DEVELOPMENT OF THE CORE-SUSPENDED ISOLATION SYSTEM

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ABSTRACT :

A new type of seismic isolation system – called the core-suspended isolation system (CSI) – has been recently developed and implementation completed in the first building in Tokyo, Japan. The core-suspended isolation 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. An office or residential structure is then suspended from a hat-truss constructed on the seismic isolation mechanism, isolating it from the motion of the core. In this paper the mechanics of the CSI system are described, followed by a discussion of results obtained from shaking table tests conducted on scale models and static loading tests of inclined rubber bearings, and an overview of the first building constructed utilizing the system.

KEYWORDS: core-suspended isolation, core-shaft, double layer, inclined rubber bearings, pendulum

1. INTRODUCTION

A conceptual drawing of a new type of seismic isolation system called the core-suspended isolation system (CSI) is shown in Fig. 1. The core-suspended isolation 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. An office or residential structure is then suspended from a hat-truss constructed on the seismic isolation mechanism, isolating it from the motion of the core.

In this paper, the mechanics of the CSI system are first described, followed by the results of shaking table tests of a scale model and static loading tests of full-scale rubber bearings. Similar to the configuration that would be used in full-scale structures, the shaking table tests of the 1/16-scale model employed a double layer of inclined rubber bearings. The static loading tests presented here are carried out to investigate the hysteresis characteristics of full-scale rubber bearings under rotational and horizontal displacements. Finally, an overview of the first building with four stories utilizing the CSI system is given. 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.

Figure 1 A conceptual drawing of the CSI system

2. MECHANICS OF CORE-SUSPENDED ISOLATION

A building utilizing the CSI system consists of two parts. One is a reinforced concrete core on top of which a seismic isolation mechanism composed of a double layer of inclined rubber bearings is installed. The other is an office or residential structure which hangs from the hat-truss which is constructed over the seismic isolation mechanism (Fig.2).

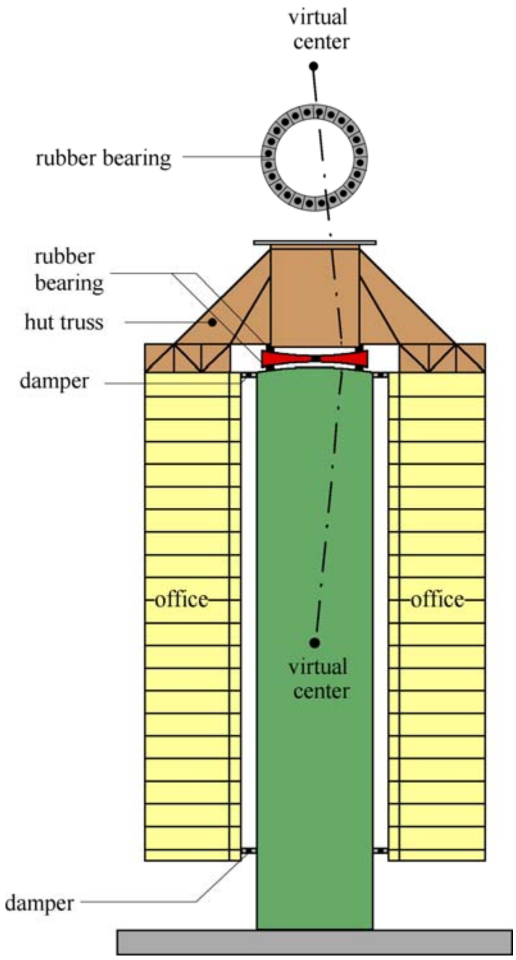


Figure 2 The CSI system

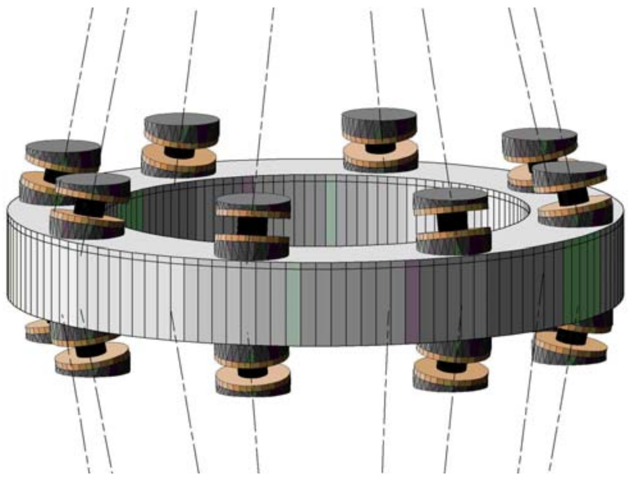


Figure 3 A double layer of inclined rubber bearings

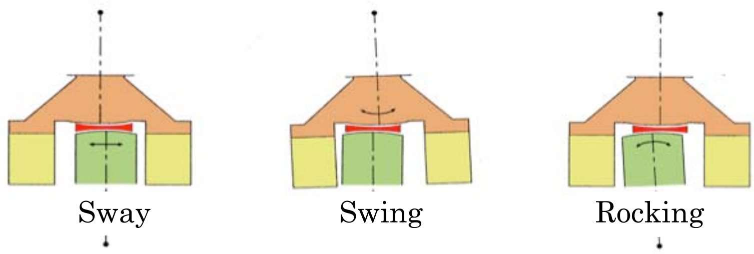


Figure 4 Motions of the seismic isolation mechanism

In each of the upper and lower layers, rubber bearings are placed in a circle and inwardly inclined with the same tilt angle so as to have a virtual center of rotation, as shown in Figs. 2 and 3. The seismic isolation mechanism allows sway and swing motions of the hanging structure, as well as, the rocking motion of the core, as shown in Fig.4.

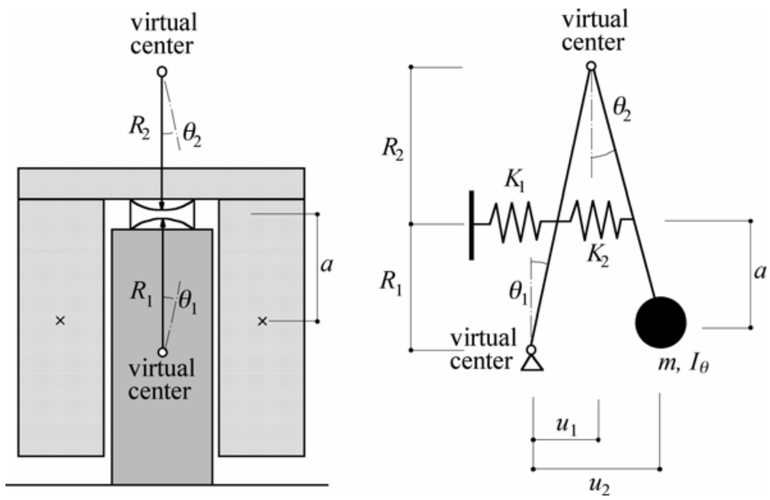


Figure 5 2DOF model of a building of the CSI system

If the deformations of the suspended structure and the core are small compared to those of the seismic isolation mechanism, the suspended structure and the core can be regarded as rigid bodies. A simplified model of a structure utilizing the CSI system can be expressed as a 2DOF system as shown in Fig. 5. In this figure, R_1 and R_2 are the lower and upper radius 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; m and I_θ are the total mass and the rotational inertia of the suspended structure (including the hat truss), respectively, and a is the position of the center of gravity of the suspended structure (including the hat truss).

The equations of motion and the natural frequencies of the 2DOF model in Fig.5 have been presented previously by the research group (Takahashi et al., Satake et al.). The first- and the second-mode frequencies, ω_1 and ω_2, are given by the following equations for the case where R_1=R_2=R and K_1=K_2=K:

$$\omega_1^2 = \frac{C_2 - \sqrt{C_2^2 - C_1 C_3}}{C_1}, \qquad \omega_2^2 = \frac{C_2 + \sqrt{C_2^2 - C_1 C_3}}{C_1} \tag{2.1}$$

where
$$C_1 = 4mR^2 I_\theta, \quad C_2 = I_\theta\left(KR^2 - mgR\right) + mK\left(R^2 + a^2\right)R^2 + m^2 g\left(R^2 - a^2\right)R$$
$$C_3 = 2\left\{KR^2 + mg\left(R+a\right)\right\}\left(KR^2 - mgR\right) - K^2 R^4 \tag{2.2}$$

When R (=R_1=R_2) reaches infinity, the vibration model reduces to a SDOF model with a double-layer of rubber bearings (with horizontal stiffness K) at no inclination. The natural frequency of this SDOF model is $\omega_0 = \sqrt{K/(2m)}$. Fig. 6 shows the relationship between the radius of gyration, R, and the ratios of the first- and second-mode periods, (T_1=2π/ω_1 and T_2=2π/ω_2) normalized to the natural period of the associated SDOF system with no bearing inclination (T_0=2π/ω_0) for a 21-story building utilizing the CSI system. For the study presented here, $m = 3455(t \cdot \sec^2/m), I_\theta = 3.21 \times 10^6 (t \cdot m \cdot \sec^2), a = 39.9(m), K = 3820(t/m)$.

Fig. 6 demonstrates that the natural periods of the CSI model become longer with decreasing radius of gyration, R. Fig. 7 shows the first and second mode shapes for R=50 m. It is seen that in the first mode, the lower and the upper layer of bearings deform in the same direction, with the upper layer's deformation being greater than that of the lower. In the second mode, the deformation of the lower bearing is predominant.

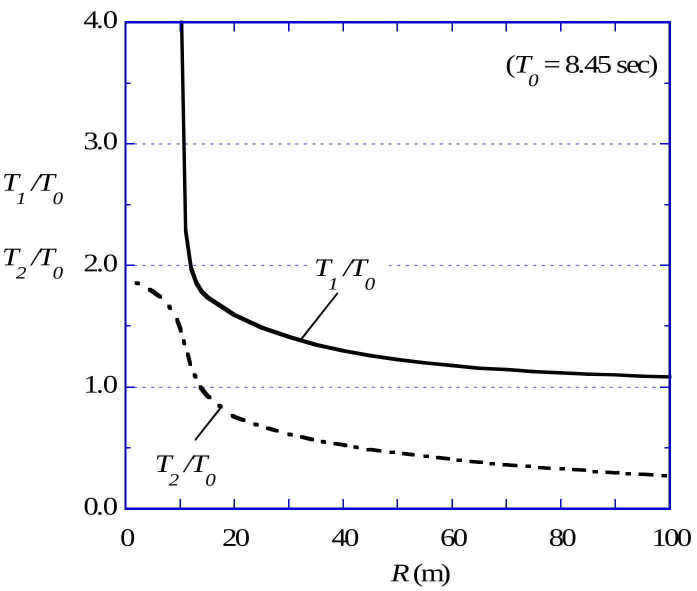


Figure 6 Relationship between the radius of gyration and the normalized first and second mode periods of the 2DOF model

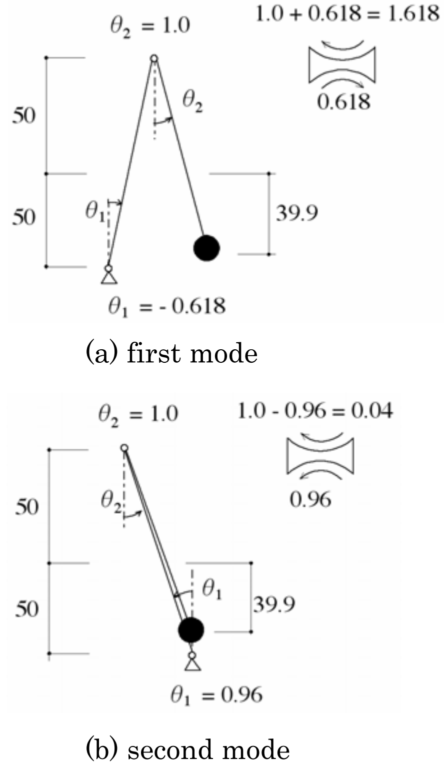


Figure 7 The first and second mode shapes for R = 50 m

3. SHAKING TABLE TESTS

Shaking table tests of a 1/16-scale model of a 21-story building utilizing the CSI system have been carried out to verify the dynamic performance of the system. Fig. 8 shows the experimental model, which consists of a structure hanging from the hat-truss constructed over the seismic isolation mechanism composed of a double layer of inclined rubber bearings on a stiff core-pedestal. The suspended structure consists of six concrete cubes, the total weight of which is 17.1 ton. As shown in Fig. 9, four rubber bearings, with horizontal stiffness equal to 126 N/mm, are inwardly inclined with the same tilt angle in the upper and lower layers. In order to study the effect of the tilt angle, the shaking table tests were conducted for two angles, 1/10 and 1/5.

Table 1 lists the first and second mode periods obtained from sinusoidal sweep tests with the values obtained through eigenvalue analyses (Saruta et al., Hori et al.). The tests indicate that in the first mode the hung structure sways, whereas, in the second mode the suspended structure rocks. The theoretical natural period for the case where the rubber bearings are installed with a zero tilt angle is 1.64sec. Table 1 indicates that the tilting of rubber bearings elongates the natural periods, and that the values obtained from eigenvalue analyses agree well with the experimental values.

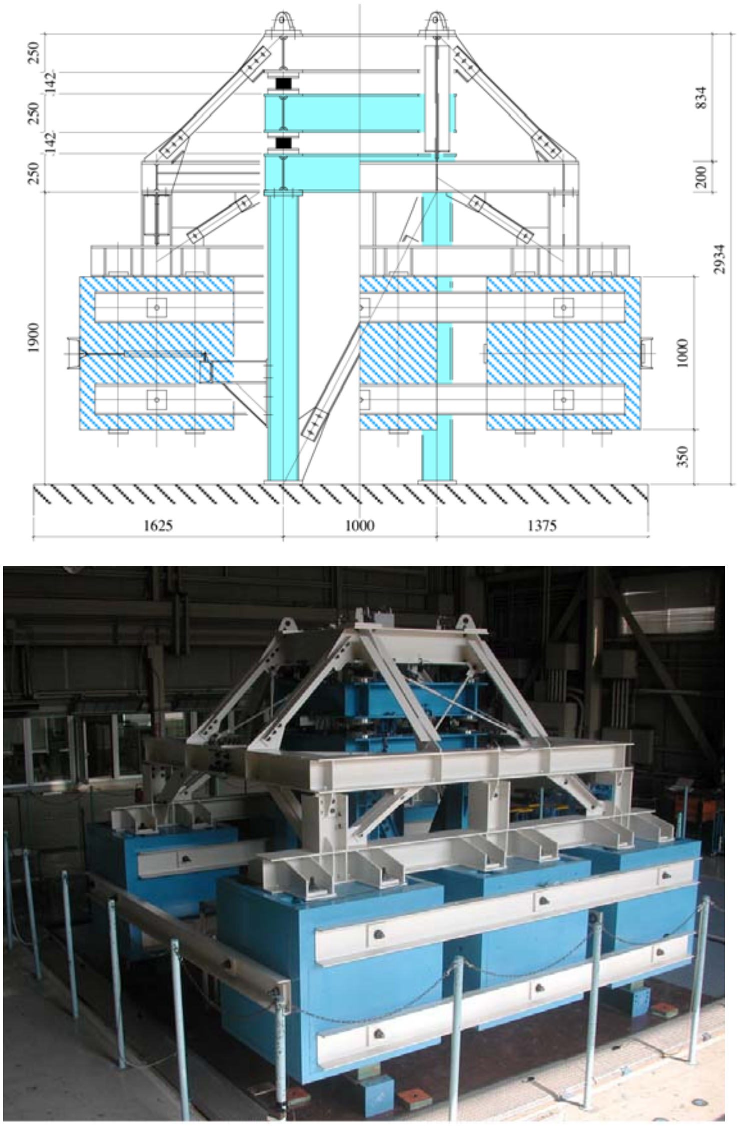


Figure 8 1/16-scale model

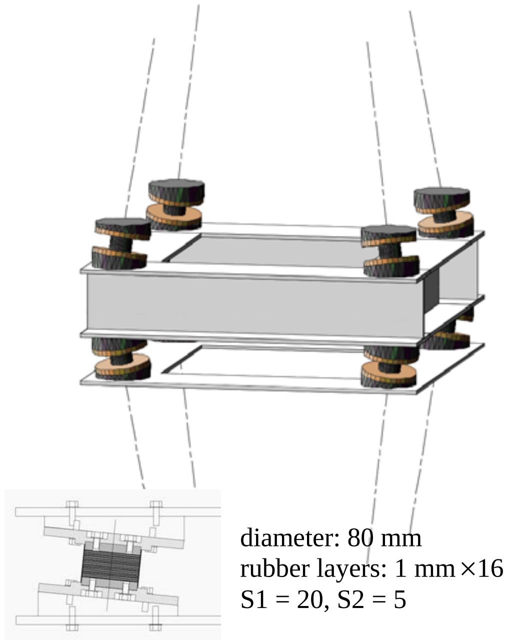


Figure 9 A double layer of four tilted rubber bearings

Table 1 Natural periods (sec)

Tilt angle		1st	2nd
0	Analysis	1.64	-
1/10	Analysis	1.80	0.32
	Experiment	1.76	0.28
1/5	Analysis	1.96	0.49
	Experiment	1.96	0.45

Fig.10 shows the maximum response values for each part of the model with a bearing tilt angle of 1/5. The maximum response of the hung structure is one-sixth to one-tenth that of the input, and thus demonstrates the ability of the CSI mechanism to significantly isolate the suspended structure. Fig. 11 shows the response on the upper layer of the rubber bearings for tilt angles of 1/5 and 1/10. It is seen that the maximum acceleration for the tilt angle of 1/5 is about 10 to 30% less than that for the tilt angle of 1/10.

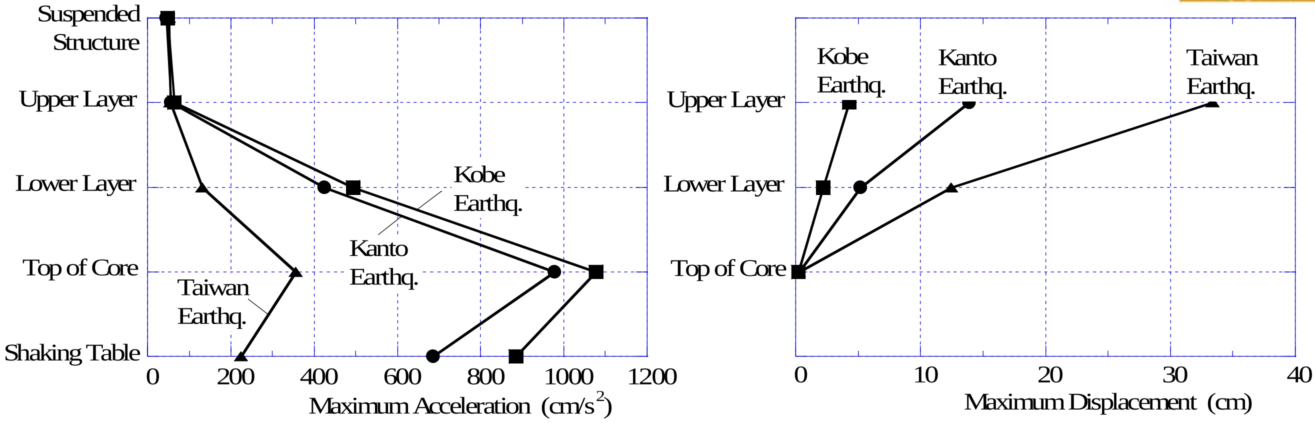


Figure 10 Maximum responses of the 1/16-scale model with a bearing tilt angle of 1/5

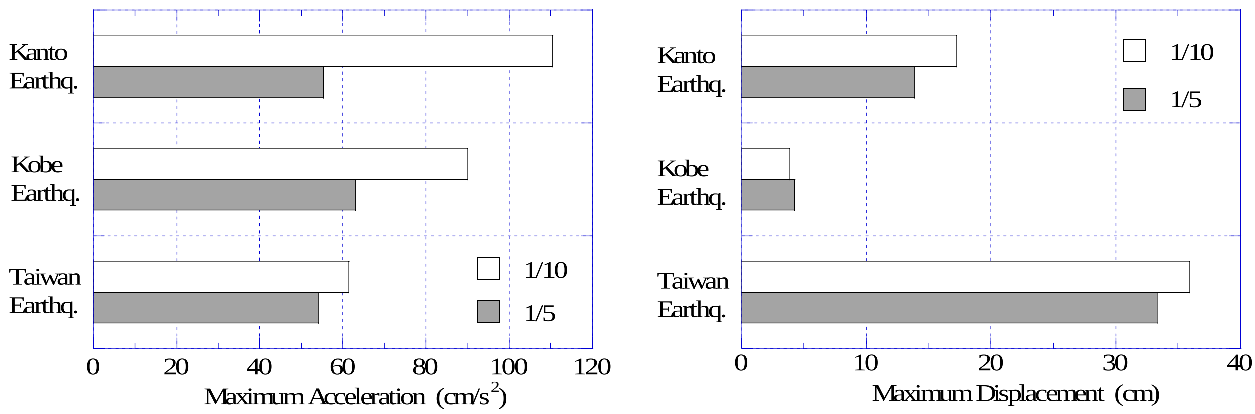


Figure 11 Maximum responses on the upper layer of the rubber bearings for tilt angles of 1/5 and 1/10

4. STATIC LOADING TESTS OF RUBBER BEARINGS

The seismic isolation mechanism of the CSI system employs a double layer of inclined rubber bearings. The rubber bearing undergoes shear deformation while the upper flange plate rotates relative to the lower flange plate as shown in Fig.12. Static loading tests have been carried out to investigate the hysteresis characteristics of full-scale rubber bearings under imposed rotational and horizontal displacements.

Fig.13 shows the loading frame with four jacks in the vertical direction and one jack in the horizontal direction. The rubber bearings tested had the following features: 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 are S1 = 36 and S2 = 4.9 and the shear modulus of elasticity, *G*, of the rubber is 0.39 MPa.

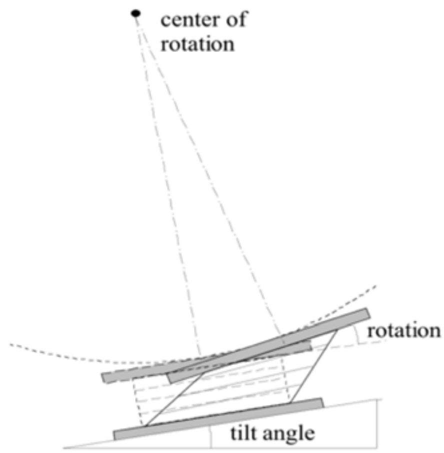


Figure 12 Deformation of rubber bearings

Fig.14 shows the relationship between the moment and the rotation of the flange of the rubber bearing under different contact pressures together with the calculated value. Fig.14 demonstrates that the rotational stiffness, K_θ, of a rubber bearing can be adequately estimated by the theory under a certain level of contact pressure.
Fig. 15 shows the relationship between the horizontal deformation and shear force for the case of no inclination of the rubber bearing, along with that obtained for bearings which are inclined (using tapered plates) to 1/100 and 1/50. Fig. 15 indicates that the horizontal stiffness, K_H, of a rubber bearing slightly decreases with increasing inclination, and that K_H for θ=1/50 is about 94% of K_H for θ=0. Although the hysteretic

property for θ=1/50 shows a little hardening at larger displacements, K_H can be regarded as linear in analysis and design.

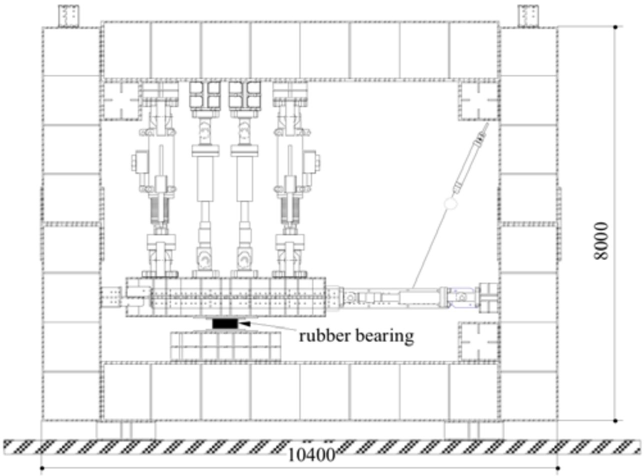


Figure 13 Loading frame

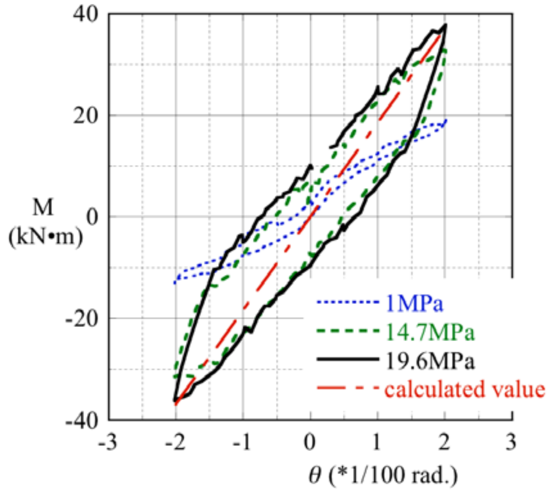


Figure 14 Moment-rotation relationship

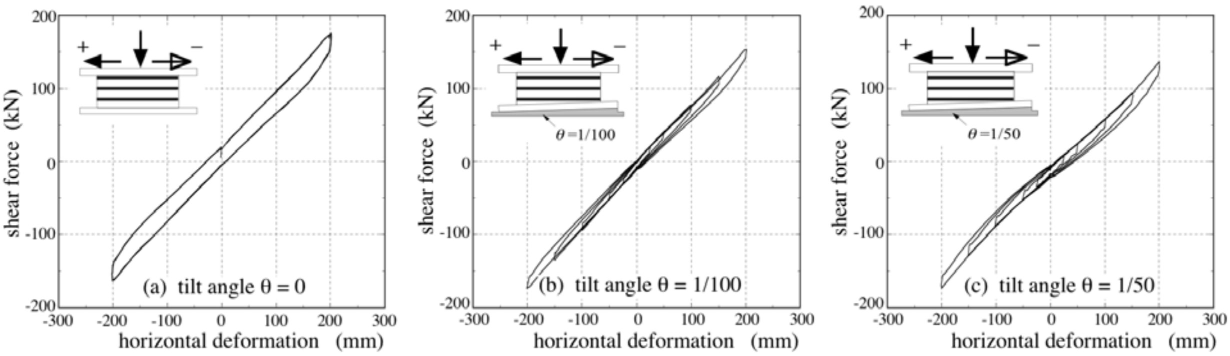


Figure 15 Relationship between horizontal deformation and shear force of inclined rubber bearings

5. IMPREMENTATION OF THE CSI SYSTEM

A four-story building utilizing the CSI system has been constructed in Tokyo, Japan (Table 2, Figs. 16 and 17). 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. Fluid dampers are placed between the core and the second and top level floors to provide additional damping to control the motion of the suspended structure.

Table 2 Overview of building utilizing the CSI system

Site	Institute of Technology, Shimizu Corporation, Koto-ku, Tokyo, Japan
Floor space	total area:213.65 m^2, 1st floor:9.05 m^2, 2nd-4th floor:66.15 m^2, penthouse:6.15 m^2
Height	total height:18.75 m, 1st story:4.15 m, 2nd-4th story: 3.0 m
Core shaft	reinforced concrete wall 200 mm thick, 40 cm clearance joint
Office structure	total weight of suspended structure: 180 ton, steel rod column 42 mm diameter
Rubber bearing	diameter: 300 mm, inner steel shims: 1.2 mm×45, rubber layers: 2.1 mm×46, S1 = 35.7, S2 = 3.11, G = 0.294 MPa
Tilt angles	lower layer: 9.9 degrees (R_1 = 9.5 m), upper layer: 6.6 degrees (R_2 = 14.25 m)


Figure 16 Appearance and perspective drawing of building utilizing the CSI system

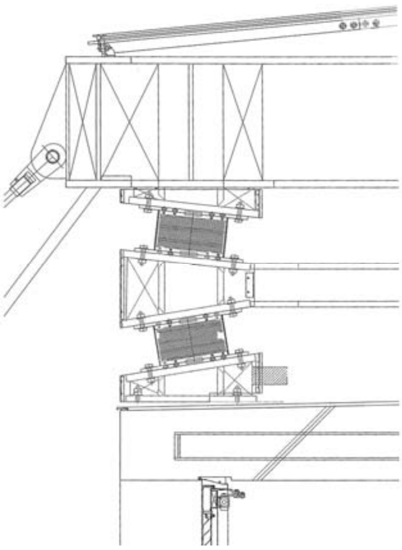
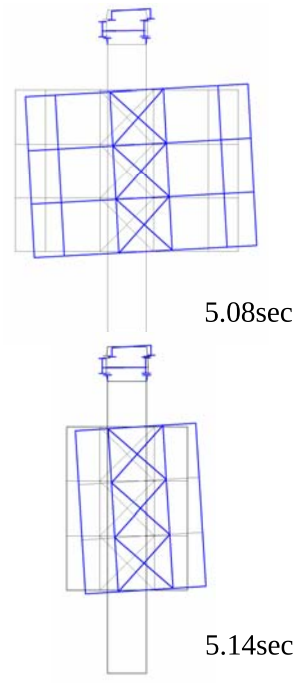



Figure 17 The seismic isolation mechanism of two layers each of four inclined rubber bearings

The first mode shapes in the longitudinal (X) and lateral (Y) directions are shown in Fig. 18. The sway motion is predominant in both directions. The natural periods are longer than 5sec, which reveals that the CSI system can elongate the natural periods of the structure.

Selected results of the earthquake response analyses of the building are shown in Fig. 19. They show that the seismic isolation mechanism of the CSI system can decrease the earthquake responses of the suspended structure significantly, and secure the high seismic performance.



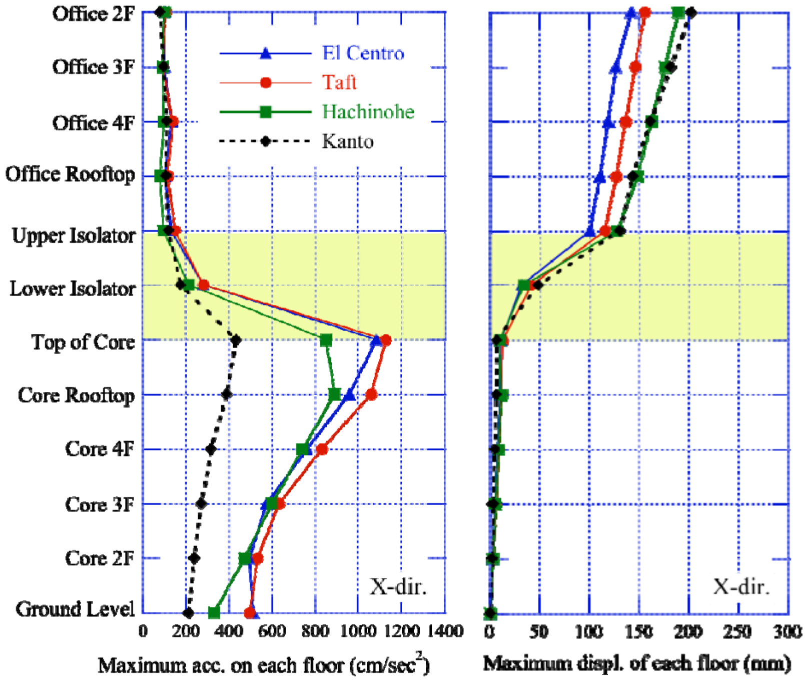


Figure 18 The first mode shapes in X and Y dirs.

Figure 19 Maximum responses of the building

6. CONCLUSION

The newly developed core-suspended isolation (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. An office or residential structure is then hung from a hat-truss constructed over the seismic isolation mechanism on the core. The tilting of the rubber bearings is found to elongate the natural periods.

The results of shaking table tests demonstrated the ability of the seismic isolation mechanism to effectively isolate the suspended structure. The results of static loading tests of inclined rubber bearings demonstrated that the horizontal stiffness of a rubber bearing slightly decreases with increasing inclination.

A four-story 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.

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