Plastic Collapse Behavior for Thin Tube with Two Parallel Cracks

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1. Introduction

The current plugging criterion is known to be too conservative for some locations and types of defects. 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[1]. 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[2~4]. Therefore, it is necessary to develop models which can be used to estimate the failure behavior of steam generator tubes with multiple cracks.

The objective of this study is to verify the applicability of the optimum local failure prediction models proposed in the previous study[5]. For this, plastic collapse tests are performed with the tube specimens containing two parallel through-wall cracks. The plastic collapse load of the steam generator tubes containing two parallel through-wall cracks are also estimated by using the proposed optimum global failure model and the applicability is investigated by comparing the estimated results with the experimental results. Also, the interaction effect between two cracks was evaluated to explain the plastic collapse behavior.

2. Optimum Global Failure Prediction Model

In the previous study[5], plastic collapse tests and finite element analyses were performed by using thin plate specimens and an optimum global failure prediction model was proposed to estimate the plastic collapse load of steam generator tube with parallel cracks. The CBM (COD Base Model) is assumed that the failure of a thin plate or tube with two parallel through-wall cracks occurs when the COD at each of two parallel cracks is equal to the COD at the failure load of single crack.

3. Plastic Collapse Test

In order to verify the applicability of the proposed optimum global failure prediction model to the steam generator tubes containing parallel cracks, a series of plastic collapse tests were performed by using tube specimens containing two parallel axial through-wall notches as shown in Fig. 1. The tube specimens were made of Inconel 600 which used as a steam generator tube material in pressurized water reactors. The machined crack length ($2c$) is 5 and 10 mm and the distance between cracks (d) is 1, 2, and 4 mm, respectively. For comparison additional tests were performed by using the tube specimen containing a single crack of 2c = 5 and 10 mm. Fig. 2 shows the typical collapse behavior of the tube specimen with collinear cracks of $2c$ = 10 mm and d = 2 mm. The obtained plastic collapse loads were reduced as the distance between parallel cracks increase and the crack length increases.

4. Verification of Optimum Global Failure Prediction Model

4.1 Finite element analysis

The plastic collapse load (P_D) of the tubes with parallel cracks was estimated by using CBM model and three-dimensional elastic-plastic finite element analysis. The deformation behavior of the tubes containing parallel cracks was estimated and ABAQUS Verson 6.4 package was used for the finite element analyses.

4.2 Results and Discussion

The plastic collapse loads of the tubes with parallel cracks were estimated by using the CBM model and the estimated results normalized with the experimental results for the tube containing a single crack were summarized in Table 1. The CBM model estimated the plastic collapse load with the maximum difference of 8.4 % and the average difference of 1.5 %. Therefore, the applicability of CBM model was verified and COD base model can also be used to estimate the plastic collapse load of the steam generator tubes containing parallel cracks.

Table 1 Plastic collapse loads of SG tube containing two parallel through-wall cracks

Crack size (mm)	Normalized plastic collapse load
$2c$=5, d=2	0.922
$2c$=5, d=4	0.925
$2c$=10, d=1	1.084
$2c$=10, d=2	1.020
$2c$=10, d=4	0.974

5. Interaction Effect

The additional analyses were carried out to evaluate the interaction effect between parallel cracks. The finite element analyses were performed with the tubes containing parallel cracks of $2c$ = 4, 6, 8, and 10 mm and d = 1, 3, 4, 6, 8, 10, 12, 14, 16, 18, and 20 mm, respectively.

Fig. 3 shows the ratio of P_D to P_S (plastic collapse load of the tubes containing a single crack) versus the d. The interaction effect appears in reverse when the distance between cracks is greater than about 6 mm. Beneficial interaction effect is getting more as the distance is getting closer and this results show a good agreement with Murakami's study for two parallel through-wall cracks[3] and Cho's study for two parallel surface cracks[4]. If the two cracks are separated greater than 20 mm for all crack length, the ratio approaches to 1. This means that the interaction effect comes to fade away and parallel cracks behave like two independent single cracks.

6. Conclusion

In this study, to estimate the plastic collapse behavior of the tube containing two parallel axial through-wall cracks, the plastic collapse tests using Inconel 600 tube specimens were conducted. Also, to verify the applicability of the optimum global failure prediction model, a series of corresponding finite element analyses were carried out. Finally, the interaction effect between two cracks was evaluated by performing additional finite element analyses. The key findings and results are as follows:

(1) By comparison of experimental results with finite element analysis results, the applicability of COD base model was verified and COD base model can also be used to estimate the plastic collapse load of the steam generator tubes containing two parallel through-wall cracks.
(2) Beneficial interaction effect appears when the distance between cracks is less than about 6 mm and negative interaction effect occurs when the distance is greater than the value.
(3) The interaction effect between two adjacent cracks disappears when the distance between cracks exceeds 20 mm and the cracks behave like two independent single cracks.

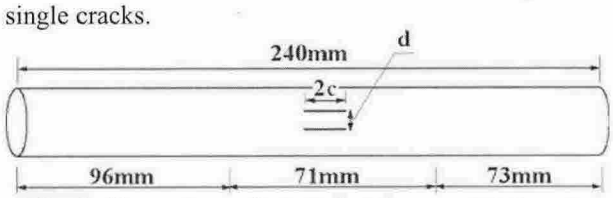
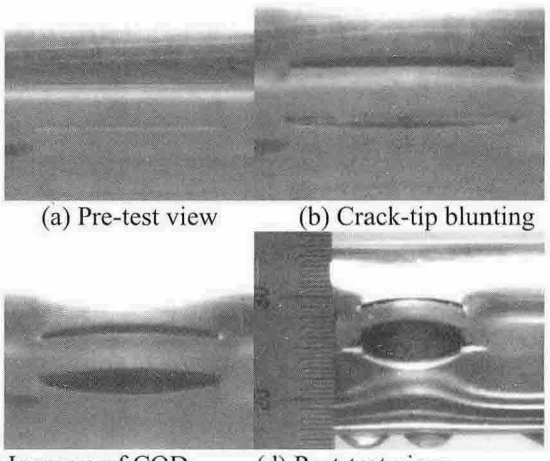


Fig. 1 Geometry of tested tube containing two parallel through-wall cracks



(a) Pre-test view (b) Crack-tip blunting

(c) Increase of COD (d) Post-test view

Fig. 2 Process of plastic collapse of SG tube containing two parallel through-wall cracks ($2c$=10 mm, d=2 mm)

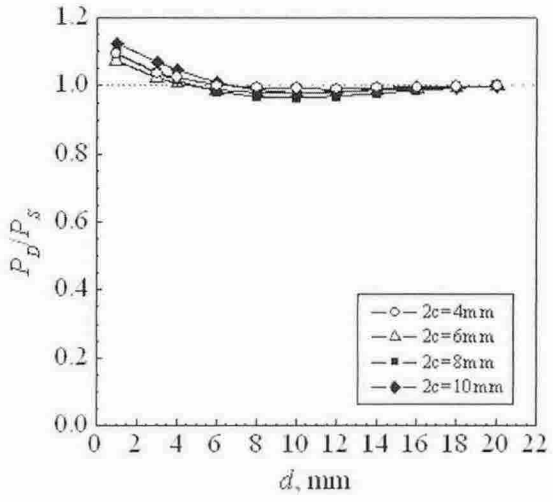


Fig. 3 P_D/P_S - d curve

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