Nuclear Engineering and Technology xxx (2017) 1–13

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

STRAIN AND DEFORMATION ANGLE FOR A STEEL PIPE ELBOW USING IMAGE MEASUREMENT SYSTEM UNDER IN-PLANE CYCLIC LOADING

SUNG-WAN KIM [a], HYOUNG-SUK CHOI [a], BUB-GYU JEON [a, *], DAE-GI HAHM [b], MIN-KYU KIM [b]

[a] *KOCED Seismic Simulation Test Center, Pusan National University, 49 Busandaehak-ro, Mulgeum, Yangsan, Kyungnam 50612, Republic of Korea*
[b] *Integrated Safety Assessment Division, Korea Atomic Energy Research Institute, 111 Daedeok-daero 989 Beon-gil, Yusung-gu, Daejeon 34057, Republic of Korea*

ARTICLE INFO

Article history:
Received 11 April 2017
Received in revised form
9 November 2017
Accepted 9 November 2017
Available online xxx

Keywords:
Deformation Angle
Failure Strain
Image Measurement System
Nuclear Power Plant Piping
Steel Pipe Elbow

ABSTRACT

Maintaining the integrity of the major equipment in nuclear power plants is critical to the safety of the structures. In particular, the soundness of the piping is a critical matter that is directly linked to the safety of nuclear power plants. Currently, the limit state of the piping design standard is plastic collapse, and the actual pipe failure is leakage due to a penetration crack. Actual pipe failure, however, cannot be applied to the analysis of seismic fragility because it is difficult to quantify. This paper proposes methods of measuring the failure strain and deformation angle, which are necessary for evaluating the quantitative failure criteria of the steel pipe elbow using an image measurement system. Furthermore, the failure strain and deformation angle, which cannot be measured using the conventional sensors, were efficiently measured using the proposed methods.

1. Introduction

In a nuclear power plant in which a seismic isolation device has been installed, it is expected that there will be a considerable displacement, which does not apply to the existing nuclear power plants because the seismic load is managed by the seismic isolation device. Therefore, in a piping system that connects the structures in which a seismic isolation device has been installed and other general structures, the plastic deformation can be concentrated in specific parts, such as the elbows or tees, and cause piping failure. Therefore, it is necessary to review the seismic safety of such a piping system.

A seismic safety evaluation of the piping system of a nuclear power plant is considered critical to the safety and operation of the nuclear power plant. Experimental and analytical studies have been conducted on piping systems to understand the possible fragility during a seismic event and to define the limit state. A shaking table was used to conduct a dynamic behavior analysis of a piping system made from different materials, considering the seismic load [1]. In the results, plastic deformation was observed in each pipe elbow. To analyze the dynamic behavior of a typical piping system subjected to a seismic load, the Japan Nuclear Energy Safety Organization (JNES) and the Nuclear Power Engineering Corporation (NUPEC) conducted cyclic loading tests on pipe elbows and shaking table tests on a piping system [2]. They conducted experiments to confirm the design method and limit state, and the experimental results indicated that the damage caused by the seismic load to the piping system was a result of low-frequency fatigue failure [3]. Overall, they determined the system to be safer than the individual components owing to factors such as the load redistribution [4].

Generally, the seismic safety review of a nuclear power plant includes a probabilistic seismic fragility analysis. The results of such an analysis vary drastically by failure criteria, and as such, it is critical to define the failure criteria with which severe accidents are actually expressed. Currently, the seismic design criteria for a piping system can identify only plastic collapse and cannot detect a rupture or leakage, which is the actual limit state. Therefore, the criteria cannot sufficiently reflect a critical accident. For a more reliable seismic fragility analysis, the definition of the limit state should be expanded. To confirm the limit state of a piping system, one study conducted an in-plane cyclic loading test at an elbow, which is one of the weakest points in the system. A crack was generated on the inside of the pipe elbow and propagated in the axis direction [5]. In

---

* *Corresponding author.*
E-mail address: bkjeon79@pusan.ac.kr (B.-G. Jeon).

https://doi.org/10.1016/j.net.2017.11.001

Please cite this article in press as: S.-W. Kim, et al., STRAIN AND DEFORMATION ANGLE FOR A STEEL PIPE ELBOW USING IMAGE MEASUREMENT SYSTEM UNDER IN-PLANE CYCLIC LOADING, Nuclear Engineering and Technology (2017), https://doi.org/10.1016/j.net.2017.11.001

addition, hoop strain and low-cycle ratcheting fatigue damage were observed. The limit state of the pipe elbow can be defined by calculating the damage index from the correlation between the load and the displacement of the in-plane cyclic loading test.

As the design criteria and the experimental limit states do not match, Organization for Economic Co-operation and Development's Nuclear Energy Agency (OECD-NEA) launched the metallic component margins under a high seismic load (MECOS) benchmark initiative as a technical interchange to quantitatively evaluate the limit state of piping components and to include rupture or leakage under high seismic loads [6]. Prior studies have found the elbow to be a fragile element in the piping system with its failure triggered by low-cycle ratcheting fatigue. As the cause of failure is known, an analytical method can be used to anticipate the occurrence of failures during experimental studies. Although a damage or fatigue curve can be used to define the limit state of the pipe elbow, the results cannot be easily used in the probabilistic seismic fragility analysis. Therefore, this paper suggests a method of image signal processing to measure the failure strain and deformation angle (moment–theta relation), which are necessary for defining a reliable limit state.

To measure the strain and deformation angle, which influence the deformation and damage of a structure, various reliable measurement techniques have been studied: use of a conventional sensor, numerical analysis using the finite element method, and image analysis using digital image processing. Generally, strain is an important factor in evaluating structural integrity. It is primarily measured using contact-type methods such as the use of an electric resistance strain gage. Such a sensor, however, is also sensitive to the external environment. Moreover, it cannot be relocated or reused, and it has a limited measurement range. Therefore, measuring a large strain is difficult. Measuring the deformation angle of pipe elbows, on the other hand, requires temporary installations for making the approach feasible and for affixing the sensor, which is not economical. In addition, as it is difficult to accurately install the temporary facility, the reliability of the measurement is low. Therefore, a method for measuring the strain and deformation angle from a remote distance, without attaching any sensor, is called for.

In this study, we used an image measurement system to measure the failure strain and deformation angle of the steel pipe elbow and the zero-normalized sum of squared differences (ZNSSD) to measure the displacement, which is necessary for measuring the strain of the steel pipe elbow. Furthermore, the second-order shape function was used to measure the subpixels. In addition, to measure the failure strain in the hoop direction of the steel pipe elbow, we measured the average strain using the pixel-based displacement for a square area marked on the steel pipe elbow. For line recognition, which is needed to measure the deformation angle, the shape of the steel pipe elbow was enhanced using image signal processing, and the deformation angle was measured using the Hough transform of the enhanced image. Finally, an in-plane cyclic loading test was conducted to validate the method of measuring the failure strain in the hoop direction and deformation angle using an image measurement system for a steel pipe elbow, which is a weak part of a seismic isolation nuclear power plant piping system. Consequently, the deformation angle and failure strain in the hoop direction, which cannot be measured using the conventional sensors, were efficiently measured.

2. Algorithm for measuring the strain and deformation angle

2.1. Strain measurement

For the analysis of the correlation between the images obtained before and after the deformation using the image measurement system, we used the gray level value of the image, which is a pattern analysis technique for measuring the difference between the two images [7–11]. The 8-bit gray level that is generally used in such an analysis expresses the information of an object with gray levels ranging from 0 to 255. The measurement conducted using the image correlation method separates the square-shaped image from both images to compare and measure the deformation. The small square-shaped image separated from the two images is called the “subset” or “window.” The window separated by the gray level value is used for comparing the correlations to measure the deformation.

Fig. 1 shows the deformation measurement principle of the image correlation method, which registers a target window with an arbitrary template and finds the most similar target window from the region of interest (ROI) window, which changes over time. In Fig. 1, $f(x_i, y_j)$ expresses the gray level pattern of the square separated from the reference image, and $g(x'_i, y'_j)$ expresses the gray level pattern of the square separated from the deformed image of an object by an external force. The size of the target window is that of a part image of the $(2M+1)(2M+1)$square, where $M$is half the size of the target window, which is a square. To measure the deformation of a structure, the correlation between the reference image and the deformed image was analyzed to find the coordinate with the highest correlation.

In this study, the zero-normalized sum of squared differences (ZNSSD), as shown in Eq. (1), was used to compare the correlations of the two images. The coordinates with the minimum value (C_{ZNSSD}) show the displacement of the object affected by the external force. In this regard, f_m is defined as the mean values of the gray level of the target window. In addition, for an image that changes with time, g_m is the mean value of $g(x'_i, y'_j)$ in the region that matches the current position of $f(x_i, y_j)$, and the calculation is carried out within the coordinates that are common to $f(x_i, y_j)$ and $g(x'_i, y'_j)$.

$$C_{ZNSSD} = \sum_{i=-M}^{M} \sum_{j=-M}^{M} \left[\frac{f(x,y) - f_m}{\Delta f} - \frac{g(x',y') - g_m}{\Delta g} \right] \tag{1}$$

$$\begin{aligned} f_m &= \frac{1}{(2M+1)^2} \sum_{i=-M}^{M} \sum_{j=-M}^{M} f\left(x_i, y_j\right), \\ g_m &= \frac{1}{(2M+1)^2} \sum_{i=-M}^{M} \sum_{j=-M}^{M} g\left(x'_i, y'_j\right) \end{aligned} \tag{2}$$

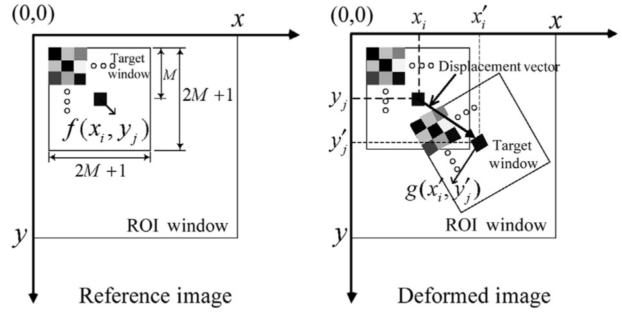

Fig. 1. Deformation measurement using the image correlation method.

Please cite this article in press as: S.-W. Kim, et al., STRAIN AND DEFORMATION ANGLE FOR A STEEL PIPE ELBOW USING IMAGE MEASUREMENT SYSTEM UNDER IN-PLANE CYCLIC LOADING, Nuclear Engineering and Technology (2017), https://doi.org/10.1016/j.net.2017.11.001