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Original Article

A Failure Estimation Method of Steel Pipe Elbows under In-plane Cyclic Loading

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ABSTRACT

The relative displacement of a piping system installed between isolated and nonisolated structures in a severe earthquake might be larger when without a seismic isolation system. As a result of the relative displacement, the seismic risks of some components in the building could increase. The possibility of an increase in seismic risks is especially high in the crossover piping system in the buildings. Previous studies found that an elbow which could be ruptured by low-cycle ratcheting fatigue is one of the weakest elements. Fatigue curves for elbows were suggested based on component tests. However, it is hard to find a quantitative evaluation of the ultimate state of piping elbows. Generally, the energy dissipation of a solid structure can be calculated from the relation between displacement and force. Therefore, in this study, the ultimate state of the pipe elbow, normally considered as failure of the pipe elbow, is defined as leakage under in-plane cyclic loading tests, and a failure estimation method is proposed using a damage index based on energy dissipation.

1. Introduction

The seismic requirements for nuclear power plants (NPPs) have been enhanced after the Fukushima nuclear accident caused by the earthquake near Tohoku, Japan in 2011. To satisfy these new requirements, many studies have been conducted on the application of isolation systems which can secure a higher seismic capacity without major changes to existing designs. However, partial isolation in an NPP can cause a large relative displacement of piping systems connecting isolated structures to nonisolated structures.

A piping system, one of the most important parts of a nuclear power system, was classified as S/O (screen out) in the 2002 probabilistic risk assessment by Korea Hydro &

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Nuclear Power Co. [1] because it is hard to effect a large relative displacement of a piping system under a non-isolated system. However, the seismic risk of a main steam pipe in an NPP can increase due to a large relative displacement of a piping system, by applying a partial isolation system. A leakage from a pipe system in an NPP can be classified as a critical accident due to the possibility of radiation leakage. To predict a leakage in a piping system, a probabilistic safety assessment should be conducted on the piping system in accordance with NPP standards. Definition of failure is one of the most important parameters needed to make an appropriate prediction in probabilistic safety assessment. Therefore, it is necessary to define the final state of a piping system to ensure the safety of NPPs under seismic conditions.

Many studies have been conducted on piping systems under seismic conditions in order to identify weak components and to perform nonlinear behavior analysis based on experimental and analytical methods.

Dynamic behavior analysis of piping systems under seismic conditions using a seismic table was performed by Touboul et al in 1999 [2]. According to their study, plastic behavior could occur at the pipe elbow under seismic conditions.

Experimental research on the dynamic behavior of typical piping systems in NPPs has been performed for several years by the Japan Nuclear Energy Safety Organization and the Nuclear Power Engineering Corporation [3]. Cyclic loading tests and shake-table tests for piping components have been performed in the research processes.

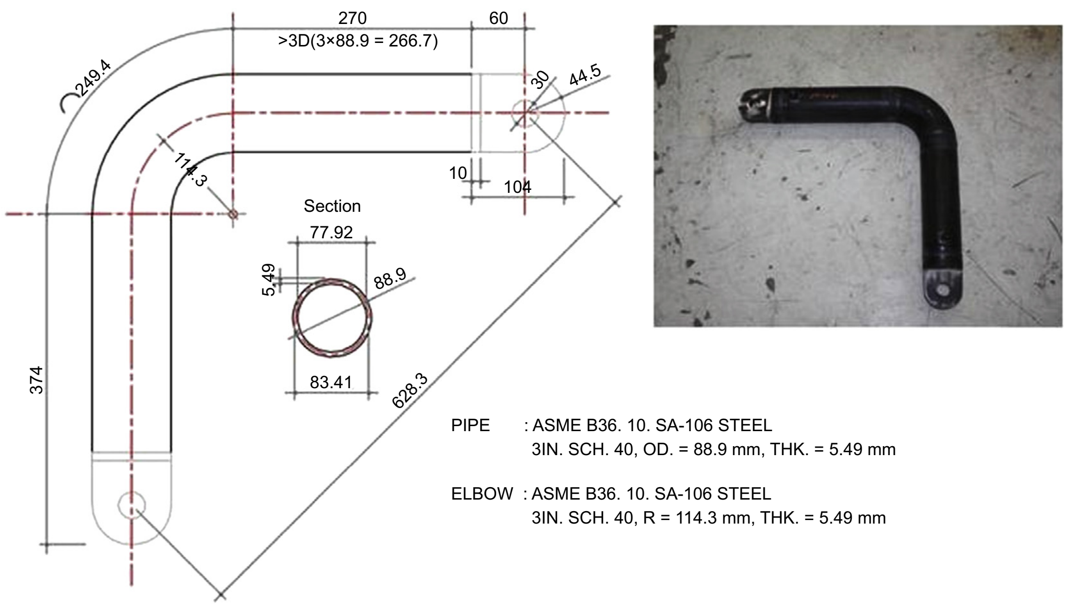

Fig. 1 – Description of test specimen. OD, outer diameter; R, radius; THK, thickness.

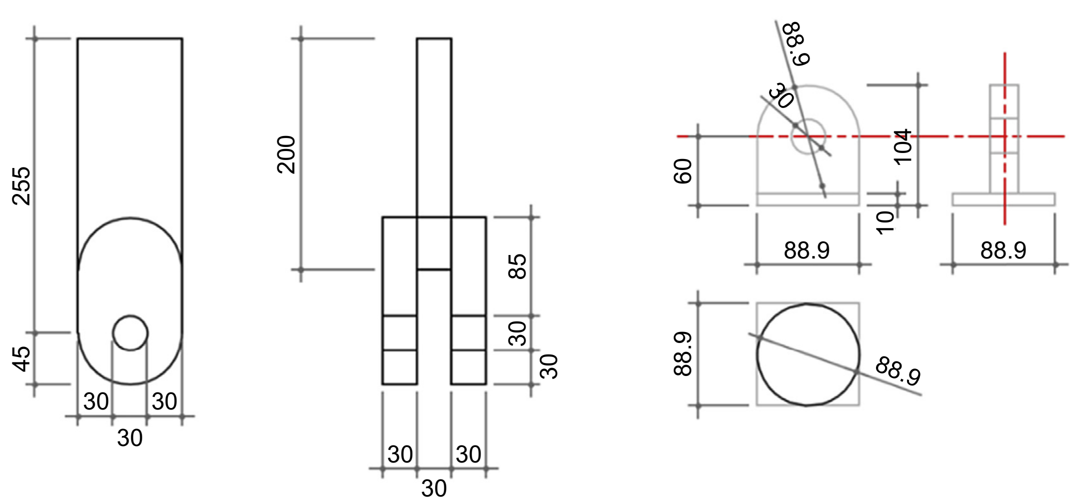

Fig. 2 – Description of connection zig.

Otoyo et al [4] performed tests to confirm the ultimate strength and design methods of the piping system. According to their research, failure usually occurred at the elbow under seismic conditions and was categorized as low cyclic fatigue failure. Meanwhile, Park et al [5] found that the component test for piping systems is a more severe condition than the whole system tests due to load-redistribution effects.

A low-cycle ratcheting fatigue test was performed by Mizuno et al [6] with a scaled model of an elbow, which is the weakest component in a piping system. In that research, a crack occurred inside an elbow and grew up in the axial direction. Dominant hoop strain and low-cycle ratcheting fatigue damage were also observed in the test. This suggested a fatigue curve of elbows which was higher than design capacity.

According to previous studies, an elbow that can fail due to low-cycle ratcheting fatigue under seismic conditions is a weak component in a piping system. Although a fatigue curve of an elbow was suggested in previous research, it is hard to find a result of quantitative evaluation for the ultimate state of piping elbows.

Therefore, in this study, in-plane cyclic loading tests were performed to evaluate the ultimate state of a piping elbow under large relative displacement occurring conditions. The failure defined as leakage at the elbow component was estimated and predicted by a damage index based on energy dissipation.

2. Test specimen

To evaluate the ultimate state of the elbow, specimens were produced as shown in Fig. 1, in accordance with ASME B36.10 SA106, Grade B, and SCH 40 (ASME, 2004). The external diameter of the specimens was 88.9 mm with a thickness of 5.49 mm. The straight part of a specimen attached to the elbow by welding was three times longer than the external diameter, so that the plastic behavior of the elbow could occur. A set of jigs, as shown in Fig. 2, was produced to enable pin connection in tests. Pins for connecting jigs and specimens were precisely produced to minimize space in order to increase the accuracy of the tests.

To minimize the effect of unknown factors, specimens were made by persons with relevant certificates and qualified to supply piping systems to NPPs in South Korea. Also, the welding of specimens was performed by internationally qualified welders.

3. Component testing

3.1. *Material property of specimens*

Test specimens were made by two different manufacturers and some specimens were made from blasting pipe made by Manufacturer A in consideration with several field conditions.

The difference error of 0.2% offset yield stresses, tensile strength, and elongation between materials used by two manufacturers was given as 3.11%, 3.03%, and 5.00%, respectively (see Table 1). Tensile tests were performed to confirm those data. As a result, it was possible to confirm the reliability of material properties because the difference errors of yield stresses based on given values by Manufacture A was < 5.00%. The difference error of each material was calculated by Eq. (1) and the results are shown in Table 2.

$$\text{Difference error} = \frac{|R_1|_{max} - |R_2|_{max}}{|R_1|_{max}} \quad (1)$$

Here, R_1 is the given yield strength from Manufacturer A and R_2 is the given yield strength from Manufacturer B, or the yield strength from the tests.

Table 1 – Material information for specimens of each manufacturer.

	YS (0.2% offset)	TS	EL (%)
Manufacturer A	331.65MPa	477.13MPa	40.00
Manufacturer B	321.31MPa	491.61MPa	38.00
Different error	3.11%	3.03%	5.00

EL, elongation; TS, tensile strength; YS, yield strength.

Table 2 – Difference errors of yield strength.

Item	Manufacturer		Tensile test specimen		
YS (0.2% offset)	A	B	1	2	3
(MPa)	331.65	321.31	327.45	336.85	344.32
Difference error (%)	0.00	3.12	1.27	1.57	3.82

YS, yield strength.

Table 3 – Description of material test coupon.

Test specimen	No. 1	No. 2	No. 3
W	18.95	19.09	18.95
	18.97	19.02	18.94
	18.99	19.02	18.93
	19.01	19.03	18.92
	19.02	19.05	18.92
T	5.48	5.51	5.66
	5.48	5.5	5.68
	5.48	5.49	5.66

T, thickness; W, width.

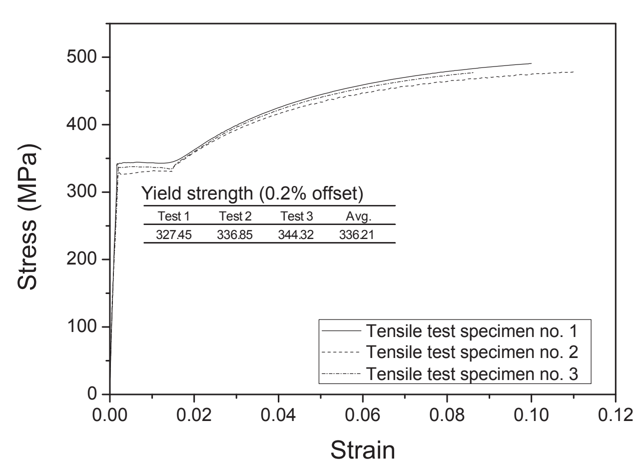

Fig. 3 – Stress-strain relationship of material.

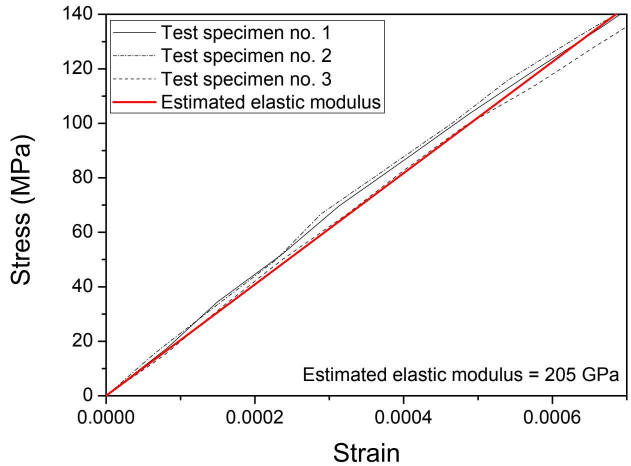

Fig. 4 – Elastic modulus of test specimen.

3.2. *Material test*

A material test was performed with test coupons collected from the pipe to produce an elbow specimen. The information from the test coupons for the material test is shown in Table 3.

Research performed by Yun [7] showed true stain and true stress can be calculated with measured displacement and force Eqs. (2) and (3), respectively.

$$\sigma_{true} = \sigma_{eng}(1 + \varepsilon_{eng}) \quad (2)$$

$$\varepsilon_{true} = \ln(1 + \varepsilon_{eng}) \quad (3)$$

Here, ε_{eng} and ε_{true} mean engineering stress and true stress, respectively. As shown in Fig. 3, material properties of test coupons were almost the same. Therefore, variations by material properties can be ignored in the in-plane cyclic loading tests.

A representative trend line of elastic behavior area in a stress-strain curve was estimated by the least squares method with coupon tests data, as shown in Fig. 4. The representative elastic coefficient of specimens can be calculated by Eq. (4).

$$E = \sigma_{true}/\varepsilon_{true} \quad (4)$$

Therefore, the representative elastic coefficient for the specimens in this study can be assumed as 205 GPa.

3.3. *Pipe elbow component*

To evaluate pipe elbow bend performance with internally pressured water under the seismic loading condition, several component tests were performed statically until leakage occurred. The experimental configuration for the component tests is shown in Fig. 5.

The test instrument for applying the load to the top of the piping component is a servo-controlled hydraulic

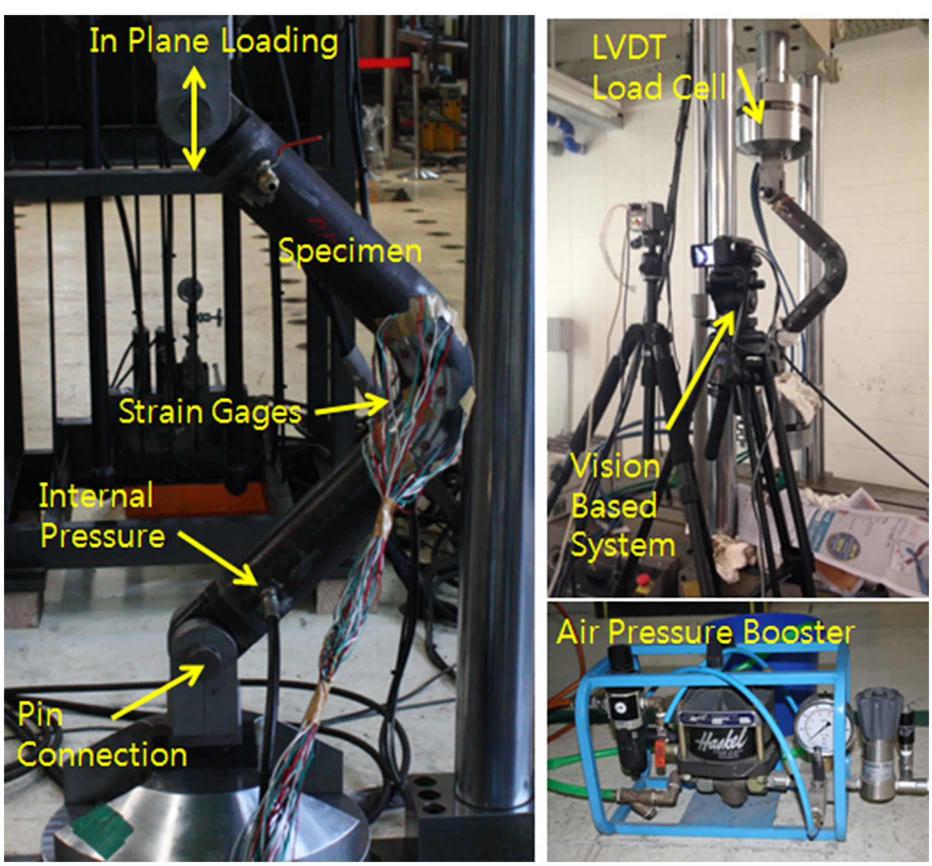

Fig. 5 – Experimental configuration for the component test. LVDT = linear variable displacement transducer.

Table 4 – Component test plan.

Amplitude	± 20 mm	± 30 mm	± 40 mm	± 50 mm	± 60 mm	± 70 mm	± 80 mm	± 90 mm	± 100 mm
Mode	Cyclic mode	Cyclic mode	Cyclic mode	Cyclic mode	Cyclic mode	Cyclic mode	Cyclic mode	Cyclic mode	Cyclic Mode
Internal Pressure (MPa)	3	3	3	3	3	3	3	3	3
No. of specimen	6	5	5	5	6	5	7	5	5
Ultimate state	Leakage	Leakage	Leakage	Leakage	Leakage	Leakage	Leakage	Leakage	Leakage

No., number.

testing machine in the Seismic Simulation Test Center at Pusan National University and Advanced Construction Materials Testing Center at Keimyung University, Daegu, Korea. The cyclic test was conducted with various displacement amplitude cases in the in-plane of piping direction and all of the specimens were tested under displacement control as shown in Table 4. The specimen was installed using pin connections at the top and bottom of the component.

The vertical displacement and force at the top of the specimen during the test were measured using a linear variable displacement transducer and a load cell installed in a hydraulic actuator. More than five tri-axial strain gages were attached around the elbow. In this paper, only the relationship between displacement and force of the specimen is reported because it was failed to get reliable strain from the strain gages near a crown of the specimens due to a large deformation at the elbow.

4. Test results

The relationship between displacement and force is shown in Fig. 6. The locations and numbers of cycles for leakage are shown in Fig. 7 and Table 5. The crack (rupture) occurred near the crown of the elbow and grew up in the axial direction. The initiation and propagation of the crack were in agreement with a previous study by Mizuno et al [6].

Fatigue curve for maximum induced displacement decreases exponentially as the number of cycles increases, as shown in Fig. 8. Here ○, ■, and △ are Manufacturer A, Manufacturer B, and blasting specimens, respectively.

According to Jelka's [8] research, yield force can be considered as the force at the intersection point of the linear area regression line and the plastic area tangent line. Also, yield displacement can be considered as the displacement corresponding to the evaluated yield force. Therefore, the maximum yield force and yield displacement from the experiment in this study are 32 kN and 9 mm, respectively, as shown in Fig. 9.

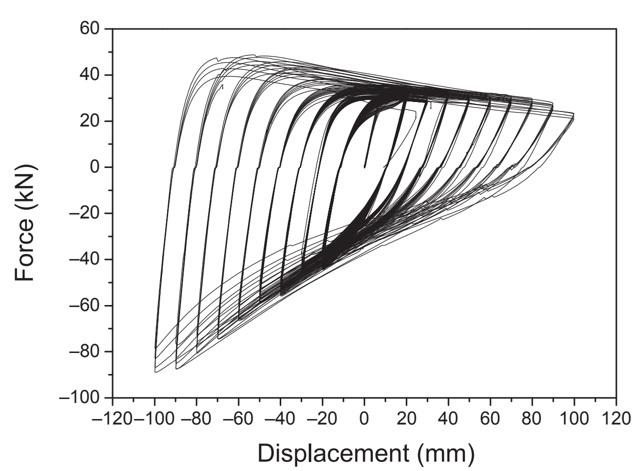

Fig. 6 – Force–displacement relationship.

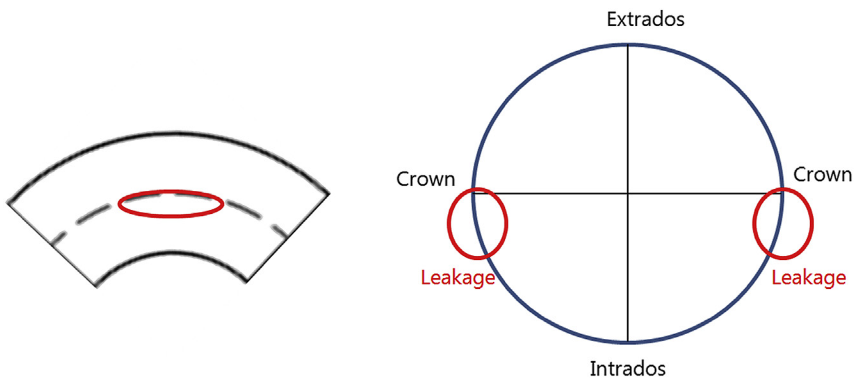

Fig. 7 – Leakage point of specimen.

Table 5 – Summary of test results.

Loading amplitude (mm)	Number of specimen	Internal pressure (MPa)	Leakage location	Leakage cycles
± 20	6	3		82, 108, 110, 87, 76, 98
± 30	5	3		45, 46, 29, 29, 38
± 40	5	1		17, 18, 18, 14, 15
± 50	5	3		11, 10, 11, 9, 12

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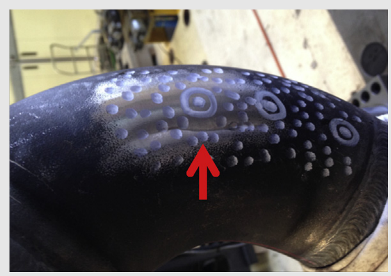
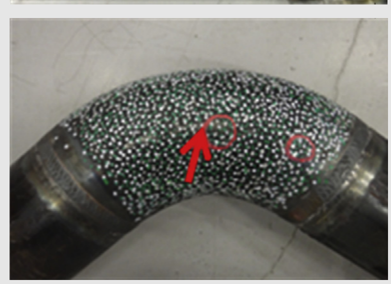
Table 5 – (*continued*)

Loading amplitude (mm)	Number of specimen	Internal pressure (MPa)	Leakage location	Leakage cycles
± 60	6	3		6, 6, 8, 8, 8, 8
±70	5	3		4, 5, 5, 4, 6
±80	7	3		5, 4, 4, 5, 4, 4, 5
±90	5	3		4, 4, 4, 4, 4
±100	5	3		4, 3, 4, 4, 3

5. Failure estimation for steel pipe elbow

There have been many previous studies on piping systems. However, it is hard to find an example of quantitative evaluation for the failure of piping elbows.

In this study, a quantitative estimation method for the failure of piping elbows is suggested using a damage index based on cumulative energy. According to Banon et al [9] a damage index can be expressed as Eq. (5);

$$D = \sqrt{\left[\max\left(\frac{D_i}{D_y} - 1\right)\right]^2 + \left[\sum_{i=1}^{N} c \cdot \left(2\frac{E_i}{F_y \cdot D_y}\right)^d\right]^2} \quad (5)$$

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

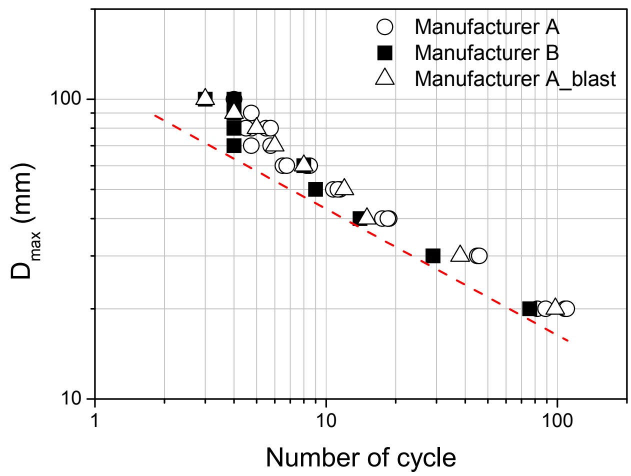


Fig. 8 – Fatigue curve for maximum induced displacement.

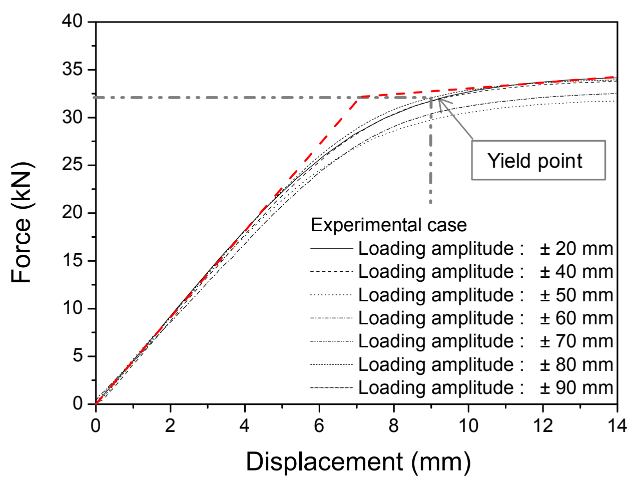


Fig. 9 – Yield point of specimen.

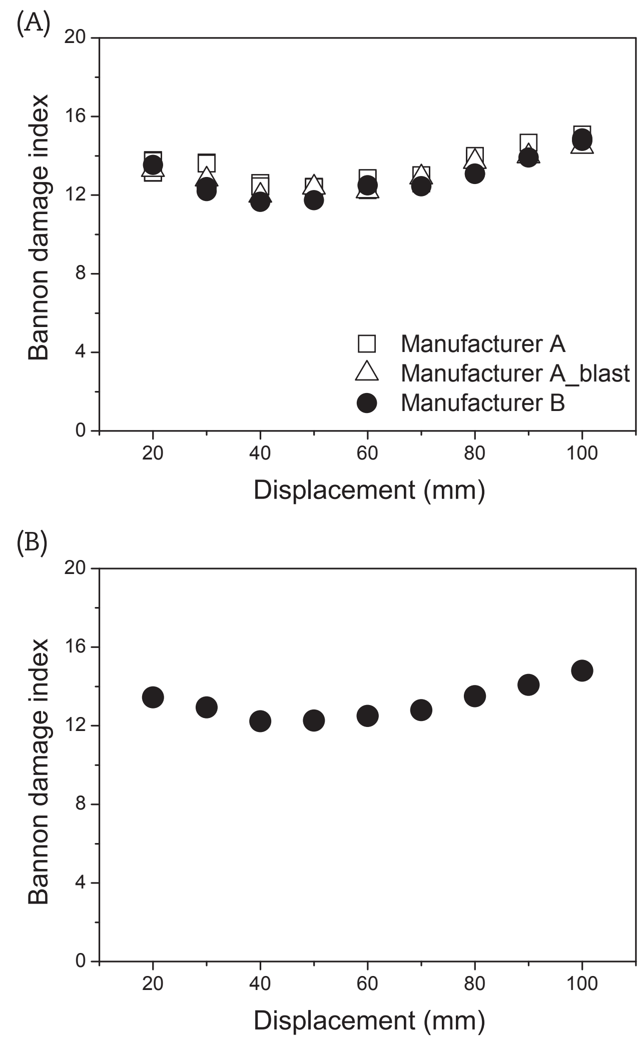


Fig. 10 – Damage index for piping elbow. (A) Damage index: individual. (B) Damage index: mean value of each loading amplitude.

and *d* was recommended as 1.1 and 0.38, respectively, for steel structure according to research by Castiglioni and Pucinotti [10]. However, test results in this paper were better matched with 3.3 and 0.21 for *c* and *d*, respectively.

Calculated damage indexes by Eq. (4) and statistical data are shown in Fig. 10 and Table 6, respectively. The individual damage index of each specimen is shown in Fig. 10A and the means of damage indexes against loading amplitude are shown in Fig. 10B.

The maximum and the minimum damage indexes from each test are 15.08 and 11.65, respectively. Also, mean and median values of each damage index are 13.17 and 13.07, respectively. Log-normal standard deviation and covariance of each damage index are calculated as 0.028 and 0.065. Meanwhile, mean value and log-normal standard deviation of the mean damage index against loading amplitude from Fig. 10B are 13.17 and 0.027, respectively. These values are similar to those from individual results.

Therefore, mean value or median value can be used for a representative value because the log-normal standard deviation is small enough. Also, it is possible to quantitatively estimate or predict the failure of the pipe elbow with the representative value of damage index recommended in this paper.

Table 6 – Statistical information of damage index.

	Max.	Min.	Mean	Median	Covariance	Log-normal standard deviation
Individual	15.08	11.65	13.17	13.07	0.065	0.028
Mean	14.80	12.22	13.17	12.93	0.062	0.027

6. Concluding remarks

Material tests and cyclic loading tests were performed under internal pressure conditions to quantitatively evaluate the ultimate state of the pipe elbow, a weak component in a piping system, under seismic conditions.

A leakage due to in-plane cyclic loading occurred on the crown or near the crown in the intrados direction; cracks (ruptures) grew in the axial direction.

The loading amplitude exponentially decreased as the number of cycles increased.

It was hard to measure reliable strain data with a general strain gage from near the crown with leakage occurring, because the observed strain was out of the mesurement range of the attached strain gages.

A failure estimation method is proposed in this paper using the damage index based on cumulative energy. We expect to use this method for defining the failure of the piping elbow in futher researches.

Conflicts of interest

All authors have no conflicts of interest to declare.

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