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SEISMIC FRAGILITY ESTIMATION OF PIPING SYSTEM OF BASE-ISOLATED NUCLEAR POWER PLANT

Bub-Gyu Jeon[1], Hyoung-Suk Choi[2], Dae-Gi Hahm[3] and Nam-Sik Kim [3]

[1] Senior researcher, KOCED Seismic Simulation Test Center, Korea
[2] Shaking table lab. manager, KOCED Seismic Simulation Test Center, Korea
[3] Senior researcher, Korea Atomic Energy Research Institute, Korea
[4] Professor, Pusan National University, Korea

ABSTRACT

Base isolation is considered as a seismic protective system in the design of Nuclear Power Plants. If seismic isolation devices are installed in nuclear power plant for seismic stability, safety against seismic load of power plant may be improved. But in case of the piping system, seismic risk may increase because relative displacement may become greater than before installation of seismic isolation device. Therefore, it is necessary to performed study on seismic fragility evaluation of piping system which seismic risk increases due to increase in displacement by the installation of seismic isolation device.
In this study, the modified NRC-BNL benchmark models were used for seismic analysis. The piping system of benchmark models was connected base isolated building with ground. In order to validation of numerical piping system model, component tests were performed. When seismic occurs, plastic deformation and failure occur in the elbow of piping system. Therefore elbow specimens were manufactured for component test.
The fragility evaluation was performed by using results of inelastic seismic response analysis. Inelastic seismic response analysis was carried out by using shell finite element model of piping system considering internal pressure. The implicit method was used for the direct integration time history analysis. Generally, Peak Ground Acceleration was used for seismic intensity of fragility curve. However, in the case of the displacement sensitive system, relative displacement could be useful for estimation of probability of failure. Thus fragility curves were plotted based on maximum relative displacement.

INTRODUCTION

Though the level of NPP(Nuclear Power Plant) technology in Korea is high, criteria for seismic performance are rather generous due to low possibility of earthquake. Since SSE(Safe Shout down Earthquake) of APR1400(Advanced Power Reactor 1400) of Korea is 0.3g [Lee et al. (2009)], it is difficult to be exported to regions with greater seismic level. However, NPP can be exported without large change in existing design through application of seismic isolation device. Implementation of seismic isolation device can create high relative displacement of piping system connecting isolated structure with general structure, arousing increased seismic risk. Accordingly, assessment of seismic fragility about such piping system could be needed.
Domestic studies on seismic fragility analysis mainly focused on nuclear facilities and equipment. Choi et al. [Choi er al. (2001), Choi et al. (2003)] conducted a study for development of fragility function based on domestic conditions with nuclear facilities, and Kim et al. [Kim et al. (2007)] performed seismic fragility analysis on emergency diesel generator and emergency diesel generator with seismic isolation device. Piping system, one of important instruments constituting nuclear facilities, was determined as sufficiently safe about earthquakes and was classified as Screen Out during probabilistic risk assessment [KHNP (2002)]. However, high relative displacement is expected to occur when piping is connecting isolated structure with general structure. Thus, there is a concern for large increase in seismic risk. It is therefore necessary to analyze and assess seismic fragility of piping system in NPP.

In this study, the procedure of seismic fragility analysis followed Figure 1. A numerical model was prepared about NPP piping system, and the numerical model was updated using component test. Also, failure mode of piping system was defined and seismic fragility analysis was performed based on the inelastic seismic response analysis. For seismic fragility of isolated NPP piping system, seismic fragility curve was generated with PGA and maximum relative displacement between ground and isolated floor as seismic intensity.

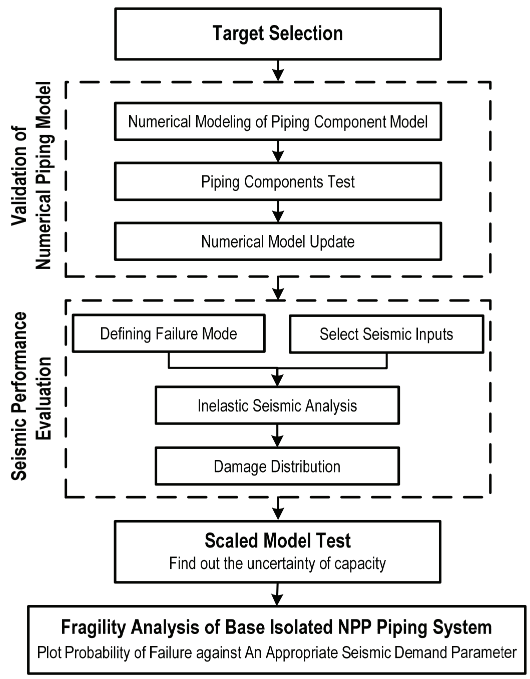
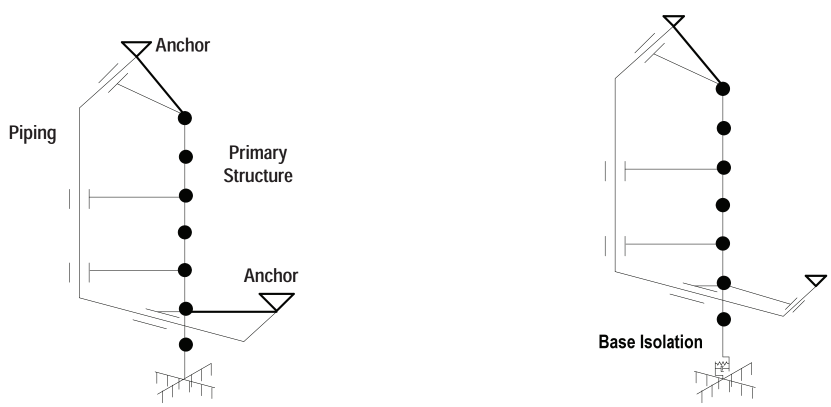


Figure 1. The procedure of seismic fragility analysis

NUMERICAL MODEL



(a) NRC-BNL benchmark model no. 4 (b) Modified NRC-BNL benchmark model no. 4

Figure 2. NRC-BNL benchmark model no. 4

As shown in Figure 2(a), inelastic seismic response analysis was carried out in this study by modifying NRC-BNL benchmark model no. 4 proposed for similar material characteristics as actual nuclear structure and piping system. The modified model is shown in Figure 2(b). Referring to the study by Huang et al. [Huang et al. (2010)], an isolation device with fundamental natural frequency of 0.5Hz and damping ratio of 10% was applied to the bottom of main structure. Piping system was prepared as a shell element to connect main structure with the ground. Natural frequency of the piping system is 4.772Hz and damping ratio is 4% [USNRC (2007)]. Table 1 shows the description of the modified benchmark model no.4.

Table 2 is natural frequencies of the primary structure and piping system. The nonlinear seismic analysis was repeated for the uncoupled model of the primary structure and piping system using the input ground motion and response signals at the appropriate points of primary system respectively.

Table 1. Description of numerical model

	Fundamental Natural Frequency	Elements	Remarks
Primary structure	8.92 Hz	Beam	Lumped mass : 17150kN Elastic modulus : 21GPa
Piping system	4.77 Hz	Shell	Elastic modulus : 204GPa External diameter : 323.85mm Thickness : 10.1mm, Radius : 457.2mm Damping ratio : 4%(Rayleigh damping)
Isolation device	0.50 Hz	Spring Dashpot	LDR(Low-damped Rubber bearing) + Linear viscous damper

Table 2. Natural frequencies of primary structure and piping system

	Primary Structure		Piping sSystem	
Mode	Frequency [Hz]	Direction	Frequency [Hz]	Direction
1	0.50311	X	4.772	Z
2	0.50311	Z	8.726	Z
3	8.9105	Z	17.050	X
4	8.9105	X	17.820	X

COMPONENT TEST

Component Test for Numerical Model Update

When seismic occurs, plastic deformation and failure occur in the elbow of piping system [Touboul et al. (1999), Zhang et al. (2010)]. Therefore, a elbow specimen was manufactured and numerical model was made. Loading and internal pressure tests were performed. In addition, the numerical model was updated using test results to improve reliability of the numerical model.

In this paper, a elbow specimen of ASME B36.10M SA53, Grade A, SCH 40 [ASME (2004)] was manufactured. A straight pipe with sufficient length was attached to the elbow by welding to generate plastic behavior in the elbow section of the specimen. Figure 3 is the drawing of the elbow specimen.

Material tension test was performed to determine physical properties of the numerical model. Modulus of elasticity estimated from the result of material tension test was 203,509 MPa as shown in Figure 4(a), and inelastic behavior is as shown in Figure 4(b).

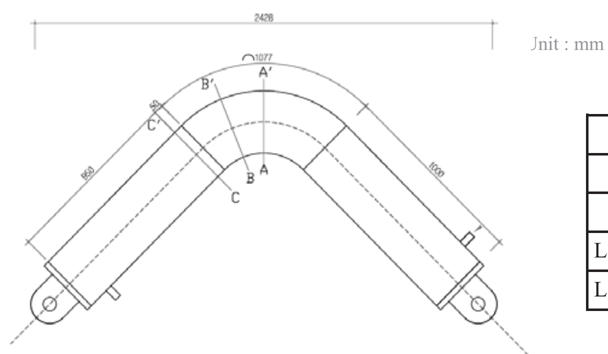
Shell element is known to express ovalization and warping, characteristics of pipe, well [Gye (2013)]. Accordingly, the numerical model of the specimen was prepared using shell element as in Figure 5, and the jig connected to UTM was prepared as beam element. Component test was performed as in Table 3. In the cyclic loading test, yield point was estimated by pre-analysis using numerical model, increasing load in the order of 50% of yield point, 100%, 200%, 400%, 800%, and maximum UTM displacement. Internal pressure was sequentially increased from 0 to 7MPa with an increment of 1MPa.

Table 3. Cases of the elbow component tests

Test No.	Type	Pressure	Load / Mode	Note
1	Elbow	Yes	Pressure Load	0MPa to 7Mpa
1	Elbow	No	Monotonic / Closing mode	150mm
2	Elbow	N0	Monotonic / Closing mode	150mm
3	Elbow	No	Monotonic / Opening mode	150mm
4	Elbow	No	Cyclic	8mm to 128mm
5	Elbow	No	Cyclic	8mm to 128mm
6	Elbow	No	Cyclic	8mm to 250mm

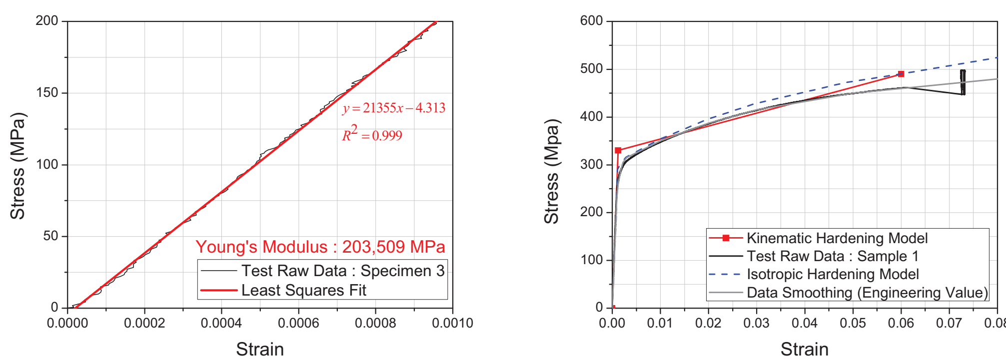
Design temperature of main steam pipe of APR1400 is 299°C [KEPCO E & C (2011)]. σ_{design} in Equation (1) is identical at 16ksi when design temperature is 316°C or lower about carbon steel, welded pipe, and SA-53 pipe [ASME (2007)]. Therefore, internal pressure of the pipe calculated from Eq. (1) is 6.31MPa. Here, I_p is the design internal pressure. d and σ_{design} are internal diameter and design stress, respectively.

$$Thickness = \left(I_p d\right) / \left(\sigma_{design} - 0.5 I_p\right) \tag{1}$$



Outer diameter	323.85mm	
Thickness	9.5mm	
Elbow radius	457.2mm	
Length of straight pipe	Part 1	950mm
Length of straight pipe	Part 2	1000mm

Figure 3. Elbow specimen drawing



(a) Estimation of modulus of elasticity (b) Inelastic behavior

Figure 4. Material properties

Figure 6 compares the test results with the results from the updated numerical model. Elastic behavior and inelastic behavior were verified to coincide relatively well. internal pressure test result was as shown in figure 6(b). The table 4 shows the difference errors of energy dissipation and correlation coefficient between test result and numerical analysis results. The difference errors of energy dissipation and the correlation coefficient were calculated by using Equation (2) and Equation (3), respectively. Here, R_1 and R_2 is the result of test and numerical analysis. τ is time increment and N is the number of data. In the Table 4, difference errors are under the 5% except cycling loading cases. and correlation coefficient are near the 1.0.

$$Difference\ Error = \left(|R_1|_{\max} - |R_2|_{\max}\right) \Big/ |R_1|_{\max} \tag{2}$$

$$\rho_{12}(\tau) = \lim_{N\to\infty} \frac{1}{N} \sum_{t=1}^{N} R_1(t_1) R_2(t_1+\tau) \tag{3}$$

Table 4. Difference errors of energy dissipation and correlation coefficient between test result and numerical analysis results.

Item			Correlation Coefficient	Difference Eerror of Energy Dissipation [%]
Elbow	Monotonic loading	Closing mode	0.9987	4.6213
		Opening mode	0.9994	1.6744
	Cycling loading		0.9965	8.9325

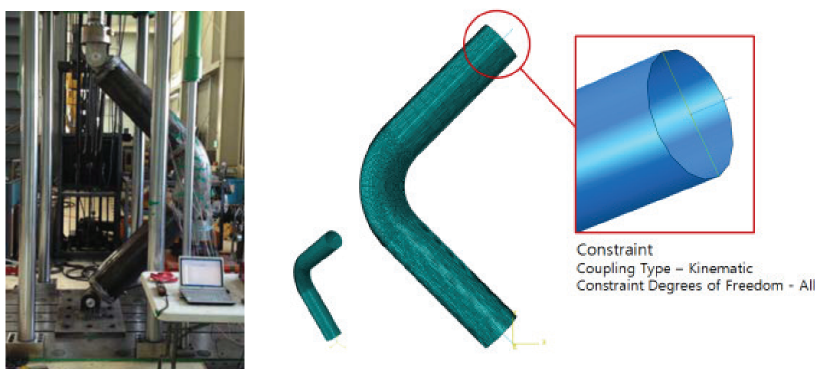
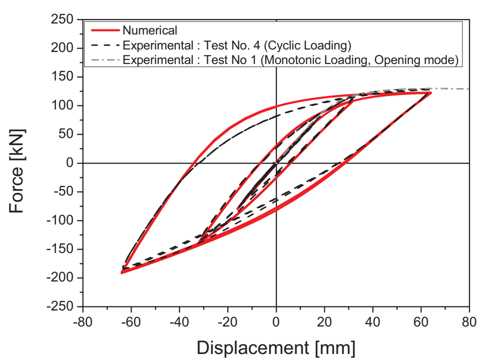
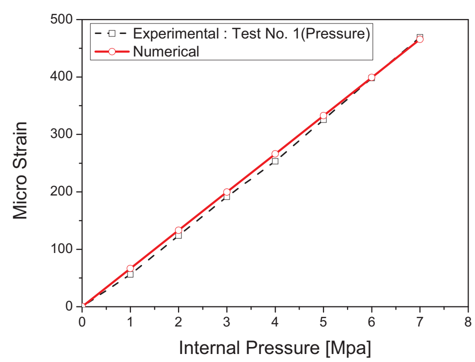


Figure 5. Photo of component test and numerical model of elbow component



(a) Cycling loading



(b) Internal pressure

Figure 6. Comparing with numerical analysis results with component test results.

Scaled Model Test for Estimation of Uncertainty Coefficient

A estimation that would use a uncertainty coefficient for a fragility calculation by log-normal standard deviation for respect to failure mode was estimate from the component experiment. However, there rises a burden on carrying out a number of experiments effectively due the limitation of size of prototype specimen and test equipment. Accordingly, the test of monotonic loading of closing mode was performed by manufacturing a scale model as in Table 5, and as shown in figure 7, the error on the collapse point by load was confirmed as less than 7%. Accordance with it, we estimate that the reliability of scaled model is enough. And calculated a log-normal standard deviation of the collapse load point as table 6. As a result, the log-normal standard deviation to the load applied was 0.02, and the log-normal standard deviation of displacement was 0.05. In this paper, greater value was used for uncertainty coefficient of capacity.

Table 5. Scaled model dimensions.

Original Model			Scaled Model Dimensions		Scale Factor
Size [in.]	Outside diameter [mm]	Wall thickness [mm]	Outside diameter [mm]	Wall thickness [mm]	
12	323.90	10.30	323.90	10.30	1.00
4	114.60	6.00	111.90	3.55	2.90
3	89.00	5.50	85.44	2.72	3.79

Table 6. Log-normal standard deviation of the collapse load point

Size	Remarks	Collapse load [kN]	ln(load)	Displacement [mm]	ln(disp.)
3in	sp01 to 12in.	144.39	5.0	55.9	4.0
	sp02 to 12in.	138.96	4.9	54.34	4.0
	sp03 to 12in.	140.85	4.9	50.55	3.9
	sp04 to 12in.	140.44	4.9	50.88	3.9
4in	sp01 to 12in.	145.6	5.0	56.4	4.0
Standard Deviation		3.07	0.02	2.47	0.05

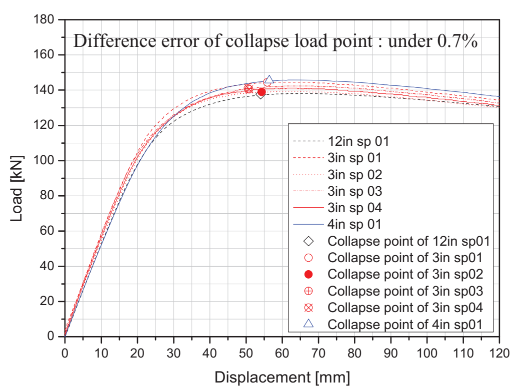


Figure 7. Collapse load point

FAILURE MODE

In general, damaging of piping component by repetitive dynamic loads such as seismic load is fatigue failure [EPRI (1994), Zhang et al. (2010)]. However, piping system on which seismic isolation device is applied have possibility of reaching failure due to high relative displacement with small number of repetitions. Consequently, failure mode by seismic load on an isolated piping system is estimated to complex mode of monotonic and fatigue failure. Thus in this paper, collapse load point [ASME (2007)] that includes limit state of pipe presented as design criterion and can be defined by the point at which permanent deformation of material occurs was selected as failure mode.

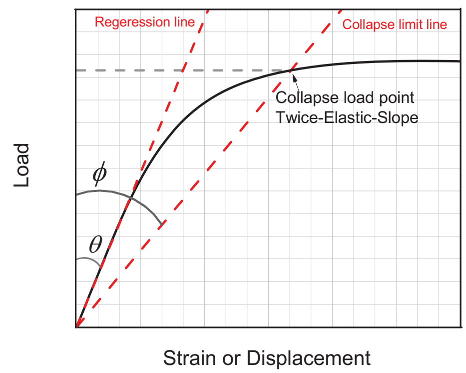


Figure 8. Collapse load point

Collapse load point was used as failure mode about wall thinned elbow of the piping system of pressurized-water reactor [Kim et al. (2003)]. Also, it has been used as limit state of piping component when analyzing seismic fragility of piping system [Ju and Jung (2013)]. Collapse load point is as shown in Figure 8. Here, as shown in Equation (4), ϕ is an angle twice as large as θ.

$$\phi = \tan^{-1}(2\tan\theta) \tag{4}$$

Collapse load point predicted using the updated numerical model was estimated as 0.0040 strain and 0.0060 strain, respectively in closing mode and opening mode. Stricter point, 0.0040 strain of closing mode, was selected as failure mode of the piping system.

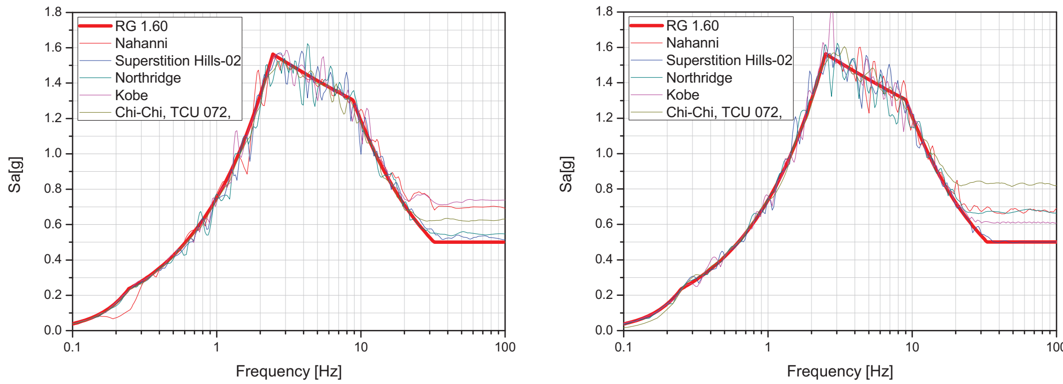
INPUT GROUND MOTION

Table 7 Input ground motions

Earthquake	Station	Inter/Intra	Mw	Distance [km]
Nahanni	S3	Intra	6.76	5.32
Superstition Hills-02	ICC	Inter	6.54	18.2
Northridge	PKC	Inter	6.69	7.26
Kobe	KJMA	Inter	6.90	0.96
Chi-Chi, Taiwan	TCU072	Inter	7.62	7.03
ChiChi, Taiwan	TCU089	Inter	7.62	8.88

With consideration on non-linear seismic response analysis, ASCE 43-05 [ASCE (2005)] recommends that an actual seismic wave recorded or recorded seismic wave is modified according to the target spectrum. In addition, ASCE 4-98 [ASCE (2000)] advises that 3 or more time histories are used for analysis. Therefore in this paper, 5 spectrum matched input ground motions [Kim et al. (2013)] shown in Table 7 were used to perform inelastic seismic response analysis. These 5 time histories were created using RspMatch, a program developed by Hancock et al [Hancock et al. (2006)]. according to the 5%

horizontal attenuation spectrum of Reg. Guide 1.60 with PGA of 0.5g, about seed earthquakes selected to include diverse conditions. Figure 9 is the target spectrum and response spectrum about each axial direction.



(a) X-direction (b) Z-direction

Figure 9. Target spectrum and response spectrum.

FRAGILITY CURVE OF BASE ISOLATED NPP PIPING SYSTEM

Fragility curves were calculated by using Equation (5). Here, C_m is the median capacity, R_m is the response median value, β is the cumulative probability distribution function of standard normal distribution and is the standard deviation of uncertainty as shown in Equation (6).

$$P_f(a) = 1 - \Phi\left[\frac{\ln C_m - \ln R_m(a)}{\beta}\right] \tag{5}$$

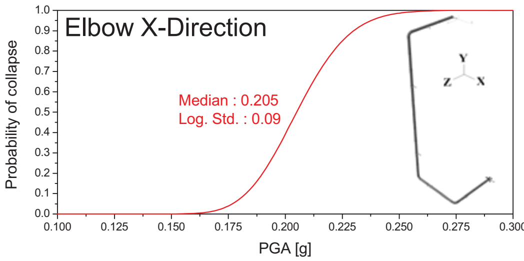
$$\beta = \sqrt{\beta_C{}^2 + \beta_R(a)^2} \tag{6}$$

In the equation (6), the β_C is the log-normal standard deviation of capacity and the β_R is the log-normal standard deviation of resistance. Table 8 shows the β_C and the β_R. There were estimated by using results of scaled model test and numerical analysis, respectively.

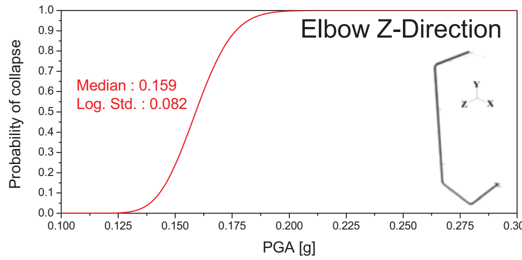
Table 8. Uncertainty coefficient

	Log-normal Standard Deviation
Log-normal Standard Deviation of Capacity, β_C	0.05
Log-normal Standard Deviation of Resistance, β_R	0.13

Figure 10 and Figure 11 show seismic fragility curve about each axial direction. Figure 10 and Figure 11 calculate seismic fragility, respectively using PGA and maximum relative displacement between ground and isolated floor as seismic intensity. Figure 10 and Figure 11 imply that log-normal standard deviation between when seismic intensity is PGA and when it is maximum relative displacement is very close, and that the shape of two fragility curves is extremely similar. When seismic fragility was calculated using maximum relative displacement as seismic intensity, median was expressed by a large value of 127mm or above. However, median value of seismic fragility was expressed by a low value of 0.2g or below when PGA was used as seismic intensity. Accordingly, during assessment on seismic fragility of piping system sensitive to displacement, it is estimated to be desirable to use maximum relative displacement as seismic intensity for better understanding by readers.

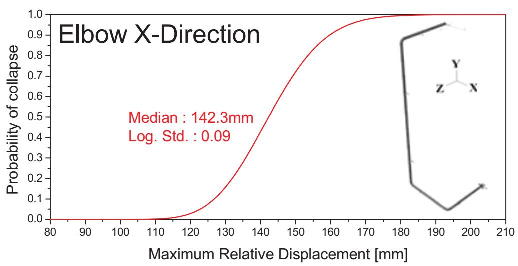


(a) X-direction

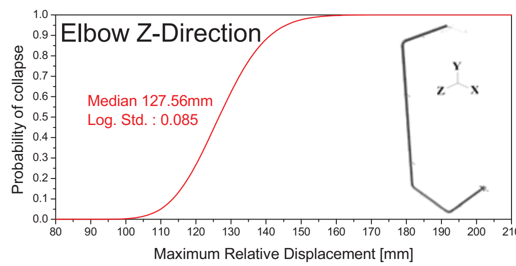


(b) Z-direction

Figure 10. Seismic fragility curve by PGA



(a) X-direction



(b) Z-direction

Figure 11. Seismic fragility curve by maximum relative displacement between ground and isolated floor

CONCLUDING REMARKS

In this paper, elbow in piping system was defined as a weakness element and numerical model was updated by component test. Failure mode of piping component under seismic load was defined in conservative terms as cases in which piping component needs to be replaced as design criteria are exceeded to cause permanent deformation. Therefore, collapse load point was applied as failure mode.
Log-normal standard deviation of seismic fragility curve is very close when seismic intensity is PGA and maximum relative displacement, and the shape of two fragility curves is extremely similar. While the median value was found to be substantially low at 0.2g or below when seismic intensity of seismic fragility curve was defined as PGA, the median value was substantially high at 127mm or above when maximum relative displacement was defined as seismic intensity. Thus, when assessing seismic fragility of systems sensitive to displacement such as isolated nuclear facility pipe, expression of seismic fragility using maximum relative displacement as seismic intensity is estimated to be useful..

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