Proceedings of the Korean Nuclear Society Spring Meeting
Cheju, Korea, October 2001

Failure Behavior of Steam Generator Tubes Containing Two Parallel Through-Wall Axial Cracks

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Abstract

It is commonly required that steam generator tubes wall-thinned in excess of 40% should be plugged whatever causes are. However, the plugging criterion is known to be too conservative for some locations and types of defects and the application of this criterion is confined to a single crack. In the previous study, was reviewed the conservatism of the present plugging criterion of steam generator tubes and proposed a crack coalescence model applicable to steam generator tubes with two collinear axial through-wall cracks. Since parallel axial cracks are more frequently detected during in-service inspections than collinear axial cracks, the studies on parallel axial cracks spaced in circumferential direction are necessary.

The objective of this paper is to investigate interaction effects between two parallel axial through-wall cracks existing in a steam generator tube. Finite element analyses are performed and a new failure model of the steam generator tube with this type of cracks is suggested. Interaction effects between two adjacent cracks are evaluated to explain the deformation behavior of cracked tubes.

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. And rupture of the tubing can result in release of fission products to the environment outside the reactor containment through the pressure relief valves, the condenser off-gas, or other paths in the secondary system [1]. To prevent tube rupture, it is required 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 types of defects, and no criterion has been suggested for the case of multiple cracks so far [4-8].

Inspection of pulled out steam generator tubes and in-service inspection results show that the formation of multiple cracks is typical, especially in transition zone. Several coalescence models have been proposed. But all of them are based on brittle fracture whereas the failure of steam generator tubes is governed by plastic collapse rather than brittle fracture. In the previous study, was reviewed the conservatism of the present plugging criterion of steam generator tubes and proposed a crack coalescence model applicable to steam generator tubes with two collinear axial through-wall cracks [9]. Since most of cracks detected during in-service inspections are located around the roll transition zone and parallel axial cracks are more frequently detected in this area during in-service inspections than collinear axial cracks [10,11], the studies on parallel axial cracks spaced in 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. 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, was reviewed the conservatism of the present plugging criterion of steam generator tubes and proposed a crack coalescence model applicable to steam generator tubes with two collinear axial through-wall cracks. Its summary is as follows:

Conservatism of present plugging criteria

It was proved using R6 approach that the failure mode of steam generator tubes is plastic collapse. Limit load method was, therefore, adopted to estimate the collapse load of steam generator tubes.

Limit load method

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) [12].

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

where s_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).

$$M_T = 0.614 + 0.481 l + 0.386 \exp(-1.25 l) \qquad \text{for} \ \ 5 \le R/t \le 50 \tag{2}$$

$$l = [12(1 - n^2)]^{0.25} (c/\sqrt{Rt}) \tag{3}$$

where l is the shell parameter, n is the 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 ANL (Argonne National Laboratory) proposed to cover shallow and deep cracks by modifying Kiefner’ s equation [13,14].

$$P_{sc} = \frac{s_f t}{R}\left[\frac{1 - a/t}{1 - \boldsymbol{a} a / M_T t}\right] \tag{4}$$

where a is the crack depth and $\boldsymbol{a}$ is the parameter given by

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

Fig. 1 shows the failure pressures calculated by using Eq. (1) for through-cracked tubes and 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 tensile strength was used as a flow stress of the given material and its value was obtained from the lower bound value in the CMTR of steam generator tubes [15]. The safety factors of 3 and 1.4 were considered for normal operation and accidential condition, respectively, in accordance with the requirements of Regulatory Guide 1.121. From this consideration, a pressure of 30.6MPa is obtained as limiting pressure. It is shown in Fig. 1 that the through-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 terms of steam generator tubes 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 could assure the tube integrity regardless of crack length.

When it comes to crack type defects in steam generator tube, the exact depth measurement could not be credited so that the crack type defects are considered in general as through wall defects whatever the depth are and all crack type defects should be plugged. But this criterion is considered to be too conservative especially for axial cracks less than 9.8mm in length because the steam generator tube with a through-wall crack less than 9.8mm 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 the applied loads. It is too conservative to apply the 40% of wall criterion to all the cases without considering defect type, its locations, and lengths. It is, therefore, necessary to develop alternative plugging criteria on the basis of SGDSM (Steam Generator Defect Specific Management) strategies. To accomplish this goal, many works have been done. But these approaches have been limited to tubes with a single crack whereas multiple cracks could be found frequently.

In the previous study, the authors proposed a crack coalescence model applicable to steam generator tubes with two collinear axial through-wall cracks.

Coalescence model of multiple collinear axial through-wall cracks

Three coalescence model are available such as ASME Sec. XI, BSI PD6493, and zero ligament length for multiple collinear axial through-wall cracks and it is known that the third shows a good agreement with the experimental results [16-18]. 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 those two cracks fails without experimental observation and this is not conservative in terms of safety. Thus, the authors proposed a coalescence criterion of two collinear axial cracks existing in a steam generator tube as follows.

For part-through crack,

$$d_0 = f(\frac{c}{\sqrt{Rt}}, \frac{a}{c}, \frac{P_i}{P_{sc}}) \qquad (6)$$

For through-wall crack,

$$d_0 = f(\frac{c}{\sqrt{Rt}}, \frac{P_i}{P_{cr}}) \qquad (7)$$

where d_0 is the maximum ligament length where coalescence could take place under the applied pressure, P_i.

As a credit could not be given to defect depth measurement so far, the assumption that all the crack type defects are considered to be through wall cracks is still valid in this study. The basis of the Eq. (7) is that the coalescence takes place when the ligament is subjected to fully yielding and no longer sustains the applied loads. The stress values were taken at the mid-thickness of the tube wall. It is also assumed that the given material behaves in an elastic-perfectly plastic manner with a flow stress of s_f. In the previous study, the validity of this model was investigated by performing 3D finite element analyses. The results were plotted in Fig. 2 as a coalescence evaluation diagram that can be used to determine whether the adjacent cracks detected by NDE (Non-Destructive Evaluation) coalesce under the given pressure.

3. TWO PARALLEL AXIAL THROUGH-WALL CRACKS

First approach based on plastic zone contact

The first approach was to use similar concept as previously proposed in the coalescence model for two collinear axial through-wall cracks. Some modification was made for the previous model to be applicable to two parallel axial through-wall cracks: in the case of two parallel axial through-wall cracks, plastic zones develop from crack tips along with maximum shear stress plane and they come into contact far before the ligament between two cracks is fully yielded. It is, therefore, assumed that the coalescence takes place when plastic zones developed from crack tips contact each other.

3D finite element analyses using ABAQUS were performed to investigate the deformation behavior of two parallel axial through-wall cracks. The same material properties and geometry as used for previous study were used as indicated in table 1. And it is assumed that the material behaves in an elastic-perfectly plastic manner with the flow stress of s_f. The flow stress is defined as mean value of yield strength and tensile strength.

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

Fig. 4 through 6 show the changes of COD when $2c$ is 8mm and d is 1, 4, and 8mm, respectively. For the case of d = 1mm, plastic zones developed from the crack tips contact at 13.8MPa, and thereafter COD increased slowly as shown in Fig. 4. For the case of d = 4mm, plastic zones were contacted at 22.4MPa, and thereafter COD increased rapidly as shown in Fig. 5. For the case of d = 8mm, plastic zones were contacted at 27.55MPa, and thereafter COD increased quite rapidly as shown in Fig. 6. In all the cases, displacement of the outer surface changed more than that of the inner. Fig. 7 shows the change of plastic zone size for the case of $2c$ = 8mm and d = 4mm as the applied pressure increases. It is observed that plastic zones increase slowly up to 21MPa and contact at 22.4MPa. Once the contact of plastic zones takes place, their size increases rapidly with a small amount of pressure increase.

After coalescence, two collinear axial through-wall cracks are considered to be a single equivalent crack, i.e., $2c_{eq} = 2c+d+2c$. If the coalescence takes place under the limiting pressure and the equivalent single crack is greater than the critical crack length under the same pressure, the concerned tube should be plugged or repaired.

Unlike two collinear axial cracks, the equivalent single crack length of two parallel cracks could not be determined by the same way. It is reasonable that when two cracks are enough far away for no interaction to occur these two cracks should behave like a single independent crack, however, when they have interaction effect, such as plastic zone contact, they are more likely to fail. Hence, when the interaction effect could take place, its consequence should be separately considered.

The first step was to determine when the plastic zones touch each other by performing 3D finite element analyses with various crack lengths and distances. Once the contact pressure was determined, an equivalent single crack was calculated using Eq. 1. That is, a single crack length which fails at the contact pressure was determined. It is thought that even though the plastic zone of two crack tips contact it does not mean the load carrying capacity of the uncracked ligament is reduced as much as in the collinear cracked case. The consequence of interaction vis-à-vis tube failure could be investigated using experimental work which will follow up this study.

The calculated crack lengths using the foregoing process, $2c_{eq}$., were shown in Fig. 8. It shows that the equivalent crack length curves consist of two linear parts and all of them have inflection point at about 3 to 4mm in distance. When the distance is greater than 4 mm the slope is gradual and vice-versa. The equivalent crack length is the same as the individual crack size when the distance between two cracks is far enough to neglect interaction effects. However, as two cracks come to closer the equivalent crack length increase more rapidly and this trend become more apparent as crack length increases. By comparing the results of Fig. 4 through 6, we can find COD changes rapidly after the contact of plastic zones when the distance between cracks is relatively large. It is because the contact of plastic zones takes place after global yielding and brings about a large deformation of the tube in this case. On the other hand, it is shown that COD changes slowly even after the contact of plastic zones when two cracks are closely spaced. It is because plastic zones are confined to local areas, and thus they do not bring about any large deformation. Hence, it seems that the proposed equivalent crack length overestimates the failure risk when cracks are closely spaced.

Analysis of interaction effects

To investigate the conservatism of the proposed model for cracks closely spaced, interaction effects were estimated by performing elastic and elastic-plastic finite element analyses using full stress-strain curve given in Fig. 9. Young's modulus is 199.8GPa, the yield strength is 240MPa, and the tensile strength is 628MPa [9]. To estimate interaction effects between two parallel cracks, both elastic analysis based on K and elastic-plastic analysis based on J-integration were carried out. We defined the factors to explain the degree of interaction in elastic analysis and elastic-plastic analysis as K_{ratio} and J_{ratio} as follows, respectively.

$$K_{ratio} = \frac{K_D}{K_S} \tag{8}$$

$$J_{ratio} = \frac{J_D}{J_S} \tag{9}$$

where K_S and K_D are stress intensity factors for a single crack and two parallel cracks, respectively. 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 $2c$ is 8mm and d is 1, 4, and 8mm, respectively. K_{ratio} has a constant value regardless of the applied pressure at the given values of $2c$ and d, and increases as d increases. When K_D is less than Ks the interaction play a positive effect and we call it "negative interaction effects" (K_{ratio} < 1). Such negative interaction effect is getting more as the distance is getting closer. These results are in a good agreement with Murakami's study for two parallel through-wall cracks [19] and Cho's study for two parallel surface cracks [20] that multiple parallel cracks interact but reduce crack-tip stress and strain fields.

Table 3 shows the values of J_{ratio} when 2*c* is 8mm and *d* is 1, 4, and 8mm, respectively. Under the given values of 2*c* and *d*, J_{ratio} is almost constant below 13MPa but increases beyond it. Like K_{ratio}, J_{ratio} also increases as *d* increases. The more negative interaction effects (J_{ratio} < 1) is observed for the closer distance, and J_{ratio} shows greater negative interaction effects than K_{ratio} in all the cases.

From these results, it can be found that when the cracks are the longer and the more closely spaced the negative interaction effect is the more produced. It means that the closely spaced parallel cracks are less detrimental in terms of integrity than a single crack with same length. It is, therefore, said that the proposed single equivalent crack model is conservative for the cracks spaced less than 4 mm and that further studies are necessary to make clear the applicability of the proposed model to cover the full range without too much conservatism.

Second approach based on COD

According to the burst test results of steam generator tubes with multiple parallel axial cracks, the crack tip tearing takes place and experiences burst without the ligament failure. It is important to define an appropriate parameter that could be used for the prediction of onset of crack tip tearing for two parallel axial crack taking the interaction effect into account. For this purpose, COD could be an appropriate candidate.

Finite element analyses for five single cracks of 2c=4, 6, 8, 10, and 14mm were performed and the changes of COD at the crack center, d_o, were plotted as shown in Fig. 10. The COD at the failure pressure for each crack length was also indicated in this figure and was marked with the symbol 'x'. It is assumed that could be used as a critical value for the two parallel cracks. That is, the tubes with parallel cracks are supposed to fail when each COD value is equal to the COD at failure pressure of single crack. The value was defined as the critical COD in this paper and denoted as $(d_{\mathrm{o}})_{\mathrm{crit}}$. The following regression line was derived from the $(d_o)_{crit}$ values.

$$(d_o)_{crit} = 24819 P_i^{-3.44} \tag{10}$$

The above power law expression was obtained using the least square method. The dotted line of the figure represents the regression line. In the case of tube with two parallel axial cracks, the COD could be affected by two crack face displacements: opening in the circumferential direction and in the radial direction. The latter could be considered to contribute to Mode III failure whereas the circumferential opening could cause the failure in Mode I. It is, therefore, assumed that only the circumferential displacement contributes the failure. The finite element results for two parallel axial through-wall cracks and the regression line of Eq. (10) were plotted together as shown in Fig. 11.

The failure pressure of each tube with two parallel axial through-wall cracks was derived from the intersection point between the regression line and the opening displacement curve. The failure pressures of tubes with two parallel cracks were derived using the proposed model and plotted for the crack length as shown in Fig. 12. The double cracked tubes of 2*c*=4mm showed higher failure pressures for *d*=1, 3, and 4mm than that of the single cracked tubes, and vice versa for *d*=8 and 12mm. As compared with those of the single-cracked tubes, the failure pressures of the double-cracked tubes of 2*c*=6, 8, and 12mm increased only for *d*=1mm and decreased for *d*=3, 4, 8, and 12mm. The differences in the failures were in the range of 4.6% to –11.9%. By normalizing the failure pressure of the double-cracked tube with that of the single-cracked tube, P_D/P_S, Fig. 12 can be transformed into

Fig. 13. The ratio of P_D to P_S was in the range of 88.1% to 104.6%. Judging from Fig. 13, we can say that P_D gets higher than P_S when cracks come closer with each other. P_D decreases and becomes lower than P_S as cracks become away. As expected, P_D approaches to P_S when cracks are separated enough far away to cancel the interaction effect.

To estimate the failure behavior of the steam generator tubes on the basis of the crack length, the value of P_D is inserted into Eq. (1), and then the relevant crack size is calculated. We defined the crack size as the equivalent crack length, $2c_{eq}$. Accordingly, the tube containing a single crack of $2c_{eq}$ has the same failure pressure that the tube containing two parallel axial cracks of $2c$ has. Fig. 14 shows the calculated $2c_{eq}$ values for d and Fig. 15 is the plot of $2c_{eq}$ normalized by $2c$. The value of $2c_{eq}$ increases when the value of P_D decreases, and vice versa. Considering this, the same trend shown in Fig. 12 and Fig. 13 can be observed in Fig. 14 and Fig. 15, respectively. The only difference is that the ratio of $2c_{eq}$ to $2c$ is in the range of 83.8% to 121.3%. In order to estimate the tube failure pressure regardless of the crack length, we can use the lower bound curve shown in Fig. 12

4. CONCLUSIONS

From the study on the interaction effect of two parallel axial through-wall cracks existing in a steam generator tube, the following conclusions could be obtained:

1. A procedure to determine a single equivalent crack for two parallel axial through-wall cracks was proposed.
2. The interaction effect of two parallel axial through-wall cracks was investigated. The approach based on the plastic zone contact, as done in the previous study for the collinear axial cracks, provides too conservative equivalent crack length when two parallel crack are closely spaced. The investigation of interaction effect shows that two parallel axial cracks are safer than a single crack when they are closely spaced.
3. COD values were selected as an appropriate parameter to predict the onset of tube failure with an assumption that the parallel cracks fail when each COD value is equal to the COD at failure pressure of single crack.
4. Using the approach based on COD, two parallel axial cracks could be converted into an equivalent crack.

However, further researches are necessary to validate the applicability of the proposed model and some experimental works are underway.

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Table 1 Specification of considered steam generator tubes [15]

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

Table 2 Evaluation of interaction effect based on *K*

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

Table 3 Evaluation of interaction effect based on *J*-integral

Crack Size (mm)	*P* (MPa)	J_S (MPa· m)	J_D (MPa· m)	J_{ratio}
2*c*=8, *d*=1	5	0.2818	0.1633	0.5795
	10	1.681	0.9565	0.5690
	13	3.458	2.024	0.5853
	15	4.774	2.652	0.5555
	20	19.65	13.13	0.6682
2*c*=8, *d*=4	5	0.2818	0.2481	0.8804
	10	1.681	1.411	0.8394
	13	3.458	2.881	0.8331
	15	4.774	4.983	1.044
	20	19.65	28.23	1.437
2*c*=8, *d*=8	5	0.2818	0.3019	1.071
	10	1.681	1.797	1.069
	13	3.458	3.614	1.045
	15	4.774	6.282	1.316
	20	19.65	32.92	1.675

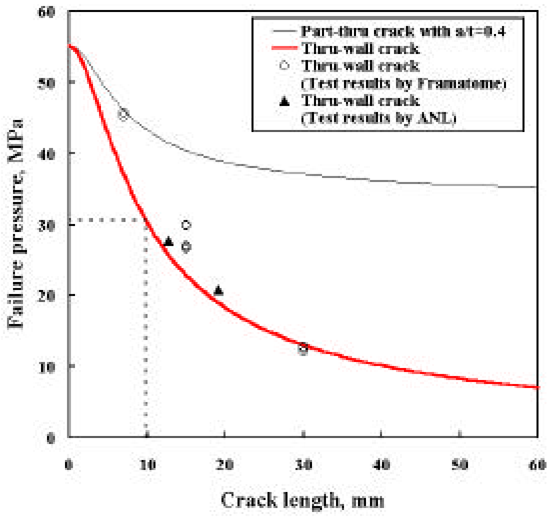


Fig. 1 Limit load solutions

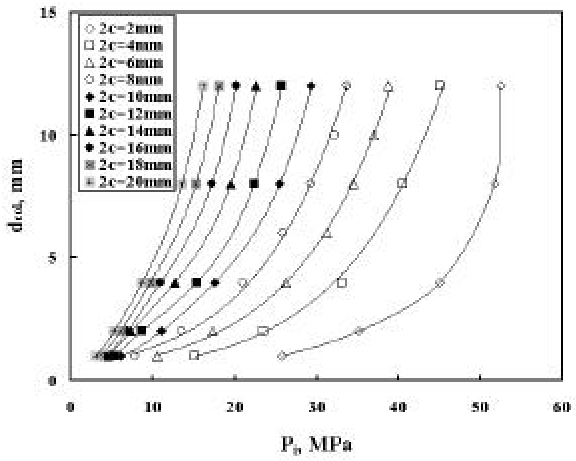


Fig. 2 Coalescence evaluation diagram

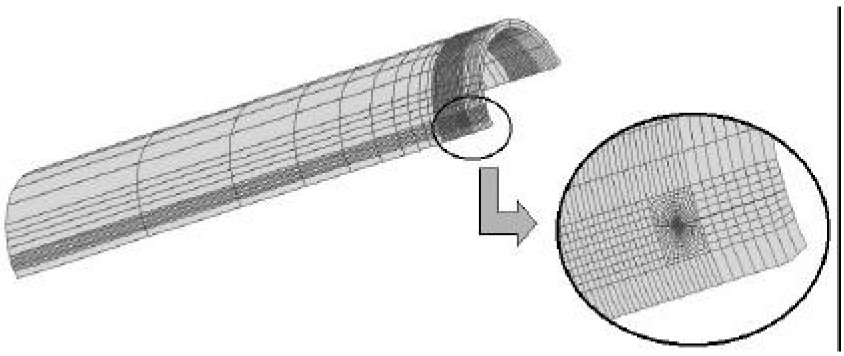


Fig. 3 Finite element mesh of steam generator tube

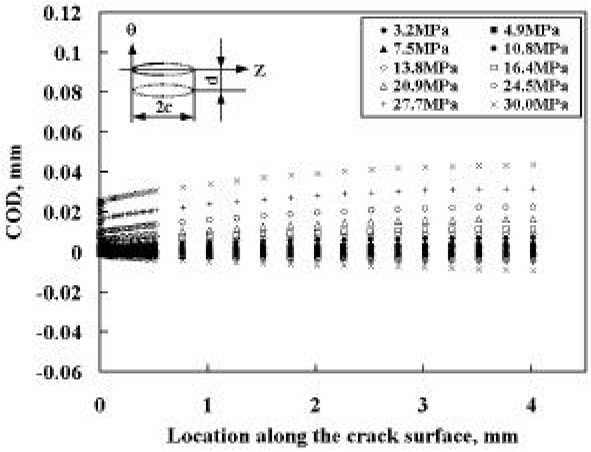


Fig. 4 Changes of COD ($2c$ = 8 mm, d = 1 mm)

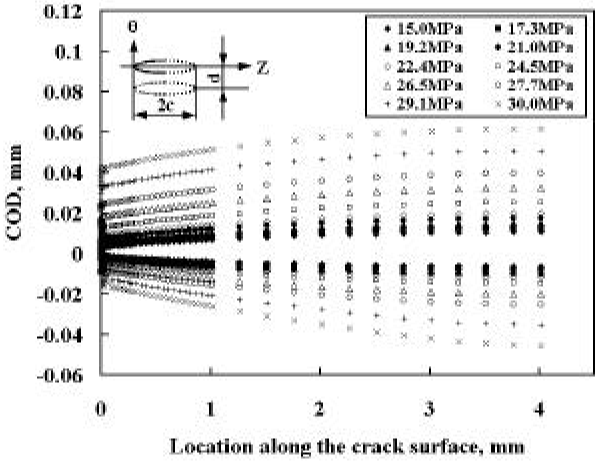


Fig. 5 Changes of COD ($2c$ = 8 mm, d = 4 mm)

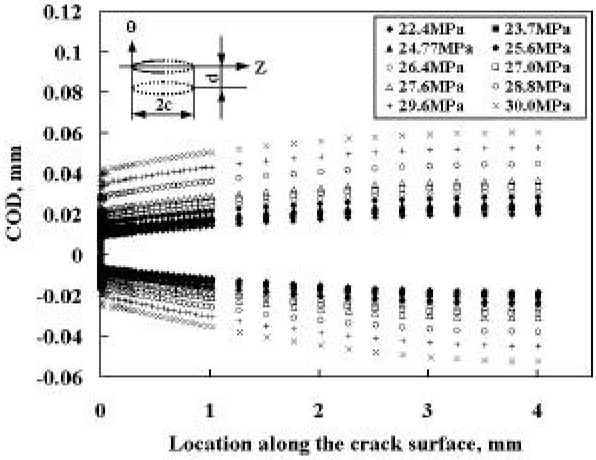
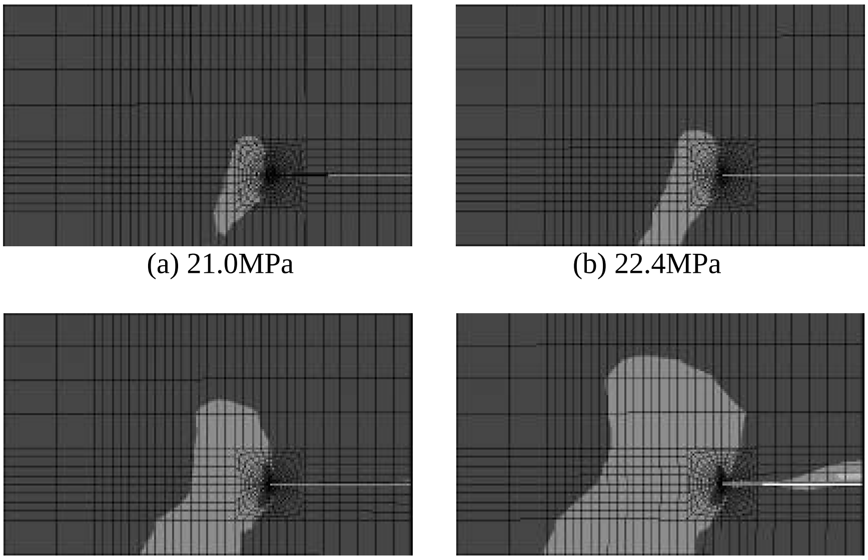


Fig. 6 Changes of COD ($2c$ = 8 mm, d = 8 mm)



(a) 21.0MPa (b) 22.4MPa

(c) 23.6MPa (d) 29.7MPa

Fig. 7 Changes in plastic zone size as pressure increases

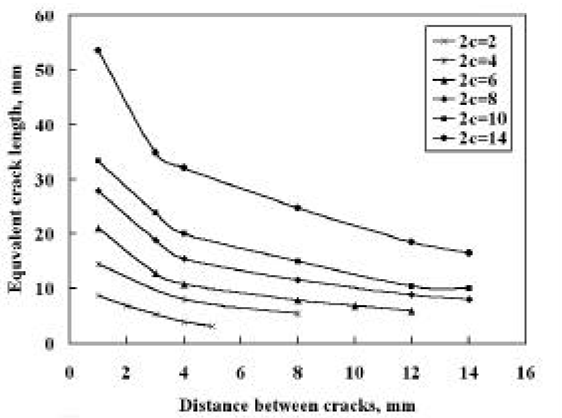


Fig. 8 Equivalent crack length of two parallel cracks

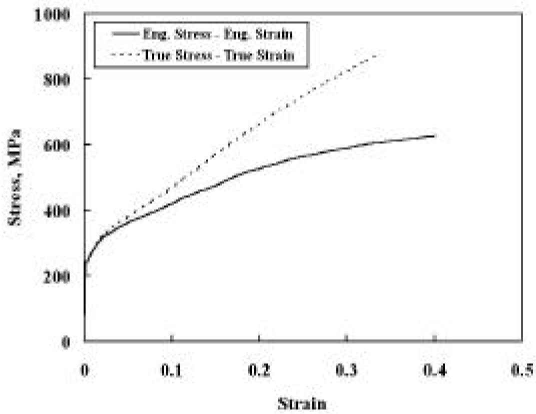


Fig. 9 Stress-strain curve used in finite element analysis

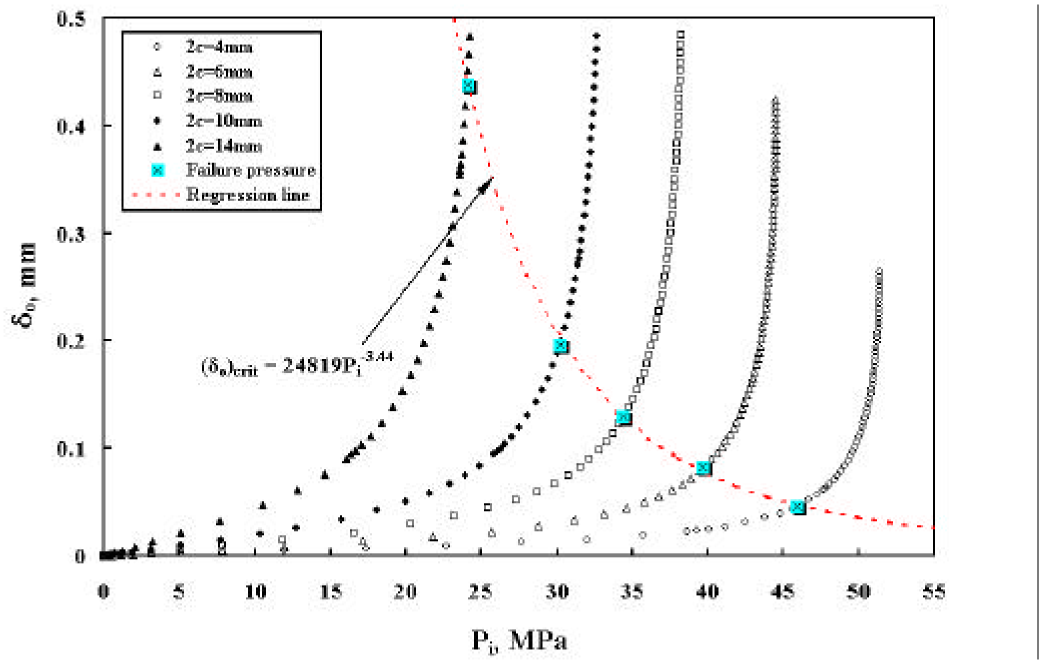


Fig. 10 Changes of COD at the crack center

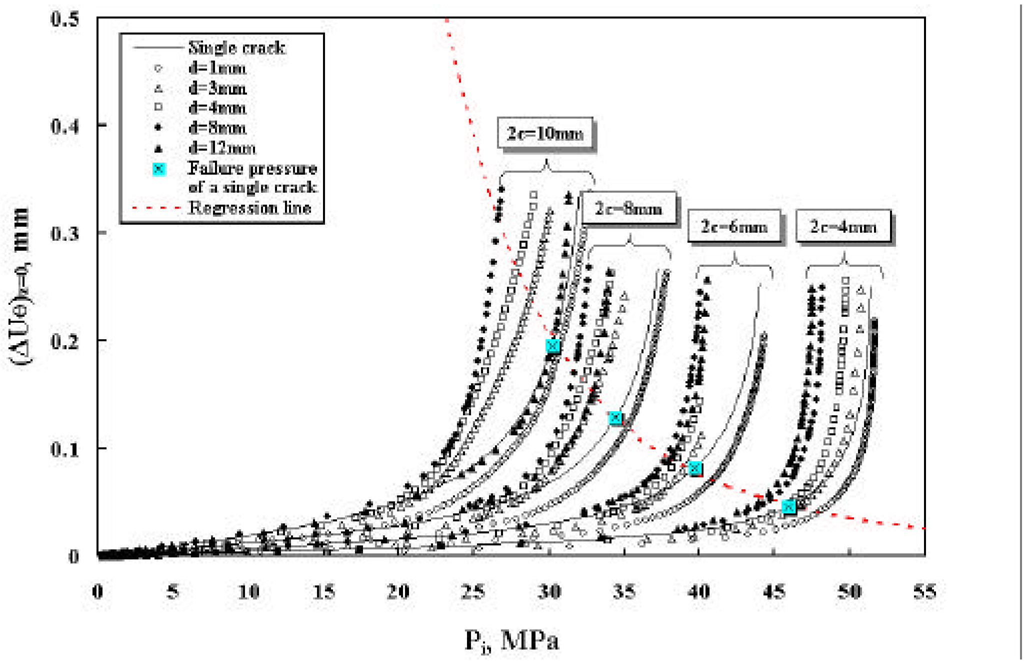


Fig. 11 Changes of $(\Delta U_q)_{z=0}$

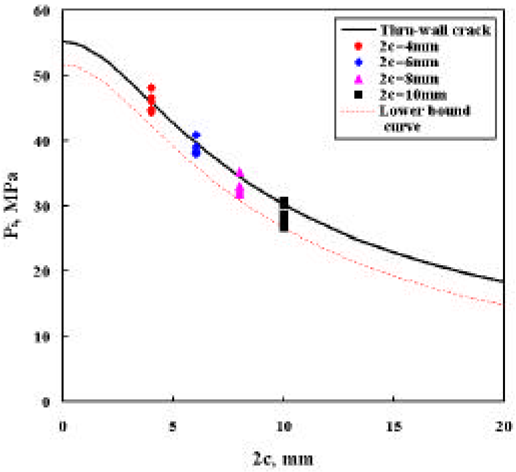


Fig. 12 Failure pressures of double-cracked tubes

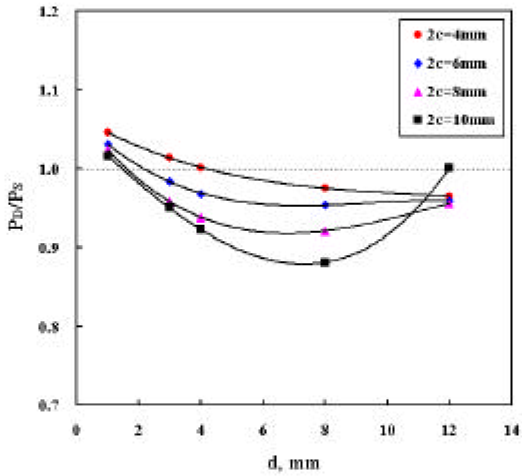


Fig. 13 P_D/P_S vs. *d* curve

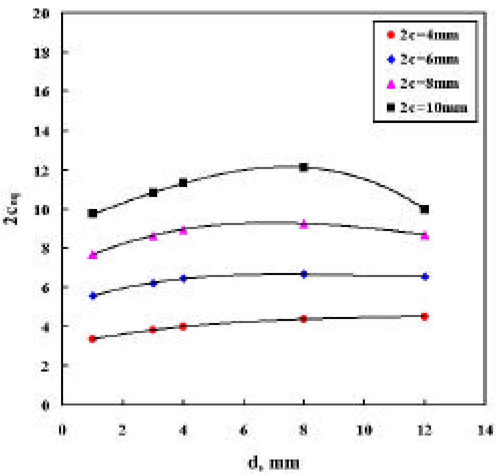


Fig. 14 Changes of equivalent crack length

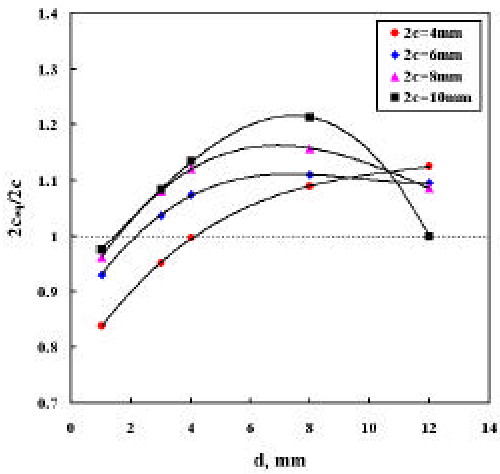


Fig. 15 $2c_{eq}/2c$ vs. *d* curve