Burst pressure models for steam generator tubes with fretting wear

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1. Introduction

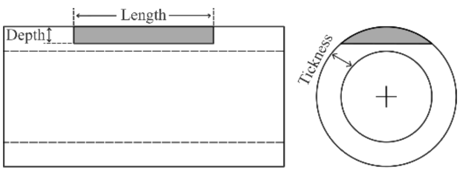
Steam generator (SG) tubes form the boundary between the primary and secondary sides of nuclear power plants. Various defects in SG tubes can lead to tube rupture, making the evaluation of their structural integrity crucial. In this study, existing burst pressure prediction models were compared, and a new repair criterion was proposed using a probabilistic approach. First, a regression analysis based on test data was performed to compare existing burst pressure models. Then, the prediction accuracy was evaluated for various defect depths and lengths. Finally, new repair criteria for fretting wear were proposed. The existing repair criterion was found to be conservative by approximately 20% of through-wall thickness compared to the proposed criterion.

2. Burst pressure models comparison

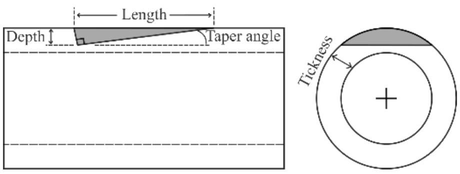
In order to compare the burst pressure prediction models, the burst tests of wear defected SG tubes and the volumetric defect burst pressure prediction models were investigated.

2.1 Burst pressure test

Burst tests of SG tubes with flat wear and tapered wear defects were investigated. The defect geometries of flat wear and tapered wear are shown in Fig. 1. The materials of SG tubes are Alloy 600 and Alloy 690. The detailed burst test conditions are summarized in Table 1.



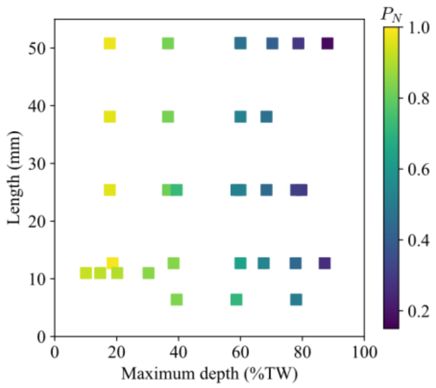
(a) Flat wear defect



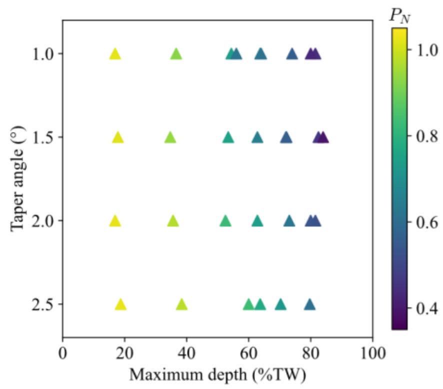
(b) Tapered wear defect
Fig. 1. Geometries of fretting wear

Table I: Summary of burst test conditions

	Flat wear			Tapered wear	
Ref.	[1]	[2]	[3]	[1]	[4]
Environ.	RT	RT	HT	RT	RT
Materials	A600	A690	A690	A600	A600
D_0(mm)	19.05	19.05	19.05	19.05	19.05
t(mm)	1.07	1.09	1.09	1.07	1.09
S_y(MPa)	260	308	239	260	241
S_u(MPa)	637	683	570	637	655
h(%TW)	18-88	39-78	10-30	17-83	56-84
L(mm)	13-51	6-25	11	5-51	25-50
Num.	22	6	4	24	6



(a) Flat wear defect



(b) Tapered wear defect
Fig. 2. Normalized burst pressure of wear defected SG tubes

The normalized burst pressure as a function of the depth and length of the defect is shown in Fig. 2. The normalized burst pressure is the ratio of the reduced burst pressure to the burst pressure of the defect-free tube. It was found that the burst pressure decreases with increasing defect depth.

2.2 Burst pressure prediction models

Electric Power Research Institute (EPRI)[5] evaluates the structure integrity of wear defected SG tubes by using the following equation.

$$P_B = 0.58(S_y + S_u)\frac{t}{R_i}\left[1 - h\frac{L}{L+2t}\right] + 291 \quad (1)$$

where S_y is yield strength, S_u is tensile strength, t is tube wall thickness, R_i is tube inner radius, h is relative depth of flaw, L is flaw length and 291 psi is model parameters.

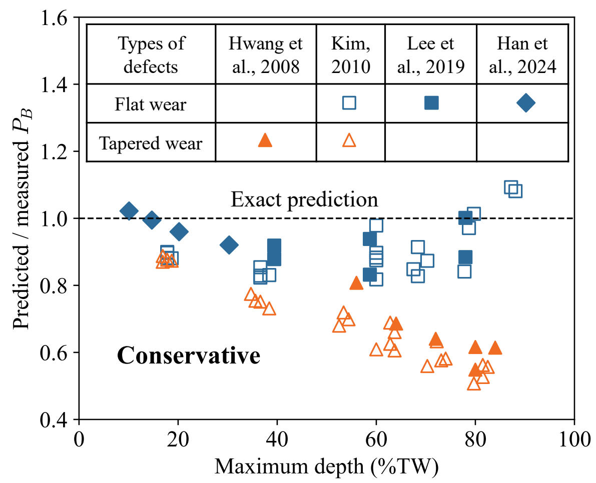


Fig. 3. Ratio of predicted by Eq. (1) to measured burst pressure

Fig. 3 shows the ratio of the predicted burst pressure using Eq. (1) to the measured burst pressure. The predicted values are generally lower than the measured values. In particular, the burst pressure of the tapered wear defected SG tube was conservatively predicted.

To enhance the conservatism of the EPRI burst pressure prediction model, a regression analysis method was applied to compare existing burst pressure models. A total of six normalized burst pressure models were analyzed, as follows

Model 1[6]: $P_N = (1-h)^{A_1}$ (2)

Model 2[6]: $P_N = (1-h)^{1-\exp[A_1 L/\sqrt{R_i t(1-h)}]}$ (3)

Model 3[5]: $P_N = [1-(hL)/(L+2t)] + A_1$ (4)

Model 4[7]: $P_N = A_1 + A_2\sqrt{1-h} + A_3 h^2 (t/L)$ (5)

Model 5[3]: $P_N = (\alpha - \beta)\exp(\gamma L/D_0) + \beta$ (6)

where $\alpha = 1 - h/A_1$, $\beta = 1 - h^{A_2}$,

$\gamma = -2(h_{\min}/h)^{4.1} + A_3$

Model 6[8]: $P_N = 1 - h\left\{1 - \exp\left[\frac{A_1 L}{\sqrt{R_i t(1-h)}}\right]\right\}$ (7)

where A_1, A_2, A_3 are the model parameters. D_0 is outer diameter of tube, $h_{\min}$ is minimum relative depth of defect.

2.3 Model regression results

The best-fit model parameters are summarized in Table. 2. Fig. 4 shows the prediction results of the best-fit burst pressure models. Model 5 has the highest prediction accuracy.

2.4 Model accuracy comparison method

To investigate the acceptability of the burst pressure model, the prediction accuracies of the models were compared over a range of defect depths and lengths. Fig. 5 shows the method of comparing model prediction accuracy.

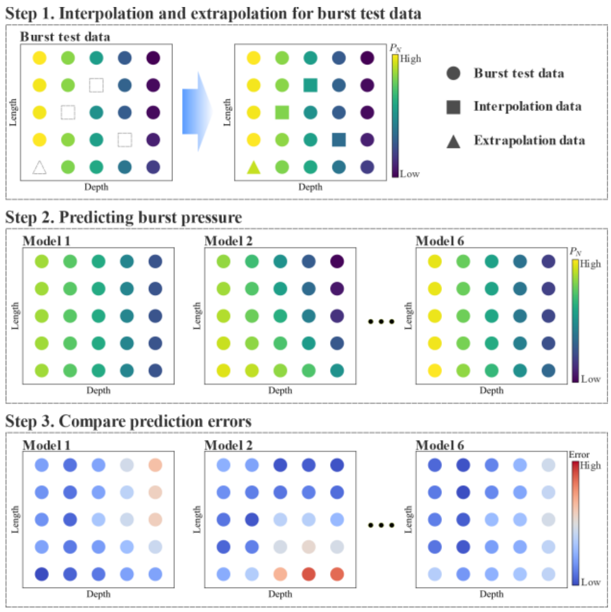


Fig. 5. Model accuracy evaluation method

Fig. 6 and 7 show the normalized burst pressure of SG tubes with flat and tapered wear defects using linear interpolation and nearest-neighbor extrapolation. The burst pressure was found to be highly dependent on defect depth and influenced by defect length.

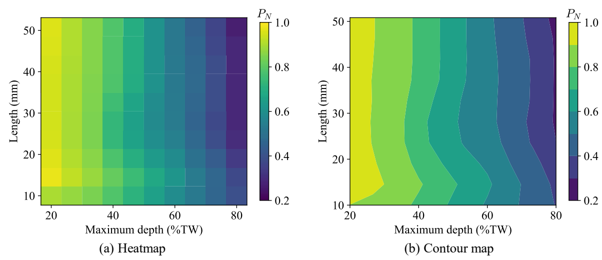


Fig. 6. Interpolation, extrapolation results of flat wear tube

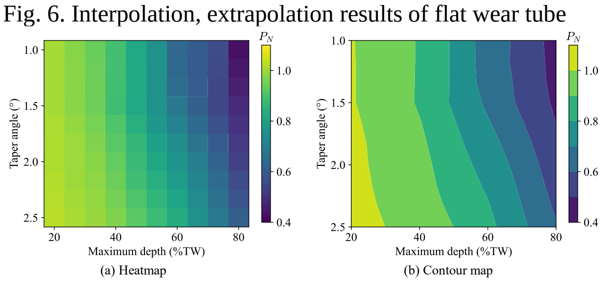


Fig. 7. Interpolation, extrapolation results of tapered wear tube

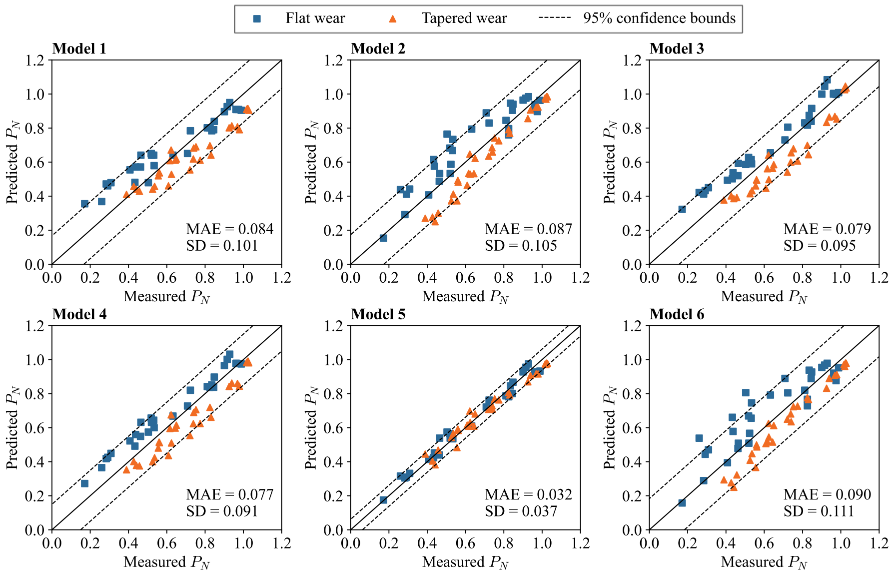


Fig. 4. Prediction results by best-fit models

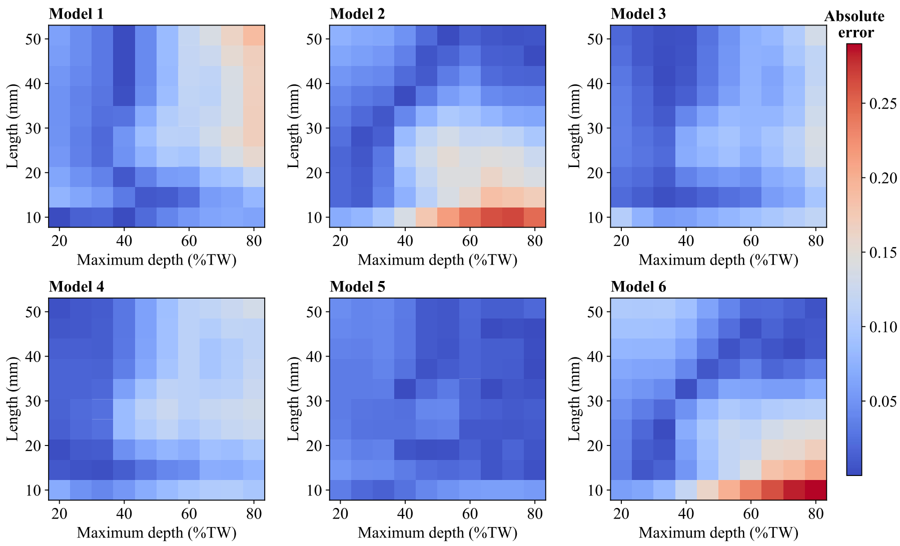


Fig. 8. Prediction errors of flat wear defected SG tubes

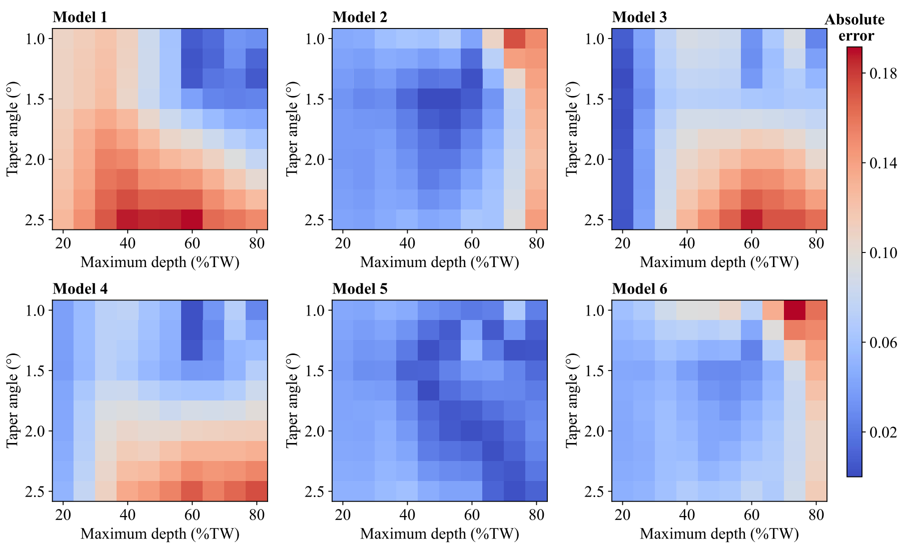


Fig. 9. Prediction errors of tapered wear defected SG tubes

Fig. 8 and 9 show the absolute errors of the best-fit models. The smaller the error, the closer the color to blue. Thus, Model 5 is the best suitable for predicting the burst pressure of flat and tapered wear defected SG tubes.

3. Probabilistic burst pressure estimation

3.1 Evaluation method

When evaluating burst pressures, it is essential to account for uncertainties. These uncertainties include material strength, inspection error, and burst pressure model error, all of which are assumed to follow a normal distribution.

The burst pressure of defect-free SG tubes is calculated as:

$$P_0 = 0.58(S_y + S_u)t/R_i \quad (8)$$

Considering material strength uncertainty, Eq. (8) can be expressed as

$$P_0 = 0.58(S_y + S_u + Z_m\sigma_m)t/R_i \quad (9)$$

where Z_m and σ_m are the Z value and standard deviation (SD) of sum of yield and tensile strength.

Inspection error uncertainty arises from measurement errors in the non-destructive examination (NDE). The actual defect size is estimated using the following NDE relation equation[9]:

$$h = 0.99h_{NDE} + 0.7 \quad (10)$$

When considering inspection uncertainty, Eq. (10) can be expressed as

$$h = 0.99h_{NDE} + 0.7 + Z_h\sigma_h \quad (11)$$

where h_{NDE} is NDE inspection defect depth, Z_h and σ_h are Z value and SD of NDE inspection error.

Burst pressure model uncertainty reflects the error in burst pressure predictions. When considering the burst pressure model uncertainty, model 5 can be expressed as

$$P_B = P_0 \times P_N + Z_P\sigma_P \quad (12)$$

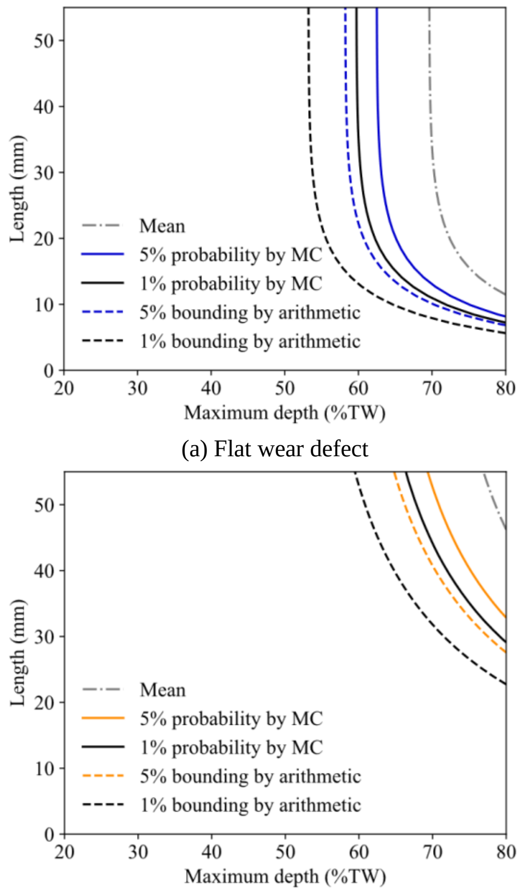
where Z_P and σ_P are Z value and SD of burst pressure.

The Z value can be chosen either randomly or as a constant, depending on the probabilistic method[10]. The probabilistic methods used in this study are the arithmetic and Monte Carlo (MC) simulation methods. As an example of the arithmetic method, the Z value of 1.645 is used to calculate the lower 5th percentile burst pressure. Another example is to iteratively calculate the burst pressure by randomly selecting the Z value. Then selecting the 5th percentile burst pressure.

3.2 Critical flaw size of fretting wear

Fig. 10 show the critical flaw size to ensure the structural integrity of SG tubes calculated by model 5 using Monte Carlo Simulation method and arithmetic method.

The inputs used to calculate the critical flaw size are summarized in Table 2. The criterion for maintaining structural integrity is generally three times the differential pressure between the primary and secondary sides under normal operating conditions. The defect critical size of tapered wear is larger than that of flat wear.



(a) Flat wear defect

(b) Tapered wear defect

Fig. 10. Critical flaw size calculated by Model 5

Table II: Summary of inputs to calculate critical flaw size

Outer diameter	19.05 mm	
Thickness	1.09 mm	
Pressure limit	24.41 MPa	
	Mean	S.D.
Sum of material strength	797 MPa	18.9 MPa
Inspection error	Eq. (10)[9]	2.89 %TW[9]
Burst pressure model	Eq. (6)	5.69 MPa

3.3 Repair limit of AVB wear

Fig. 11 shows the defect repair limits for the lower 5% and 1% burst probability for flat wear and tapered wear with a defect length of 50.8 mm. Assuming an inspection cycle is 1.5EFPY, the repair thresholds depth for flat wear and tapered wear are 60 %TW and 52%TW, respectively.

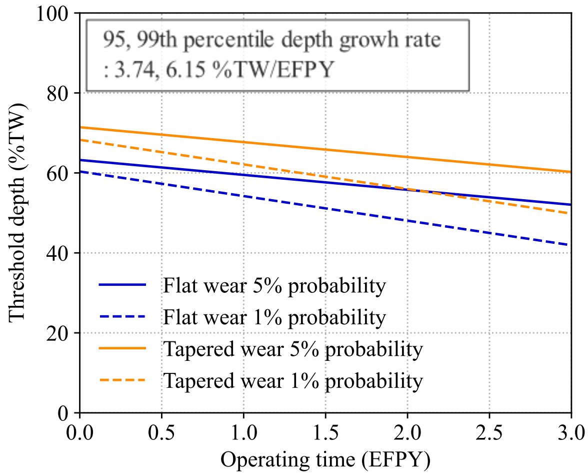


Fig. 11. Repair limit for anti-vibration bar fretting wear

4. Conclusions

In this study, existing burst pressure models were compared using burst test data from SG tubes with wear defects, and new repair criteria for fretting wear were proposed. The following key results were obtained:

(a) The burst pressure of SG tubes with wear defects is highly dependent on defect depth and is also influenced by defect length.
(b) Burst pressure models were evaluated using interpolation and extrapolation approaches based on the test data.
(c) A burst pressure model suitable for SG tubes with flat wear and tapered wear defects was investigated.
(d) New repair criteria for flat wear and tapered wear defects were proposed.

Acknowledgements

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