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A SEISMIC DESIGN OF NUCLEAR REACTOR BUILDING STRUCTURES APPLYING SEISMIC ISOLATION SYSTEM IN A HIGH SEISMICITY REGION –A FEASIBILITY CASE STUDY IN JAPAN-

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A feasibility study on the seismic design of nuclear reactor buildings with application of a seismic isolation system is introduced. After the Hyogo-ken Nanbu earthquake in Japan of 1995, seismic isolation technologies have been widely employed for commercial buildings. Having become a mature technology, seismic isolation systems can be applied to NPP facilities in areas of high seismicity. Two reactor buildings are discussed, representing the PWR and BWR buildings in Japan, and the application of seismic isolation systems is discussed. The isolation system employing rubber bearings with a lead plug positioned (LRB) is examined. Through a series of seismic response analyses using the so-named standard design earthquake motions covering the design basis earthquake motions obtained for NPP sites in Japan, the responses of the seismic isolated reactor buildings are evaluated. It is revealed that for the building structures examined herein: (1) the responses of both isolated buildings and isolating LRBs fulfill the specified design criteria; (2) the responses obtained for the isolating LRBs first reach the ultimate condition when intensity of motion is 2.0 to 2.5 times as large as that of the design-basis; and (3) the responses of isolated reactor building fall below the range of the prescribed criteria.

KEYWORDS : Seismic Design, Seismic Safety, Nuclear Reactor Building, Seismic Isolation, Base Isolation, Lead Rubber Bearing, High Seismicity

1. INTRODUCTION

The seismic isolation technologies have been widely developed in the world and in Japan as well. In Japan, during the 1995 Hyogo-ken Nanbu earthquake hitting the city of Kobe, Hyogo-ken, the seismic isolation technology has been recognized as effective in obtaining seismic safety during strong ground excitation. A large number of commercial buildings have been designed and constructed utilizing seismic isolation systems. A wide variety of isolating systems have been developed. Application of seismic isolation systems was extended to nuclear power plant facilities after the 2007 Chuetsu-oki earthquake hitting the Kashiwazaki-Kariwa Nuclear Power Plant.

With the maturation of seismic isolation technology, a research program was initiated in Japan to develop the evaluation method for seismic isolation systems for nuclear power plant facilities. Within the national program entitled “Safety Enhancement for LWRs” supported by the Japanese Government, a research and development program on development for evaluation methods for seismic isolation systems has been carried out between the years from 2010 to 2012 for the first phase, and for the year of 2013 to 2014 for the second phase of the program. Within the R&D program, a feasibility study has been carried out upon the seismic design for nuclear reactor buildings with the application of seismic isolation systems [1, 2]. Two types of reactor buildings, PWR and BWR buildings, innovated for the application of seismic isolation systems, are taken into consideration. With this application of seismic isolation systems to nuclear power plant facilities, we can plan, design and construct safer nuclear power plant facilities on sites with high seismic activity, as in Japan, and higher cost-effective nuclear power plant facilities as well through standardization of design, determined independently based on variations in either seismic conditions or site conditions. Applying seismic isolation systems for nuclear power plant facilities on sites with high seismicity, significant reduction of seismic responses is expected during an intense ground motion, which leads to the standardization of design on nuclear power plant facilities possible and practical.

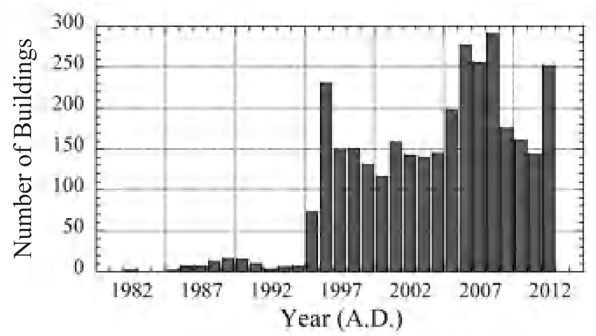


Fig. 1. The number of seismic isolated buildings constructed between years from 1982 to 2012. The first seismic isolated building in Japan was constructed in 1982. Note that the number of seismic isolated buildings increased after the year of 1995 when the Hyogo-ken Nanbu earthquake hit the city area of Kobe, Hyogo-ken, Japan.

2. DEVELOPMENT AND DIFFUSION OF SEISMIC ISOLATION TECHNOLOGY IN JAPAN

2.1 Seismic Isolation Technologies for Commercial Buildings

It was our first experience that seismic isolated buildings were subjected to real strong ground motions when the Hyogo-ken Nanbu earthquake hit Kobe on January 17, 1995 in Japan. The reported magnitude of the quake is 7.3, and the peak ground acceleration and ground velocity observed at the Kobe Meteorological Observatory Station were 0.85G and 1.1 m/s, respectively. Two buildings were located in northern Kobe to the heavily damaged area, one of which is a six-storied computer center building, and the other, a four-storied research center building. During the earthquake both seismic isolated buildings revealed good structural response behaviors. Within both buildings, accelerometers have been installed. The peak accelerations of the seismic isolated building on the horizontal components are significantly yielded less being around 1/5 to 1/2.5 times as large as those obtained in the non-isolated buildings closely located to the isolated buildings, while no response reduction was observed on the vertical components.

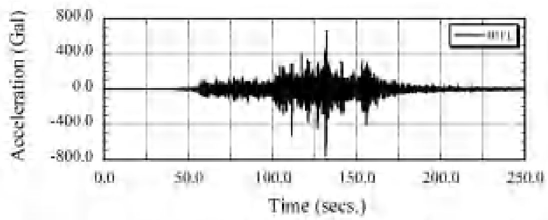
The evidence obtained during the 1995 Hyogo-ken Nanbu earthquake can be recognized that the innovated seismic isolation technologies have been found efficient, making seismic responses significantly less, producing no structural damage on building structures during an intense seismic action. It has been promoting the application of seismic isolated systems for buildings, for hospitals, for central and local government office buildings, for disaster emergency responses, high-rise buildings of high quality for either offices or condominiums. Figure 1 illustrates the number of seismic isolated buildings constructed in Japan between the years from 1982 to 2012 [3].

2.2 Seismic Isolation Technologies for Nuclear Power Plant Facilities

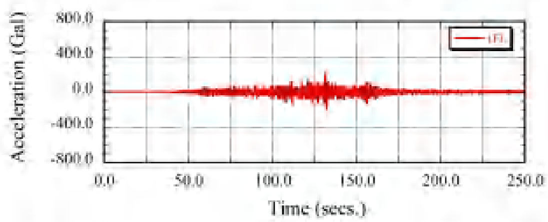
The M6.8 Niigata-ken Chuetsu-oki earthquake occurred on July 16, 2007 and hit the Kashiwazaki-Kariwa (KK) nuclear power plant station, Tokyo Electric Power Co. Ltd. (TEPCO). No serious structural damage for the reactor buildings was observed. It was reported that the two-storied administration office building, construction of which was a ductile steel frame, suffered damage in the non-structural components. The typical damage observed was the falling of ceiling panels in the building and tuning over of office cabinets, leading to the loss of essential functions which should have enabled it to be used as an emergency response center, as was intended.

With maturation of seismic isolation technologies developed for commercial buildings since the 1995 Hyogo-ken Nanbu earthquake, seismic isolation technologies have been applied to building structures on nuclear power plant sites as well as those used for new administration office buildings, auxiliary buildings for emergency response centers and others [4-6].

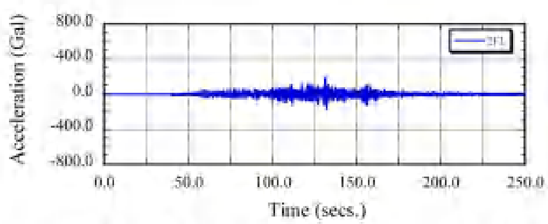
The efficiency of the seismic isolation technology was realized again during the 2011 Off the Pacific Coast of Tohoku Earthquake of March 11, 2011. A two-storied building was constructed with the application of seismic isolation technology in the year of 2010 on the site for the purpose of emergency responses from the lesson learned from the KK NPP station during the 2007 Niigata-ken Chuetsu-oki earthquake. The general configuration of the isolated building on the site is as follows [7]: (1) two-storied; (2) steel-reinforced concrete composite structure, (3) structural plan of 52.6 m by 40.6 m. The isolation system is composed of four types of device as follows: (1) natural rubber bearings (NRB) [10 units]; (2) lead-plug rubber bearings (LRB) [four units]; (3) sliding bearings [31 units]; and (4) oil dampers [16 units].



(a) Time trace of the recorded acceleration obtained at the basement (base mat).



(b) Time trace of the recorded acceleration obtained at the first floor level.



(c) Time trace of the recorded acceleration obtained at the second floor level.

Fig. 2. Time trace of the recorded acceleration obtained in the seismic isolated building on the Fukushima Dai-ichi Nuclear Power Station, TEPCO, Japan during the 2011 Off the Pacific Coast of Tohoku Earthquake of March 11, 2011. The component was obtained along the east-west direction of the building.

Figures 2 (a) through (c) illustrate the time traces of acceleration obtained along the east-west direction of the building obtained at the base mat (non-isolated), first floor level (isolated) and second floor level, respectively [8]. The recording point positioned at the base mat is placed on a non-isolated location, and those at the first and second floor levels, isolated. The peak accelerations of motion at these recording points are 756.035 cm/s2 at the base mat, 212.968 cm/s2 at the first floor level and 184.656 cm/s2 at the second floor level, respectively. The time traces within the interval from 120 to 130 seconds is shown in Fig. 3. While the PGA is 0.8G at the base mat point, the acceleration responses of the building are 0.2G with application of seismic isolation system making the responses significantly less. From observation of Fig. 3, one can realize that high fluctuation of oscillating components producing high acceleration have been eliminated from the components obtained within the isolated building. In Figs. 4 (a) and (b), the acceleration response spectrums are shown. Figure 4 (a) shows the acceleration response spectrum for the three acceleration records

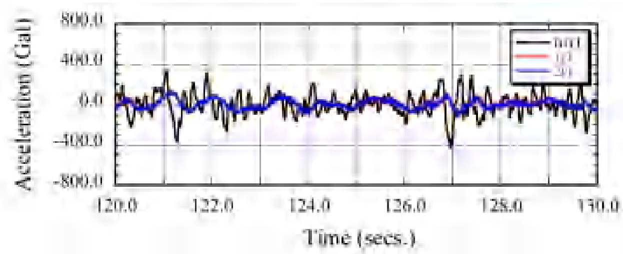


Fig. 3. Detailed time trace of the recorded acceleration within the interval of 120 seconds to 130 seconds. The recorded acceleration obtained in the seismic isolated building on the Fukushima Dai-ichi Nuclear Power Station, TEPCE, Japan during the 2011 Off the Pacific Coast of Tohoku Earthquake of March 11, 2011. The component was obtained along the east-west direction of the building.

obtained at the base mat, the first and second floor levels. Figure 4 (b) shows the spectrum describing the ratios of responses obtained at the first and second floor levels compared with those obtained at the base mat. Note that in Figs. 4 (a) and (b), the axis Y is expressed by an arithmetic scale and a logarithmic scale, respectively. It is found clearly that the seismic isolation system placed for the building can make significant reduction of responses in the range of fundamental periods less than around 2.0 seconds [9].

3. PRELIMINARY STUDY ON FEASIBLITY OF APPLICATION OF SEISMIC ISOLATION TECHNOLOGY TO NUCLEAR REACTOR BUILDINGS

3.1 Reactor Buildings Discussed in the Study

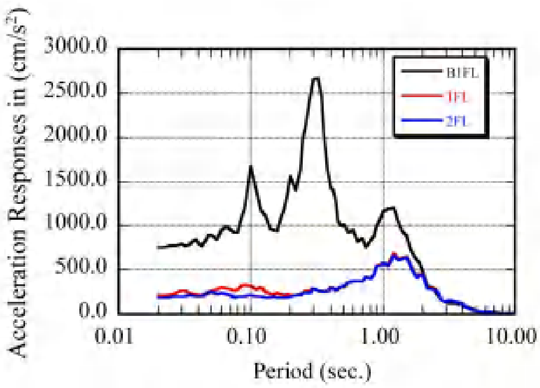
Within the feasibility study presented herein introducing an application of seismic isolation technologies for nuclear power facilities in Japan, we have developed a new reactor structure. In Japan we have employed two types of reactor building, one of which is a pressurized water reactor (PWR) and the other, a boiling water reactor (BWR). Within the study, two types of reactor buildings, PWR and BWR, are discussed and examined. Figures 5 and 6 illustrate general view of the reactor buildings, respectively. The weight of the reactor buildings is estimated at around 2.7 TN (Tera N) for the PWR and around 3.2 TN for the BWR in the case when a reactor building individually isolated or about 8.6 TN when both reactor and turbine buildings coupled isolated on an identical mat above the seismic isolation system.

3.2 Preliminary Discussions on Reactor Buildings and Seismic Isolation Systems

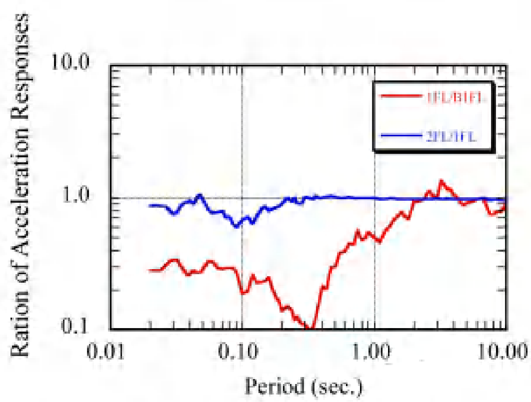
The following discussions were conducted when we initiated the feasibility study.

(1) Reactor buildings:

· Two representative reactor building models are



(a) Acceleration response spectrum obtained at the base mat, the first floor level and the second floor level.



(b) Acceleration ratio spectrum given by the ratios of acceleration response obtained at the first floor level compared with that obtained at the base mat, and that obtained at the second floor level compared with that at the first floor level. The spectrum diagram given by the ratios of acceleration responses (1FL/Base Mat) and (2FL/1FL), respectively.

Fig. 4. Acceleration response spectrum of the recorded acceleration obtained in the seismic isolated building on the Fukushima Daiichi Nuclear Power Station, TEPCE, Japan during the 2011 Off the Pacific Coast of Tohoku Earthquake of March 11, 2011. The component was obtained along the east-west direction of the building.

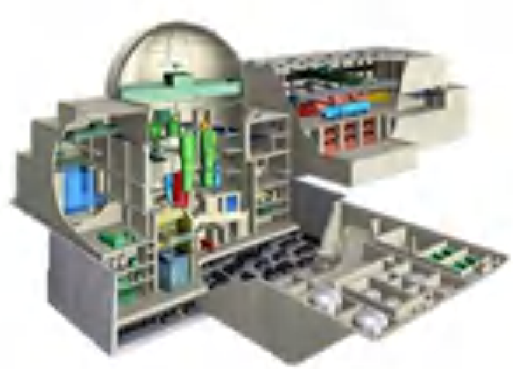


Fig. 5. Schematic view of the pressurized water reactor (PWR) building developed within the study. The reactor building exclusively positioned on the raft of isolation system.

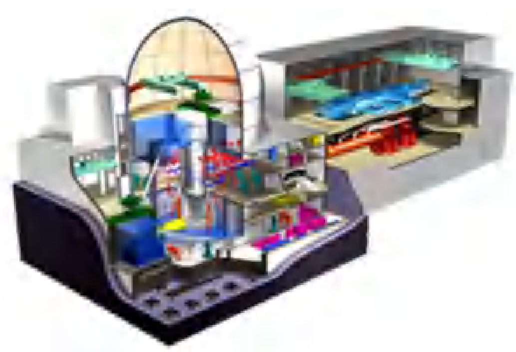


Fig. 6. Schematic view of the boiling water reactor (BWR) building developed within the study. Two kinds of isolation planning are discussed within the study. One is that a reactor building is exclusively isolated on the raft of isolation system. The other both the reactor building and the turbine building are coupled positioned on an identical raft of isolation system.

examined, one for the PWR and the other for the BWR, covering nuclear reactor buildings constructed in Japan. Within the models, variation should be covered associated with the site dependent conditions such as those of regional seismicity around the site, deep and shallow local subsoil conditions and other regional perspectives in Japan.

(2) Seismic isolation system:

- Common seismic isolation system for both PWR and BWR buildings should be developed; and
- The seismic isolation system developed herein should preferably be as simple as possible for either easier maintenance and less cost.

3.3 Preliminary Discussion on Feasibility of Seismic Isolation Design

Within the preliminary discussion on feasibility of application of seismic isolation systems, the following remarks have been obtained.

- We will develop the seismic isolation system employing the lead-plug rubber bearings (LRB hereinafter) within the study; and
- We will employ the LRB bearings available in the commercial market in Japan.

For seismic isolation systems employed in the commercial buildings developed in Japan, it is found that a wide variation of seismic isolation systems have been employed. For bearings, the fundamental function of which is to carry the weight of the building, natural rubber bearings (NRB) and sliding bearings are widely employed as well as LRB. For damping devices, the fundamental function of which is to dissipate the oscillating energy of building so as to yield seismic responses less, elasto-plastic steel dampers, lead dampers, viscous oil dampers, friction dampers and others are employed. Combinations of those devices such as a combination of elasto-plastic steel dampers and visco-elastic oil dampers or that of lead plug damper and visco-elastic oil dampers has been widely accepted. Within the combination, damping forces produced for the damping devices are given by the response displacement and the response velocity, respectively. The lead plug placed within the LRB is taking the damping characteristics identical to a lead damper.

When designing the seismic isolation system, a combination of bearings and dampers would be one of significant issues to be examined. When we use the combination of rubber bearings and oil dampers, (1) vertical loads of reactor building are supported by rubber bearings; (2) lateral forces are carried by rubber bearings when seismic action and/or strong wind is applied to the reactor building; and (3) oscillating energies are dissipated by oil dampers produced during seismic action and/or strong wind. When we use the LRB bearings exclusively, an identical discussion can be extended. The lead plug positioned within the LRB takes an energy dissipating function of elasto-plastic hysteretic damper. Within the study, for the reasons that (1) the seismic isolation system should be simple; and (2) although not combustible, it will not be favorable to place a volume of viscous oil made of high-molecular compound, we will accept the LRB bearings for the seismic isolation system examined herein.

At the beginning of the preliminary design of a seismic isolation system, we have evaluated the number of LRB units required for the reactor buildings established within the study. The essential condition for the evaluation is that the stress of rubber bearings produced by the vertical dead and live loads of the reactor building would be around 5 N/mm^2, yielding the rubber bearing system kept stable. The actual vertical stress on the rubber bearings of the world's first seismic isolated nuclear reactor building at Cruas-Meysse, France is reported to be 7.5 N/mm^2 on an average [10].

When we employ the LRB bearings, of which diameters are 1600, 1400 and 1200 mm, the resulting number of bearing units required are given for the modeled PWR and BWR reactor buildings in Table 1. Note that the

Table 1. The Number of LRB Bearings Evaluated for the PWR and BWR on the Prescribed Design Basis

Diameter of Bearing	PWR Building	BWR Building	
		Single-RB Model	RB and TB Coupled-Model on Common Mat
1,200	480	570	1,500
1,400	360	420	1,200
1,600	270	320	860
1,800	220	250	680

RB: Reactor building
TB: Turbine building

cross-sectional area of the bearings has been approximately calculated. Based upon the following judgments, we have reached the tentative decision to use the LRBs of 1600 mm in diameter:

(a) When we use bearings of which diameters are 1,400 mm or 1,200 mm, which are widely accepted in the commercial market, the number of bearing units was excessively large and not able to be arranged within the limited space prepared for seismic isolation devices; and

(b) When we use the bearings of 1,800 mm or greater in diameter, the number of bearing units became less, favorable for bearing arrangement within the isolation system. Since, however, the large-scaled bearings have not been widely provided in the market and mechanical and structural properties of those large-scale bearings have not yet been clearly identified, the application of the large-scaled bearing units shall remain as a possible choice in the next research phase.

4. FEASIBLITY STUDY AND DISCUSSION ON SEISMIC DESIGN OF NUCLEAR REACTOR BUILDIGNS WITH APPLICATION OF SEISMIC ISOLATION SYSTEM

4.1 Design Criteria Prescribed for the Feasibility Study

Design criteria specified in this feasibility study are tabulated in Table 2.

(1) The deformation produced for the bearings during the prescribed design earthquake ground motions shall remain in the range within which the LRB bearings are stable against the vertical loads;

(2) The displacement produced for the isolation system during the design seismic action shall be less than or equal to 400 mm for the seismic design of umbilicals crossing over the interface between the isolated and non-isolated buildings such as the main steam piping for a BWR building, the piping system for refueling water storage pit for a PWR building.

(3) The response acceleration produced for the seismic isolated building shall be less than or equal to 0.3G. Making the response acceleration not greater than 0.3G, a standardization of nuclear power facilities can be performed which can yield a higher reliability and cost effectiveness for design and construction of a nuclear power plant.

4.2 Design Earthquake Ground Motion

The earthquake ground motions described in the following are employed for design and for response analysis to verify the seismic design carried out. Identical design earthquake ground motions for both PWR and BWR buildings have been evaluated, not depending upon the site location of nuclear power plant facilities in Japan. Figure 7 shows the design earthquake ground motion specified in the study expressed by a form of response spectrum diagram with fraction of critical damping of 0.05. Figure 7 illustrates the spectrum on the horizontal component of ground motion.

The design earthquake ground motion defined herein can be employed for the nuclear power plant facilities in

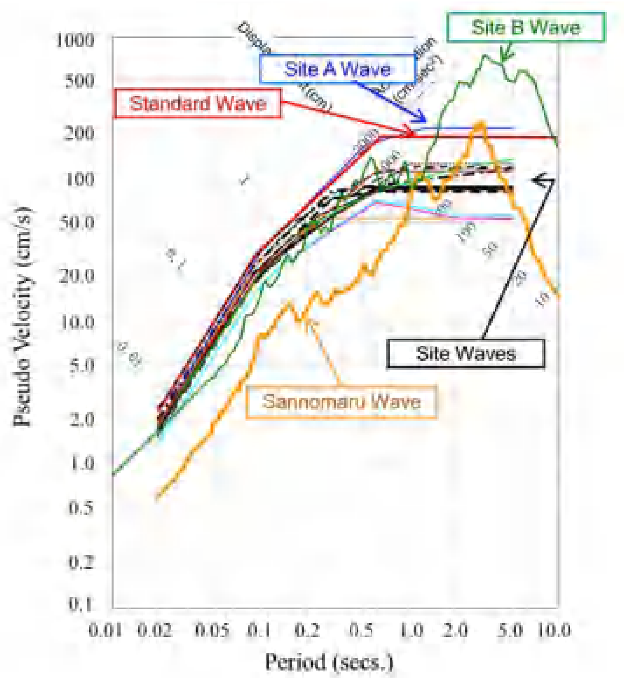


Fig. 7. Design earthquake ground motion utilized in the seismic design of nuclear power plant facilities with application of seismic isolation system and the verification of appropriateness of design through dynamic response analyses. Spectral diagrams are obtained with a fraction of critical damping of 0.05.

Table 2. Fundamental Design Criteria Considered within the Feasibility Study

Isolating LRB bearing	Shear Deformation	Less than δe/1.5
	Lateral Displacement	Less than 40 cm
Isolated Reactor Building	Response Acceleration	Less than 300 cm/s^2

* Deformation de denotes the elastic limit deformation of isolating bearings.

Japan, except the facilities on Site-A and Site-B which will have specific regional conditions where high and intense seismicity activities should be considered. The so-named "standard wave" will be prepared as standard design for facilities with application of seismic isolation systems. Within Fig. 7, an earthquake ground motion named "Sannomaru Wave" is illustrated. The "Sannomaru Wave" is one of the synthetic design earthquake motions proposed in Japan for buildings of which fundamental period is given greater than 2.0 seconds. The "Sannomaru Wave" is used as one of reference earthquake motions for high-rise buildings and/or seismic isolated buildings.

The standard wave reveals the maximum response acceleration of 800 cm/s^2 (i.e., 800 gal) for a stiff structure, that of 2,000 cm/s^2 for structures whose fundamental periods fall in the range of 0.10 secs. to 0.60 secs. and the maximum response velocity of 200 cm/s (i.e., 200 kine) for those whose fundamental periods are greater than 0.60 secs. A set of three synthetic "standard wave" ground motions are generated, named as SsH1, SsH2 and SsH3, respectively, with variation of phase properties defined when generating synthetic motions. Another set of thee vertical components, hereinafter SsV1, SsV2 and SsV3, are produced, modifying the spectral amplitudes to be two-thirds determined for those of horizontal components. A set of time traces of three horizontal components of motion, SsH1, SsH2 and SsH3, are illustrated in Fig. 8. The "standard wave" defined herein will cover the so-defined design basis earthquake ground motion, Ss, for nuclear power plant facilities in Japan.

4.3 Design of Seismic Isolation System

The fundamental specifications for the LRB bearings utilized for seismic isolation system are summarized in Table 3 and Fig. 9, respectively. Lead rubber bearings of which diameter is 1,600 in mm are employed for both PWR and BWR reactor buildings. The dimension of the bearings are, as previously discussed, as large as possible to reduce the number of bearings required while not excessively large from a viewpoint of production. The diameter of ϕ1600 is the largest available in the market in Japan to meet the requirement within our study.

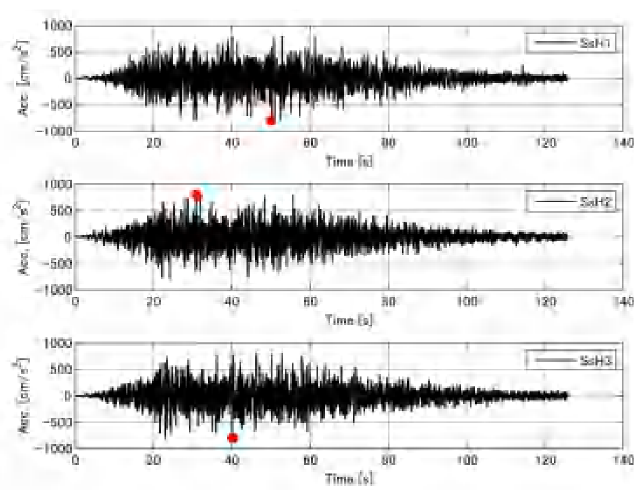


Fig. 8. Time trace of acceleration of the synthetic "standard waves." Horizontal components of SsH1, SsH2 and SsH3, respectively. The solid circles within the figures indicate the peak acceleration on the standard waves.

Table 3. Fundamental Structural Properties of LRB Bearings

Diameter	ϕ = 1600 mm (Maximun available in the market in Japan)
Rubber Material	G4 (Shear Modulus: 4N/mm^2)
Primary Period T_1	$T_1 = T_2 / \sqrt{K_2 / K_1} \cong T_2 / \sqrt{13}$
Isolator Period T_2	0.2-0.4 secs. < T2 < 4.0-5.0 secs.
Yielding Strength β (Shear Coefficient)	0.05 or greater
Dominant Frequency in Vertical Direction	Around 10 to 20 in Hz

* Ratio K_2/K_1 indicates the stiffness ratio given by (Primary Stiffness/Secondary Stiffness).

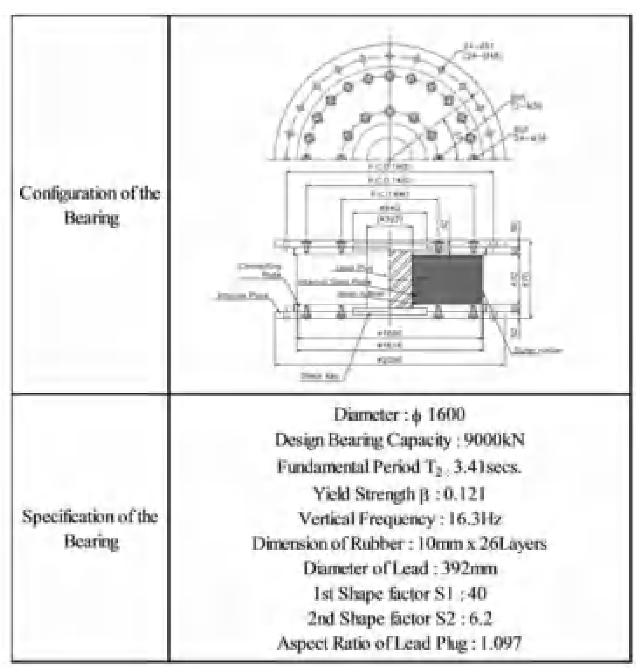


Fig. 9. Fundamental configuration and specification of lead rubber bearings (LRB) for the seismic isolation system examined herein.

Table 4. The Number of LRB Bearings Used within Feasibility Study on Seismic Design

LRB Bearing (ϕ: 1600)	PWR Building	BWR Building	
		Single-RB Model	RB and TB Coupled-Model on Common Mat
Shear Modulus	G4	G4 or G6	
Number of Units	310	360	960

RB: Reactor building
TB: Turbine building

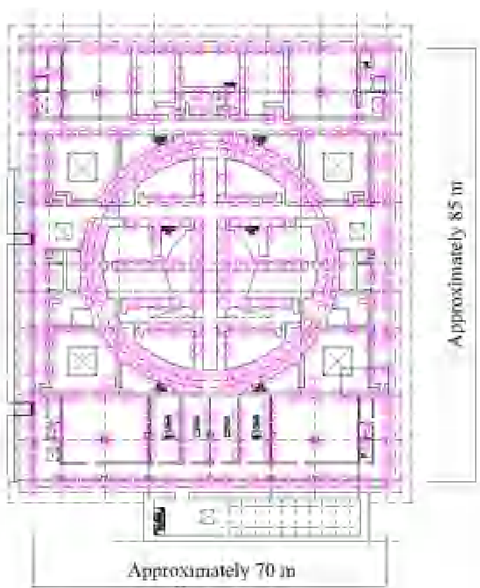


Fig. 10. Arrangement of LRB bearing units at the seismic isolating layer for a PWR reactor building.

With detailed examination considering the net cross-sectional area of the rubber bearings, the number of bearings required is re-evaluated. Table 4 summarizes the number of bearing units, and Figs. 10 and 11 illustrate images of the arrangement of bearings at the seismic isolation story, for a PWR building and for a RB and TB coupled BWR building on a common base mat, respectively.

4.4 Load-Deflection Characteristics of Lead Rubber Bearing

The load-deflection characteristics of a LRB bearing can be evaluated separately for laminated sheets of rubber and a lead plug. The load-deflection of a bearing can be found with the combination of those obtained for rubber and lead plug obtained individually. Load-deflection curves obtained for the rubber sheet and the lead plug are illustrated in Figs. 12 (a) and (b), respectively. Within Fig. 12, the load-deflection characteristics for natural rubber are briefly summarized as follows:

(1) The load-deflection characteristics are shown linear in the range when shear deflection γ remains less than 250% ;
(2) With shear deflection increased, the instantaneous stiffness is increased showing inelastic load-deflection characteristics;
(3) When the shear deflection reaches around 450%, the rubber reaches an ultimate condition; and
(4) The load-deflection characteristics of the lead plug can be well expressed by a simple elasto-plastic bi-linear curve shown in Fig. 12 (b).

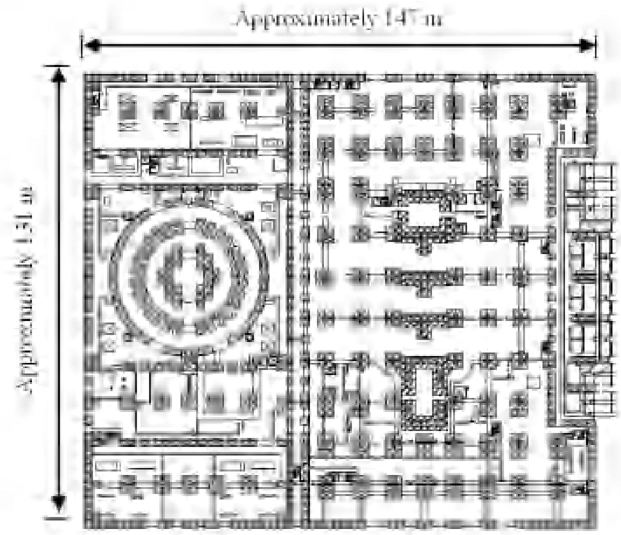
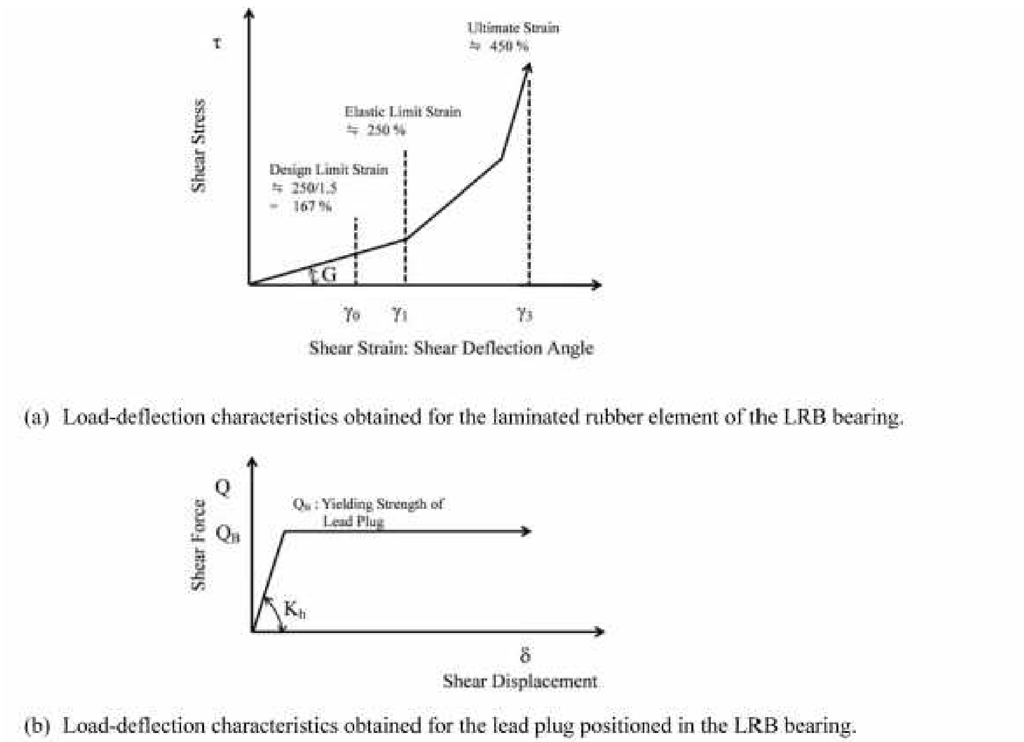


Fig. 11. Arrangement of LRB bearing units at the seismic isolating layer for a BWR reactor building, in which the reactor building and turbine building coupled are positioned on the common mat.

Design criteria specified in this feasibility study indicates that the deformation produced for the bearings during the specified design seismic action shall remain in the range within which the LRB bearings are stable against the vertical loads. We prescribe a safety factor of 1.5 to determine the design limit for the LRB bearings, being $\gamma = 250/1.5 = 166$ (%) within linear behavior range. The resultant load-deflection characteristics of LRB bearing is expressed by the so-called bi-linear model, representing stiffness deterioration caused by the perfect yielding of the lead plug positioned within the bearing. The hysteresis rule can be established in an identically similar manner to that for the load-deflection characteristics.

To determine the LRB specifications suitable for both PWR and BWR buildings, a parametric study is conducted using a simple oscillating model of a single-degree-of-freedom system as shown in Fig. 13. Within the study, the yield seismic intensity β and the second-order period



(a) Load-deflection characteristics obtained for the laminated rubber element of the LRB bearing.

(b) Load-deflection characteristics obtained for the lead plug positioned in the LRB bearing.

Fig. 12. Load-deflection characteristics obtained for the LRB bearing.

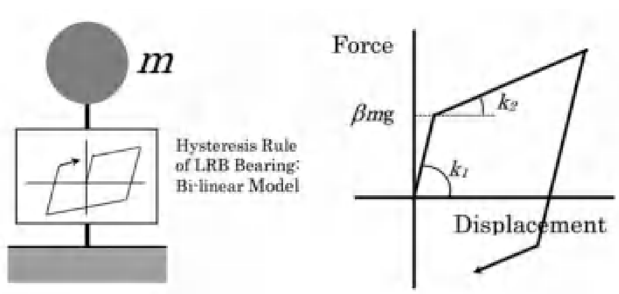


Fig. 13. Analytical model of a single-degree-of-freedom oscillating system and the load-deflection characteristics determined for LRB bearings. Letters m, β, k_1 and k_2 represent mass of the reactor building, yielding strength of LRB bearing, primary stiffness of LRB bearing and secondary stiffness of LRB bearing, respectively, and g denotes the acceleration of gravity.

of oscillation T_2 are taken for parameters in analysis. The yield seismic intensity β is given by the lateral capacity of lead plug normalized by the total weight of the building. The second-order period T_2 is determined by the secondary stiffness K_2 in Fig. 13. Note that the stiffness K_2 in Fig. 13 is essentially given by the stiffness of laminated rubber described in Fig. 12. Through a series of analyses with trials and errors, we reach a decision on the specifications of the LRB bearings utilized in the study, as summarized in Fig. 9.

4.5 Seismic Response Analyses Verifying the Appropriateness of Seismic Design

4.5.1 General

The seismic design carried out within the feasibility study applying a seismic isolation system to nuclear reactor buildings in a high seismic activity zone is examined by a series of dynamic response analyses. Through the analyses using the design earthquake ground motions, we discuss the appropriateness and feasibility of the application of seismic isolation systems to nuclear reactor buildings in Japan. Two types of response analysis have been carried out, one of which is the so-called lumped mass-spring-dashpot stick model, hereinafter LMSM, and the other the finite element model (FEM) in detail.

Within the analyses, we perform additional studies to find out what conditions could be realized at an ultimate stage of the system for the seismic isolated reactor buildings. In the analytical studies, we multiply simply the amplitudes of design earthquake ground motion by the prescribed scaling factors. Through an inelastic response analysis, making magnitude of the earthquake ground motions great by the scaling factors, we undertake to find the so-defined load factor with which the seismic isolation system is found reaching the prescribed ultimate conditions. Note that within the additional study herein, the amplitudes of horizontal component are multiplied by scaling factors, while the amplitudes of vertical components shall remain unchanged.

The criteria for design-basis earthquake ground motions in the dynamic response analysis are summarized in Table 5. Within the table, criteria at ultimate states during the beyond design basis seismic action are tabulated next to the column summarizing those for design-basis seismic action.

4.5.2 Seismic Responses of PWR Building Using a Lumped Mass-Spring-Dashpot Stick Model

The analytical model utilized within the study is illustrated in Fig. 14, in which the reactor building is represented by three sticks of a mass-spring-dashpot oscillating system describing the inner concrete structure (I/C), the concrete vessel structure (CV) and the reactor enclosure building (RE/B), respectively. The seismic isolation system positioned under the reactor building is modeled by the spring elements both in the horizontal and vertical directions. The soil-interaction effect on the local subsoil is expressed by the sway-rocking model with a set of three spring elements describing sway, heaving and rocking motions. Both the load-deflection curve and the inelastic hysteresis rule for the LRB bearings are established and modified based on the empirical research studies carried out in this study.

The results of the seismic response analysis are shown in Figs. 15 and 16 for the seismic isolation system of LRB bearings and for the isolated reactor building, respectively. Three cases of response analyses are conducted utilizing three set of input earthquake ground motions with combination of (SsH1 and SsV1), (SsH2 and SsV2) and (SsH3 and SsV3.) Within the figures, the results obtained from additional analyses evaluating possible ultimate conditions are included, in which the scale factors of 1.5, 2.0, 2.5 and 3.0 are taken to amplify the intensity of design earthquake ground motions. The results of the response analyses can be itemized as in the following:

· During the so-defined “standard waves,” the responses of both the isolating LRB bearings and the isolated reactor structure can fulfill the prescribed requirement tabulated in Table 5.

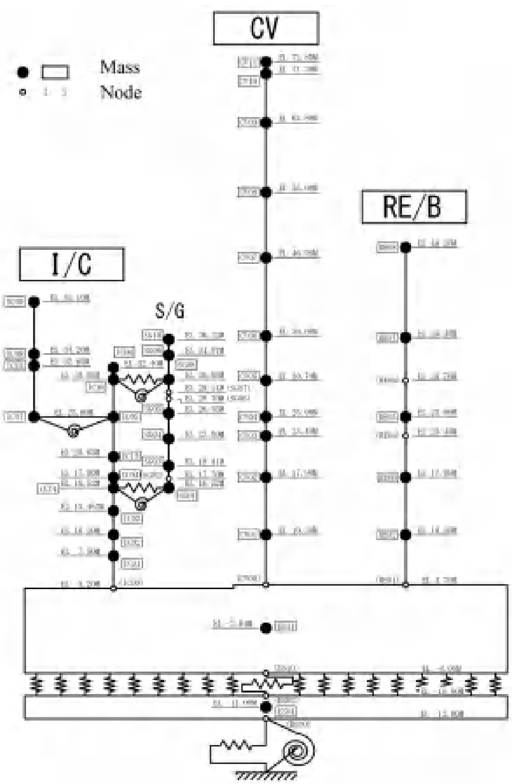


Fig. 14. Lumped mass-spring-dashpot stick model utilized in response analyses for the PWR building within which three sticks illustrate CV, I/C and RE/B structures, respectively.

Table 5. The Criteria for the Response Analysis Against Design-basis Earthquake Ground Motions and Against Beyond Design-basis Earthquake Ground Motions

		Seismic Criteria	
		Design Basis Ground Motion	Beyond Design Basis Ground Motion
Reactor Building	Shear Strain in Wall Element	Elastic, with which not producing significant stiffness deterioration.	Less than the value of $6.0x10^{-3}$.*1)
Lead Rubber Bearing	Shear Strain in Bearing	Shear strain less than 250%/ϕ, where ϕ is taken 1.5.	Shear strain less than 450%.
	Tensile Stress Produced for Bearing	Tensile stress less than 1.0 N/mm^2.	-
	Tensile Strain Produced for Bearing	-	Tensile strain less than 300%.

*1) The shear walls of reactor buildings studied herein are constructed by the SC (Steel Plate Reinforced Concrete) [11]. When the conventional RC (Reinforced Concrete) shear walls are employed critical shear strain should be $4.0x10^{-3}$.

· The responses obtained on shear deflection of the LRB bearings during a set of three standard waves fall in the value less than the prescribed figure of 166% with additional safety factors included.
· The normal stress produced on the bearings can satisfy the condition required in both compressive and tensile directions.
· The responses of isolated reactor buildings fulfill the requirement specified.
· The finding obtained above indicates the evidence that the seismic design on nuclear reactor buildings utilizing a seismic isolation system is possible and practicable.
· In the additional analyses multiplying the amplitudes of motion by load factors to realize beyond the design basis condition, the shear strain of the LRB bearings first reaches the ultimate strain of 450% yielding probable tear in laminated rubber. The load factor is found around 2.0 to 2.5. The responses of reactor building remain less than the prescribed critical figures. The results indicate speculation that the critical element of the seismic isolated reactor building studied herein is the seismic isolation system of LRB bearings.

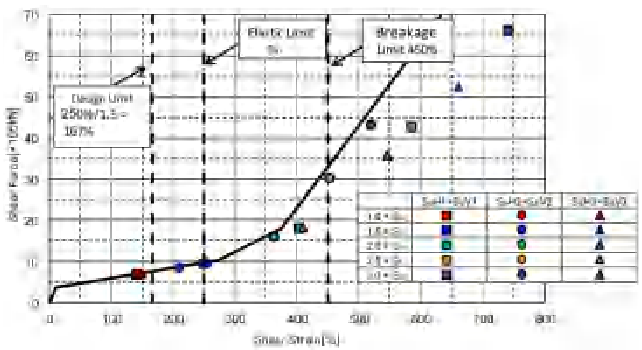


Fig. 15. Responses of the isolating LRB bearing when subjected to a set of standard waves. To evaluate the ultimate conditions of the PWR building with application of seismic isolation system, response analyses are carried using the standard waves, amplitudes of which are multiplied by the load factors of 1.5, 2.0, 2.5 and 3.0. Note that the critical shear strain for the bearings is 167% (=250%/1.5) for the design basis seismic action, and is 450% for the beyond design basis seismic action.

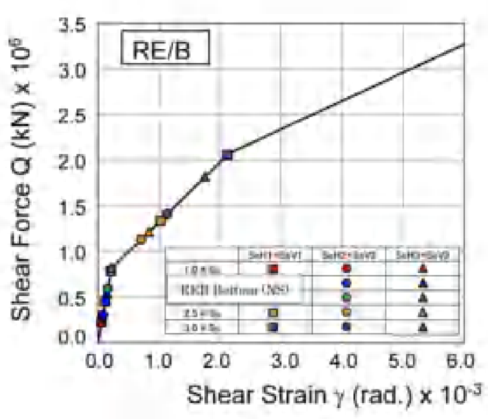


Fig. 16. Responses of the isolated PWR reactor building when subjected to a set of standard waves. The shear force responses obtained at the bottom of RE/B building are indicated. To evaluate the ultimate conditions of the PWR building with application of seismic isolation system, response analyses are carried using the standard waves, amplitudes of which are multiplied by the load factors of 1.5, 2.0, 2.5 and 3.0. Note that the shear deflection angle for shear walls γ is critical with 6.0×10^{-3} for a steel plate reinforced concrete wall [11] and 4.0×10^{-3} for a reinforced concrete wall [6] for the beyond design basis seismic action.

4.5.3 Seismic Responses of BWR Building Using a Lumped Mass-Spring-Dashpot Stick Model

Two cases of isolation system are examined. One is that the reactor building exclusively is positioned on the isolating system, and the other is that both the reactor building and the turbine building are coupled positioned on the common isolating system. Figure 17 shows the analytical model used for the coupled isolated building on a common isolating system.

Analytical conditions are identical to those employed for the PWR reactor buildings. The results of seismic responses obtained for the case of single reactor building isolated are similar to those obtained for the PWR reactor building previously described. The results of seismic responses for the case of both the reactor and turbine buildings isolated on a common isolating system is shown in Figs. 18 and 19 for the isolated structure and for the bearing system, respectively. The results of the response analyses can be itemized identically to those obtained for the PWR reactor building previously summarized. Major findings are itemized as follows:

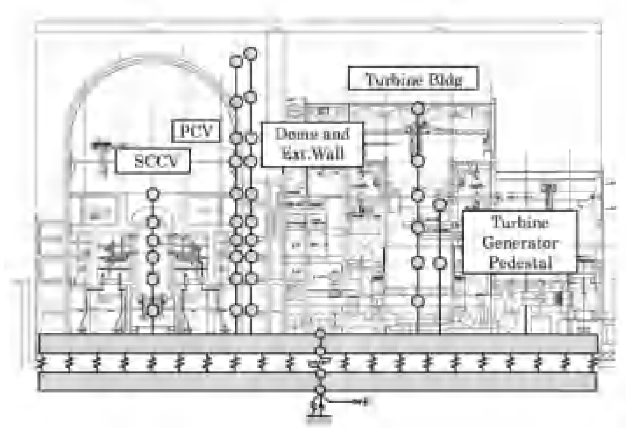


Fig. 17. Lumped mass-spring-dashpot stick model utilized in response analyses for the BWR building within which five sticks represent SCCV, PCV, Dome and Exterior Wall, Turbine Building and Turbine Generator Pedestal structures, respectively.

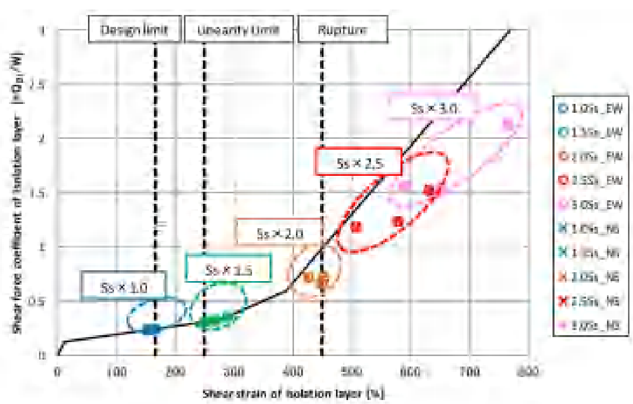


Fig. 18. Responses of the isolating LRB bearing when subjected to a set of standard waves. To evaluate the ultimate conditions of the BWR building with application of seismic isolation system, response analyses are carried using the standard waves, amplitudes of which are multiplied by the load factors of 1.5, 2.0, 2.5 and 3.0. Note that the critical shear strain for the bearings is 167% (=250%/1.5) for the design basis seismic action, and is 450% for the beyond design basis seismic action.

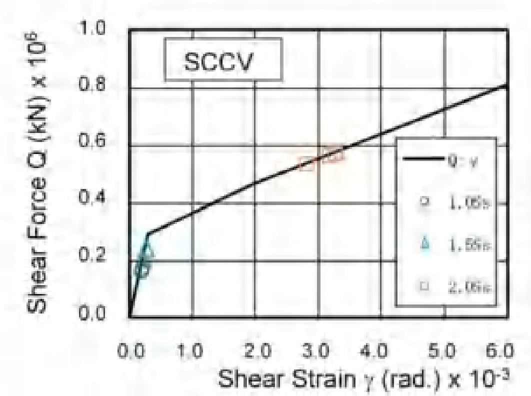


Fig. 19. Responses of the isolated BWR reactor building when subjected to a set of standard waves. The shear force responses obtained at the bottom of SCCV structure are indicated. To evaluate the ultimate conditions of the BWR building with application of seismic isolation system, response analyses are carried using the standard waves, amplitudes of which are multiplied by the load factors of 1.5 and 2.0. Note that the shear deflection angle for shear walls γ is critical with 6.0×10^{-3} for a steel plate reinforced concrete wall [11] and 4.0×10^{-3} for a reinforced concrete wall [6] for the beyond design basis seismic action.

- During the so-defined “standard waves,” the responses of both the isolating LRB bearings and the isolated reactor structure can fulfill the prescribed requirement tabulated in Table 5.
- The finding obtained herein indicates the evidence that the seismic design on nuclear reactor buildings utilizing a seismic isolation system is possible and practicable.
- In the analyses to realize beyond the design basis condition, the shear strain of the LRB bearings first reaches the critical state, as well. The critical level of seismic action is found to be around twice as large as that on the design basis.

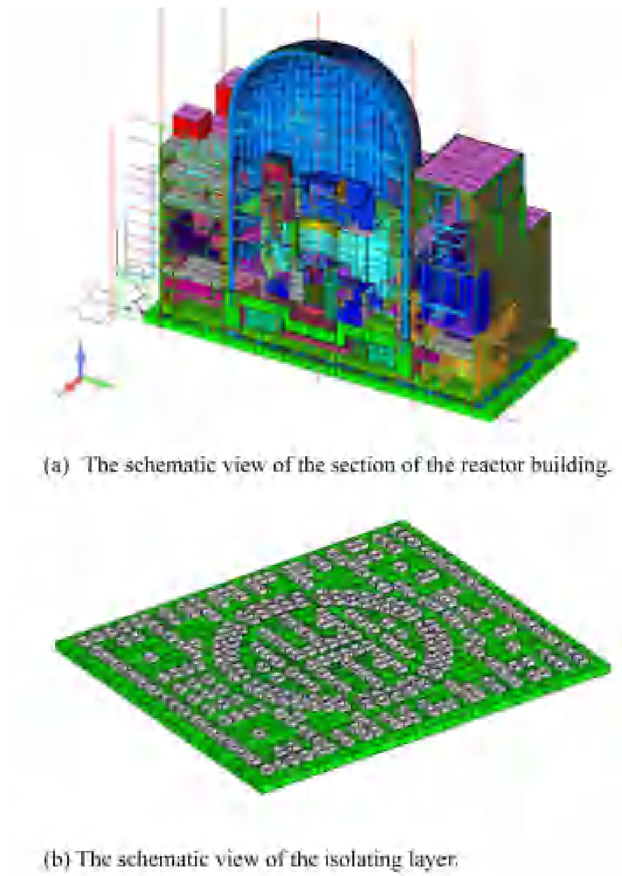


Fig. 20. Three-dimensional finite element model utilized in the sophisticated response analyses for the PWR building.

4.5.4 Evaluation of Seismic Responses Using Three-Dimensional Finite Element Modeling for the PWR Building

For the seismic isolated PWR building system, establishing a three-dimensional (3D) finite element model, we carry out a seismic response analysis to evaluate the responses of the system in detail. The results from the 3D finite element analysis are extended to be utilized to examine the appropriateness of the simple mass-spring-dashpot stick model employed in dynamic response analyses to evaluate the general seismic responses. Figures 20 (a) and (b) illustrate the schematic view of the reactor building and isolation system, respectively.

Through the analysis, we can find, for example, the normal stresses produced for the bearings can be sepa-

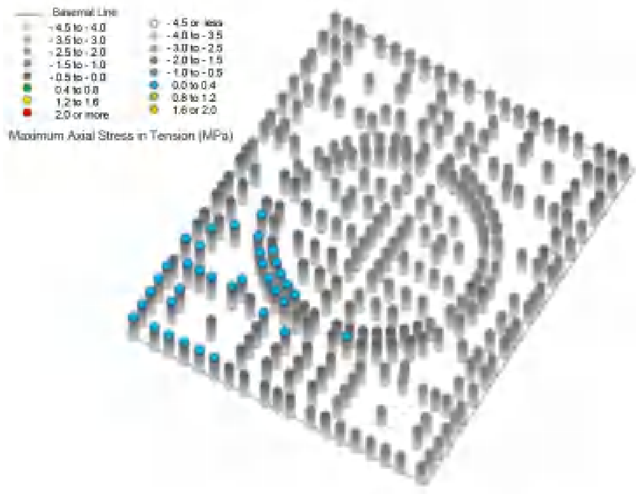


Fig. 21. Maximum tensile and compressive stresses produced for the LRB bearings of the PWR building obtained when subjected to both the horizontal and vertical components of ground motion simultaneously. The level of seismic intensity is the design basis earthquake motion, and the horizontal component is applied in the direction along the diagonal axis of building.

rately evaluated. One of the analytical results is shown in Fig. 21 illustrating the normal stress determined for bearings separately, when seismic excitation is applied along both the horizontal and vertical directions simultaneously. Through the observation upon the results, we can find out issues probably included in the seismic design fundamentals prescribed such as that on which bearing a large amount of axial force fluctuation will be produced.

The evaluation of seismic responses using the 3D finite element modeling for the BWR building has not been carried out within the study.

4.6 Other Studies Making the Seismic Design Improved and Advanced

In this study, other studies have been conducted making the seismic design procedure improved and advanced. The additional studies examined and discussed in this study can be summarized as in the following. General reports on these studies can be found in the references [1, 2].

1) Evaluation of thermal effects on LRB bearings during the long-period and long-duration of seismic excitation;
2) A proposal of the advanced design for LRB bearings which are subjected to tensile axial force when produced by the overturning moment given during an intense seismic action;
3) Discussion on the placement of hard stop mechanisms within the seismic isolation system; and others.

5. CONCLUDING REMARKS

Through a feasibility study on the application of seismic isolation systems for nuclear power plant facilities, we reach the conclusion that a seismic design for seismic isolated nuclear reactor buildings is possible in a region with high seismic activities. With application of a seismic isolation system, nuclear reactor buildings are made stable and safe with a safety margin corresponding to the condition that the level of seismic excitation is twice or more as large as that with which the reactor building falls in the design condition determined for conventional non-isolated reactor buildings.

The analytical results obtained in this study can be summarized as follows.

(1) We discuss the design criteria required both for isolating and isolated structures.
(2) We establish the standard design earthquake motion, the standard waves in the study, for the nuclear power plant facilities in Japan with the purpose of structural and system standardization.
(3) We determine technical specifications for a seismic isolation system. In the study, LRB bearings are employed for the seismic isolation system. Geometrical, mechanical and structural specification is determined to meet the prescribed design criteria.
(4) Through a series of response analyses using the standard design earthquake motions, we verify the appropriateness of the seismic design proposed. We find the evidence that the seismic isolated reactor buildings studied herein fulfill the specified design criteria during the design-basis earthquake motions. Responses of both seismic isolated reactor buildings and seismic isolating LRB bearings remain stable less than the so-defined elastic deflection and the prescribed deformation given by two-thirds of elastic deformation, respectively.
(5) Simply modifying the amplitudes of design ground motion by a so-defined load factor, through inelastic response analyses, we reveal a probable ultimate stage of the reactor buildings placed on the isolation system for the purpose of evaluating the responses against the beyond design basis seismic excitation. We reach the finding that the seismic isolation system first yields the specified ultimate criteria when the intensity levels of seismic motions are taken around 2.0 to 2.5 times as large as that of the design seismic motion. When the isolating system is yielded critical, the isolated reactor buildings are stable, keeping the responses less than the specified criteria.

Within the study, the acceleration responses obtained for the isolated reactor buildings are given less than 300 cm/s^2 for the lower levels of a building, while those obtained for higher levels of a building are greater than the specified criteria, i.e., 300 cm/s^2 in acceleration. Since the peak ground acceleration of the design-basis earthquake motion is around 800 cm/s^2, we cannot find out the set of design parameters for the isolating system. We need further studies to mitigate the responses in acceleration obtained for the isolated reactor building. We need a sophisticated examination of the combination of stiffness and strength in lateral, and stiffness in vertical and other specification parameters for the isolating system. When we modify the lateral stiffness of the isolating system, the acceleration responses of the isolated building is yielded less satisfying the design condition, while the response displacement at the interface between the isolated and non-isolated building is yielded greater not fulfilling the design conditions for umbilicals such as those of piping systems. Within the design procedures, we can find complicated and cross-tangled correlations among design parameters on the trade-off basis.

6. ACKNOWLEDGMENTS

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In a series of response analyses, we use the strong motion records on the K-NET network, operated by the National Research Institute for Earth Science and Disaster Prevention (NIED).

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