Failure Strain Measurement of the Piping System of a Nuclear Power Plant Using Image Signals

S W Kim*, B G Jeon, D U Park and D W Yun

1Seismic Research and Test Center, Pusan National University, 49 Busandaehak-ro, Mulgeum, Yangsan, Kyungnam 50612, Republic of Korea

*corresponding author, Email: swkim09@pusan.ac.kr

Abstract. When seismic isolation devices are installed in piping systems, it is expected that such devices will be subjected to larger displacement than before their installation because they handle seismic loads, and it is likely that the seismic risks of some facilities will be increased by such displacement increase. In particular, it is highly likely that the seismic risks of piping systems, which connect seismic-isolated structures with conventional ones, will be increased. Previous studies have revealed that the vulnerable part of piping systems is the elbow, and that failures occur due to the low-cycle ratcheting fatigue in the hoop direction. Therefore, in this study, the ultimate state of the elbow was defined as a leakage, and an in-plane cyclic loading test was conducted. In addition, the hoop-direction strain of the steel pipe elbow was measured using an image measurement system, and the failure strain, which cannot be measured using the conventional sensors, was also measured.

1. Introduction

Seismic-isolated structures are likely to be subjected to larger displacement than conventional structures because seismic isolation devices deal with seismic loads. Therefore, in the case of piping systems that connect seismic-isolated structures with conventional ones, piping systems can be damaged due to plastic deformation concentrated on specific areas, such as the elbow and tee. As such, it is necessary to examine the seismic safety of seismic-isolated piping systems.

Studies to identify the vulnerable part of piping systems under seismic loads and to analyze the nonlinear behavior of such systems have been conducted using experimental and numerical methods, according to the development of the related industries. The dynamic behavior of piping systems with different materials under seismic loads was analyzed using a shaking table [1] in particular, special attention was paid to the behavior of the pipe elbow. As a result, it was confirmed that plastic deformation occurred in each pipe elbow. Japan Nuclear Energy Safety Organization (JNES) and Nuclear Power Engineering Corporation (NUPEC) conducted an experimental study [2] to analyze the dynamic behavior of the representative piping systems of nuclear power plants under seismic loads. They conducted a cyclic loading test with piping systems and a shaking table test with the piping systems. They also performed tests to examine the design method and the limit state. As a result, it was found that the damage type of the piping systems under seismic loads was the fatigue failure at low frequencies [3]. In addition, the entire system was assessed to be safer compared to the results of the component test due to reasons such as the redistribution of loads [4]. A low-cycle ratcheting fatigue test [5] was conducted using a scaled model of the elbow, which previous studies have revealed to be the vulnerable part of piping systems. In the component test, it was observed that the
elbow crack started from the inside and grew in the axial direction. The hoop-direction strain and the low-cycle ratcheting fatigue damage were also observed. As mentioned earlier, previous studies have revealed that the vulnerable part of piping systems is the elbow, and it was also revealed that failures occur due to the low-cycle ratcheting fatigue, but it is difficult to quantitatively define the limit state [6] of the elbow. As such, this study proposed a method of measuring the hoop-direction ratcheting strain using image signals to define a reliable limit state of the elbow. Towards this end, the ultimate state of the elbow was defined as a leakage, and an in-plane cyclic loading test was conducted.

2. Strain measurement using image signals

The image of an object acquired using the image measurement system was deformed by an external force, and the correlation between the reference and the deformed images was analyzed using the gray level values of the images. The deformation was measured by analyzing such correlation after separating the square-shaped images from the two images. In this case, the separated square-shaped area is called a “window,” and the deformation was measured by analyzing the correlation between the window images separated by the gray level. Figure 1 shows the deformation measurement principle of the image correlation method. $f(x_i, y_j)$ is the reference window, which is the gray level pattern of the square area separated from the reference image before deformation, and $g(x'_i, y'_j)$ is the deformed window, which is the gray level pattern of the square separated from the deformed image. The size of the window was $(2M+1) \times (2M+1)$. $M$ denotes the size of the target window. The deformation of a structure can be measured by analyzing the correlation between the reference window and the deformed window, and detecting the coordinates with the highest correlation. In this study, the zero-normalized sum of squared differences (ZNSSD) method of equation (1) was used to analyze the correlation between the two images.

![Figure 1. Deformation measurement using the image correlation method](image)

$$C_{ZNSSD} = \sum_{i=-M}^{M} \sum_{j=-M}^{M} \left[ \frac{f(x_i, y_j) - f_m}{\Delta f} - \frac{g(x'_i, y'_j) - g_m}{\Delta g} \right]$$

$$f_m = \frac{1}{(2M+1)^2} \sum_{i=-M}^{M} \sum_{j=-M}^{M} f(x_i, y_j), \quad g_m = \frac{1}{(2M+1)^2} \sum_{i=-M}^{M} \sum_{j=-M}^{M} g(x'_i, y'_j)$$

$$\Delta f = \sqrt{\sum_{i=-M}^{M} \sum_{j=-M}^{M} \left[ f(x_i, y_j) - f_m \right]^2}, \quad \Delta g = \sqrt{\sum_{i=-M}^{M} \sum_{j=-M}^{M} \left[ g(x'_i, y'_j) - g_m \right]^2}$$

As the object deformation caused by an external force occurs continuously, it is possible to estimate the deformation values of the surrounding points. To correct the geometric errors of the surroundings caused by deformation, subpixel was calculated using the shape function.
In equation (4), $\Delta x = x_i - x_0$ and $\Delta y = y_j - y_0$, $u$ and $v$ represent the displacement components of the reference window center in the $x$ and $y$ directions. $u_x$, $u_y$, $v_x$, and $v_y$ denote the first-order displacement gradients of the reference window while $u_{xx}$, $u_{xy}$, $u_{yx}$, $u_{yy}$, $v_{xx}$, and $v_{yy}$ represent the second-order displacement gradients. Considering the bending of the object caused by an external force as well as the influence of the nonlinear behavior, subpixel was calculated using the second-order shape function of equation (4).

$$
\xi^2(x_i, y_j) = u + u_x \Delta x + u_y \Delta y + \frac{1}{2} u_{xx} \Delta x^2 + \frac{1}{2} u_{yy} \Delta y^2 + u_{xy} \Delta x \Delta y
$$

$$
\eta^2(x_i, y_j) = v + v_x \Delta x + v_y \Delta y + \frac{1}{2} v_{xx} \Delta x^2 + \frac{1}{2} v_{yy} \Delta y^2 + v_{xy} \Delta x \Delta y
$$

The average strain measurement method [7] was applied to measure the failure strain of a structure using image signals. As shown in figure 2, an arbitrary area was divided by pixels, and the strain was measured for the divided area. For an arbitrary area, the hoop-direction strain was measured using the average strain. To measure the average strain in an arbitrary area, the slope was calculated first using the following linear function that plotted the hoop-direction relative displacement against the hoop-direction pixel position. The average strain was then measured using the slope calculated from each image over time. The ratcheting strain was calculated by using the curve fitting algorithm. Finally, it shows the contour analysis using the ratcheting strain measured at an arbitrary time.
In the figure, at the upper left part is the image acquired using the image measurement system at an arbitrary time, and at the upper right part is the pixel-based relative displacement of the steel pipe elbow. At the lower left part is the slope that was calculated for the upper left image, and at the lower right part is the strain that was measured using the calculated slope.

![Figure 3. Summary of algorithm](image)

**Figure 3. Summary of algorithm**

![Figure 4. Program for estimating failure strain using MATLAB](image)

**Figure 4. Program for estimating failure strain using MATLAB**

3. **Failure strain measurement of the steel pipe elbow**

The image measurement system used a CMOS camera (IMB-7050G, 2448 x 2048 pixels) and two laptop computers considering portability and easy installation. The CMOS camera and laptop computers transferred and controlled data using LAN communication. A lens (M5018-MP2) was used in the experiment to measure the deformation of the remote piping systems.

In this study, the elbow of piping systems was selected as a vulnerable part in the case of a seismic load, and specimens with an 88.9 mm outer diameter and a 5.49 mm thickness were prepared using SA106 Grade B and SCH 40 (ASME, 2004) of ASME B36.10. To enable plastic behavior in the elbow, the straight length of each specimen was made more than three times longer than the outer diameter, and the specimens were welded onto the elbow. In addition, a jig was manufactured and installed to implement pin connection on both ends. The jig and the pin were manufactured precisely to ensure the accuracy of the experiment.

![Figure 5. Experimental setup](image)

**Figure 5. Experimental setup**

Figure 5(a) shows the steel pipe elbow installed at the universal testing machine (UTM). An in-plane cyclic loading test was conducted through displacement control, and a target was installed in the
jig for the UTM connection, to compare its displacement with that of the linear variable differential transformer (LVDT) installed inside the UTM. Figure 5(b) shows the randomly marked targets that were installed to measure the hoop-direction strain of the piping systems. In the experiment, two 2448x2048 images were acquired at 2 frames per second using the image measurement system. The UTM performed measurement at the 1 Hz data acquisition speed, and the strain gage performed measurement at 0.25 Hz.

To verify the strain measurement algorithm using image signals, the in-plane cyclic loading test was conducted. Table 1 shows the load cases of the steel pipe elbow. The in-plane cyclic loading test was continued until a leakage occurred in the elbow. Figure 6 shows the steel pipe elbow in which a through crack occurred. It was confirmed that the crack occurred near the crown.

### Table 1. Load cases

| Load Case | Loading Amplitude (mm) | Internal Pressure (MPa) | Leakage Cycles N |
|-----------|------------------------|-------------------------|------------------|
| 1         | ±20                    |                         | 96               |
| 2         | ±40                    | 3                       | 15               |
| 3         | ±60                    |                         | 6                |

![Figure 6. Elbow with a through crack](image)

![Figure 7. Comparison of the response measured at the LVDT of the UTM](image)

**Figure 7.** Comparison of the response measured at the LVDT of the UTM

### Table 2. Error analysis of the response measured at the LVDT of the UTM

| Load Case | Percent Error (%) | RMS Error (mm) |
|-----------|-------------------|----------------|
| 1         | 0.085             | 0.831          |
| 2         | 0.076             | 0.774          |
| 3         | 0.053             | 0.687          |

Figure 7 is a graph that compares the response measured by the LVDT of the UTM with those measured using image signals in the in-plane cyclic loading test. In table 2, the error rate of the percent error in each load case was within 1 %, and the RMS error was less than 0.5 mm, indicating that the error was very small. Therefore, it was found that the displacement response estimated using image signals exhibited reliability.
In figure 8, the strain in the hoop direction and the ratcheting strain measured using the image signals of the symmetry point of the area to which the strain gage had been attached was compared with the response measured by the strain gage. The black line shows the strain response and the red line shows the ratcheting strain. As shown in figure 8(c), it could not measure that the load case 3 exceeded the performance limit of the electric-resistance strain gage from the first cycle. This confirmed that the electric-resistance strain gage could not measure the strain until a leakage occurs in the elbow because its performance limit is exceeded soon after nonlinear behavior starts. In tables 3 and 4, error analysis was conducted for the measured data. In the table 3, the error was considered
somewhat large because the percent error rate was within 6% and the RMS error rate was within 0.003. In table 4, the difference is also within 10%, which indicates that the difference is somewhat large. This appears to be due to the installation of the strain gage in the symmetry point as well as local problems. In table 4, it is considered that the limit state of a piping system can be quantitatively expressed in the future using the ratcheting strain.

4. Conclusions

In this study, for the case of conducting an in-plane cyclic loading test of a piping system, a non-contact measurement method through image signals based on an image measurement system is proposed as an appropriate method of measuring the hoop-direction strain of the elbow.

As the response measured using the LVDT of the UTM and the image signals obtained through the in-plane cyclic loading test exhibited small errors, the reliability of the image processing data was confirmed. In addition, although the response measured by the strain gage and that estimated using the image signals differed depending on the measurement location, the accuracy of the measured responses was confirmed by comparing them with the results of the electric-resistance strain gage.

Furthermore, it is expected that the measured strain response and the ratcheting strain can be used for estimating the failure criteria. It was confirmed that the strain could be measured from a remote distance without having to install the conventional sensors if the strain measurement algorithm that uses the image measurement system would be utilized. Therefore, the failure strain measured in this study is expected to be used in the future as an important factor in defining the failure criteria of seismic-isolated piping systems.

Acknowledgments

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20171510101910).

References

[1] Touboul F, Sollogoub P, Blay N 1999 Seismic behaviour of piping systems with and without detect: experimental and numerical evaluations Nucl Eng Design 192(2-3) 243-260
[2] Zhang T, Brust FW, Wikowski G, Shim DJ, Nie J, Hofmayer CH, Ali SA 2010 Analysis of JNES seismic tests on degraded piping, ASME 2010 Pressure Vessels and Piping Conference Bellevue Washington USA PVP2010-25333
[3] Otoyo T, Otani A, Fukushima S, Jimbo M, Yamamoto T, Sakakida T, Onishi S 2014 Development of an evaluation method for seismic isolation system of nuclear power facilities (Part 4) failure behavior of crossover piping for seismic isolation system ASME 2014 Pressure Vessels and Piping Conference Anaheim California USA PVP2014-29011
[4] Park Y, DeGrasssi G, Hofmayer C, Bezler P, Chokshi N 1997 Analysis of nuclear piping system seismic tests with conventional and energy absorbing supports 14th International Conference on Structural Mechanics in Reactor Technology Lyon France BNL-NUREG-64173
[5] Mizuno K, Shimizu H, Jimbo M, Oritani N, Onishi S 2014 Development of an evaluation method for seismic isolation systems of nuclear power facilities (Part 5) fatigue test of the crossover piping Proceedings of the ASME 2014 Pressure Vessels & Piping Conference Anaheim California USA PVP2014-29032
[6] Jeon BG, Kim SW, Choi HS, Park DU, Kim NS 2017 A failure estimation method of steel pipe elbows under in-plane cyclic loading Nucl Eng Technol 49(1) 245-253
[7] Kim SW, Choi HS, Jeon BG, Hahm DG, Kim MG 2018 Strain and deformation angle for a steel pipe elbow using image measurement system under in-plane cyclic loading Nucl Eng Technol 50(1) 190-202