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Seismic Integrity of Main Steam Line Depending on Seismic Isolator in Lead-cooled Small Modular Reactor

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1. Introduction

Earthquakes can cause extensive damage to large structures such as buildings and bridges, primarily due to horizontal ground motion. Most structures, including old nuclear power plants, had been designed to withstand horizontal ground motion, with vertical seismic isolation being sufficient using the stiffness and damping of the structure itself. [1]. However, earthquakes such as the Kobe earthquake, which have vertical acceleration, have highlighted the need for structures to withstand both horizontal and vertical acceleration equally, as emphasized by the US Nuclear Regulatory Commission [2]. In particular, in situations with short periods, near the earthquake's location, the vertical acceleration is similar to or exceeds the horizontal acceleration [3]. Nevertheless, attempts to increase seismic integrity by utilizing three-axis seismic isolators have not been actively conducted in nuclear power plants or general structures, and seismic isolations of most general buildings are also adjusted to horizontal motion.

Small modular reactors (SMRs), a promising alternative to traditional nuclear power plants due to their economic advantages and safety features, can use in various environments. While most nuclear power systems use water, SMRs are being designed with a variety of materials, including lead-cooled fast reactors, which offer safety benefits due to not only their atmospheric pressure operation and high gamma-ray shielding but also efficiency with lead's high boiling and low neutron absorption cross-section [4]. However, ensuring seismic safety is critical for SMRs to be viable in various environments, and there have been numerous studies evaluating seismic isolation methods for these reactors. [5-6].

In this paper, we analyzed the seismic structure of MicroURANUS, a lead-cooled SMR currently under design, by evaluating stress on the main steam line under three different seismic isolation scenarios: 2D seismic isolation, 3D seismic isolation, and fixed foundation without seismic isolation. Our analysis highlights the importance of seismic isolation direction and its impact on the safety of nuclear power plants by evaluating the stress on the main steam line, which is pointed out as one of the parts with high possibility of failure.

2. Experimental design

2.1 Superstructure seismic analysis design

We designed a lead-cooled SMR (MicroURANUS) on a seismic isolator in three-dimensional modeling. The weight of the structure, such as the lead coolant and nuclear fuel inside the reactor vessel, was applied to the reactor vessel's wall. Additionally, the water inside the superstructure was applied to the superstructure's wall surface as a conversion density. Modal analysis was used to obtain the first mode frequency to apply Rayleigh damping to the superstructure. Alpha (mass coefficient) and beta (stiffness coefficient) were obtained from this analysis, with a value of 2.1364 for Alpha and 1.6934E-4 for beta.

Fig. 2 shows the input seismic acceleration, which has a total time of 20 seconds and a maximum acceleration of 0.3 g in the x, y, and z directions, respectively. Three types of seismic isolators were designed for the structure: a fixed foundation design without seismic isolators, a 2D seismic isolator with only horizontal seismic isolation, and a 3D seismic isolator with both horizontal and vertical seismic isolators installed. The horizontal isolator has a frequency of 0.5 Hz, while the vertical isolator's frequency is designed to be 2.3 Hz. When only the horizontal isolator is installed, the frequency in the vertical direction becomes 20 Hz due to the horizontal isolator's structure.

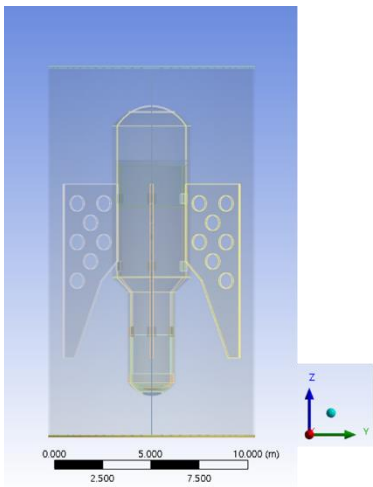

Fig.1. Vertical section of a MicroURANUS superstructure

Table I: Conversion density of MicroURANUS superstructure

System	Component	Total mass (ton)	Total volume (m^3)	Conversion density (ton/m^3)
Superstructure	SS top	-	-	8
	SS middle	2009.81	63.27	31.76
	SS bottom	-	-	8
	CV supporter	-	-	8
Containment vessel	CV	-	-	8
Reactor vessel	RV top	-	-	8
	SG	105.20	1.46	72.24
	RV core-SG	117.77	1.16	101.94
	RV core	81.87	0.71	115.82
	RV bottom	35.12	0.48	72.66

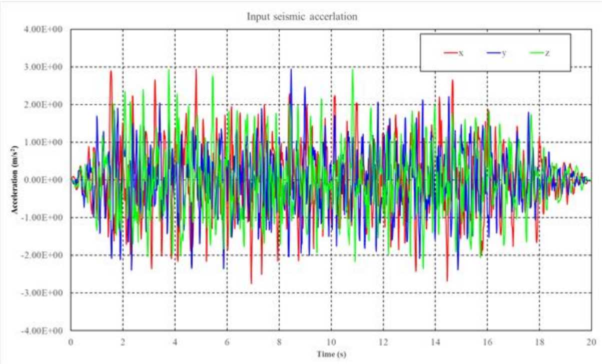

Fig. 2. The input seismic acceleration

Table II: The stiffness and damping coefficient of each isolator depending on the axis

	X, Y axis	Z axis	
Frequency (Hz)	0.4999	2.3	20
Mass (kg)	2762300	2762300	2762300
Damping ratio (%)	21.53	30	3
Stiffness (N/m)	2.725E+7	5.769E+8	4.301E+10
Damping coefficient (N s/m)	3.736E+6	2.395E+7	2.068E+7

2.2 Main steam line

The analysis focused on the main steam line, which is a pipe that comes out of the steam generator and is connected to the upper part of the containment vessel. Modal analysis was used to obtain the mass and stiffness coefficients for the pipe to apply Rayleigh damping to it. The seismic displacement was obtained for each steam pipe inlet and outlet by conducting a superstructure seismic analysis. To avoid convergence issues, the piping at the center of the reactor vessel was fixed, and a displacement value obtained by subtracting the displacement at the center of the reactor vessel from the displacement at the top of the containment vessel was applied to the top of the containment vessel.

We conducted additional analyses for the case where the time interval of the seismic displacement was increased by 15% (23 second) and the case where it was reduced (17 second) to satisfy the 15% tolerance range in stress calculation for seismic displacement.

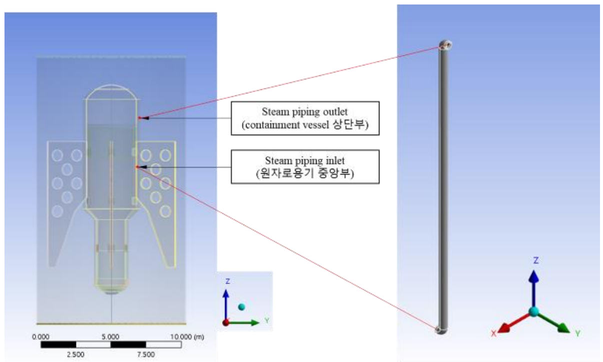

Fig. 3. Main steam line three-dimensional design

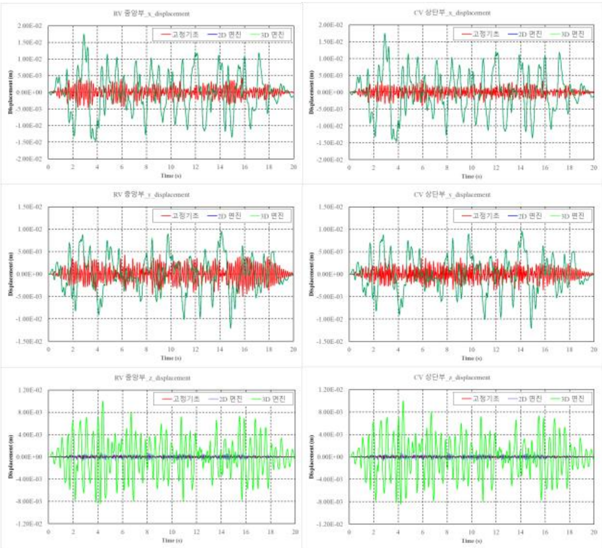

Fig. 4. Seismic displacement of main steam line at the center of the reactor vessel (left) and at the top of the containment vessel (right) depending on axis.

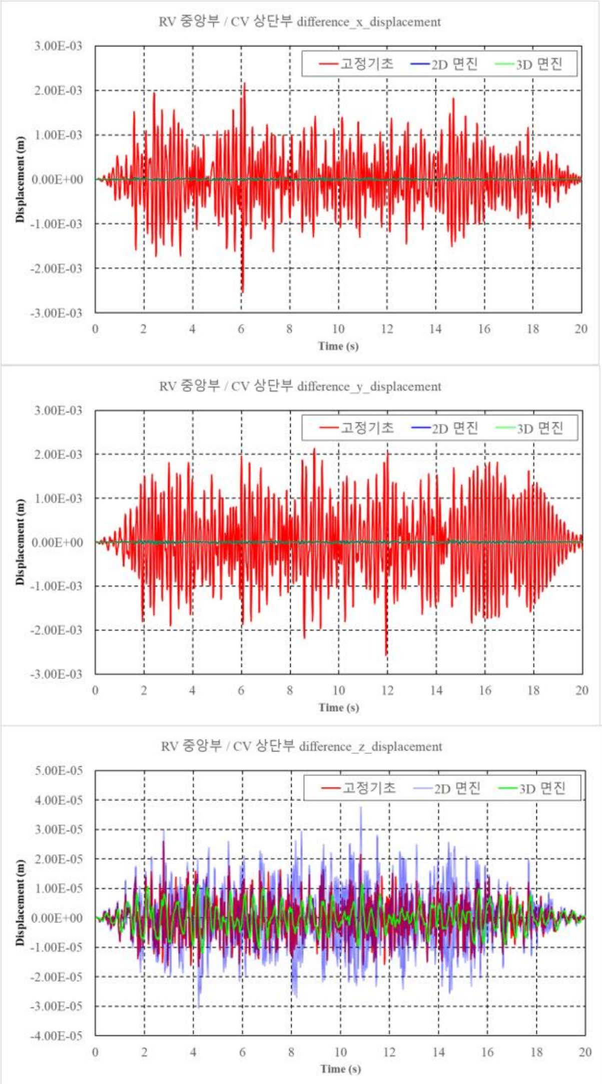

Fig. 5. Seismic displacement difference of main steam line between at the center of the reactor vessel and at the top of the containment vessel depending on axis.

3. Result and Discussion

In the same time interval stress analysis, the fixed basis shows the highest von mises stress value. In the 2D seismic isolation, the stress is reduced compared to the stress of the fixed foundation. In the case of 3D seismic isolation, it has the smallest stress in the three cases. For the same design, the shorter the time interval of displacement is, the faster it shakes and shows greater stress than the time interval in other cases.

The stress of 3D seismic isolation shows 3 times and 12 times less stress values than 2D seismic isolation and fixed foundation, respectively. Therefore, it can be confirmed that the stress of steam piping can be significantly reduced by installing the seismic isolator. Compared to the rate of stress reduction when horizontal isolation is installed in a fixed foundation state, the rate of stress reduction when vertical isolation is installed in a structure with only horizontal isolation is comparable, and it can be seen that the stress is reduced by more than three times. It is thought that the effect of 3D seismic isolation will be evident when analyzing other vulnerable structures. In Figure 4, the design with the seismic isolator has a larger displacement, but as shown in Figure 5, the difference in displacement between the two parts is not large. This is a phenomenon caused by the seismic isolation design. As the buildings or structures on the seismic isolator move simultaneously, the overall displacement increases, but the displacement difference between the parts on the seismic isolator is greatly reduced, contributing to greatly reducing the stress of internal structures such as piping by installing the seismic isolator.

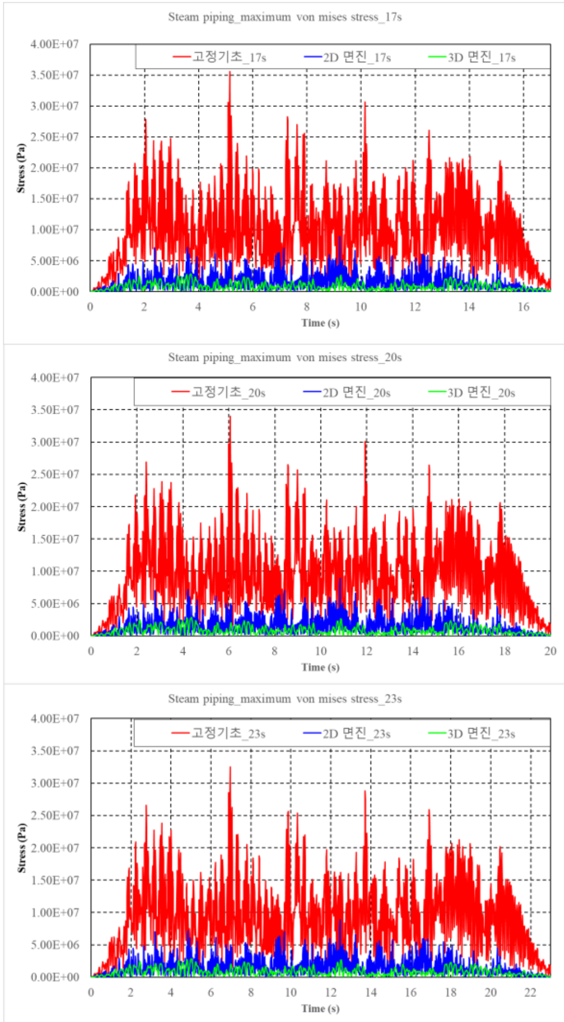

Fig. 5. Maximum Von Mises stress of main steam line (total time: 17 s (top), 20 s (middle), 23 s (bottom)) depending on seismic isolator

Table III: Maximum Von Mises stress of main steam line depending on seismic isolator and time interval

Stress (MPa)	17s	20s	23s	Stress average	stress평균 / stress평균최소값
고정기초	35.56	33.96	32.51	34.01	12.01
2D 면진	8.904	8.885	8.876	8.888	3.14
3D 면진	2.835	2.828	2.828	2.831	1.00

4. Conclusion

The importance of vertical seismic isolation has become increasingly apparent in recent years due to the occurrence and observation of various earthquakes. Evaluating the safety against earthquakes is crucial for the installation of SMRs in various environments. Our analysis of the stress on the main steam line of MicroURANUS, a lead-cooled SMR under design, showed that the seismic isolation direction of the seismic isolator can significantly impact safety.

By installing both horizontal and vertical isolation simultaneously, stress on the steam pipe line can be reduced, as similar as stress decrease rate between vertical seismic isolation and fixed foundation. Although displacement of the steam piping itself increased with the seismic isolator, the displacement difference between structures inside the building decreased, leading to a significant reduction in stress caused by earthquakes. Therefore, the implementation of three-axis seismic isolators is crucial for ensuring the safety of nuclear power plants, including SMRs, in the face of seismic events.

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