SEISMIC RESPONSE CONTROL OF A SOFT-FIRST-STORY BUILDING

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ABSTRACT:

The building plane is 7.75m×8.35m and the height is 47.8m. The height/width is over 6. Because of the building form, it became difficult to control the building response for not only seismic loading but also wind loading. So, we planed to change the vibration mode from the rocking-mode to the sway-mode by softening the translation stiffness at the first story, and to make the first story into the energy-absorbing story by concentrating the building deformation. We call this system the soft first story structure. The system consists of the following three items; a) to stiffen the structure above the second story, b) to make columns of the first story flexible laterally and rigid axially, c) to develop the hardening-type oil-damper. In this paper, it is reported about details of these structural elements and the dynamic performance of the proposed response control system against wind and seismic loadings throughout the time history response analysis.

KEYWORDS: soft-first-story, passive response control, slender building, P-Δ effect

1. INTRODUCTION

Soft-first-story building is a kind of passive response-controlled building. The concept is similar to the seismic isolated building. By softening the horizontal stiffness of the first story, the deformation of the building under seismic or wind loadings are concentrated to the first story and the input energy is absorbed at the first story effectively.

The steel building shown in photo 1 and figure 1 was completed in 2005 at Ginza, Tokyo, JAPAN. The usage is a clinic. The construction site is located at downtown and the construction area is very small. The building plane is 7.75m×8.35m and the height is 47.8m. The ratio of the height to the width, that is, aspect ratio is over 6. Such a slender building tends to increase the seismic and wind-induced response. Then, we needed the response control system to work well for both of seismic and wind loading, and soft-first-story response control system was adopted in this building.

In this paper, we report details and response analysis results of this response control system.

2. SOFT FIRST STORY RESPONSE CONTROL SYSTEM

2.1. Structural system

Usual slender buildings vibrate with rocking mode. In case of rigid framed structure and braced structure, it is difficult to control the deformation and acceleration at the top of the building because the main horizontal deformation component of the rocking mode is due to the axial deformation of the columns (figure.2 (a)). Moreover, slender buildings have the problem of habitability by wind-induced vibration. To improve the habitability, Tuned Mass Damper (TMD) at the top of the building or viscous dampers at every story as the response control devices are installed generally. But, the amount of the additional damping by TMD is very small and viscous dampers do not fully work because the story deformation is very small. So, authors developed a new response control system called “soft-first-story response control system”. The characteristics of this system are to increase the horizontal stiffness of story above the second floor level and to decrease the horizontal stiffness at the first story. By transforming the vibration mode shape to the sway mode (figure.2 (b)) from the rocking mode (figure.2 (a)), the horizontal deformation of the whole deformation of the building is concentrated into the first story. Oil-dampers are installed at the first story, and the deformation and acceleration at the top of the building are able to be controlled effectively because input energy of earthquake or strong wind is absorbed intensively. By the application of this system, we could also control the seismic response.

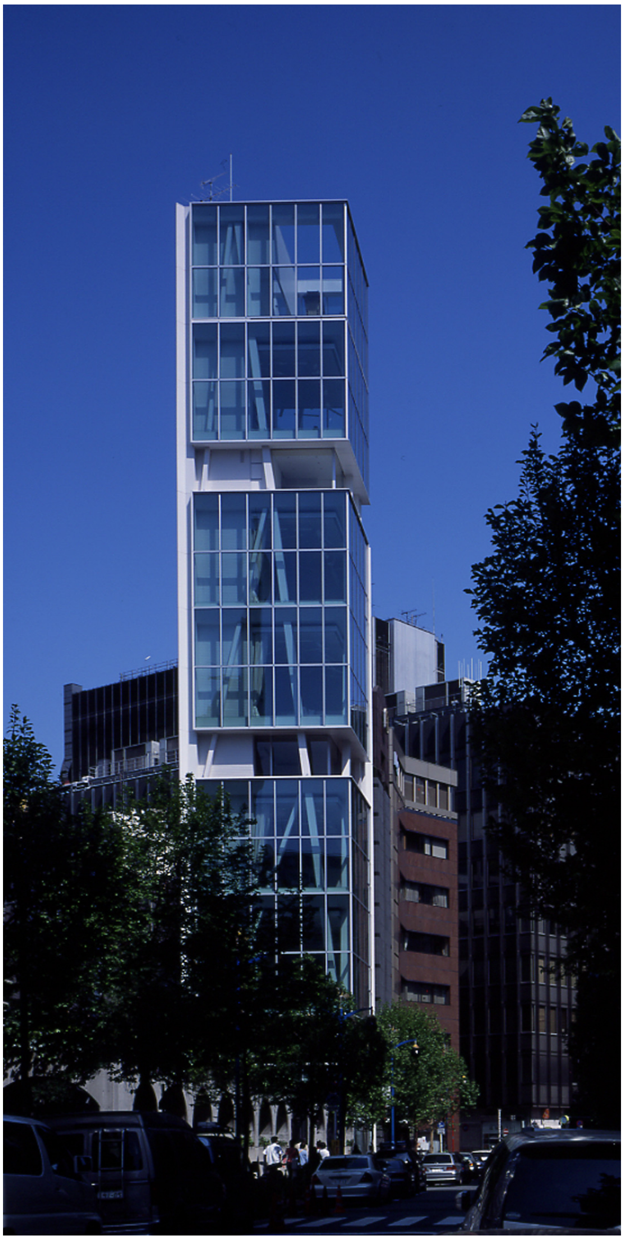


Photo 1 Outward of the building

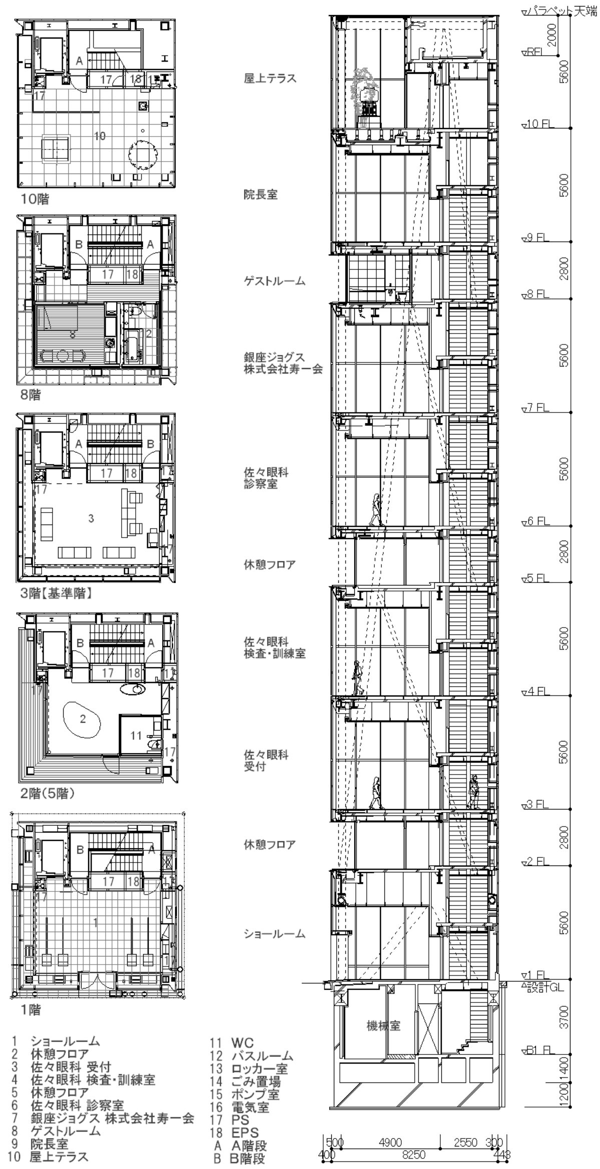


Figure 1 Plans and section of the building

And the following is the practical measures.

1) This building has 10 stories. The bracing structure is adopted for the second to tenth stories to increase the horizontal stiffness of the building.
2) Slender steel column with full section was developed to soften the horizontal stiffness of the first story.
3) The building response was controlled by oil-dampers installed at the first story. Especially, the hardening type of oil-damper was developed for this building.

4) A fail-safe mechanism is set up for the unexpected seismic input level.
5) The final important topic is P-Δ effect of the slender steel column statically and dynamically. "Soft-first-story system" has the following characteristics.

The structural system is shown in figure 3 visually.

2.2. *Slender steel column*

The first important point to achieve "soft-first-story system" is how to make of flexible column and how to transform the vibration mode from rocking mode to sway mode. The required performance of such a column is to be high stiffness for axial direction, to be low stiffness for bending and not to yield for the story deformation angle 1/100. As the solution, we have developed a slender steel column with full section using high strength steel, SA440, as the material. The yield point of SA440 steel is 440 N/mm^2. The cross section of the slender column is 240mm×240mm which is laminated by three steel plates of 80mm×240mm. Three plates are welded with groove depth of 40mm as shown in figure 4. The comparison by FEM analysis was carried out to clarify that is the section property of the slender steel column of three plates 80mm×240mm is almost equal to the full square section. The model and results are given at Table 1. The difference of the horizontal stiffness was 0.7%. Then, it is clarified that the developed slender steel column with full section is very effective.

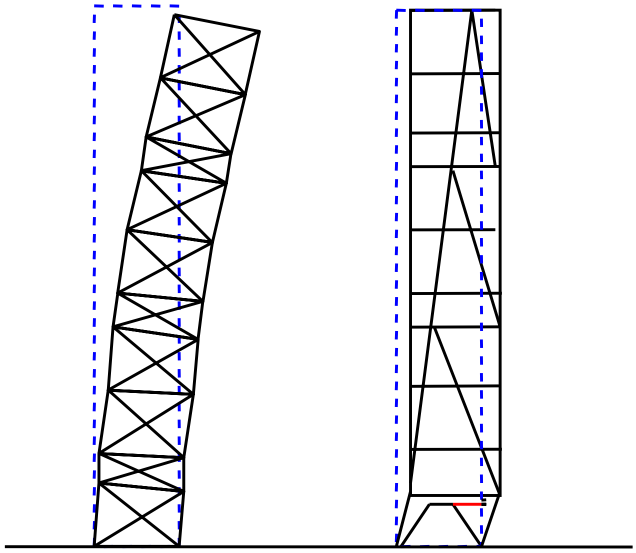


Figure 2 Vibration Mode

2.3. *Hardening-type of oil-damper*

The second important point to achieve "soft-first-story system" is how to control the response. Oil-damper as response control devise is very effective. Especially, hardening-type of oil-damper has developed for this building. In the relationship of damping force and response velocity of usual oil-damper, the second damping coefficient is smaller than the first one. But, the second damping coefficient is larger than the first one in this hardening-type of oil-damper. The relationship of damping force and response velocity is shown in figure 5. The first damping coefficient is set to the optimal value by the results of complex eigen-value analysis as shown in figure 6. This value is effective for wind loading. For seismic loading, the larger value is adopted so that the damper fills role of brake so that the building don't deform over the story deformation angle of 1/100. Figure 7 shows the relationship of load and displacement of the damper in the region of minute amplitude based on test. Figure 8 shows the relationship of load and

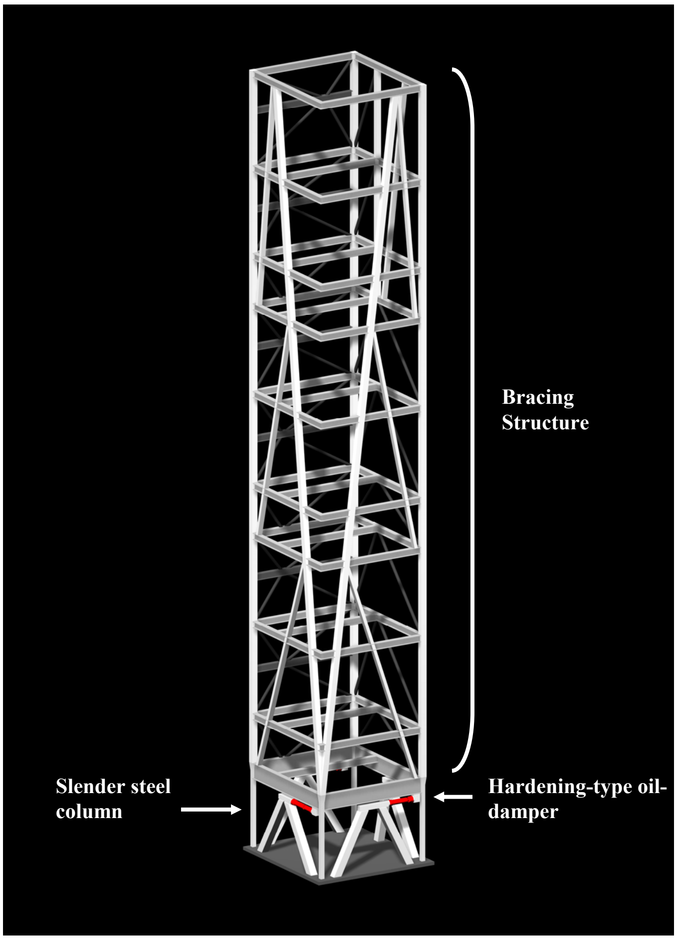
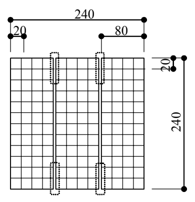
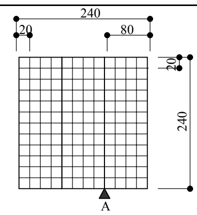


Figure 3 Structural System

displacement of the damper in the region of large amplitude based on theory.

Table 1 FEM analysis result comparison

Model	3-PL80x240 welding material	Full square section steel 240×240
Section of analysis model B = 240mm D = 240mm L = 5000mm		
Total horizontal deformation	75.16mm	74.64mm
Bending deformation (theory value)	74.5mm	74.5mm
Shear deformation	0.66mm	0.14mm
Maximum shear stress.	(Welded section) 22.38N/mm2	(A-part) 13.33N/mm2

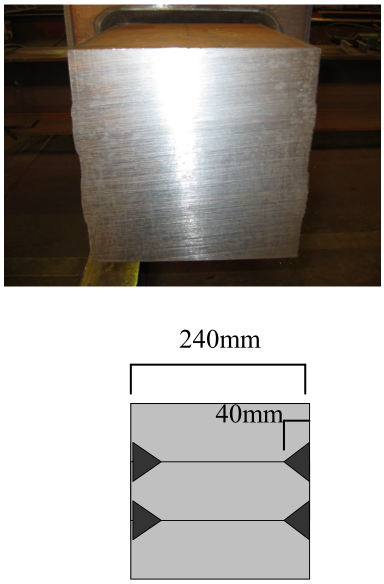


Figure 4 Cross Section of Slender Steel Column （Welded column of 3PL -80x200）

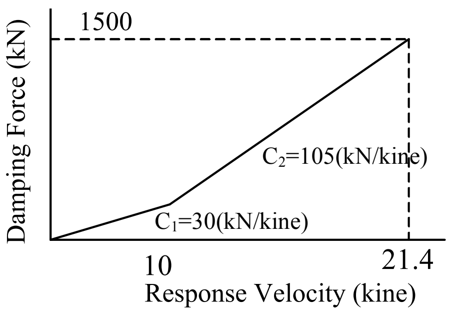


Figure 5 Relationship of damping force and response velocity

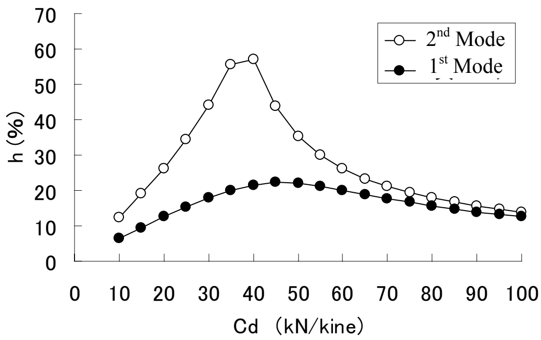


Figure 6 Relationship of Damping Coefficient C_d and Damping ratio h

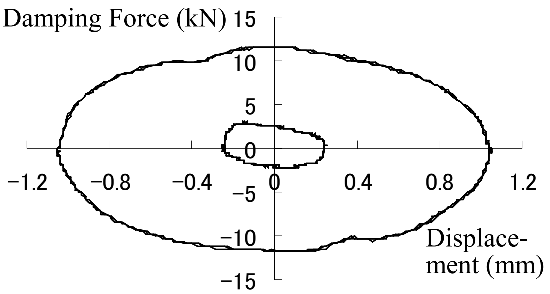


Figure 7 Relationship of load and displacement in the region of minute amplitude

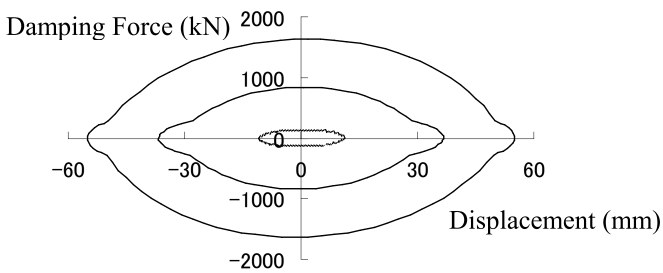


Figure 8 Relationship of load and displacement in the region of large amplitude

2.4. *Fail safe mechanism*

When the top and bottom of the column at the first story yield and the first story collapse by the huge earthquake over the design seismic input, the braced frames supporting oil-dampers work as the fail safe mechanism. The collapse process is shown in figure 9. First, the building behaves the elastic state. Next, when columns at the first story yield, the building will reach to the state 1. Finally, the building will get on the braced frames as the state 2 and the building will be able to avoid from the collapse. The building will reach the state 2 at the story deformation angle of 1/34, and at this moment, the deformation in the up-down direction is 2mm.

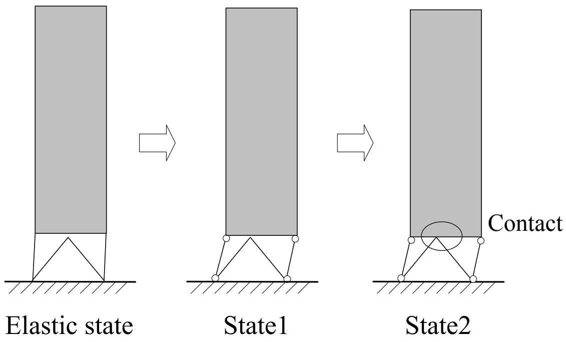


Figure 9 Collapse Process

3. P-Δ EFFECT

P-Δ effect is very important problem as a structural stability problem. We designed the slender steel column of this building in consideration of this problem.

3.1. *Effective length factor*[1)]

The bottom of the slender column is embedded into the sub-structure and the top of the slender column connects the girder at the second floor. The effective length factor K is calculated from Eq. (1).

$$\frac{G_A G_B (\pi / K)^2 - 36}{6(G_A + G_B)} = \frac{\pi / K}{\tan(\pi / K)}, \quad G = \frac{\sum (I_c / l_c)}{\sum (I_g / l_g)} \tag{1}$$

where I is the moment of inertia, l is length of member, suffix c means column and suffix g means girder.

The properties of the slender column and the girder at the second floor are as follows. Size of the slender column is 240mm×240mm, I_c=2.76×108mm^4, l_c=5200mm, size of the girder is H-950×300×22×36, I_g=5.75×109mm^4 and l_g=6750mm. From these values, G_A=0.0515 is obtained. And GB=∞ is assumed because the condition of the bottom of the column is fixed. Substituting GA and GB into Eq. (1), K=1.0 is obtained.

3.2. *Moment amplification factor for P-Δ effect*[1)]

Next, we take into account the moment amplification factor A_F for the P-Δ effect caused by the horizontal deformation Δ under the lateral loading. The factor AF is given by Eq. (2).

$$A_F = \frac{1}{1 - \dfrac{N\Delta}{HL}} \tag{2}$$

where N is axial force, H is lateral force and L is story height.

Then, the design moment for the column becomes $M_D=A_F \cdot M_c$. From L=5200mm, N=5743kN, D=45.1mm and H=177kN, A_F=1.39 is obtained.

3.3. M-N interaction curve for column design[2)]

As M-N interaction curve for the slender column, formulas in Ref. 2) are adopted. Eq. (3) is used for short term and eq. (4) is used for elastic limit state.

$$\frac{\sigma_b}{f_b}+\frac{\sigma_c}{f_c}\leq 1 \quad \text{: for allowable stress state} \qquad (3)$$

where σ_b is bending stress, σ_c is compressive stress, f_b is the allowable bending stress and f_c is the allowable compressive stress.

$$\frac{N}{N_{cr}}+\frac{M}{M_{pc}}\leq 1 \quad \text{: for elastic limit state} \qquad (4)$$

where

$$N_{cr}/N_Y\,1.0 \qquad \text{for } 0\leq\bar{\lambda}\leq 0.3$$

$$N_{cr}/N_Y=1-0.545(\bar{\lambda}-0.3) \quad \text{for } 0.3<\bar{\lambda}\leq 1.3$$

$$N_{cr}=N_e/1.3 \qquad \text{for } 1.3<\bar{\lambda}$$

$$\bar{\lambda}=\frac{1}{\pi}\sqrt{\frac{\sigma_y}{E}}\lambda \quad \text{: non-dimensional slenderness ratio}$$

$$N_y=\sigma_y\cdot A \quad \text{: yield strength}$$

$$N_e=\frac{\pi^2 EI}{l_k^2} \quad \text{: Euler's buckling strength}$$

l_k : effective buckling length

$$\frac{M_{pc}}{M_p}+\left(\frac{N}{N_y}\right)^2=1$$

M_{pc} is plastic moment with axial loading and M_p is plastic moment without axial loading.

Response moments and axial forces of slender columns from time history analysis are plotted in figure 10 and 11. The plotted bending moments are multiplied by the P-Δ moment amplification factor A_F.

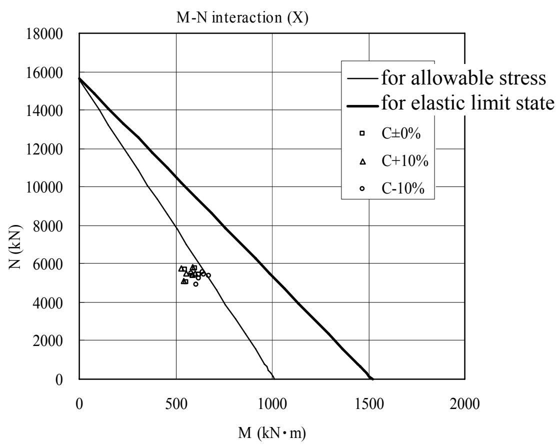


Figure 10 Moment and axial force of slender column for X-direction seismic input of level 2

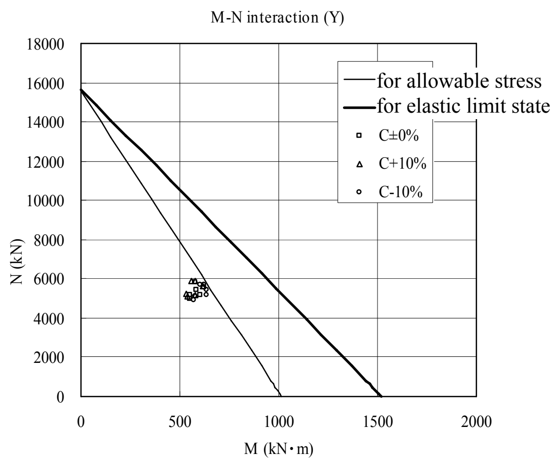


Figure 11 Moment and axial force of slender column for X-direction seismic input of level 2

4. TIME HISTORY RESPONSE ANALYSIS

4.1. Analysis model

The story stiffness of the main frame are estimated by rotating spring giving the bending deformation component and shear spring giving the shear deformation component as shown in figure 12. The structural damping ratio is assumed 2% for the natural frequency.
Results of the eigen-value analysis are shown in figure 13. In this figure, the first to third mode shapes are indicated. The deformation ratio at the first story to the total deformation in the first mode shape is 45%. Therefore, it is confirmed that the first mode became sway mode shape.

4.2. P-Δ effect in time history analysis

The equation of motion for single-degree of freedom system under P-Δ effect is given by Eq. (5).

$$m\ddot{x} + kx - \frac{mg}{h} \cdot x = f(t) \tag{5}$$

$$\therefore m\ddot{x} + \left(k - \frac{mg}{h} \right) x = f(t)$$

Here, $-mg/h$ gives a negative stiffness for P-Δ effect. For the horizontal stiffness of the first story, this negative stiffness is taken into account of time history analysis. In practice, the horizontal stiffness of the first story is 19040N/mm. The building weight above the second floor is 6780kN. The story height is 5200mm. Then effective stiffness is

$$19040 - 6780000/5200 = 19040 - 1304 = 17736 \text{N/mm}$$

The ratio of this negative stiffness to the horizontal stiffness of the first story is about 7%.

4.3. Analysis results

It is performed to compare the response of “soft-first-story system” and a usual braced structure. The stiffness at the second to tenth story of the braced structure for comparison is same as “soft-first-story system” and the stiffness at the first story is assumed same as the second story.
Some article seismic waves are used in time history analysis. The intensity of seismic input is two levels, that is, “Level 1 seismic wave” and “Level 2 Seismic wave”. The maximum accelerations at the ground of Level 1 seismic wave are 110 to 140 cm/sec^2. On the other hand, the maximum accelerations at the ground of Level 2 seismic wave are 500 to 580 cm/sec^2.
Figure 14 shows the comparison with the response accelerations for the level 1 seismic wave. The response acceleration at the top of the building with “soft-first-story system” is very small in comparison with responses of the usual braced structure. The effect to control the response acceleration is confirmed.
Figure 15 shows the comparison with the response displacements for the level 2 seismic wave. It is found that the response displacement of this system concentrates into the first story. At the time, the story deformation angle at the first story is 1/110. It is confirmed that the response satisfied the design criteria of 1/100.

5. CONCLUSIONS

It was reported about “soft-first-story system” as a response control system developed by authors. Four technical elements organizing this system were introduced, that is, upper bracing frame, slender steel column, hardening-type of oil-damper and fail safe mechanism. And the design method of the slender column was introduced in consideration with P-Δ effect. Finally, the validity of this structural system was confirmed throughout time history analysis in consideration with P-Δ effect, too.

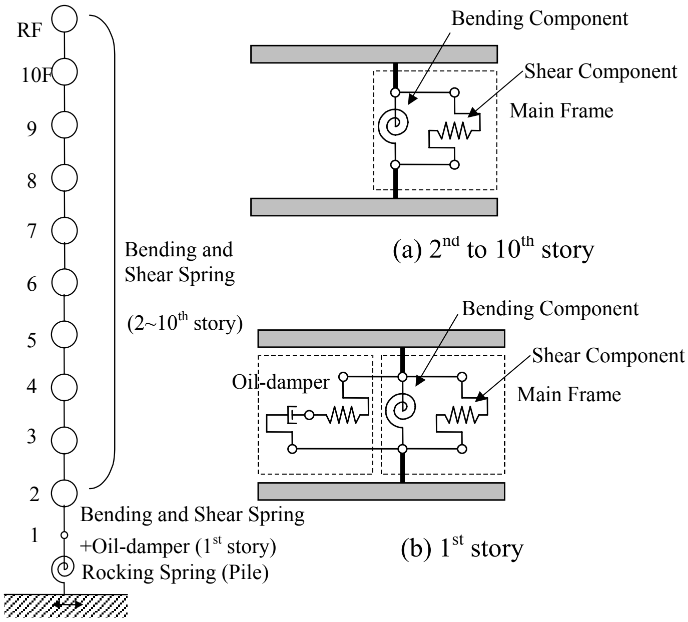


Figure 12 Analysis Model

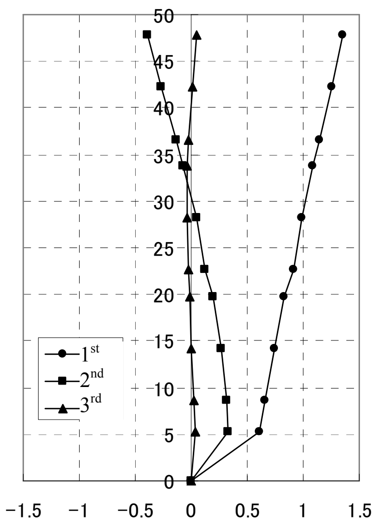


Figure 13 Mode Shape

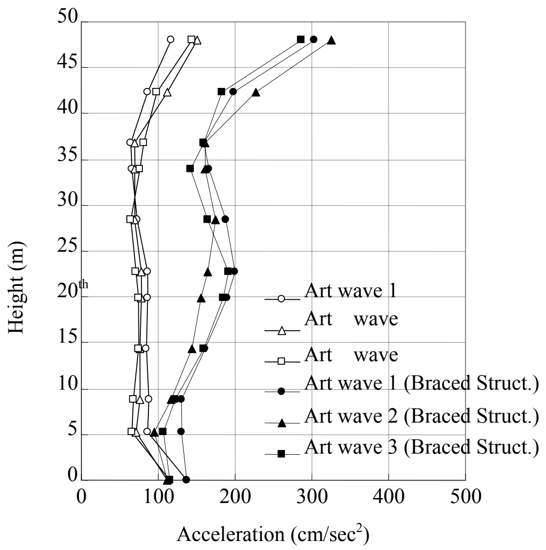


Figure 14 Response Acceleration
for Level 1 Seismic Input

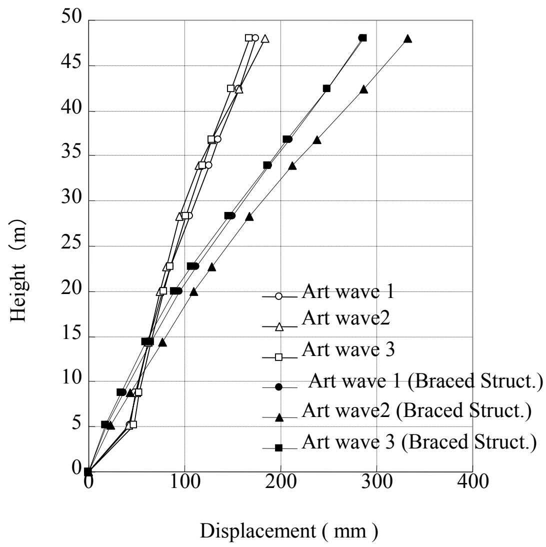


Figure 15 Response Displacement
of Level 2 Seismic Input

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2) Architectural Institute of Japan, (1975), Recommendations for the Plastic Design of Steel Structure.