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Conservatism of Present Plugging Criteria on Steam Generator Tubes and Coalescence Model of Collinear Through-Wall Axial Cracks

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Abstract

The steam generator tubing covers a major portion of the primary pressure-retaining boundary, so that very conservative approaches were taken in the light of steam generator tube integrity. According to the present criteria, tubes wall-thinned in excess of 40% should be plugged whatever the cause was. However, it is reported that there is no safety problem even with thickness reductions greater than 40%. Recently, the plant specific plugging criteria are introduced in many countries by demonstrating that the cracked tube has a sufficient safety margin. One of the drawbacks of such criteria, even though not yet codified, is that it is developed based on tubes with single cracks regardless of the fact that the appearance of multiple cracks is general. Their failure analyses have been, therefore, carried out using an idealized single crack to reduce complexity till now.

The objective of this paper is to review the conservatism of the present plugging criteria of steam generator tubes and to propose a new coalescence criterion for twin through-wall cracks existing in steam generator tubes. Using the existing failure models and experimental results, we review the conservatism of the present plugging criteria. In order to verify the usefulness of the proposed new coalescence criterion, we perform finite element analysis.

I. Introduction

The heat transfer area of the steam generators in a pressurized water reactor can comprise well over 50% of the total primary pressure-retaining boundary. The steam generator tubing, therefore, represents an integral part of a major barrier against fission product release to the environment. For this reason, it is commonly required that tubes with defects exceeding 40% of wall thickness should be plugged[1,2]. However, this criterion is considered to be too conservative for some locations and types of defects because analytical results show that the integrity of steam generator tubes that are locally thinned or cracked is still maintained under normal operations and even during postulated accidents[3,4].

As a practical approach, the U.S. Nuclear Regulatory Commission allows licensees to develop and implement steam generator defect specific management (SGDSM) strategies provided that structural and leakage integrity of tubes are ensured. Many studies have been done to develop alternative plugging criteria and have shown that a certain range of through-wall axial cracks in steam generator tubes could remain in service without safety or reliability problems[3~5]. But these approaches are confined to tubes with single cracks regardless of the fact that the appearance of multiple cracks is general. Until now, therefore, failure analyses have been carried out for idealized single cracks to reduce complexity.

In this paper, the conservatism of the present plugging criteria of steam generator tubes is reviewed and a new coalescence criterion for twin through-wall cracks is proposed. Using the existing failure models and experimental results, we reviewed the conservatism of the present plugging criteria. In order to verify the usefulness of the proposed new coalescence criterion, we performed finite element analysis.

II. Conservatism of Present Plugging Criteria

In order to determine the analysis method for steam generator tubes, Yu et al.[4] used the R6 approach developed by the Central Electricity Generating Board (CEGB). This approach uses K_r and L_r as variables. K_r is the ratio of the elastically calculated stress intensity factor to the fracture toughness of the material. L_r is the ratio of the applied load to the plastic limit load of the structure. The failure assessment curve used to classify the failure mode is given as follows:

$$K_r = (1 - 0.14 S_r^2)\{0.3 + 0.7 \exp(-0.65 L_r^6)\} \quad (1)$$

This failure assessment curve and the applied K_r and L_r values for the given loading condition and crack lengths are plotted in Fig. 1. The material properties and geometry of the steam generator tubes of Ulchin #1 (Korea, Framatome type PWR) are used in this analysis. The applied K_r and L_r values lie in the region of $K_r/L_r < 0.2$. Therefore the failure mode is plastic collapse, and limit load analysis can be used to assess the failure of steam generator tubes.

2.1 Limit Load Aanalysis

The pressure that is necessary to cause unstable ductile (plastic collapse) failure of tubes with a through-wall axial crack, P_{cr}, is calculated using Eq. 2.

$$P_{cr} = \frac{\sigma_f t}{M_T R} \tag{2}$$

where σ_f is the flow stress, t is the wall thickness, M_T is the bulging factor, and R is the mean radius of the tube. In Eq. (2), the accuracy of the failure pressure depends on M_T because all the other factors are set constant for the tubes concerned. Several expressions for M_T were proposed as shown below[6~10]:

$$M_T = [1 + 1.61(c/\sqrt{Rt})^2]^{0.5} \quad \text{for } \lambda \le 2 \tag{3}$$

$$M_T = [1 + 1.255(c/\sqrt{Rt})^2 - 0.0135(c/\sqrt{Rt})^4]^{0.5} \quad \text{for } \lambda \le 9 \tag{4}$$

$$M_T = [1 + 1.05(c/\sqrt{Rt})^2]^{0.5} \quad \text{for } R/t \ge 10 \tag{5}$$

$$M_T = [1 + 1.2987(c/\sqrt{Rt})^2 - 0.026905(c/\sqrt{Rt})^4 + 0.00053549(c/\sqrt{Rt})^6]^{0.5} \quad \text{for } c/\sqrt{Rt} \le 5 \tag{6}$$

$$M_T = 0.614 + 0.481\lambda + 0.386\exp(-1.25\lambda) \quad \text{for } 5 \le R/t \le 50 \tag{7}$$

where $2c$ is the axial crack length and λ is the shell parameter defined by Eq. (8). Among these equations, Eq. (7) is widely used and Fig. 2 shows its usefulness. In this paper, Eq. (7) is used to calculate the failure pressure of the tube with a single through-wall crack.

$$\lambda = [12(1-\nu^2)]^{0.25}(c/\sqrt{Rt}) \tag{8}$$

For part-through axial cracks, the pressure required to fail the remaining ligament, P_{sc}, can be calculated from an empirical equation reported by Kiefner et al[8].

$$P_{sc} = \frac{\sigma_f t}{R}\left[\frac{1 - a/t}{1 - a/M_T t}\right] \tag{9}$$

In Eq. (9), a is the crack depth and M_T is the bulging factor as in the through-wall cracks except that $2c_{eq}$ is used instead of $2c$ for crack length. When A indicates the actual area of the part-through axial crack, $2c_{eq}$ is defined by $2c_{eq} = A/a$. In this paper, however, $2c$ is used instead of $2c_{eq}$ for conservatism.

Fig. 3 shows the failure pressures obtained from Eq. (2) and (9) for the through-wall cracked tube and for the surface cracked tube with a/t=0.4 as a function of axial crack length. On the basis of the 40% of wall criterion, it can be seen that 0.4 is the maximum allowable a/t ratio in the surface cracked tube. The material properties, geometry, and operating conditions of the steam generator tubing of Ulchin #1 were used in calculating the failure pressures and were summarized in Table 1. The definition of the flow stress given in Eq. (10) was used and its value was derived from the lower bound value in the CMTR of the steam generator tubes of Ulchin #1[11].

$$s_f = 0.5(s_{YS} + s_U) \tag{10}$$

where s_{YS} is the yield strength and s_U is the ultimate tensile strength. The safety factors of 3 and 1.4 are considered for the cases of normal operation and accidential condition, respectively, to satisfy the requirements of Regulatory Guide 1.121[1]. Considering these factors, we can obtain 30.6MPa as a maximum pressure which occurs in the steam generator tubes of Ulchin #1.

Table 1 Specification of Ulchin #1 steam generator tubes

Outer Diameter	22.22 mm
Thickness	1.27 mm
Material	Inconel Alloy 600TT
Young's Modulus at 300℃	199.8 GPa
Flow Stress at 300℃	456.0 MPa
Pressure across the wall at Normal Operation	10.2 MPa
Pressure across the wall at Accident Condition	18.3 MPa

It is shown in Fig. 3 that the through-wall cracked tube fails at the crack length of 9.8mm but the surface cracked tube never fails regardless of crack length. Therefore there is no problem in the structural integrity of steam generator tubes whenever the 40% of wall criterion is satisfied. But this criterion is considered to be too conservative especially for axial cracks because the steam generator tube with a through-wall crack less than 9.8mm maintains its structural integrity in the event of the foregoing maximum pressure as shown in Fig. 3. 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 the applied loads. Thus it is too conservative to apply the 40% of wall criterion for all cases without considering location or length. Thus it is necessary to develop alternative criteria on the basis of SGDSM strategies. To accomplish this goal, many works have been done. But these approaches have been confined to tubes with a single crack regardless of the fact that the appearance of multiple cracks is general.

III. Coalescence Criterion for Collinear Through-wall Cracks

In this chapter, we reviewed the present coalescence criteria of multiple surface cracks and proposed a new coalescence criterion for the collinear through-wall axial cracks existing in steam generator tube.

3.1 Present Coalescence Criteria for Collinear Surface Cracks

Until now, several criteria as shown below have been used to determine the onset of the coalescence between two adjacent surface cracks.

- ASME Sec. XI, IWA-3000 : $\boldsymbol{d}_0 = \max(2a_1, 2a_2)$ (11)
- BSI PD 6493 : $\boldsymbol{d}_0 = c_1 + c_2$ (12)
- Coalescence of surface points : $\boldsymbol{d}_0 = 0$ (13)

where $\boldsymbol{d}_0$ is the distance between two adjacent surface cracks at the onset of coalescence, a_1 and a_2 are the crack depths, and c_1 and c_2 are the half crack lengths. Of these equations, it is known that Eq. (13) shows a good agreement with the experimental results[12~15]. This means that two adjacent cracks coalesce when there is no remaining ligament between them, i.e., immediately after the ligament between the adjacent cracks can no longer sustain the applied loads. However, these three criteria can be applied to the case of small scale yielding.

As discussed before, the failure behavior of cracked steam generator tubes is dominated by large scale yielding. Therefore it is necessary to develop a new criterion applicable to the case of large scale yielding.

3.2 Coalescence Criterion for Collinear Through-wall Axial Cracks

Unlike the case of small scale yielding, $\boldsymbol{d}_0$ depends on plastic zone size in large scale yielding , and thus becomes a function of the geometry, crack size, and applied loads as follows:

$$\boldsymbol{d}_0 = f\left(\frac{c}{\sqrt{Rt}}, \frac{a}{c}, \frac{P_i}{P_{sc}}\right) \tag{14}$$

where P_i is the pressure applied across the wall. In the case of through-wall cracks, Eq. (14) can be arranged like Eq. (15).

$$\boldsymbol{d}_0 = f\left(\frac{c}{\sqrt{Rt}}, \frac{P_i}{P_{cr}}\right) \tag{15}$$

If the ligament between the adjacent cracks is subject to fully yielding, it can no longer sustain the applied loads. Therefore we can establish this condition as a new crack coalescence criterion applicable to the steam generator tube with the collinear through-wall axial cracks.

3.3 Finite Element Analysis

We applied the suggested coalescence criterion to the steam generator tube with twin through-wall axial cracks. In order to verify its usefulness, we performed elastic-plastic finite element analysis. The material properties and geometry of the steam generator tubing of Ulchin #1 were used. And it is assumed that this material behaves in an elastic-perfectly plastic manner with a yield strength of $\boldsymbol{s}_f$. ABAQUS code was used for this analysis. Fig. 4 shows the finite element mesh of the steam generator tube. A quarter of the tube was modeled using the symmetry. The axial crack length, *2c*, is 6mm and the distance between the cracks, *d*, is 4mm. Increasing the pressure linearly, we observed the changes in crack opening displacement (COD), stress distribution in the ligament between the adjacent cracks, and plastic zone. These changes were observed along the plane located in the middle of the inner and outer wall surfaces.

Another set of analyses was performed to create a diagram, which could be used to determine whether the adjacent cracks detected by nondestructive evaluation (NDE) techniques were coalesced with each other. For the various crack lengths and distances between the cracks, we determined the applied pressures at the moment when cracks were coalesced with each other. Using these results, we completed the diagram.

IV. Results and Discussion

4.1 Usefulness of Proposed Coalescence Criterion

Fig. 5 shows the changes in COD as the pressure increases from 0MPa to 30MPa. In this figure, symbols and solid lines indicate the results of twin through-wall cracks and a single through-wall crack, respectively. It is shown that the displacement of twin through-wall cracks increases rapidly after 26.7MPa. This trend is more conspicuous in the inner sides of the adjacent cracks than in the outer sides. Fig. 6 shows the distributions of the Mises stress in the ligament between the adjacent cracks as the pressure increases. It is shown in this figure that the ligament is fully yielded at 26.7MPa. Fig. 7 shows the changes in plastic zone size as the pressure increases. The plastic zone size of the inner side is similar to that of the outer side at 23.5MPa. It increases substantially at 25.6MPa and the ligament is fully yielded at 26.7MPa. In addition, it was observed that the COD and plastic zone size on the inner and outer wall surfaces increase rapidly after 26.7MPa.

From the above results, we can find that the rapid changes in COD and plastic zone size take place immediately after the ligament between the adjacent cracks is fully yielded. These take place because the ligament can no longer sustain the applied loads after it is fully yielded. Therefore the usefulness of the proposed coalescence criterion was verified.

4.2 Coalescence Evaluation Diagram

Performing finite element analyses, we created the diagram shown in Fig. 8, which could be used to determine the pressure at the moment of crack coalescence, P_{cl}. In this figure, the thick solid line indicates the failure pressure of the tube with a single crack. Each symbol and its regression line indicate the pressure at the moment of crack coalescence. This figure shows that the coalescence pressure decreases as $2c$ increases with a constant d, and it increases as d increases with a constant $2c$. In this figure, it is noted that the coalescence pressure for two adjacent cracks with the value of d greater than 12mm coincides with the failure pressure by a single crack. This means that the interaction effect between two adjacent cracks disappears when the ligament length exceeds 12mm for present model.

The parameter d in Fig. 8 can be replaced with d_0 because it is the value at the onset of crack coalescence. We changed the coordinate system of Fig. 8 and plotted the results in Fig. 9. Using Fig. 9, we can determine whether the adjacent cracks detected by NDE coalesce under a given pressure.

V. Conclusions

From the study on the plugging criteria for steam generator tubes and coalescence behavior of through-wall axial cracks, the following conclusions are obtained.

(1) The conservatism of the present plugging criterion for steam generator tubes is reviewed and it is concluded the criterion is too conservative for some locations and types of defects.

(2) The steam generator tubes with a through-wall axial crack less than 9.8mm can maintain its integrity under not only normal operation but also accident condition.

(3) A new crack coalescence criterion applicable to the steam generator tube with collinear through-wall axial cracks was proposed and its usefulness was verified through finite element analysis.

(4) A coalescence evaluation diagram for the steam generator tube was generated. And it can be used to determine whether the adjacent cracks detected by NDE coalesce under a given pressure.

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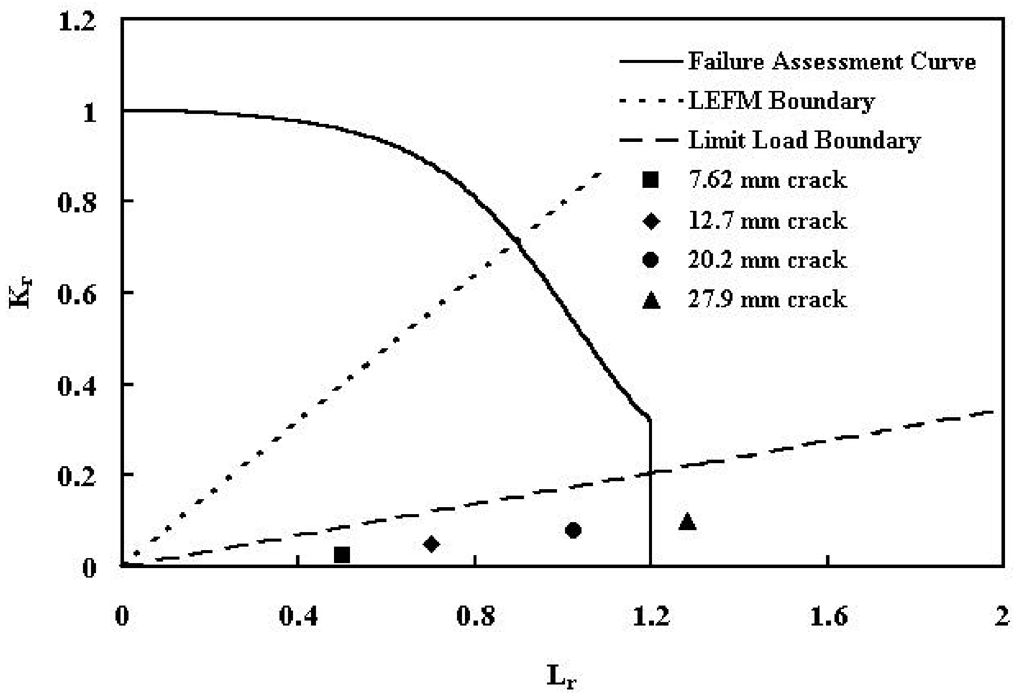


Fig. 1 Failure assessment diagram

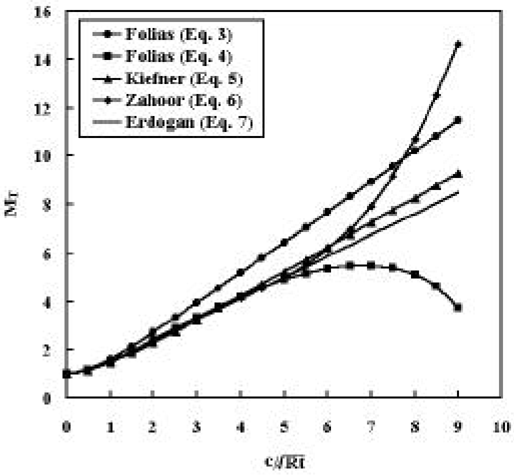


Fig. 2 Bulging factor

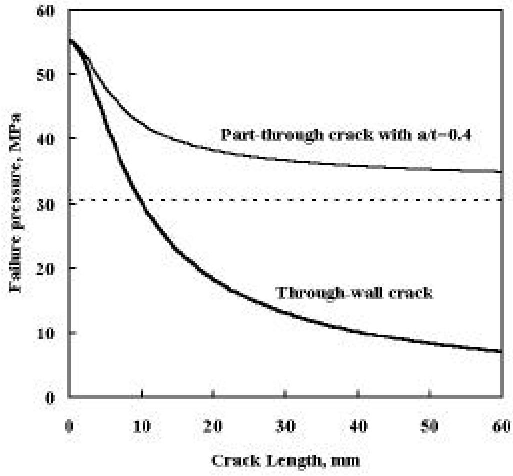


Fig. 3 Limit load solutions

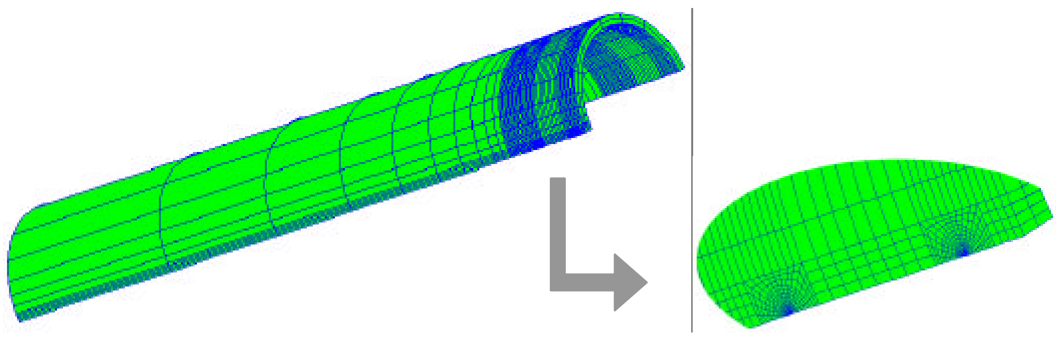


Fig. 4 Finite element mesh of steam generator tube

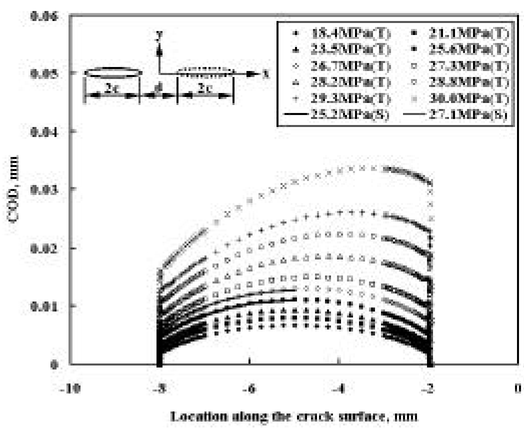


Fig. 5 Changes in COD

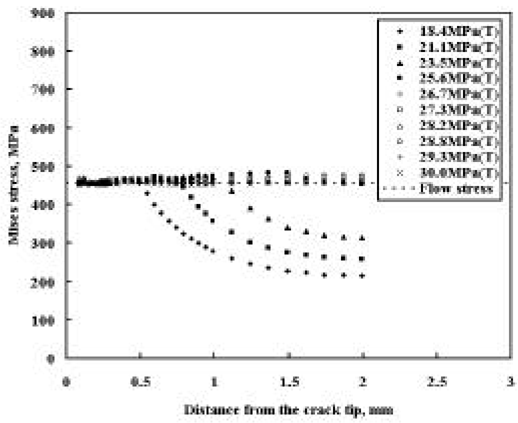
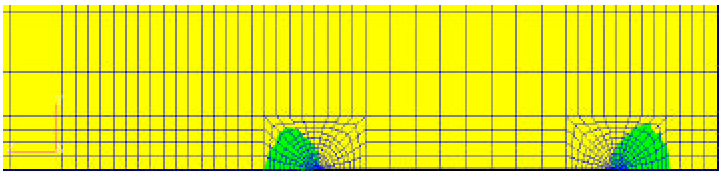
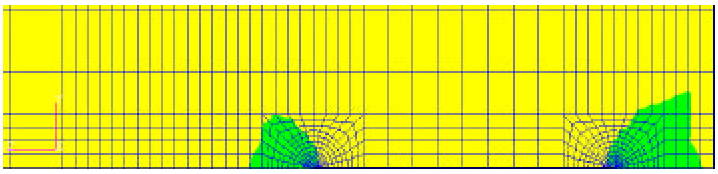


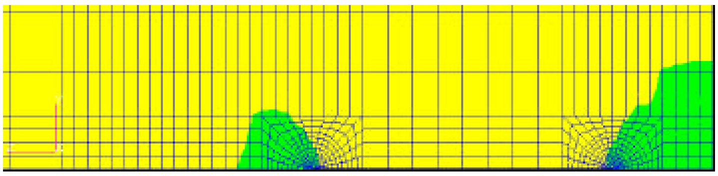
Fig. 6 Distributions of Mises stress



(a) P_i=23.5Mpa



(b) P_i=25.6Mpa



(c) P_i=26.7MPa

Fig. 7 Changes in plastic zone size as pressure increases

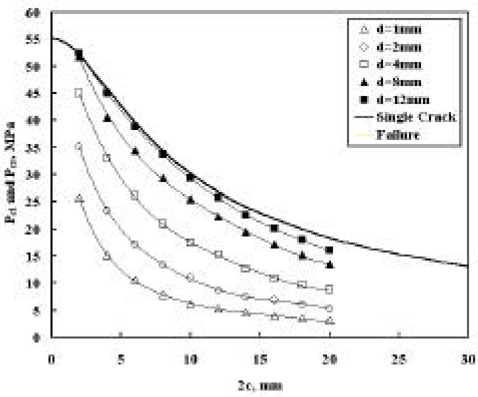


Fig. 8 Coalescence pressure

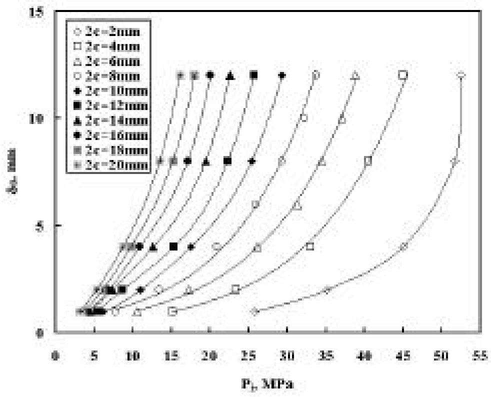


Fig. 9 Coalescence evaluation diagram