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

2016.05.12

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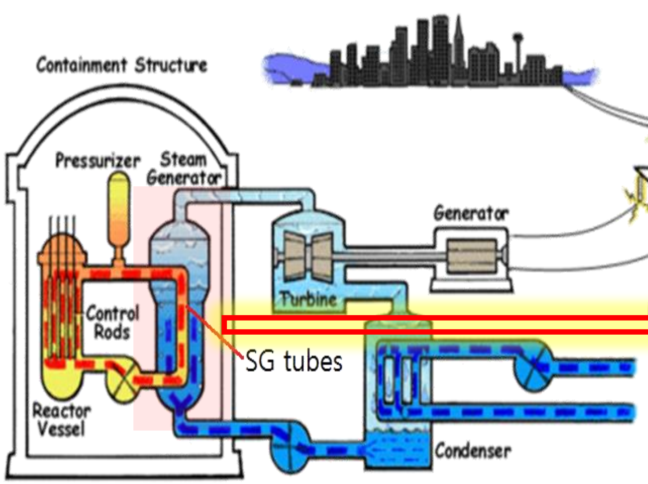
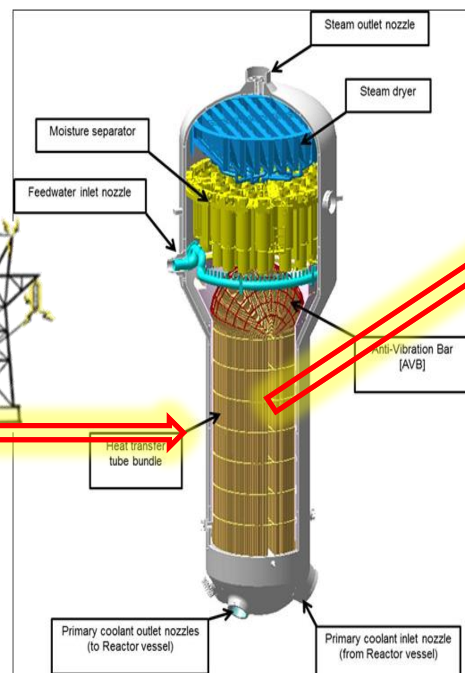
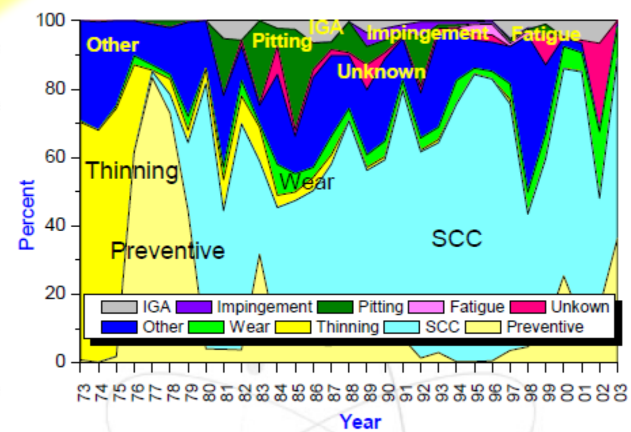
Introduction

- **SG tubes** in PWRs have an **important safety role**.
- Some SG tubes have experienced some **PWSCC**s.
- PWSCC growth can cause **leakage** of reactor coolant and SG tube **rupture**.
- PWSCC growth behavior and **burst pressure** of SG tube should be evaluated to **assess structural integrity**.





[SCC and Rupture of U-4 SG Tube]



[Root Causes of Worldwide SG Tube Plugging]

Introduction

- ❖ The PWSCC assessment procedures (ASME Code Sec.XI, EPRI SGMP) are based on the **empirical models for single flaw**.
- ❖ The procedures aren't sufficient for the **multiple PWSCCs**.
- ❖ **Flaw modeling** (alignment and combination rules) has been used to evaluate the multiple PWSCCs.

➔ **Are alignment and combination rules applicable?**

- ❖ For experimental validation, series of burst test performed.

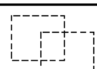
➔ Parametric study based on burst test.

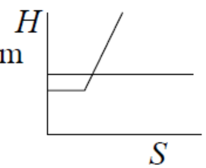
- ❖ Test geometry (particularly flaw depth) so limited that FE damage analysis were carried out.

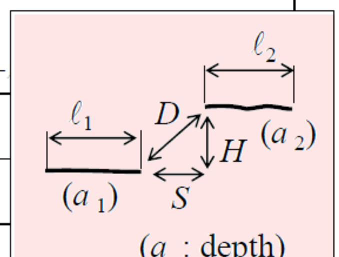
➔ Parametric study based on FE damage analysis.

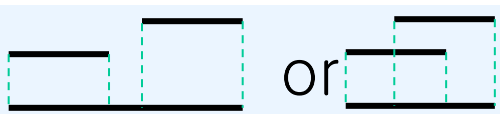
Alignment & Proximity Rules in Various Codes

• Alignment rule

ASME	$H \le 12.5$ mm
JSME	NDI : $H \le 12.5$ mm Grwoth: $H \le 10$mm, if $S \le 5$ mm $H < 2S$, if $S > 5$ mm Fracture : $H \le 12.5$ mm
WES	$H \le 0.5\min(\ell_1, \ell_2)$ for through-wall flaws $H \le \min(a_1, a_2)$ for surface flaws
API 579	$H \le 0.5(\ell_1+\ell_2)$ $H \le 0.5(\ell_1+\ell_2)$ & $S \le 0.5(\ell_1+$
BS 7910	$D \le 0.5(\ell_1+\ell_2)$
FKM	$D \le 0.5(\ell_1+\ell_2)$
A16	$D \le 0.5(\ell_1+\ell_2)$
GB/T 19624	$D \le \min(\ell_1, \ell_2)$ for through-wall flaws $D \le \min(a_1, a_2)$ for surface flaws
RSE-M	 Interaction rectangles



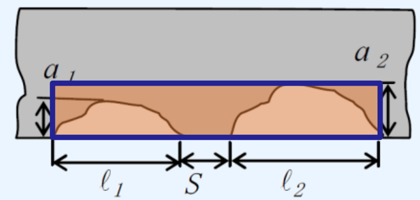




$l_{eff}=l_1+S+l_2$ $l_{eff}=l_1-S+l_2$

$a_{eff}=max(a_1,a_2)$

• Proximity rule



$l_{eff}=l_1+S+l_2$

$a_{eff}=max(a_1,a_2)$

ASME, JSME	$S \le 0.5\max(a_1, a_2)$
BS 7910	$S \le \min(l_1, l_2)$ 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	$S \le \min(l_1, l_2)$
API579, A16	$S \le 0.5(l_1 + l_2)$

• Non-re-characterized flaw

The flaws are treated as each single flaw.

KEM345:411, **PVP2009-77068**, JPVT-041403, BS7910 (7.1.2.2), ASME XI (IWA-3000), API579 (9.3.6.5), A16 (3250)

Burst Pressure Experiment (CHOSUN Univ.)

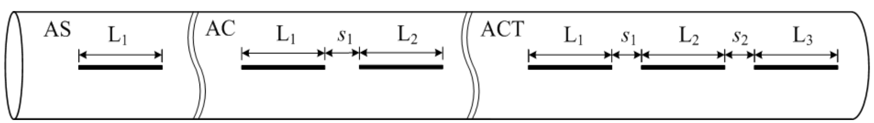
J. W. Kim and K. H. Eom, Burst Test on the Steam Generator Tube with Multiple Part through-wall flaws, *ASME Conference Proceedings,* **2015**, PVP2015-45273.

- From burst pressure test

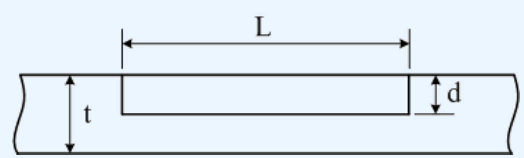
→Interaction effect of multiple PTW flaws on the failure of SG tubes were evaluated

- Cases of multiple PTW flaws

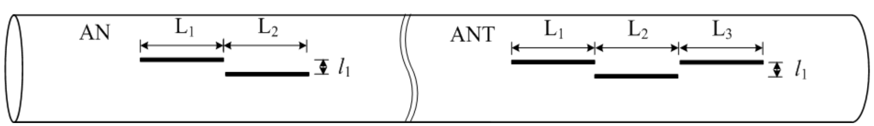
→ Collinear axial flaws // non-aligned axial flaws // parallel axial PTW flaws are tested



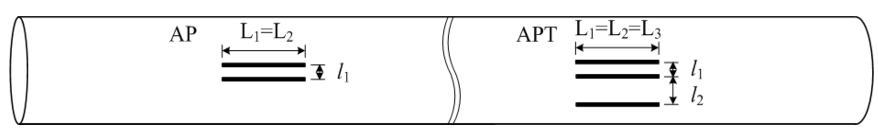
AS: L=6.3, 12.7, 25.4, 50.8mm (single flaw)
AC: L=6.3/6.3mm(s_1=1,2,5mm) & 25.4/25.4mm(s_1=1,2mm)
ACT: L=6.3/6.3/6.3mm(s_1=s_2=2mm) & 12.7/25.4/12.7mm(s_1=s_2=1mm)



Rectangular shape with d/t=0.5



AN: L=6.3/6.3mm(l_1=1,2,15mm) & 25.4/25.4mm(l_1=1,2,15mm)
ANT: L=6.3/6.3/6.3mm(l_1=1,2mm) & 12.7/25.4/12.7mm(l_1=1mm)



AP: L=6.3/6.3mm(l_1=1mm) & 25.4/25.4mm(l_1=1mm)
ANT: L=6.3/6.3/6.3mm(l_1=1mm/l_2=2,15,30mm)
& 25.4/25.4/25.4mm(l_1=1mm/l_2=2,15,30mm)

Net-Section Collapse Load Approach

For tube with axial single flaw

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

$A = 1.104$ *for Actual flaw*

$A = 1$ *for EDM Slot*

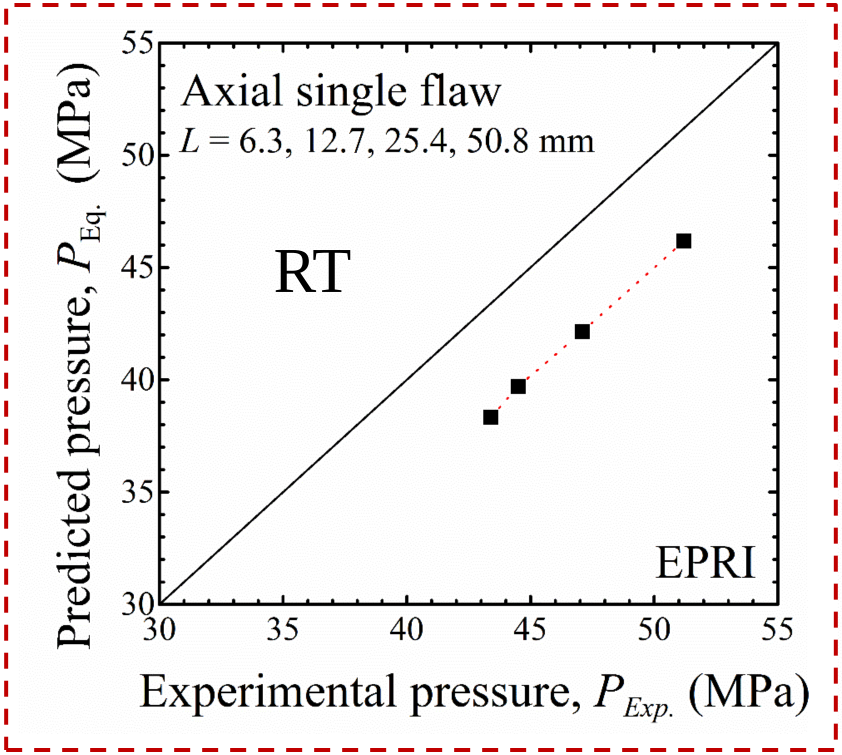
ANL $$P_f^S = \left(\frac{YS + UTS}{2}\right)\frac{t}{M_P R_m}$$

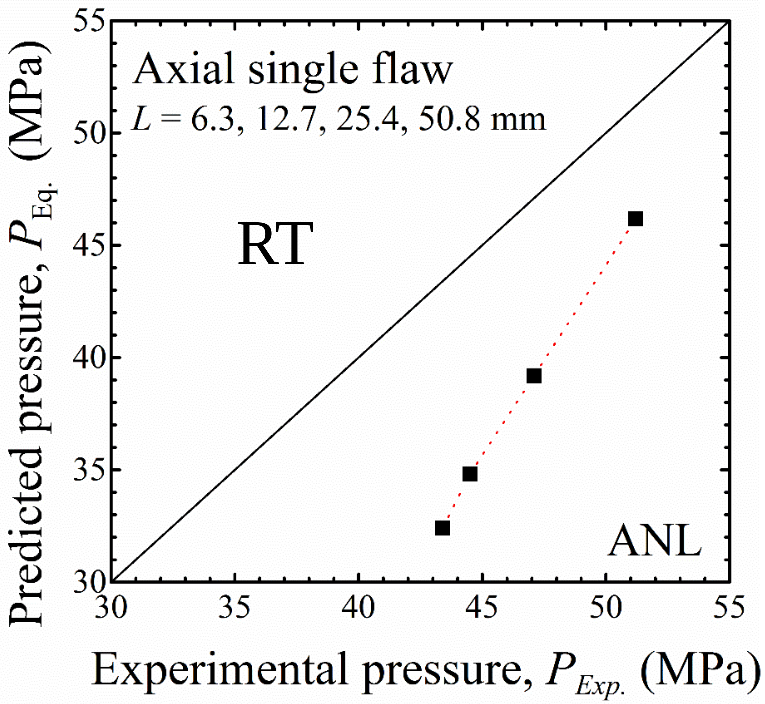
$$M_p = (1 - \alpha a / Mt)/(1 - a/t)$$

$$\alpha = 1 + (a/t)^2 (1 - 1/M)$$

$$M = 0.614 + 0.481\lambda + 0.386e^{-1.25\lambda}$$

$$\lambda = \frac{1.82c}{\sqrt{R_m t}}$$





EPRI, Steam Generator Degradation Specific Management Flaw Handbook, **2001**, EPRI 1001191.

ANL, Validation of Failure and Leak-Rate Correlations for Stress Corrosion Cracks in Steam Generator Tubes, **2002**, NUREG/ CR-6774.

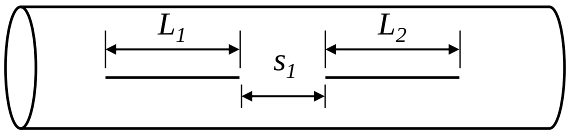
Parametric Study based on Experiment

- Various depth effect on burst pressure

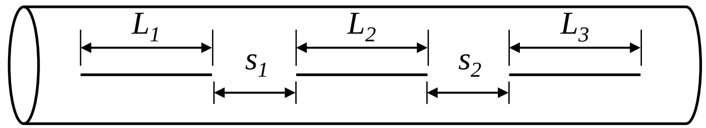
1. Collinear axial flaws
2. Non-aligned axial flaws
3. Parallel axial flaws

Multiple Flaws Assessment based on Experiment

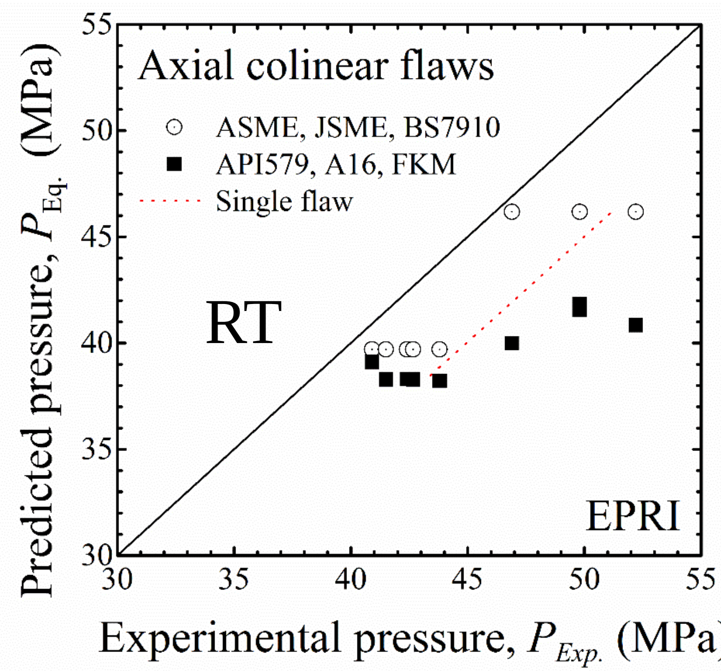
- Collinear axial flaws



or

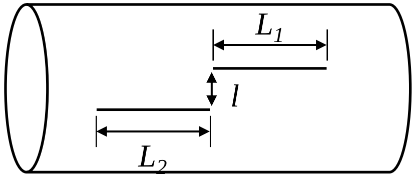


Cases of collinear axial flaws											
	No. of flaws	L_1	L_2	L_3	s_1	s_2	Exp.	EPRI			
								ASME, JSME, BS7910		API579, A16, FKM	
AC_A	2	6.3	6.3		1		49.8	46.2	Not combined min($P_{L,i}$)	41.8	Combined $P_{L,eff}$ $L_{eff} = \Sigma L_i + \Sigma S_i$
AC_B	2	6.3	6.3		2		49.8	46.2		41.6	
AC_C	2	6.3	6.3		5		52.2	46.2		40.8	
AC_D	2	6.3	25.4		1		40.9	39.7		39.1	
AC_E	2	25.4	25.4		1		42.4	39.7		38.3	
AC_F	2	25.4	25.4		2		42.7	39.7		38.3	
AC_G	2	25.4	25.4		3		43.8	39.7		38.2	
ACT_A	3	6.3	6.3	6.3	2	2	46.9	46.2		40.0	
ACT_B	3	12.7	25.4	12.7	1	1	41.5	39.7		38.3	



✓ 균열이 짧을 수 록 combined flaw의 보수성 증가

- Non-aligned axial flaws



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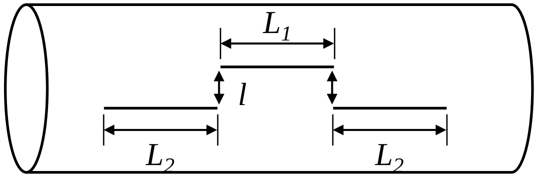
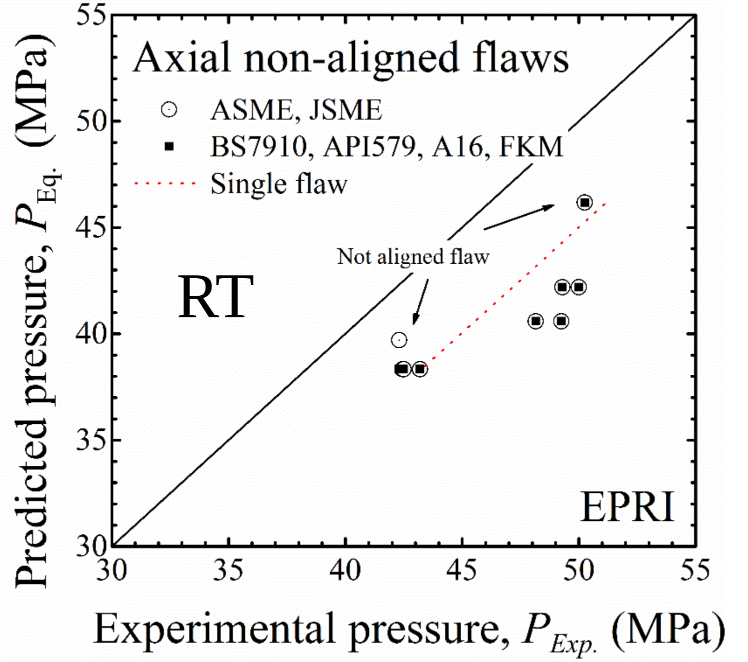


Cases of non-aligned axial flaws

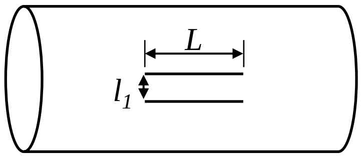
	No. of flaws	L_1	L_2	L_3	l	Exp.	EPRI: ASME, JSME		EPRI: BS7910, A16, API579, FKM	
AN_A	2	6.3	6.3		1	50.0	42.2	Aligned		
AN_B	2	6.3	6.3		2	49.3	42.2	Aligned		
AN_C	2	6.3	6.3		15	50.3	46.2	Not aligned		
AN_D	2	25.4	25.4		1	43.2	38.3	Aligned		
AN_E	2	25.4	25.4		2	42.5	38.3	Aligned		
AN_F	2	25.4	25.4		15	42.3	39.7	Not aligned	38.3	Aligned
ANT_A	3	6.3	6.3	6.3	1	48.2	40.6	Aligned		
ANT_B	3	6.3	6.3	6.3	2	49.3	40.6	Aligned		
ANT_C	3	12.7	25.4	12.7	1	42.5	38.3	Aligned		



Aligned flaw: $P_{L,eff}$, $L_{eff} = \Sigma L_i$

Non aligned flaws: $\min(P_{L,i})$

- Parallel axial flaws



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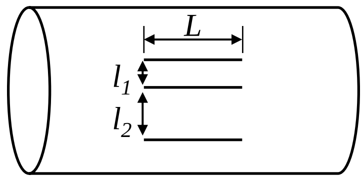
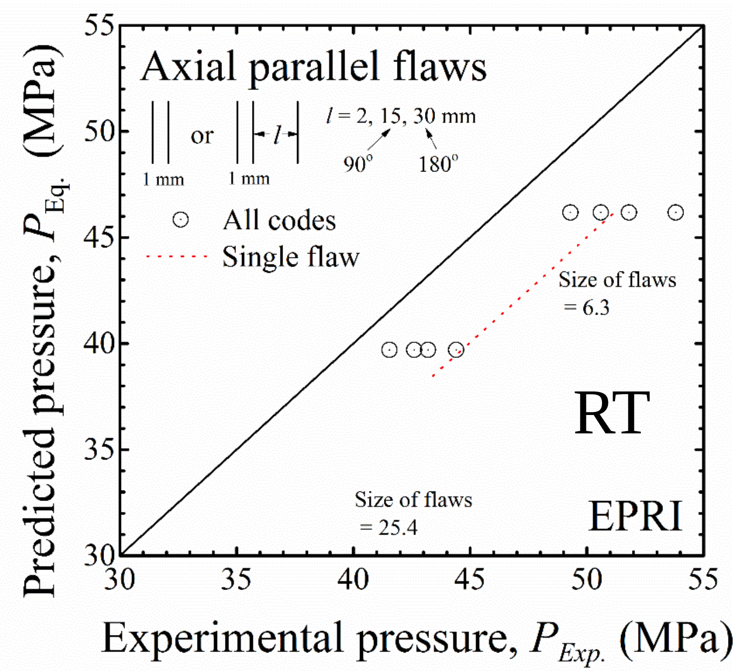


<table>
<tr><th colspan="10">Cases of parallel axial flaws</th></tr>
<tr><th rowspan="2"></th><th rowspan="2">No. of flaws</th><th rowspan="2">L</th><th rowspan="2">l_1</th><th rowspan="2">l_2</th><th rowspan="2">Exp.</th><th colspan="4">EPRI</th></tr>
<tr><th colspan="2">ASME, JSME</th><th colspan="2">BS7910, A16, API579, FKM</th></tr>
<tr><td>AP_A</td><td>2</td><td>6.3</td><td>1</td><td></td><td>53.8</td><td>46.2</td><td rowspan="3" colspan="3">Aligned</td></tr>
<tr><td>AP_B</td><td>2</td><td>25.4</td><td>1</td><td></td><td>43.2</td><td>39.7</td></tr>
<tr><td>APT_A</td><td>3</td><td>6.3</td><td>1</td><td>2</td><td>51.8</td><td>46.2</td></tr>
<tr><td>APT_B</td><td>3</td><td>6.3</td><td>1</td><td>15</td><td>49.3</td><td>46.2</td><td rowspan="2" colspan="3">Non aligned</td></tr>
<tr><td>APT_C</td><td>3</td><td>6.3</td><td>1</td><td>30</td><td>50.6</td><td>46.2</td></tr>
<tr><td>APT_D</td><td>3</td><td>25.4</td><td>1</td><td>2</td><td>44.4</td><td>39.7</td><td colspan="3">Aligned</td></tr>
<tr><td>APT_E</td><td>3</td><td>25.4</td><td>1</td><td>15</td><td>41.6</td><td>39.7</td><td>Non aligned</td><td>39.7</td><td>Aligned</td></tr>
<tr><td>APT_F</td><td>3</td><td>25.4</td><td>1</td><td>30</td><td>42.6</td><td>39.7</td><td colspan="3">Aligned</td></tr>
</table>



l_2 : 15 mm ≒ 90° **위치 차**, 30 mm ≒ 180° **위치 차**
평행 균열의 길이가 같아 정렬 유무와 관계없이 동일 P_L

✓ **평행 균열 사이의 간격에 따라 파열압에 증가 및 감소 효과 발생**
균열 간격 0~32 ° : Positive / 32~128 ° : Negative / 128 ° **이상 : 독립 균열**

S. I. Moon el al, Fatigue Fract. Enging. Mater. Struct., **2006**, Vol.29, pp.623-631

Ductile Failure Simulation Method and Application to SG tube Burst Test

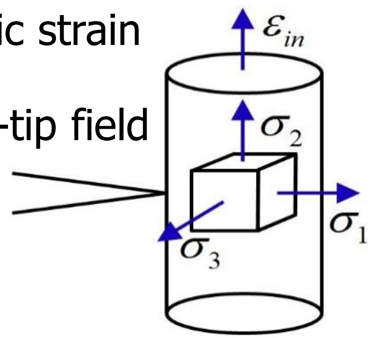
J. Y Jeon, Y. J. Kim and J. W. Kim, Burst Pressure Prediction of Cracked Steam Generator Tube using FE Damage Analysis, *ASME Conference Proceedings,* **2015**, PVP2015-45401.

Stress-Modified Fracture Strain and Ductile Damage Model

- Stress-modified fracture strain model

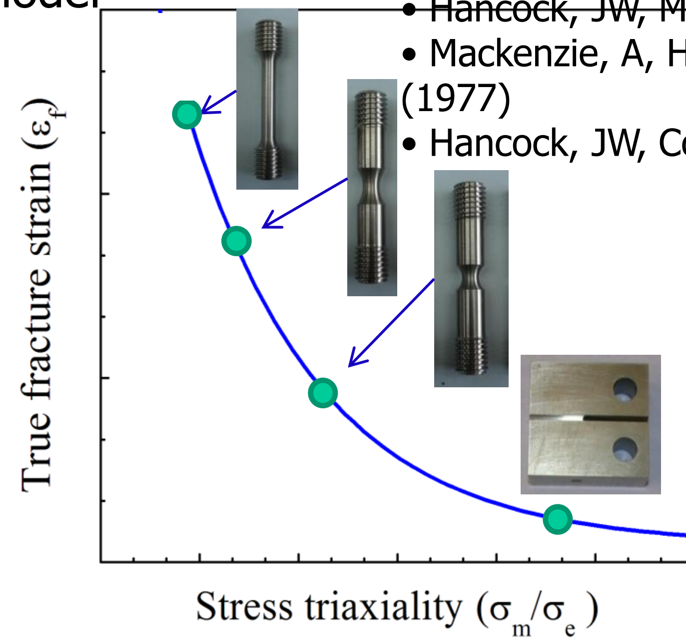
Inelastic strain

Local crack-tip field



$$\varepsilon_f = A\exp\left(-C\frac{\sigma_m}{\sigma_e}\right) + B$$

A,B,C = material constants



- McClintock, FA (1968)
- Rice, JR, Tracey, DM (1969)
- Hancock, JW, Mackenzie, AC (1976)
- Mackenzie, A, Hancock, J, Brown, D (1977)
- Hancock, JW, Cowling, MJ, (1980)

$$\frac{\sigma_m}{\sigma_e} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3\sigma_e}$$

Stress triaxiality

- Incremental damage (Ductility exhaustion)

$$\Delta\omega = \frac{\Delta\varepsilon_e^P}{\varepsilon_f} \qquad \Delta\varepsilon_e^p = \frac{\sqrt{2}}{3}\sqrt{\left(\Delta\varepsilon_1^p - \Delta\varepsilon_2^p\right)^2 + \left(\Delta\varepsilon_2^p - \Delta\varepsilon_3^p\right)^2 + \left(\Delta\varepsilon_3^p - \Delta\varepsilon_1^p\right)^2}$$

- Local fracture $\omega = \sum \Delta\omega = \omega_c\ (=1)$ (cf) Miner's rule in high-cycle fatigue

Failure Simulation using Finite Element Analysis

- From FE analysis

→ Calculate stress triaxiality and plastic strain increment

→ Calculate incremental damage due to plastic strain

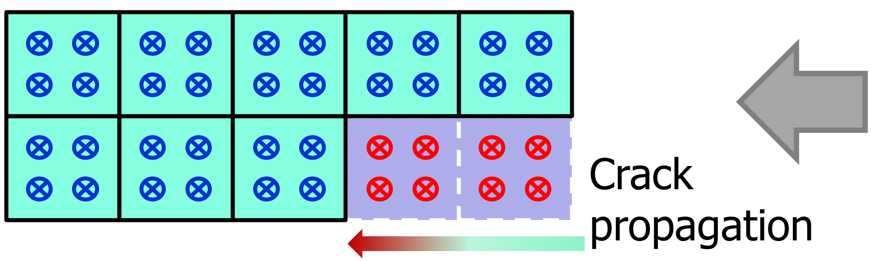
→ When accumulated damage becomes critical

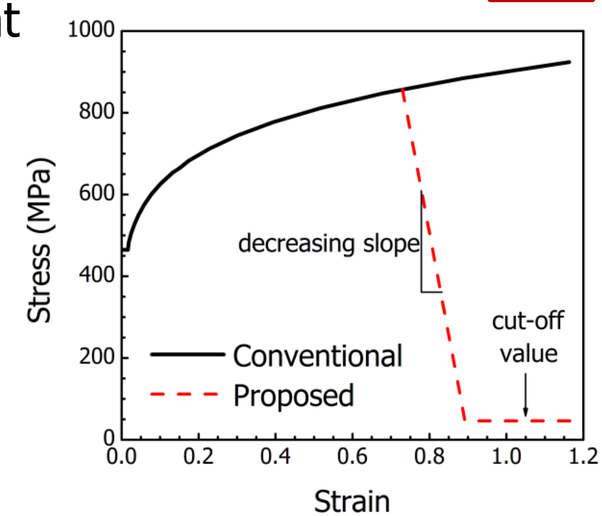
$$\frac{\sigma_m}{\sigma_e} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3\sigma_e}$$

$$\Delta\omega = \frac{\Delta\varepsilon_e^P}{\varepsilon_f}$$

$$\omega = \sum \Delta\omega = \omega_c$$

- ➢ Reducing yield surface at integration point
- ➢ Implemented into ABAQUS (UHARD)

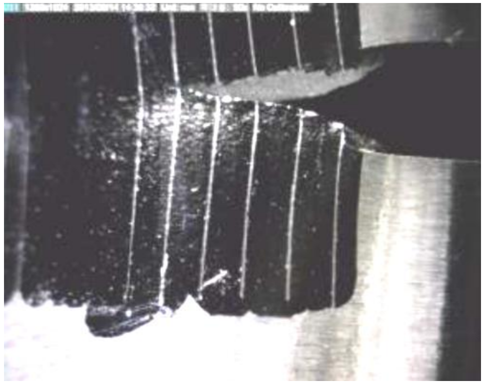


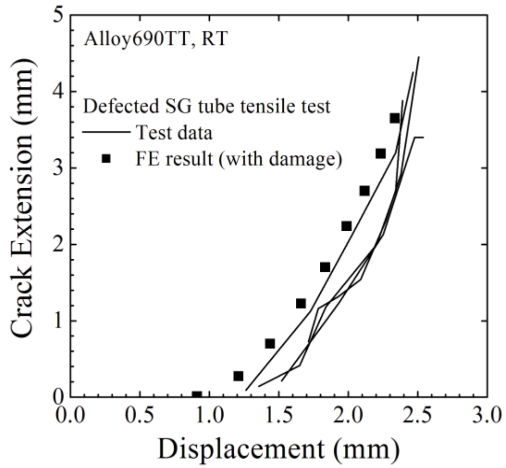


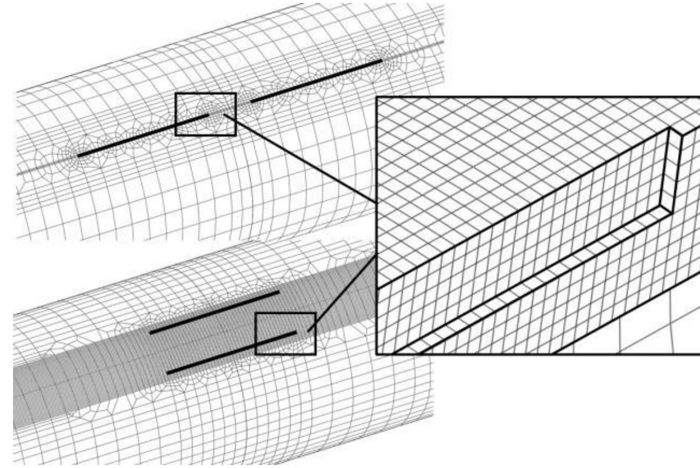
cf) Element removal, Cohesive zone element, Node release

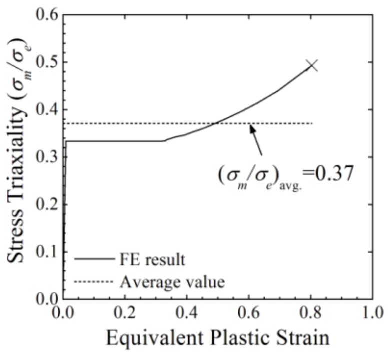
❖ Element size effect on simulation results

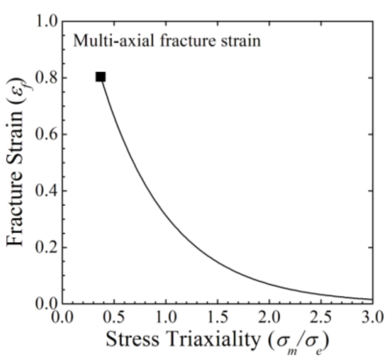
Comparison of FE with Experiment

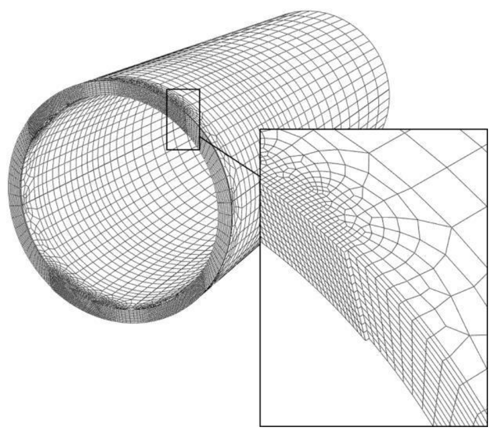




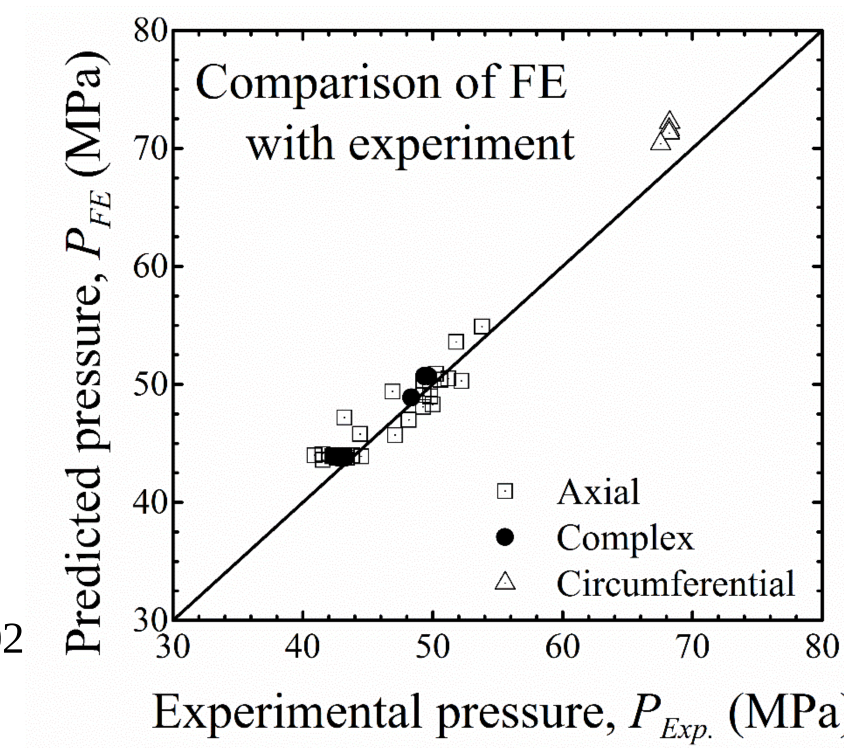








$$\varepsilon_f = \alpha \exp\left(-1.5\frac{\sigma_m}{\sigma_e}\right),\ \alpha = 1.402$$



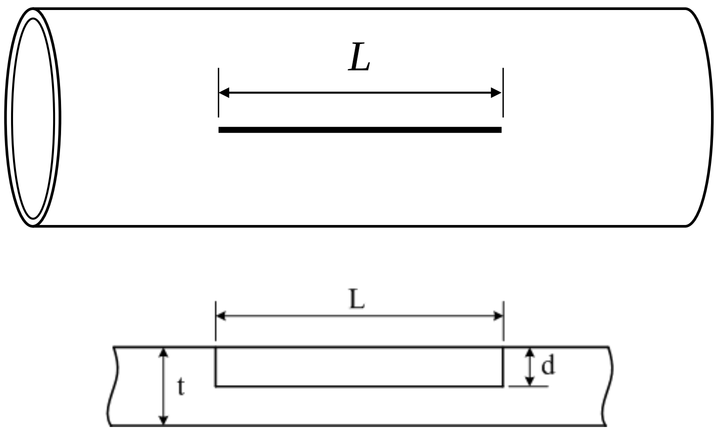
Parametric Study based on Finite Element Analysis

- Various depth effect on burst pressure

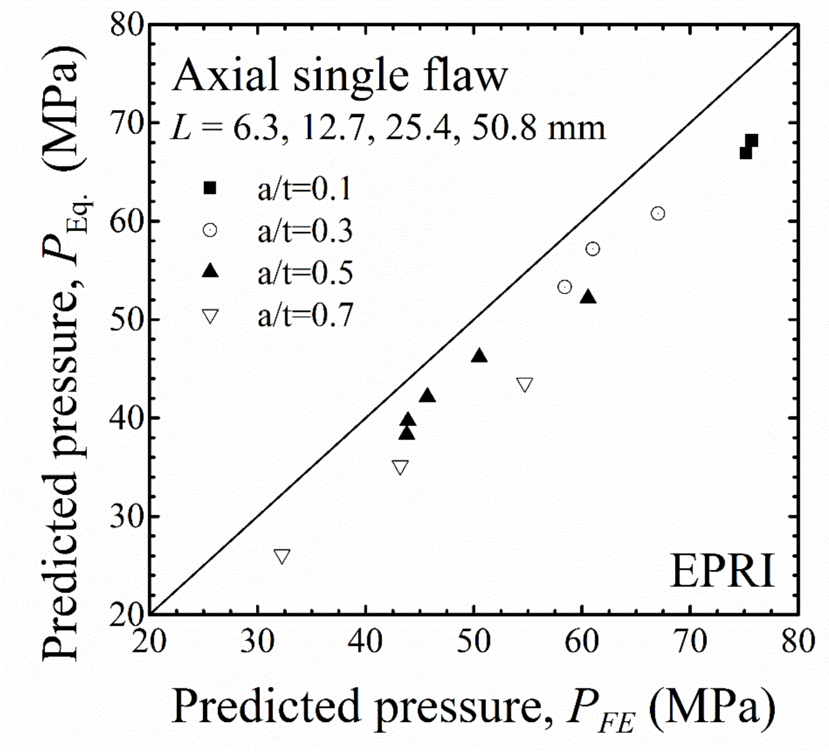
1. Single surface flaw
2. Collinear axial flaws
3. Parallel axial flaws

Single Flaw Assessment based on FEA

- Single axial flaw that have various depth

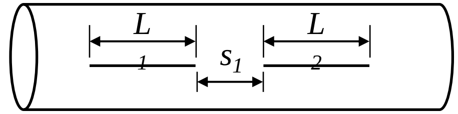


Rectangular shape with
d/t=0.1, 0.3, 0.5, 0.7

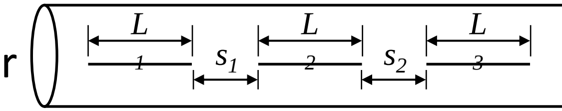


Multiple Flaws Assessment based on FEA

- Collinear axial flaws

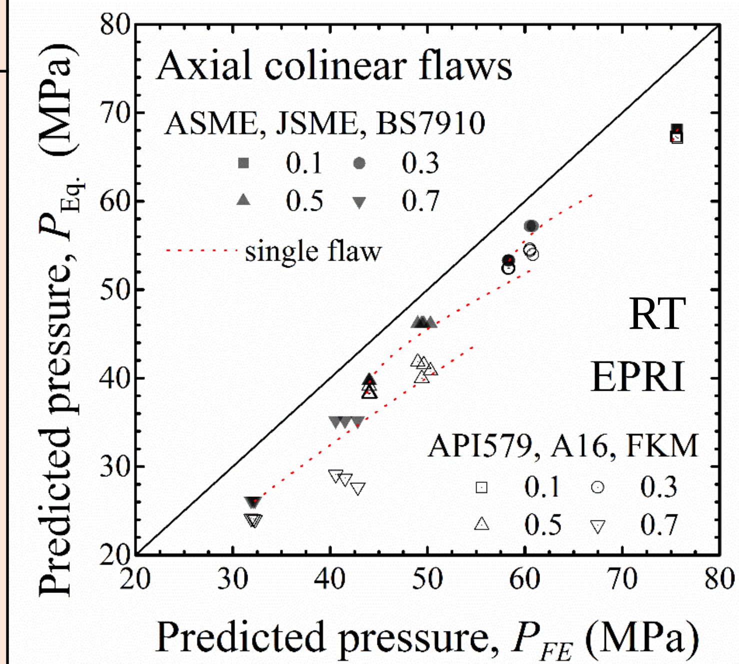


or

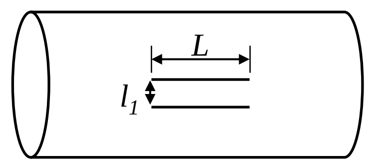


Cases of collinear axial flaws

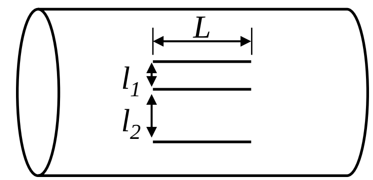
a/t	No. of flaws	L_1	L_2	L_3	s_1	s_2	FE	EPRI: ASME, JSME, BS7910		EPRI: API579, A16, FKM	
0.1	2	6.3	6.3		2		75.6	68.2	Not combined min($P_{L,i}$)	67.3	Combined $P_{L,eff}$ $L_{eff} = \Sigma L_i + \Sigma S_i$
	2	6.3	6.3		5		75.7	68.2		67.1	
0.3	2	6.3	6.3		1		60.5	57.2		54.6	
	2	6.3	6.3		2		60.5	57.2		54.4	
	2	6.3	6.3		5		60.8	57.2		54.0	
0.5	2	6.3	6.3		1		49.0	46.2		41.8	
	2				2		49.6	46.2		41.6	
	2				5		50.3	46.2		40.8	
	2	6.3	25.4		1		44.0	39.7		39.1	
	2	25.4	25.4		1		44.0	39.7		38.3	
	2				2		44.0	39.7		38.3	
	2				5		44.0	39.7		66.6	
0.7	2	6.3	6.3		1		40.6	35.2		29.1	
	2	6.3	6.3		2		41.5	35.2		28.7	
	2	6.3	6.3		5		42.8	35.2		27.7	
0.3	2	25.4	25.4		1		58.3	53.3		52.5	
	2	25.4	25.4		2		58.4	53.3		52.5	
	2	25.4	25.4		5		58.3	53.3		52.4	
0.5	2	25.4	25.4		1		44.0	39.7		38.3	
	2	25.4	25.4		2		44.0	39.7		38.3	
	2	25.4	25.4		5		44.0	39.7		38.2	
0.7	2	25.4	25.4		1		31.9	26.1		24.2	
	2	25.4	25.4		2		32.1	26.1		24.1	
	2	25.4	25.4		5		32.3	26.1		24.0	
0.5	3	6.3	6.3	6.3	2	2	49.4	46.2		40.0	
	3	12.7	25.4	12.7	1	1	44.1	39.7		38.3	



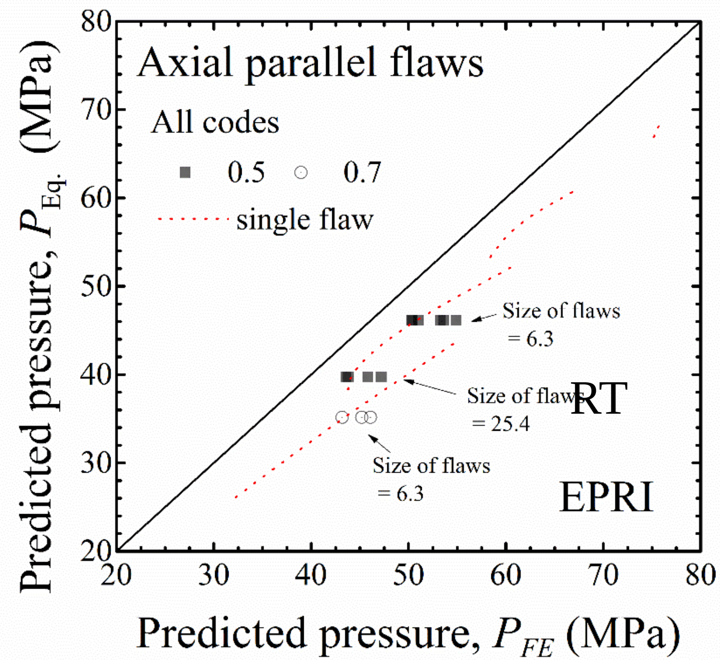
- Parallel axial flaws



or



Cases of collinear axial flaws						
a/t	No. of flaws	L	l_1	l_2	FE	EPRI All codes
0.5	2	6.3	1		54.9	46.2
0.5	2	6.3	2		53.3	46.2
0.5	2	6.3	5		51.0	46.2
0.7	2	6.3	1		46.1	35.2
0.7	2	6.3	2		45.2	35.2
0.7	2	6.3	5		43.2	35.2
0.5	2	25.4	1		47.2	39.7
0.5	3	6.3	1	2	53.6	46.2
0.5	3	6.3	1	15	50.3	46.2
0.5	3	6.3	1	30	50.4	46.2
0.5	3	25.4	1	2	45.8	39.7
0.5	3	25.4	1	15	43.6	39.7
0.5	3	25.4	1	30	43.8	39.7



l_2 : 15 mm ≒ 90° **위치 차**, 30 mm ≒ 180° **위치 차**

평행 균열의 길이가 같아 정렬 유무와 관계없이 동일 P_L

Conclusions

❖ Applicability of net-section collapse loads for multiple circumferential cracked pipes

- Systematic analysis using FE damage analysis
- FE damage analysis validated against existing pipe test data
- Generate maximum loads for more general cases (crack depth and length)
- Comparison with estimated NSC loads

❖ Comparison shows that

- Good agreement for two symmetrical surface crack cases
- For asymmetric cases, deeper crack tends to be more dominant

❖ More parametric study might be needed ?

→ Need experts' help for careful selection of cases

Thank you very much!