ABSTRACT

Low cycle fatigue tests were conducted using 100A elbow specimens with local wall thinning. Local wall thinning of 50% of the nominal pipe wall thickness was machined on the inside of elbow in order to simulate erosion/corrosion metal loss. The local wall thinning areas are located at three different areas, called extrados, crown and intrados. The elbow specimens were subjected to cyclic in-plane bending under displacement control without internal pressure. When the local wall thinning was located at intrados, fatigue life was the shortest. In addition, three-dimensional elastic-plastic analyses were also carried out using the finite element method. As a result, the crack penetration area and the crack growth direction were successfully predicted by the analyses. The fatigue lives estimated by the analyses were close to those obtained by the experiments.

INTRODUCTION

Carbon steel pipes are commonly used in the piping systems of power plants. Erosion corrosion can cause a wall thinning due to high temperature and high pressure water and steam flowing at high velocities through these pipes. Therefore, it is important to evaluate the strength of piping undergoing local wall thinning in order to maintain the integrity of the piping systems. Several experimental and analytical studies have been performed with the aim of developing a methodology for evaluating the integrity of piping undergoing wall thinning [1, 2, 3]. Full scale pipe tests were carried out for straight pipes [4], tee [5] and orifice [6] and analytical models for evaluating the integrity of wall-thinned piping systems were proposed. Most of these studies are monotonic tests.

The power plant piping is designed to withstand seismic events. It is important to establish a method to estimate the safety margin of the degraded pipes against seismic loading. A series of large-scale experiments about this topic has been carried out under the “New Aged-Piping Committee” sponsored by the National Research Institute for Earth Science and Disaster Prevention (NIED). Results of these experimental works have been reported in detail [7].

The wall thinning due to erosion corrosion is enhanced at elbows. However, the low-cycle fatigue strength of elbow with local wall thinning is not yet clear. The number of experiments is limited because they are expensive, laborious, and time consuming. It is preferable to establish an analytical approach to simulate the experimental procedure.

Shiratori et al. proposed an analytical model by which the failure of the degraded piping against the seismic loading can be estimated reasonably. A series of finite element analyses has been performed for 3D piping system against the seismic loading [7]. It has been shown that the proposed analytical models can describe the experimental behaviors such as ratcheting, buckling and penetration of a surface crack through the wall thickness.

In this paper, in order to investigate the low-cycle fatigue behaviors of elbows undergoing local wall thinning, low-cycle fatigue tests have been carried out using 100A elbow specimens having local wall thinning. The local wall thinning areas are located at three different areas, called extrados, crown and intrados. The elbow specimens were subjected to cyclic in-plane bending under displacement control without internal pressure. Then, elastic-plastic finite element analyses were carried out to simulate low-cycle fatigue behaviors of elbows. The analytical results have been compared with the experimental ones.
EXPERIMENTS

Experimental procedures
The material for elbow specimens used in the experiments was carbon steel pipes called "carbon steel pipes for high temperature", STS410 in JIS (Japanese Industrial Standards), which are used in the class 2 piping of nuclear power plants in Japan. The nominal pipe dimensions are 100A, sch80 (the nominal outer diameter is 114.3 mm and the nominal thickness is 8.6 mm). Figure 1(a) shows the shape and geometry of elbow specimens. Figure 1(b) shows the position and dimensions of local wall thinning. Table 1 shows the conditions of the eroded sizes of the elbow pipe specimens. Four elbow specimens were used in this study. The local wall thinning was machined on the inside of the pipes to simulate erosion/corrosion metal loss. In this paper, eroded areas are located at three different areas, called extrados, crown and intrados. The sound elbow specimen without eroded area was also used. The elbows specimens were called as sound, extrados, crown and intrados, respectively. The depth of metal loss in the thickness direction is called eroded depth \( d \). The ratio of \( d \) to wall thickness \( t \) is defined as eroded ratio \( \frac{d}{t} \) and fixed at \( \frac{d}{t} = 0.5 \). Eroded angle \( \theta \) is the circumferential wall thinning angle and fixed at \( \theta = 90^\circ \). Eroded length \( l \) is the length of the wall thinning in the axial direction and is fixed at \( l = 100 \text{ mm} \).

Figure 2 shows experimental apparatus and elbow specimen. The low cycle fatigue tests were conducted using universal testing machine (250 kN) at room temperature without internal pressure. The elbow specimens were subjected to cyclic in-plane bending under displacement control. Loading frequency was 0.1 Hz. The relative opening-and-closing displacements \( \delta \) between the two ends is an important factor to control fatigue life. Prior to the experiments, we carried out preliminarily finite element analysis to decide the value of \( \delta \). The number of cycles considered in seismic event are less than 100. As a result of analysis, the value of \( \delta \) was decided to be \( \pm 30 \text{ mm} \).

In the experiments, we measured and evaluated the relationship between load and displacement, time history of strain, crack initiation point, direction of crack, and fatigue life \( N_c \). In this study, \( N_c \) is defined as the number of cycles to crack penetration.

Table 1 Test conditions for elbow specimens having local wall thinning.

<table>
<thead>
<tr>
<th>Specimen name</th>
<th>Eroded part</th>
<th>Eroded ratio ( \frac{d}{t} )</th>
<th>Eroded angle ( \theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound</td>
<td>Extrados</td>
<td>0.5</td>
<td>90°</td>
</tr>
<tr>
<td>Extrados</td>
<td>Extrados</td>
<td>0.5</td>
<td>90°</td>
</tr>
<tr>
<td>Crown</td>
<td>Crown</td>
<td>0.5</td>
<td>90°</td>
</tr>
<tr>
<td>Intrados</td>
<td>Intrados</td>
<td>0.5</td>
<td>90°</td>
</tr>
</tbody>
</table>

Fig.2 Experimental apparatus and elbow specimen.

Experimental results
Figure 3 shows photographs of elbow specimens after low-cycle fatigue tests showing crack penetration site.

In sound specimen, crack penetrated and propagated longitudinal direction at crown as shown in Fig. 3(a). The fatigue life of the sound pipe was \( N_c = 87 \). At the other side of crown, only axial line was observed and crack penetration was not occurred as shown in Fig. 3(b).
In extrados specimen, axial line occurred at crown as shown in Fig. 4(a). Then, crack penetrated and propagated longitudinal direction as shown in Fig. 4(b). The fatigue life of the sound pipe was \( N_f = 88 \) which was similar to that of the sound pipe.

In crown specimen, axial line occurred at crown as shown in Fig. 5(a). Then, crack penetrated and propagated longitudinal direction as shown in Fig. 5(b). The fatigue life of this pipe was \( N_f = 77 \) which was smaller than that of the sound and extrados specimens.

In intrados specimen, crack initiated at outer surface of intrados as shown in Fig. 6(a). Then, the crack penetrated and propagated along hoop direction. The fatigue life of this pipe was \( N_f = 61 \) which was the smallest among the elbow specimens tested in this study.

On the basis of the crack penetration behavior, it appears that crack initiation point in the sound, extrados and crown specimens was inner surface of crown and that in the intrados specimen was outer surface of intrados.

Fig. 3 Crack penetration in sound specimens \((N_f = 87)\).

Fig. 4 Crack penetration in extrados specimens \((N_f = 88)\).

Fig. 5 Crack penetration in crown specimens \((N_f = 77)\).

Fig. 6 Crack penetration in intrados specimens \((N_f = 61)\).

**ANALYSIS**

**Finite element analysis**

Elastic-plastic analyses of the elbow specimens are performed. The software codes used in the analyses are Excel and Hyper Mesh for generating the finite element model and element breakdown, ABAQUS as the solver, and ABAQUS VIEWER for post processing.

Elbow specimens including attached straight pipes were modeled using 8-node solid elements; this model has 11208 nodes and 8720 elements. Figure 7 shows finite element model of eroded area. Figure 8 shows the relationship between true stress and true strain of carbon steel STS410. A bilinear stress-strain curve has been assumed in the analysis, where

- Young's modulus \( E = 203 \) GPa
- Poisson’s ratio \( \nu = 0.3 \)
- Yield stress \( \sigma_y = 424 \) MPa
- Second slope \( S' = 1200 \) MPa

A kinematical hardening rule has been assumed to simulate the ratcheting behavior of materials. The relative opening-and-closing displacements between the two ends of the elbow were \( \pm 30 \) mm. The analyses were carried out up to 50 cycles of loading.

In the analysis, we analyzed time history of strain, distribution of equivalent plastic strain.

Fig. 7 Finite element model of eroded area.

Fig. 8 Stress-strain curve for FE analysis.
Estimation of fatigue lives

In order to estimate the low cycle fatigue lives with the ratchets, Nakamura et al. have made use of two approaches proposed, one is based upon Miner’s rule, and the other is based upon Asada’s experimental formula [7]. For the carbon steel used in the experiment, the characteristic of low cycle fatigue tests is expressed by [8]

\[ \Delta \varepsilon_f = 0.6158 N_f^{-0.0736} + 89.08 N_f^{-0.5414} \]  

for room temperature, where \( \Delta \varepsilon_f \) is the applied total strain amplitude and \( N_f \) is the number of cycles to the rupture. If the applied strain amplitude changes, the fatigue damage \( \eta \) is defined by

\[ \eta = \sum_{i=1}^{n} \frac{N_i}{N_f}, \]

where \( N_i \) and \( N_f \) are the number of cycles actually applied in the present test and the one corresponding to the failure, respectively, for the applied amplitude \( \Delta \varepsilon_f \). Then Miner’s rule is described such that the low-cycle fatigue life can be estimated by the criterion of

\[ \eta = 1. \]

On the other hand, Asada et al. proposed the following approach [9,10] such that

\[ F = D_f + 2 \sqrt{D_f D_d} + D_d = 1, \]

where

\[ F \quad \text{: fatigue factor}, \]
\[ D_f = \eta^{0.6} \quad \text{: fatigue damage}, \]
\[ D_d = \varepsilon_f / \varepsilon_{fr} \quad \text{: ductility consumption}, \]
\[ \varepsilon_{fr} = \ln \frac{100}{100 - \varphi} \quad \text{: true rupture ductility} \]

(\( \varphi \): reduction in area).

By applying the above equation, the fatigue life at crack penetration can be estimated.

Calculation method of fatigue lives under multi-axial strain

The elbow specimens are subjected to multi-axial stress and strain. That is to say, we should consider the multi-axial stress and strain when we evaluate the fatigue lives. In this section the fatigue life evaluation method mentioned above is developed to the case of multi-axial strain state. As shown in Fig. 9, local coordinate \( x'-y' \) is introduced into each element that constitute the FEM model and the \( x' \) axis is set up in the direction of the flow in the pipes and the \( y' \) axis is at the right angles to the \( x' \) axis. The angle \( \theta \) is clockwise taken from the \( x' \) axis. The nominal strains \( \varepsilon_x, \varepsilon_y, \gamma_{xy} \) are transformed into \( \varepsilon_\theta \) with

\[ \varepsilon_\theta = \varepsilon_x \cos^2 \theta + \varepsilon_y \sin^2 \theta + \gamma_{xy} \cos \theta \sin \theta \]
\[ = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2} \cos 2\theta + \gamma_{xy} \sin 2\theta, \]

The total strain range \( \Delta \varepsilon(\theta) \) and the cumulative strain \( \varepsilon(\theta) \) are calculated in each angle direction by Eq.(8). Then, fatigue damage \( D(\theta) \) and ductility consumption \( D_d(\theta) \) are calculated by Eq.(5) and Eq.(6), respectively. As a result, the relationship between \( F(\theta) \) and angle at most-strain concentrated area is evaluated. We assumed that the crack propagates perpendicular to the direction where the \( F \) has the maximum value.

![Fig.9 Local coordinate.](image)

Analytical results

Figure 10 shows contour figure of equivalent plastic strain at inner or outer surface for each specimen. The most strain-concentrated points are shown by circles. In sound and crown specimens, the most strain-concentrated point occurred at inner surface of crown as shown in Figs. 10(a) and 10(c). In extrados pipe, the most strain-concentrated point occurred at inner surface of crown as shown in Figs. 10(b), regardless of wall thinning at extrados. In intrados specimen, the most strain-concentrated point occurred at outer surface of intrados as shown in Figs. 10(d).

![Fig.10 Contour figure of equivalent plastic strain.](image)
Fig. 11 Strain history at the most strain-concentrated point.

Figure 12 shows the estimation of low cycle fatigue factor ($F$) as a function of the angle $\theta$ at the most strain-concentrated point after the elbow specimens were subjected to 50 cycles of loading for each specimen. In sound, extrados and crown specimens, the $F$-value shows the maximum at around 90°. It can be predicted that crack propagation occurs in longitudinal direction in these specimens. In intrados specimens the $F$-value shows the maximum at around 0° or 180°. It can be predicted that crack propagation occurs in hoop direction in intrados specimen.

Comparison with experimental results

Table 2 compares the crack penetration area and direction of crack propagation by experiments and analyses. Comparing the experimental and analytical results, they are coincident in every elbow specimen. Thus, it can be said that the crack penetration area and direction of crack propagation can be successfully predicted by the analysis.

Figure 13 shows the comparison of low cycle fatigue factor ($F$). The maximum $F$-values at outer and inner surfaces are shown on left and right column, respectively for each specimen. Here, we assumed the $F$-value increases linearly with number of cycles and the crack penetration occurs when the largest $F$ value reaches 1. From these assumptions, we can predict the number of cycles to crack penetration.

Figure 14 shows the number of cycles to failure obtained from experiments and analysis. The estimated fatigue lives from analyses are shown on the left, and the experimental results are shown on the right. Comparing the experimental results and analytical results, it can be said that the number of cycles to crack penetration can be successfully predicted by the analysis.

Table 2 Failure behavior of elbow pipes, experiments and analysis.

<table>
<thead>
<tr>
<th>Specimen name</th>
<th>Experimental results</th>
<th>Analytical results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crack penetration area</td>
<td>Direction of crack</td>
</tr>
<tr>
<td>Sound</td>
<td>Inner surface</td>
<td>Axial</td>
</tr>
<tr>
<td></td>
<td>Crown</td>
<td>Crown</td>
</tr>
<tr>
<td>Extrados</td>
<td>Inner surface</td>
<td>Axial</td>
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<tr>
<td></td>
<td>Crown</td>
<td>Crown</td>
</tr>
<tr>
<td>Crown</td>
<td>Inner surface</td>
<td>Axial</td>
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<tr>
<td></td>
<td>Crown</td>
<td>Crown</td>
</tr>
<tr>
<td>Intrados</td>
<td>Outer surface</td>
<td>Hoop</td>
</tr>
<tr>
<td></td>
<td>Crown</td>
<td>Hoop</td>
</tr>
</tbody>
</table>

Fig. 12 Low cycle fatigue factor ($F$) at the most strain-concentrated point.

Fig. 13 Comparison of low cycle fatigue factor ($F$).
FIG. 14 Number of cycles to failure, experiments and analysis.

CONCLUSIONS

Low cycle fatigue tests were conducted using elbow specimens with local wall thinning. The local wall thinning areas are located at three different areas, called extrados, crown and intrados. The elbow specimens were subjected to cyclic in-plane bending under displacement control without internal pressure. In addition, three-dimensional elastic-plastic analyses were also carried out using the finite element method. The conclusions obtained are as follows.

(1) If the local wall thinning was located at extrados or crown, the crack initiated at inner surface of crown and propagated longitudinal direction. These failure behaviors were quite similar to those of the sound specimen. The fatigue lives of extrados or crown specimens were almost as same as that of sound specimen. Thus, the local wall thinning introduced in this study (d/t = 0.5 and 2θ = 90°) didn’t affect the low-cycle fatigue behavior if it was located at extrados or crown.

(2) If the local wall thinning was located at intrados, the crack initiated at outer surface of intrados and propagated hoop direction. This failure behavior has different from that of the sound specimen. The fatigue life of intrados specimens was shorter than that of the sound specimen. Thus, attention should be paid if the local wall thinning is located at intrados.

(3) The crack penetration area and the crack growth direction were successfully predicted by the analyses. The fatigue lives estimated by analysis were close to those obtained by experiments.

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