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 1 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 Nf. The moment range was between 28.788 and 42.876 kN•m, and the angle range was between 0.073 and 0.438 rad. Figure 3 shows the leakage point of carbon steel pipe tee. The cracks (ruptures) grew in the axial direction.

Table 1. Test results for each loading amplitude

Loading Amplitude (mm)	Number of cycles to failure (Nf)	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

Figure 3. Leakage point of carbon steel pipe tee under in-plane cyclic loading

NUMERICAL ANALYSIS

Shell elements are known to express ovalization and warping, characteristics of the pipes. Accordingly, the numerical model of the specimen was made by using shell element(S4R) of ABAQUS 6.14. Figure 4 shows the model of the specimen. The part of jig connected to UTM was created as beam element(B31). The shell element and the beam element are constrained by the MPC-beam constraint function. Figure 5 shows the material properties for numerical analysis. The numerical procedure is divided into two steps. First is pressurized the internal pressure. And the same test conditions are simulated by the displacement control. Table 2 shows the procedure of numerical analysis

Table 2 Numerical analysis procedure

		Step 1	Step 2
Load type	Internal pressure	Created	Propagated
	Cyclic loading		Created

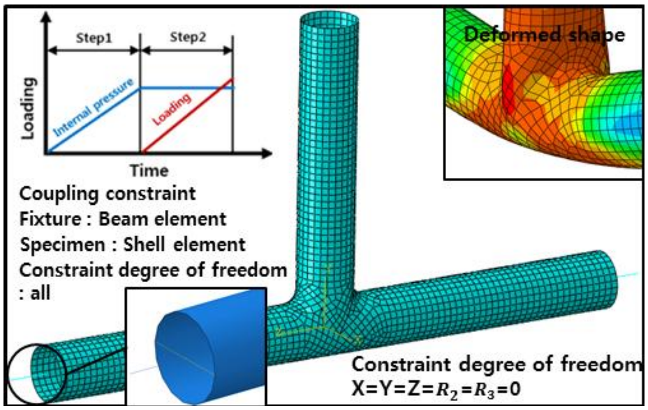

Figure 4. Numerical analysis for internal pressured carbon steel pipe tee under in-plane cyclic loading

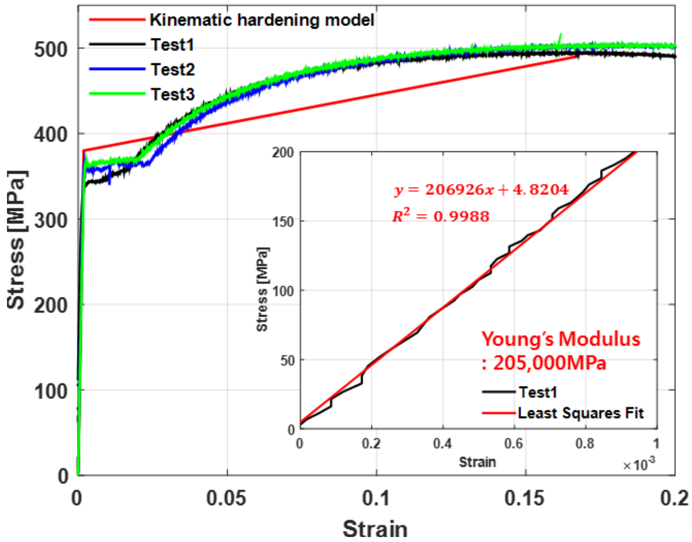

Figure 5. Material properties

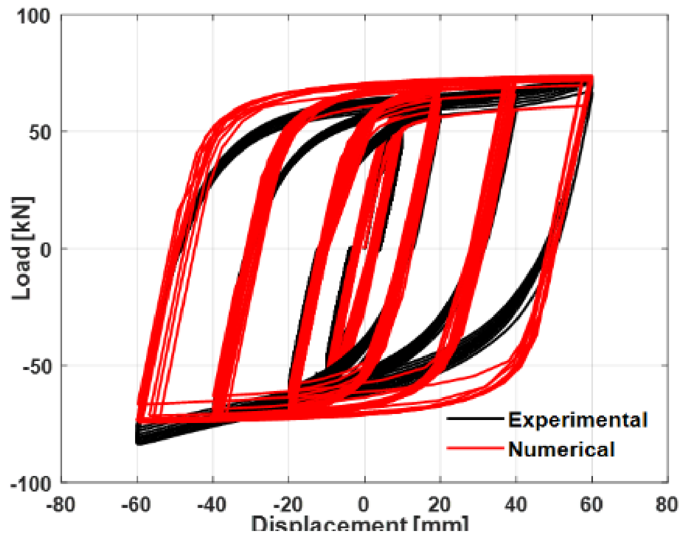

Figure 6. Comparison of test and analysis results

A numerical model was built by using results of coupon test. And it was updated with cyclic loading test results. Figure 6 shows the results from test and numerical analysis. The relationships between displacement and force from tests and numerical analysis was well matched.

QUANTITATIVE LIMIT STATE OF THE CARBON STEEL PIPE TEE

In this study, a quantitative estimation method for the limit state of carbon steel pipe tee is suggested using a damage index based on cumulative energy. According to Bannon et al.(1981), a damage index can be expressed as equation (1);

$$D = \sqrt{\left(\max\left(\frac{D_i}{D_y} - 1\right)\right)^2 + \left(\sum_{i=1}^{N} c \cdot \left(2\frac{E_i}{F_y \cdot D_y}\right)^d\right)^2} \tag{1}$$

D_y and F_y mean yield displacement and yield force, respectively. Also, D_i and E_i mean displacement amplitude and dissipated energy at cycle number of i. The constant of c and d was recommended as 3.3 and 0.21, respectively[Jeon et al. (2017)]. Damage indexes are calculated by using the results of test and numerical analysis. Figure 7 shows the one of damage indexes from each loading displacement cases.. The average value of each damage index is 13.62 and 13.44. The percent error of the average value of the damage index between the test and numerical analysis is 1.32%. At low displacement range less than ±20 mm, the error is less than 1%. However, the error is greater than 5% at a displacement range of ±40 mm or more.

Table 3 Comparison of percent error of damage index between test and numerical analysis

Loading Amplitude (mm)	10	20	40	60
Percent Error (%)	0.06	0.58	5.74	9.75
Percent Error of Average value (%)	1.32			

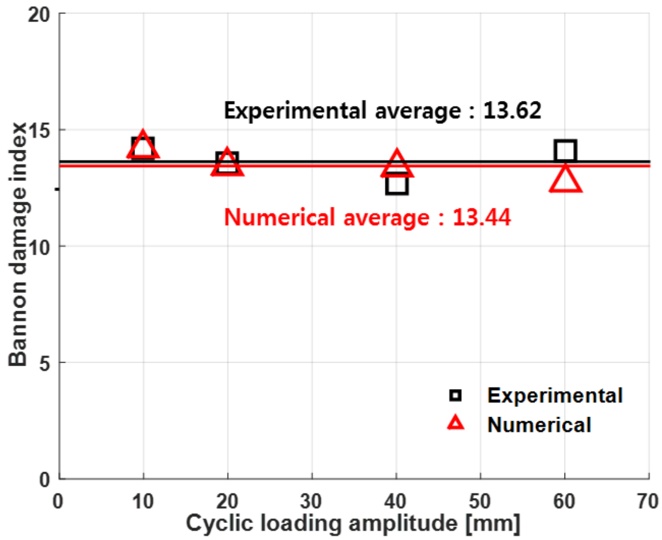

Figure 7. Comparison of damage index between test and numerical analysis

CONCLUDING REMARKS

In this study, the limit state of a carbon steel pipe tee, is the fragility part of the seismically isolated nuclear power plant's piping system, is defined as rupture or leakage. A leakage due to in-plane cyclic loading test for carbon pipe tee occurred on the upper part of the center of the tee. The cracks (ruptures) grew in the axial direction.

Bi-linear kinematic hardening model was useful for simulated the nonlinear behavior of pipe tee under cyclic loading condition.

For quantitative failure estimation, damage index based on cumulative energy was used. And it is expected to use for defining the failure of the carbon steel pipe tee.

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