A New Repair Criterion for Inconel690 Alloy Steam Generator Tube with Fretting Wear

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Abstract. Structural integrity assessment of steam generator tubes (SGT) is important for the safety operation of pressurized water reactor. In this work, a repair criterion for Inconel690 SGT with fretting flaw was proposed. Firstly, experiments were conducted to address material strength, eddy current examination and bursting pressure of defected SGT. Then, a numerical method was proposed to predict bursting pressure. At last, all factors were concluded in a simplified statistical method of structural integrity assessment. For anti-vibration bar fretting, Condition Monitoring criterion, Operational Assessment criterion as well as the repair criterion for different inspection interval were proposed. The present criterion can provide reference for the inspection interval considering long-term temporary shutdown or standby.

1. Introduction
In Pressurized Water Reactor (PWR), Steam Generator Tubes (SGTs) consists the most vulnerable part of pressure boundary between primary and secondary loop. Structural integrity assessment of defected SGT is an important task of PWR maintenance. In China, most SGTs in PWRs are made from Inconel690 alloy. Fretting induced by fluid induced vibration has been recognized as the primary degradation mechanism of Inconel690 SGT[1-2]. In the structural integrity of a defective SGT, repair criterion such as 40%TW plugging criterion proposed by ASME or more conservative criterion such as repair on detection (ROD) are applied[3-4]. Evidences support that existing repair criterions are extremely conservative[5-7]. Investigations have been devoting on reducing conservatism of repair criterion[8-10]. However, as the structural integrity of SGT depends strongly on the technologies such as material, tube manufacturing and non-destructive examination accuracy. The repair criterion based on foreign operating experiences is not suitable for domestic PWRs. In China, a program is undergoing for SGT structural integrity assessment. The aim is to deal with the key technologies of flexible operation as long-term temporary shutdown or standby. The present work is a part of this program.

The purpose of this paper is to present a repair criterion with acceptable conservatism based on domestic technology fundamentals. The crucial uncertainties affecting the accuracy of SGT structural integrity assessment will be addressed by experiments. Numerical method is employed to predict bursting pressure. Probabilistic method is performed to evaluate the influence of uncertainties. A repair criterion with adjustable inspection interval was proposed for Inconel690 SGT with fretting flaw.
2. Experiment program

In order to obtain information about the uncertainties controlling SGTR event, a series of experiments were conducted on the material strength, the eddy current uncertainty and bursting pressure of Inconel690 alloy SGT. All investigated specimens were extracted from ∅19.05mm×1.09mm SGT, the chemical composition of the investigated material is listed in Table 1.

| Element       | C     | Si    | Mn    | S     | Ni     | Cr     | Fe     | Cu    |
|---------------|-------|-------|-------|-------|--------|--------|--------|-------|
| RCCM-M NC30Fe | 0.010–0.030 | ≤0.5 | ≤0.5 | ≤0.010 | ≥58.00 | 28.00–31.00 | 8.00–11.00 | ≤0.5 |
| UNS N06690    | ≤0.05 | ≤0.5 | ≤0.5 | ≤0.015 | ≥58    | 27–31  | 7–11   | ≤0.5 |
| Present work  | 0.022 | 0.05  | 0.02  | 0.0007 | 59.98  | 29.65  | 9.97   | 0.02  |

2.1 Tensile test of Inconel690 Alloy under 350°C

In order to measure yield and tensile strength of Inconel690 Alloy at 350°C, tensile test specimens were prepared. The specimen is curved plate extracted along the longitudinal direction of SGT. Both ends of the specimen were flatted and reinforced for connection purpose but leaving middle part of the specimen undeform. The sketch and dimensions of the specimen is shown in Fig.1. The applied strain rate was 2.5×10⁻⁴ s⁻¹. Extensometer with gauge of 50mm was used. Three specimens were tested.

![Sketch](image1) ![Photograph](image2)

Fig.1 Curved plate specimen for uniaxial tensile test

The resulting engineering stress-strain curves are shown in Fig.2, it is demonstrated that all specimens rupture in the middle part. The fracture strain is larger than 50%, rupture surface along shear band direction (45°) were found, which indicating the occurrence of typical ductile rupture. The yield and tensile strengths of Inconel690 alloy were listed in Table 2. It is demonstrated that Inconel690 alloy has a high tensile to yield strength ratio, indicating significant strain hardening behavior during deformation.

| Specimen 1 | Specimen 2 | Specimen 3 | RCCM-M specification |
|------------|------------|------------|----------------------|
| Yield strength $S_y$/MPa | 236 | 244 | 238 | ≥215 |
| Tensile strength $S_m$/MPa | 577 | 567 | 566 | ≥533 |

Considering that the present experiment cannot contain the variation of material strength in different batches and heats, we uses the RCCM-M specification value as the minimal material strength, hence the standard deviation of material strength $\sigma_m$ is...
Where \( Z \) is the normal deviate. Using Eqn.(1) will guarantee the worst case of material strength equals to RCCM-M specification value.

### 2.2 Bursting test of defected SGTs under 350°C

A total of 3 intact and 15 SGT specimens with artificial defects were prepared. The chosen defect type is general thinning (marked with A). The intact SGTs are marked with B. The defected specimens are illustrated in Fig.3. Actual dimensions of specimens are listed in Appendix A.

![Defected SGT specimens with artificial defects](image)

![Test facility of high temperature bursting test](image)

Bursting test of defected SGT specimens were conducted on the test facility shown in Fig.4. The facility consists of a loading system, a temperature control system and a signal collection system. The specimens were installed in a protective shell, and then the specimens were heated to 350°C before test. Temperature in the furnace was kept constant during test process. Pressurizing rate was 13.8MPa/min. Bursting pressure of the defected SGT specimens are listed in Table.3.

| Mark | Bursting pressure \( p \)/MPa |
|------|------------------------------|
| A-01 | 59.5                         |
| A-02 | 58.9                         |
| A-03 | 52.7                         |
| A-04 | 55.7                         |
| A-05 | 55.6                         |
| A-06 | 44.1                         |
| A-07 | 54.1                         |
| A-08 | 52.4                         |
| A-09 | 41.3                         |

| Mark | Bursting pressure \( p \)/MPa |
|------|------------------------------|
| A-10 | 52.6                         |
| A-11 | 47.4                         |
| A-12 | 39.8                         |
| A-13 | 41.5                         |
| A-14 | 37.8                         |
| A-15 | 30.7                         |
| B-01 | 59.9                         |
| B-02 | 59.5                         |
| B-03 | 59.6                         |

### 2.3 Eddy current examination uncertainty

Eddy current examination technique contributes uncertainty to the repair criterion of SGT significantly. In order to quantify the eddy current uncertainty, 81 defected SGT with different type volume defects were measured. The eddy current examinations were conducted by qualified employee with bobbin probe. Four type defects were considered: general corrosion, pitting, local corrosion and fretting. A type defect denotes general corrosion represented by circumferential thinning, B type defect is local corrosion represented by rectangular groove, C type defect is pitting represented by blinded hole, and D type defect is fretting scar as shown in Fig.5. Eddy current examination results are shown in Fig.6.
Fig. 5 Defected SGT for eddy current examination

Eddy current examination results was evaluated by relative error defined as

$$\varepsilon_{NDE} = \frac{\alpha_{EC} - \alpha_0}{\alpha_0} \times 100\%$$

(2)

Where $\alpha_{EC}$ is the eddy current measurement depth of defects, %TW. $\alpha_0$ is the actual value of defect depth, %TW. The eddy current measurement error distribution is shown in Fig. 7. It is demonstrated that the relative error obeys a normal distribution with middle value of -0.81% and standard deviation of 7.26%. Fig. 8 shows the linear regression of eddy current results, which provides the relationship between defect depth for structural assessment $\alpha_{FFS}$ and eddy current signal $\alpha_{EC}$ as

$$\alpha_{FFS} = 0.995\alpha_{EC} + 0.7069 \text{ %TW}$$

(3)

Fig. 6 Eddy current examination results

Fig. 7 Relative error distribution of eddy current examination

Fig. 8 Eddy current result linear regression

2.4 Defect growth rate

Growth of existing flaws must be evaluated in the operational assessment of next operating period. In the case of fretting, the length of flaws usually remains unchanged during the operating and therefore the growth of defect length can be ignored. The growth rate of flaw depth can be obtained from statistical analysis of previous inspection reports and the growth rate is usually different from period to period. In the present work, deterministic depth growth is represented by a projected worst case value which covers the upper boundary of existing inspection results. The 95th percentile fretting flaw growth rate is 3.5%TW/year at anti-vibration bar (AVB), which will be used in the establishing of repair criterion.
3. Numerical prediction of SGTR

3.1 Finite element models and analysis techniques
Plastic limit load of defected tube was calculated to estimate bursting pressure of SGT. Plastic limit load is that causes unrestricted plastic deformation by applying a small load perturbation. This limit state is considered as bursting in the case of SGTR. In order to perform a limit analysis, commercial finite element analysis (FEA) package ABAQUS 6.14 was employed. As per bursting test in Section 2, investigated was carried out on SGT with circumferential thinning using 2D axisymmetric model. The finite element model and boundary conditions of the problem is shown in Fig. 9. The model is composed of 3116 CAX4R elements which is 2D brick axisymmetric element with reduced integration. A constant inner pressure 100MPa is applied to all inner surface. Symmetrical boundary condition is applied to the section of the model.

![Fig.9 Geometric and finite element model](image)

Elasto-perfectly plastic material associates with J2 flow rule was used to describe material plasticity. Elastic module $E=180$GPa, Poisson’s ratio $\nu=0.35$, the flow stress was chosen as following. Limit load equation of cylindrical shell

$$p_L = \frac{2}{\sqrt{3}} \sigma_f \ln \left( \frac{D}{D-2t} \right)$$ (4)

Substituting bursting pressure of intact SGT specimens into Eqn.(4), B-01, B-02 and B03 specimen correspond to flow stress of 481MPa, 464MPa and 464MPa(calculated with actual SGT dimensions) respectively. Therefore, flow stress adopted in the numerical calculation is chosen as 464MPa for conservatism.

The nonlinear problem was solved with full Newton-Raphson iteration algorithm. Plastic limit load of the model is achieved when the iteration fails to convergence. The diverging criterion is when the load increment shrinks down to $1\times10^{-6}$.

3.2 Numerical results
In order to investigate the accuracy of bursting pressure prediction, all cases in the bursting test were calculated. Fig.10 shows the comparison between experiment bursting pressure and the prediction values. The results demonstrate that the proposed numerical prediction method is conservative, most prediction results are 10%~30% lower than experiment bursting pressure, which can be considered as safety margin.

![Fig.10 Bursting pressure prediction result](image)
A series of calculations were performed using the numerical method. The calculations were based on nominal dimensions of SGTs, i.e. ∅19.05mm×1.09mm. The numerical cases and results are listed in Table 4.

| L (mm) | L=2 | L=5 | L=8 | L=11 | L=13 | L=15 | L=16 | L=17 | L=18 | L=20 | L=30 |
|--------|-----|-----|-----|-----|------|------|------|------|------|------|------|
| 10 % TW | 63.6 | 61.9 | 60.6 | 59.8 | 59.4 | 59.1 | 59   | 58.9 | 58.9 | 58.8 | 58.7 |
| 30 % TW | 59   | 53.8 | 50.5 | 48.4 | 47.5 | 46.9 | 46.7 | 46.5 | 46.4 | 46.2 | 46.1 |
| 50 % TW | 51.8 | 44.5 | 39.8 | 36.6 | 35   | 34   | 33.7 | 33.6 | 33.5 | 33.4 | 33.4 |
| 70 % TW | 36.8 | 32.1 | 27.7 | 24   | 22   | 20.5 | 20.4 | 20.3 | 20.3 | 20.3 | 20.3 |
| 90 % TW | 12.7 | 11.4 | 9.7  | 8.2  | 7.4  | 6.9  | 6.8  | 6.8  | 6.8  | 6.8  | 6.8  |

3.3 Bursting pressure estimation model

Least square method was performed based on the results in Table 4. The regression yields following bursting pressure estimation model

\[ p_b = \sigma \left( A_1 \alpha + A_2 \alpha^2 + A_3 \alpha + 0.1392 \right) \]

where

\[ A_1 = 3.8793 \times 10^{10} L^2 + 1.7543 \times 10^8 L - 1.7968 \times 10^7 \]
\[ A_2 = 1.5194 \times 10^4 L^2 - 7.2103 \times 10^7 L - 6.2659 \times 10^6 \]
\[ A_3 = 2.0812 \times 10^9 L^2 - 9.2430 \times 10^5 L - 3.3094 \times 10^4 \]

(5)

With

\[ L = \begin{cases} 20 & \text{if } l \leq 20 \text{ mm} \\ l & \text{if } l > 20 \text{ mm} \end{cases} \]

(6)

Where \( p_b \) is bursting pressure, MPa. \( \alpha \) and \( l \) are defect depth in %TW and defect length in mm. Eqn.(6) implies a defect length of 20mm is long enough to ignore bulging effect.

Fig.11(a) shows the comparison between data in Table 4 and the prediction given by Eqn.(5). It is demonstrated that good fitness has been achieved. The bursting pressure decreases with the increasing of defect sizes. After \( l > 20 \text{mm} \), the defect is long enough to ignore bulging effect, as is indicated in Eqn.(6). Fig.11(b) displays the comparison between Eqn.(5) and experimental results. The results show that Eqn.(5) is conservative for most cases. The prediction error distribution of Eqn.(5) is shown in Fig.12.
4. SGTs integrity assessment method

At the end of next operating period (EOC), the actual size of flaws can be predicted with the eddy current examination result (EC) at the beginning of the operating period (BOC) as

$$\alpha_{EOC} = 0.995\alpha_{EC} + 0.7069 + 1.12Z_{EC} + 1.2G_{m}\Delta t \ %TW$$

Where $\sigma_{EC}$ is the standard deviation of eddy current examination. $Z_{\alpha}$ is the normal deviate of defect depth distribution. A factor of 1.12 is used to contain analytical error of the technique. $G_{m}$ is the growth rate of defect depth. $\Delta t$ is the time interval of inspection. A factor of 1.2 is used to contain the defect growth analytical error. The growth rate is a deterministic value as described in Sec 2.4.

Material strength uncertainty can be represented as

$$\sigma_{\sigma} = 0.574 (S_{\sigma} + S_{\alpha} - Z_{\sigma} \sigma_{m})$$

Where $\sigma_{m}$ and $Z_{m}$ are the standard deviation and normal deviate of material strength.

The bursting pressure of a predicted flaw at EOC is predicted with

$$p_b = \sigma_{p} \left( A_1\alpha_{EOC}^3 + A_2\alpha_{EOC}^2 + A_3\alpha_{EOC} + 0.1392 \right) - Z_{\sigma} \sigma_{p}$$

with

$$A_1 = -3.8793 \times 10^{-10} L^2 + 1.7543 \times 10^{-8} L - 1.7968 \times 10^{-7}$$

$$A_2 = 1.5194 \times 10^{-4} L^2 - 7.2103 \times 10^{-2} L - 6.2659 \times 10^{-4}$$

$$A_3 = 2.0812 \times 10^{-6} L^2 - 9.2430 \times 10^{-4} L - 3.3094 \times 10^{-4}$$

Where $\sigma_{p}$ and $Z_{p}$ are the standard deviation and normal deviate of bursting pressure estimation model.
Eqn.(5). In the case of fretting at AVB, \( l = 11 \text{mm} \).

For an SGT with a fretting flaw \((a_{EC}, l)\) which has been inspected, the bursting pressure of this SGT at EOC is a function of normal deviate of all known uncertainties.

\[
p_b^{a_{EC} \cdot l} = p_b^* (Z_n, Z_{a}, Z_p) \tag{10}
\]

Simplified statistical method described in EPRI steam generator integrity assessment guideline\[11\] is used to combine all the uncertainties as

\[
\begin{align*}
\Delta p_1 &= p_0 \cdot p_b^{a_{EC} \cdot l} (Z_c, 0, 0) \\
\Delta p_2 &= p_0 \cdot p_b^{a_{EC} \cdot l} (0, Z_c, 0) \\
\Delta p_3 &= p_0 \cdot p_b^{a_{EC} \cdot l} (0, 0, Z_c) \\
p_b^{a_{EC} \cdot l} &= p_0 - \sqrt{\Delta p_1^2 + \Delta p_2^2 + \Delta p_3^2} \tag{11}
\end{align*}
\]

Where \( Z_c \) is the critical normal deviate used in the evaluation, \( Z_c = 1.645/2.0/3.0 \) for a failure probability of 0.050/0.023/0.002 respectively.

5. Repair criterion of defect steam generator tube

With the development method, the structure integrity assessment of SGT with fretting can be evaluated. In AVB fretting case, the performance criterion of SGT is 25.83MPa which is 3 times of pressure differences applied to SGT at normal operating condition. Probabilistic parameters used in the assessment are listed in Table.5.

| Table.5 Probabilistic parameters for SGT integrity assessment |
|---------------------------------------------------------------|
| **Parameter** | **Distribution** | **Mean value** | **Standard deviation** |
|----------------|------------------|----------------|----------------------|
| Material strength* | Normal | 809 MPa | 37.08/30.5/20.33MPa for \( Z = 1.645 \), 2.0 and 3.0 |
| Defect depth | Normal | Eqn.(2) | 7.26 %TW |
| Defect length | Normal | 11mm | 0 |
| Bursting pressure model | Normal | Eqn.(4) | 3.27 MPa |
| Defect depth growth | Deterministic | 3.5 %TW/year | 0 |
| Defect length growth | Deterministic | 0 mm/year | 0 |

*Material strength deviation is designed to ensure the worst case equals to the RCCM-M specification value.

5.1 Condition monitoring

Fig.13 shows the Condition Monitoring(CM) result of SGT with fretting flaw. AVB fretting is investigated for illustration purpose, the CM critical depth of AVB fretting flaw is 49.8 %TW, 46.2%TW and 35.8%TW at cumulative failure probability of 0.05, 0.023 and 0.002 respectively. A more strict failure probability restriction will leads to lower tolerance of flaw size, as shown in Fig.13, when cumulative failure probability decrease from 0.05 to 0.002, the critical depth of flaw decrease 14%TW. However, cumulative failure probability of 0.05 is generally acceptable in engineering practice, as suggested by EPRI steam generator integrity assessment guideline[11].

5.2 Operational assessment

Operational assessment(OA) evaluate the potential of SGT failure at EOC, using the projected 95th percentile flaw depth growth rate 3.5%TW/year and \( Z = 1.645 \) for all uncertainties, OA results are demonstrated in Fig.14. The results show that critical depth of flaw depends on the time interval of inspection. As the proposed assessment method using deterministic flaw growth rate, the decrease of critical depth will be 3.5×1.2=4.2 %TW/year. Starting from CM results, 4.2%TW will be removed from allowable flaw depth for each operating year.
5.3 Repair criterion

Based on aforementioned discussions, the new repair criterion for typical fretting flaws is obtained. As shown in Fig.15, the dash line is the acceptable boundary of flaw dimension, which is translated from base line according to specific flaw growth rate and operating period. The critical dimension of a given flaw can be represented as

\[ \alpha_{\text{critical}} = \alpha_{\text{base line}} - 1.2 G_r \Delta t \]  \hspace{1cm} (12)

Where both \( \alpha_{\text{base line}} \) and \( \alpha_{\text{critical}} \) are the eddy current examination signal. In engineering application, one should determine the coordinates of the given flaw on base line according to eddy current examination, then calculating the critical flaw depth \( \alpha_{\text{critical}} \) with Eqn.(12), if the detected flaw depth is less than \( \alpha_{\text{critical}} \), it can be leave without plugging or repair until next inspection interval.

Using the proposed repair criterion and \( G_r = 3.5\% \text{TW/year} \), repair criterion for AVB fretting is shown in Fig.16. The classical 40%TW plugging criterion is also plotted. It depicts that at cumulative failure probability of 0.05, 40%TW plugging criterion will be conservative when inspection interval is less than 2 years. However, with the increase of inspection interval, the repair critical flaw depth decreases monotonous. For inspection interval longer than 3 years, the proposed repair criterion is less than 40%TW. Nevertheless, the proposed method shows how to extent inspection interval safely with regards to fretting degradation, which will be practical in Nuclear Station operation.

6. Conclusion

Experiment program was performed on Inconel690 alloy material strength, eddy current examination
uncertainty and bursting pressure measurement. A numerical method was suggested to predict SGTR pressure. Simplified statistical method was used to conduct the structural integrity assessment. Following conclusions can be made:

(1) A repair criterion was proposed for Inconel690 steam generator tube with fretting flaw.
(2) The proposed criterion indicates that 40%TW plugging is conservative for inspection interval less than 2 years.
(3) The present criterion provides theoretical evidence for the extension of inspection interval in engineering practice.

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Appendix A

| Mark | Nominal Diameter /mm | Nominal Thickness /mm | Diameter D/mm | Thickness t/mm | Defect depth a/mm | Defect length l/mm |
|------|----------------------|-----------------------|--------------|----------------|------------------|-------------------|
| A-01 | 19.05                | 1.09                  | 19.01        | 0.99           | 0.330            | 2.001             |
| A-02 | 19.05                | 1.09                  | 19.01        | 1.00           | 0.441            | 2.002             |
| A-03 | 19.05                | 1.09                  | 19.02        | 0.99           | 0.651            | 2.002             |
| A-04 | 19.05                | 1.09                  | 19.02        | 1.00           | 0.331            | 5.001             |
| A-05 | 19.05                | 1.09                  | 19.01        | 0.99           | 0.449            | 5.002             |
| A-06 | 19.05                | 1.09                  | 19.02        | 1.00           | 0.651            | 5.003             |
| A-07 | 19.05                | 1.09                  | 19.00        | 0.99           | 0.334            | 8.010             |
| A-08 | 19.05                | 1.09                  | 19.01        | 0.99           | 0.441            | 8.012             |
| A-09 | 19.05                | 1.09                  | 19.02        | 1.00           | 0.652            | 8.013             |
| A-10 | 19.05                | 1.09                  | 19.01        | 0.98           | 0.334            | 10.011            |
| A-11 | 19.05                | 1.09                  | 19.01        | 1.00           | 0.442            | 10.010            |
| A-12 | 19.05                | 1.09                  | 19.02        | 1.00           | 0.652            | 10.003            |
| A-13 | 19.05                | 1.09                  | 19.01        | 0.98           | 0.331            | 30.011            |
| A-14 | 19.05                | 1.09                  | 19.00        | 0.99           | 0.442            | 30.010            |
| A-15 | 19.05                | 1.09                  | 19.00        | 1.00           | 0.651            | 30.001            |
| B-01 | 19.05                | 1.09                  | 18.99        | 0.97           | /                | /                 |
| B-02 | 19.05                | 1.09                  | 19.03        | 1.00           | /                | /                 |
| B-03 | 19.05                | 1.09                  | 19.01        | 1.00           | /                | /                 |

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