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Division II

FAILURE ANALYSIS AND ASSESSMENT OF STEAM GENERATOR TUBE WITH MULTIPLE CRACKS

Myeong-Woo Lee[1], Ji-Seok Kim[2], Jun-Young Jeon[3], Yun-Jae Kim[4]

[1] Graduate Student, Mechanical Engineering, Korea University, Korea
[2] Research engineer, FNC Technology Co., Korea
[3] Senior Research Engineer, Doosan Heavy Industry Co., Korea
[4] Professor, Mechanical Engineering, Korea University, Korea

ABSTRACT

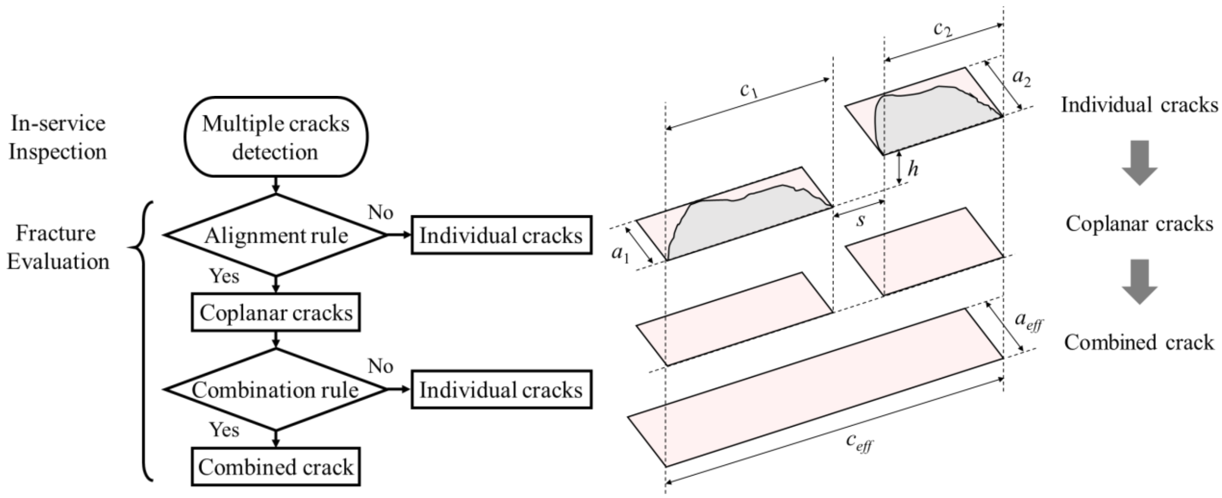
This paper summarize alignment rules and combination rules in the Codes and compares evaluated results using these rules with experimental burst pressure of multiple axial surface cracked Alloy 690TT steam generator tubes. An equation based on the local collapse load approach was used to compare the experimental data with the evaluation results using each alignment rules and combination rules in the Codes. From the comparison of the evaluation results and experimental data, it can be concluded that all the Codes are conservative for all cases of the axial collinear and non-aligned multiple surface cracked tube. In the case of parallel cracks, conservative evaluation was made except for three parallel axial crack tubes of 25.4 mm length at high temperature. For parallel cases, there was no difference between the evaluation results of each Code. Based on these observations, further studies are underway.

INTRODUCTION

Due to the role of primary water boundary, steam generator (SG) tubes of pressurized water reactors (PWRs) are designed conservatively to avoid leakage and failure by using high ductile alloys such as Alloy 600 series and conservative design criterion. Despite of these efforts, SG tube are damaged by stress corrosion cracking during the operation and required to re-evaluation. Stress corrosion cracks (SCCs) generally have been detected in the form of multiple cracks. To assess the multiple cracked tube, the collapse load approach and flaw re-characterization rules was adopted in various commonly used Codes and Standards such as ASME B&PV Code, British Standard and so on. However, the re-characterization rules provided in various Codes and Standards have difference. Therefore, in this paper, the conservatism of various codes is investigated using SG tube burst test results (performed at Chosun University).

FLAW RE-CHARACTERIZATION IN FIT-FOR-SERVICE CODES

In the case of steam generator tubes, multiple surface cracks often occur because the tube wall is thin and damaged by stress corrosion cracking. When multiple cracks are detected during in-service inspection, the crack dimensions are determined by flaw re-characterization rule considering the interaction effects between cracks. If the neighbouring cracks is in close proximity, those might be required to be combined into a virtual larger crack for the fracture evaluation. As shown in figure 1 (a), the re-characterization of multiple cracks is divided into alignment rule and combination rule. If the multiple cracks are parallel planar cracks, the alignment rule is applied to determine whether they should be aligned or not. If the



(a) (b)

Figure 1. Re-characterization of multiple cracks.

Table 1: Flaw re-characterization rules for multiple surface cracks.

Codes and Standards	Flaw re-characterization rules for multiple surface cracks	
	Alignment rules	Combination rules
ASME BPVC (2015)	$h \le 13$ mm $(1/2$ inch$)$	$s \le 0.5\max(a_1, a_2)$
BS 7910 (2015)	$d = \sqrt{s^2 + h^2}$ $d \le a_1 + a_2$	$s \le \min(c_1, c_2)$ for a_1/c_1 or $a_1/c_1 > 0.5$ $s \le 0.5\max(a_1, a_2)$ for a_1/c_1 and $a_1/c_1 \le 0.5$
API 579 (2007)	$h \le 0.5(c_1 + c_2)$ and $s \le 0.5(c_1 + c_2)$	
AFCEM A16 (2015)	$d = \sqrt{s^2 + h^2}$ $d \le 0.5(a_1 + a_2)$	$s \le 0.5(c_1 + c_2)$

multiple cracks are coplanar or aligned, the combination rule is applied to determine whether to treat them as one virtual larger crack (figure 1 (b)).

There are many codes and standards that provide the alignment rule and combination rule. Table 1 show the alignment rules and combination rules of four fitness-for-service codes. Almost all rules are based on a comparison of the distance between cracks with a crack size.

In ASME BPV Code Section XI, if a vertical distance h is shorter than 13 mm (1/2 inch), parallel planar cracks should be aligned. If the multiple cracks are coplanar or aligned and the horizontal distance s is less than half of maximum crack depth, multiple cracks are treated as one virtual large crack.

In the British Standard BS7910 alignment rule, the multiple cracks should be aligned if the direct distance between cracks d is less than the sum of the crack depths. When all ratios of crack depth to length a/c are less than 0.5, the combination rule in BS7910 is the same as the ASME BPV Code. If one of the ratios is greater than 0.5 and the horizontal distance s is less than minimum crack length, multiple cracks are treated as one virtual large crack.

In American Petroleum Institute API 579 Code, the alignment rule and combination rule consist of vertical distance h and horizonal distance s, where $h \leq 0.5(c_1+c_2)$ and $s \leq 0.5(c_1+c_2)$. If both equations are satisfied, the multiple cracks become coplanar and combined.

In AFCEN A16 code, the alignment rule consists of the direct distance d and crack depths a, where $d \leq 0.5(a_1+a_2)$. If the equation is satisfied, the multiple cracks become coplanar. If the horizontal distance s is smaller than the average of the crack lengths, coplanar multiple surface cracks are combined.

In all the Codes described in this paper, the combined crack dimensions are defined as the sum of the two crack lengths and the horizontal distance between cracks, $c_{eff} = c_1+c_2+s$, and the maximum crack depth, $a_{\mathrm{eff}} = \max(a_1,a_2)$.

CRACKED TUBE BURST TEST

Alloy 690TT steam generator tube, having 19.05 mm outer diameter and 1.067 mm thickness, with single and multiple cracks was tested, as listed in Table 2, both at room (23 ^{o}C) and elevated temperature (343 ^{o}C). The cracks were machined into the outer surface of the tube specimen using electro discharge machining (the tip radius=125 μm). In all cases, the crack had constant ratio of depth to length (a/t=0.5). Specimen overall size and crack shape are illustrated in Figure 2. The multiple axial surface cracked specimens are schematically illustrated in Fig. 3 and briefly explained below. For comparison with evaluation results using Codes, test data will be given in the next section.

Tubes with single crack, collinear cracks, non-aligned cracks and parallel cracks were tested. For single axial surface cracked tube (AS) test, the crack length was from 6.3 mm to 50.8 mm. For collinear axial surface cracks, two or three collinear cracks (AC or ACT) were considered. The crack length c and the horizontal distance s between neighbouring cracks vary in the burst test. Similarly, for non-aligned axial surface cracks, two or three non-aligned cracks (AN or ANT) were considered. The crack length c and the vertical distance h between neighbouring cracks vary in the burst test. For parallel axial surface cracks, two or three parallel cracks (AP or APT) were considered with various crack length c and vertical distance h between neighbouring cracks.

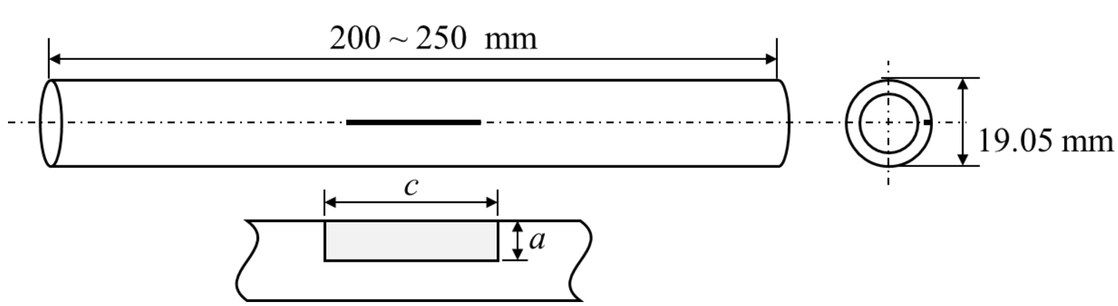


Fig. 2. Axial surface cracked tube specimens for burst test

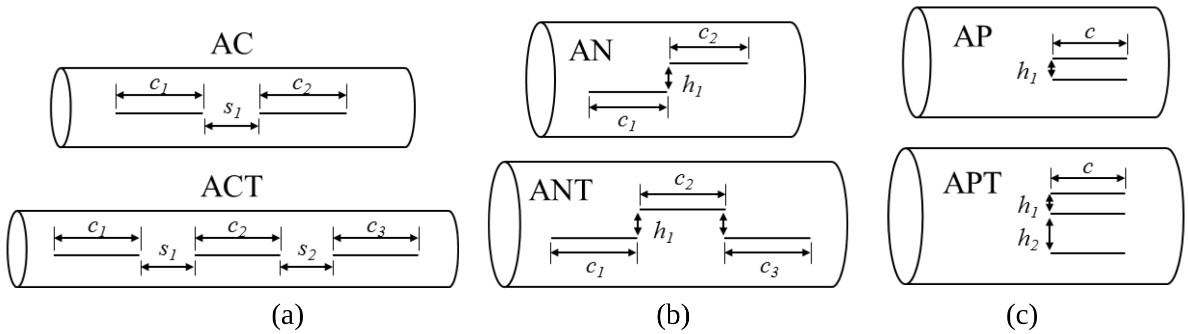


Fig. 3. Schematics of multiple axial surface cracks in the tube: (a) two or three axial collinear cracks, (b) two or three axial non-aligned cracks, (c) two or three axial parallel cracks,

Table 2. Summary of burst test specimens and geometries.

Type of specimen	I.D.	No. of cracks	Axial crack length $c_1/c_2/c_3$(mm)			Ligament length s_1/s_2 (mm)		Ligament Length h_1/h_2(mm)	
Axial single crack	AS_A	1	6.3			N/A		N/A	
	AS_B	1	12.7						
	AS_C	1	25.4						
	AS_D	1	50.8						
Two collinear axial cracks	AC_A	2	6.3	6.3		1			
	AC_B	2	6.3	6.3		2			
	AC_C	2	6.3	6.3		5			
	AC_D	2	6.3	25.4		1			
	AC_E	2	25.4	25.4		1			
	AC_F	2	25.4	25.4		2			
	AC_G	2	25.4	25.4		5			
Three collinear axial cracks	ACT_A	3	6.3	6.3	6.3	2	2		
	ACT_B	3	12.7	25.4	12.7	1	1		
Two non-aligned axial cracks	AN_A	2	6.3	6.3		N/A		1	
	AN_B	2	6.3	6.3				2	
	AN_C	2	6.3	6.3				15	
	AN_D	2	25.4	25.4				1	
	AN_E	2	25.4	25.4				2	
	AN_F	2	25.4	25.4				15	
Three non-aligned axial cracks	ANT_A	3	6.3	6.3	6.3			1	-1
	ANT_B	3	6.3	6.3	6.3			2	-2
	ANT_C	3	12.7	25.4	12.7			1	1
Two parallel cracks	AP_A	2	6.3	6.3				1	
	AP_B	2	25.4	25.4				1	
Three parallel cracks	APT_A	3	6.3	6.3	6.3			1	2
	APT_B	3	6.3	6.3	6.3			1	15
	APT_C	3	6.3	6.3	6.3			1	30
	APT_D	3	25.4	25.4	25.4			1	2
	APT_E	3	25.4	25.4	25.4			1	15
	APT_F	3	25.4	25.4	25.4			1	30

Table 3. Summary of effective crack length. (Colored cells are combined.)

I.D.	Effective crack length			
	ASME	BS7910	API 579	A16
AC_A	6.3	6.3	13.6	13.6
AC_B	6.3	6.3	14.6	14.6
AC_C	6.3	6.3	17.6	17.6
AC_D	25.4	25.4	32.7	32.7
AC_E	25.4	25.4	51.8	51.8
AC_F	25.4	25.4	52.8	52.8
AC_G	25.4	25.4	55.8	55.8
ACT_A	6.3	6.3	22.9	22.9
ACT_B	25.4	25.4	52.8	52.8

I.D.	Effective crack length			
	ASME	BS7910	API 579	A16
AN_A	12.6	12.6	12.6	6.3
AN_B	12.6	6.3	12.6	6.3
AN_C	6.3	6.3	6.3	6.3
AN_D	50.8	50.8	50.8	25.4
AN_E	50.8	25.4	50.8	25.4
AN_F	25.4	25.4	50.8	25.4
ANT_A	18.9	18.9	18.9	6.3
ANT_B	18.9	6.3	18.9	6.3
ANT_C	50.8	50.8	50.8	25.4

I.D.	Effective crack length			
	ASME	BS7910	API 579	A16
AP_A	6.3	6.3	6.3	6.3
AP_B	25.4	25.4	25.4	25.4
APT_A	6.3	6.3	6.3	6.3
APT_B	6.3	6.3	6.3	6.3
APT_C	6.3	6.3	6.3	6.3
APT_D	25.4	25.4	25.4	25.4
APT_E	25.4	25.4	25.4	25.4
APT_F	25.4	25.4	25.4	25.4

COMPARISON OF FRACTURE EVALUATION AND BURST TEST

Effective cracks length for fracture evaluation of multiple cracked tubes were calculated using Codes. Calculated results are summarized in Table 3. There is an equation of each Code, but one equation is used for comparison of re-characterization rules. For burst-pressure evaluation of single cracked tubes, the following equation was used (referred by EPRI Handbook). Comparison of fracture evaluation results and experimental data were illustrated in Fig. 4.

$$P_f^S = 0.58\left(\sigma_y + \sigma_u\right)\frac{t}{r_i}\left(1 - \frac{c}{c+2t}\frac{a}{t}\right) \tag{1}$$

For collinear and non-aligned cracked tubes, when the cracks are combined, the shorter the crack length, the more conservative the evaluation results are. In addition, compared with the evaluation tendency of the single cracked tube, there is a large difference in the conservativeness depending on whether multiple cracks are combined or not. This is because first, the ligament between multiple cracks increases load capacity compared to a large single crack that have same length as the sum of two independent crack lengths, but combined flaws using combination rules reduce the evaluation load. Second, if multiple cracks cannot be combined the evaluation load is increased in staircase-like way (because it uses the evaluation load of short single cracked tube).

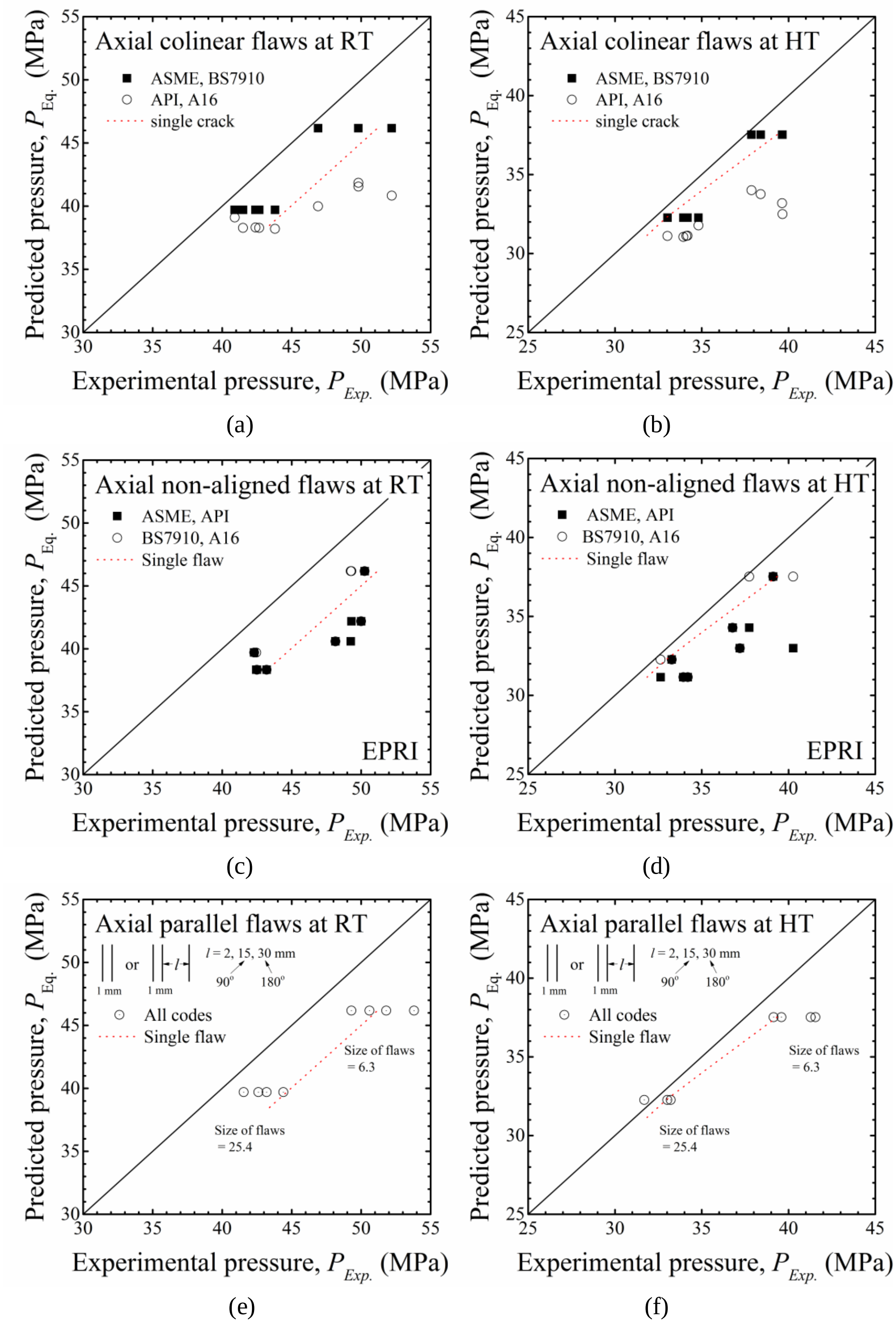


Fig. 4. Comparison of fracture evaluation results and experimental data; (a)-(b) collinear cracked tube, (c)-(d) non-aligned cracked tube and (e)-(f) parallel cracked tube.

In the case of parallel cracks, conservative evaluation results were obtained with the exception of three axial crack tubes of 25.4 mm length at high temperature. There was no difference in the evaluation results because the effective crack length did not change even if parallel cracks were combined. However, the experimental data show a difference of about 10% depending on the vertical distance between cracks.

CONCLUSIONS

Alignment and combination rules in various Codes and Standards are used to determine whether multiple cracks are treated as non-aligned cracks or collinear cracks, and as independent single crack or combined crack. Alignment and combination rules in ASME, BS7910, API 579 and A16 Codes were summarized for multiple surface cracks. In addition, to understand the these rules, fracture evaluation results using various Codes are compared with experimental burst pressure of various multiple axial surface cracked Alloy 690TT steam generator tubes.

From the comparison of the evaluation results and experimental data, it can be concluded that all the Codes are conservative for all cases of the axial collinear and non-aligned multiple surface cracked tube. However, in those cases, the conservativeness of the evaluation results varies greatly depending on whether multiple cracks are combined or not. In the case of parallel cracked tubes, except for one case at high temperature, the evaluation results were conservative. For parallel cases, there was no difference between the evaluation results of each Code. This is because the effective crack length of parallel cracked tubes are all the same whether parallel cracks are combined or not.

Therefore, for more precise fracture evaluation, firstly, it is necessary to study the improvement of the combination rule and, secondly, to study the effective crack length determination method considering the horizontal and vertical distance between multiple cracks. The continuous study on them is currently underway.

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