ULTIMATE SEISMIC RESPONSE OF A BASE-ISOLATED BUILDING SUPPORTED ON RUBBER BEARINGS

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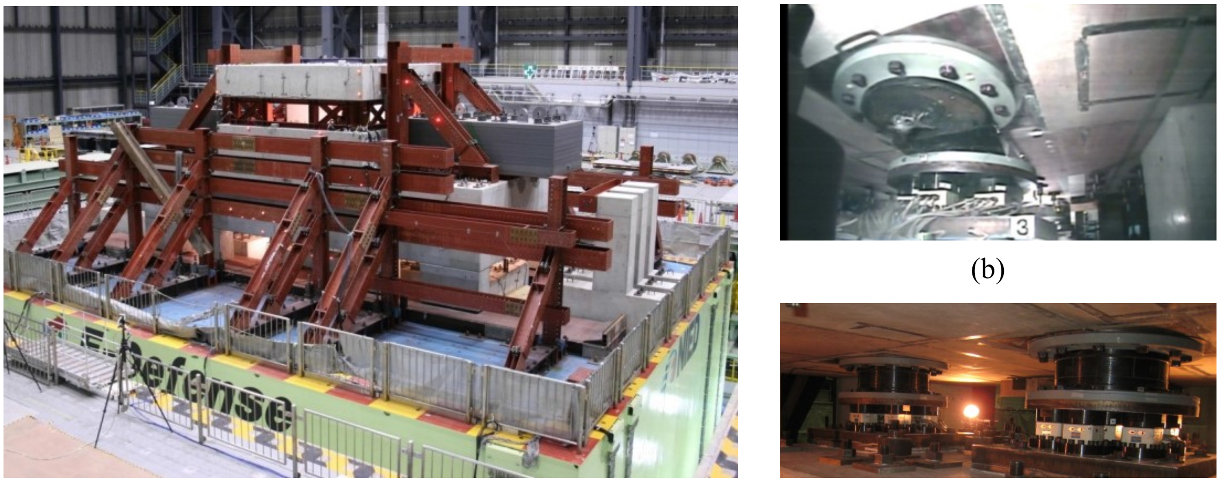
ABSTRACT

Although the ultimate seismic response is not strictly considered in the seismic design of seismically isolated (SI) nuclear power plants, it is preferable for the limit state to be reached with a soft landing rather than a hard stop. The authors have previously demonstrated through load tests and FEM analysis that rubber bearings (RBs) remain stable even after rupture (e.g. Umemura et al., 2024). The authors have also confirmed that the seismic response of a seismically isolated building remains stable even after some RBs rupture in shear. This was demonstrated using a single-degree-of-freedom (SDOF) one-horizontal model, as previously discussed by Umezu et al. (2016). This paper presents seismic response analyses of three-degree-of-freedom (3DOF) models coupled with horizontal, vertical, and rotational motions, and discusses the stability of an SI building when isolators undergo shear and tensile ruptures.

The seismic response of a superstructure supported by 100 sets of lead rubber bearings (LRBs) is analysed under horizontal and vertical rupture strain distribution models. Two rupture distributions, such as the horizontal one for Model A and the vertical one for Model C, are set up in reference to our previous experiments. These are considered the “standard rupture” models in the study. To investigate the seismic response characteristics of isolated buildings with isolators of different breaking strength, a virtual rupture distribution of Model B is set up as an 'early rupture' model, in which the LRBs rupture at a lower strain than in Model A. The results of comparing the seismic response when all the LRBs are set to the standard rupture model with the response when half of the LRBs are set to the early rupture model are as follows: (1) By installing a mixture of early rupture LRBs as Model B, the peak response can be controlled to reduce accelerations and displacements. (2) The maximum response differs depending on the rupture strain distribution and the shape of the superstructure. The response is larger when the building's height-to-width ratio is two or more. (3) Severe events, such as the rupture of all the LRBs, should be avoided; otherwise, permanent displacement and acceleration shocks due to hard stops to the superstructure will occur largely.

INTRODUCTION

The use of seismic isolation (SI) has increased over the last 30 years, with the most common applications being in non-nuclear structures such as buildings, bridges, offshore oil and gas platforms, high-hazard storage tanks and industrial facilities. The IAEA (2020) reports that many benefits are expected from SI in the design and construction of new nuclear facilities, including lower acceleration, simpler structural behaviour, increased safety due to reduced uncertainties, simpler layouts and cost reductions. However, nuclear power engineers in some earthquake-prone countries have recently been reluctant to adopt SI, as discussed by Huang (2017) and Kanazawa (2017). The main reason for this is that the response of SI buildings has increased with the recent increase in design ground motions; therefore, the responses are likely to exceed the current design limits of SI devices. To facilitate the introduction of seismic isolation structures in high seismic zones, it is essential to extend the design and ultimate limits. In order to achieve this, it is necessary to be able to numerically simulate what happens outside the current design limits and to understand what happens outside the current ultimate limits, as well as to confirm whether the enough margin from the design limits to the ultimate state limits can be secured.



(b)

(a) (c)

Figure 1. A shaking Table Test used as reference for modelling the lead rubber bearing (LRB): (a) the base-isolation model; (b) a LRB at the moment rupturing; (c) LRBs after ruptured.

Table 1. Specifications of the Lead Rubber Bearings

	Shaking table test	Seismic response analysis in this study
Dead load [kN]	980	9800
Design Compression [MPa]	5.15	5.15
Diameter [mm]	505	1600
Total thickness of rubbers	3 mm by 24 layers	9 mm by 24 layers
Horizontal period [s]	2.358	2.270
Vertical frequency [Hz]	29	15
Shape Factors, S1/S2	72/7.0	44/7.4
Yield seismic intensity	0.08	0.08

For rubber bearings (RBs), the design limit is often defined within the linear displacement range, where load and displacement are linearly related (e.g. JEA, 2020). Beyond these limits, an RB deforms nonlinearly, either hardening under lateral loads or after softening then hardening under vertical tensile loads. Ultimately, it ruptures at the rubber layer (e.g. Fujita et al., 1988). RB rupture is one of the ultimate states in SI buildings. Another ultimate state is the hard stop, which occurs when the upper foundation hits the moat wall. If the clearance is greater than the rupture displacement of the RBs, the ultimate state is RB rupture; otherwise, it is a hard stop.

From the perspective of removing the rupture event of RBs from the ultimate state, the authors re-evaluated the static and dynamic behaviour of RB and SI building specimens after rupture through static loading tests and shaking table experiments (e.g. Yabana et al., 2009; Kanazawa et al., 2012; Umemura et al., 2024). The authors already have also confirmed that the seismic response of an SI building remains stable even after some of the RBs rupture in shear. This was confirmed using a single-degree-of-freedom (SDOF) model in one horizontal direction, as previously discussed by Umezu et al. (2016). As extending on the previous

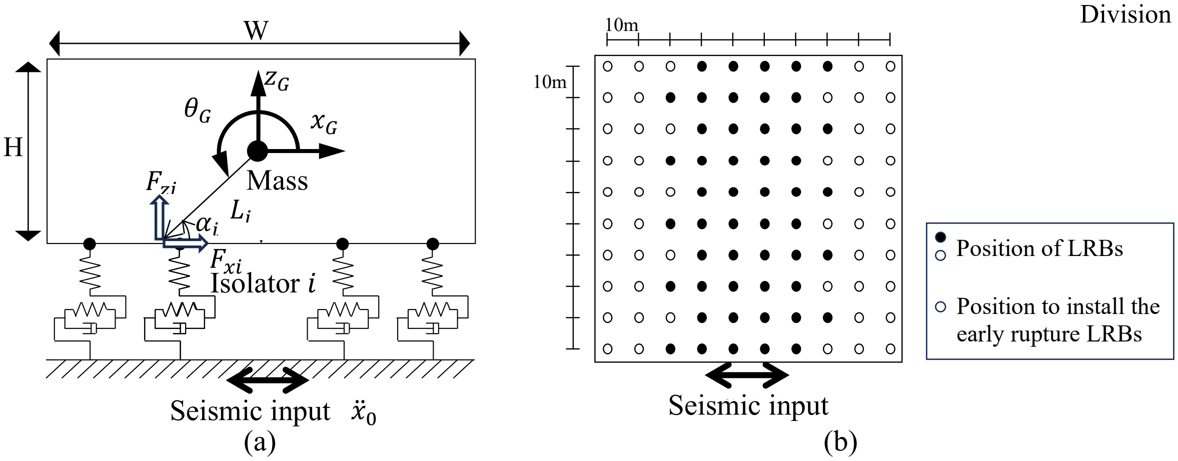
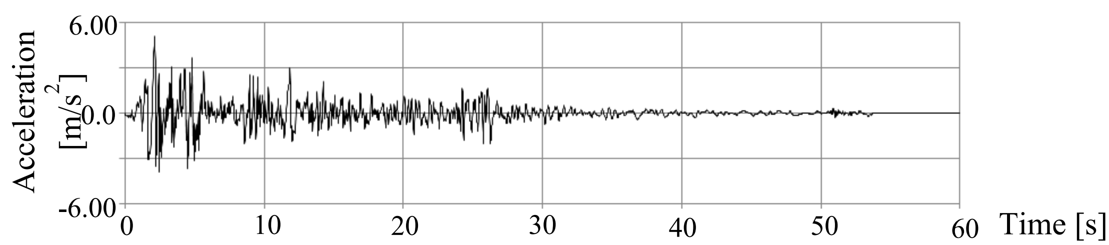


Figure 2. A horizontal-vertical vibration model: (a) a distributed-springs model; (b) a layout of LRBs.

(a)

Peak ground velocity [m/s]	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00
Peak Acceleration [m/s^2]	5.11	10.22	15.32	20.43	25.54	30.65	35.75	40.86



(b)

Figure 3. Seismic inputs: (a) 8 amplitudes; (b) a standard input with amplitude adjusted to 0.50 m/s.

paper, this paper presents seismic response analyses of three-degree-of-freedom (3DOF) models incorporating horizontal, vertical and rotational motions, and discusses the ultimate behaviour of an SI building when some of the isolators ruptures in shear and tension.

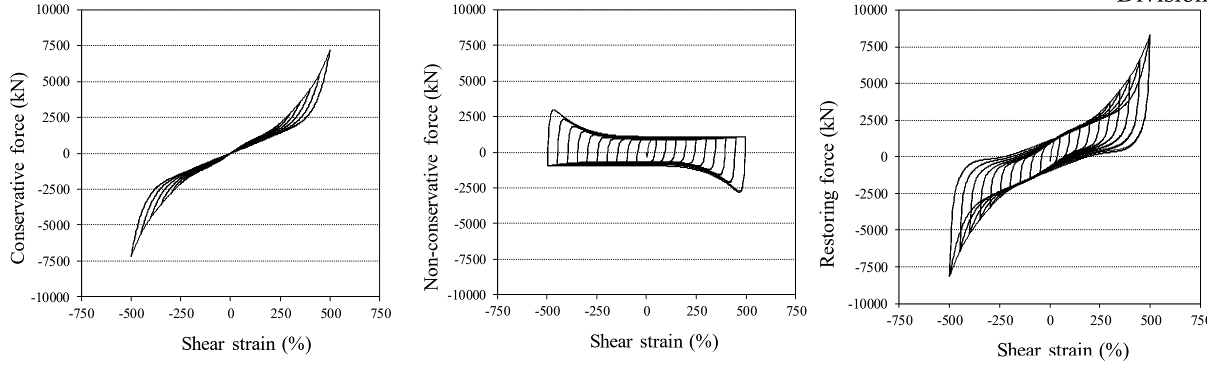
SEISMIC RESPONSE ANALYSIS MODEL

Specification of Rubber Bearing

The seismic response analysis assumes the installation of lead rubber bearings (LRBs) with a diameter of 1600 mm in the large reactor building, in reference to previous shaking table tests (e.g. Yabana et al., 2009; Kanazawa et al., 2012), where one-third scaled isolators were used in Figures 1 and 2 and Tables 1 and 2. During these tests, one or two of the six bearings ruptured as a result of severe seismic shaking.

A Horizontal-Vertical Vibration Model and a Seismic Input

Figure 2 shows the horizontal-vertical vibration model using in the study, in which a mass is supported by one hundred LRBs. The mass is located at the centre of gravity (CG) of the building, which has 3DOF in the horizontal, vertical and rotational directions. The LRBs are modelled as horizontal and vertical springs, and their relative positions from the CG are considered. Some numerical examples will be conducted using a combination of standard-strength and early-rupture LRBs, with the latter placed outside the horizontal



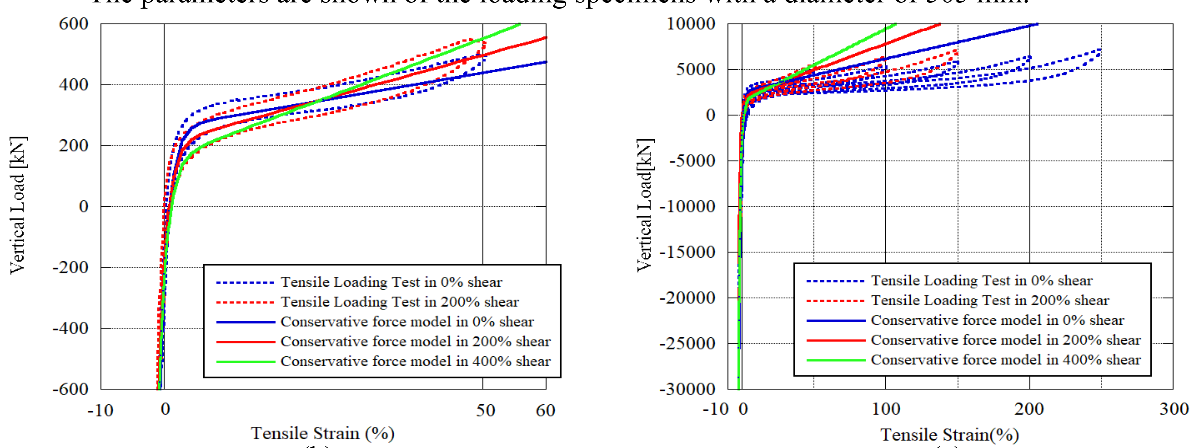
(a) (b) (c)

Figure 4. Horizontal restoring force model of LRBs used in the seismic response analysis: (a) Conservative force models; (b) Non-conservative force models; (c) Total restoring force of the conservative and the non-conservative forces.

(a)

Tensile loading conditions	α	β	γ	δ	ε
Offset shear 0%; regressed	310	1.1	0.4	5	50
Offset shear 200%; regressed	290	1.1	0.2	8	80
Offset shear 400%; extrapolated	270	1.1	0.0	11	110

The parameters are shown of the loading specimens with a diameter of 505 mm.



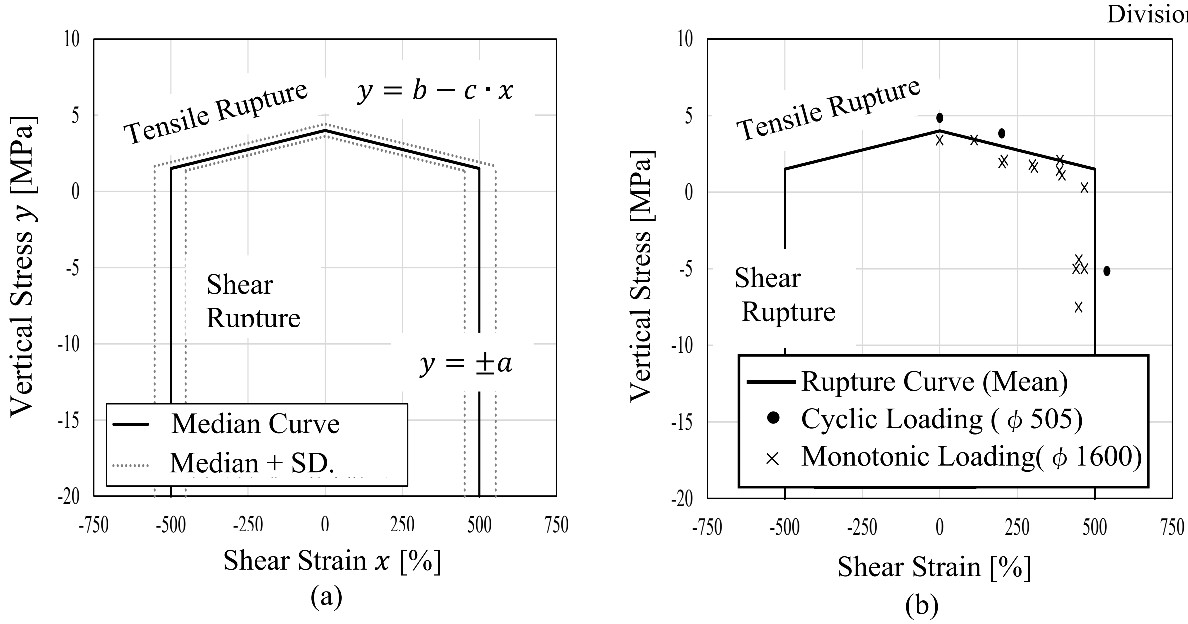
(b) (c)

Figure 5. Vertical restoring force model of LRBs used in the seismic response analysis: (a) Regression parameters estimated from the past loading tests; (b) the regression results of the one-third scale models of LRBs; (c) the graph displayed in the analytical scale.

vibration direction. The model is given a seismic input in the horizontal direction only, using the eight amplitude-adjusted waves of the 1940 El Centro NS earthquake, as shown Figure 3.

Restoring Force Models

The horizontal and vertical springs of the LRBs are modelled based on a unit static loading test conducted prior to the previous shaking table tests, as reported by Yabana et al. (2009). As shown in Figure 4, the horizontal spring is the same as that cited in the previous paper by Umezu et al. (2017). In this model, the load-displacement relations of the LRBs are divided into conservative and non-conservative forces, a method originally proposed by Hiraki et al. (2016). This paper presents the modelling of the vertical spring



(c)

Models		a [%]	b [MPa]	c [MPa/%]
Standard rupture LRB	Median	500	-4.97×10^{-3}	4
	SD	0.1	0	0.1
Early rupture LRB (Virtual)	Median	200	-4.97×10^{-3}	4
	SD	0.1	0	0.1
Reference: Regression results of the past loading test shown in the figure (b).				
Monotonic loading(ϕ 1600 ㎜)	Median	453.5	-4.97×10^{-3}	3.37
Cyclic loading(ϕ 505 ㎜)	Median	538.9	-4.94×10^{-3}	4.86

Figure 6. Rupture limit model for earthquake response analysis: (a) standard rupture model of shear and tensile relations; (b) comparison to the past loading test results; (c) Parameters of two rupture model employed in the analysis.

for the first time, with the following equations assumed for the total restoring force $q_z(z, \dot{z}, x)$, the conservative force $q_{zC}(x, z)$ and the non-conservative force $q_{zN}(\dot{z})$:

$$q_z(z, \dot{z}, x) = q_{zC}(x, z) + q_{zN}(\dot{z}), \tag{1}$$

$$q_{zC}(x, z) = \alpha\left(1 - e^{\{-\beta(z-\gamma)\}}\right) + \delta z - \varepsilon, \tag{2}$$

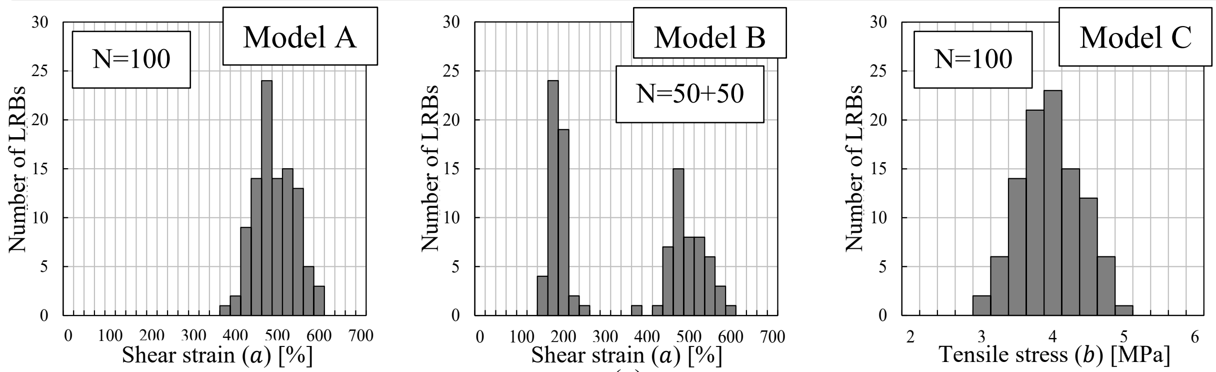
$$q_{zN}(\dot{z}) = c_z \dot{z}, \tag{3}$$

where α, β, γ, δ and ε are the regression parameters; c_z is the vertical viscous damping coefficient.

The conservative force model is estimated using the results of two tensile tests with offset shear strains of 0% and 200%, as shown in Figure 5. The coefficient c_z gives a damping constant of 7% at the first-order vertical natural frequency referenced to the shake table test. This paper focuses on the initial softening region up to 50% tensile strain. In this region, the LRB softens immediately upon entering the tensile state from compression in the dead load region. The mechanical behaviour in this region can be accurately simulated. However, modelling of larger tensile regions is inadequate and requires further research.

(a)

No	Rupture model	Building shape	Input	Vibration Model and Remarks
1,2,3	Model A + Model C	H/W=1,2,3	El Centro NS	Horizontal and Vertical.
4,5,6	Model B +Model C			
7	Model A	H/W=0		Horizontal only, cite by Umezu et al. (2020).
8	Model B			



(b) (c) (d)

Figure 7. Simulation models of seismically isolated buildings and examples of rupture strain distribution: (a) Lists of the seismic response analyses; (b) Shear strain distribution of the standard rupture model (Model A); (c) Shear strain distribution of the early rupture model (Model B); (d) Tensile stress distribution used commonly in both rupture models (Model C).

Rupture Limit Models and Constitutive Law of an LRB During and After Rupture

As shown in Figure 6, the rupture limit condition is modelled using shear strain and tensile stress as variables a, b and c, where a and c are stochastic variables with log-normal distributions. The rupture limit model variables a, b and c are determined based on a unit static loading test conducted prior to the shaking table tests reported by Yabana et al. (2009). The LRB corresponding to this rupture limit model, estimated from the previous test data, is used as the 'standard rupture' LRB. Assuming that laminated rubber can be produced that ruptures at a lower strain than the standard LRB, the authors set hypothetical LRBs with lower horizontal shear strength than the standard model. Here, they are called as 'early rupture' LRB. In seismic response analyses, an LRB is considered to have ruptured if the displacements or loads exceed the rupture limit once. The constitutive rules for the LRB at and after rupture are the same as in the previous paper by Umezu et al. (2017). Roughly, the LRB is assumed to behave similarly to an elastic sliding bearing.

Simulation Cases

Seismic response analyses are conducted by varying the rupture models, height-to-width (H/W) ratios and vibration models, as shown in Figure 7. Monte Carlo simulations are performed using 20 samples for each rupture distribution to investigate variations in rupture strength and LRB layout. Figures 7(b) to (d) show examples of the distribution of the rupture parameters a and b. Models A and C are considered “standard ruptures”, while Model B is considered an “early rupture”.

NUMERICAL EXAMPLES OF SEISMIC RESPONSE

Figure 8 shows two examples of seismic response results for 3 m/s in PGV, 1 or 3 in H/W, to investigate the effect of RB rupture on the seismic response. In Figures 8(a) and 8(c), the ruptures progress at five second as the end of the main motion in the seismic input. All the LRBs are standard rupture models, and the CG is low (H/W = 1), thus it can be said as the "not rupture-prone" model. In turn, in Figures 8(b) and

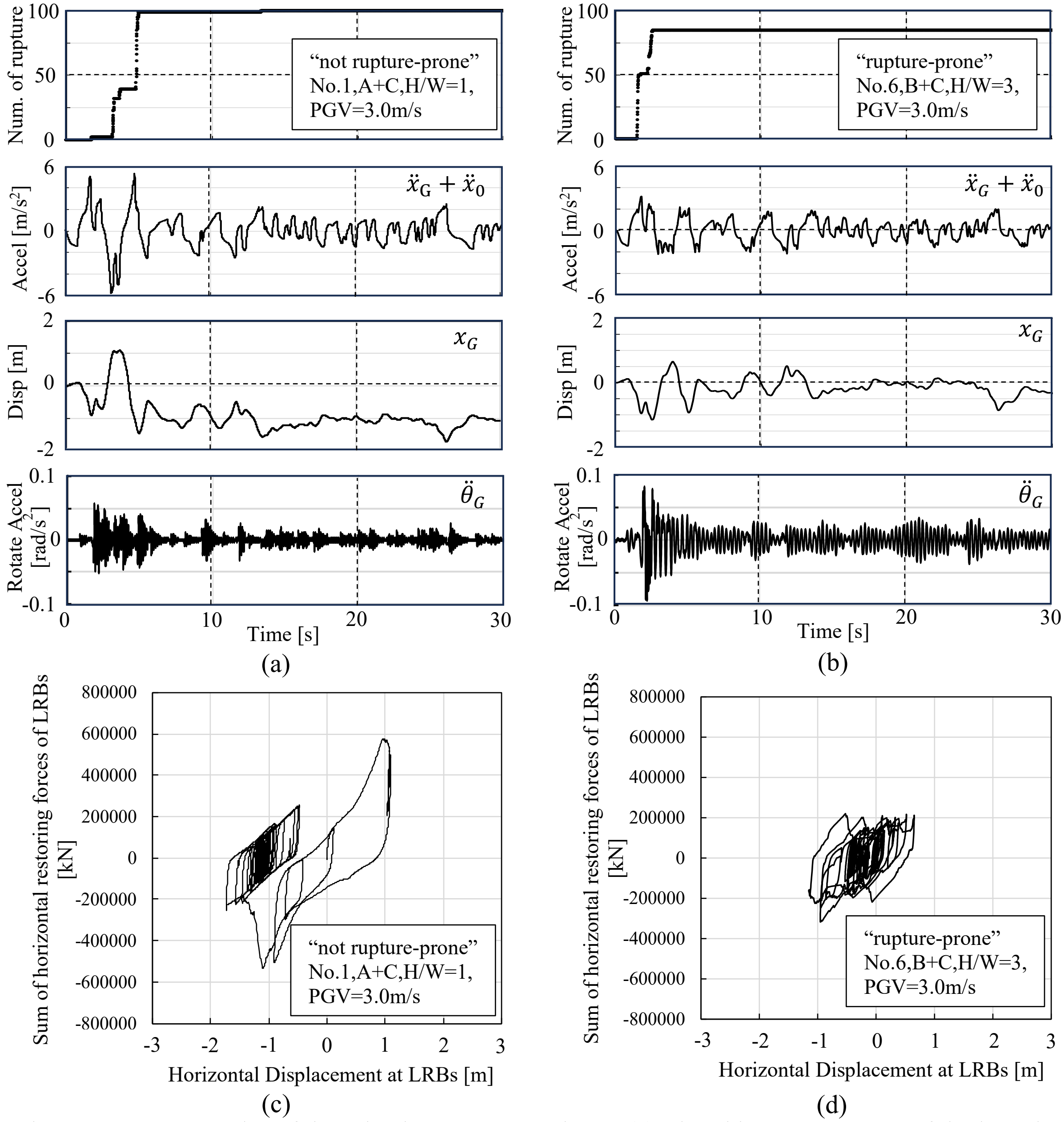


Figure 8. Two examples of the seismic response analyses: (a) Time history responses of the low-rise building (H/W=1) supported on the standard rupture LRBs; (b) Time history responses of the high-rise building (H/W=3) supported on the early rupture LRBs; (c) Restoring forces at the SI layer corresponding to fig(a); (d) Restoring forces at the SI layer corresponding to fig(b).

8(d), rupture progresses at the beginning of the main motion. Half of the 100 LRBs are early rupture models, and the CG is high (H/W = 3). Thus, it can be said as the "rupture-prone" model.

In the “rupture-prone” model, as shown in Figure 8 (b) and (d), the peak acceleration is small and all LRBs do not rupture: some LRBs maintain horizontal restoring forces without rupturing, therefore, there is no residual displacement and, as a result, the peak displacement will be small. The reason for such a small response is considered to be that the rupture event occurs at the beginning of the main motion, and the vibrational resonance phenomenon during the main motion can be suppressed.

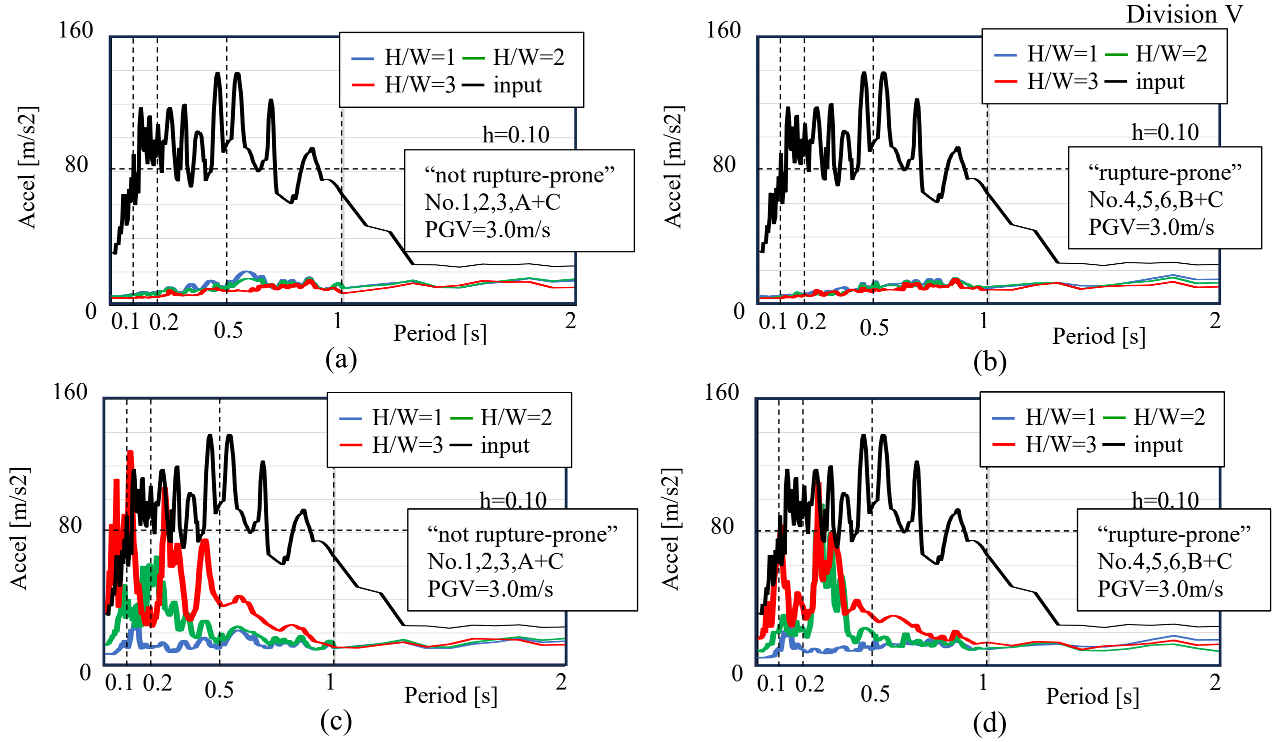


Figure 9. In-structure response spectra of the vertical-horizontal vibration models with the ratio of height to width (H/W) against the seismic input of 3.0 m/s in PGV: (a) at the center of gravity of the building with only the standard rupture LRBs; (b) at the center of gravity of the building with the early rupture LRBs; (c) at the lowest right corner of the building with only the standard rupture LRBs; (d) at the lowest right corner of the building with the early rupture

In turn, in the "not rupture-prone" model, Figures 8(a) and (c) show that all LRBs rupture at the end of the main motion. Once all the LRBs have ruptured, a permanent horizontal displacement around −1 meter occurs significantly. If all LRBs rupture, the centring function of the seismic isolation layer — which restores the building's centre of gravity to the initial position — is impaired, resulting in increased maximum displacement. This severe event should be avoided as it can lead to collisions with retaining walls and cause high accelerations in the upper part of the nuclear power plant structures, systems, and components.

The rotational acceleration of both models vibrates at high frequencies, thus there is concern about the effect on equipment at the corners of the building. As shown in in-structure response spectra of Figure 9, when the H/W ratio exceeds 2, the floor response at the corners of the building tends to be quite large. Consideration may need to be given to lowering the centre of gravity of the building and a mechanism to suppress rotation may be required.

CHANGES IN PEAK RESPONSE WITH RUPTURED RUBBER BEARINGS

The results of the Monte Carlo simulation are shown in Figures 10 to 12. It should be noted that the peak acceleration and maximum displacement are evaluated at the centre of gravity of the building and in the horizontal deformation of the isolation layer, respectively. In the displacement graph, the failure displacements of 1.138m and 1.365m are shown, corresponding to shear strains of 500% and 600%, which are the mean and maximum of the rupture distribution of the standard LRBs shown in Figure 7 (b) and (c). In the standard models of Models A and A+C, the rupture event of LRBs progresses rapidly over short PGV ranges of 2.0 to 2.5 m/s, whereas in the early rupture models of Models B and B+C, the rupture events occur gradually over wide ranges of PGVs, with the widest range being 1.0 to 3.5 m/s: Ultimate response can be the most stable and sustainable when the most rupture-prone RB are mixed in, to make account tensile and shear ruptures. If the speed of rupture process can be slowed down, the increase in both the maximum acceleration and the maximum displacement can be slowed down simultaneously. To achieve the slow rupture process, it will be concluded to mix and use RBs with various rupture properties.

CONCLUDING REMARKS

Considering a seismically isolated (SI) building supported by one hundred isolators, seismic response analyses of three-degree-of-freedom models coupled with horizontal, vertical and rotational motions were conducted in which some rubber bearings (RBs) were allowed to rupture, and the seismic response to different rupture patterns is discussed. The results confirmed that the peak acceleration on the building and the relative displacement of the SI layer are reduced by the deliberate addition of RBs which have low strength and ruptures early. The fact shows here, the response of a SI building that uses a mixture of “rupture-prone” RBs was smaller than that uses only “not rupture-prone” RBs. This is because, once the vibration characteristics suddenly change, the remaining “not rupture-prone” RBs will not break easily even if larger seismic inputs are given. It is very interesting that the ultimate response of the SI system can be stabilized by intentionally mixing in the various strength of RBs, rather than using uniform strength of RBs.

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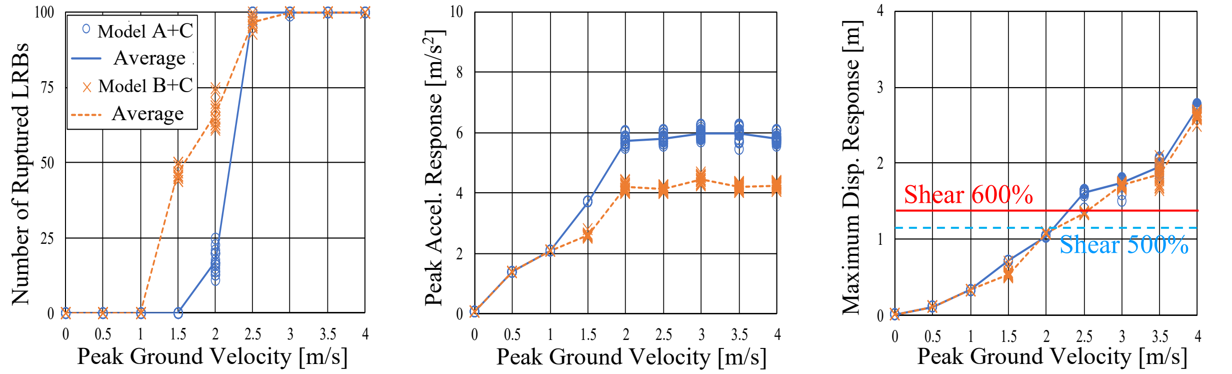
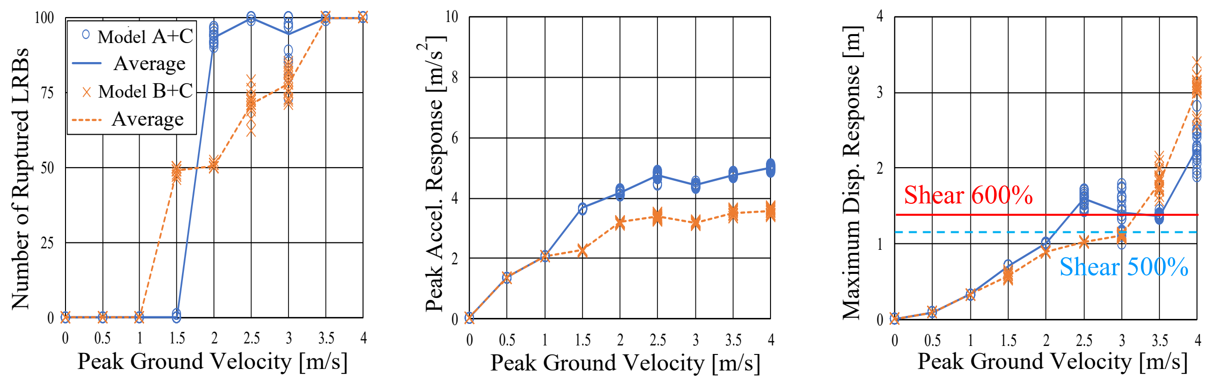


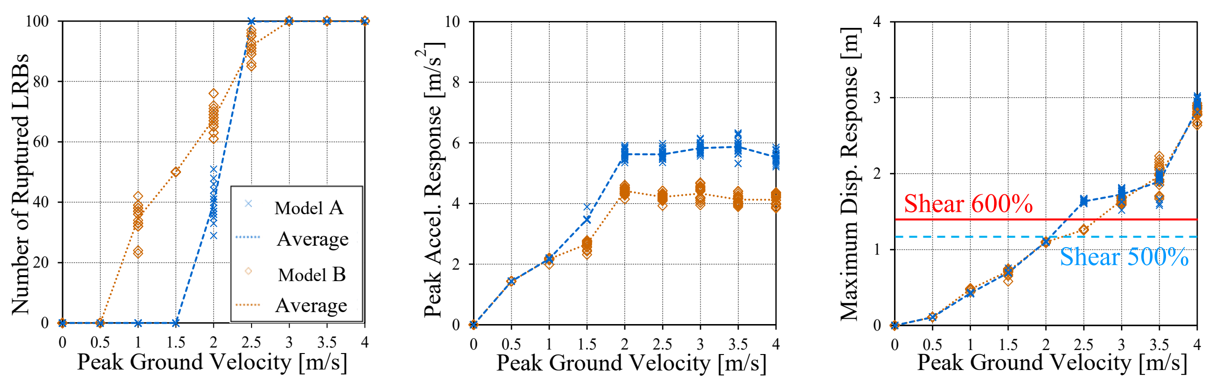
(a) (b) (c)

Figure 10. Ruptured states and Maximum responses of the "horizontal-vertical" vibration model of H/W=1 with increasing seismic inputs, as comparing two models without and with the early ruptured LRBs: (a) number of ruptured LRBs, (b) Peak horizontal acceleration at the CG, and (c) Maximum lateral displacement at the SI layer.



(a) (b) (c)

Figure 11. Results for "the horizontal-vertical" model of H/W=3 under the same conditions as the figure 10: (a) number of ruptured LRBs, (b) Peak horizontal acceleration at the CG, and (c) Maximum lateral displacement at the SI layer.



(a) (b) (c)

Figure 12. Results for "the only horizontal" model of H/W=0 under the same conditions as the figure 10, cited by Umezu and Kanazawa et al. (2016): (a) number of ruptured LRBs, (b) Peak horizontal acceleration at the CG and (c) Maximum lateral displacement at the SI layer.