Applicability of Alignment and Combination Rules to Burst Pressure Prediction of Multiple-flawed Steam Generator Tube.

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1. Introduction

Alignment and combination rules for multiple flaws are provided in many codes and standards such as ASME, JSME, BS7910, API579, and so on. However, these rules defined in the various codes are different [1]. This study investigates the applicability of alignment and combination rules for multiple flaws on the failure behavior of Alloy 690TT steam generator (SG) tubes that widely used in the nuclear power plan. Experimental data of burst tests on Alloy 690TT tubes with single and multiple flaws that conducted at room temperature (RT) by Kim el al. [2] compared with the alignment rules of these codes and standards. Burst pressure of SG tubes with flaws are predicted using limit load solutions that provide by EPRI Handbook [3].

2. Existing Experiment summary

Burst tests on steam generator (SG) tube specimens containing multiple axial part-through-wall (PTW) flaws at room temperature (RT) conducted by Kim el al. [2]. The specimens were machined from Alloy 690TT SG tube that have the outer diameter of 19.05 mm and the thickness of 1.07 mm. In the experiment, single flaw with four different lengths and six types of multiple flaws with a constant depth were considered, shown as figure 1 and table I. Detailed information and results can be found in Ref. [2]

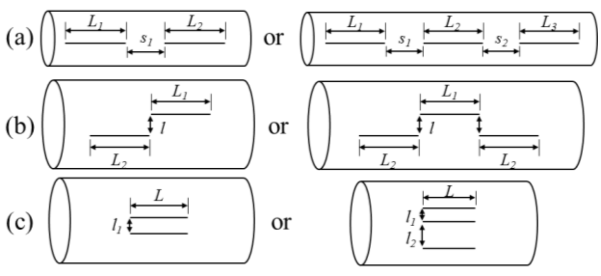


Fig. 1. Shape of multiple flaws: (a) Collinear axial flaws, (b) Non-aligned axial flaws, (c) Parallel axial flaws.

Table I: Matric for burst tests of SG tubes

I.D.	Flaw geometries			Burst pressure
	L1, L2, L3	s1, s2	l1, l2	
	(mm)	(mm)	(mm)	(MPa)
AS-A	6.3	n/a	n/a	50.6
AS-B	12.7	n/a	n/a	46.4
AS-C	25.4	n/a	n/a	44.3
AS-D	50.8	n/a	n/a	44.6
AC-A	6.3, 6.3	1	n/a	49.8
AC-B	6.3, 6.3	2	n/a	49.8
AC-C	6.3 6.3	5	n/a	52.2
AC-D	6.3, 25.4	1	n/a	41.7
AC-E	25.4, 25.4	1	n/a	43.5
AC-F	25.4, 25.4	2	n/a	43.4
AC-G	25.4, 25.4	5	n/a	43.8
ACT-A	6.3, 6.3, 6.3	2, 2	n/a	46.9
ACT-B	12.7, 25.4, 12.7	1, 1	n/a	41.5
AN-A	6.3, 6.3	n/a	1	49.6
AN-B	6.3, 6.3	n/a	2	49.5
AN-C	6.3, 6.3	n/a	15	50.5
AN-D	25.4, 25.4	n/a	1	42.1
AN-E	25.4, 25.4	n/a	2	42.3
AN-F	25.4, 25.4	n/a	15	42.3
ANT-A	6.3, 6.3, 6.3	n/a	1, 1	47.6
ANT-B	6.3, 6.3, 6.3	n/a	2, 2	48.7
AP-A	6.3 6.3	n/a	1	53.8
AP-B	25.4, 25.4	n/a	1	43.2
APT-A	6.3, 6.3, 6.3	n/a	1, 2	51.8
APT-B	6.3, 6.3, 6.3	n/a	1, 15	49.7
APT-C	6.3, 6.3, 6.3	n/a	1, 30	51
APT-D	25.4, 25.4, 25.4	n/a	1, 2	45
APT-E	25.4, 25.4, 25.4	n/a	1, 15	41.6
APT-F	25.4, 25.4, 25.4	n/a	1, 30	42.8

3. Alignment and combination rules

Multiple flaws have been often detected in a nuclear components. If the flaws are far from each other, they are treated as each single flaws. If the flaws are proximity, they are not treated as single flaws due to large interaction between them.

Process of multiple flaws modeling are consist of two part. First, if the multiple flaws are non-aligned flaws, shown as figure 2(a), alignment rule is applied to determine whether the flaws should be treated as non-aligned or coplanar flaws. Table I shows alignment rules of various codes and standards. Second, if they are treated as coplanar flaws, shown as figure 2(b), a combination rule is applied to determine whether the flaws should be treated as independent or may be combined to be assessed as single large flaw. Table II shows combination rules of the codes and standards. These rules are based on a comparison of the distance between flaws with a flaw dimension. Results of multiple flaws modeling for cases of SG tube burst tests are tabulated in Table IV and V. The white color box mean that flaws are treated as independent. The yellow color box mean that flaws are combined to be assessed as single large flaw.

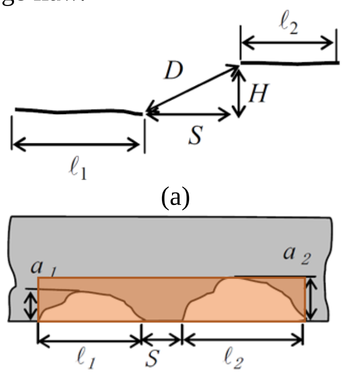


Fig. 2. Shape of multiple flaws: (a) non-aligned flaws, (b) coplanar flaws.

Table II: Flaw alignment rules

Code	Rules
ASME	$H \leq 12.5$ mm
JSME	NDI : $H \leq 12.5$ mm Growth: $H \leq 12.5$ mm, if $S \leq 5$ mm $H \leq 12.5$ mm Fracture: $H \leq 12.5$ mm
API 579	$H \leq 0.5(l_1+l_2)$ $S \leq 0.5(l_1+l_2)$
BS 7910, FKM, A16	$D \leq 0.5(l_1+l_2)$

Table III: Combination rule for coplanar flaws

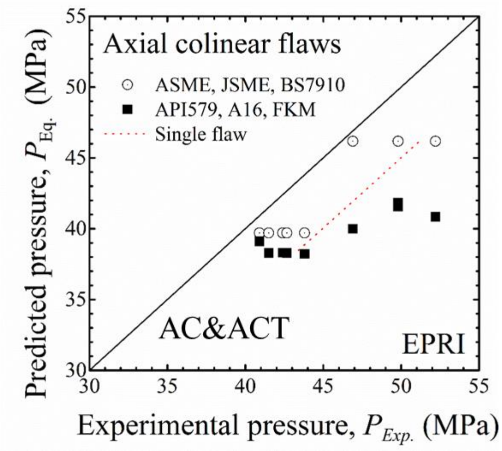
Code	Rules
ASME, JSME	$S \leq 0.5\max(a_1, a_2)$
BS 7910	$S \leq \min(l_1, l_2)$ for a_1/l_1 *or* $a_2/l_2 > 0.5$ $S = 0$ for a_1/l_1 *or* $a_2/l_2 < 0.5$
FKM	$S \leq \min(l_1, l_2)$
API 579, A16	$S \leq 0.5(l_1 + l_2)$

Table IV: Multiple flaws modeling of planar flaws

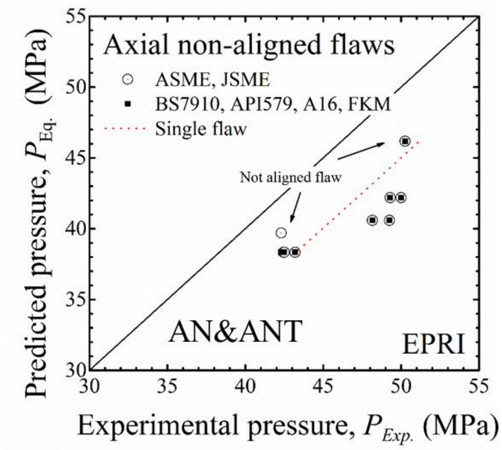
I.D.	Effective flaw length	
	ASME, JSME, BS7910	API 579, A16, FKM
AC_A	6.3	13.6
AC_B	6.3	14.6
AC_C	6.3	17.6
AC_D	25.4	32.7
AC_E	25.4	51.8
AC_F	25.4	52.8
AC_G	25.4	55.8
ACT_A	6.3	22.9
ACT_B	25.4	52.8

Table V: Multiple flaws modeling of non-aligned flaws

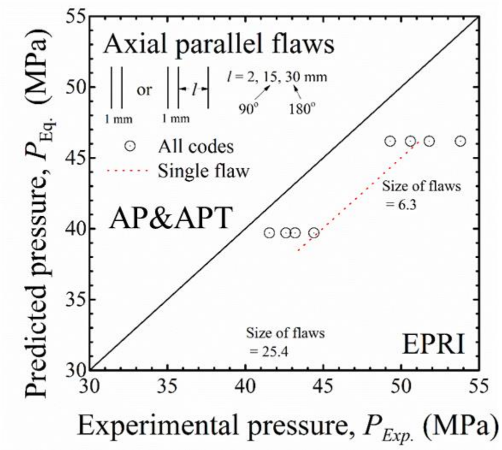
I.D.	Effective flaw length	
	ASME, JSME	BS7910, FKM, A16, API 579
AN_A	12.6	12.6
AN_B	12.6	12.6
AN_C	6.3	6.3
AN_D	50.8	50.8
AN_E	50.8	50.8
AN_F	25.4	50.8
ANT_A	18.9	18.9
ANT_B	18.9	18.9
AP_A	6.3	6.3
AP_B	25.4	25.4
APT_A	6.3	6.3
APT_B	6.3	6.3
APT_C	6.3	6.3
APT_D	25.4	25.4
APT_E	25.4	25.4
APT_F	25.4	25.4



(a)



(b)



(c)

Fig. 3. Comparison of predicted result with experimental data: (a) axial collinear flaws, (b) axial non-aligned flaws, (c) axial parallel flaws.

To compare of assessment results based on alignment rules and combination rules with experimental data, burst pressure of SG tubes with flaws are predicted using limit load solutions that provide by EPRI Handbook [3]. The equation (1) is for axial single surface flaw. Comparison of predicted result with experimental data were illustrated in figure 3.

$$P_f^S = 0.58\left(YS + UTS\right)\frac{t}{R_i}\left(1 - \frac{L}{L+2t}\frac{d}{t}\right) \qquad (1)$$

4. Summary and further study

Alignment and combination rules are provided by various codes and standards. These rules are used to determine whether multiple flaws should be treated as non-aligned or as coplanar, and independent or combined flaws. Experimental results on steam generator (SG) tube specimens containing multiple axial part-through-wall (PTW) flaws at room temperature (RT) are compared with assessment results based on the alignment and combination rules of the codes and standards. In case of axial collinear flaws, ASME, JSME, and BS7910 treated multiple flaws as independent flaws and API 579, A16, and FKM treated multiple flaws as combined single flaw. Assessment results of combined flaws were conservative. In case of axial non-aligned flaws, almost flaws were aligned and assessment results well correlate with experimental data. In case of axial parallel flaws, both effective flaw lengths of aligned flaws and separated flaws was are same because of each flaw length were same.

In the experiment, flaws had constant depth that were 50% of wall thickness. Therefore, flaw depth effect on interaction between flaws will be investigated using FE damage analysis [4]. These analysis data also compared with the alignment rules of these codes and standards.

5. Acknowledgment

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