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RESPONSE REDUCTION EFFECT OF SEISMIC ISOLATION SYSTEM CONSIDERING UNCERTAINTY PARAMETERS FOR SEISMIC MARGIN ASSESSMENT

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ABSTRACT

The purpose of this study is to assess a seismic margin against cliff-edge effects on a piping, which is very important for nuclear power plants, especially for sodium-cooled fast reactors because their piping thickness is thinner than light water reactors. Through assessments of failure probabilities (fragility), this study has examined seismic margins of simulated two kinds of thin- and thick-walled piping by using response waveforms of the reactor building with or without a seismic isolation system obtained by seismic response analyses. The fragility analyses have shown that the seismic isolation technology reduced the structural response effects nearly 1.2 times as much as that of the non-isolated plant. In focusing on the uncertainty of response factor of components, the seismic isolation plant has a significant margin compared to the non-isolated plant even if factors from 0.5 to 2.0 are considered. This study concludes that the seismic isolation technology is effective to avoid cliff-edge effects.

INTRODUCTION

Cliff-edge effects of nuclear power plants (NPPs) have attracted much attention after the TEPCO Fukushima Daiichi nuclear power plant accident (Takada et al., 2017). Various possible countermeasures for avoiding and mitigating the cliff edge effects are intensively developed and quantitatively assessed in our project (Takada et al., 2019). A seismic isolation system is one of the key technologies to prevent cliff-edge effects. The objective of this study is to assess cliff edge effects, which are of great importance for NPPs, especially for sodium-cooled fast reactors (SFRs) because their piping thickness is thinner than one for light water reactors (LWRs).

For the seismic isolation system applied to LWRs, fracture tests have been performed for laminated rubber bearing embedded by lead plug of 1,600 mm in diameter corresponding to the reactor scale. The test results were consistent with half-scale tests (800 mm in diameter) in terms of structural characteristics, such as linear limits and fracture characteristics, and concluded that the half-scale test results were applicable to reactor cases (Kosugi et al., 2017).

For thick laminated rubber bearing applied to SFRs, fracture and aging tests have been conducted. The fracture tests included conditions of monotonic loading, cyclic loading, vertical and horizontal combination. Scattering of stiffness in the design range was approx. 5% with 95% of confidence level (Fukasawa et al., 2016). The aging tests indicated approx. 5% increment of stiffness in the design range in accelerated degradation test corresponding to 30 - 60 years under no loading condition (Watakabe et al., 2016). It can be said that the current experimental data are applicable to reactor plant design.

Vibration tests on LWR piping elbows and tees conducted in the U.S. revealed that the fittings did not exhibit ductile rupture nor plastic collapse even when a stress range exceeding 20 times the allowable primary stress is applied. The fittings eventually failed because of fatigue. Similar results were obtained from vibration tests on piping fittings of LWRs and SFRs conducted in Japan. This suggests that the dominant failure mode of the pipe fittings is fatigue failure caused by deformation accumulated during an earthquake, and this is the important factor that should be considered in fragility analysis.

The previous study examined seismic margins of simulated two kinds of thin- and thick-walled reactor vessels with/without the seismic isolation system (Yamano et al., 2019). The fragility analyses showed that the seismic isolation technology largely reduced the structural response effects nearly twice as much as that of the non-isolated plant. In focusing on uncertainty of response factor of components, the seismic isolation plant has a significant margin compared to the non-isolated plant using factors from 0.5 to 2.0. This study concluded that the seismic isolation technology is effective to avoid cliff-edge effects.

This study is intended to assess seismic margins with failure probabilities (fragility) of a simulated piping system by using response waveforms of the reactor building for an SFR with or without the seismic isolation system obtained by seismic response analyses. For the comparison, the fragility analysis is also carried out for a thick-walled piping of an LWR with or without the isolation system. Based on the results, the second purpose is to quantitatively evaluate response reduction effects of the seismic isolation system considering uncertainty parameters to assess the seismic margin against cliff-edge effects.

FRAGILITY ANALYSIS

Fragility of the Thin-Walled Piping System

On a premise that fatigue failure is the dominant failure mode, seismic response analyses were conducted for a piping model which is shown in Figure 1. In this analysis, the material used was stainless steel type 304 at 400°C. The outer diameter and thickness of the piping were 610 mm and 7.1 mm, respectively. The piping weight was 346 kg/m. The piping was modelled by simulating shape and mass which were consistent with natural frequencies of 4 Hz and 20 Hz in the horizontal and 7 Hz in the vertical directions.

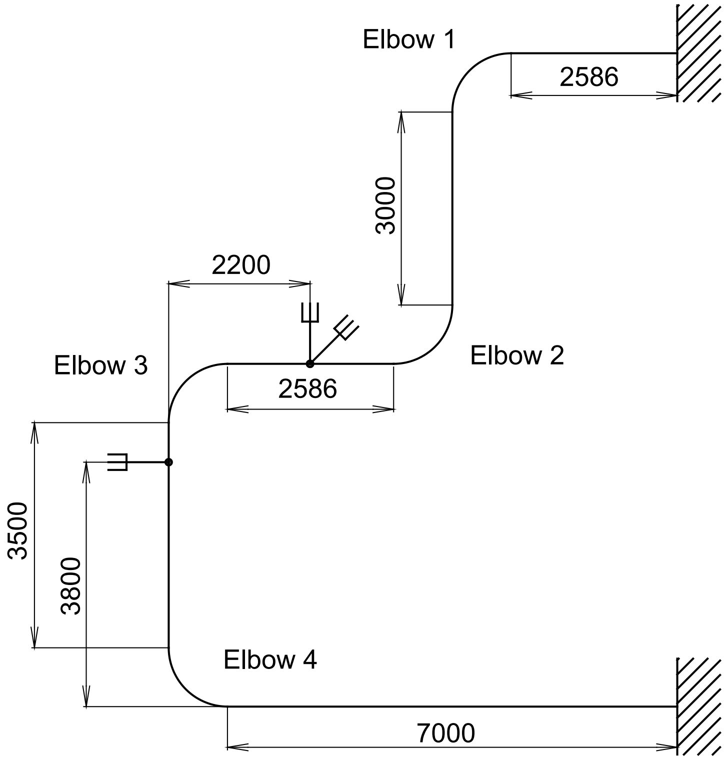
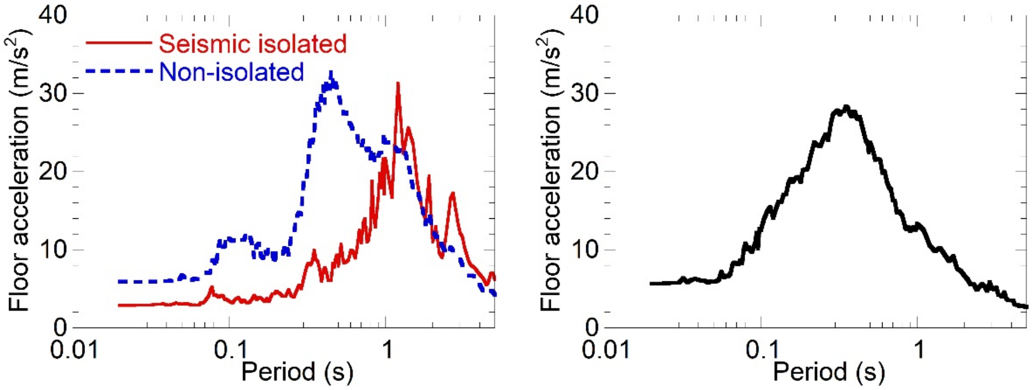


Figure 1. Analytical model for thin-walled piping.



(a) Horizontal direction (b) Vertical direction

Figure 2. Floor response spectra of design-basis earthquake.

This study defined a design-basis earthquake (hereinafter referred to as Ss) of floor response curves for seismically isolated plant and non-isolated earthquake-proof one shown in Figure 2, which was evaluated by Nishida et al. (2018).

The bending buckling evaluation of the piping was conducted by the following equation (JSME, 2012),

$$B_2 M / Z \le 1.5 K_S S_m \tag{1}$$

where B_2 is stress factor, M is moment, Z is cross-section factor, S_m is design strength, K_S is cross-sectional shape factor (K_S =1.27 for thin-walled piping). The moment can be obtained from the seismic response analysis.

Table 1: Safety factors and uncertainty parameters in the fragility analysis for the thin-walled piping in the non-isolated plant.

		Safety factor (F)	Uncertainty (β)	
Margin in the elbow evaluation		2.4	Aleatory uncertainty (βr)	Epistemic uncertainty (βu)
Response factor of the reactor building	Ground behavior: F1	1.0	0.4	0.2
	Isolation system behavior: F2	-	-	-
	Building behavior: F3	1.0	0.3	0.2
Response factor of components	Model: F4	1.1	0.1	-
	Synthesis method of the moment: F5	1.0	-	-
	Attenuation rate: F6	1.2	0.1	0.1
	Combination of horizontal and vertical motions: F7	1.4	0.1	0.3
	Response reduction effects of ductility: F8	1.6	-	0.1
	Relation of elbow deformation (angular displacement) and strain: F9	1.0	0.3	0.1
Resistance factor	Ratio of fatigue to buckling: F10	3.1	-	-
	Margin of design fatigue : F11	2.0	0.4	0.1
Safety factor: F		44	0.8	0.4

Table 2: Safety factors and uncertainty parameters in the fragility analysis for the thin-walled piping in the isolated plant.

		Safety factor (F)				Uncertainty (β)	
Earthquake conditions		Ss	2Ss	3Ss	4Ss	Aleatory uncertainty (βr)	Epistemic uncertainty (βu)
Margin in the elbow evaluation		6.2	2.1	1.2	0.8		
Response factor of the reactor building	Ground behavior: F1	1.0				-	-
	Isolation system behavior: F2	1.0	1.2	1.2	1.2	0.1	0.2
	Building behavior: F3	1.0				-	-
Response factor of components	Model: F4	1.1				0.1	-
	Synthesis method of the moment: F5	1.0				-	-
	Attenuation rate: F6	1.2				0.1	0.1
	Combination of horizontal and vertical motions: F7	1.4				0.1	0.3
	Response reduction effects of ductility: F8	1.6				-	0.1
	Relation of elbow deformation (angular displacement) and distortion: F9	1.0				0.3	0.1
Resistance factor	Ratio of fatigue to buckling: F10	3.1				-	-
	Margin of design fatigue: F11	2.0				0.4	0.1
Safety factor: F		113	47	26	18	0.6	0.4

Calculated stresses at the elbows 1, 2, 3, and 4 were respectively 20, 85, 44, and 29 MPa for the seismic isolated plant against the allowable stress 203 MPa. Therefore, the margin was calculated 10.2, 2.4, 6.1, and 7.0. For the non-seismic isolated plant, the calculated stresses at the elbows 1, 2, 3, and 4 were 16, 33, 25, and 15, respectively, against the allowable stress 203 MPa, thereby estimating the margin of 12.7, 6.2, 8.1, and 13.5, respectively.

A safety factor was specified to take into account the fatigue failure caused by an earthquake. Although the buckling evaluation was performed, this study can consider the fatigue failure of the piping by multiplying the ratio of the allowable fatigue limit to the allowable buckling limit.

This study performed a fragility analysis by setting uncertainty parameters for non-isolated and isolated plants obtained from past studies in JAEA, which are listed in Tables 1 and 2, respectively. Safety factors are calculated by the product of all values of the response factors and capacity factors. Uncertainty values are calculated by the root mean square of all values of these factors. When exceeding 2 Ss, the response factor of seismic isolation system increases to 1.2 because the hardening effect of laminated rubber bearing is taken into account.

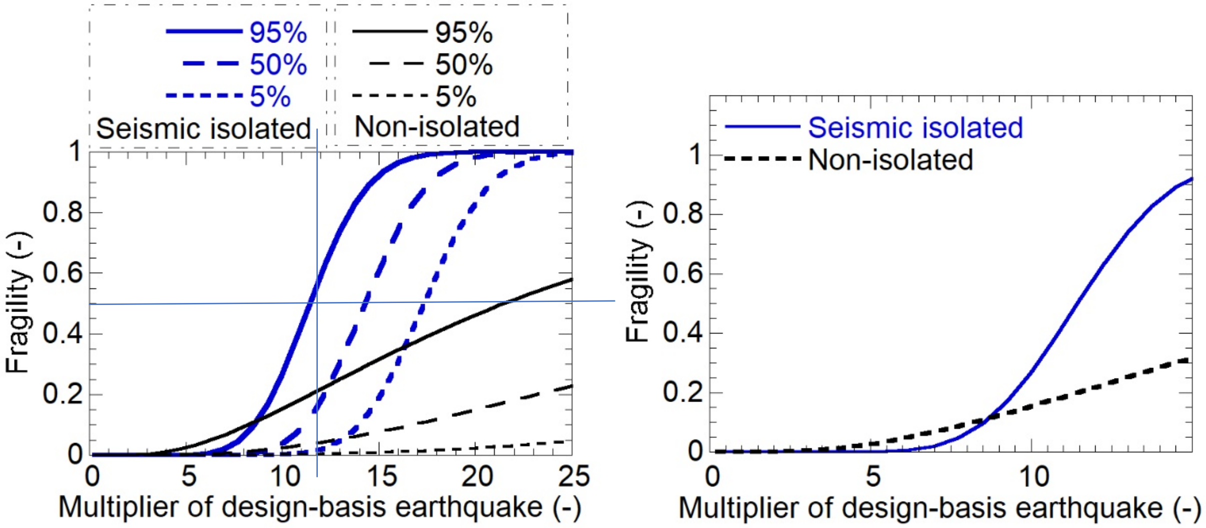
The fragility is calculated by the following equation (AESJ, 2015)

$$p_f\left(Z_m(s)\right)=\varphi\left[\frac{\ln\left(Z_m(s)/A_m\right)+\beta_u\varphi^{-1}(Q)}{\beta_r}\right] \tag{2}$$

where p_f is the fragility, A_m is the median value of response acceleration, β_u is the logarithmic standard deviation which expresses epistemic uncertainty, β_r is the logarithmic standard deviation which expresses aleatory uncertainty, $\phi(-)$ is the standard normal probability distribution function, $\phi^{-1}(-)$ is the inverse function, and Q is the non-exceedance probability considering the epistemic uncertainty.

Figure 3 shows the obtained fragility curves of 95%, 50% and 5% confidence levels for the thin-walled piping. The right-side figure shows the comparison between the seismic isolated and non-isolated plants with 95% confidence level. A High-Confidence and Low-Probability of Failure (HCLPF) value, which is generally considered to be approximately 95% confidence with less than 5% probability of failure, is used as an index value to compare the seismic response analysis results. The comparison results indicate that the seismic isolation technology is effective to prevent cliff-edge effects: the HCLPF of seismically isolated plant (7.8 Ss) is about 1.2 times as high as that of non-isolated plant (6.3 Ss). The piping system is in general robust against an earthquake; therefore, the sensitivity on the response reduction effect by the seismic isolation system is small.

Looking at a failure probability of 0.5, on the other hand, 95% line for the seismic isolated plant is smaller than that for the non-isolated one. When the earthquake motion exceeds a certain level, the failure probability increases because the hardening effect brings increase in the response of the isolated plant. Figure 3 shows the noticeable difference between the fragility curves of the thin-walled piping of isolated and non-isolated plants, on the assumption that isolated one has non-linearity and non-isolated one has simple linearity.



(a) 95%, 50% and 5% confidence level (b) 95% confidence level

Figure 3: Fragility curves of thin-walled piping of the isolated and non-isolated plants.

Fragility of the Thick-Walled Piping System

A seismic response analysis was conducted for the same piping model as the thin-walled piping (Figure 1). For the thick-walled piping system, the thickness of the piping was increased to 31 mm, and supports were also increased to have a natural frequency of 20 Hz or greater. The strength evaluations of the piping system of the isolated and non-isolated plants showed that calculated stresses at the elbow 4 were 2.5 MPa for the isolated plant and 3.3 MPa for the non-isolated one, which corresponded to design margins of 82 and 62, respectively. This suggests that an earthquake is extremely unlikely to cause thick-walled piping systems to fail.

Tables 3 and 4 list the safety factors and uncertainties used in the evaluations, and Figure 4 shows the fragility curves of 95%, 50% and 5% confidence levels on the left side and the comparison between the seismic isolated and non-isolated plants with 95% confidence level on the right side. These demonstrate that both buildings with the thick-walled piping have physically meaningless high HCLPFs.

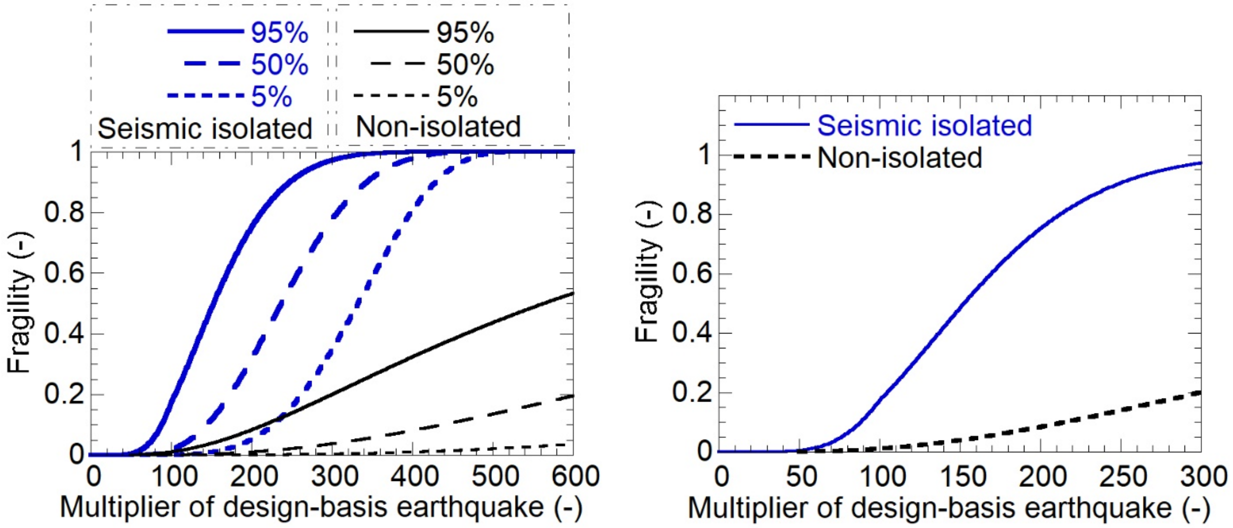
Table 3: Safety factors and uncertainty parameters in the fragility analysis for the thick-walled piping in the non-isolated plant.

	Safety factor (F)	Aleatory uncertainty (β_r)	Epistemic uncertainty (β_u)
Value	18	0.8	0.4

Table 4: Safety factors and uncertainty parameters in the fragility analysis for the thick-walled piping in the isolated plant.

	Safety factor (F)				Uncertainty (β)	
	Ss	2Ss	3Ss	4Ss	Aleatory uncertainty (β_r)	Epistemic uncertainty (β_u)
Value	18	15	13	12	0.6	0.4

(Ss: Design-basis earthquake)



(a) 95%, 50% and 5% confidence level (b) 95% confidence level

Figure 4: Fragility curves of thick-walled piping of the isolated and non-isolated plants.

EVALUATION OF RESPONSE REDUCTION EFFECTS

This section describes quantitative evaluations of the response reduction effects of the seismic isolated system, focusing on uncertainty of the response factors of components, which are emphasized in the case that various components are installed in and around the reactor vessel and piping. To consider potential cliff-edge effects in areas beyond existing knowledge, this study attempts to identify the appearance of cliff-edge effects under very severe conditions within the physically possible range.

As discussed above, the thick-walled piping is unlikely to fail, and its HCLPFs are so high that the representing values multiplied by Ss seems unnecessary; we did not evaluate the response reduction effects on the thick-walled piping. Therefore, this section describes only the response reduction effects on the thin-walled piping system.

To evaluate the response reduction effect, this study introduced a factor for the uncertainty for the response factor of components, as listed in Table 5. The response factor of components was multiplied by factors from 0.5 to 2. The values of aleatory and epistemic uncertainties are calculated as root mean squares of all values. When the factor is 2.0, the aleatory uncertainty is 0.98, nearly equal to 1, so it can be said that this range covers the physically highest possible uncertainty. Using these uncertainty values, the fragility analyses are conducted for thin- and thick-walled piping with and without the seismic isolated system.

Figure 5 shows fragility curves with 95% confidence level considering uncertainties of the response factors of components. Figure 6 compares HCLPF acceleration of the thin-walled piping between the isolated and non-isolated plants. If the uncertainty of the response factors is doubled, the HCLPF acceleration of the isolated plant is 4.8 Ss, whereas that of non-isolated plant is 2.7 Ss. If the HCLPF is regarded as the strength limit with high confidence, the HCLPF value of the horizontally isolated plant is greater than that of the non-isolated plant regardless of uncertainties of the response factors of components. This study revealed that the isolation technology has notable effects on reducing the seismic response regardless of the degree of uncertainty.

Table 5: Uncertainty values introducing factor of uncertainty parameter.

Factor	Total values of uncertainty for response factor of components		Non-isolated plant		Seismic isolated plant	
α	$\beta_{r,C}$	$\beta_{u,C}$	β_r	β_u	β_r	β_u
0.5	0.2	0.2	0.7	0.3	0.5	0.3
1.0	0.4	0.3	0.7	0.4	0.6	0.4
1.5	0.5	0.5	0.9	0.6	0.7	0.6
2.0	0.7	0.7	1.0	0.7	0.9	0.7

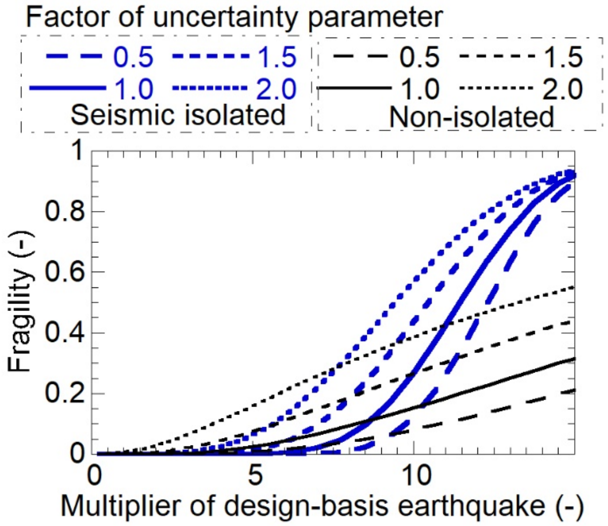


Figure 5: Fragility curves of thin-walled piping considering the uncertainty parameters.

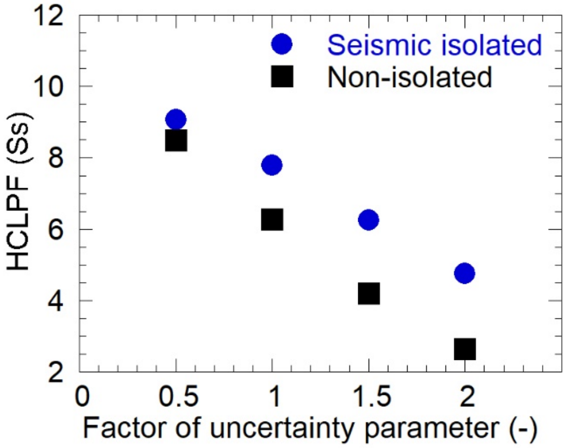


Figure 6: Response reduction effects on the thin-walled piping

SEISMIC COUNTERMEASURES AGAINST CLIFF-EDGE EFFECTS

According to past seismic risk assessment studies, cliff-edge effects could be caused by the loss of function of the auxiliary cooling system or the power supply system important for decay heat removal in non-isolated LWRs, whereas it can be caused by the loss of components boundary in SFRs. Countermeasures against cliff-edge effects, therefore, are required to seismically reinforce components or to introduce the seismic isolation system so as to withstand greater earthquakes.

When a seismic acceleration exceeds the limit of linear behavior of the laminated rubber, the hardening behaviour could occur in the horizontal direction, and softening could occur in the vertical direction. Significant hardening and softening effects remarkably increase loads on the systems and components and tend to increase these fragilities in the seismically isolated plant. However, such a coupled behavior is yet to be investigated. For countermeasures against the cliff-edge effect, this study suggests mitigation of the hardening and softening effects and mitigation of the deformation of laminated rubber.

For the mitigation of the hardening and softening, these phenomena should be understood correctly, and then the findings should be reflected to seismic response analyses. As previously mentioned, the fracture and aging tests have provided experimental findings for the hardening and softening behaviours. The mitigation of hardening and softening has been observed in the thick laminated rubber developed for SFRs.

For the mitigation of the deformation of laminated rubber, one of the solutions is to strengthen a damping function in the horizontal direction in order to suppress the horizontal deformation of laminated rubber, namely hardening. The other one is a vertical isolation technology for mitigating significant vertical deformation, namely softening.

Since the thin-walled piping in the non-isolated plant has a large seismic margin already, the response reduction effect of the seismic isolation is small from the fragility analysis which showed 1.2 times higher HCLPF for the isolated plant than for the non-isolated one. In addition, the thick-walled piping structure has a high natural frequency in the horizontal direction that contributes to a failure mode, and it also has a large seismic margin even in the non-isolated plant. Therefore, the response reduction effect of the seismic isolation system is not so significant in the thick-walled piping system.

CONCLUSIONS

The fragility analysis showed that the effectiveness of the seismic isolation technology is not so significant because both the thin-walled and thick-walled piping systems have remarkably robust against an earthquake. Looking at the uncertainty focusing on response factors of component, however, the HCLPF of the isolated plant is nearly twice as high as the non-isolated plant in the fragility analysis calculated by multiplying the factors from 0.5 to 2.0. This analysis allowed us to have quantitative understanding of the response reduction effects, showing that seismic isolation is effective to prevent cliff-edge effects. The seismic countermeasures against the cliff edge effect of the seismic isolation technology were also proposed to mitigate the hardening and softening effects and the deformation of laminated rubber. To reduce these potential cliff edge effect, further research and development efforts are necessary in future.

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