COALESCENCE MODEL OF TWO COLLINEAR CRACKS EXISTING IN STEAM GENERATOR TUBES

Seong-In Moon, Yoon-Suk Chang, Young-Jin Kim
Sungkyunkwan University, Korea
Phone: +82-31-290-5274, Fax: +82-31-290-5276
E-mail: yjkim50@skku.edu

Youn-Won Park, Myung-Ho Song, Young-Hwan Choi, Jin-Ho Lee
Korea Institute of Nuclear Safety, Korea

ABSTRACT

The 40% of wall thickness criterion has been used as a plugging rule of steam generator tubes but it can be applicable just to a single-cracked tubes. In the previous studies preformed by the authors, a total of 10 local failure prediction models were introduced to estimate the coalescence load of two adjacent collinear through-wall cracks existing in thin plates, and the reaction force model and plastic zone contact model were selected as optimum models among them. The objective of this study is to verify the applicability of the proposed optimum local failure prediction models to the tubes with two collinear through-wall cracks. For this, a series of plastic collapse tests and finite element analyses were carried out using the tubes containing two collinear through-wall cracks. It has been shown that the proposed optimum failure models can predict the local failure behavior of two collinear through-wall cracks existing in tubes well. And a coalescence evaluation diagram was developed which can be used to determine whether the adjacent cracks detected by NDE coalesce or not.

Keywords: Four Steam Generator Tube, Plastic Collapse, Failure Prediction Model, Plugging Criteria, Collinear Cracks, Coalescence Evaluation Diagram

1. INTRODUCTION

It is commonly requested that the steam generator tubes with defects exceeding 40% of wall thickness in depth should be plugged[1~3]. However, this criterion is known to be too conservative for some locations and types of defects[4,5]. Many defects detected during in-service inspection take on the form of multiple cracks at the top of tube sheet but there is no reliable plugging criterion for the steam generator tubes with multiple cracks[4~10]. Most of the previous studies on multiple cracks are confined to elastic analyses and only few studies have been done on the steam generator tubes failed by plastic collapse[11~14]. Therefore, it is necessary to develop models which can be used to estimate the failure behavior of steam generator tubes with multiple cracks.

In the previous study[15], the authors introduced a total of ten local failure prediction models including the flow stress model, necking base model, stress base model, reaction force model, plastic zone contact model, etc. In addition, a series of plastic collapse tests and finite element analyses were carried out using the thin plates with two collinear through-wall cracks. By comparing the experimental results with the estimated results, the reaction force model and the plastic zone contact model were selected as the optimum local failure prediction models to predict the coalescence load of two adjacent collinear axial through-wall cracks (hereafter described as collinear cracks) in steam generator tubes.
The objective of this study is to verify the applicability of the optimum local failure prediction models proposed in the previous study. For this, six plastic collapse tests are performed with the tube specimens containing collinear cracks that the crack length \((2c)\) is 5 and 10 mm and the distance between cracks \((d)\) is 1, 2, and 4 mm, respectively. The coalescence loads of the collinear cracks are also estimated by using the proposed optimum local failure models and their applicability is investigated by comparing the estimated results with the experimental results. Also, a crack coalescence evaluation diagram which can be used to determine whether the collinear cracks detected by NED coalesce or not is developed.

2. OPTIMUM LOCAL FAILURE PREDICTION MODEL

Several criteria have been used to determine the onset of coalescence between two adjacent surface cracks: ASME Section XI IWA-3000[16], BSI PD6493[17], the contact model of surface points, etc. Among these criteria, the contact model of surface points shows a good agreement with the corresponding experimental results[18~20] and this means that two adjacent cracks coalesce when the ligament between cracks can no longer sustain the applied load. However, these criteria were developed for the application to the pressure vessels and piping of which the failure behavior is dominated by small scale yielding condition and quite different from that of steam generator tubes: the failure behavior of steam generator tubes is governed by plastic collapse. So, it is necessary to develop a new criterion applicable to the steam generator tubes with multiple cracks.

2.1 Local Failure Prediction Model

In the previous study[15], a total of ten local failure prediction models were introduced to estimate the coalescence load of collinear cracks existing in steam generator tubes. Their main features are as follows:

1. Flow Stress Model I (FSM-I)[9,21,22]: It is assumed that coalescence occurs when the ligament between cracks is fully yielded. A given material is assumed to show elastic-perfectly plastic behavior and be yielded at the flow stress level. The flow stress is defined as the mean value of the yield strength and the ultimate tensile strength.

2. Flow Stress Model II (FSM-II): The same definition with FSM-I is used but the flow stress is defined as the ultimate tensile strength.

3. Necking Base Model (NBM)[23]: It is assumed that coalescence occurs when the average ligament thickness between cracks begins to decrease rapidly.

4. Stress Base Model I (SBM-I)[23]: It is assumed that coalescence occurs when the average Mises stress in the ligament equals to the ultimate tensile strength.

5. Stress Base Model II (SBM-II)[23]: The same definition with SBM-I is used but the engineering stress-engineering strain curve is used in this model.

6. Reaction Force Model (RFM)[23]: It is assumed that coalescence occurs when the reaction force in the ligament between cracks begins to decrease following the increase.

7. Plastic Zone Contact Model I (PZC-I): It is assumed that coalescence occurs when plastic zones developed from the crack tips come into contact. This model is based on the contour plot of the Mises stress, which equals to the yield strength.

8. Plastic Zone Contact Model II (PZC-II): The same definition with PZC-I is used but this model is based on the contour plot of the Mises stress, which equals to the ultimate tensile strength.

9. Plastic Zone Contact Model III (PZC-III): The same definition with PZC-I is used but this model is based on the contour plot of the Mises stress, which equals to the true stress value of the ultimate tensile strength.

10. Plastic Zone Contact Model IV (PZC-IV): It is assumed that coalescence occurs when the ligament between cracks is fully yielded. This model is based on the contour plot of the Mises stress, which equals to the ultimate tensile strength.

2.2 Determination of Optimum Local Failure Prediction Model

In the author’s previous study[15], plastic collapse tests and analyses were conducted by using the thin plate specimens containing collinear cracks for simplication of tests and analyses. Thereafter, the coalescence loads predicted by local failure prediction models were compared with those obtained from plastic collapse tests. The coalescence loads predicted by applying the RFM model showed a good agreement with the corresponding experimental results by the maximum difference and the average difference of 14 and 5 %, respectively. Also, the PZC-II, III and IV model predicted the coalescence loads well with the maximum difference of 15, 10, and 15 % and the average difference of 7, 1 and 6 %, respectively. From this, the RFM, PZC-II, III, and IV model were selected as the optimum local failure prediction models to estimate the local failure behavior of steam generator tubes containing collinear cracks.
3. PLASTIC COLLAPSE TEST FOR TUBE WITH COLLINEAR CRACKS

In this study, a series of plastic collapse tests performed by using tube specimens to verify the applicability of the proposed optimum local failure prediction models to the steam generator tubes containing collinear cracks.

3.1 Material and Specimen

The tube specimens were made of Inconel 600 which used as a steam generator tube material in pressurized water reactors. The outer diameter and thickness of the specimen are 19.05 mm and 1.09 mm, respectively. The chemical composition of this material was given in Table 1. The tensile properties obtained by using the full-size tubular specimens according to ASTM E 8M[24] were given in Table 2.

Plastic collapse tests were performed using the tube specimens containing collinear axial through-wall notches as shown in Fig. 1. All the notches were wrought by EDM (Electro-Discharge Machining) method which has a gap width of 0.18 mm. It has been known that the failure behavior of a cracked tube is not significantly influenced by notch sharpness[24]. The machined crack length is 5 and 10 mm and the distance between cracks is 1, 2 and 4 mm, respectively. For comparison, additional tests were performed using the tube specimen containing a single crack of \(2c = 5\) and 10 mm.

3.2 Test Facility and Method

The plastic collapse tests for steam generator tubes are to measure the applied pressure at the moment of plastic collapse as the internal pressure increases with a constant pressurization rate. The facilities used in the plastic collapse tests consist of a high pressure pump, data acquisition system, protective chamber and control system.

It is also known that the plastic collapse load increases with the increase of the pressurization rate in general. The plastic collapse test results of steam generator tubes containing an axial single crack under various pressurization rates which were obtained by ANL (Argonne National Lab.) and Framatome were summarized in Table 3[25,26]. The ANL test results indicate that the plastic collapse loads increase 13 and 24 %, respectively, as the pressurization rate increases from the quasi-static state to 13.78 MPa/s (2000psi/s) and 48.23 MPa/s (7000psi/s). From the test results of Framatome, it can also be seen that there is no effect of pressurization rate when the pressurization rate is below 3.45 MPa/s (500 psi/s). Based on these results, in this study, the plastic collapse tests were conducted under the pressurization rate of 2.8~4.1 MPa/s (400~600 psi/s) to minimize the effect of pressurization rate.

To prevent the leakage through the crack, the sealing bladder made of a Tygon hose was inserted into the cracked tube. Since a flexible bladder extruded through the crack may cause unanticipated pressure on the crack faces, a back-up foil was also inserted between the bladder and tube. According to the recommendation given by EPRI etc. that it should not be thicker than 0.1524 mm (0.006 in), the back-up foil of 0.15 mm thickness was used[27].

In Fig. 2, the experimental results obtained by using both bladder and back-up foil or only bladder were compared with the finite element analysis results to investigate the effects of back-up foils. In the finite element analyses, crack face pressure was not considered. The detailed explanation for the finite element model will be covered in the following chapter. For \(2c = 5\) mm, the measured COD (Crack Opening Displacement) which obtained by using the 0.2 mm back-up foil was slightly smaller than the corresponding finite element analysis results. It is thought that relatively small COD values were obtained due to the increase of stiffness, which is caused by the use of the thick back-up foil. On the other hand, the measured COD values obtained by using 0.15 mm back-up foils showed a good agreement with the analysis results except a high pressure region. In the cases that the back-up foil was not used or a relatively thin back-up foil of 0.1 mm was used, the bladder extrudes through the crack and the experiment gave larger COD values than the analysis under all loading conditions. From these results, it can be said that the bladder pressurizes crack faces not only under high loading conditions but also under low loading conditions when only the bladder is used without any back-up foil. And relatively small COD values as compared with the analysis results can be produced when a relatively thick back-up foil is used.

In this study, the brass foil of 0.15 mm thickness which can mimic the effects of the back-up foil was inserted between the tube and the bladder. Fig. 3 is a schematic of the tube with a bladder and a back-up foil. Plastic collapse tests were continued until collinear cracks were coalesced with each other. The plastic collapse behavior of the tube with collinear cracks was monitored by a high resolution camera and the internal pressure was measured using two separated pressure sensors. The images captured by the camera and the pressure data were continuously stored in a computer.
3.3 Test Results

Fig. 4 represents a typical plastic collapse behavior of the tube specimen with collinear cracks of \(2c = 5\) mm and \(d = 1\) mm. Fig. 4(a) taken before the test shows two cracks and the ligament between the adjacent collinear cracks. Fig. 4(b) shows a deformed shape of the ligament and a COD increase right before the coalescence. Fig. 4(c) shows one main crack which was formed as a result of the coalescence of two cracks. The crack length of the newly formed one main crack equals to the sum of two crack lengths and the ligament length between cracks. In this case, the main crack was collapsed as soon as two cracks coalesced with each other because the plastic collapse load of the main crack was lower than the coalescence load of the two cracks. Fig. 4(d) indicates a post-test photograph showing an unstable crack growth.

The plastic collapse loads were obtained from two tube specimens with a single crack, which were prepared to acquire baseline data. The coalescence loads were also obtained from six tube specimens with collinear cracks and compared with the experimental results. Fig. 5 shows that the coalescence loads obtained from the experiment were reduced as the ligament length between collinear cracks decreased and the crack length increased. The experimental data were used to normalize the predicted results as summarized in Table 4.

4 ESTIMATION OF COALESCEENCE LOAD USING OPTIMUM LOCAL FAILURE PREDICTION MODEL

4.1 Finite Element Analysis

To verify the applicability of the RFM, PZC-II, III and IV model proposed as the optimum local failure prediction models in the previous study[15], the estimated coalescence load \(P_{cl}\) of collinear cracks was estimated by applying each model to three-dimensional elastic-plastic finite element analysis results and compared with the corresponding experimental result. The finite element analysis was performed using ABAQUS Version 6.4 package.

Fig. 6 shows a typical finite element mesh of the tube containing collinear cracks. A forth of the tube was modeled by considering symmetry. The finite element mesh was constructed by using 20-node quadratic brick elements with reduced integration points. The notch tip was rounded with the same radius of curvature as the tube specimen, \(\rho = 0.09\) mm.

A series of finite element analyses were carried out for the tubes containing collinear cracks of \(2c = 5\) and \(10\) mm and \(d = 1, 2\) and \(4\) mm, respectively. The coalescence loads of collinear cracks were estimated by using each of the proposed optimum local failure prediction models.

4.2 Results and Discussion

Table 4 represents the estimated results obtained by using coalescence models and normalized by the experimental data. In this paper, the unstable failure loads of tubes with a single through-wall crack \(P_{cr}\) were calculated using Eq. (1)[28].

\[
P_{cr} = \frac{\sigma_f t}{M_T R}
\]

where \(\sigma_f\) is the flow stress, \(t\) is the wall thickness, \(R\) is the mean radius of the steam generator tube and \(M_T\) is the bulging factor expressed by Eqs. (2) and (3).

\[
M_T = 0.614 + 0.481\lambda + 0.386\exp(-1.25\lambda) \quad \text{for} \quad 5 \leq R/t \leq 50
\]

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

where \(\lambda\) is the shell parameter, \(\nu\) is the Poisson’s ratio and \(c\) is the half crack length. The plastic collapse loads estimated by using Eq. (1) showed a good agreement with the corresponding experimental results within 3 %.

Fig. 7 shows the changes of the reaction force in the ligament between two cracks with the increase of applied load. In this figure, the point where the reaction force begins to decrease became smaller with the increase of crack length and the decrease of ligament length. The maximum reaction force that can sustain the applied load mainly depends on the ligament length and the effect of crack length is negligible. Fig. 8 shows contour plots of von Mises stress in case of \(2c = 5\) mm and \(d = 2\) mm with the increase of the applied pressure, which represents the changes of the plastic zone shape and size. The growth rate of the plastic zone is in the order of mid-plane, inner surface and outer surface when the ligament is small, and in the order of inner surface, mid-plane and outer surface when the ligament is relatively large.
In the previous study\cite{15}, the PZC-III model estimated the coalescence load of collinear cracks existing in thin plates well. However, it overestimated the load carrying capacity of collinear cracks existing in tubes.

Fig. 9 shows the normalized coalescence loads estimated using the RFM, PZC-II and PZC-IV model. The estimated results showed a good applicability of the three models except in the case of $2c=5$ mm and $d=1$ mm. The RFM and PZC-IV model underestimated the coalescence loads a little. The the maximum difference and the average difference are 8 % and 3 %, respectively. The PZC-II model estimated the coalescence load with the maximum difference of 10 % and the average difference of 4 %. From this, it can be said that the RFM and PZC-IV model selected as the optimum local failure prediction models of thin plates can also be used to estimate the coalescence load of collinear cracks existing in steam generator tubes.

For the comparison between thin plates and tubes, the coalescence loads of collinear cracks existing in the tubes specimens under internal pressure and the thin plates under tension load were estimated by using the PZC-IV model. The finite element mesh of the thin plate was generated in the form of a rectangular plate with the same size as the unrolled tube. And the tensile distribution load equivalent to the hoop stress produced by internal pressure was applied. In all cases, the coalescence loads of collinear cracks existing in thin tube specimens were lower than those existing in plates. It is thought that the lower coalescence load is caused by the bulging displacement developed around the crack by internal pressure. In this study, the bulging factor of collinear cracks (MD) was defined as follows.

\[
M_D = \frac{P_{\text{plate}}}{P_{\text{tube}}}
\]

where $P_{\text{plate}}$ and $P_{\text{tube}}$ denote the coalescence loads of collinear cracks existing in thin plates and tubes, respectively. Table 5 indicates the estimated bulging factors. As summarized in Table 5, the effects of the bulging displacement increased with the increase of $2c$ and the decrease of $d$.

As the distance between two cracks increases, the coalescence load of collinear cracks approaches the plastic collapse load of a single crack. Thus, if the distance between a pair of cracks are longer than a specific value, the interaction effect comes to fade away and collinear cracks behaves like two independent single cracks. To find the condition in which the interaction effect disappears, additional analyses which will be covered in the next chapter were performed in this study.

5. COALESCEENCE EVALUATION DIAGRAM

As shown in the previous chapter, the RFM and PZC-IV model can be used as promising models to estimate the coalescence loads of collinear cracks existing in tubes. In this chapter, the additional finite element analyses were carried out to make a coalescence evaluation diagram which can be used to determine whether the adjacent collinear cracks coalesce or not. To estimate the coalescence load of collinear cracks, finite element analyses adopting the PZC-IV model were performed by changing $2c$ from 2 mm to 12 mm and $d$ from 1 mm to 8 mm.

Fig. 10 shows the coalescence load - crack length curve obtained from the finite element analysis results. This curve can be used to determine the crack coalescence load ($P_{\text{cl}}$). In this figure, the solid line indicates the plastic collapse load of the tubes containing a single crack and each symbol indicates the coalescence loads of collinear cracks existing in tubes. It is noted that the coalescence loads of adjacent collinear cracks with a value of $d$ greater than 4 mm approaches to the plastic collapse loads of the tube containing a single crack. This means that if the distance between a pair of cracks are longer than 4 mm, the interaction effect comes to fade away and collinear cracks behave like two independent single cracks.

In Fig. 10, the parameter $d$ can be replaced with $d_0$, which is the value at the onset of the crack coalescence. Fig. 11, named as a coalescence evaluation diagram, can be obtained from Fig. 10 by changing the parameters. Using the coalescence evaluation diagram, it is possible to determine whether the adjacent cracks detected by NED coalesce or not under a given operating condition. Once the adjacent cracks coalesce with each other, it can be regarded as a single crack with the equivalent length of $2c_{\text{new}} = 2c + d + 2c$.

6. CONCLUSIONS

In this study, to estimate the plastic collapse behavior of the tube containing two collinear axial through-wall cracks, the plastic collapse tests using Inconel 600 tube specimens were conducted. And a series of corresponding finite element analyses were carried out to verify the applicability of the optimum local failure prediction models, which were developed based on thin plates, to the steam generator tubes. Finally, the coalescence evaluation diagram which can be used to determine whether the adjacent cracks coalesce or not was developed by performing additional finite element analyses. From these studies the following conclusions were obtained.
The effects of pressurization rate and back-up foil on plastic collapse loads were reviewed and the optimum test condition was determined. Under the optimum test condition, the coalescence loads of collinear cracks existing in tubes were measured.

By the comparison of experimental results with finite element analysis results, the reaction force model and plastic zone contact model IV were selected as the optimum ones to estimate the coalescence loads of collinear cracks existing in tubes.

The interaction effect between two adjacent cracks disappears when the ligament length exceeds 4 mm and the cracks behave like two independent single cracks.

A coalescence evaluation diagram for steam generator tubes was developed by using the plastic zone contact model IV and it can be used to determine whether the adjacent cracks detected by NDE conaoesec under the given operating conditions.

REFERENCES

### Table 1 Chemical composition of Inconel 600 tube specimen

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt. %</td>
<td>0.025</td>
<td>0.21</td>
<td>0.19</td>
<td>0.005</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt. %</td>
<td>&lt;0.001</td>
<td>74.19</td>
<td>15.52</td>
<td>0.018</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>Ti</th>
<th>Al</th>
<th>Cu</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt. %</td>
<td>0.29</td>
<td>0.22</td>
<td>0.012</td>
<td>9.30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>N</th>
<th>B</th>
<th>-</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt. %</td>
<td>0.024</td>
<td>&lt;0.0005</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 2 Tensile properties of Inconel 600 tube specimen

<table>
<thead>
<tr>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Young’s modulus (GPa)</th>
<th>Elongation (%)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>285</td>
<td>674</td>
<td>214</td>
<td>40</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Table 3 Influence of pressurization rates on plastic collapse load

<table>
<thead>
<tr>
<th>I.D.</th>
<th>2c (mm)</th>
<th>a/t</th>
<th>Pressurization rate (MPa/s)</th>
<th>Plastic collapse load (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANL</td>
<td>19.05</td>
<td>0.8</td>
<td>21.36</td>
<td>24.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13.78</td>
<td>26.39</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>48.23</td>
<td>45.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.12</td>
<td>45.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.00</td>
<td>45.20</td>
</tr>
<tr>
<td>Framatome</td>
<td>7.00</td>
<td>1.0</td>
<td>0.12</td>
<td>29.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.62</td>
<td>29.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.36</td>
<td>27.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.39</td>
<td>26.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.55</td>
<td>26.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.12</td>
<td>12.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.52</td>
<td>12.80</td>
</tr>
</tbody>
</table>
### Table 4 Normalized coalescence loads of tubes containing collinear cracks

<table>
<thead>
<tr>
<th>Crack size (mm)</th>
<th>Normalized plastic collapse load of a single crack</th>
<th>Normalized coalescence load of two collinear cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erdogan’s Eq.</td>
<td>RFM</td>
<td>PZC-II</td>
</tr>
<tr>
<td>2c=5, d=1</td>
<td>0.967</td>
<td>0.917</td>
</tr>
<tr>
<td>2c=5, d=2</td>
<td>0.972</td>
<td>0.949</td>
</tr>
<tr>
<td>2c=5, d=4</td>
<td>0.971</td>
<td>0.974</td>
</tr>
<tr>
<td>2c=10, d=1</td>
<td>0.984</td>
<td>0.989</td>
</tr>
<tr>
<td>2c=10, d=2</td>
<td>0.988</td>
<td>0.983</td>
</tr>
<tr>
<td>2c=10, d=4</td>
<td>0.967</td>
<td>0.970</td>
</tr>
</tbody>
</table>

### Table 5 Estimated Bulging Factors of tubes containing collinear cracks

<table>
<thead>
<tr>
<th>Crack size (mm)</th>
<th>Bulging factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2c=5, d=1</td>
<td>1.37</td>
</tr>
<tr>
<td>2c=5, d=2</td>
<td>1.21</td>
</tr>
<tr>
<td>2c=5, d=4</td>
<td>1.17</td>
</tr>
<tr>
<td>2c=10, d=1</td>
<td>2.18</td>
</tr>
<tr>
<td>2c=10, d=2</td>
<td>1.75</td>
</tr>
<tr>
<td>2c=10, d=4</td>
<td>1.44</td>
</tr>
</tbody>
</table>
Fig. 1 Geometry of tube specimen containing two collinear through-wall cracks

Fig. 2 Comparison of CODs obtained from experiment and FEA
Fig. 3 Schematic of tube specimen with bladder and back-up foil

Fig. 4 Plastic collapse behavior of tube containing two collinear through-wall cracks \((2c=5 \text{ mm}, d=1 \text{ mm})\)
Fig. 5 Coalescence loads of collinear cracks obtained from experiment

Fig. 6 A typical finite element mesh of tube containing two collinear cracks (2c=5 mm, d=4 mm)
Fig. 7 Change of reaction force in the ligament between collinear cracks

Fig. 8 Contour plots of von Mises stress according to pressure changes
Fig. 9 Estimated coalescence load which normalized by the experimental data

Fig. 10 Coalescence load - crack length curve
Fig. 11  Coalescence evaluation diagram