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Parametric Study on Ultimate Failure Criteria of Elbow Piping Components in Seismically Isolated NPP

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1. Introduction

Recently, to design the nuclear power plants (NPPs) more efficiently and safely against the strong seismic load, many researchers focus on the seismic isolation system. For the adoption of seismic isolation system to the NPPs, the seismic performance of isolation devices, structures, and components should be guaranteed firstly. Hence, some researches were performed to determine the seismic performance of such items. For the interface piping system between isolated structure and non-isolated structure, the seismic capacity should be carefully estimated since that the required displacement absorption capacity will be increased significantly by the adoption of the seismic isolation system.

It is well known that the interface pipes between isolated & non-isolated structures will become the most critical in the seismically isolated NPPs [1]. Therefore, seismic performance of such interface pipes should be evaluated comprehensively especially in terms of the seismic fragility capacity. To evaluate the seismic capacity of interface pipes in the isolated NPP, firstly, we should define the failure mode and failure criteria of critical pipe components. Hence, in this study, we performed the dynamic tests of elbow components which were installed in a seismically isolated NPP, and evaluated the ultimate failure mode and failure criteria by using the test results. To do this, we manufactured 25 critical elbow component specimens and performed cyclic loading tests under the internal pressure condition. The failure mode and failure criteria of a pipe component will be varied by the design parameters such as the internal pressure, pipe diameter, loading type, and loading amplitude. From the tests, we assessed the effects of the variation parameters onto the failure criteria. For the tests, we generated the seismic input protocol of relative displacement between the ends of elbow component. The results of ultimate failure mode and failure criteria are presented in terms of the number of cyclic loading counts, damage indices which are the functions of dissipated energy and inelastic deformation.

2. Method and Results

When seismic event occurs, plastic deformation and failure occur in the elbow of piping system [2, 3]. Therefore, we manufactured the elbow component specimens and performed cyclic loading tests under the internal pressure condition. The figure of the elbow specimens of ASME B36.10M SA53, Grade A, SCH 40 [4] shown in Fig. 1. Straight pipes with sufficient length were attached to the ends of elbows by welding to generate plastic behavior in the elbow section of the specimen.

To ensure the straight movement of the actuator, we produced a special zig. A CAD drawing and a picture of the zig are illustrated in Fig. 2. Also, to prevent the play of the hinge, we introduced high-precision hinge components to the ends of elbow specimen (Fig. 3). In Fig. 4, the total configuration of the dynamic test is presented. For the dynamic test, a 250 kN dynamic actuator and a MTS FlexTest controller are used.

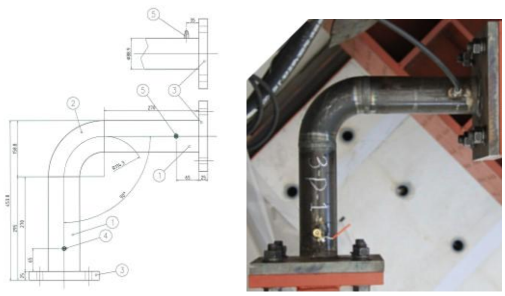

Fig. 1. Elbow test specimen.

Fig. 2. A special zig to ensure the straight movement of actuator.

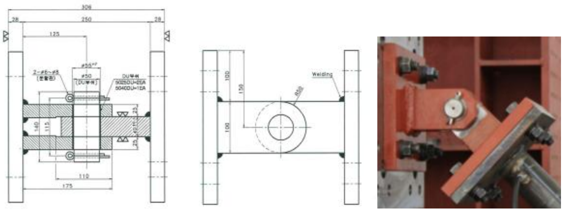

Fig. 3. A high-precision hinge component to prevent the play at the hinge element.

Fig. 4. Dynamic test setup configuration using straight moving zig, hinge elements, and elbow specimen.

With the dynamic test to evaluate the ultimate failure mode and failure criteria, we also tried to verify the effects of many variation parameters, such as the internal pressure, loading amplitude, loading type, and the size of elbow specimens. In Table 1, the test plans are summarized. We used sinusoidal input wave with amplitudes of 60, 80, and 100 mm, and also earthquake input motions which has maximum displacements between the elbow arms of 40 to 160 mm. From all of the 24 elbow component specimens, the penetration cracks and leakage of waters were captured as the ultimate failure mode of pipes. Fig. 5 depicts one of the ultimate failure states of elbow specimens. In Table 2, the results of ultimate failure criteria are listed in terms of the number of cyclic loading counts required to occur the ultimate failure. From the results, we found that the increase of the internal pressure will slightly increase the failure criteria. Tested elbow components had a very good sustainability against to the earthquake loading since that more than 34 times of 0.5g earthquakes (in this case, 40 mm amplitude case) were required to make a penetration crack at the tested pipes.

Table 1. Test plans for the dynamic cyclic loading test to evaluate the failure mode & failure criteria.

Specimen #	Diameter (in)	Amp.(±mm)	Loading Type	Internal Prs.(MPa)
3-A	3.0	60.0	Sine	2.0
3-C				5.0
3-B		80.0		2.0
3-D-1		40.0	EQ	
3-D-2		60.0		
3-D-3		80.0		
3-D-4		120.0		
3-D-5		140.0		
3-D-6		160.0		
3-E		100.0	Sine	
6-A	6.0	160.0		
6-B		120.0		

Fig. 5. Ultimate failure state of elbow specimen: penetration crack & leakage of water at the crown of elbow.

Table 2. Test results: ultimate failure criteria in terms of the number of cyclic loadings.

Specimen #	Amp.(±mm)	Internal Prs.(MPa)	# of Cycles to Failure	Maximum Loading (kN)
3-A	60.0	2.0	18.3	44.2
3-C		5.0	21.0	47.2
3-B	80.0	2.0	10.2	51.9
3-D-1	40.0		34.5	49.8
3-D-2	60.0		15.0	56.6
3-D-3	80.0		8.0	71.5
3-D-4	120.0		3.0	91.7
3-D-5	140.0		2.0	97.4
3-D-6	160.0		1.5	104.4
3-E	100.0		8.0	62.6
6-A	160.0		6.5	194.3
6-B	120.0		11.9	151.4

Fig. 6 present the force-displacement hysteresis curves for specimen 3-D-5 & 3-D-6, respectively. In Fig. 6, the actual relative displacements between the ends of elbow components were loaded dynamically to compare and verify the failure criteria evaluated from the simple cyclic loading test.

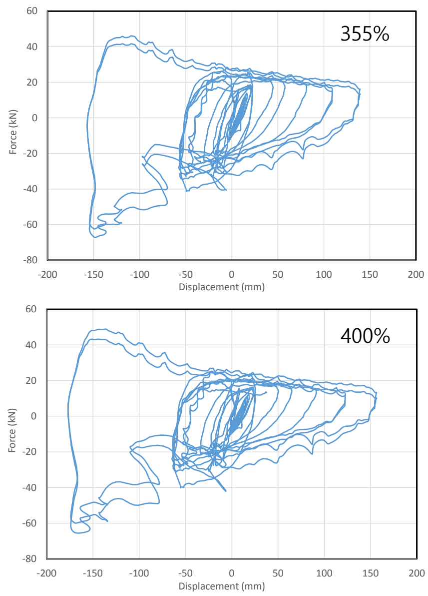

Fig. 6. Force-displacement hysteresis curves for specimen 3-D-5 & 3-D-6.

For the elbow piping component under seismic loading, the ultimate failure criteria can be introduced in terms of the dissipated energy or plastic dissipated energy. In Table 3, the dissipated energy and plastic dissipated energy at the ultimate failure states of elbow piping component under seismic loading cases were listed compared to those of the simple cyclic loading cases.

In Table 4, the dissipated energy and damage indices at the ultimate failure states of 6" specimen were listed with comparing those of the 3" specimen. From the results, we can found that the total amounts of dissipated energy are quite different between 3" and 6" specimen, while the damage index terms are relatively similar at both test cases.

Table 3. The dissipated energy and plastic dissipated energy at the ultimate failure states of elbow piping component.

Case	Description	Dissipated Energy (kN-mm)	Plastic Dissipated Energy (kN-mm)
3-D-2	133% Scale EQ	131857.7	65834.6
3-D-5	355% Scale EQ	63805.0	50734.5
3-D-6	400% Scale EQ	65160.2	53868.9
3-A-1	Cyclic 60mm Amp.	91970.9	67658.9
3-B-1	Cyclic 80mm Amp.	85740.3	65801.0

Table 4. The dissipated energy and damage indices at the ultimate failure states of 6" specimen compared to the 3" specimen.

Term	6″ Pipe	3″ Pipe
Dissipated Energy	51254.16	14506.80
Damage Index Term	242.79	265.79

5. Conclusions

In this paper, elbow in piping system was defined as a fragile element and numerical model was updated by component test. Failure mode of piping component under seismic load was defined by the dynamic tests of ultimate pipe capacity. For the interface piping system, the seismic capacity should be carefully estimated since that the required displacement absorption capacity will be increased significantly by the adoption of the seismic isolation system. In this study, the dynamic tests were performed for the elbow components which were installed in an actual NPPs, and the ultimate failure mode and failure criteria were also evaluated by using the test results. From the results, we found that the tested elbow specimens sustained healthiness against to the earthquakes stronger than 1.0 g scale. Even under the 4 times larger amplitude of earthquake compared to the 0.5 g scale earthquake, the penetration crack was not occurred in the tested specimen.

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