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Seismic Isolation Effects on Core Seismic Response of KALIMER

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ABSTRACT

The seismic response characteristics for conceptually designed KALIMER(Korea Advanced LIquid MEtal Reactor) with a seismic isolation technology are investigated using the single row model for SSE load conditions by SAC-CORE code. To study the seismic isolation effects on core seismic responses, the input motions of seismic isolation and non-isolation cases are generated from the seismic time history analysis of reactor system. From the results of analyses, it is verified that an efficient seismic isolation design of reactor system gives significantly reduced core seismic responses and can make to easily satisfy the structural design requirements.

1. INTRODUCTION

In general, seismically isolated system gives a great reduction of seismic acceleration responses. Many researchers are studying to apply this concept to nuclear power plant for enhancing the safety and economy of the structural design[1,2].

The advantages of seismic isolation of reactor system are both on reductions of absolute acceleration response and relative displacement of internal structures. These become more apparent for the LMR core assemblies which have no intermediate core support plates and thus more vulnerable to seismic loads[3].

The analysis modeling of core structure is very complex due to the collision of adjacent assemblies. In this paper, a single row model of conceptually designed KALIMER core is used for seismic time history analysis. This modeling method has been studied to produce more accurate results than the clustering method for RAPSODIE core mock-up[4].

To investigate the seismic isolation effects on core seismic responses, the input motions at the lower diagrid are obtained from the seismic analysis of KALIMER reactor system for 0.5 Hz seismic isolation case and non-isolation case.

2. CORE SEISMIC ANALYSIS

2.1 Core Layout

The conceptually designed KALIMER reactor core is shown in Fig.1, consisting of 379 identical assemblies; 66 drive fuel, 30 internal blanket, 42 radial blanket, 6 control rod, 1 self-actuated shutdown system, 6 gas expansion module, 48 reflector, 54 B_4C shield, 54 in-vessel storage space, 72 shield. The duct material is HT9 and the duct wall thickness, the outer flat to flat, and the gap between ducts are 4 mm, 157 mm and 4 mm respectively. The assemblies, 4546.7 mm in length with 384.3 mm nosepiece, are locked at the lower diagrid. To prevent the direct contact between adjacent ducts, the load pads are provided at the locations of above active core top and the top of ducts. At the top locations of the outer shield assemblies, a former ring is designed to restrain core free-flowering behavior.

2.2 Seismic Analysis Model

For the core seismic analysis model of very complex core layout, a single row model of a diametral row of the core is used as shown in Fig.1. A single row model used in this paper consists of 21 assemblies including shield, reflector, blanket, GEM, drive fuel, control rod, and USS assembly. Table 1 shows the sectional properties of assembly used in analysis model. In this table, the equivalent density is obtained using the assumed total mass of each assembly.

Table 1. Input Properties for KALIMER Core Seismic Model

Assembly Type		Elastic Modulus (GPa)	Moment of Inertia (10^{-6} m^4)	Sectional Area (10^{-3} m^2)	Equi-Density (kg/m^3)	Poisson's Ratio	Damping Ratio (%)
Shield	Nosepiece	174.8	1.39	1.206	47619.0	0.3	3.0
	Duct	159.9	6.90	2.120	47619.0	0.3	3.0
Reflector	Nosepiece	174.8	1.39	1.206	50523.9	0.3	3.0
	Duct	159.9	6.90	2.120	50523.9	0.3	3.0
Blanket	Nosepiece	174.8	1.39	1.206	50938.0	0.3	3.0
	Duct	159.9	6.90	2.120	50938.0	0.3	3.0
GEM	Nosepiece	174.8	1.39	1.206	41498.1	0.3	3.0
	Duct	159.9	6.90	2.120	41498.1	0.3	3.0
Drive Fuel	Nosepiece	174.8	1.39	1.206	43676.7	0.3	3.0
	Duct	159.9	6.90	2.120	43676.3	0.3	3.0
Control Rod	Nosepiece	174.8	1.39	1.206	42743.0	0.3	3.0
	Duct	159.9	6.90	2.120	42743.0	0.3	3.0
USS	Nosepiece	174.8	1.39	1.206	42743.0	0.3	3.0
	Duct	159.9	6.90	2.120	42743.0	0.3	3.0

Fig.2 shows the core seismic model used in analysis, consisting of 168-beam elements and 42-impact gap elements. The locations of gap elements are the top load pad (TLP), above-core load pad (ALP), and the top of the outer shield assemblies.

The elastic modulus of the duct using HT9 is calculated using the equation as[5]

$$E = 212.0(1.144 - 4.856\text{x}10^{-4}\text{T}),\ GPa,$$

where T is absolute temperature, °K.

The calculated elastic modulus of duct and nosepiece is 159.86 GPa (530°C) and 174.79 GPa (380°C) respectively.

The gap properties used in analyses are as follows:

Gaps at ACLP and TLP;

$$K_g = 10.0\ MN/m,\ C_g = 2.44\ kN.s/m,\ \text{gap}=3.0\ mm$$

Gaps between former ring and outer shields;

$$K_g = 10.0\ MN/m,\ C_g = 2.44\ kN.s/m,\ \text{gap}=4.0\ mm$$

The shock damping, C_g during impact is calculated as follows[6];

$$C_g = K_g \frac{(1-\varepsilon^2)T_s}{\pi},$$

where K_g, ε and T_s are the gap stiffness, the contact coefficient of restitution, and the shock duration respectively. In this analysis, ε=0.55, which is for the steel-steel contact, is used and the shock duration is assumed 2.0 ms.

The sectional properties of the duct are calculated as

Area; $A_D = 2\sqrt{3}(DT - T^2) = 2\sqrt{3}(0.157\text{x}0.004 - 0.004^2) = 2.12\text{x}10^{-3}\ m^2$

Moment of Inertia;

$$I_D = \frac{5}{48\sqrt{3}}\left[D^4 - (D-2T)^4\right] = \frac{5}{48\sqrt{3}}\left[0.157^4 - (0.157 - 2\text{x}0.004)^4\right] = 6.9\text{x}10^{-6}\ m^4$$

The sectional properties of the nosepiece are calculated as

Area; $A_N = \frac{\pi}{4}(D_o^2 - D_i^2) = \frac{\pi}{4}(0.1^2 - 0.092^2) = 1.206\text{x}10^{-3}\ m^2$

Moment of Inertia; $I_N = \frac{\pi}{64}(D_o^4 - D_i^4) = \frac{\pi}{64}(0.1^4 - 0.092^4) = 1.392\text{x}10^{-6}\ m^4$

The structural damping is assumed as 3% critical damping uniformly. This damping is converted to the proportional damping considering the natural frequencies of each assembly as follows;

$$[C] = \alpha[M] + \beta[K],$$

where α and β are calculated using the relationships

$$\alpha + \beta\omega_i^2 = 2\omega_i\zeta_i.$$

The general assumptions used in modeling are as follows;

- All ducts have uniform sectional properties.
- Ducts are supported as a cantilever at the lower diagrid.
- Core shroud attached to the lower diagrid has a rigid body motion, i.e. there is no relative motion between the core shroud and the lower diagrid.
- Sodium damping and squeeze film damping are ignored.
- No information concerning assembly bowing due to thermal and neutron flux gradients is available so all assemblies are assumed as a straight beam.

2.3 Modal Analysis

The natural frequencies of each assembly are shown in Table 2. From this table, the fundamental frequencies of core assemblies are in range of 1.9Hz to 2.1Hz. This result is used to generate the core stick model included in full seismic analysis model of KALIMER reactor structure. Fig.3 shows the mode shapes of core assemblies obtained from SAC-CORE code.

Table 2. Natural frequencies of Each Assembly Type

Assembly Type	1st frequency (Hz)	2nd frequency (Hz)
Shield	1.96	15.15
Reflector	1.91	14.71
Blanket	1.90	14.65
GEM	2.10	16.23
Drive Fuel	2.05	15.82
Control Rod	2.07	15.99
USS	2.07	15.99

2.4 Seismic Loads

The input motions for the core seismic analysis are generated from the full seismic analysis model of KALIMER reactor system as shown in Fig.4. From the seismic analysis for SSE 0.3g load in cases of the seismic isolation (0.5Hz) and the non-isolation design, the acceleration time history responses at the lower diagrid, which will be used as the input motions of the core seismic analysis, are obtained as shown in Fig.5. From the Fig.5, it is evident that the seismic isolation design gives a significant reduction of the seismic responses in KALIMER design compared with the non-isolation design. This can be showed in the floor response spectra of Fig.6. The maximum peak acceleration of the core input motion is about 0.14g for the seismic isolation case and 0.95g for the non-isolation case.

For the input motions obtained from the seismic analyses of KALIMER reactor structures, the non-linear time history analyses are carried out using the SAC-CORE code. The time interval used in analyses is 2.0ms and the total analysis time is 21 seconds.

3. ANALYSIS RESULTS AND DISCUSSIONS

Fig.7 and Fig.8 show the time history displacement responses of the top locations of the control rod assembly (node 72) and the USS assembly (node 99). In these results, the maximum displacement response of the seismic isolation case is about 2 times lower than that of the non-isolation case. Actually the maximum relative displacement of the core may be so increased in case of the non-isolation design when considering the deflection of the core shroud. The displacement responses at top locations of the control rod assembly and the USS assembly is very important in functional design of the upper internal structure (UIS). The significantly reduced core seismic displacement response affords to easily satisfy the requirements of the relative deflection limits between UIS and core for SSE load condition. Therefore, the seismic isolation design of KALIMER reactor structures gives a great benefit in seismic design of the core and main structures.

Fig.9 shows the maximum peak displacements at top locations of core assemblies. In these results, the displacement responses of the outer shield assemblies are smaller than other ducts because the former ring attached to the core shroud structures restrains severe deflection of outer duct assemblies. The seismic isolation case gives significantly reduced responses in all assemblies than the non-isolation case.

Fig.10 shows the maximum impact forces at the top load pads. The impact responses are smaller in case of the seismic isolation at most load pads than the case of the non-isolation. The small impact force at load pads can ensure the structural integrity of the core in seismic events.

4. CONCLUSIONS

This paper investigates the seismic isolation effects on the core seismic responses of a conceptually designed KALIMER reactor system. From the seismic analyses using 21- single row model of core assemblies by SAC-CORE code, we can see that the seismic isolation design provides significantly reduced core seismic responses compared with the non-isolation design. It is expected that the significantly reduced core seismic displacement response can make to easily satisfy the requirements of the UIS/core relative deflection limits and the core compaction and reactivity insertions for SSE load condition.

ACKNOWLEDGMENT

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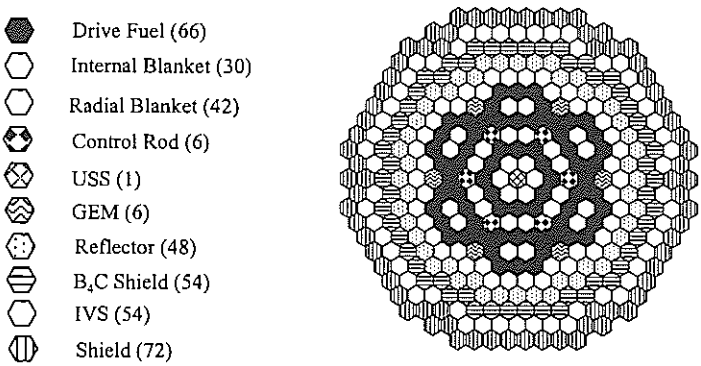


< Total 379 Assemblies >

Fig. 1 KALIMER Core Assembly Layout

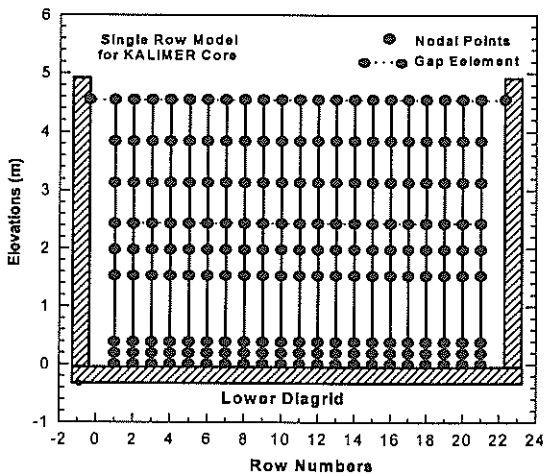
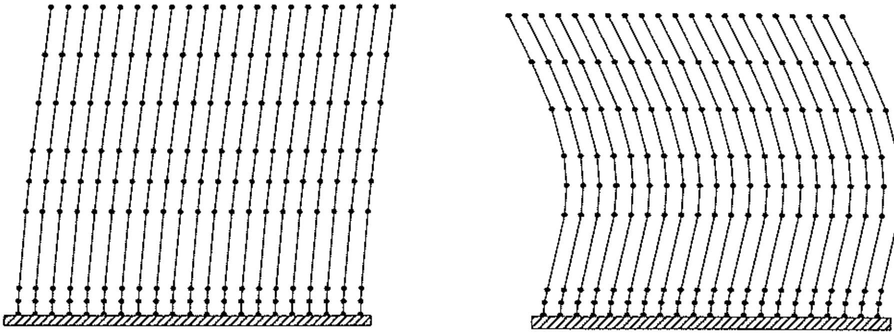


Fig. 2 KALIMER Reactor Core Seismic Analysis Model



(a) 1st Mode (b) 2nd Mode

Fig. 3 Mode Shapes of Duct Assemblies

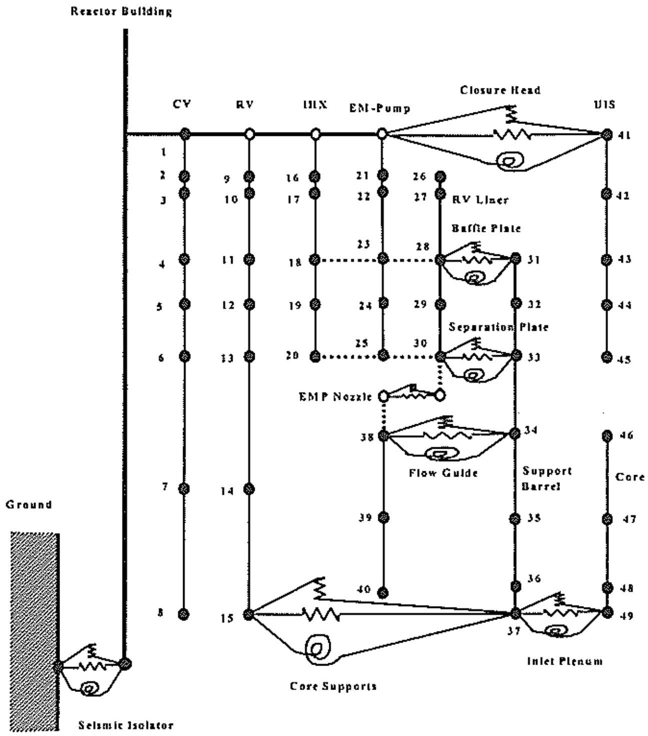


Fig. 4 Seismic Analysis Model for KALIMER Reactor Structures

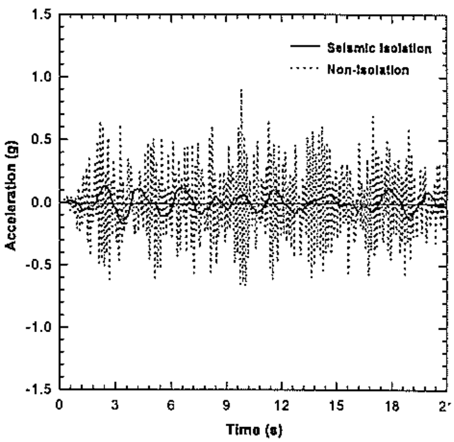


Fig. 5 Input Motions

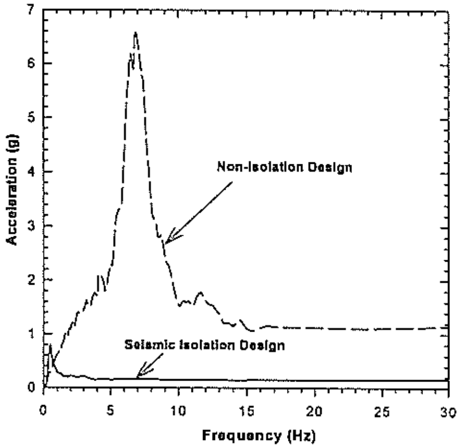
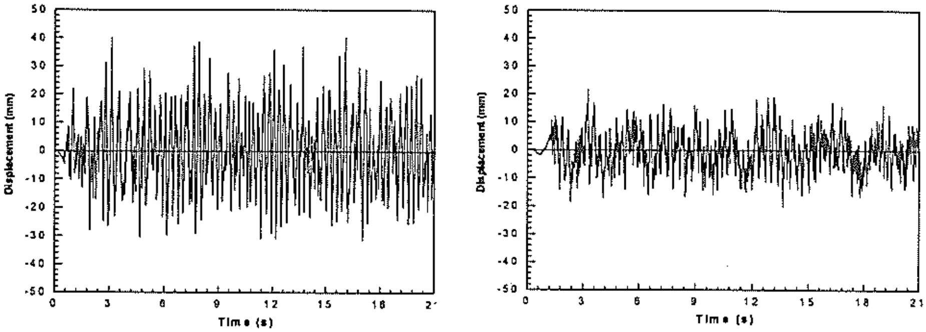
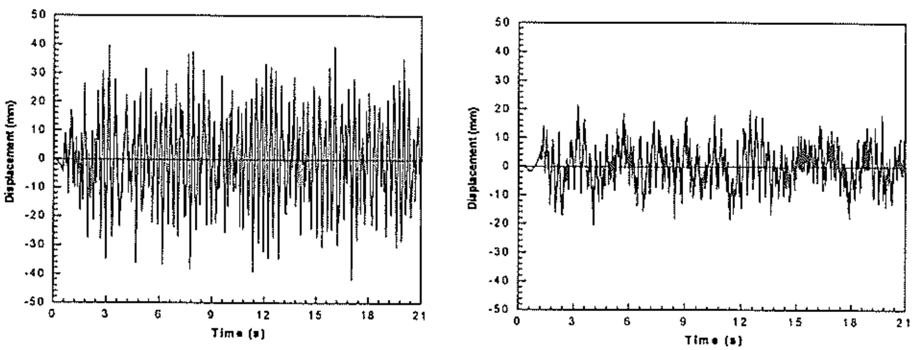


Fig. 6 Spectra for Input Motions



(a) Non-Isolation Case (b) Seismic Isolation Case

Fig. 7 Displacement Responses at Top of Control Rod Assembly (Node 72)



(a) Non-Isolation Case (b) Seismic Isolation Case

Fig. 8 Displacement Responses at Top of USS Assembly (Node 99)

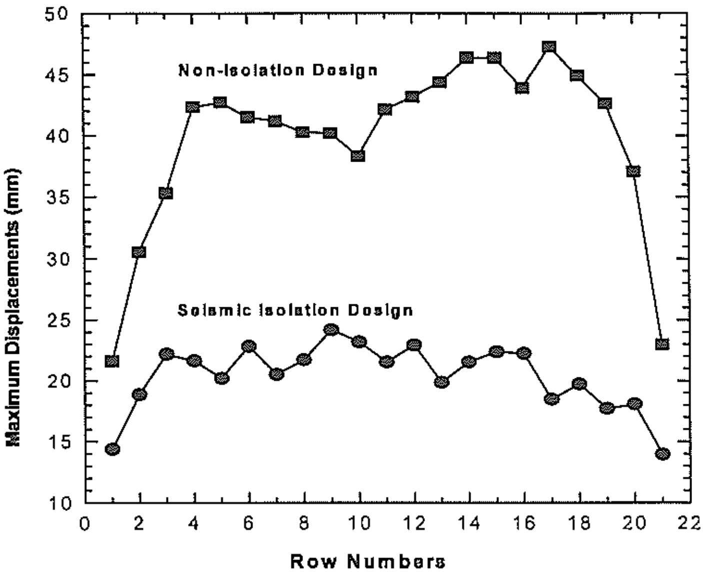


Fig. 9 Maximum Peak Displacements at Core Top Nodes (SSE Load)

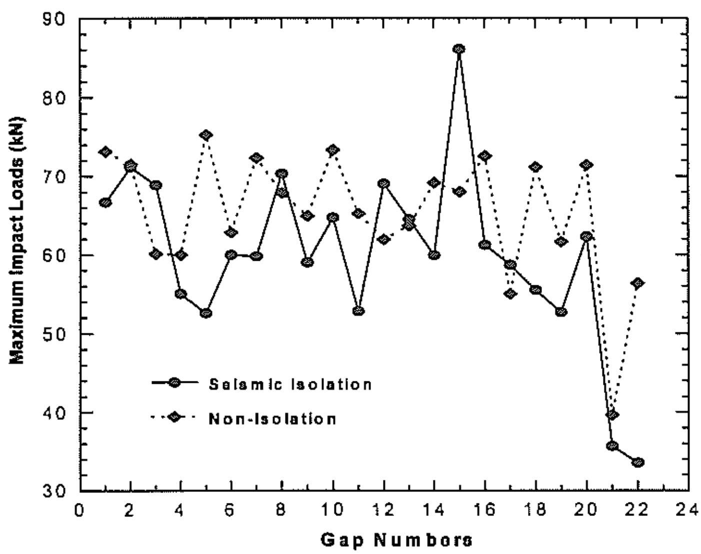


Fig. 10 Maximum Impact Loads at Load Pads (SSE Load)