LIMIT LOAD ANALYSIS FOR LOCAL WALL-THINNING STEAM GENERATOR TUBES

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ABSTRACT
Steam generator(SG) tubes form approximately 80% of pressure boundary of the reactor primary coolant\(^1\). During the past 40 years, a large number of operating PWP\(s\) have experienced degradation due to local wall-thinning of SG tubes, which was caused by corrosion or squeezing of tubes at support plate or tubesheet intersections or other reasons.

This paper introduced the study of experiment and numerical analyses for plastic limit loads of local wall-thinning SG tubes. The effect of the dimension of local wall-thinning on plastic limit load was analyzed.

The main contents in this paper were summarized as follows:

1 Experiment equipment which could test not only bursting pressure but also plastic limit load was built. Two kinds of local wall-thinning shapes were respectively made on SG tubes. One kind of local wall-thinning shape was rectangle-like flaw, which was used to simulate local wall-thinning caused by squeezing of tubes at support plate. The other kind of local wall-thinning shape was arc-like flaw, which was used to simulate local wall-thinning caused by corrosion. Different size local wall-thinning SG tubes of these two kinds of shape were test by using the equipment.

2 Regularization method for local wall-thinning defect was provided based on experimental and finite element method.

3 The effect order of local wall-thinning configuration on plastic limit load was studied. It was found that:

Except defect thickness, the longitudinal length and circumferential length of SGT defect can also influence the plastic limit load; When the longitudinal length of SGT defect exceeded 6mm, the effect of longitudinal length on plastic limit load can be ignored; When the circumferential angle of defect exceed 45°, the effect of circumferential angle on plastic limit load can be ignored.

Keywords: SG tubes , local wall-thinning, limit load

1 INTRODUCTION
Steam generator (SG) tubes form approximately 80% of pressure boundary of the reactor primary coolant\(^1\). During the past 40 years, a large number of operating PWP\(\text{s} have experienced degradation due to local wall-thinning or stress corrosion crack of SG tubes, which was caused by corrosion, squeezing of tubes at support plate or tubesheet intersections or other reasons\(^2\).

After 1990, Inconel 690 became the main SG tube material all over the world. Except in Qinshan and Tianwan nuclear power plant, Inconel 690 is the tube material that being used in operating steam generator in China\(^3\). Stress corrosion crack hasn’t been found on Inconel 690 ST tubes since its application\(^4\). Local wall-thinning is the main type of degradation of Inconel 690 SG tubes.

The main aim of this research was to find effect order of local wall-thinning on SG tube strength.

2 TEST PROGRAM AND EXPERIMENTAL RESULTS

2.1 Inconel 690 ST tubes and mechanical properties of Inconel 690

Inconel 690 steam generator tubes had an outside diameter of 19.05mm and wall thickness of 1.09mm. The mechanical properties of Inconel 690 such as yield strength and ultimate tensile strength at room temperature and 300\(^\circ\)C were test and the characteristic data is list on table 1. These data were also being used for the analytical investigations that are reported here.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>20(^\circ)C</th>
<th>300(^\circ)C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield stress</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sy (MPa)</td>
<td>291</td>
<td>260</td>
</tr>
<tr>
<td>Ultimate Tensile Strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Su (MPa)</td>
<td>718</td>
<td>558</td>
</tr>
</tbody>
</table>

2.2 Experiment equipment

Experiment equipment (see Figure 1) which can test not only burst pressure but also plastic limit load was established. Displacement sensor was used to test the radial displacement of SG tube’s outside wall, meanwhile, the pressure data was test by a pressure sensor. Both pressure and displacement signal were sent to computer by data collection system and the curve of pressure vs. radial displacement can be got in computer. According to the curve, the failure course and plastic limit load can thus be got.

![Figure 1 Experimental device](image)

2.3 Test for undegraded SG tubes

Burst tests for three undegraded SG tubes were performed and the curves of pressure vs. radial displacement were got. The three curves were very alike, thus only one curve was plot (see Figure 2). Displacement sensor was pulled away before burst in order to protect it. So only the pressure data was recorded by computer after the displacement being removed. According to Figure 2, plastic limit load of
undegraded SG tube was got by using “double elastic slope method” recommended by ASTM[5]. The plastic limit load was 37.3MPa and the burst pressure was 72MPa.

2.4 Test for some degraded SG tubes

Two typical kinds of local wall-thinning defect were respectively made on SG tubes. One kind of local wall-thinning shape was rectangle-like flaw (projection geometry, see Figure 3), being used to simulate local wall-thinning caused by squeezing of tubes at support plate. The other kind of local wall-thinning shape was arc-like flaw (projection geometry, see Figure 4), being used to simulate local wall-thinning caused by corrosion. Different sized local wall-thinning SG tubes of these two kinds of shape were test at room temperature by using the equipment. In these test, the displacement sensor probe was installed to aim at the center of local wall-thinning area. The shape and size of local wall-thinning listed in Table 2, and the plastic limit load and burst pressure listed in Table 3. Curves of some specimen(specimen 2 and specimen 3) were plot on Figure 5 and Figure 6 as example and the picture of the two specimens after burst were plot on Figure 7 and Figure 8 respectively.

Figure 2 Experimental curve of pressure vs. radial displacement

Figure 3  Rectangle-like flaw

Figure 4  Arc-like flaw
Table 2  Defect size of specimen

<table>
<thead>
<tr>
<th>Item</th>
<th>Specimen</th>
<th>Defect thickness (mm)</th>
<th>Defect Length (mm)</th>
<th>Circumferential angle</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0.462</td>
<td>6.00</td>
<td>35.0°</td>
<td>rectangle</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.413</td>
<td>6.00</td>
<td>35.0°</td>
<td>rectangle</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.500</td>
<td>6.00</td>
<td>19.3°</td>
<td>arc</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.575</td>
<td>6.00</td>
<td>21.6°</td>
<td>arc</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.252</td>
<td>5.25</td>
<td>16.8°</td>
<td>arc</td>
</tr>
</tbody>
</table>

Table 3  Experimental results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Plastic limit load(MPa)</th>
<th>Burst pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>26.27</td>
<td>29.21</td>
</tr>
<tr>
<td></td>
<td>56.81</td>
<td>59.25</td>
</tr>
</tbody>
</table>

Figure 5  Experimental curve of pressure vs. radial displacement of specimen 2

Figure 6  Experimental curve of pressure vs. radial displacement of specimen 3

Figure 7  Picture of specimen 2

Figure 8  Picture of specimen 3

3 FINITE ELEMENT ANALYSIS OF DEGRADED SG TUBES

The shape and size of local wall-thinning defect were various. It was impossible to test for all of these...
degraded SG tubes. So, finite element method was used to study the effect of local wall-thinning on SG tube’s strength.

A local wall-thinning defect can be regularized to be a segment of regular annular volume, which involves the defect (see Figure 9). A regular defect has three dimension: the thickness, the longitudinal length and the circumferential length.

![Figure 9.a Regular defect of local wall-thinning](image)

![Figure 9.b Regular defect of local wall-thinning](image)

Material was supposed to be ideal elastic-plastic material in limit analysis. The stress-strain curve of the material can be seen from Figure 10. The flow stress $\sigma_f$ had several definition. For example, the value of flow stress was determined to be equal to that of yield stress ($\sigma_f = \text{Sy}$) in some standards[6], otherwise, in other documents and standards[7] the value of flow stress was determined to be equal to half of the summary of yield stress and ultimate tensile strength ($\sigma_f = (\text{Sy} + \text{Su})/2$). In this paper, it was found that the calculational value of plastic limit load was much more close to the experimental results when $\sigma_f$ is equal to yield stress ($\sigma_f = \text{Sy}$). The calculational result analyzed by finite element method listed on table 4. It could be seen from table 4 that the calculational value of plastic limit load for regularized defect was appreciably smaller than experimental plastic limit load of the fact defect. Thus, the conservative result will be got by using finite element analysis.

### Table 4  Calculational result and experimental results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Pressure</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>22.4</td>
<td>25.0</td>
<td>22.8</td>
<td>20.6</td>
<td>31.4</td>
</tr>
<tr>
<td></td>
<td>Calculational result of Plastic limit load (MPa)</td>
<td>26.27</td>
<td>29.21</td>
<td>27.38</td>
<td>24.41</td>
<td>31.78</td>
</tr>
<tr>
<td></td>
<td>Experimental result of Plastic limit load (MPa)</td>
<td>-14.7</td>
<td>-14.4</td>
<td>-16.7</td>
<td>-15.6</td>
<td>-0.01</td>
</tr>
</tbody>
</table>
Plastic limit load of degraded SG tubes with different values of \( Z/T (0.2, 0.4, 0.6, 0.8) \times (2\text{mm}, 4\text{mm}, 6\text{mm}, 8\text{mm}, 10\text{mm}) \) and \( \theta (6^\circ, 12.25^\circ, 22.5^\circ, 45^\circ, 180^\circ) \) were studied (See Figure 11~17).

Here, \( P_{LO} \): plastic limit load of undegraded tube; \( P_L \): plastic limit load of degraded tube.

R: average radius of SG tube; T: thickness of SG tube wall;

Figure 11 Curves of plastic limit load vs. longitudinal length when \( \theta = 6^\circ \)

Figure 12 Curves of plastic limit load vs. longitudinal length when \( \theta = 11.25^\circ \)

Figure 13 Curves of plastic limit load vs. longitudinal length when \( \theta = 22.5^\circ \)

Figure 14 Curves of plastic limit load vs. longitudinal length when \( \theta = 45^\circ \)

Figure 15 Curves of plastic limit load vs. \( \theta / \pi \)
It could be seen from Figure 11~17 that:

1. Thickness was the main factor influencing the plastic limit load of SGT. The value of plastic limit load decreased about 7%~35% when the defect thickness increased 20%. The decrease extend relate to the longitudinal length and the circumferential length.

2. The longitudinal length of SGT defect was an important factor influencing the plastic limit load of SGT; The smaller the circumferential length, the more prominent of the effect of the longitudinal length. When the longitudinal length of SGT defect exceeded 6mm, the effect of longitudinal length on plastic limit load can be ignored.

3. The circumferential length of SGT defect has effect on the plastic limit load. When the thickness is large and the longitudinal length is small, the effect is large. To most of the defect, when the circumferential angle of defect exceed 45°, the effect of circumferential angle on plastic limit load can be ignored.

4. CONCLUSION AND EXPECTATION

Experiment equipment which can test not only bursting pressure but also plastic limit load of SG tubes has been built. SG tubes with typical local wall-thinning defects have been analyzed by both experimental and finite element analytic method. The results show that the calculational value of plastic limit load for a regular defect is conservative when compared with the experimental result of SG tubes with fact defect.
Finite element analysis of a number of SG tubes with regular defects showed that: Except defect thickness, the longitudinal length and circumferential length of SGT defect can also influence the plastic limit load; When the longitudinal length of SGT defect exceeded 6mm, the effect of longitudinal length on plastic limit load can be ignored; When the circumferential angle of defect exceed 45°, the effect of circumferential angle on plastic limit load can be ignored.

Continuation of the program is still in progress to study effect of local wall-thinning configurations in U-bends on plastic limit load and to study a new plugging criterion based on three parameters (three dimensions of local wall-thinning defect). Compared with the plugging criterion based only on defect thickness, the new plugging criterion may be more accurate and scientific. Of course, the application of the new plugging criterion must be based on the advanced method for defect inspection.

REFERENCES
5 ASME Boiler and Pressure Vessel Code Section III, Division 1, Nuclear Power Plant Components, New York: Publish by the ASME,2001 Edition