a greater negative interaction effect. This is because longer cracks

Table 2. Evaluation of Interaction Effect Based on *K*

Crack Size (mm)	K_S (MPa $\sqrt{m}$)	K_D (MPa $\sqrt{m}$)	K_{ratio}
2c=8, *d*=1	60.47	45.50	0.7524
2c=8, d=4		56.61	0.9362
2c=8, *d*=8		62.42	1.0322

Table 3. Evaluation of Interaction Effect Based on J-integral

Crack Size (mm)	P (MPa)	JS (Mpa · m)	JD (MPa · m)	Jratio
2c=8, d=1	5	0.2818	0.1633	0.5795
	10	1.681	0.9565	0.5690
	13	3.458	2.024	0.5853
2c=8, d=4	5	0.2818	0.2481	0.8804
	10	1.681	1.411	0.8394
	13	3.458	2.881	0.8331
2c=8, d=8	5	0.2818	0.3019	1.071
	10	1.681	1.797	1.069
	13	3.458	3.614	1.045

develop larger plastic zones and closer cracks make two plastic zones that come into contact more easily. The study on the interaction effects results in the conclusion that the approach based on plastic zone contact, unlike an approach based on a collinear crack case, is not appropriate for determining the equivalent single crack, due to the exaggerated interaction effect when two cracks are closely spaced.

3.2. Failure Prediction Model Based on Crack Opening Displacement

According to the burst test results of steam generator tubes with multiple parallel axial cracks, the crack tip tearing and burst take place without ligament failure [18, 19]. It is important to define an appropriate parameter that could be used for the failure prediction of the tube with two parallel axial cracks, considering previous observations. That is, an approach that is not based on ligament collapse is necessary. It was thought that a model based on COD [20] could be an appropriate candidate for this purpose.

As the tube with two parallel axial through-wall cracks is deformed under the applied pressure loading, the COD could be affected by two crack face displacements: opening in the circumferential direction (U_θ) and in the radial direction (U_r). The latter could be considered to contribute to Mode III failure, whereas the circumferential opening could cause a failure in Mode I. The difference between the sum of both directions and the circumferential displacement only is negligible, so that only the circumferential displacement is assumed to contribute to the tube failure and the CODs obtained from opening in the circumferential direction are considered hereafter.

Finite element analyses for five single cracks of $2c$ = 4, 6, 8, 10, and 14 mm were performed, and the changes of COD at the crack center, δ_o, were plotted, as shown in Fig. 7. For the case with a single crack, the failure pressure can be determined from Fig. 1 with a given crack length. It was assumed that the failure of parallel cracks takes place when each COD value is equal to the COD obtained at the failure pressure of a tube with a single crack. The COD at the failure pressure for each single crack was indicated in this figure and marked with the symbol 'x'. In this paper, the value was defined as the critical COD and denoted as $(\delta_o)_{crit}$. The following regression line was derived from the $(\delta_o)_{crit}$ values:

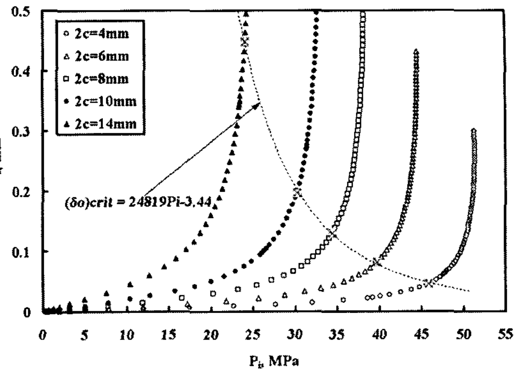


Fig. 7. Changes of COD at the Crack Center

$$(\delta_o)_{crit} = 24819 P_i^{-3.44} \tag{8}$$

where P_i is in MPa. The above power law expression was obtained using the least square fit of the data points indicated as 'x' in Fig. 7 and illustrated as a dotted line. This curve can be used to determine critical COD values and the associated failure pressures for different cases with parallel axial cracks. The COD curves obtained from finite element analyses were plotted in Fig. 8 for four different crack lengths having a pair of parallel axial cracks with various distances between them.

Therefore, the failure pressure of each case could be derived from the intersection point between the regression line and each COD curve.

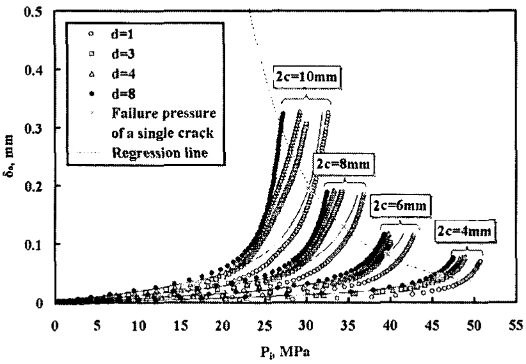


Fig. 8. Changes of $(\Delta U_\theta)_{z=0}$

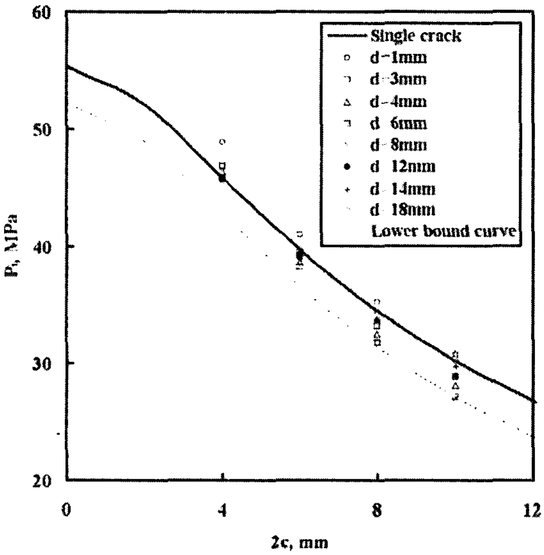


Fig. 9. Failure Pressures of Double Cracked Tubes

Fig. 9 shows that the failure pressures obtained from this procedure match well with those of the cases involving a single crack, for all the different distances separating the pair cracks. We can recognize that the COD approach provides appropriate results even for a case in which the pair of cracks are closely spaced. Putting the failure pressure into equation (1), the equivalent crack lengths could be determined. The 'beneficial interaction effect' is also confirmed in Fig. 10. When the pair of cracks are closely spaced, such as when d=1mm, the failure pressure of the pair

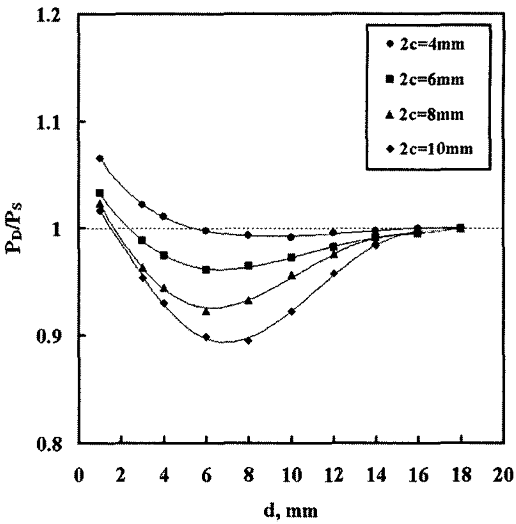


Fig. 10. P_D/P_S vs. *d* Curve

cracks is higher than that of the corresponding single crack at all four crack lengths. Fig. 10 shows the ratio of PD to PS versus separation. The interaction effect appears in reverse when the separation is greater than 2 mm for all cases, except for $2c$ = 4 mm. To know when the interaction effect disappears, a bounding analysis was done for a case in which $2c$ = 10 mm and d = 12 mm. As shown in Fig. 10, the ratio approaches 1, and the interaction effect diminishes if the pair of cracks are separated by a distance of greater than 12 mm. This result seems to be consistent with that of the collinear crack case, in which the interaction effects diminish when the separation distance between two collinear cracks is greater than 12 mm. From a safety standpoint, the lower bound curve shown in Fig. 9 can be used to determine an allowable crack length for multiple axial pair cracks in steam generator tubes for a given limiting pressure. That is, once the limiting pressure is determined, the maximum allowable crack size, denoted by $2c_a$, can be determined using the lower bound curve for a case involving parallel axial cracks, regardless of distance separating them. Subsequently, if the longer crack length of two parallel axial cracks detected in a steam generator tube is greater than $2c_a$, it is unacceptable.

4. Conclusions

A procedure applicable to determine the acceptability of the steam generator tube with multiple axial cracks was proposed, by taking into account the interaction effects of two adjacent cracks.

The interaction effects of two collinear or two parallel axial through-wall cracks existing in a steam generator tube were investigated. For the former case, a coalescence criterion based on limit load was proposed and a coalescence evaluation diagram was generated. This diagram could be used to determine whether the adjacent collinear cracks detected by NDE coalesce under a given pressure. Then the determined single equivalent crack will replace two collinear axial through-wall cracks.

For the latter case, the interaction effect, considered to be more complicate was investigated using two approaches: one approach based on the plastic zone contact and the other approach based on COD. The former approach provides too conservative equivalent crack length when two parallel cracks are closely spaced. The investigation of interaction effects shows that when a pair of axial cracks is closely spaced, it is less detrimental to structural integrity than a single crack. By taking into account the experimental observation that crack tip tearing and burst in steam generator tubes with multiple parallel axial cracks take place without ligament failure, COD values were selected as an appropriate parameter with which to predict the failure pressure. It was assumed that the failure of the tube with parallel cracks takes place when each COD value is equal to the COD obtained at the failure pressure of the tube with a single crack. Once critical COD is obtained, the failure pressure can be determined from Eq. (8), and the equivalent crack length can be calculated using equation (1). From a safety standpoint, the lower bound curve shown in Fig. 9 can be used to determine the maximum allowable crack length for multiple axial pair cracks existing in steam generator tubes under the given limiting pressure.

References

1. USNRC, "NUREG/CR-6365, Steam Generator Tube Failures" (1996).
2. USNRC, "Regulatory guide 1.121, Bases for Plugging Degraded PWR Steam Generator Tubes" (1976).
3. ASME, "Rules for Construction of Nuclear Power Plant Components," ASME Code, Sec. III (1998).
4. Cochet, B. and Flesch, B., "Crack Stability Criteria in Steam Generator Tubes," 9th Int. Conference on SMiRT, Vol. D, pp.413-419 (1987).
5. Yu, Y.J., Kim, J.H., Kim, Y., and Kim, Y.J., "Development of Steam Generator Tube Plugging Criteria for Axial Crack," *ASME PVP*, Vol. 280, pp.79-83 (1994).
6. Gorman, J. A., Harris, J. E., and Lowenstein, D.B., Steam Generator Tube Fitness-for-Service Guidelines, AECB Report No. 2.228.2 (1995).
7. Lee, J.H., Park, Y.W., Song, M.H., Kim, Y.J., and Moon, S.I., "Determination of Equivalent Single Crack based on Coalescence Criterion of Collinear Axial Cracks," *Nuclear Engineering and Design*, Vol. 205, pp.1-11 (2001).
8. Kim, J.S. et al., "Investigation Report for Steam Generator Tubes Pulled out from Ulchin Unit 1" (1999).
9. Knag, S.C. et al., "Regulatory Technical Report on the Steam Generator Tubes Safety of

Nuclear Power Plants," KINS/AR-669 (1999).

10. Erdogan, F., "Ductile Failure Theories for Pressurized Pipes and Containers," *Int. J. PVP*, Vol. 4 (1976).
11. Kiefner, J. F., Maxey, W. A., Eiber, R. J., and Duffy, A. R., "Failure Stress Levels of Flaws in Pressurized Cylinders," ASTM STP536, pp.461-481 (1973).
12. Majumdar, S., Shack, W. J., Diercks, D. R., Mruk, K., Franklin, J., and Knoblich, L., "Failure Behavior of Internally Pressurized Flawed and Unflawed Steam Generator Tubing at High Temperatures ? Experiments and Comparison with Model Predictions," NUREG/CR-6575, ANL-97/17 (1998).
13. Kim, Y. J., Choy, Y. S., and Lee, J. H., "Development of Fatigue Life Prediction Program for Multiple Surface Cracks," ASTM STP 1189, pp.536-550 (1993).
14. Shibata, K., Yokoyama, N., Ohba, T., Kawamura, T., and Miyazono, S., "Growth Evaluation of Fatigue Cracks from Multiple Surface Flaws (I)," *J. Japanese Nuclear Society*, Vol. 27, No. 3 pp.250-262 (1985).
15. Shibata, K., Yokoyama, N., Ohba, T., Kawamura, T., and Miyazono, S., "Growth Evaluation of Fatigue Cracks from Multiple Surface Flaws (II)," *J. Japanese Nuclear Society*, Vol. 28, No. 3, pp.258-265 (1986).
16. Murakami, Y., "Stress Intensity Factors Handbook," pp.204-205 (1987).
17. Cho, Y.J., "A Study on the Interaction Effect of Adjacent Semi-Elliptical Crack," Thesis for M.S., Sungkyunkwan University (1990).
18. Framatome, " Steam Generator Tube Integrity," EPRI Report NP-6865-L, Vol.1 (1991).
19. Argonne National Laboratory, "Steam Generator Tube Integrity Program," Monthly Pregress Report of ANL, April 3 & 28 (2000).
20. Moon, S.I, Kim, Y.J., and Lee, J.H, "Estimation of Plastic Collapse Load of Steam Generator with Two Parallel Axial Through-Wall Cracks," *ASME PVP*, Vol. 464, pp.223-230 (2003).