Flaw Evaluation of Japanese Carbon Steel Piping by Load Curve Approach

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ABSTRACT

New simplified flaw evaluation method, "Load Curve Approach" was developed to evaluate the fracture load of circumferentially surface-cracked pipe. This approach has the same functions with the current Two-criteria approach. Fracture stress and fracture criteria are easily estimated by two load curves based on J-resistance and plastic collapse.

Fracture analysis was conducted for Japanese carbon steel piping using this approach. The approach showed the dependency of flaw geometry and pipe diameter on pipe fracture.

1. Introduction

It is necessary for the aged nuclear power plants to rationalize inspection process and to establish the effective evaluation method for flaws detected by in-service inspection. ASME-XI pipe flaw evaluation procedures and R6 (Two-criteria approach) are representative approaches to be used in code analysis [1-2]. However, they are relatively complex procedures. More simplified flaw evaluation methods are desired for maintenance engineers at nuclear power plants.

The new flaw evaluation method, "Load Curve Approach" was developed to make fracture assessment for circumferentially surface-cracked nuclear piping under tensile and bending loads and to estimate the allowable crack geometry for continued plant operations. In this approach, the evaluation method is highly simplified because the screening of pipe fracture criteria and the estimation of fracture load can be simultaneously performed, based on two load curves from elastic-plastic fracture mechanics and plastic collapse.

This approach was applied to Japanese nuclear carbon steel piping. The effects of flaw geometry and pipe size on fracture load were examined. Estimated fracture loads were highly dependent on pipe diameters.

It is found that Load Curve Approach has the equivalent analytical functions to the R6 approach developed by Nuclear Electric in UK and it is fully applicable for flaw evaluation of Japanese nuclear piping.

2. Pipe Flaw Evaluation by Load Curve Approach

2.1 Analysis Method

The simplified pipe flaw evaluation method, "Load Curve Approach" was developed based on the concept in Two-criteria approach [2]. Two load curves were calculated from the
corresponding fracture criteria of elastic-plastic fracture mechanics and plastic collapse (section collapse). Fracture loads and fracture criteria can be simultaneously estimated from two load curves.

(1) Calculation of Load Curve based on J-integral

In Two-criteria approach, "Kr", a parameter on fracture toughness is given by

\[ K_r = (J_e/J)^{1/2} = f_{FAC} \]  \hspace{1cm} (1)

where \( J \) is elastic-plastic J-integral, \( J_e \) is elastic part of J-integral and \( f_{FAC} \) is a failure assessment curve (FAC). Then, J-integral is

\[ J = J_e / (f_{FAC})^2 \]  \hspace{1cm} (2)

As the failure assessment curve, R6 option 2 is used for simplicity.

\[ f_{FAC} = [(E \varepsilon \text{ref}/L_r \sigma_Y) + (L_r^3 \sigma_Y/2E \varepsilon \text{ref})]^{0.5} \]  \hspace{1cm} (3)

where \( E \) is Young's modulus, "\( L_r \)" is a parameter on plastic collapse load, \( \sigma_Y \) is yield stress of the material (=\( E \varepsilon_Y \), \( \varepsilon_Y \):yield strain), \( \sigma_{\text{ref}} \) is reference stress and \( \varepsilon_{\text{ref}} \) is reference strain. If stress (\( \sigma \)) - strain (\( \varepsilon \) ) relationship of the material is approximated by Ramberg-Osgood formulation:

\[ \varepsilon / \varepsilon_Y = \alpha (\sigma / \sigma_Y)^n \]  \hspace{1cm} (\( \alpha, n \): Ramberg-Osgood constants) \hspace{1cm} (4)

Using Eq.(4) in Eq.(3), the failure assessment curve can be expressed as

\[ f_{FAC} = [\alpha L_r^{n-1} + 1/(2 \alpha L_r^{n-3})]^{0.5} \]  \hspace{1cm} (5)

Fig.1 shows the analysis model of circumferentially surface-cracked straight pipe subjected to internal pressure (p) and bending moment (Pb). For this geometry and loading conditions,

\[ L_r = Pb / Pb' = \sigma b / \sigma b' \]  \hspace{1cm} (6)

\[ \sigma b = Pb / \pi Rm^2 t \]  \hspace{1cm} (7)

\[ Pb' = 2 \sigma_\gamma Rm^2 t [2 \sin \beta -(a/t) \sin \theta ] \]  \hspace{1cm} (8)

\[ \sigma b' = Pb' / \pi Rm^2 t = 2(\sigma_\gamma / \pi) [2 \sin \beta -(a/t) \sin \theta ] \]  \hspace{1cm} (9)

\[ \beta = (\pi / 2) [1 - (\theta / \pi)(a/t) - \sigma_m / \sigma f] \]  \hspace{1cm} (10)

where \( Pb \) (or \( \sigma b \)) is applied bending load (or applied bending stress), \( Pb' \) (or \( \sigma b' \)) is plastic collapse load \([3]\) (or plastic collapse stress) based on the yield stress, \( \sigma f \) is flow stress, \( \sigma m \) is membrane stress, \( \theta \) is half crack angle, \( a \) is crack depth, \( t \) is pipe thickness and \( Rm \) is pipe mean radius.
Elastic J-integral ($J_e$) can be calculated by

\begin{align}
J_e &= \frac{K_l^2}{E'} \\
K_l &= K_{lm} + K_{lb} \\
K_{lm} &= \sigma_m (\pi a)^{0.5} F_m \\
K_{lb} &= \sigma_b (\pi a)^{0.5} F_b \\
E' &= E/(1-\nu^2) \\
F_m &= 1.10+\chi[0.15241+16.772(\chi \theta / \pi)^{0.855}-14.944(\chi \theta / \pi)] \\
F_b &= 1.10+\chi[-0.09967+5.0057(\chi \theta / \pi)^{0.565}-2.8329(\chi \theta / \pi)]
\end{align}

where $K_l$ is Stress intensity factor, $K_{lm}$ is stress intensity factor for membrane stress ($\sigma_m$), $K_{lb}$ is stress intensity factor for bending stress ($\sigma_b$), $\nu$ is Poisson’s ratio, $F_m$ is a correction factor for $K_{lm}$, $F_b$ is a correction factor for $K_{lb}$ [4] and $\chi = a/t$.

The above equations are introduced to Eq. (2), the J-integral is given by the following:

$$J = [\alpha L_r^{n-1} + 1/(2 \alpha L_r^{n-3})]J_e$$

In ductile material like nuclear piping steels, unstable pipe fracture occurs after some amount of stable crack growth. The relationship between load and crack length (or crack extension) is defined as "Load Curve". Load curve under J-integral controlled crack growth, LC($J$) can be obtained by solving the following equation with regard to bending stress as a function of crack length (or crack extension):

$$J = [\alpha L_r^{n-1} + 1/(2 \alpha L_r^{n-3})](K_{lm} + K_{lb})2/E' = JR$$

where $JR$ is J-integral resistance of the material. Fracture stress under J-controlled crack growth is easily given as the maximum value on Load curve, LC($J$).

(2) Calculation of Load Curve based on Plastic Collapse

The concept of load curve for plastic collapse is similar to LC($J$). Load curve for plastic collapse (net-section collapse), LC($N$) is expressed as Eq. (9) with a replacement of yield stress ($\sigma_Y$) by flow stress ($\sigma_f$).
(3) Estimation of Fracture Stress by Load Curve Approach

Fracture stress and corresponding fracture criteria are easily estimated by graphical use of two load curves, LC(J) and LC(N). Load variation during stable crack growth is described as the lower one of the two load curves. Therefore, fracture bending stress \( (\sigma_{b,f}) \) can be defined as the maximum value on this lower load curve.

\[
\sigma_{b,f} = \text{Max}(\sigma_{b,\text{lower}})
\]

\[
\sigma_{b,\text{lower}} = \text{Lower}(\text{LC(J), LC(N)})
\]

\( \sigma_{b,f} \): Fracture stress

Fig. 2 shows schematic 3 cases (Case A-C) to be considered. Case A shows that LC(N) is situated lower than LC(J) and therefore the maximum stress (fracture stress) is generated at crack initiation with crack length of \( a_0 \). Case B shows that two load curves intersect at the point, prior to the maximum stress on LC(J). In this case, the fracture stress is defined at the intersection point. In Case C, LC(J) is situated lower than LC(N) and the maximum stress on LC(J) is defined as the fracture stress.

Fig. 2 also clearly shows the fracture criteria in each case. Plastic collapse (net-section collapse : NSC) condition is met for Case A and B. Elastic-plastic fracture mechanics condition (J-R) is met for Case C. Case B shows that pipe fracture occurs after some amount of stable crack growth.

It should be pointed out that Load Curve Approach is essentially equivalent to the Two-criteria approach. Fig. 3 shows the comparison of fracture conditions for Case 1-3 in two methods. Fracture stress is calculated when the failure assessment curve is tangential to the ductile crack growth locus (DCGL) in Two-criteria approach. In Load Curve Approach, fracture stress is defined as the maximum value on the lower Load Curve.

![Fig. 2 Concept of Load Curve Approach](image)

2.2 Fracture Analysis of Surface-Cracked Pipe

Fracture analysis was conducted by Load Curve Approach for circumferentially surface-cracked Japanese carbon steel pipe of STS410. The effects of crack geometry and pipe diameter on pipe fracture were investigated. In the analysis, the aspect ratio of initial crack is assumed to be constant during crack growth.

1. Effects of Crack Geometry

Table 1 shows the material properties of STS410 base metal at 300 °C used in the
Flow stress is given as $2.7Sm$ (Sm: Stress intensity) from material tests. Pipe dimensions are given by

Pipe Diameter $D_0 = 165.2$ mm (6 inch)

Pipe Thickness $t = 14.3$ mm

![Diagrams of Two-Criteria Approach and Load Curve Approach](image)

(i) Case 1

(ii) Case 2

(iii) Case 3

Fig. 3 Comparison of Load Curve Approach with Two-Criteria Approach
42 cases are calculated for 7 initial crack depths (a_o) with 6 initial half crack angles (θ_o). They are:

\[ a_o = 0.1t, 0.2t, 0.3t, 0.4t, 0.5t, 0.6t, 0.7t \]
\[ θ_o = 5, 10, 15, 20, 25, 30 \text{ (deg)} \]

Fig. 4 shows the results of load curves for cases A1 (a_o/t=0.1, θ_o=30°) and case A2 (a_o/t=0.5, θ_o=30°). For case A1, the maximum stress is estimated at the intersection point of two load curves and fracture criterion is plastic collapse (NSC). For case A2, the load curve for J-integral is constantly lower than the load curve for plastic collapse. Then, the maximum stress is generated on the load curve for J-integral, LC(J) and fracture criterion is J-resistance (J-R).

Table 2 shows the dependence of crack geometry on pipe fracture criteria. From the analysis, it is found that with the increase of crack depth or crack angle, fracture criteria transfer from net-section collapse type (NSC) to elastic-plastic fracture mechanics type (J-R).

(2) Effects of Pipe Diameter

Using the same material properties shown in Table 1, parametric analysis was conducted by Load Curve Approach. Crack geometries are given:

Initial crack depth (a_o): 0.25t, 0.5t
Initial half crack angle (θ_o): 10, 20, 30 (deg)

6 pipe diameters (D_o) and pipe thicknesses (t) are used in the analysis.

\[ D_o=114.3\text{mm} \quad t=11.1\text{mm} \]
\[ D_o=165.2\text{mm} \quad t=14.3\text{mm} \]
\[ D_o=318.5\text{mm} \quad t=21.4\text{mm} \]
\[ D_o=406.4\text{mm} \quad t=26.2\text{mm} \]
\[ D_o=660.4\text{mm} \quad t=33.3\text{mm} \]

Table 3 shows fracture criteria for the case of a_o=0.25t. It is clear that fracture criteria transfer from NSC type to J-R type with the increase of pipe diameter or crack angle.

Fig. 5 shows the relationship between fracture load ratio and initial crack angle for different pipe diameters and crack depth. Fracture load ratio is defined as a ratio of σ_b, f (the estimated maximum stress) to σ_b,0 (bending stress at plastic collapse for initial crack geometry). It is clear that the fracture load ratios decrease with initial crack angle. This trend becomes significant with the increase of pipe diameter or initial crack depth.

3. Conclusions

(1) New simplified flaw evaluation method, Load Curve Approach was developed to evaluate the fracture stress of circumferentially surface-cracked pipe. This approach has the same functions with Two-criteria approach. Fracture stress and fracture criteria are easily and simultaneously estimated by two load curves derived from J-resistance and net-section collapse conditions.

(2) Several pipe fracture analyses were conducted using this approach. The approach showed the dependency of crack geometry and pipe diameter on pipe fracture.
Table 1  Pipe Material Properties

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>STS410, Base Metal (300°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's Modulus, E(GPa)</td>
<td>178.4</td>
</tr>
<tr>
<td>Poisson's Ratio, ν</td>
<td>0.3</td>
</tr>
<tr>
<td>Yield Stress, σy(MPa)</td>
<td>183.3 (Japanese Code Value)</td>
</tr>
<tr>
<td>Stress Intensity, S_n(MPa)</td>
<td>122.5 (Japanese Code Value)</td>
</tr>
<tr>
<td>Membrane Stress, σ_m(MPa)</td>
<td>61.3 (=0.55S_n)</td>
</tr>
<tr>
<td>Flow Stress, σf(MPa)</td>
<td>330.8 (=2.7S_n)</td>
</tr>
<tr>
<td>Ramberg-Osgood Constant</td>
<td></td>
</tr>
<tr>
<td>α</td>
<td>4.412</td>
</tr>
<tr>
<td>Ramberg-Osgood Constant</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>3.309</td>
</tr>
<tr>
<td>J-R Curve 1</td>
<td>1.898</td>
</tr>
<tr>
<td>C_1</td>
<td>2.228</td>
</tr>
</tbody>
</table>

*) (Δa) = C_1J + C_2J^1
[Δa] = mm, [J] = MN/m

Fig.4  Analysis by Load Curve Approach

Table 2  Dependence of Crack Geometry on Fracture Criteria

<table>
<thead>
<tr>
<th>Initial Crack Depth(ao)</th>
<th>Initial Half Crack Angle (θao, deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>0.1t</td>
<td>NSC</td>
</tr>
<tr>
<td>0.2t</td>
<td>NSC</td>
</tr>
<tr>
<td>0.3t</td>
<td>NSC</td>
</tr>
<tr>
<td>0.4t</td>
<td>J-R</td>
</tr>
<tr>
<td>0.5t</td>
<td>J-R</td>
</tr>
<tr>
<td>0.6t</td>
<td>J-R</td>
</tr>
<tr>
<td>0.7t</td>
<td>J-R</td>
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</table>

Table 3  Dependence of Pipe Diameters on Fracture Criteria

<table>
<thead>
<tr>
<th>Pipe Diameter Dp(mm)</th>
<th>Pipe Thickness tp(mm)</th>
<th>Initial Half Crack Angle (θao, deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>114.3</td>
<td>11.1</td>
<td>NSC</td>
</tr>
<tr>
<td>165.2</td>
<td>14.3</td>
<td>NSC</td>
</tr>
<tr>
<td>318.5</td>
<td>21.4</td>
<td>NSC</td>
</tr>
<tr>
<td>406.4</td>
<td>26.2</td>
<td>J-R</td>
</tr>
<tr>
<td>660.4</td>
<td>33.3</td>
<td>J-R</td>
</tr>
</tbody>
</table>
Fig. 5 Effects of Crack Geometry and Pipe Diameter on Fracture Stress

References
5. NUPEC, Proving Test on the Integrity of Carbon Steel Piping in LWRs, 1989.