EARTHQUAKE ENGINEERING AND STRUCTURAL DYNAMICS
*Earthquake Engng Struct. Dyn.* (2010)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/eqe.1036

# Development of the core-suspended isolation system

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SUMMARY

A new type of seismic isolation system—called the core-suspended isolation (CSI) system—has been developed and first building application recently completed. The CSI system consists of a reinforced concrete core on top of which a seismic isolation mechanism composed of a double layer of inclined rubber bearings is installed to create a pendulum isolation mechanism. A multi-level structure is then suspended from a hat-truss or an umbrella girder constructed on the seismic isolation mechanism. In this paper, the mechanics of the CSI system are described, followed by a discussion of results of shaking table tests and quasi-static loading tests of rubber bearings with rotated flanges, and a description of the first building constructed utilizing the CSI system, located in Tokyo, Japan. Copyright © 2010 John Wiley & Sons, Ltd.

Received 29 May 2009; Revised 28 May 2010; Accepted 31 May 2010

KEY WORDS: core-suspended isolation; core-shaft; double layer; inclined rubber bearings; pendulum; shaking table test

## 1. INTRODUCTION

The most common structural materials used for modern buildings are steel and concrete. The primary motivation for the development of a new type of seismic isolation system that is presented in this paper was to attain the highest possible level of earthquake resistance along with an architecturally desirable form in a structural system that takes best advantage of the right structural material for the right function, that is, steel for tension and concrete for compression. The research and development of the new core-suspended isolation (CSI) system, comprising a double layer of inclined rubber bearings, were based on the following design concepts:

(1) The occupied structure of the building is suspended from the core structure to create a pendulum isolation mechanism.
(2) The columns of the suspended structure are slender steel members that remain always in tension, and the core is made of reinforced concrete that is always in compression.
(3) The new seismic isolation system achieves the architectural advantages of transparent façades for the suspended structure and functional and attractive open space underneath the suspended building.

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Figure 1. Conceptual drawings of the CSI system.

Conceptual drawings of the new type of seismic isolation system are shown in Figure 1.

It has been recognized that suspending floors from a core is a feasible building structural configuration, and one which has been implemented in a few actual buildings [1–9]. A typical configuration for a suspended structure is to construct a hat-truss or an umbrella girder over a stiff core, from which a suspended structure is hung from cables or rods. The main goal of the present work was to achieve high seismic performance for a suspended building structure through the use of a pendulum isolation mechanism at the top of a stiff core. Although a pendulum motion is theoretically able to achieve seismic isolation [2, 5, 10, 11], no practical isolation device has been developed to suspend a building as a pendulum. The friction pendulum system (FPS) has been developed to replicate the effect of pendulum support [12, 13], but it is not possible to create the dual, real and virtual radius of curvature pendulum configuration for a suspended structure with the FPS that is possible with rubber bearings. Multilayered laminated rubber bearings are the most practical and widely used devices, and most recent seismically isolated buildings in the world are *base-isolated* buildings that interpose rubber bearings between the base of the structure and the foundation [14–16]. However, to date there is no practical pendulum seismic isolation mechanism for suspended structures.

A new type of seismic isolation system—called the CSI system—has been developed to provide a practical pendulum isolation mechanism for suspended structures. The CSI system comprises a double layer of inclined rubber bearings installed on the top of a reinforced concrete core, and an occupied structure is suspended from a hat-truss constructed on the seismic isolation mechanism. The unique aspect of the system is the realization of the pendulum isolation mechanism by the use of a circular arrangement of inwardly inclined rubber bearings with the same tilt angle so as to have a virtual center of rotation. Furthermore, the CSI system employs a double layer of inclined rubber bearings to isolate the structure from the rocking motion of the core.

In this paper, the development process of the mechanics of the CSI system is first described, followed by the results of shaking table tests of a scale model and quasi-static loading tests of full-scale rubber bearings. Similar to the configuration that would be used in full-scale structures, the CSI system model for the shaking table tests employed a double layer of inclined rubber bearings. The quasi-static loading tests were carried out to investigate the hysteresis characteristics of full-scale rubber bearings under rotational and horizontal displacements. Finally, the paper gives an overview of the first building to utilize the CSI system, a four-level building in Tokyo, Japan. The seismic isolation mechanism for the building consists of two layers each of four inclined

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rubber bearings installed at the top of a reinforced concrete core, from which three floors of office structure are suspended by high-strength steel rods.

## 2. MECHANICS OF CSI

The CSI system concept evolved from the idea of simple pendulum mechanics into a practical seismic isolation system using a double layer of inclined rubber bearings. The development process of the mechanics is described here to illustrate the uniqueness and advantages of the CSI system [17–21]. Since the CSI system has the potential to be effective for high-rise buildings, a 21-story suspended structure is taken as a numerical example, with dimensions typical of a high-rise building with a center core.

### *2.1. Simple pendulum isolation*

A suspended structure on a pin support at the top of a core can be regarded as a single degree of freedom (SDOF) system, like a simple balancing toy, as shown in Figure 2, if the suspended structure is regarded as a rigid body. In the figure, $m$ and $\boldsymbol{I}_\theta$ are the total mass and the rotational inertia of the suspended structure, respectively, and $a$ is the position of the center of gravity of the suspended structure, and $u$ and $\theta$ are the horizontal displacement and the rotational angle of the suspended structure, respectively.

The equation of moment equilibrium around the pin support is given by

$$I_\theta \ddot{\theta} + m\ddot{u}a + mg\theta a = 0 \tag{1}$$

where $g$ is the acceleration due to gravity. Substituting $\ddot{u} = a\ddot{\theta}$ into Equation (1) leads to the following equation:

$$\ddot{\theta} + \frac{mga}{I_\theta + ma^2}\theta = 0 \tag{2}$$

By defining $\theta = A\exp(\mathrm{i}\omega t)$, in Equation (2), the natural period is given by:

$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{\boldsymbol{I}_\theta + ma^2}{mga}} \tag{3}$$

By way of numerical example, consider a 21-story suspended structure as shown in Figure 7 of $m = 5.5\times10^7\,\mathrm{kg}$, $a = 40\,\mathrm{m}$, $I_\theta = 4.9\times10^{10}\,\mathrm{kg\,m^2}$. The resulting natural period, $T$, is 15.8 s from Equation (3), which is regarded as a very long natural period for a seismic isolation system. Although an idealized pendulum support would elongate the natural period and provide for seismic

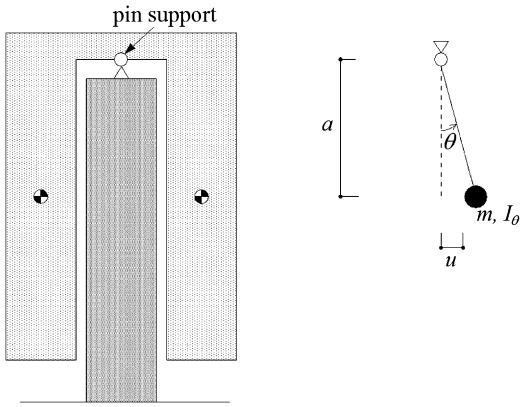


Figure 2. A simple, pin-supported pendulum system.

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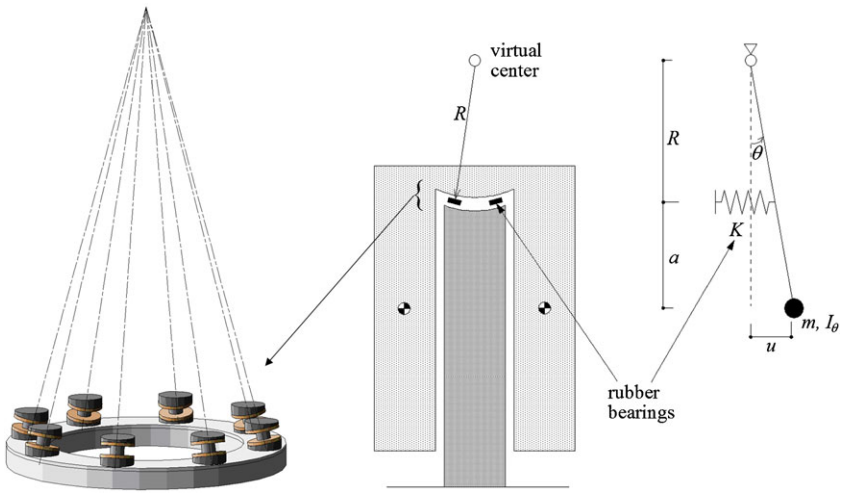


Figure 3. Pendulum isolation using a circular arrangement of inclined rubber bearings.

isolation, there is no practical device for the pin support that could support the entire weight of the suspended structure.

### 2.2. *Isolation using a circular arrangement of inclined rubber bearings*

To create a practical pendulum isolation mechanism for suspended structures, the authors developed a mechanism that comprises laminated rubber bearings in a circular pattern and inwardly inclined with the same tilt angle on the core so as to have a virtual center of rotation as shown in Figure 3. In this figure, $R$ is the radius of gyration of the seismic isolation mechanism, and $K$ is the horizontal stiffness of the rubber bearings.

The equation of moment equilibrium around the virtual center is given by:

$$I_\theta\ddot{\theta}+m\ddot{u}(R+a)+KR^2\theta+mg\theta(R+a)=0 \tag{4}$$

Substituting $\ddot{u}=(R+a)\ddot{\theta}$ into Equation (4) leads to the following equation:

$$\ddot{\theta}+\frac{KR^2+mg(R+a)}{I_\theta+m(R+a)^2}\theta=0 \tag{5}$$

The natural period is given by

$$T=2\pi\sqrt{\frac{\boldsymbol{I}_\theta+m(R+a)^2}{KR^2+mg(R+a)}} \tag{6}$$

As an example, suppose that 24 rubber bearings (each with a diameter of 1.3 m) are placed in a circular pattern and inwardly inclined so as to have $R=40\,\mathrm{m}$ and $K=54\times10^6\,\mathrm{N/m}$ on the core in the same 21-story suspended structure (Figure 7) described in the previous section. The natural period, $T$, turns out to be 11.1 s by Equation (6), which is much longer than 6.3 s ($=2\pi\sqrt{m/K}$) for the case in which the same mass of the suspended structure, $m$, is assumed to be simply *base-isolated* by the rubber bearings with the same horizontal stiffness, $K$.

In a real building, the core will not be rigid and would experience deformations by an earthquake. In preliminary shaking table tests, the proposed isolation mechanism with inwardly inclined rubber bearings was found to be unable to isolate or decouple the suspended structure from the rocking motion of the core, and the suspended structure would respond as shown in Figure 4.

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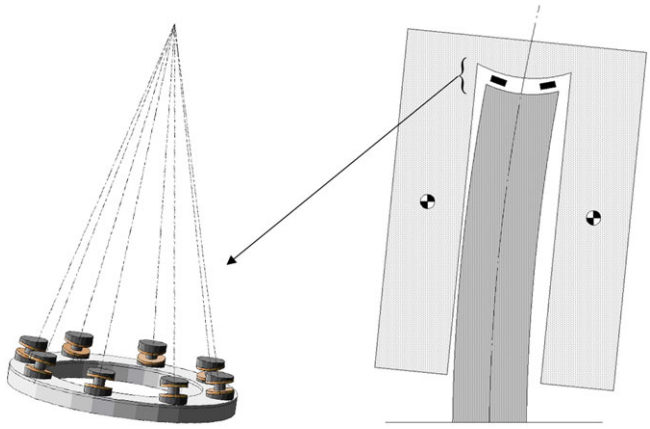

Figure 4. Core rocking motion response of suspended structure.

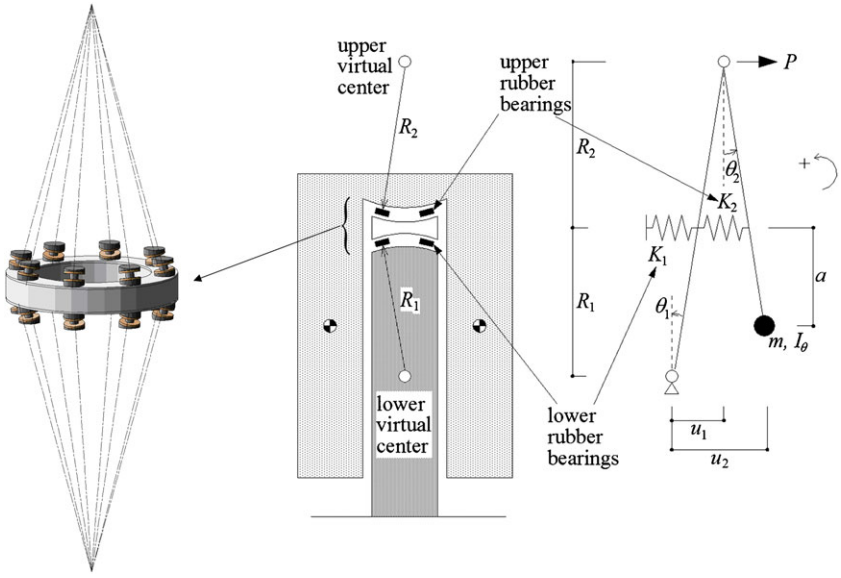


Figure 5. Isolation by a double layer of inclined rubber bearings placed in a circle.

### *2.3. Isolation by a double layer, circular arrangement of inclined rubber bearings*

The authors have developed a double layer of inclined rubber bearings the lower layer of which is able to isolate the suspended structure from the rocking motion of the core. The upper and lower layers consists of a circular arrangement of rubber bearings that are inwardly inclined with the same tilt angle so as to have a virtual center of rotation above or below the layer, as shown in Figure 5.

A simplified model of a structure utilizing the CSI system can be expressed as a 2DOF system as shown in Figure 5. In this figure, $R_1$ and $R_2$ are the lower and upper radii of gyration of the seismic isolation mechanism, respectively; $K_1$ and $K_2$ are the horizontal stiffnesses of the rubber bearings in the lower and the upper layers, respectively. The equations of motion for undamped free vibrations of the 2DOF model in Figure 5 can be presented as follows.

The equations of moment equilibrium around the upper and lower virtual centers in Figure 5 are given by the following two equations:

$$I_\theta \ddot{\theta}_2 + m\ddot{u}_2(R_2+a) + K_2 R_2^2(\theta_2-\theta_1) + mg\theta_2(R_2+a) = 0 \tag{7}$$

$$P(R_1+R_2) + K_1 R_1^2 \theta_1 + K_2 R_1 R_2(\theta_2-\theta_1) - mg(R_1+R_2)\theta_1 = 0 \tag{8}$$

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where $\theta_2$ and $\theta_1$ are the rotation angles of the upper and the lower layers, respectively, $P$ is the horizontal force applied at the upper virtual center and $u_2$ is the horizontal displacement of the center of gravity of the suspended structure. $P$ is given by

$$P = -m\ddot{u}_2 - K_2 R_2(\theta_2 - \theta_1) \tag{9}$$

$u_2$ is given by:

$$u_2 = u_1 + (R_2 + a)\theta_2 = -(R_1 + R_2)\theta_1 + (R_2 + a)\theta_2 \tag{10}$$

The equations of motion with respect to $\theta_1$ and $\theta_2$ can be derived from Equations (7)–(10), and are given in the following matrix when defining $\theta_1 = A_1 \exp(\mathrm{i}\omega t)$, $\theta_2 = A_2 \exp(\mathrm{i}\omega t)$:

$$\begin{bmatrix} -\{I_\theta + m(R_2+a)^2\}\omega^2 + K_2R_2^2 + mg(R_2+a) & m(R_2+a)(R_1+R_2)\omega^2 - K_2R_2^2 \\ m(R_2+a)(R_1+R_2)\omega^2 - K_2R_2^2 & -(R_1+R_2)^2\omega^2 + K_1R_1^2 + K_2R_2^2 - mg(R_1+R_2) \end{bmatrix} \times \begin{Bmatrix} \theta_1 \\ \theta_2 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{11}$$

The frequency equation can be derived from the condition that the determinant of the above matrix vanishes. For the case where $R_1 = R_2 = R$ and $K_1 = K_2 = K$, the frequency equation is given by

$$C_1\omega^4 - 2C_2\omega^2 + C_3 = 0 \tag{12}$$

where

$$\begin{aligned} &C_1 = 4mR^2 I_\theta, \quad C_2 = I_\theta(KR^2 - mgR) + mK(R^2 + a^2)R^2 + m^2 g(R^2 - a^2)R \\ &C_3 = 2\{KR^2 + mg(R+a)\}(KR^2 - mgR) - K^2R^4 \end{aligned} \tag{13a–c}$$

The first- and the second-mode frequencies, $\omega_1$ and $\omega_2$, are given by the following equations for the case where $R_1 = R_2 = R$ and $K_1 = K_2 = K$:

$$\omega_1^2 = \frac{C_2 - \sqrt{C_2^2 - C_1C_3}}{C_1}, \quad \omega_2^2 = \frac{C_2 + \sqrt{C_2^2 - C_1C_3}}{C_1} \tag{14}$$

When $R$ $(= R_1 = R_2)$ is infinitely large, the vibration model reduces to an SDOF system with a double layer of rubber bearings (with horizontal stiffness $K$) at no inclination. The natural frequency of this SDOF system is $\omega_0 = \sqrt{K/(2m)}$. Figure 6 shows the relationship between the radius of gyration, $R$, and the ratios of the first- and second-mode periods, ($T_1 = 2\pi/\omega_1$ and $T_2 = 2\pi/\omega_2$) normalized to the natural period of the associated SDOF system with no bearing inclination ($T_0 = 2\pi/\omega_0$) for the same example of a 21-story suspended structure (Figure 7). Figure 6 demonstrates that the natural periods of the CSI model become longer with decreasing radius of gyration, $R$.

### *2.4. A building utilizing the CSI system*

A building utilizing the CSI system consists of two parts, as shown in Figure 7, where the dimensions are specified for the aforementioned numerical examples. One is a reinforced concrete core on top of which a seismic isolation mechanism comprising a circular, double layer of inclined laminated rubber bearings is installed. The other is a multi-level structure which hangs from the hat-truss or an umbrella girder which is constructed over the seismic isolation mechanism. Supplementary damping devices are installed between the core and the hung structure to suppress large relative earthquake displacements and restrain motion due to strong winds.

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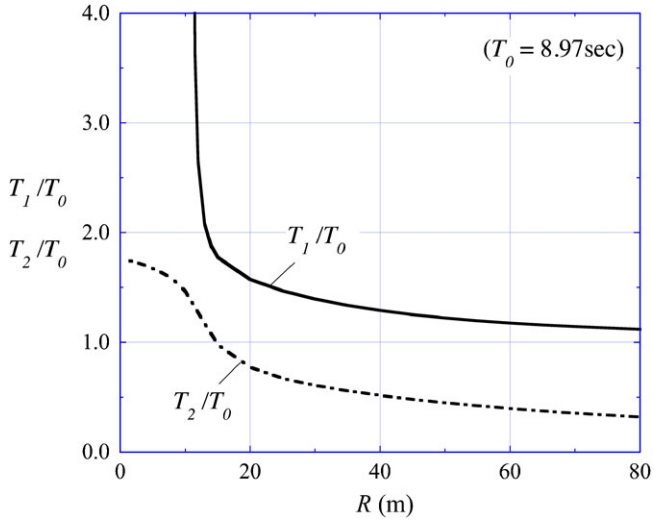


Figure 6. Relationship between the radius of gyration and the normalized first and second mode periods of the 2DOF system.

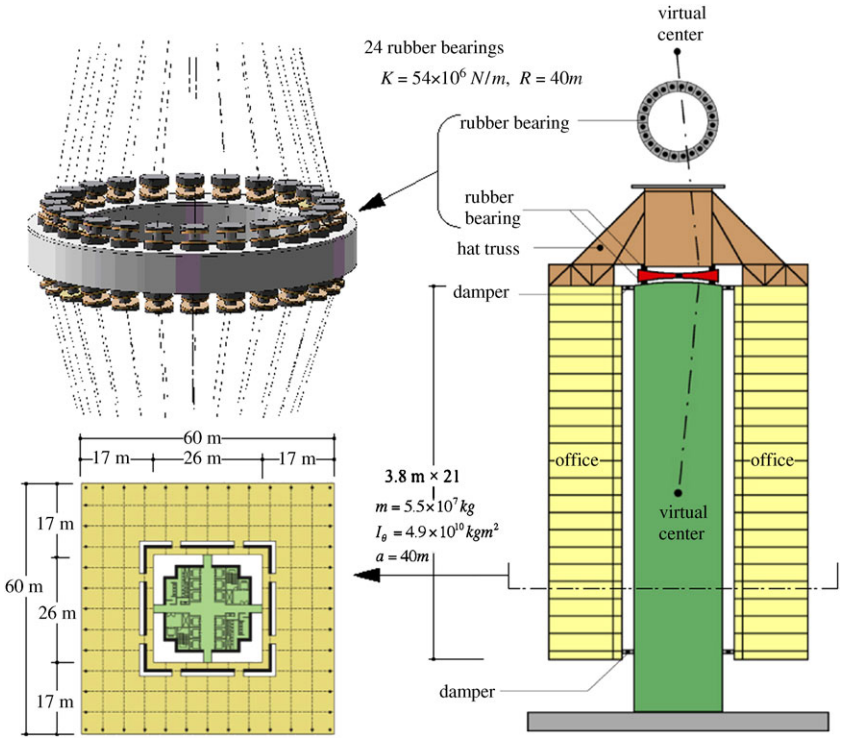


Figure 7. A prototype of the CSI system.

The advantages of the CSI system are the followings:

(1) The CSI system can achieve a practical pendulum isolation mechanism for suspended structures by a double layer of inclined rubber bearings that allows sway and swing motions of the hung structure, as well as, the rocking motion of the core, as shown in Figure 8. Because of high load capacity and durability of laminated rubber bearings, the CSI system is a practical pendulum isolation mechanism.

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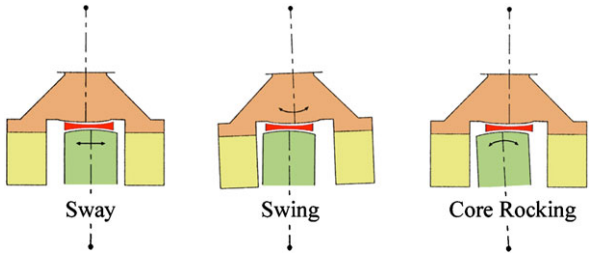


Figure 8. Vibration modes of a CSI structure.

(2) The tilting of the rubber bearing (or decreasing the radius of gyration) in the upper and the lower layers of the seismic isolation mechanism can elongate the natural period of the suspended structure several times beyond that of a standard base-isolation system with no bearing inclination. The CSI system can give the structure a natural period greater than 10 s that would be longer than the predominant period of expected long-period ground motions in the Tokyo area [22, 23].
(3) The CSI system can combine the seismic isolation effect and the architectural advantages of a suspended structure. Since steel bars, rods or cables are used for suspension members, the structure can have open and transparent façades. The bottom level can be column-free and provide open space, as illustrated in Figure 1.

## 3. SHAKING TABLE TESTS OF THE CSI SYSTEM

No prior work has investigated pendulum isolation using a double layer of inclined rubber bearings. Therefore, shaking table tests were undertaken to verify that such a mechanism would practically achieve the pendulum isolation effect, and that the natural period of the system is elongated by tilting of the rubber bearings in accordance with theory [18–21, 24]. The size and weight of the specimen were selected to be the biggest possible given the performance limits of the shaking table used, and the rubber bearings were selected to have the same level of the axial pressure as the actual four-level building described in Section 5.

Figures 9 and 10 shows the experimental model, which consisted of a structure hanging from the top beam constructed over the seismic isolation mechanism, comprising a double layer of inclined rubber bearings located on a stiff core-pedestal. The suspended structure consisted of six concrete cubes, the total weight of which was 17.1 ton. As shown in Figure 11, four rubber bearings, each with a measured horizontal stiffness of 110 N/mm, were inwardly inclined with the same tilt angle for the upper and lower layers. In order to study the effect of tilt angle, shaking table tests were conducted for two different angles, $\frac{1}{10}$ ($\phi = 5.7^\circ$, $R = 7.11$ m) and $\frac{1}{5}$ ($\phi = 11.3^\circ$, $R = 3.61$ m). No supplementary damping devices are installed here in the tests.

Figure 12 shows the first and second mode periods for the two tilt angles investigated, obtained from sinusoidal sweep tests with the theoretical curves given by Equation (14) with $m = 1.71 \times 10^4$ kg, $\boldsymbol{I}_\theta = 2.23 \times 10^4$ kg m$^2$, $K = 4.40 \times 10^5$ N/m, and $a = 1.60$ m for the experimental model. Figure 12 shows that tilting of the rubber bearings elongates the natural periods in accordance with the theory.

The earthquake response at the top of the core-shaft of the 21-story building (Figure 7) subjected to selected earthquakes was used as the input for the shaking table test. The earthquake motions selected include a simulated Kanto earthquake motion, the 1995 Hyogoken-Nanbu earthquake (JMA Kobe NS record), and the 1999 Chi-chi (Taiwan) earthquake (TCU129 EW record), each scaled to a peak ground acceleration of 1 m/s$^2$. Figure 13 shows the maximum response values for each part of the model, for the system with a bearing tilt angle of $\frac{1}{5}$. The maximum response of the hung structure is one-sixth to one-tenth that of the input, and demonstrates that a double layer of inclined rubber bearings provides very effective pendulum isolation.

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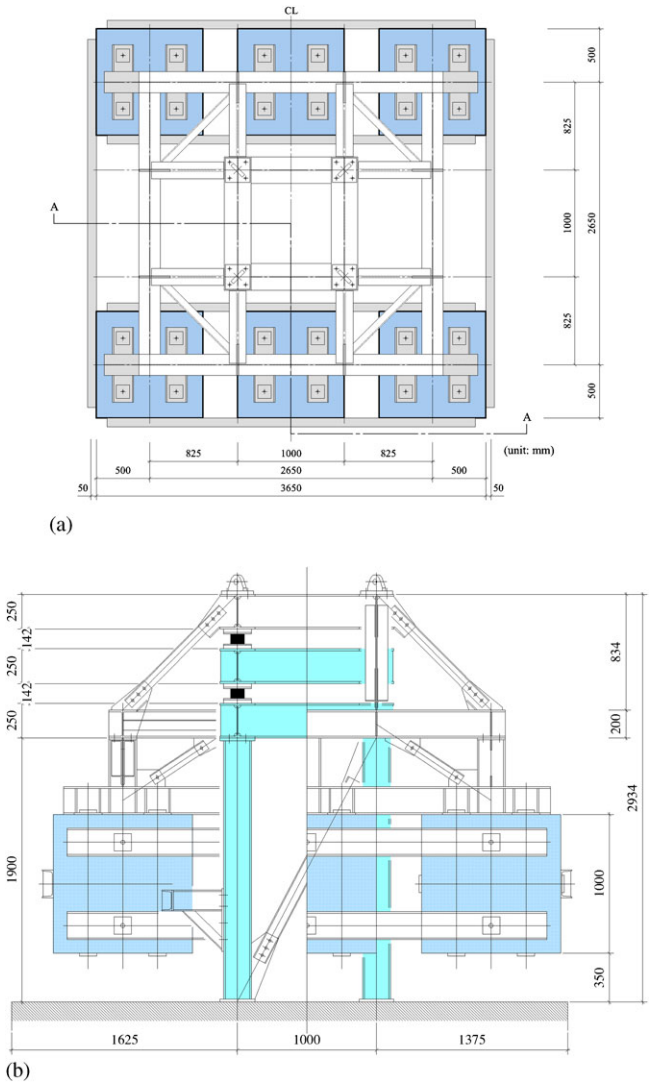


Figure 9. Schematics of the CSI system model for shaking table tests: (a) Plan view and (b) Section (A-A elevation view).

Figure 14 shows the responses at the upper layer of rubber bearings, for tilt angles of $\frac{1}{5}$ and $\frac{1}{10}$. The results indicate that the tilt angle is able to regulate the earthquake response without adjusting the stiffness of the rubber bearings and to play the role of a design parameter that is not available for conventional rubber bearing-based seismic isolation systems.

## 4. QUASI-STATIC LOADING TESTS OF RUBBER BEARINGS WITH FLANGE ROTATION

The seismic isolation mechanism of the CSI system employs a double layer of inclined rubber bearings. When the CSI system vibrates, the inclined rubber bearings undergo shear deformation and at the same time the upper flange plates rotate slightly relative to the lower flange plates, as shown in Figure 15. Quasi-static loading tests were performed to investigate the hysteresis characteristics of full-scale rubber bearings with flange rotation [18–21, 24], because of limited prior research, and only on small-scale rubber bearings [25–27].

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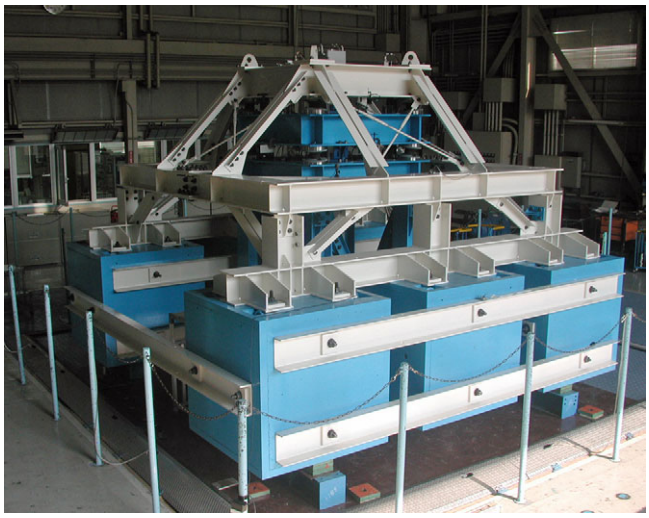

Figure 10. CSI system model on shaking table.

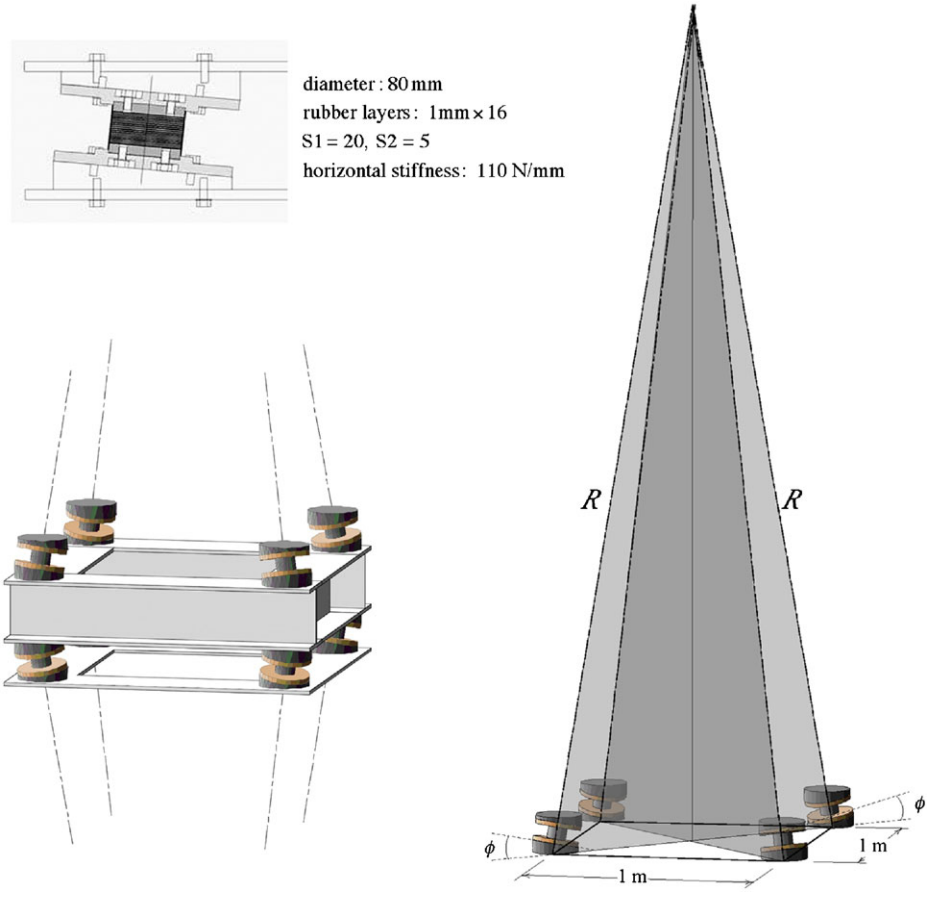


Figure 11. A double layer of four inclined rubber bearings.

The rubber bearings tested had the following characteristics: a diameter of 500 mm, 29 inner steel shims of 3.1-mm thickness and 30 rubber layers of 3.4-mm thickness. The shape factors for the bearings were $S1 = 36$ and $S2 = 4.9$, and the shear modulus, $G$, of the rubber was 0.39 MPa.

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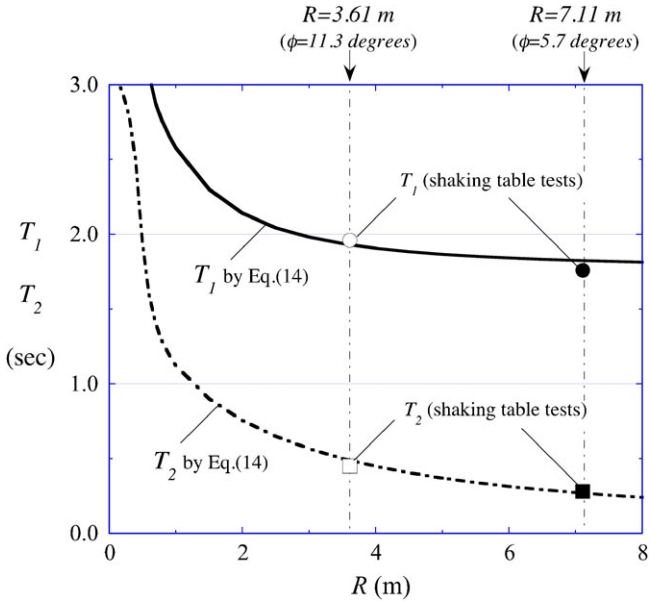


Figure 12. Natural periods of the experimental model.

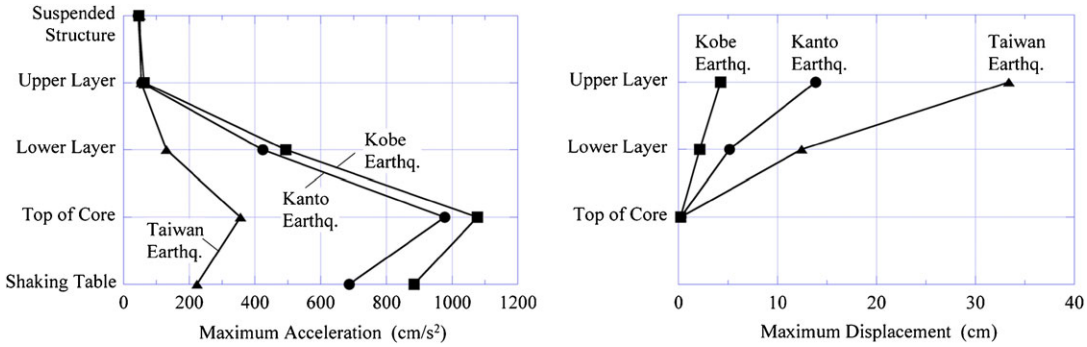


Figure 13. Maximum responses of the experimental model with a bearing tilt angle of $\frac{1}{5}$.

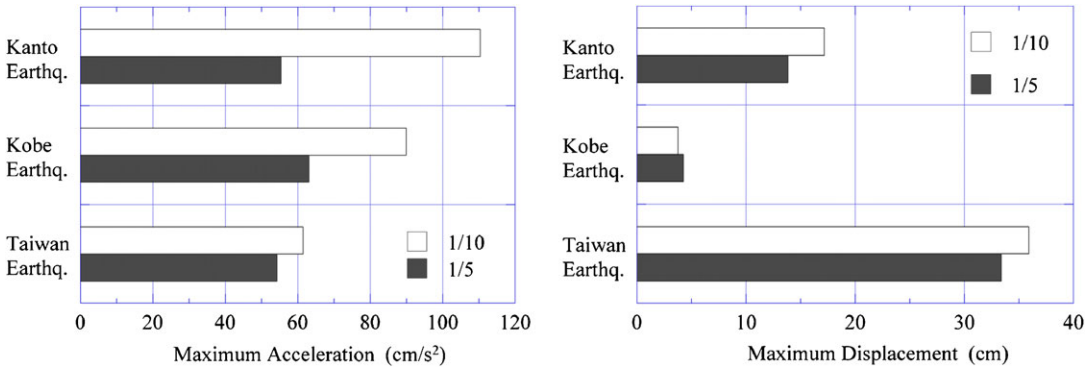


Figure 14. Maximum responses at the upper layer of rubber bearings, for tilt angles of $\frac{1}{5}$ and $\frac{1}{10}$.

The specimen was designed to be the largest possible, considering the performance limits of the testing machine used.

Figure 16 shows the relationship between horizontal deformation and shear force for the case of the rubber bearing with parallel flange plates and a compression stress of 14.7 MPa, along with that

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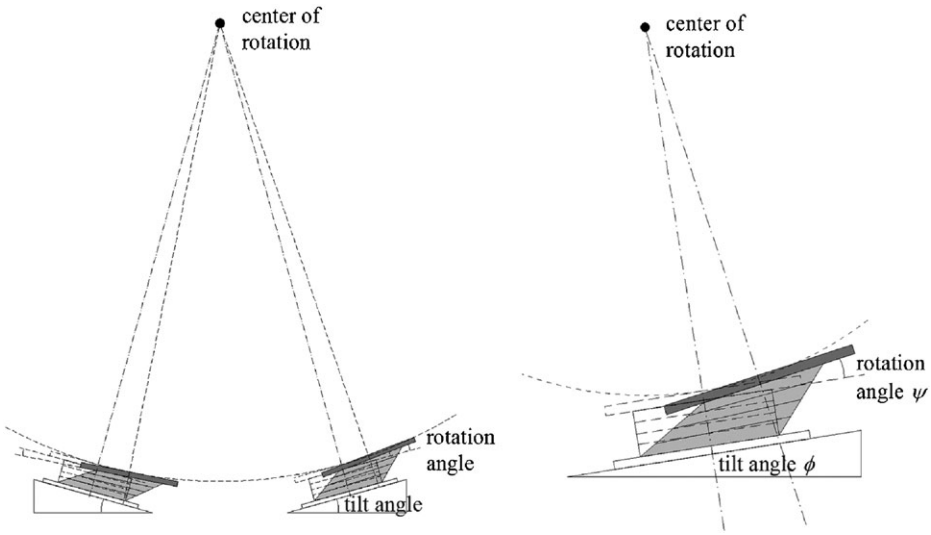


Figure 15. Deformation of inclined rubber bearings.

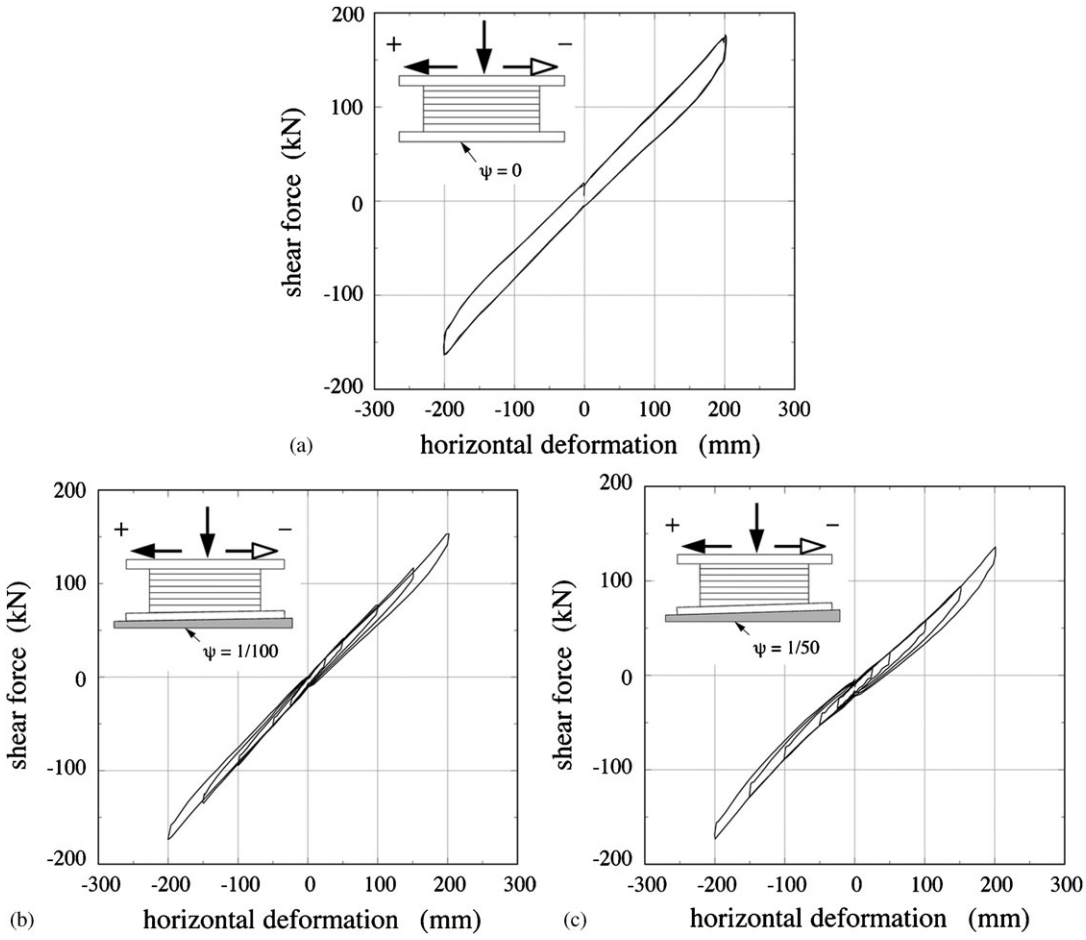


Figure 16. Relationship between horizontal deformation and shear force of rubber bearings with rotated flange: (a) parallel flange plates $\psi = 0$; (b) rotation angle $\psi = 1/100$; and (c) rotation angle $\psi = 1/50$.

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obtained for bearings with flanges rotated using tapered plates to rotation angles of $\psi = \frac{1}{100}$ and $\frac{1}{50}$. The corresponding radii of gyration, $R$, with $\psi = \frac{1}{100}$ and $\frac{1}{50}$, are $R = 20$ and 10 m, respectively, for the horizontal deformation of 200 mm. Figure 16 indicates that the horizontal stiffness, $K_H$, of a rubber bearing slightly decreases with increasing flange plate rotation $\psi$, and that $K_H$ for $\psi = \frac{1}{50}$ is about 94% of $K_H$ for $\psi = 0$. This finding is consistent with that of other similar research [25–27]. Although the hysteresis loop for a bearing with $\psi = \frac{1}{50}$ (Figure 16(c)) shows a slight hardening at larger displacements, $K_H$ can nonetheless be regarded as linear for analysis and design.

## 5. IMPLEMENTATION OF THE CSI SYSTEM

The CSI system is applicable to buildings of all heights, without any loss of system effectiveness (Figure 17). Because it was considered too large a step to first apply the system to a high-rise building, a four-level building utilizing the CSI system has been constructed in Tokyo, Japan, as the first application of the concept [20, 21]. The project was undertaken with the following objectives:

(1) To demonstrate the attractive architectural features of the CSI system.
(2) To prove the isolation effect of the CSI system through structural health monitoring.
(3) To implement the lift-up construction process for the suspended structure.

### *5.1. Overview of the first CSI system building*

Figures 18 and 19 show the four-level building with the CSI system constructed in Tokyo, Japan, and Table I gives design details of the building. The pendulum seismic isolation mechanism for the building consists of two layers each of four inclined rubber bearings installed at the top of a reinforced concrete core, from which three floors of office structure are suspended by high-strength steel rods.

Fluid dampers shown in Figure 20 are placed between the core shaft and the suspended office structure to control the motion of the building. A structural health monitoring (SHM) system is installed in the building [28]. The fluid dampers employ a safety lock mechanism which normally operates to hold the suspended office structure against wind loads, and which is automatically

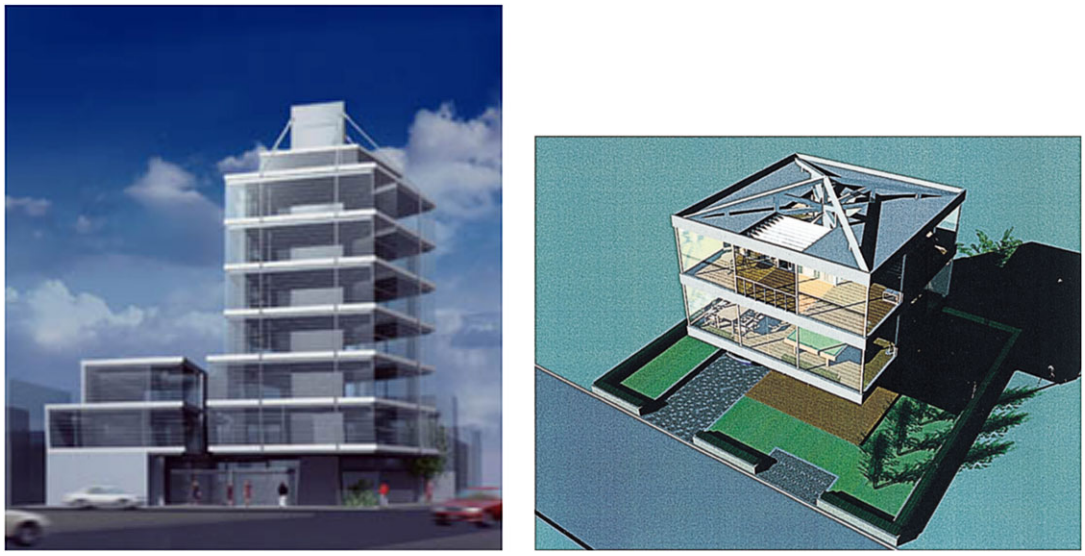

Figure 17. Examples of the CSI system for low-rise buildings.

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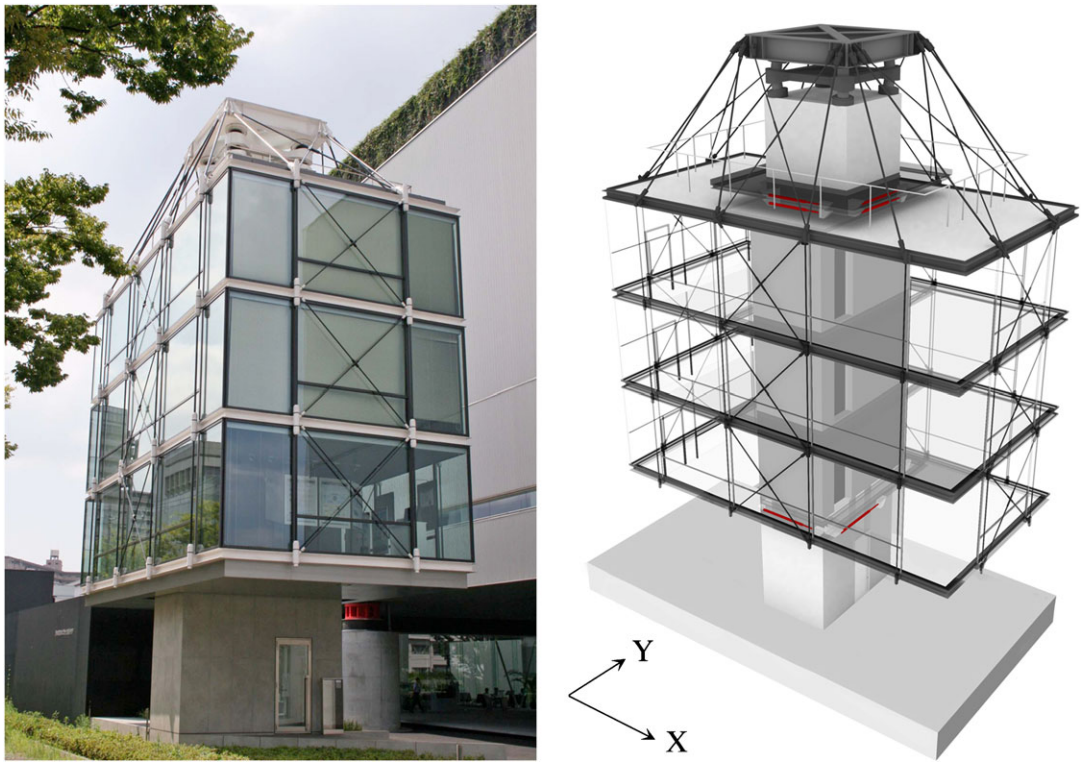


Figure 18. Photo and perspective drawing of the first CSI system building.

Figure 19. Pendulum seismic isolation mechanism, comprising two layers each of four inclined rubber bearings.

released in the event of earthquake when the ground motion exceeds the threshold value. The threshold values are set at $5\,\mathrm{cm/s^2}$ and $8\,\mathrm{cm/s^2}$ RMS over a 1-s duration in the horizontal and vertical directions, respectively.

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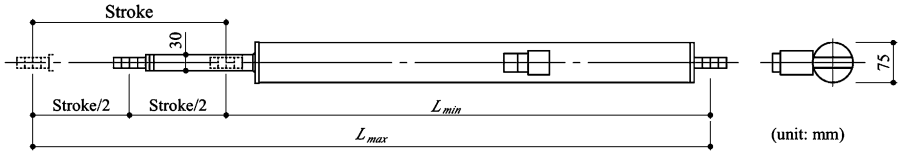
Table I. Details of the first CSI system building.

| Location | Institute of Technology, Shimizu Corporation, Koto-ku, Tokyo, Japan |
|---|---|
| Floor area | Total: 213.65 $m^2$, 1st floor: 9.05 $m^2$, 2nd–4th floor: 66.15 $m^2$, penthouse: 6.15 $m^2$ |
| Height | Total: 18.75 m, 1st story: 4.15 m, 2nd–4th stories: 3.0 m |
| Core shaft | Reinforced concrete wall 200 mm thick; 400 mm clearance joint |
| Suspended structure | Total weight: 180 ton; steel rod column 42 mm diameter |
| Rubber bearings | Diameter: 300 mm, inner steel shims: 1.2 mm × 45, rubber layers: 2.1 mm × 46, S1 = 35.7, S2 = 3.11, G = 0.29 MPa, horizontal stiffness = 215 kN/m |
| Tilt angles | Lower layer: $\phi_1 = 9.9$ degrees ($R_1 = 9.5$ m), Upper layer: $\phi_2 = 6.6$ degrees ($R_2 = 14.25$ m) |




| Maximum force (kN) | Limit velocity (m/s) | $L_{min}$ (mm) | $L_{max}$ (mm) | Stroke (mm) | Damping coefficient (kN s/m) | Lock force (kN) |
|---|---|---|---|---|---|---|
| 50 | 1.0 | 1480 | 2200 | 720 | 50 | 50 |

Figure 20. Fluid damper with a safety lock mechanism.

### *5.2. Design and analyses of the four-level CSI building*

The design of the four-level CSI building was developed to meet the target seismic performance defined in Table II. Figure 22 shows the velocity response spectra for the synthetic design earthquakes expected for the site. The spectra show that a 5 s natural period was a desirable target for the CSI system. The tilt angles of the rubber bearings and the properties and arrangement of fluid dampers were adjusted as design variables using the following procedure:

(1) Through eigenvalue analyses of the analytical model (Figure 21) without fluid dampers, the tilt angles of the rubber bearings in the lower and the upper layers were selected as shown in Table I and Figure 23 such that the sway motion of the suspended structure was predominant and the first mode period was around 5 s in both the $X$ and $Y$ directions (Figure 21).
(2) Through earthquake response analyses of the analytical model with the inclined rubber bearings as selected in (1), the number and the placement of the fluid dampers was selected so that the maximum building responses meet the performance criteria. An arrangement of four fluid dampers at the top of the suspended structure and two fluid dampers at the bottom of the suspended structure in each of the $X$ and $Y$ directions, as shown in Figure 21, was found to satisfy the target seismic performance.

Maximum rotations of the rubber bearings in the lower and the upper layers are $\frac{1}{16.3}$ and $\frac{1}{91.9}$, respectively, for level 2 input motions, as shown in Figure 23. As these rotations are within the range of the quasi-static loading tests of the rubber bearings with rotated flanges, the horizontal stiffness of the rubber bearing was assumed to be 94% of the design value for the earthquake response analyses.

Selected results of the earthquake response analyses for the level 2 input motions are shown in Figure 24. Each earthquake motion selected was scaled to a peak ground velocity of 0.5 m/s. Although the acceleration responses are amplified through the core shaft, the acceleration responses of the suspended structure are reduced significantly owing to the pendulum seismic isolation

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Table II. Target seismic performance for the four-level CSI building.

| | Level 1 input motion (moderate earthquake) | Level 2 input motion (severe earthquake) |
|---|---|---|
| Core shaft | Maximum stress within allowable unit stress | |
| Suspended structure | Story drift angle $<\frac{1}{200}$ | Story drift angle $<\frac{1}{100}$<br>Response acceleration $<2\,\mathrm{m/s^2}$<br>Relative displacement against core shaft $<300\,\mathrm{mm}$ |
| Rubber bearings | Maximum deformation is within level of stability ($=106\,\mathrm{mm}$)<br>Maximum shear strain $<110\%$ | Maximum deformation is within the level of performance ($=155\,\mathrm{mm}$)<br>Maximum shear strain $<160\%$ |

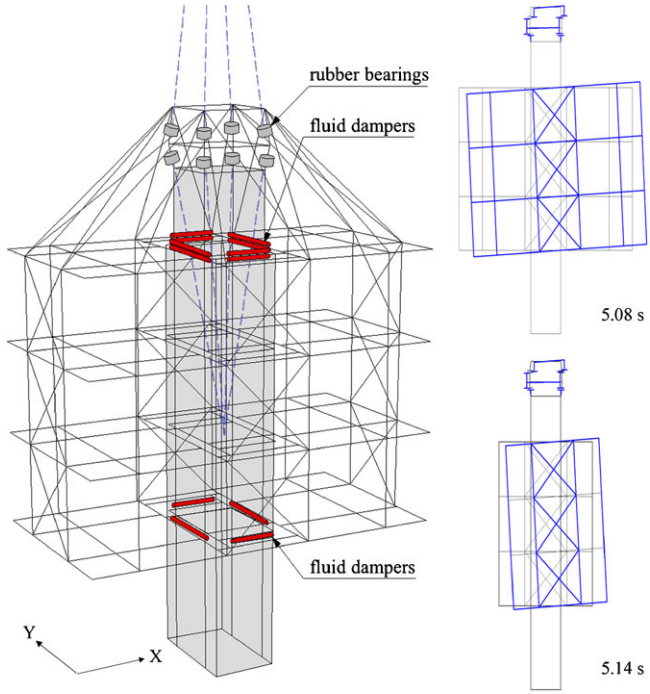


Figure 21. Analytical model and the first mode shapes in the $X$ and $Y$ directions.

mechanism. The essentially linear distribution of maximum floor displacement illustrates the pendulum isolation motion where the deformations of the rubber bearings are predominant.

## 6. CONCLUSIONS

The newly developed core-suspended isolation (CSI) system creates a practical pendulum isolation mechanism for suspended structures using a double layer of inclined rubber bearings on the top of a reinforced concrete core. In each of the upper and lower layers, rubber bearings are placed in a circular arrangement and inwardly inclined with the same tilt angle, so as to have a virtual center of rotation above or below the layer, and to create a virtual pendulum mechanism.

A double layer of inclined rubber bearings allows sway and swing motions of the suspended structure, as well as, the rocking motion of the core. The tilting of the rubber bearing (or decreasing the radius of gyration) in the upper and the lower layers serves to elongate the natural periods of the suspended structure to be several times longer than the natural period of a conventional

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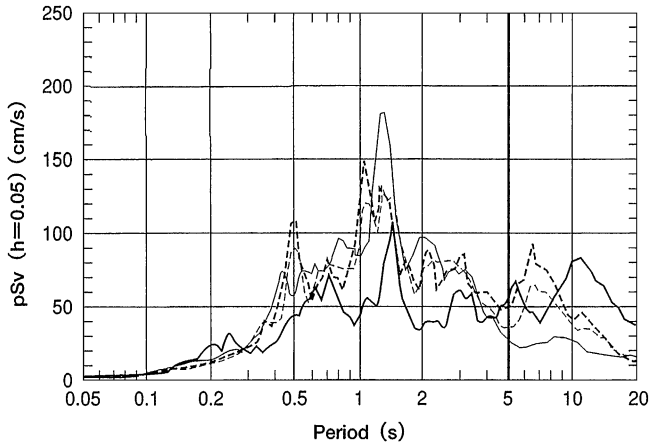


Figure 22. Velocity response spectra of the synthetic design earthquakes for the site.

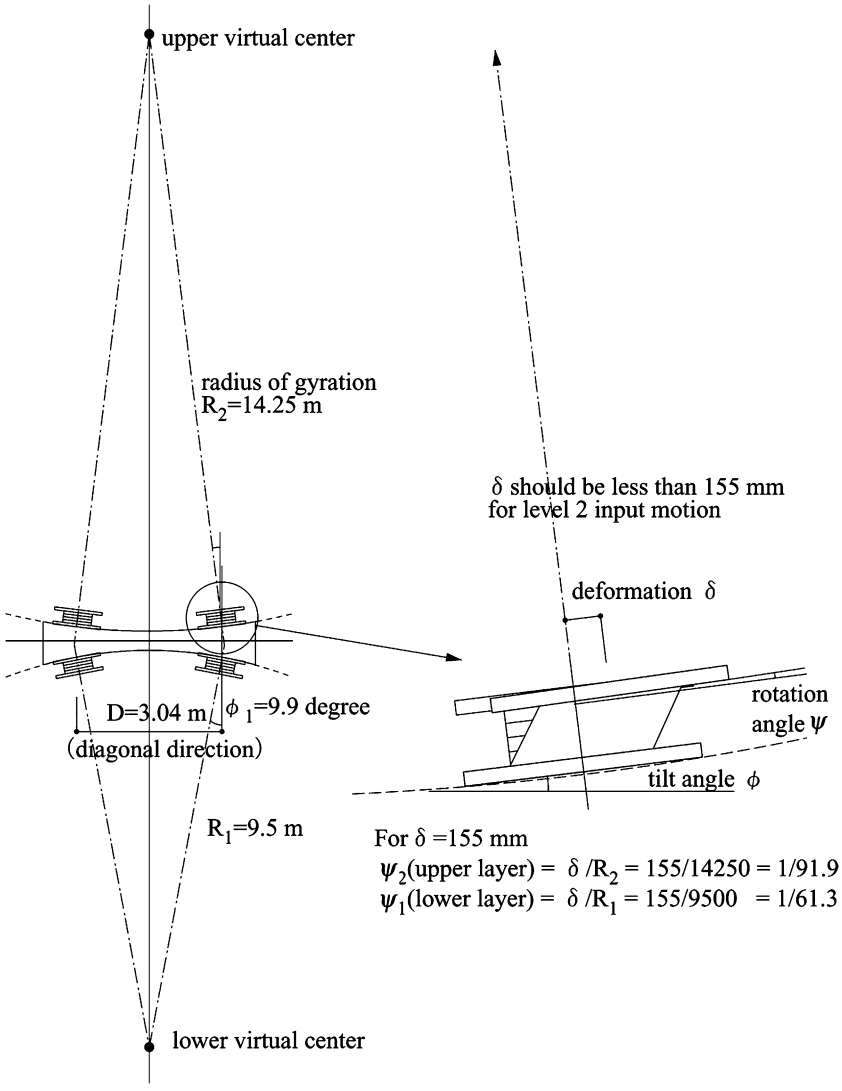


Figure 23. Upper and lower layer rubber bearing tilt angles and allowable bearing flange rotations.

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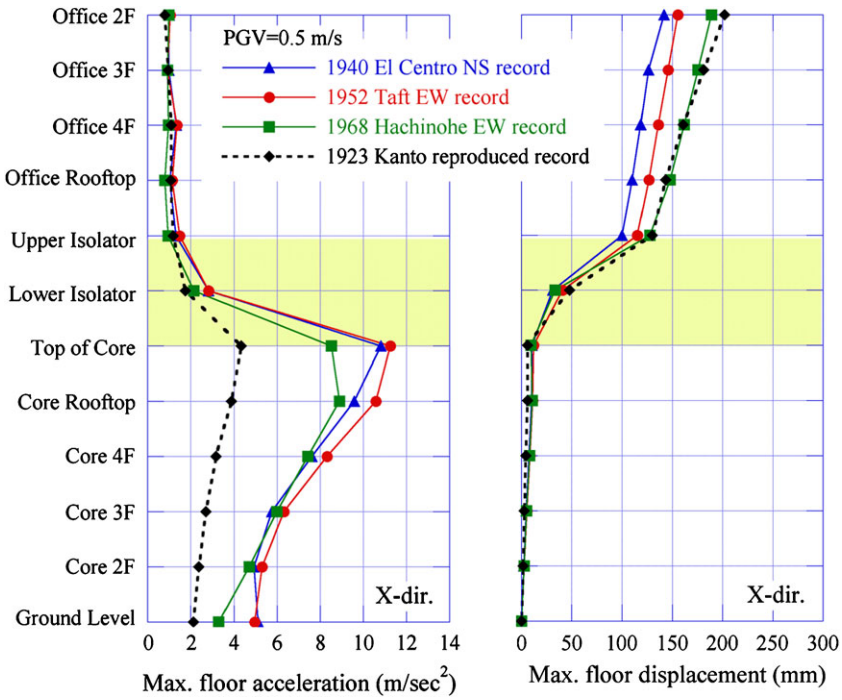


Figure 24. Maximum responses of the four-level CSI building for level 2 input motions.

seismic isolation system with bearings located at the base of the structure, and with no bearing inclination.

The results of shaking table tests of the CSI system demonstrated that the tilting of rubber bearings elongates the natural periods of the suspended structure in accordance with theory and that the tilt angle is able to regulate the earthquake response without adjusting the stiffness of the rubber bearings and to play the role of a design parameter that is not available for conventional seismic isolation systems.

The upper flange plate of the rubber bearing in the CSI system rotates slightly relative to the lower flange plate when the tilted rubber bearing undergoes shear deformation around the virtual center of rotation. The results of quasi-static loading tests of rubber bearings with rotated flange plates indicate that the horizontal stiffness of a rubber bearing decreases slightly with increasing rotation, which should be taken into consideration in analysis and design.

A four-level building utilizing the CSI system has been constructed in Tokyo, Japan. The seismic isolation mechanism for the building consists of two layers each of four inclined rubber bearings installed at the top of a reinforced concrete core, from which three floors of office structure are suspended by high-strength steel rods. In addition to having high seismic performance, the building utilizing the CSI system has attractive architectural features, including a transparent facade as only thin steel rods rather than columns are needed to support the floors, as well as achieving usable open space beneath the structure.

The CSI system concept is a new and high performance means of seismic isolation that presents new opportunities for the enhanced seismic protection of buildings.

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