Failure Pressure Assessment of the Circumferentially Flawed Heat Exchanger Tubes*

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Abstract

Since the structural integrity of thin-walled tubes in the heat exchanger is crucial from the viewpoint of safety and reliability, the integrity evaluation for flawed tubes is quite important. Accurate estimation of the failure pressure is a key element of the structural integrity assessment. With regard to the prediction of the failure pressure, most of preceding researches have been focused on the limit load approach. However, the integrity assessment scheme based on the elastic plastic fracture mechanics concept has not been settled despite of its accuracy and efficiency. In this paper, three-dimensional finite element analyses assuming elastic plastic material behavior are carried out for the thin-walled tubes with various sizes of the circumferential flaws. As for the flaw location, both the top of tube sheet and transition regions are considered. The flaw instability is evaluated by comparing the driving force with the fracture toughness of the tube material. Analysis results show that the elastic plastic fracture mechanics approach accurately predicts the failure pressures compared to the experimental data. Thus, it is thought that the elastic plastic fracture mechanics concept can be applied to the integrity assessment of the heat exchanger tubes with the circumferential through-wall flaws.

Key words: Thin-Walled Tube, Elastic Plastic Fracture Mechanics, J-Integral, Failure Pressure, Integrity Assessment

1. Introduction

Heat exchangers in the nuclear power plants are equipped with thousands of thin-walled tubes. Operating experience of the heat exchangers shows that the tubes are affected by various degradation mechanisms\(^{(1,2)}\). Since the structural integrity of the tubes is crucial from the viewpoint of safety and reliability, the integrity evaluation of the flawed tubes is very important. Accurate estimation of the failure pressure is a key element of the structural integrity assessment. With regard to the prediction of the failure pressure, most of the preceding researches have been focused on the limit load (LL) approach\(^{(3-5)}\). Noting that the materials of the heat exchanger tubes are very ductile, the application of the limit load approach seems plausible\(^{(6)}\). However, several terms are used in the literature to define the limit load in that the limit load is in a generic sense to collectively indicate either the plastic instability or the collapse loads\(^{(7,8)}\). Therefore, one has to determine the appropriate definition of the limit load and the corresponding solution for a given structure before performing the
integrity assessment. Moreover, to gain the sufficient confidence of the limit load, extensive test data would be needed. In contrast to this, the integrity assessment based on the elastic plastic fracture mechanics (EPFM) concept has not been settled despite of its accuracy and efficiency. The advantage of the EPFM approach, compared with the limit load one, is that the EPFM approach can be easily generalized. For instance, when a different service condition is considered, then the limited experimental validation would be sufficient. The objective of this study is to evaluate the failure pressure of the heat exchanger tubes with circumferential through-wall flaws (TWFs) based on the EPFM concept and to investigate the applicability of the EPFM approach to the integrity evaluation of the thin-walled tube. To achieve this goal, a number of elastic plastic finite element analyses for the flawed tubes are carried out. As for the flaw location, both the top of tube sheet (TTS) and transition regions, where circumferential flaws have been found in many heat exchangers during operation(1)(2), are considered. The flaw instability is evaluated by comparing the driving force with the corresponding fracture toughness of the tube material.

Nomenclature

\(E\) : Young’s modulus, MPa
\(J\) : J-integral, kJ/mm²
\(J_C\) : fracture toughness, kJ/mm²
\(BS_N\) : normalized bending stress \(=\sigma B R_m/t\sigma_f\)
\(M\) : bending moment, N-mm
\(P\) : failure pressure, MPa
\(P_N\) : normalized failure pressure \(=PR_m/t\sigma_f\)
\(R_{\text{bend}}\) : bend radius of tube, mm
\(R_m\) : mean radius of tube, mm
\(R_o\) : outer radius of tube, mm
\(t\) : thickness of tube, mm
\(\Delta a\) : crack extension, mm
\(\theta\) : a half of flaw angle, radian
\(\lambda\) : normalized bend radius \(= R_{\text{bend}}/R_m^{\frac{2}{3}}\)
\(\sigma_B\) : bending stress, MPa
\(\sigma_f\) : flow stress \(= (\sigma_{YS}+\sigma_{UTS})/2\), MPa
\(\sigma_{UTS}\) : tensile strength, MPa
\(\sigma_{YS}\) : yield strength, MPa

2. Existing Solutions

There are no closed-form solutions based on the EPFM approach for the circumferentially flawed tube. Under the combined internal pressure and bending load condition, the well-known limit load solution for a circumferential TWF in a straight tube was put forward by Kanninen, et al. (8), given as

\[ M = 2R_m^3t\sigma_f (2\sin \beta - \sin \theta) \]  \tag{1}

where \(M\) : bending moment
\(R_m\) : mean radius of the tube
\(t\) : thickness of the tube
\(\sigma_f\) : flow stress
\[ \beta = \frac{\pi - \theta}{2} - \frac{\pi}{4} \frac{PR_m}{t\sigma_f} \]
\[ \theta : \text{a half of the flaw angle} \]
\[ P : \text{failure pressure.} \]

Another solution was given by Zahoor\textsuperscript{(9)}.

\[ M = 4R_o^2\sigma_f(1 - \zeta + \frac{\zeta^2}{3})(\cos \alpha - 0.5 \sin \theta) \]

(2)

where \( R_o : \) outer radius of the tube
\[ \zeta = t/R_o \]
\[ \alpha = \frac{\theta}{2}(1 - \zeta)(1 + 0.5\zeta)/[1 - \zeta^2] + \frac{P}{4\sigma_fR_o(1 - \zeta)}. \]

Although there are no limit load solutions for the circumferential TWF at the transition region, it seems that the limit load solutions for the TTS can be used instead due to the geometrical analogy between the two locations.

3. Analysis Method

The integrity evaluation based on the EPFM concept requires two elements. The first one involves the measurement of the fracture toughness of the material, for instance, in terms of the \( J \)-resistance (\( J \)-\( R \)) curve. The other one is to estimate the driving force in terms of the \( J \)-integral. Tensile properties of the tube material, Alloy 600, were obtained from the tensile test by the authors in accordance with ASTM E 8\textsuperscript{(10)} and the resulting true stress-strain data is illustrated in Fig. 1. Yield strength of the tube material is 325 MPa, tensile strength is 670 MPa, and Young’s modulus is 200 GPa. The fracture toughness of the tube material was determined by some of the authors from the experimental load-load line displacement data of the tubular specimens\textsuperscript{(11)}. The \( J_c \) value characterizes the toughness of a material near the onset of crack extension. It was determined at the intersection of the regression line with the 0.2 mm offset line that is parallel to the construction line defined as

\[ J = A\sigma_f\Delta a \]

(3)

![Fig. 1. True stress-strain curve of the tube material](image-url)
Table 1. Fracture toughness of the tube material\(^{(11)}\)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>(J_C) (kJ/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>945</td>
</tr>
<tr>
<td>A2</td>
<td>1052</td>
</tr>
<tr>
<td>A3</td>
<td>945</td>
</tr>
</tbody>
</table>

where \(A\) is \(2^{(12)}\) and \(\Delta a\) is the crack extension. The resulting \(J_C\) values are summarized in Table 1.

To investigate the applicability of the EPFM concept to the heat exchanger tube integrity, the predicted failure pressure by using the \(J\)-integral obtained from the finite element (FE) analysis and the fracture toughness of the tube material was compared with the corresponding experimental results. For the flaw location, both the top of tube sheet and transition regions from U-bend to straight tube were considered, as shown in Fig. 2. Table 2 describes the geometry and dimensions for the circumferential TWFs at the TTS region, and Fig. 3 depicts a typical FE model, considered in this paper.

![Schematic of the TTS and transition regions](image)

(a) Top of tube sheet region  (b) Transition region

Table 2. Geometry and dimensions of the TTS and transition regions

<table>
<thead>
<tr>
<th>Location</th>
<th>(R_m) (mm)</th>
<th>(t) (mm)</th>
<th>(\lambda = R_{Bend}/R_m^2)</th>
<th>(\theta/\pi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTS</td>
<td>7.5</td>
<td>1.0</td>
<td>-</td>
<td>0.32, 0.50, 0.68</td>
</tr>
<tr>
<td>Transition</td>
<td>7.5</td>
<td>1.0</td>
<td>7.4, 16.1</td>
<td>0.32, 0.50, 0.68</td>
</tr>
</tbody>
</table>

In order to avoid the numerical problems associated with incompressibility, reduced...
integration twenty-noded isoparametric solid elements were utilized. Elastic plastic analyses based on the incremental plasticity theory with the small deformation assumption were performed by using ABAQUS code\(^{(13)}\). Materials were assumed to be elastic plastic, obeying von Mises flow criterion, and symmetric conditions were utilized in the FE models. As for the boundary condition, one end of the tube was modeled as fixed and the other as simply supported to simulate the tube sheet and support plate respectively. The length of the tube was about 1,150mm, which was the same with the test specimens\(^{(14)}\). During the FE analyses, internal pressure was applied to the internal surface of the FE model as a distributed load, and bending load was applied to as a concentrated load. To consider the effect of the flaw face pressure, a half of the internal pressure was applied to the flaw face. As for the failure criterion, a commonly used flaw initiation criterion was adopted. That is, when the applied \(J\)-integral value reaches the lowest fracture toughness of the tube material described in Table 1, then the failure of the tube occurs. Considering the thin section of the tube, this assumption seemed to be theoretically sound. The applied \(J\)-integral values were obtained by domain integral method in ABAQUS code.

Table 2 describes the geometry and dimensions for the circumferential TWFs at the transition region, and a typical FE model is illustrated in Fig. 4. The elastic plastic analyses were also performed for the transition region by using the same procedure and method for the TTS region. As for the boundary condition, both ends of the tube were simulated as fixed to simulate the support plates.

![Fig. 4. Typical FE model for a circumferential TWF at the transition region](image)

### 4. Analysis Results

#### 4.1 Circumferential Flaw at Top of Tube Sheet Region

Figure 5 shows the comparison of FE results with analytical limit load solutions and test data\(^{(14)}\), which are available only for \(\theta/\pi=0.32\) and 0.5 cases. As shown in this figure, the failure pressure decreases as the applied bending stress increases. The results also show that the predicted failure pressures by FE analyses agree well with the corresponding test data, whereas the analytical limit load solutions significantly under-predict the failure pressures. In the case of the small flaw (\(\theta/\pi=0.32\)), as shown in Fig. 5(a), the difference between the FE result and the analytical limit load increases as the applied bending stress increases; the difference is minimum at the pure pressure case, where the only internal pressure is applied, and reaches the maximum at the pure bending case. In the case of the medium and large flaws, the similar trends were observed as depicted in Figs. 5(b) and 5(c). However, the difference between the FE result and the analytical limit load significantly
increases as the flaw size increases. The reason for such behavior seems that the effect of
the compressive bending stress at the flaw plane caused by the support plate is not properly
considered in both analytical solutions\(^{(15)}\). Therefore, the existing limit load solutions are
not appropriate in the integrity evaluation of the flawed heat exchanger tubes, because the
predicted failure pressures could be significantly lower than the actual ones.

In order to develop the EPFM solution based on the present FE results, a non-linear
regression analysis was performed for the normalized failure pressure, \(P_N = \frac{P_{L}}{\sigma_{f}}\), versus
normalized bending stress, \(BS_N = \frac{\sigma_{BR}}{\sigma_{f}}\), curve. The resulting solution given in Eq. (4)
agrees very well with the corresponding FE results within 5% deviation, as depicted in Fig.
6. The proposed FE-based solution is believed to be accurate and thus can be simply used in
the practical integrity assessment of the flawed heat exchanger tubes.

\[
P_N = A_1 + A_2 BS_N + A_3 BS_N^2 + A_4 BS_N^3
\]  

(4)

where

\[
A_1 = 1.01 - 0.1580 \theta
\]

\[
A_2 = -0.087 + 0.0650 \theta - 0.0150 \theta^2
\]

\[
A_3 = 0.018 - 0.0177 \theta + 0.0050 \theta^2
\]

\[
A_4 = -0.0012 + 0.00060 \theta - 0.00020 \theta^2.
\]

![Graph showing failure pressure prediction results for TWFs at TTS](image)

Fig. 5. Failure pressure prediction results for TWFs at TTS

4.2 Circumferential Flaw at Transition Region

Figures 7 and 8 show the comparison of FE results with analytical limit load solutions
Fig. 6. Comparison of the normalized failure pressures for TWFs at TTS

Fig. 7. Failure pressure prediction results for TWFs at transition to short radius U-bend ($\lambda=7.4$)

and test data\(^{14}\), which are available only for $\theta/\pi=0.68$ case. As shown in these figures, the failure pressure decreases as the applied bending stress increases in a similar manner to that observed for the TTS. The results also show that the predicted failure pressures by FE
analyses agree well with the corresponding test data, whereas the analytical solutions significantly under-predict the failure pressures. In the case of the small flaw ($\theta/\pi=0.32$) at the transition to the short radius U-bend ($\lambda=7.4$), the difference between the FE result and the analytical limit load is minimum at the pure pressure case and reaches the maximum at the pure bending case, as shown in Fig. 7(a).

However, in the case of the large flaw ($\theta/\pi=0.68$), the difference is drastically increased for both the pure pressure condition and the pure bending condition. Similar results were obtained for the transition to the long radius U-bend ($\lambda=16.1$), as illustrated in Fig. 8. In addition, the bend radius affects the failure pressures of the transition region: Increase of the bend radius results in smaller failure pressure. The reason for such behavior seems that the effects of the compressive bending stress at the flaw plane caused by the support plate and the difference in flexibility between the straight and U-shaped tube are not properly considered in both analytical solutions\(^{(15)}\). Therefore, the existing limit load solutions are not appropriate in the integrity evaluation of the flawed heat exchanger tubes, because the predicted failure pressures could be significantly lower than the actual ones.

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**Fig. 8.** Failure pressure prediction results for TWFs at transition to long radius U-bend ($\lambda=16.1$)

In order to develop the EPFM solution based on the present FE results, the non-linear regression analysis was performed for the normalized failure pressure versus normalized bending stress curve for the transition to the long radius U-bend. Because the failure pressures of the transition to the long radius U-bend are lower than those for the transition
to the short radius U-bend. The resulting solution given in Eq. (5) agrees very well with the corresponding FE results within 4% deviation, as depicted in Fig. 9. The proposed FE-based solution is believed to be accurate and thus can be simply used in the practical integrity assessment of the flawed heat exchanger tubes with $\lambda \leq 16.1$.

\[
P_N = B_1 + B_2 BS_N + B_3 BS_N^2 + B_4 BS_N^3
\]  

where $B_1 = 1 - 0.17\theta$

$B_2 = -0.138 + 0.084\theta - 0.0138\theta^2$

$B_3 = 0.0373 - 0.0285\theta + 0.0062\theta^2$

$B_4 = -0.0027 + 0.0011\theta - 0.0002\theta^2$.

![Fig. 9. Comparison of the normalized failure pressures for TWFs at transition](image)

5. Conclusion

In this paper, a number of the elastic plastic finite element analyses were carried out for the heat exchanger tubes containing circumferential through-wall flaws. The flaw instability was evaluated by comparing the driving force with the fracture toughness of the tube material. The analysis results show that the EPFM approach accurately predicts the failure pressures compared to the experimental data. Thus, it is thought that the EPFM concept can be applicable to the integrity assessment of the flawed thin tubes. Based on the FE results, EPFM solutions are developed. The proposed FE-based solutions given in a polynomial form are believed to be accurate and thus can be simply used in the practical integrity assessment of the heat exchanger tubes with circumferential through-wall flaws.

References

(4) Frederick, G. and Hernalsteen, P., Belgian Approach to Steam Generator Tube Plugging for Primary Water Stress Corrosion Cracking, EPRI NP-6626SD (1990).