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Article

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Fatigue behaviors of the steel pipe tee in a nuclear power plant piping system under in-plane cyclic loading

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Abstract

The safety of a nuclear power plant against earthquakes can be improved by installing seismic isolation devices. As such seismic isolation devices handle seismic loads, however, displacements larger than those generated before the application of such devices may occur. Therefore, the seismic risks are likely to increase for some facilities. In particular, pipes that connect structures with seismic isolation devices to ordinary structures are likely to have higher seismic risks. The piping is affected by the behavior of the two supports, and damage may occur due to the displacement-dominant repeated behavior. In addition, to assess the low-cycle fatigue behavior of the piping system under seismic loads, it is essential to identify the relationships among the number of cycles, moment, and deformation angle until leakage occurs, through an in-plane cyclic loading test. In this study, an in-plane cyclic loading test was conducted to assess the fatigue behavior of a steel pipe tee against seismic loads from the correlation between the moment and the deformation angle.

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Keywords: Steel pipe tee; Nuclear plant piping system; Low-cycle fatigue behavior; Moment-deformation angle

1. Introduction

A nuclear power plant consists of numerous pipes, and these pipes are connected to the main devices. Therefore, pipes are very important for their own functions as well as in terms of the safety of a nuclear power plant. The pipes installed in a nuclear power plant must secure sufficient seismic performance against design earthquake [1].

Many studies have been conducted to identify the fatigue life of pipe components and to define their limit states against earthquakes considering the ratcheting strain for nuclear power plant piping systems, resulting in the increasing number of visible achievements [2–5]. Strain is local, however, and it is difficult to measure the limit state using the conventional sensors [6]. In addition, it may also be difficult to clearly define certain phenomena, such as stress concentration, during finite element analysis. Therefore, component-based assessment may bring more reliable

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results in terms of defining the failure of pipes. The limit state of pipes is mostly assessed through the correlation between the applied load and the loading amplitude from the component-based failure test of the piping system. It may be difficult, however, to directly simulate the direction of the applied force of the test condition for the piping system. This may not be effective and economical in analyzing the seismic fragility of the piping system. As with the study of the Network for Earthquake Engineering Simulation (NEES) conducted to assess the limit states of pipe components and to analyze their seismic fragilities using an experimental method, studies capable of directly describing the deformation of the pipe components and considering the low-cycle fatigue failure effect are required [7]. Therefore, defining the failure criteria and limit states of pipes against earthquakes using the correlation between the moment and the deformation angle will present a fatigue life that is more reliable and easy to use in the field [8]. In this study, a component-based test was conducted for the steel pipe tee, and a low-cycle fatigue test was performed for the constant amplitude. This study proposed a leakage line and low-cycle fatigue curves using the relationship between the moment and the deformation angle of a 3-inch steel pipe tee.

2. Low-cycle fatigue life of the steel pipe tee

In this study, a tee was regarded as a vulnerable point in the piping system in the event of an earthquake. 3-inch SA106, Grade B, and SCH 40 standard pipes were fabricated in accordance with ASME B36.10, and an in-plane cyclic loading test was conducted. The pipes had an 88.9 mm diameter and a 5.49 mm thickness. The length of the straight pipe was at least three times larger ($3D=270$ mm) than the diameter, and the straight pipe was welded onto a tee so that plastic behavior could occur at the tee. Jigs for realizing pin connection were fabricated and welded onto both ends of the specimen, and the specimen was installed at a universal testing machine (UTM) for the test.

Fig. 1 shows the positions of the targets required to measure the loading amplitude of the UTM as well as the moment and deformation angle of the steel pipe tee using the image-based measurement system [6]. The in-plane cyclic loading test was conducted through the displacement control of the UTM. To obtain the loading of the UTM, the loading amplitude of the UTM must be measured. The displacement measured by installing target 1 to the jig for UTM connection and using the image-based measurement system, and the displacement measured through the LVDT installed inside the UTM, were compared and synchronized [9]. In addition, the moment was obtained by multiplying distance d , which was the difference in the horizontal displacement measured at target 2 marked on the steel pipe tee. The reaction force was calculated by dividing the loading force in half. The deformation angle was measured using the displacement responses measured at the target 1 - target 4 points. In the test, 2448×2048 pixel images were obtained at five frames per second using the image-based measurement system. The data acquisition rate of the UTM was 10 Hz, and its loading amplitude was set to 60 mm/min.

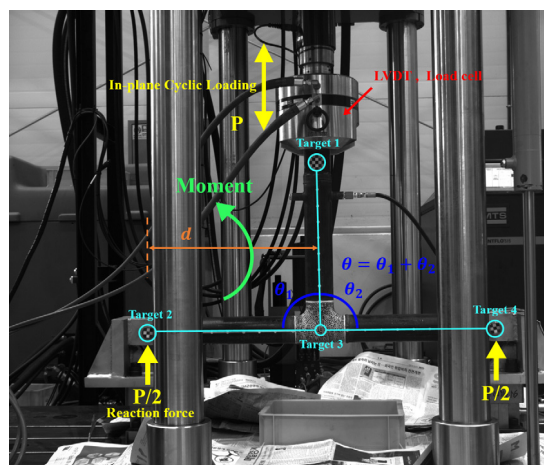


Fig. 1. Steel pipe tee installed at the UTM.

Table 1 shows the number of cycles, moment range, and deformation angle range when a leakage occurred at the steel pipe tee due to the loading amplitude. As shown in the table, the number of cycles to failure ranged from

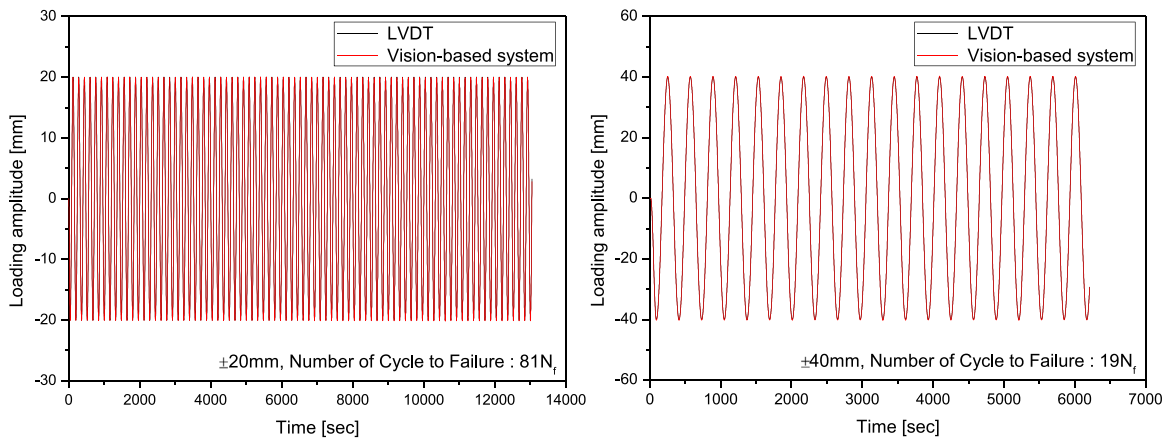
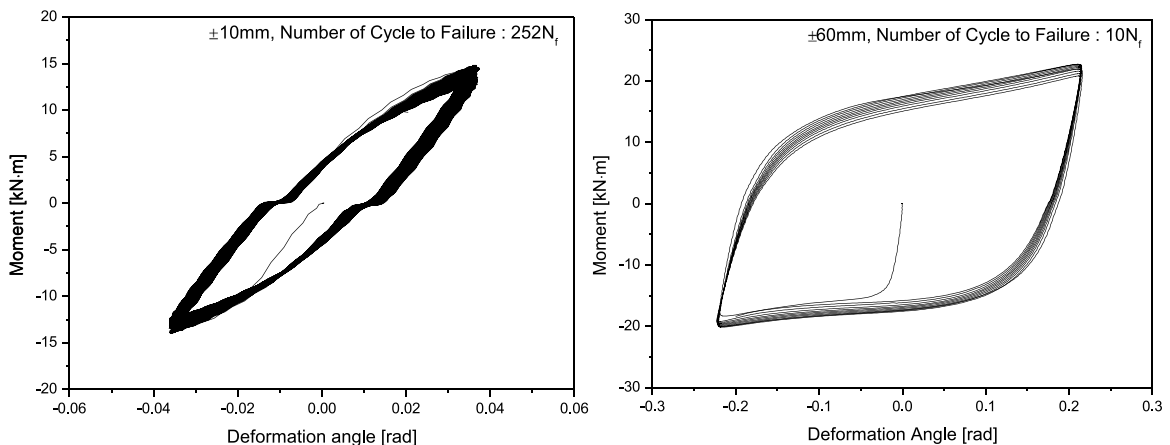
Table 1. Test results for each loading amplitude.

Loading amplitude (mm)	Number of cycles to failure (N_f)	Moment range (kN m)	Deformation angle range (rad)
± 10	252	28.788	0.073
± 10	306	29.284	0.072
± 20	81	33.669	0.145
± 40	19	38.930	0.287
± 40	21	38.462	0.290
± 60	10	42.876	0.438

10 to 306 N_f . The moment range was between 28.788 and 42.876 kN m, and the deformation angle range was between 0.073 and 0.438 rad.

Fig. 2 is a graph showing the displacement response measured at target 1 using the image measurement system, and the displacement response measured by the LVDT installed inside the UTM for the representative specimens. It was confirmed that the two responses are in good agreement with each other. Fig. 3 shows the hysteresis loops of the moment and deformation angle measured in the in-plane cyclic loading test with the representative specimens.

Fig. 4 shows the leakage line using the relationship between the moment and the deformation angle, and the mean regression curve calculated using the least-square method is shown in Eq. (1). Eq. (1) shows the relationship

**Fig. 2.** Comparison of the response measured from LVDT of the UTM.**Fig. 3.** Moment-deformation angle hysteresis loops.

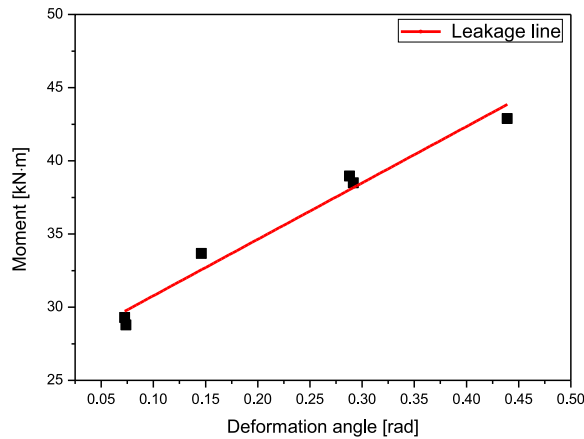


Fig. 4. Leakage line using moment-deformation angle relationship.

between the moment and deformation angle when a leakage occurred in the steel pipe tee during the in-plane cyclic loading test. In Eq. (1), the coefficient of determination (R^2) was 0.96 or higher, indicating that the moment and the deformation angle have a linear relationship.

$$Moment \text{ (kN m)} = 38.543 \cdot Deformation \text{ Angle (rad)} + 26.927, R^2 = 0.967 \tag{1}$$

$$Moment \text{ (kN m)} = 54.980N_f^{-0.113}, R^2 = 0.989 \tag{2}$$

$$Deformation \text{ Angle (rad)} = 1.501N_f^{-0.541}, R^2 = 0.995 \tag{3}$$

For the reliability assessment of the results of the in-plane cyclic loading test, the number of cycles to failure was expressed for the moment and the deformation angle in Fig. 5. The determination coefficient was 0.96 or higher, indicating very high reliability. The relations of the low-cycle fatigue curves of the piping system shown in Fig. 5 can be expressed as Eqs. (2) and (3). It appears that the low-cycle fatigue curves for the moment and the deformation angle can be predicted through these relations.

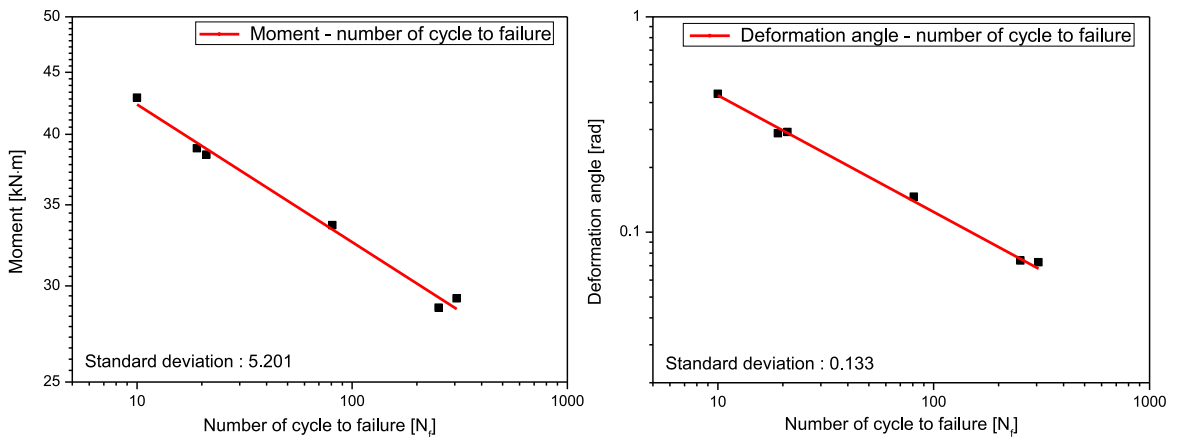


Fig. 5. Low-cycle fatigue curves.

3. Conclusions

In this study, a leakage line for the moment and deformation angle of a steel pipe tee in a seismic-isolated nuclear power plant was proposed. It is expected that the proposed leakage line can be used as data for analyzing the limit state and fatigue failure behavior of a steel pipe tee in a nuclear power plant against earthquakes. Moreover, as the

results of this study were obtained from a test with limited loads, further experimental studies under various loading conditions are required.

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