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STUDY ON SEISMIC RESPONSE CONTROL SYSTEM FOR HEAVY, RIGID BUILDINGS OF REINFORCED CONCRETE PART-1 SEISMIC RESPONSE CONTROL METHOD AND RESPONSE REDUCTION

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SUMMARY

A seismic response control building with soft upper steel frame " has been developed for boiling water reactor (BWR) buildings. The upper steel frame story, positioned above the crane level of the building, was designed much less stiff than the reinforced concrete structure below the crane level. The weight of the roof and the steel frame works as a kind of "tuned mass" for a conventional seismic response control building. A couple of viscous dampers were installed in each span of the steel frame to prevent excessive acceleration of the steel frames. Turning the stiffness and weight of the upper steel frame has enabled that the steel frame to control the motion of the structure below the crane level, including the containment vessel itself. According to our calculations, by applying this system to the conventional BWR, seismic response was demonstrated to be reduced by more than 20%.

INTRODUCTION

Technologies such as isolation from seismic input and/or seismic response control are indispensable for the realization of a "standard design" for nuclear reactor buildings (R/Bs) when constructed at varying locations and seismicity. Seismic response control systems have been developed and used mainly for high-rise steel structures such as office buildings. However, because a conventional R/B is a heavy and rigid structure made of massive concrete, as shown in cross section on Figure 1-1, controlling the seismic response of such a structure by applying conventional methods is considered too costly. Therefore a new seismic response control system for such a heavy, rigid structure needs to be developed.

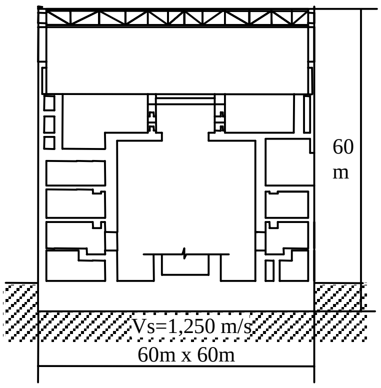

Figure 1-1 A nuclear reactor building

Our development of the new structural system is important not only for the realizing the standardized nuclear reactor buildings but for improving the seismic safety of the existing, especially aged, nuclear structures. The base isolation system for existing buildings might induce some difficulties, particularly on piping design concerning the level adjustment and/or the flexible devices on pipe joints against the relative deformation when a piping system runs between a base-isolated and an ordinary building.

On the other hand, the seismic response control device has little influence on the existing system and components because the device is relatively easy to install on the part of the steel frames. Therefore, this seismic response control technique is a promising and effective method for the structural improvement of aged nuclear power plant.

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SEISMIC RESPONSE CONTROL SYSTEM FOR NUCLEAR REACTOR BUILDING

The conventional nuclear R/B is primarily made of a reinforced concrete (RC) structure. The shape of this structure is almost cubic and the length of each side is approximately 60m, as shown in Figure 1-1. The total weight of this building is more than 200,000 tons. The foundation mat is directly set on a support rock ground. The building's structure has a reinforced concrete containment vessel (RCCV) and box wall surrounding the RCCV. These shear walls are interconnected through the floor slabs. Therefore, the overall building is a structure with high degree of rigidity.

As shown in Figure 2-2(a), the sway/rocking (SR) model (two-cantilever model of the bending shear-type building) is adopted for the dynamic analysis model. The base spring constant is derived using the vibration admittance theory, where Novak's theoretical solution is used to derive the side-surface spring constant.

Because the conventional R/B is primarily made of reinforced concrete from top to toe, the natural period is relatively short (the first-order natural period T_1=0.28sec) and the natural vibration mode is drawn in a smooth curve, as shown in the upper frame of Table 3-1. Conventional seismic response control systems, such as tuned mass damper, are not considered feasible because the tuned mass needed in such a case would be too heavy.

"A seismic response control building with soft upper steel frame", referred to as 'the (seismically) controlled R/B', has been developed for boiling water reactor (BWR) buildings. The outlook of the structure is shown on Figure 2-1. The upper steel frame story, positioned above the crane level of the building, was designed much less stiff than the RC structure below the crane level. The weight of the roof and the steel frame works as a kind of "tuned mass" for a conventional seismic response control building. The weight occupies approximately 2% of the total weight, which is heavy enough to control the whole building. A couple of viscous dampers were installed in each span of the steel frame for the purpose of preventing excessive acceleration of the steel frames. The dynamic analysis model for the seismically controlled R/B is shown on Figure 2-2(b). The vibration characteristics of "the controlling structure", called the upper steel frame, can be defined by the stiffness of the steel frame, K, and the damping coefficient, C.

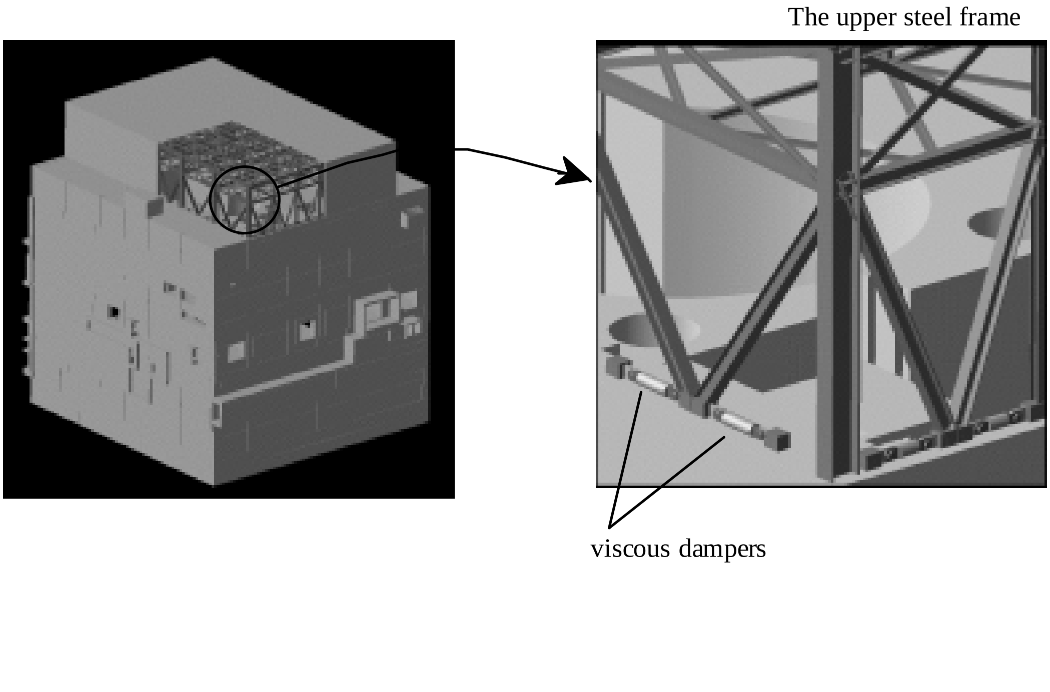
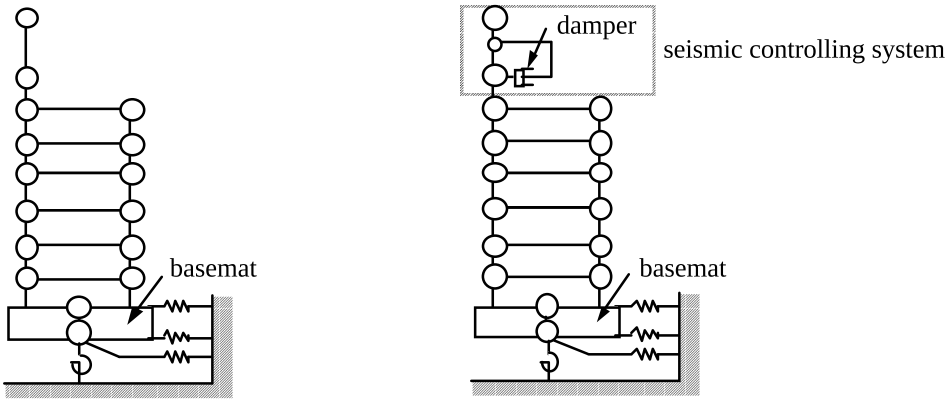


Figure 2-1 Outlook of the Seismic Response Controlled R/B



(a) Conventional R/B (b) Seismic Response Controlled R/B

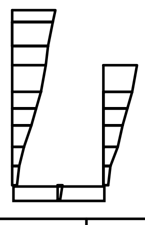
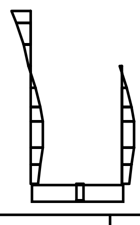
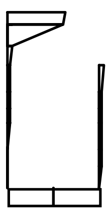
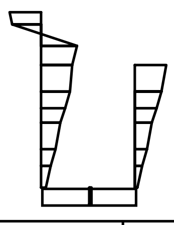
Figure 2-2 SR models for dynamic analysis

MECHANISMS OF SEISMIC RESPONSE REDUCTION

The mechanisms of seismic response reduction of the seismic response control building with soft upper steel frame can be explained by the eigenvalue analyses results, shown in Table 3-1. The first-order natural vibration mode of the conventional R/B, which is shown on the upper frame in Table 3-1, is the principal vibration mode with a high participation factor, β, where the deformation simply increase from bottom to the top. On the other hand, the seismically controlled R/B has two principal modes, the first-order and the second-order mode. In the first-order natural vibration mode of the controlled R/B, which is shown on the lower frame in Table 3-1, the deformation is concentrated at the upper frame, and little deformation can be observed in lower RC structure. The second-order natural vibration mode of the controlled R/B corresponds to the first-order mode of the conventional R/B. In this mode, the deformation of the lower RC structure increases from the bottom to the top, but the upper structure deforms in the opposite direction from the lower structure as if the upper structure controls the deformation of the lower structure. As a result of the contribution by this mode, the seismic responses of whole building, such as the overturning moment of the building and/or the shear stress in the shear walls, are expected to be reduced.

Furthermore, by installing the dampers in each span of the steel frames, the energy consumption by these dampers can also contribute the response reduction in the dynamic analyses.

Table 3-1 results of the eigenvalue analysis

	1st-order mode		2nd-order mode	
(a) conventional BWR				
	T1=0.28sec	β1=1.61	T2=0.12sec	β2=0.72
(b) seismic response controlled BWR				
	T1=0.39sec	β1=2.12	T2=0.25sec	β2=1.32

OPTIMIZATION OF THE SYSTEM CHARACTERISTICS

Fundamental Investigation On Response Characteristics

Dynamic response characteristics of the seismic response control building with soft upper steel frame is controlled by the stiffness of the steel frames, 'K', the weight of the upper structure, 'm', and the damping coefficient, 'C' of the dampers. Here, where 'm' is considered a constant, designing the controlling structure means finding the optimum and realizable values for 'K' and 'C'. Dynamic response analyses using the stationary sine wave of various frequencies are performed for this purpose.

Figure 4-1 illustrates the response function of the overturning moment (Md) of the building with steel frames of various stiffnesses (K) without dampers (C=0). And Figure 4-2 illustrates the response function of the shear force (Qs) at the bottom of the steel frame under the same conditions. The former represents the responses of the whole building, and the latter represents the responses of the upper controlling structures. The optimum value must be decided considering both responses of the whole building and the upper structure. K_0 in these figures represents the stiffness of the steel frame of the seismic resisting type structure. The parameters of this analysis, the stiffness of the steel frame 'K', is described as a fraction of the K_0, such as K=1/4 K_0. According to these results on Figure 4-1 and 4-2, as K decreases, both the first-order and the second-order peaks shift to the lower frequency side and the highest peak switches from the first-order peak to the second.

Figure 4-3 and 4-4 illustrate the response functions of the analysis model with various damping coefficients, C=0~30 (tf sec/cm), when the constant stiffness is assumed K=1/6 K_0. From these results, the shear force on steel frame, Qs, reduced drastically even by the small damping coefficients. With the dampers the reduction of the first-order peak value of the overturning moment, Md, is great compared to very little reduction of the second-order peak value resulting in the second-order peak controlling the response.

By picking up the peak values on Figures 4-1, 4-2, 4-3, and 4-4, Figures 4-5 and 4-6 are illustrated with two parameters, 'K' and 'C'. The design criteria for Md and Qs, those are: Md=28,000 (tf m/gal) and Qs=55 (tf /gal), are also shown on those figures. From the efficiency of the damper, just small differences can be found between C=20 and C=30. On the other hand, the damping coefficient C=20 (tf sec/cm) can be realized by the existing devices. As a result of these considerations, C=20 (tf sec/cm) is selected as the value of the damping coefficient. Then, in the case of C=20, both design criteria are satisfied when the peak values of Md and Qs drop in the shaded region in the Figures 4-5 and 4-6. According to Figure 4-5, the stiffness K must be equal or lower than 1/7 K_0 ($K \leq 1/7\ K_0$) by the criterion of the overturning moment. On the other hand, according to the Figure 4-6, K must be equal or higher than 1/5 K_0 ($K \geq 1/5\ K_0$) by the criterion of the shear force in the steel frame. As a result of this investigation, the optimum frame stiffness is in the range of K=1/5 K_0~ 1/7 K_0. The design dimension of 'K' must be settled from among this range by performing the seismic response analyses using the design earthquakes.

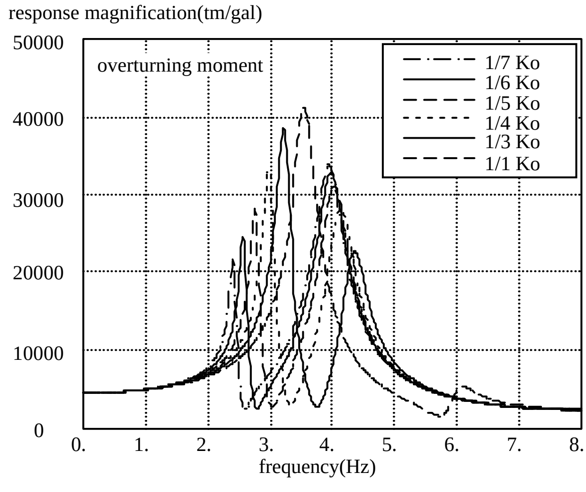


Figure 4-1 response function of Md (C=0)

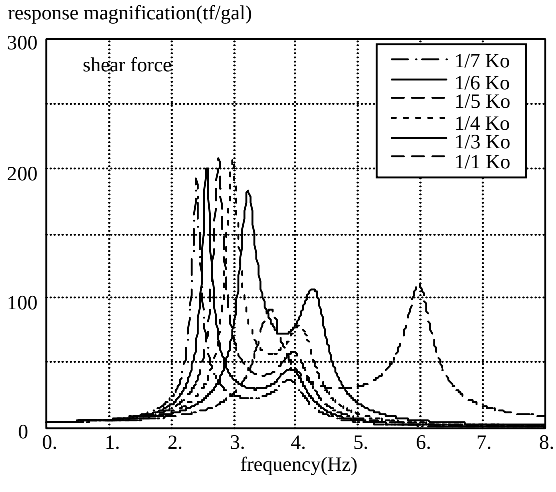
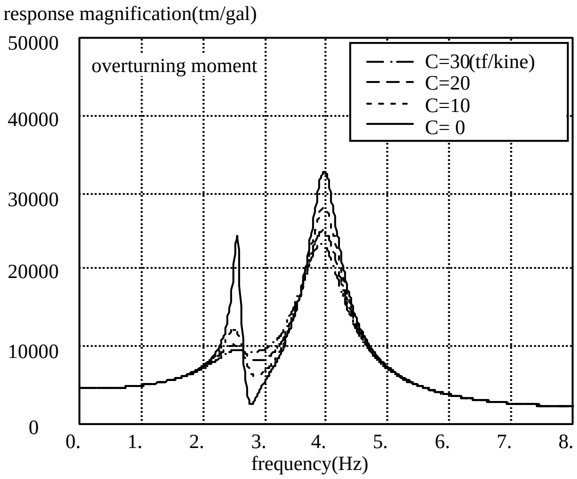
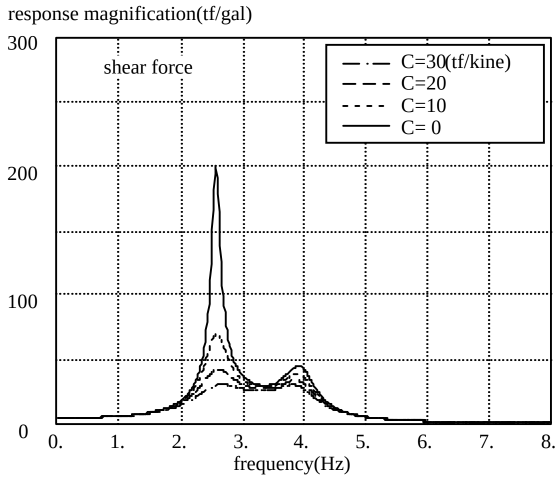
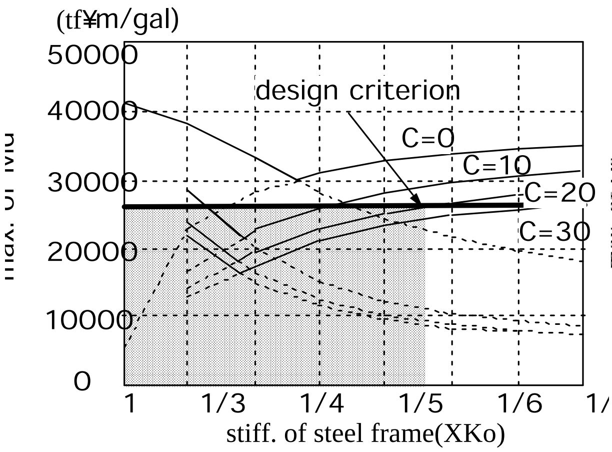


Figure 4-2 response function of Qs (C=0)







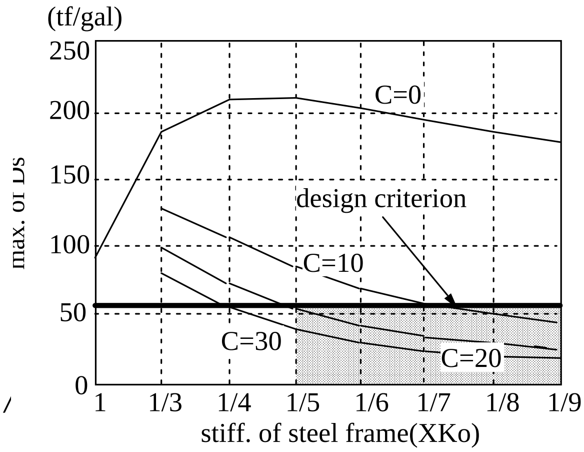
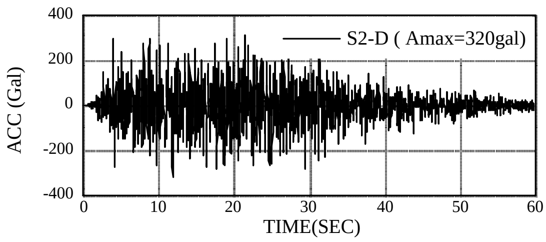


Figure 4-5 peak value of the response function of Md

Figure 4-6 peak value of the response function of Qs

Selection Of The Design Demension By Seismic Response Analyses

For the purpose of investigating the performance of the seismically controlled reactor building, a seismic response analysis was performed using a range of the optimum dimensions determined in the previous section, those are; C=20 (tf sec/cm) and K=1/5 K_0, 1/6 K_0, and 1/7 K_0. The time history acceleration wave and the response spectrum of artificial seismic wave, which corresponds to the extreme design earthquake (S2-D), were shown in Figure 4-7.



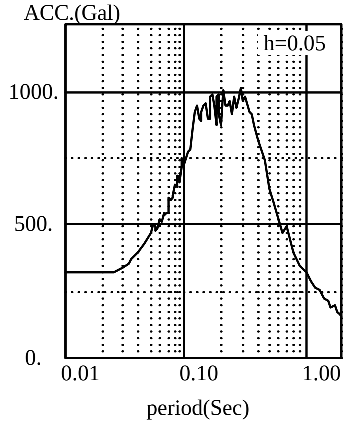


Figure 4-7 the extreme design earthquake S2-D

A parameter study on the stiffness of the steel frame, 'K', using the S2-D earthquake, was performed. Figures 4-8 and 4-9 show the maximum responses of the overturning moment and the shear force on the steel frame, respectively. From these figures, K=1/6 K_0 was selected as the optimum value of the frame stiffness because the case 'K=1/6 K_0' showed the best performance on the overturning moment and satisfied the design criteria of the steel frame.

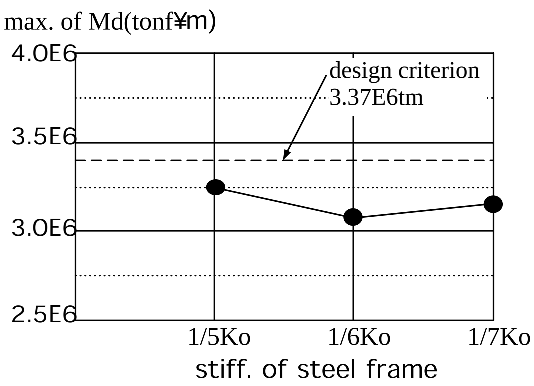


Figure 4-8 maximum value of Md

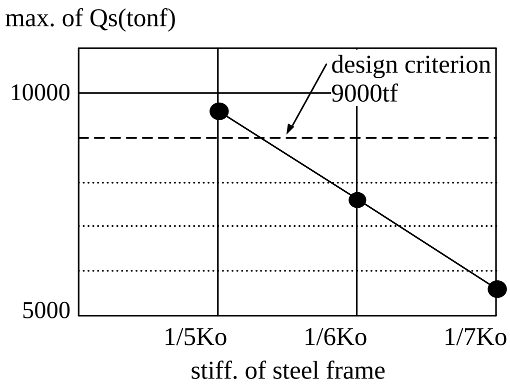
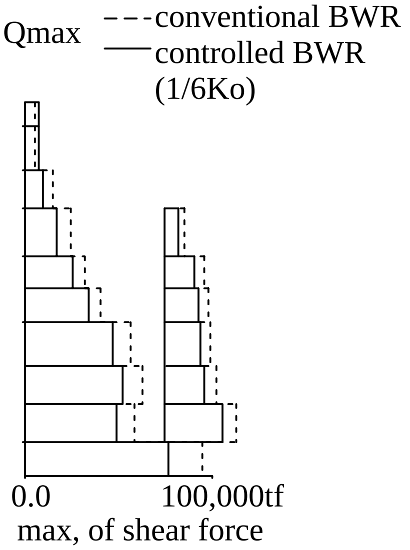


Figure 4-9 maximum value of Qs

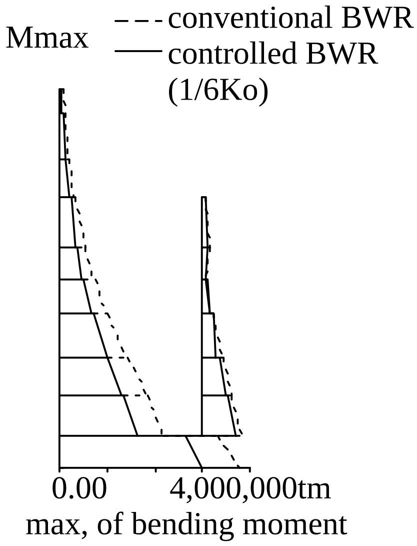
PERFORMANCE OF THE SEISMICALLY CONTROLLED REACTOR BUILDING

Using the design value determined in the previous section, the performance of a seismically controlled reactor building was investigated. The maximum response shear force and bending moment on the 'controlled' building are shown in Figure 5-1 and 5-2, respectively, compared with the responses of the 'conventional' earthquake resisting reactor building. According to these results, seismic response reduction of the RC structure is observed by adopting our seismic response control system. The maximum response shear force was reduced by 17% and the maximum response bending moment was reduced by 24% at the bottom of the shear walls.



ratio controlled/conventional=0.08
(at the foot)

Figure 5-1 maximum response shear force



ratio controlled/conventional=0.76
(at the foot)

Figure 5-2 maximum response bending moment

CONCLUSIONS

A new concept of seismic response control building, “ a seismic response control building with soft upper steel frame” is introduced as one method of applying seismic response control technologies to heavy, rigid buildings such as nuclear reactor buildings. Turning the stiffness and weight of the upper steel frame has enabled that the steel frame to control the motion of the structure below the crane level, including the containment vessel itself. According to our calculations, by applying this system to the conventional BWR, seismic response was demonstrated to be reduced by more than 20%. This system can be one of the effective methods for the structural improvement of existing nuclear power plants because the installation of this system has little influence on the existing system and components.

REFERENCE

Matsumoto H., Sugawara R., et al. (1995), *Study on Seismic Response Control System of Nuclear Reactor Building Part. 1 Seismic Response Control Method and Response Reduction,* AIJ annual report (1995) in Japanese.