Structural Integrity Estimates of Steam Generator Tubes Containing Wear-Type Defects

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It is requested that steam generator tubes with defects exceeding 40% of wall thickness in depth should be plugged to sustain all postulated loads with appropriate margin. This critical defect size has been determined based on a concept of plastic instability, however, which is known to be too conservative for some locations and types of defects. The application of this concept may even cause premature retirement of steam generator tubes. In reality, a reliable structural integrity estimation for steam generator tubes containing a defect has received increasing attention. Although several guidelines have been developed and used for assessing defect containing tubes, most of these guidelines are focused on stress corrosion cracking or wall-thinning phenomena. Because some of steam generator tubes fail due to fretting and so on, specific integrity estimation schemes for relevant defects are required. In this paper, more than a hundred three-dimensional finite element analyses of steam generator tubes under internal pressure condition are carried out to simulate the failure behavior of steam generator tubes with specific defect configurations: elliptical wear-type, tapered wedge-type, and flat wear-type defects. After investigating the effect of key parameters such as defect depth, defect length, and wrap or tapered angle on equivalent stress across the ligament thickness, burst pressure estimation equations are proposed in relation to material strengths. Predicted burst pressures agreed well with the corresponding experimental data, so the proposed equations can be used to assess the structural integrity of steam generator tubes with wear-type defects.
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Keywords: burst pressure, plastic limit pressure, steam generator tube, wear-type defects

1 Introduction

A steam generator in nuclear power plants is the major component not only making up the pressure boundary but also transferring excess heat generated in the reactor core to the secondary side. Generally, in the case of a pressurized light-water reactor, each of the steam generators consists of approximately 5000 of tubes of about 10 mm in radius and 1 mm in thickness. A significant number of steam generator tubes are defective and are removed from service or repaired. This widespread damage is caused by many diverse degradation mechanisms [1]. Since the structural integrity of a steam generator tube is crucial with respect to reactor reliability and cost, an accurate failure evaluation of steam generator tube with defects is quite important.

Most of previous studies on steam generator tube are confined to cracks, including our studies in [2–4], and relatively fewer researches have been done on volumetric material loss or removal resulting from the combination of flow-induced vibration (FIV) and contact between a tube and a support structure [5,6]. In the late 1970s, a series of burst tests was undertaken for steam generator tubes with wear-type defects [7]. Also, more extensive testing and analytical program have been carried out to establish technical maintenance guidelines for steam generator tubes with wear-type defects, from which burst pressure estimation equations were suggested [8–10]. However, the majority of these equations have been developed either empirically based on limited test data or analytically based on simple approximation. For example, although the burst pressure of a steam generator tube with wear-type defects is influenced by defect depth, defect length, wrap angle, or tapered angle, geometric variables were not fully considered in the previous studies. Consequently, systematic investigations on the effect of geometric variables of wear-type defects and relevant engineering estimation schemes to predict the burst pressure are needed.

The objective of the present study is to predict the structural integrity of steam generator tubes with specific wear-type defects. To achieve this goal, the burst pressures of steam generator tubes containing wear-type defects are evaluated by detailed three-dimensional (3D) elastic-plastic finite element (FE) analyses, and compared with existing solution and experimental results. In terms of the wear defect shape, three idealized types are considered for the steam generator tubes under internal pressure. Finally, based on the FE analysis results, new burst pressure estimation equations of steam generator tubes with wear-type defects are proposed.

2 Existing Burst Pressure Solutions for Steam Generator Tubes With Part Through-Wall Cracks

Undefected Tubes. The burst pressure of undefected steam generator tubes can be used as a base line for analyzing that of defected tubes. Under the internal pressure condition, the well-known limit pressure solution for an undefected cylinder is given by [11]

$$\frac{p_L}{\sigma_y} = \frac{2}{\sqrt{3}} \ln\left(\frac{R_o}{R_i}\right) \qquad (1)$$

where p_L denotes the burst pressure, σ_y is the yield strength of material, $2/\sqrt{3}$ is a factor derived from von Mises yield criterion, and R_o/R_i is the ratio of the outer radius to the inner radius of tube.

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Table 1 Summary of tensile properties for Alloy 600

Material	σ_y (MPa)	σ_u (MPa)	$\sigma_f\left(=\frac{\sigma_y+\sigma_u}{2}\right)$ (MPa)
Alloy 600 (20°C)	329	669	499

Tubes With a Part Through-Wall Axial Crack. A general failure criterion for a single part through-wall axial crack is given by [12,13]

$$p_{\text{burst}} = \frac{\sigma_f t}{m_p R_m} \tag{2}$$

where σ_f is the flow stress, R_m is the mean radius, and m_p is the ligament stress magnification factor.

$$m_p = \frac{1 - \alpha \dfrac{a}{mt}}{1 - \dfrac{a}{t}} \tag{3}$$

$$\alpha = 1 + 0.9\left(\frac{a}{t}\right)^2\left(1 - \frac{1}{m}\right)$$

$$m = 0.614 + 0.481\lambda + 0.386\exp(-1.25\lambda) \tag{4}$$

$$\lambda = [12(1-\nu^2)]^{0.25}\rho; \quad \rho = (c/\sqrt{R_m t})$$

In the above equations, ν is Poisson's ratio, a is the crack depth, and c is the half crack length.

Tubes With a Part Through-Wall Circumferential Crack. Among the several models proposed, the most popular failure criterion for a single part through-wall circumferential crack can be also expressed by [12,13]

$$p_{\text{burst}} = \frac{2\sigma_f t}{m_p R_m} \tag{5}$$

$$m_p = \frac{1}{\left[m + \left(\dfrac{\theta}{\pi}\right)\left(1 - \dfrac{a}{t} - m\right)\right]} \tag{6}$$

Although the detailed description is not given here for brevity, the burst pressure estimation equations as well as experimentally based semiempirical procedures have been well established for through-wall crack and some volumetric degradations [10,12,13]. However, it is difficult to predict the burst pressure of steam generator tubes containing wear-type defects pertinently by using Eqs. (2)–(6). In this context, detailed 3D elastic-plastic FE analyses are performed in the present work to derive burst pressure solutions of steam generator tubes with wear-type defects, and their results are compared with experimental ones.

3 Geometry and Finite Element Analyses

Material, Geometry, and Defect Shape. Steam generator tubes made of Alloy 600 are considered. The outer diameter and thickness of the tube are 19.05 mm and 1.09 mm, respectively. Tensile properties of this material are summarized in Table 1 and comparable with those of foreign materials [14]. Figure 1 shows the true stress-strain data used in the present work, normalized with respect to the yield strength of Alloy 600. Additional six normalized stress-strain curves of Alloy 600 and two normalized stress-strain curves of Alloy 690 were also included to show a representativeness of employed data. All the data were obtained from archival steam generator tube materials of operating nuclear power plants in Korea. Three types of wear defects, typically found in operating condition, are employed in the present work. Figure 2 depicts three geometries of steam generator tubes under internal pressure, p, containing wear defects. Relevant dimensions are also noted in the figure. The defect depth, defect length, wrap angle, tapered angle, and outer radius of the steam generator tube are denoted by d, l, θ_w, θ_t, and R_o, respectively, and the thickness of the steam generator tube is t.

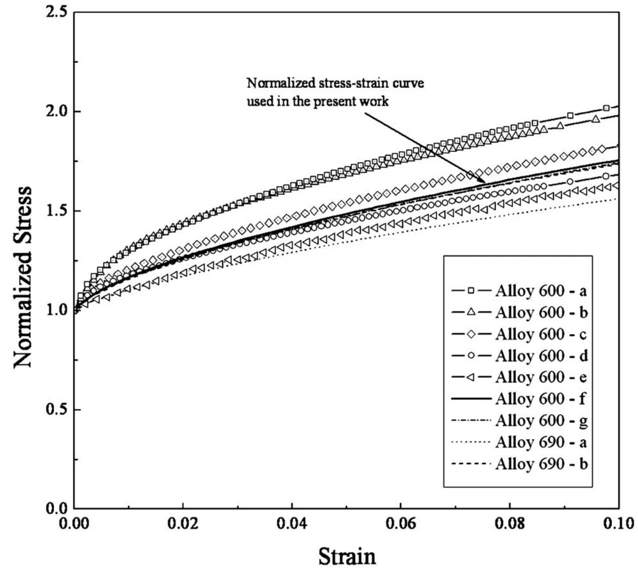

Fig. 1 Normalized stress-strain data of Alloy 600 and 690 materials

The first type of wear defect considered in the present work is elliptical shape. It may be generated by a FIV in a steam generator tube. For the elliptical wear type, the relevant parameters influencing the burst pressure were systematically varied to quantify their effects. Thus, a total of 60 cases are considered and the details are listed in Table 2. The second type of wear is the tapered wedge defect, which is usually formed in the free span of the tube at the nominal axial location of the batwing [15]. In the case of the tapered wedge-type defect, the remaining thickness can be determined if the defect length and tapered angle are known. While the variables represented in Table 3 were considered to simply cover the practical range by application of a limiting condition—the remaining thickness is greater than 10% of the wall thickness—a total of 18 analysis cases were selected. The third one is the flat wear-type defect. Especially, for engineering application, an elliptical wear can be idealized as a flat wear-type defect. To compare the results of the flat wear with those of the elliptical wear-type defect, the parameters of the flat wear-type defect influencing the FE results—defect depth, defect length, and wrap angle—are assumed to be identical to those of the elliptical wear-type defect.

Finite Element Analyses. Figure 3 depicts typical 3D FE meshes of defected steam generator tubes given in Fig. 2. Considering the symmetric condition, only one-quarter of the tube was modeled for the elliptical and flat wear-type defects, whereas one-half of the tube was modeled for the tapered wedge-type defect to reduce the computation time. A series of FE analyses was performed by using the general-purpose FE program, ABAQUS [16]. To avoid problems associated with incompressibility, the reduced integration 20-node element within ABAQUS (C3D20R in ABAQUS element library) was used. The number of elements ranged from 3213 to 4980, and the number of nodes ranged from 16,895 to 25,357 depending on the wear type. The material was modeled as isotropic elastic-plastic materials that obey the J_2 flow theory, and incremental plasticity using actual stress-strain data was em-

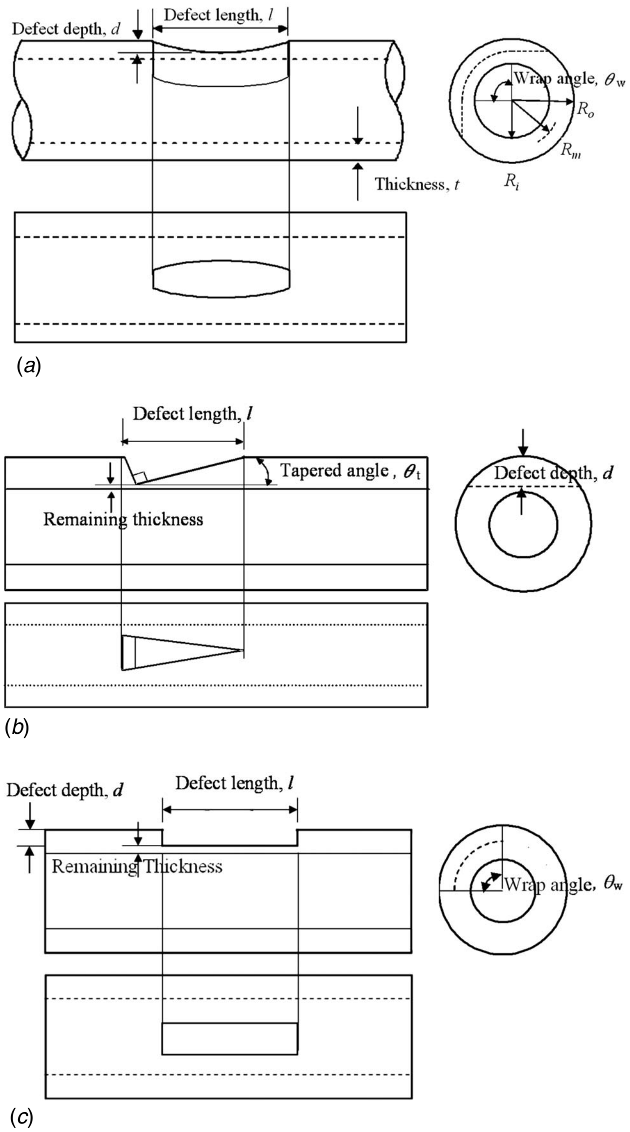

Fig. 2 Schematic illustration of wear-type defects in steam generator tubes. (*a*) Elliptical wear-type defect, (*b*) tapered wedge-type defect, and (*c*) flat wear-type defect.

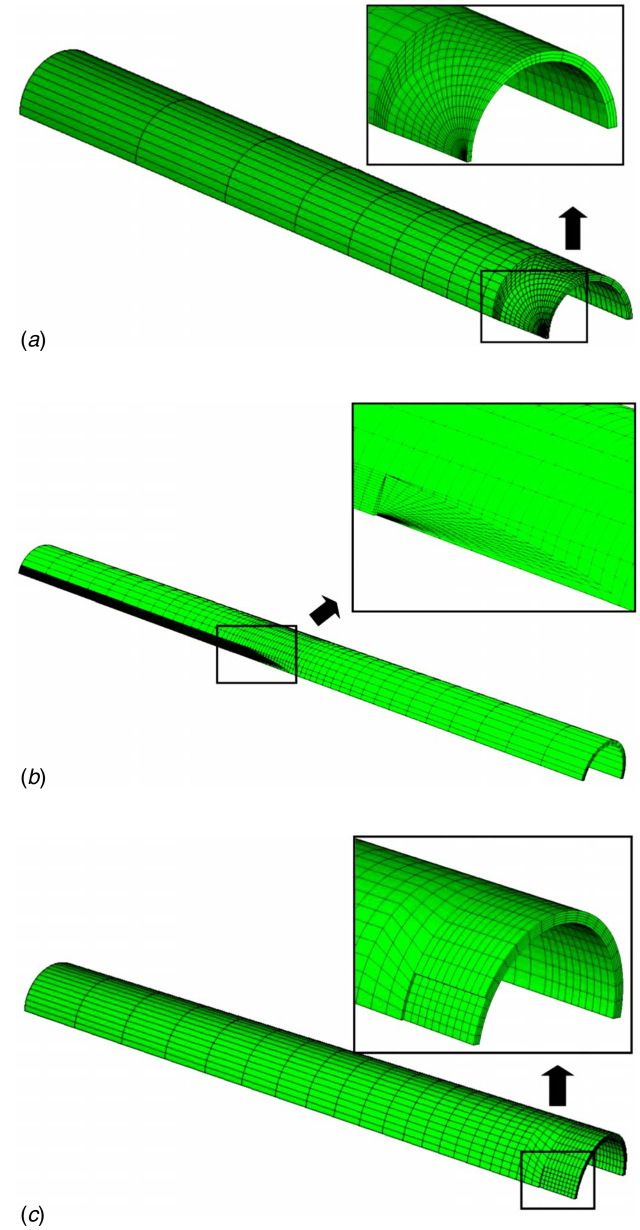

Fig. 3 Typical 3D FE meshes employed in the present study. (*a*) Elliptical wear-type defect, (*b*) tapered wedge-type defect, and (*c*) flat wear-type defect.

ployed. Thus, the true stress-strain data for the Alloy 600 were directly given in the FE analysis. The large geometry change continuum FE model was employed (NLGEOM option within ABAQUS is invoked).

As a loading condition, internal pressure prevailing on steam generator tubes was considered. The internal pressure was applied as a distributed load to the inner surface of the FE model, together with an axial tension equivalent to the internal pressure applied at the end of the tube to simulate the closed end condition. The failure of steam generator tubes was assumed to occur when the von Mises equivalent stress distribution across the ligament thickness reached the critical material strength, and corresponding internal pressure was defined as the burst pressure of the tubes. As critical material strengths, yield strength (σ_y), flow strength (σ_f), 80% of ultimate tensile strength ($0.8\sigma_u$), 90% of ultimate tensilte strength ($0.9\sigma_u$), and ultimate tensile strength (σ_u) were used. Finally, the resulting FE burst pressure values based on these critical material strengths were compared with experimental results to determine the optimum critical material strength for the prediction of burst pressure of steam generator tubes with a wear-type defect.

Table 2 Analysis cases for elliptical wear-type defect

Normalized defect depth, d/t	Defect length, l (mm)	Wrap angle, θ_w (deg)
0.3, 0.45, 0.6, 0.75, 0.9	15, 25, 35	0, 45, 90, 135

Table 3 Analysis cases for tapered wedge-type defect. A limiting condition: remaining thickness ⩾10% of wall thickness.

Tapered angle, θ_t (deg)	Defect length, l (mm)
0.5, 1, 1.5, 2, 2.5	10, 20, 30, 40, 50, 60

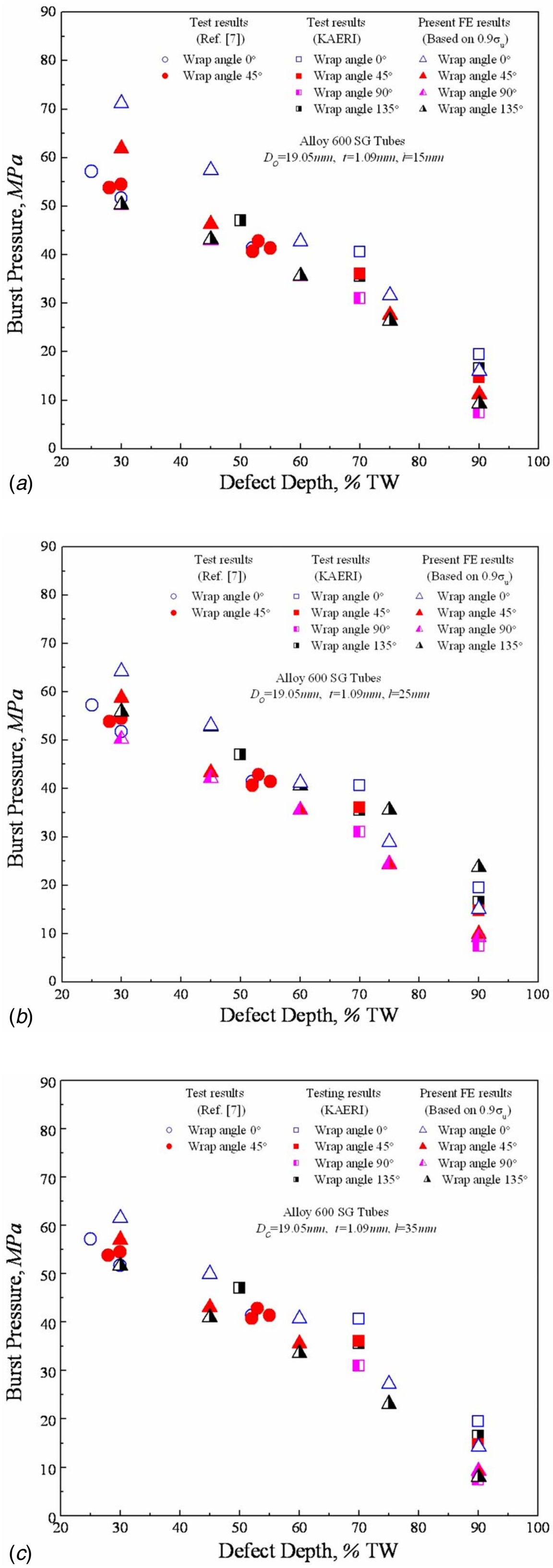

Fig. 4 Comparison of the FE burst pressures with experimental data for elliptical wear-type defect. (*a*) l=15 mm, (*b*) l=25 mm, and (*c*) l=35 mm.

4 Burst Pressure of Steam Generator Tubes With a Wear-Type Defect

Tubes With an Elliptical Wear-Type Defect. Figure 4 compares the FE burst pressures with experimental burst pressure for the elliptical wear-type defect. As indicated in Fig. 4, the burst pressures based on 90% of the ultimate tensile strength criterion correspond well with the experimental ones. The burst pressures based on the yield strength, flow strength, and ultimate tensile strength underestimated the experimental results although these burst pressures are not provided here. Thus, $0.9\sigma_u$ was chosen as the optimum failure criterion for the elliptical wear-type defect.

Note that the existing solution for elliptical wear is given by Ref. [7].

$$p_{\text{burst}} = p_L\left(1 - \frac{d}{t}\right)^{a^*} \tag{7}$$

where p_{burst} denotes the burst pressure of the tube with elliptical wastage, p_L is the aforementioned burst pressure of the undefected tube, d is the defect depth, t is the thickness of tube, and a^* is a coefficient. Based on experimental results of the tubes, the value of a^* is proposed as 0.604 by the least square method [7].

However, in Eq. (7), the effects of defect length and wrap angle on burst pressure were not systematically considered as well as the normalized defect depth (d/t), which was less than 60% of the through-wall thickness (60% TW). The following polynomial approximation is proposed based on detailed FE results for elliptical wear-type defect incorporating test data by Korea Atomic Energy Research Institute (KAERI) up to d/t=90% TW [17]. The relevant experiments, summarized in Table 4, were aimed to fill in the gaps in the existing data [7] that are relatively sparse in deep flaws.

Table 4 Test cases at room temperature for elliptical wear-type defect [17]

Defect length, l (mm)	Wrap angle, θ_w (deg)	Normalized defect depth, d/t
25	0, 45, 90	0.7, 0.9
	135	0.5, 0.7, 0.9

$$p_{\text{burst}} = 0.9\sigma_u \frac{4t}{\sqrt{3}D_i}\left\{A_1\left(\frac{l}{\sqrt{R_m t}}\right)^2 + A_2\left(\frac{l}{\sqrt{R_m t}}\right) + A_3\right\} \tag{8}$$

$$A_1, A_2, A_3 = X_1\left(\frac{d}{t}\right)^2\left(\frac{\theta}{\pi}\right) + X_2\left(\frac{d}{t}\right)\left(\frac{\theta}{\pi}\right) + X_3\left(\frac{\theta}{\pi}\right) + X_4\left(\frac{d}{t}\right) + X_5 \tag{9}$$

where D_i is the inner diameter of steam generator tube. X_1, X_2, X_3, X_4, and X_5 are the coefficients corresponding to A_1, A_2, and A_3, which are summarized in Table 5. In order to check the applicability of Eqs. (8) and (9), further statistical analysis was carried out to determine Pearson's correlation coefficient and F-statistic value [18]. The correlation coefficient was calculated as 0.991 and F-statistic was 548.5. The values of correlation coefficient and F-statistic were sufficiently large. This means that the polynomial approximation is suitable to estimate burst pressure and represents well the variation of geometric variables.

The burst pressure estimation equation is expressed as a function of defect depth, defect length, and wrap angle. As described, $0.9\sigma_u$ is used as the failure criterion to determine the burst pres-

Table 5 Resulting constants for burst pressure estimation equation of elliptical wear-type defect

Coefficient	X_1	X_2	X_3	X_4	X_5
A_1	0.0058	−0.0110	0.0044	0.0035	−0.0023
A_2	−0.0117	0.0468	−0.0562	−0.0057	0.0200
A_3	−1.0873	1.5828	−0.7894	−0.7340	1.0000

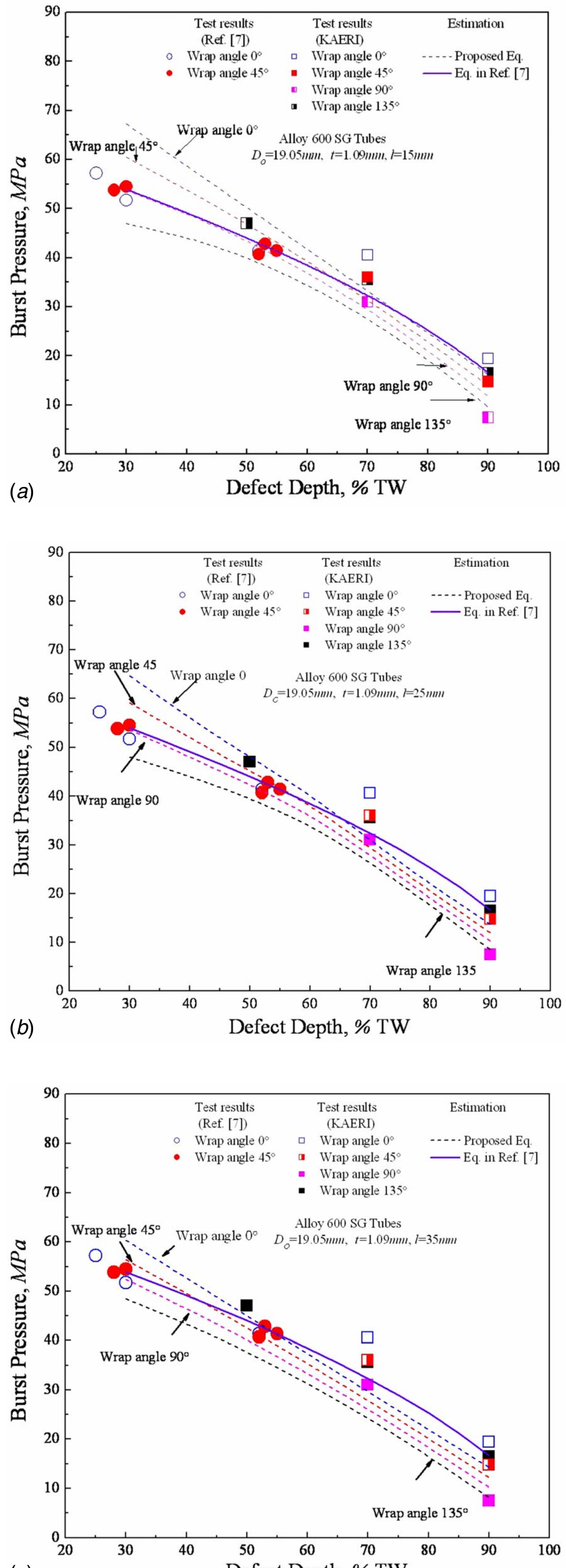

Fig. 5 Burst pressure solution with experimental data for elliptical wear-type defect. (*a*) l=15 mm, (*b*) l=25 mm, and (*c*) l=35 mm.

sure. Figure 5 compares the new burst pressure solutions with results from Eq. (7), as the reference solution, and with the experimental results for the elliptical wear-type defect. The burst pressures predicted by Eqs. (8) and (9) decrease with the increase of defect length as well as wrap angle, and the effect of wrap angle reduces when the defect becomes deeper. Since Eq. (7) was obtained by numerical regression using experimental data given in Fig. 5, as expected, Eq. (7) provides the mean values and cannot consider the effect of defect length and wrap angle on burst pressure exactly. Further discussion on the application of the proposed equation will be given later.

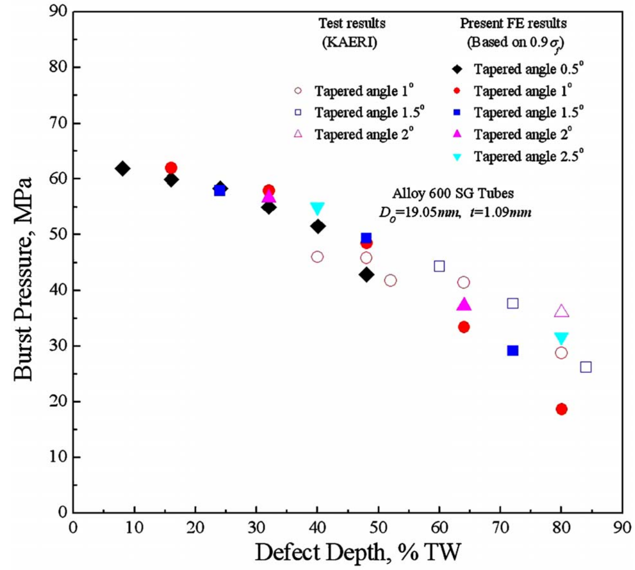

Fig. 6 Comparison of the FE burst pressures with experimental data for tapered wedge-type defect

Tubes With a Tapered Wedge-Type Defect. Figure 6 compares the FE burst pressure results for the tapered wedge-type defect with limited test data provided by KAERI. The details of the test cases are shown in Table 6 [17]. For this type of defect, due to different geometric characteristics, the burst pressure was estimated based on 90% of the flow strength criterion. For a shallower defect depth, $d/t < \sim 0.6$, the present FE results were quite close to the experimentally obtained values. However, for a deeper defect, $d/t > \sim 0.6$, the present FE results overestimated the experimental data and thus resulted in nonconservative estimates of the actual burst pressure. This inconsistency and the possible solution to this inconsistency will be dealt later in this paper.

Based on detailed FE analysis results, the following polynomial approximation for tapered wedge-type defect is proposed:

Table 6 Test cases at room temperature for tapered wedge-type defect [17]

Tapered angle, θ_t (deg)	Normalized defect depth, d/t
1	0.4, 0.48, 0.52, 0.64, 0.8
1.5	0.6, 0.72, 0.84
2	0.8

Table 7 Resulting constants for burst pressure estimation equation of tapered wedge-type defect

Coefficient	X_1	X_2	X_3
A_1	0.0114	−0.0080	0.0015
A_2	−0.2286	0.1150	−0.0174
A_3	0.3894	−0.5520	1.0000

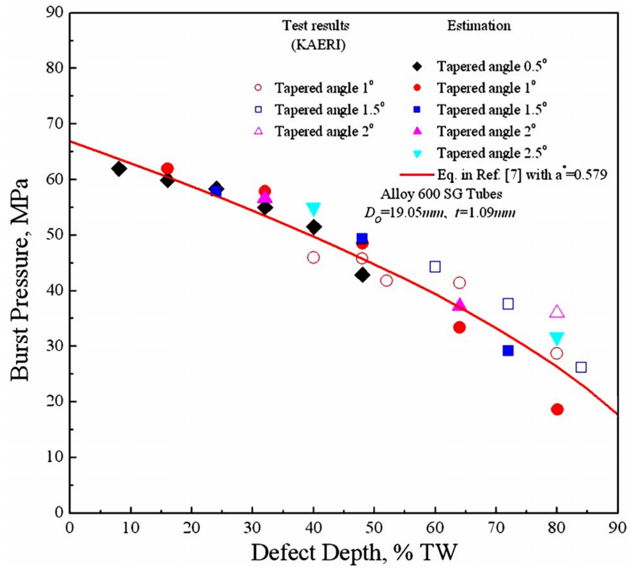

Fig. 7 Comparison of the burst pressure prediction with experimental data for tapered wedge-type defect

$$p_{\text{burst}} = 0.9\sigma_f \frac{4t}{\sqrt{3}D_i}\left\{A_1\left(\frac{l}{\sqrt{R_m t}}\right)^2 + A_2\left(\frac{l}{\sqrt{R_m t}}\right) + A_3\right\} \quad (10)$$

$$A_1, A_2, A_3 = X_1\left(\frac{d}{t}\right)^2 + X_2\left(\frac{d}{t}\right) + X_3 \quad (11)$$

where X_1, X_2, and X_3 are the coefficients corresponding to A_1, A_2, and A_3, which are summarized in Table 7. From further statistical analysis to check the applicability of Eqs. (10) and (11), 87.3 of F-statistic as well as 0.995 of Pearson's correlation coefficient were obtained. Since the value of correlation coefficient is almost equal to unity, while a relatively small F-statistic value was obtained due to reduced number of geometric variables comparing to other defect types, the polynomial approximation is suitable to estimate burst pressure.

Furthermore, the burst pressure estimation equation of tapered wedge-type defect is also proposed in the form of Eq. (7). Based on the least square method employing limited test data, the value of coefficient a^* was calculated as 0.579 by the authors. Figure 7 compares the proposed solutions by Eqs. (10) and (11) with experimental results, in which the results based on Eq. (7) employing $a^*=0.579$ are also included.

Tubes With a Flat Wear-Type Defect. Although there are no experimental results for the flat wear-type defect for comparison, the burst pressure estimation equation based on detailed 3D FE analysis results is proposed for the flat wear-type defect. The FE burst pressures based on 90% of the ultimate tensile strength criterion along with the existing solution for elliptical wastage are given in Fig. 8 [7]. Using these FE results, the same polynomial approximation represented as Eqs. (8) and (9) with different values of coefficients in Table 8 is proposed for the flat wear-type defect. As expected, the burst pressures of the flat wear-type defect are smaller than those of the elliptical wear due to the relatively larger shape of volumetric loss and the wrap angle has little influence on tubes with deeper flat wear-type defect. From further statistical analysis to check the applicability of the polynomial approximation for the flat wear-type defect, due to the absence of test data, only the value of F-statistic was calculated as 715.6. However, the value of correlation coefficient was sufficiently large and, thus, the polynomial approximation represents well the variation of geometric variables.

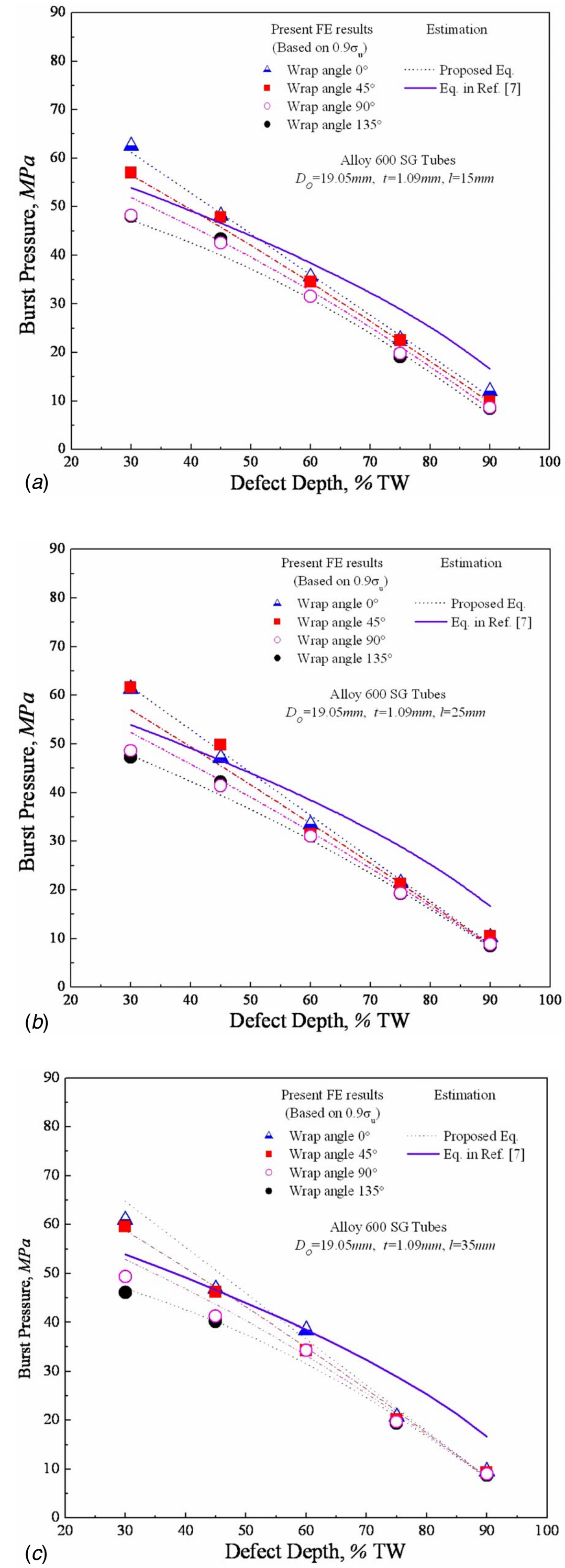

Fig. 8 Burst pressure solution with FE results for flat wear-type defect. (*a*) *l*=15 mm, (*b*) *l*=25 mm, and (*c*) *l*=35 mm.

Discussions. As shown in Fig. 5, in particular, the burst pressure estimation equation of the elliptical wear-type defect overestimated the existing test data when the defect length was short. Also, in Figs. 6 and 7, the present FE results and proposed solu-

Table 8 Resulting constants for burst pressure estimation equation of flat wear-type defect

Coefficient	X_1	X_2	X_3	X_4	X_5
A_1	−0.0290	0.0359	0.0008	−0.0108	0.0019
A_2	0.4571	−0.5383	0.0055	0.1541	−0.0137
A_3	−2.2186	2.8447	−0.8979	−0.9637	1.0000

tions of the tapered wedge-type defect overestimate the experimental results for a shallower defect, $d/t < \sim 0.6$, and thus result in nonconservative estimates of the actual burst pressure. The reason for such behavior can be explained as follows. For an undefected tube, the hoop stress plays an important role in plastic collapse, and the burst pressure of an undefected tube can be estimated from Eq. (1). The value of the burst pressure of an undefected tube for the material employed in the present study was about 83.2 MPa. The present FE results converged to this limiting value; on the other hand, the corresponding test data converged to a significantly lower value of 66.9 MPa. Thus, for a shallow defect, the experimental results differed significantly from the present FE results. Therefore, more experimental investigations for shallower tapered wedge-type defect would be needed to quantify such a discrepancy between FE and testing results.

To account for the uncertainty discussed above, for practical applications, a lower bound prediction would be more desirable. Thus, Eqs. (12) and (13) with different values of coefficients were derived for the elliptical and flat wear-type defects based on all of the present FE results, in which the effect of the wrap or tapered angle was neglected conservatively. Equation (14) for the tapered wedge-type defect was also reproposed.

$$p_{\mathrm{burst}} = 0.9\sigma_u \frac{4t}{\sqrt{3}D_i}\left\{A_1\left(\frac{l}{\sqrt{R_m t}}\right)^2 + A_2\left(\frac{l}{\sqrt{R_m t}}\right) + A_3\right\} \quad (12)$$

$$A_1, A_2, A_3 = X_1\left(\frac{d}{t}\right)^2 + X_2\left(\frac{d}{t}\right) + X_3 \quad (13)$$

$$p_{\mathrm{burst}} = 0.9\sigma_f \frac{4t}{\sqrt{3}D_i}\left\{-0.7559\left(\frac{d}{t}\right)^2 - 0.1499\left(\frac{d}{t}\right) + 0.9605\right\} \quad (14)$$

where X_1, X_2, and X_3 are the coefficients corresponding to A_1, A_2, and A_3, respectively, which are summarized in Table 9.

The best fit as well as the lower bound curves for the three types of wear defects are also plotted together with the test data in Fig. 9. Although there are other evaluations that are usually performed, the governing criterion for a degraded steam generator tube is the normal operating differential pressure (Δp_{NO}) requirement [10]. When considering margin of 3 against the normal operating differential pressure ($3\times\Delta p_{\mathrm{NO}}$), defect depths of 66–72% TW based on the lower bound curve and 68–77% TW based on the best-fit curve can be retained, respectively. It is well known

Table 9 Resulting constants for lower bound curve of elliptical and flat wear-type defects

Coefficient		X_1	X_2	X_3
Elliptical wear	A_1	0.0261	−0.0322	0.0090
	A_2	−0.3573	0.4388	−0.1263
	A_3	0.43533	−1.2925	1.0000
Flat wear	A_1	0.0082	−0.0107	0.0036
	A_2	−0.1789	0.2376	−0.0783
	A_3	0.3648	−1.3044	1.0000

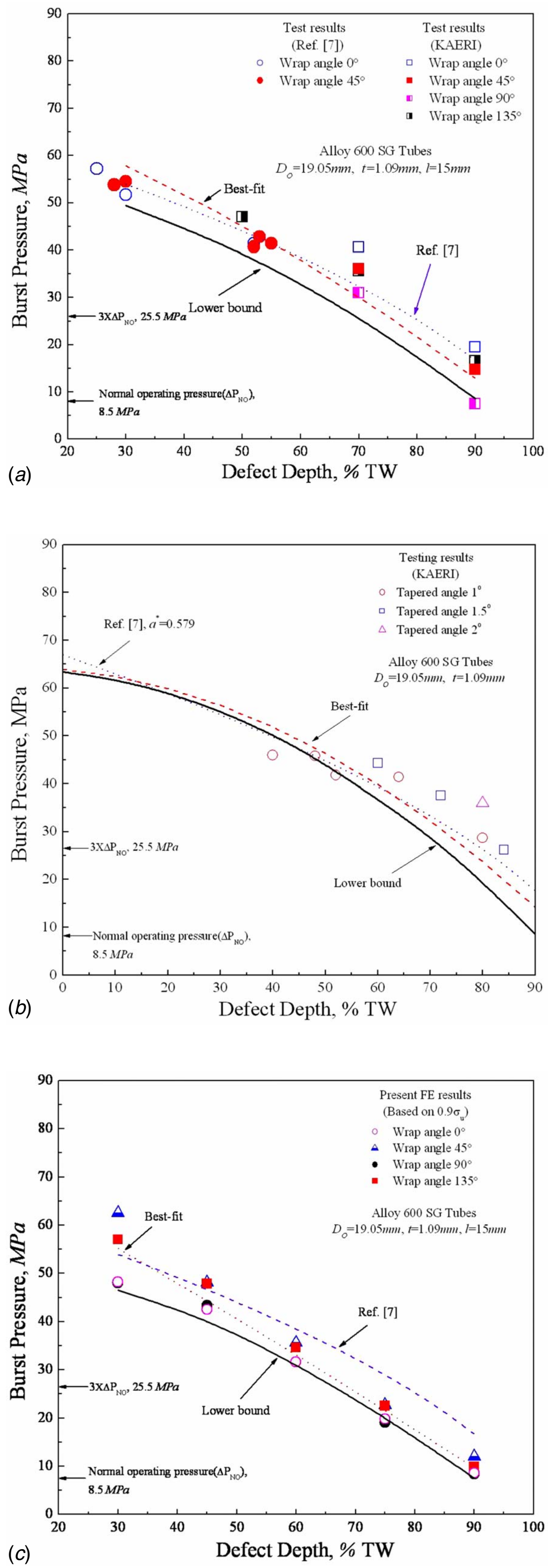

Fig. 9 Lower bound and best-fit curves. (*a*) Elliptical wear-type defect, (*b*) tapered wedge-type defect, and (*c*) flat wear-type defect.

that ASME Code limit was essentially derived from absolute limits of about 50–65% TW for a uniformly thinned tube with Code minimum properties. Therefore, it is anticipated that FE and experimental results as well as the proposed equations can be used as technical backgrounds for establishing a practical structural integrity assessment guideline of steam generator tubes with wear-type defects.

5 Concluding Remarks

In this paper, detailed 3D elastic-plastic FE analyses were performed for steam generator tubes containing elliptical wear, tapered wedge, and flat wear-type defects to predict the burst pressure.

In order to propose a failure criterion, burst tests for tubes with elliptical wear and tapered wedge defects were performed and the test results were compared with the present FE analysis results. Failure of the steam generator tubes with wear-type defects was assumed to occur when the von Mises stress across the ligament thickness reached the critical material strength of interest across the entire ligament. Based on the comparison results, the failure criterion employing either 90% of the ultimate tensile strength or 90% of the flow stress was selected as the optimum failure criterion for prediction models of steam generator tubes with wear-type defects. Using these criteria and FE results, the polynomial equations for the three wear-type defects used to predict the burst pressure were proposed in terms of the changes in the geometric parameters of the defect such as defect length, defect depth, wrap, or tapered angle. Furthermore, for practical applications, the lower bound and best-fit equations were also proposed.

Based on detailed 3D FE results, the present solutions provide valuable information not only for the estimation of burst pressure but also for the understanding of the failure behavior of steam generator tubes with a wear-type defect.

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Nomenclature

a = crack depth
a^* = coefficient of burst pressure estimation represented in Ref. [7]
A_i = coefficients of burst pressure estimation
c = half crack length
d = defect depth
D_i = inner diameter
D_o = outer diameter
E = Young's modulus
l = defect length
m = bulging factor
m_p = ligament stress magnification factor
p = internal pressure
p_{burst} = burst pressure of defected steam generator tubes
p_L = plastic limit pressure of undefected steam generator tubes
R_i = inner radius
R_m = mean radius
R_o = outer radius
t = wall thickness
X_i = coefficients of burst pressure estimation
λ = shell parameter
ν = Poisson's ratio
θ = half circumferential crack angle
θ_t = tapered angle
θ_w = wrap angle
σ_f = flow stress
σ_u = ultimate tensile strength
σ_y = yield strength
Δp_{NO} = normal operating differential pressure

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