Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 23-24, 2019

Fatigue Behaviors of the Steel Pipe Tee in the Nuclear Power Plant Piping System

Sung-Wan Kim [a*], Bub-Gyu Jeon [a], Da-Woon Yun [a], Min-Kyu Kim [b]
[a]*Seismic Research and Test Center, Pusan National University, Yangsan, Korea*
[b]*Structural and Seismic Safety Research Team, Korea Atomic Energy Research Institute, Daejeon, Korea*
[*]*Corresponding author: swkim09@pusan.ac.kr*

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].

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. ASCE 7-16 [2] suggests that the relative seismic displacements between supports can be more important than the inertial forces for steel pipes produced with welded connections. In other words, the piping is affected by the behavior of the two supports (i.e., seismic anchor motion [SAM]), and damage may occur due to the displacement-dominant repeated behavior [3]. 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 theta until leakage occurs, through an in-plane cyclic loading test [4]. 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 theta. In addition, an image-based measurement system [5] was used because it is difficult to measure the moment and theta of the steel pipe tee using the conventional sensors.

2. Methods and Results

In this study, a tee was regarded as a vulnerable point in the piping system in the event of an earthquake. Three-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.

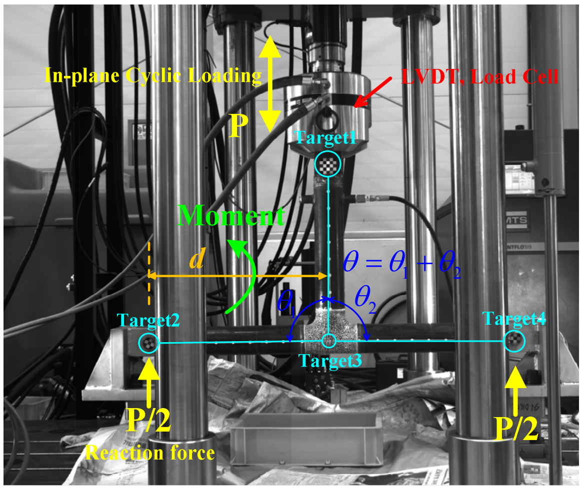
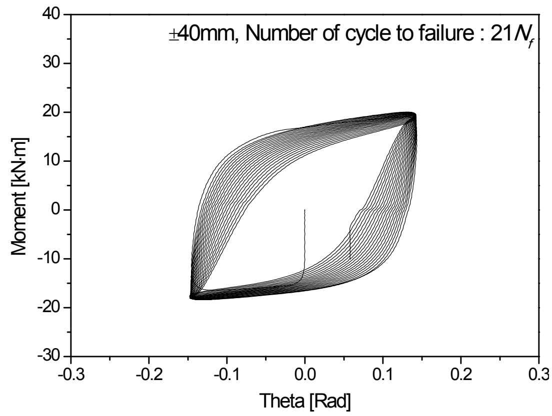
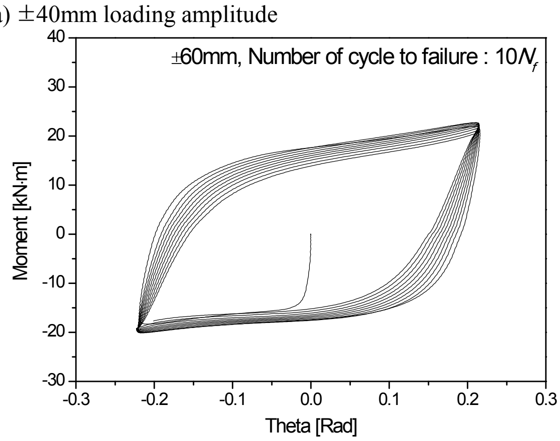


Figure 1. Steel pipe tee installed at the UTM



(a) ±40mm loading amplitude



(b) ±60mm loading amplitude

Fig. 2. Moment-theta hysteresis loops

Fig. 1 shows the positions of the targets required to measure the loading displacement of the UTM as well as the moment and theta of the steel pipe tee using the image-based measurement system. The in-plane cyclic loading test was conducted through the displacement control of the UTM. To obtain the loading of the UTM, the loading displacement of the UTM must be measured. The displacement measured by installing target1 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. In addition, the moment was obtained by multiplying distance d, which was the difference in the horizontal displacement measured at target2 marked on the steel pipe tee. The reaction force was calculated by dividing the loading force in half. The theta was measured using the displacement responses measured at the target1-target4 points. In the test, 2448x2048-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 displacement was set to 60 mm/min.

Table I shows the number of cycles, moment range, and theta 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 10 to 306 N_f. The moment range was between 28.788 and 42.876 kN·m, and the angle range was between 0.073 and 0.438 rad.

Table I: Test results for each loading amplitude

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

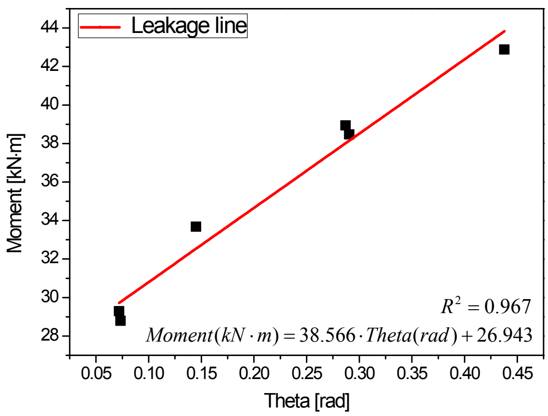


Fig. 3. Leakage line

Fig. 3 shows the leakage line using the relationship between the moment and the theta, and the mean regression curve calculated using the least-square method is shown in Eq. (1). Eq. (1) shows the relationship between the moment and theta 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 theta have a linear relationship.

$$Moment(kN \cdot m) = 38.566 \cdot Theta(rad) + 26.943 \quad (1)$$
$$R^2 = 0.968$$

3. Conclusions

In this study, a leakage line for the moment and theta 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.

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (NRF-2018M2A8A4024087). Moreover, the authors would like to thank the KOCED Seismic Research and Test Center for their assistance with the test equipment.

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