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DEVELOPMENT OF EVALUATION METHOD FOR SEISMIC ISOLATION SYSTEMS OF NUCLEAR POWER FACILITIES
- PROPOSAL FOR A BASE-ISOLATED DESIGN METHODOLOGY TO INSTALL NPP'S FACILITIES -

Hiroshi Shimizu[1], Kotoyo Mizuno[2], Masakazu Jimbo[3], Shinji Kosugi[4], Tsutomu Hirotani[5], Takemi Norimono[6] and Yasuo Ookouchi[7]

[1] Research Manager, Structure No.1 Lab., Strength Research Dept., Research & Innovation Center, Mitsubishi Heavy Industries, Ltd., Japan
[2] Staff, Structure No.1 Lab., Strength Research Dept., Research & Innovation Center, Mitsubishi Heavy Industries, Ltd., Japan
[3] Chief Specialist, Plant Design & Engineering Dept., Isogo Nuclear Engineering Center, Toshiba Corporation Power Systems Company, Japan
[4] Researcher, Aseismic Engineering Sec., Nuclear Plant Engineering Dept., Hitachi-GE Nuclear Energy, Ltd, Japan
[5] Manager, Technology Dept., Nuclear Projects Div., Shimizu Corporation, Japan
[6] Senior Manager, Power Facilities, Engineering Dept., Takenaka Corporation, Japan
[7] Assistant Manager, Nuclear Power Plant Architectural Engineering Section, Civle & Architectural Dept., Chubu Electric Power Co. Inc., Japan

ABSTRACT

Since the 1995 Hyogo-ken Nanbu (Kobe) Earthquake, base isolation systems have been installed in many buildings in Japan. In the 2011 off the Pacific coast of Tohoku Earthquake, it could be confirmed that many base-isolated buildings had enough seismic resistance and succeeded in functional maintenance against the huge earthquake. Nuclear power plants in Japan have partly installed base-isolation systems to maintain the function of the nuclear facilities against a huge earthquake; however, a base-isolated reactor building has never been seen in Japan.

In order to maintain the integrity of reactor buildings against huge earthquakes in the future, base isolation systems are effective approaches. Therefore, under the auspices of the Ministry of Economy, Trade and Industry of Japan (METI), domestic power companies and reactor venders have been engaged in promoting a development project of seismic isolation systems for NPPs through 2008 to 2015.

This paper proposes a base isolation design methodology to install NPP's facilities, based on the results in the characteristic tests of full-scale isolators that adopted the Lead Rubber Bearing (LRB), the demonstration of a base-isolation pedestal, and the seismic response analysis by the three-dimensional finite element method (3D FEM) and a multi-degree-of-freedom (MDOF) stick model, all of which have been implemented in this development project.

INTRODUCTION

Not many seismic isolated buildings are used for domestic NPP facilities. However, application of the seismic isolation technology to important anti-seismic buildings is important as one of fundamental technologies to enhance earthquake-proof safety and realize standard design that doesn't depend of conditions of the site.

In order to maintain the integrity of reactor buildings against huge earthquakes expected to occur in the future, base isolation systems are effective approaches. Therefore, as part of this study, domestic power companies and reactor venders have been promoting a development project of seismic isolation systems for NPP facilities through 2008 to 2015 under the auspices of METI.

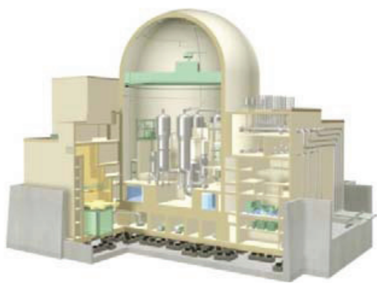
This project has constructed a base isolation design methodology to install NPP facilities by leveraging a

design methodology sophisticated by seismic response analyses and various types of characteristic tests with isolators. Especially, this project adopted a full-scale breaking test using LRB with a diameter φ of 1600 mm, where a huge scale event was assumed for the first time in the world.
Based on the results obtained in this project, this paper describes earthquake design motion, fundamental design properties, modeling approaches of isolators, seismic response analysis, and evaluation of seismic integrity as part of the seismic isolation design methodology to be applied to NPP facilities.

OUTLINE OF SEISMIC ISOLATION DESIGN

Target facilities

Figure 1 shows schematic views of light-water reactor building into which base-isolation systems are adopted. There are two major types of light-water reactors in Japan: pressurized-water reactors (PWR) and boiling-water reactors (BWR). With a target of these types of nuclear reactor buildings, this paper discusses the seismic isolation design methodology to install NPP facilities. Just to make sure, depending on the design seismic response, it is necessary to take into consideration a scope of applying seismic isolation not only a reactor building but also common base isolation including a turbine building.


PWR plant

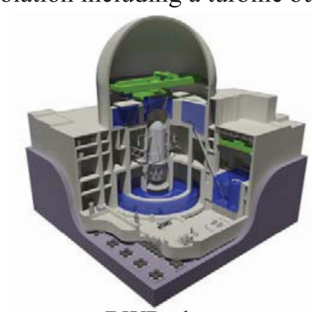

BWR plant

Figure 1. Schematic views of light-water reactor building

Seismic isolation design flow

Figure 2 shows a seismic isolation design flow to apply to NPP facilities. The seismic isolation design begins with overall planning and proceeds to implementation of basic design and engineering for each division of a plant, namely seismic isolation systems, buildings, and equipment/piping. Earthquake-proof safety should be evaluated through a seismic response analysis to be made after modeling each division based on results of these basic design and engineering tasks. Furthermore, by adding evaluation on external events other than earthquakes, safety of NPP facilities where base isolation systems are applied should be confirmed to complete seismic isolation design.
Next, in order to deal with events beyond postulated ones used in design, an earthquake probabilistic risk assessment(PRA) should be made. The earthquake hazard curves should be formulated and fragility indices should be set. Based on information from them, a seismic response analysis should be made to calculate fragility of each division. Safety of the seismic isolation plant should be evaluated through calculation of a core damage frequency using results of the fragility calculation.
Items marked with green were actually the verification tests carried out in this project, and results of these tests have been reported in 13th World Conference on Seismic Isolation, ASME PVP-2014 and other international conferences. Based on the results of these demonstrations/tests, design methods of the seismic isolation systems, buildings, and equipment/piping have been constructed. Among these design methods, this paper intends to organize and describes the seismic isolation design methodology targeting design items marked with yellow in Figure 2.

STUDY ON SEISMIC ISOLATION DESIGN

Based on results from this project, this section describes earthquake design motion, fundamental design properties, modeling approaches of isolators, seismic response analysis, and evaluation of seismic integrity as part of the seismic isolation design methodology to be applied to NPP facilities.

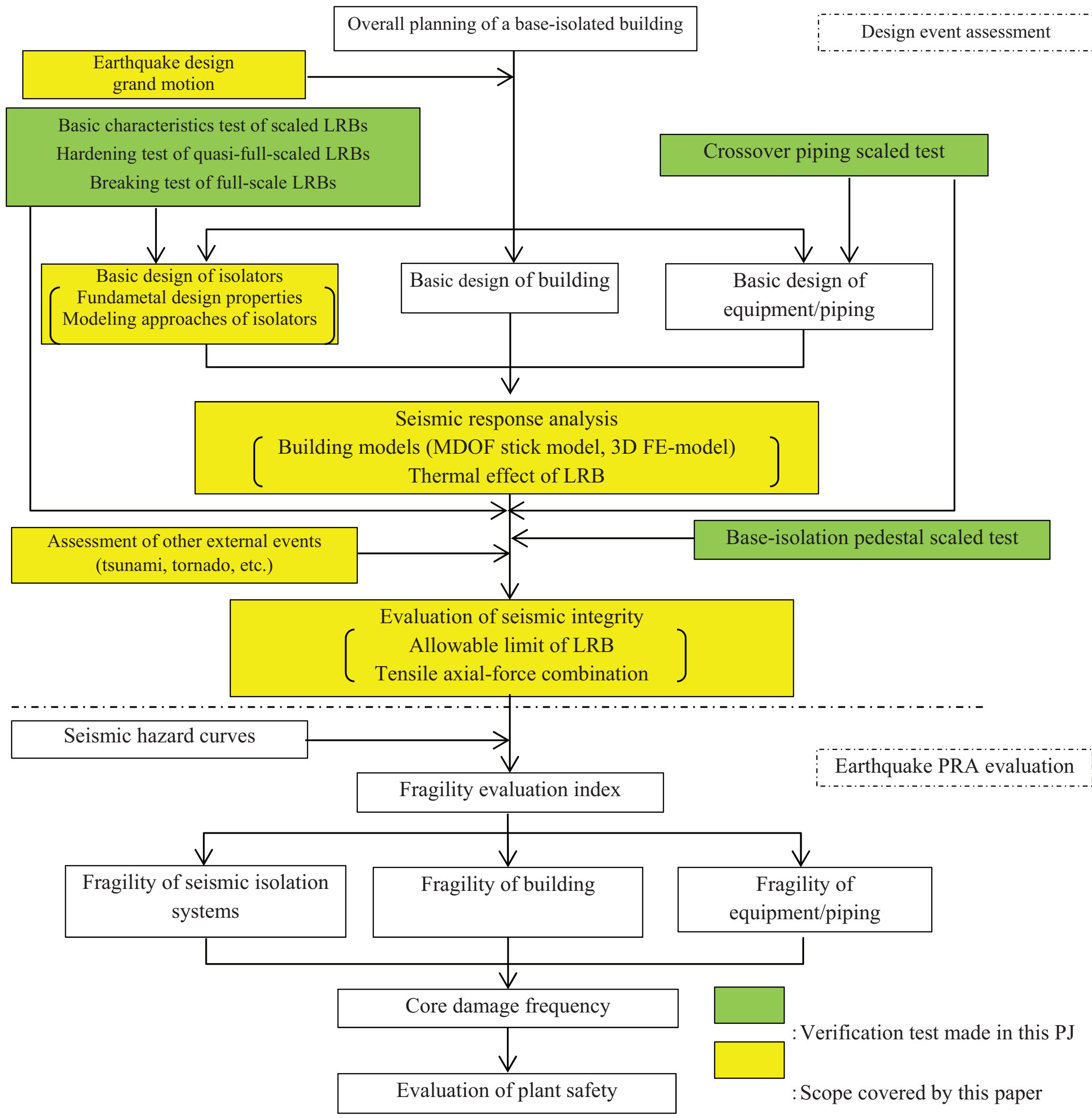


Figure 2. Seismic isolation design flow to NPP facilities

Earthquake design grand motions

As for earthquake motions to be used in seismic isolation design, it is necessary to adopt and set motions with a long cycle and relatively long duration, assuming that they will have an influence on the natural period in a range of 2 to 4 seconds that is dominant in earthquake response.

From this point of view, the design earthquake ground motion (called the standard wave) shown in Figure 3 was adopted for setting. Specifically, in setting up the standard wave, the response acceleration on the short cycle side was set at 800 Gal, and the pseudo velocity response spectrum (h = 0.05) on the long cycle side was set at 200cm/sec (kine). Then three standard waves, Ss-H1, Ss-H2, and Ss-H3, were designed as artificial seismic waves in the horizontal direction with different phases. The earthquake wave motion in the vertical direction was set so as to be 2/3 times the motion in the horizontal direction.

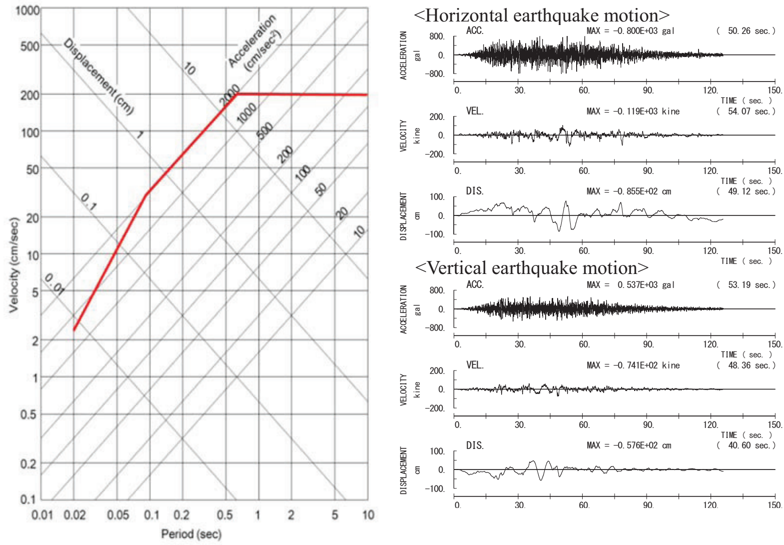


Figure 3. Target spectrum and time history waveforms of design earthquake ground motion

Fundamental design properties

(1) Basic features and response targets of seismic isolators

A horizontal two-dimensional base isolation system consisting of Lead Rubber Bearing (LRB) with the largest diameter that could be manufactured in Japan was chosen as our seismic isolation system, as shown in Figure 4, taking into account scales of assumed nuclear reactor facilities and supporting performance of the system.

When designing specifications of a seismic isolation system, it is necessary to decide a quake absorbing period in reference to the natural period of each piece of nuclear equipment. Accordingly**,** fundamental design properties of our isolators were specified as shown in Table 1, in accord with requirements for typical equipment. Response targets of the isolators were also set as indicated in Table 2.

Taking into account these requirements and assumed nuclear reactor facilities, LRB with a diameter φ of 1600 mm, was adopted for the isolators to be applied to a nuclear reactor building.

Table 1: Fundamentarl design properties of seismic isolators

Rubber diameter	φ1600 mm (Maximum available at the market in Japan)
Rubber type	G4 rubber, G6 rubber
The first cycle T1	$T1=T2/\sqrt{(K_1/K_H)}$ * G4 rubber: $(K_1/K_H) = 13$, G6 rubber: $(K_1/K_H) = 10$
Quake absorbing period T2	0.2 to 0.4 sec < T2 < 4.0 to 5.0 sec
Yield seismic intensity β	0.05 or more
Dominant vertical frequency	about 10 to 20 Hz

* K_1/K_H: the ratio between the first and the second rigidity of the seismic isolation system

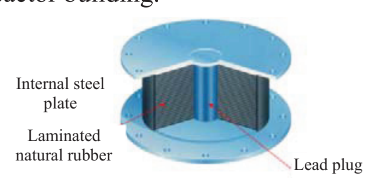


Figure 4. Schematic view of Lead Rubber Bearing (LRB)

Table 2: Response targets of our seismic isolation system

Relative displacement between buildings	40 cm or less
Building response acceleration	300 Gal or less
Design limit	1/1.5 of the linear limit

(2) Evaluation of crossover piping's relative displacement

In order to confirm adequacy of relative displacement set as a response target of the isolators, the crossover piping design was evaluated. The evaluation target was the steam piping running between a nuclear reactor building (R/B) with base isolation and a turbine building (T/B) without base isolation. As shown in Figure 5, the evaluation result of crossover piping design led to confirmation of design soundness even under an influence of relative displacement between the buildings.

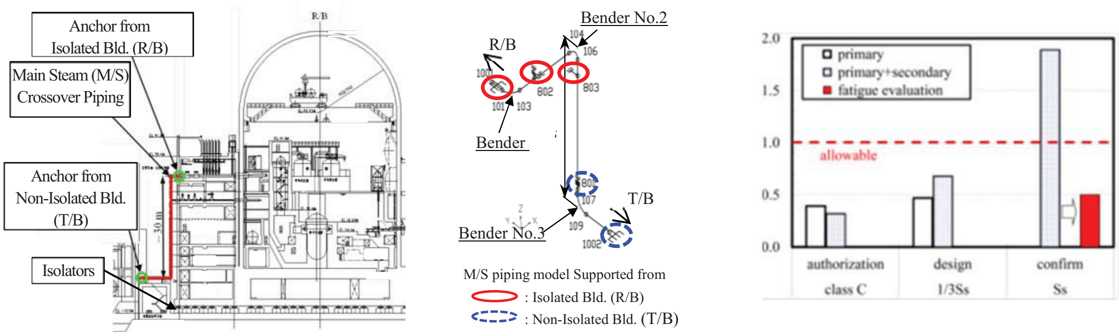


Figure 5. Evaluation of crossover piping (PWR plant)

Modeling approaches of the isolators

(1) Seismic isolator design

A seismic response analysis was made by the 1-degree-of-freedom (1-DOF) beam model with yield seismic intensity β and secondary frequency T2 as parameters, in order to make the specifications of the isolators optimal for a nuclear reactor building. And then, the specifications of the isolators to which G4 rubber was applied were formulated based on maximum response displacement and maximum response acceleration of the base isolated layer, as shown in Table 3. In addition, as the diameter of the lead plug became thick, specifically 392 mm accounting for about 25% of the laminated rubber's diameter, another isolators was designed where the lead plug was divided into four.

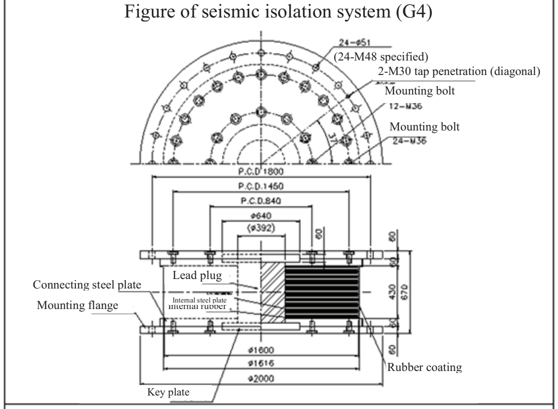
(2) Examination of seismic isolators variation

The stiffness and the yield load of the LRB undergo fluctuation due to variation in manufacture, ambient temperature, and aging. Study was made on the LRB that has been designed in Sub-section (1) about fluctuation range of the stiffness and yield load caused by such variety.

Table 4 shows fluctuation ranges caused by variation of the isolators. First, for the fluctuation caused by

Table 3: Seismic isolator specifications

Figure of seismic isolation system (G4)



Rubber diameter: ϕ1600	Rubber layer: 10 mm × 26 layers
Support load: 9000kN	Lead plug diameter: 392mm
Horizontal frequency T2 : 3.41 sec	Primary shape factor S1 : 40
Yield seismic intensity β: 0.121	Secondary shape factor S2 : 6.2
Vertical frequency: 16.3 Hz	Lead plug ratio: 1.097

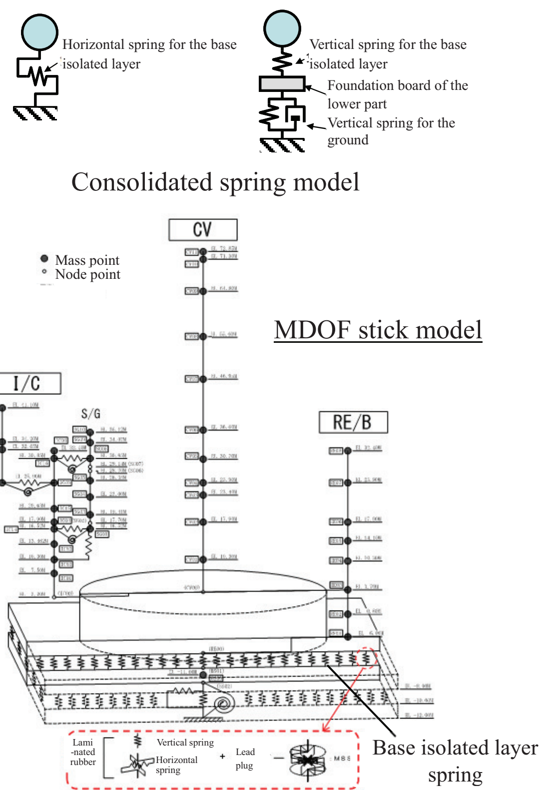
Table 4: Fluctuation due to variation of seismic isolators

Cause of variation	Horizontal direction				Vertical direction	
	Kh		Qd		Kv	
	Plus side	Minus side	Plus side	Minus side	Plus side	Minus side
Manufacture	+10%	-10%	+10%	-10%	+10%	-10%
Ambient temperature	+5%	-5%	+15%	-10%	—	—
Aging	+20%	—	+5%	—	+20%	—
Adopted value for total variation	+35%	-15%	+30%	-20%	+30%	-10%

manufacture was used by a laminated rubber manufacturer, was adopted. For the fluctuation by ambient temperature, a range of ± 10 ºC was set against the standard temperature of 15 ºC used in the design formula specified by a laminated rubber manufacturer. As for the aging-induced fluctuation, the change in stiffness corresponding to 80 years was adopted in characteristics of the laminated rubber.

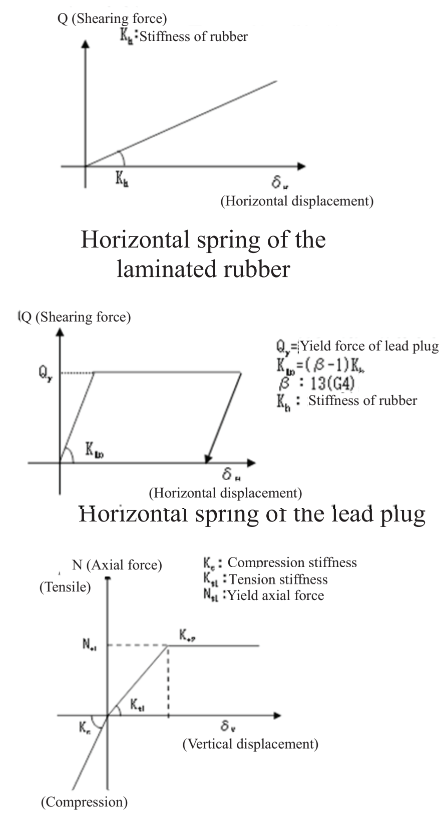
(3) Spring model of the seismic isolators
Candidate methods for modeling hysteretic behaviors of the entire seismic isolators (called the base isolated layer) arranged in a building are a modeling method of consolidating the layer into one spring, another modeling method of replacing the layer with two or more springs, and a multi-spring (MS) modeling method where multidirectional behaviors can be reproduced as shown in Figure 6.

(4) Hysteretic behaviors of the seismic isolators
Figure 7 shows hysteretic behaviors at the design phase. A seismic response analysis at the design level can be made by using a horizontal spring for modeling the laminated rubber and the lead plug and by using vertical spring for modeling the laminated rubber. The parameter β related to initial rigidity of the lead plug and the damping constant of the laminated rubber were set by taking into account results of the characteristics test conducted in this project as well as recommended values of manufacturers concerned.
Figure 8 shows hysteretic behaviors at the beyond-design phase in the horizontal direction. Hardening characteristics were specified based on results of past studies. It was confirmed that this modeling could be expanded to apply to large-diameter isolators, from a hardening test with a diameter φ of 1200 mm.



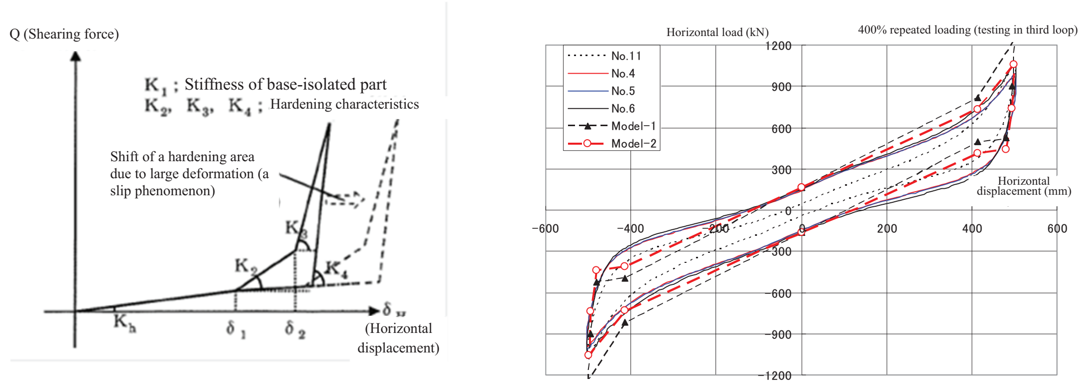
3D spring model of the base isolated layer

Figure 6. Overview of modelling the base isolated layer (PWR plant)



Vertical spring of the laminated rubber

Figure 7. Hysteretic behaviors at the design phase



Hardening characteristics

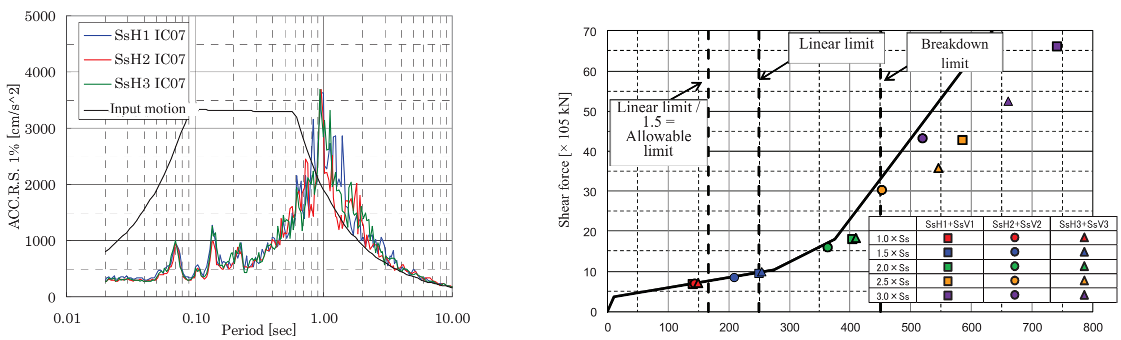
Comparison with the hardening test

Figure 8. Hysteretic behaviors at the beyond-design phase (horizontal direction)

Seismic response analysis

(1) Overview of seismic response analysis

One of typical models used in seicmic response analysis is the MDOF stick model as shown in Figure 6. In order to evaluate seismic integrity of a building and isolators, their responses should be calculated, as shown in Figure 9, by making a seismic response analysis with the MDOF stick model based on time history. For evaluation of the seismic margin, it is necessary to confirm the ultimate limit of a building and isolators by response analysis using the design wave multiplied by a coefficient (α).



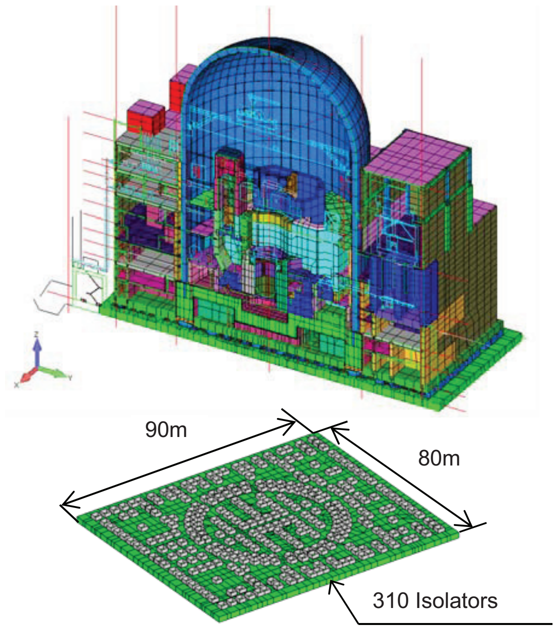
Floor response spectrum(FRS) at the operating floor

Seismic isolator to the design waves multiplied by α

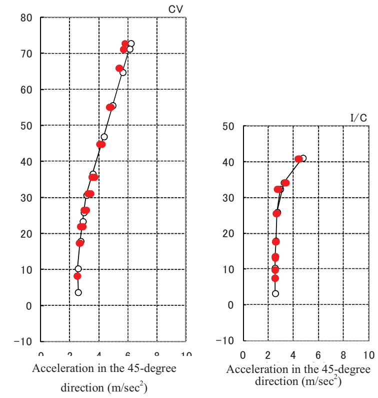
Figure 9. Results of seismic response analysis (PWR plant)

(2) Comparison of MDOF stick model and 3D FE-model

Figure 10 shows results of comparison between the MDOF stick model and the 3D FE-model. In order to verify adequacy of the MDOF stick model, a seismic response analysis was made in the case of receiving two inputs simultaneously from the horizontally 45-degree direction and the vertical direction. Both the models showed almost identical building response acceleration, while the MDOF stick model produced more conservative results in terms of tensile axial stress of isolators. From these results, it was verified that the MDOF stick model enabled a high-accuracy analysis in despite of 2D or 3D spring model of the base isolatede layer.



3D FEM model



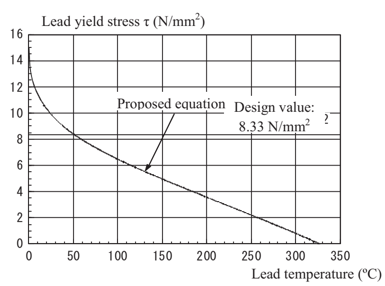
Tensile axial stress of isolators

(Unit : MPa)	3D FEM	MDOF
SRSS	-0.49	0.34
Combination coefficient method	-0.19	0.62
Simultaneous inputs	0.04	0.05
Envelope value*1	**0.04**	**0.62**

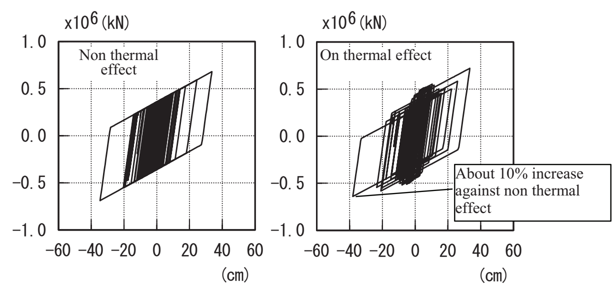
*1: An envelope value of SRSS, a coefficient method, and simultaneous inputs
*2: Above positive values mean tension.

Figure 10. Comparison results between the MDOF stick model and the 3D FEM model (PWR plant)

(3) Thermal effect of LRB
Figure 11 shows results of a study on thermal effect of LRB (PWR plant). A focus has been on an increase in deformation of the seismic isolators due to a decrease in the yield caused by heat generation of the lead plug receiving a long earthquake motion. Therefore, thermal effect study was conducted with a seismic response analysis.
As the results, response displacement to the design wave was about 10 % increase at most, even if the temperature rise was taken in consideration. Accordingly, it was confirmed that there was no significant thermal effect.



Lead temperature vs yield stress



Response results

Figure 11. Thermal effect of LRB (PWR plant)

Evaluation of seismic integrity
(1) Allowable limit of LRB
Based on the basic characteristics test, the hardening test, and the full-scale breaking test, it is thought that 275% of shearing strain, which becomes almost a lower limit, can be used as the linear limit in the compression domain. Based on the linear limit of shearing strain, the allowable limit can be set at 183% of shearing strain, which is 2/3 times the linear limit. For the linear limit of tensile-shear, the lower limit value in the test results was adopted just like in the compression domain.

With reference to the *Seismic Design Guidelines for Base-Isolated Structures of Nuclear Power Plant,(JEAG4614-2013)*, the allowable limit of the seismic isolators specified based on the above discussion is shown in Figure 12. This figure shows results of design seismic response in the MDOF stick model at PWR and BWR. the results were within the allowable limit of the design nominal value that was 2/3 times the linear limit.

(2) Evaluation of tensile axial force combination
On the laminated rubber at the peripheral part of the base isolated layer, axial forces caused by overturning moment and vertical seismic force, in addition to long-term axial force. Judging from the seismic response where horizontal and vertical inputs were applied simultaneously, designing these axial forces using an absolute sum would result in too much conservative. Accordingly, a study was made on a method of combining axial forces that would provide relatively conservative results and enable rationalization of the design.
Figure 13 shows axial force evaluation results on the peripheral LRB using earthquake motions consisting of 200 waves. From results of a seismic response analysis using the 1-DOF stick model with input of these seismic waves, it was confirmed that envelopes of a simultaneous input analysis, SRSS, the combination coefficient method, etc. could be used as a practical evaluation method that could replace the absolute sum method.

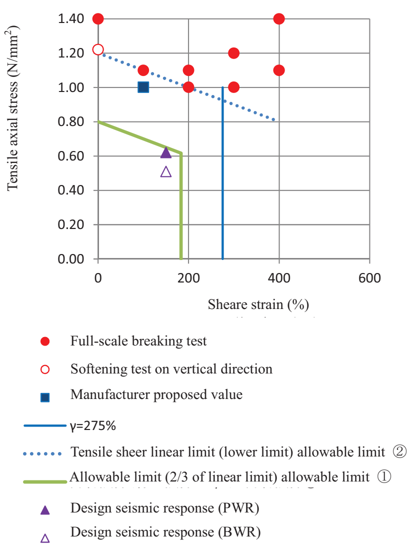
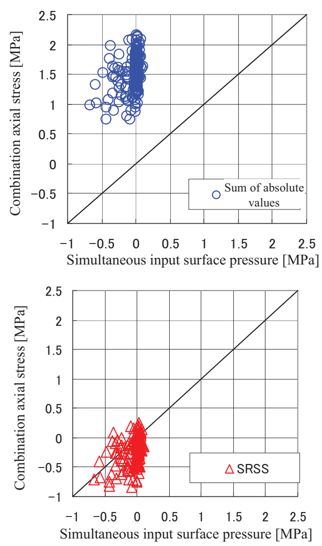


Figure 12. Allowable limit of LRB



(i) Absolute values

(ii) SRSS

Figure 13. Axial force evaluation results on peripheral LRB using 200-wave-based earthquake motions

Study other external events
In reference to various examples and sources such as the nuclear accident of the Fukushima Daiichi Nuclear Power Plant, nuclear regulations in foreign countries, etc.. Japan put into force new regulatory standards for NPPs in July 2013. The standards not only adopt more severe assumption of earthquakes and tsunamis but also require new measures to be taken against volcanos, tornados, and internal flooding. Against the above background, the following four categories of events were chosen as the external events to be considered in this study, from a result of examination of external events that could have an impact on base-isolated buildings: (i) earthquakes, (ii) tsunamis, (iii) tornados, and (iv) airplane crashes. It is necessary to properly make an assessment on these four external events to confirm integrity of base-isolated buildings.

CONCLUSIONS

Through this study, the authors have constructed a seismic isolation design methodology to install NPP's facilities, leveraging achievements of the seismic isolation system development project carried out from 2008 to 2015. Major achievements on base-isolated design of this project are as follows:

- It has designed the lead rubber bearig (LRB) of ϕ1600mm as full-scale isolators to install NPP's facilities, which is maximum available at the market in Japan.
- It has verified the modeling approaches of isolators from design phase to beyond-design phase based on hardning and beaking test of isolators.
- It has confirmed MDOF stick model can be available for the seismic response analysis with comparison to 3D FE-model.
- It has developed the seismic evaluation with related in allowable limit, combinated tensile axial stress and so on as a seismic integrity method.

A part of the achievements of this project was reflected in the *Seismic Design Guidelines for Base-Isolated Structures of Nuclear Power Plant* (JEAG4614-2013) issued by the Japan Electric Association.
We plan to continue this project to complete it in 2015. Our efforts will be aimed at preparation necessary for revision of related standards such as JEAG4614-2013, while building a new seismic isolation design methodology thoroughly covering all the steps from design evaluation to earthquake PRA evaluation.

ACKNOWLEDGMENT

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