VIBRATION CONTROL OF RC HIGH-RISE BUILDING WITH SOFT-STORY

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Abstract

Response caused by long-period ground motion can be reduced effectively by adding adequate number of dampers. This is, however, difficult in the case of reinforced concrete (RC) structures because of their high stiffness and heavy weight. This paper presents our newly developed damping system that is effective for high-rise RC buildings. This system is composed of three parts: lower layers with lowered stiffness, rocking-wall with semi-rigid connection at the bottom, and oil-dampers settled between the walls. In addition, laminated rubber has been applied for semi-rigid connection.

I conducted time-history response analysis and made comparison between our newly developed system and the conventional vibration control system. The results showed that the new system is much superior in damping performance to the conventional one despite the fewer oil-dampers. I also conducted experiments on semi-rigid connection and damper-wall connection. After the experiments, there was not significant deterioration in stiffness. High-rise RC building with high damping performance can be realized by integrating some specific elements into lower layer.

Introduction

In Tohoku earthquake, high-rise buildings got shaken for quite a long time because of long-period ground motion, even though they were located far from the hypocenter. Many people living in high-rise buildings felt terror and overturning of furniture were observed in the upper floor. Response caused by long-period ground motion can be reduced effectively by adding adequate number of dampers. This is, however, difficult in the case of reinforced concrete structures because of their high stiffness, heavy weight and lack of the space where dampers can be settled. Conventional vibration controlled RC buildings absorb earthquake energy mainly with structural frame itself rather than dampers.

Here I present our newly developed damping system that is effective for high-rise RC buildings. The system applies the concept which is generally called "Soft-story", and is composed of three parts: lower layers with lowered stiffness, pairs of rocking-walls with semi-rigid connection using laminated rubber bearings, and oil-dampers settled between rocking-walls. Perspective drawing of the system is shown in figure 1.

Damping performance of a structure is improved by amplifying the deformation of the oil-dampers by utilizing relative displacement of rocking-walls and low stiffness of lower layers. Rocking-walls equalize the deformation of lower layers and prevent one story collapse.

In this paper, I report the outline of our new vibration control system, case study of time-history analysis, the result of rotary deformation test of laminated rubber and cyclic loading test of damper-wall connection.

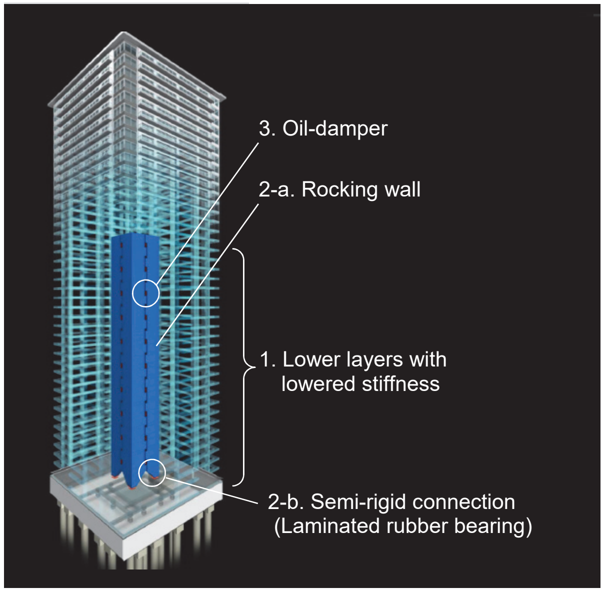


Figure 1. Perspective drawing of the system.

Outline of the System

1. Low Layers with Lowered Stiffness. Damping factor is inversely proportional to square root of stiffness, therefore, it is effective to properly lower the stiffness of the low layers, in order to add damping factor. In the case of medium-rise buildings, the number of stories with lowered stiffness is 1 or 2. And tolerance of story drift of low layers is bigger than that of other stories. In the case of high-rise buildings, in comparison with medium-rise buildings, there are many stories and axial force of column is big. To keep enough lowered stiffness part, number of stories with lowered stiffness of proposed structure should be more than 1/4 of whole stories. And considering the p-delta effect under a big axial force, tolerance of story drift is same as all stories.

Lowered stiffness is realized with high strength materials and adjustment of beam height. Using high strength materials make beam height shorter, and shorter beam height equals smaller story stiffness. Beams have wide elastic range because of their high strength and small height. Columns have to support huge axial force at all time, and which makes it difficult to have columns section smaller.

2. Rocking-Wall with Semi-Rigid Connection at the Bottom. "When high-rise buildings are subjected to intense earthquake ground motions, deformation concentrates into a restricted lower part of a building frame in the process of collapse even though it is designed in accordance with the strong-column-weak-beam concept." said Misaki. Proposed structure has a low layers with lowered stiffness, therefore deformation is easy to concentrate lower part, and the risk of deformation localization is bigger than conventional high-rise buildings. Then, rocking-walls are settled to low layers to prevent deformation localization.

Laminated rubber bearings are adopted to the bottom of rocking-walls to realize semi-rigid connection. Due to the semi-rigid connection at the bottom, rocking-wall can equalize the story drift of low layers without the increasing of story stiffness. This effect is called "Shin-bashira effect" in Japan. Conceptual diagram of Shin-bashira effect of rocking-wall is shown in figure 2.

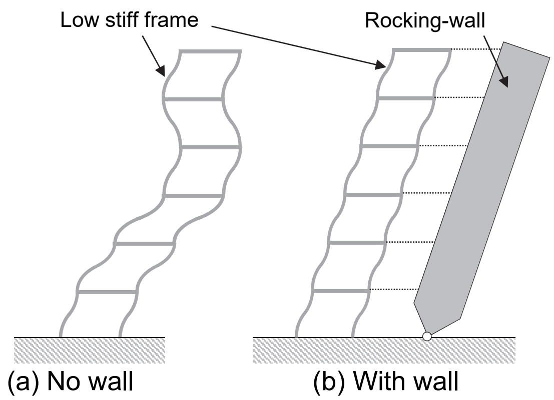


Figure 2. Conceptual diagram of "Shin-bashira effect" of rocking-wall.

3. Oil-Dampers Settled between Rocking-Walls. Relative vertical displacement between rocking-walls occurs along with building lateral displacement. If the rocking-walls have enough stiffness, the ratio of vertical displacement to lateral displacement will be nearly the ratio of wall width to story height. By settling oil-dampers vertically between rocking-walls, and making wall width bigger than story height, the deformation of oil-dampers is bigger than that of oil-dampers settled laterally between stories. The efficiency of energy absorption is proportional to square of deformation; therefore, amplification of oil-dampers deformation improves damping performance dramatically. Conceptual diagram of amplification of oil-dampers deformation is shown in figure 3.

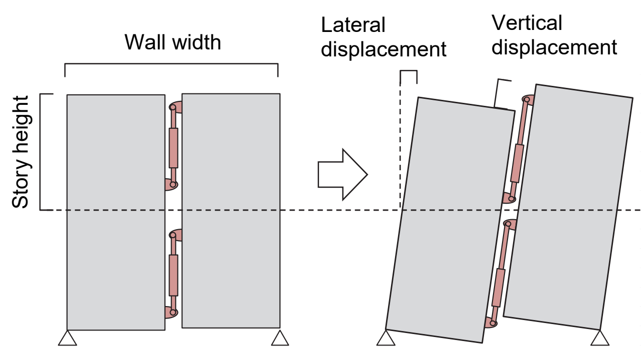


Figure 3. Conceptual diagram of amplification of oil-dampers deformation.

Rotary Deformation Test of Laminated Rubber Bearing

Long-period ground motion causes repeated rotary deformation and fluctuation axial force to laminated rubber bearing which is adopted to bottom of rocking-wall. Lateral multi-cyclic test is conducted by Hibino while there is no test for the rotary direction. To confirm the durability of rotary deformation of laminated rubber bearing, I conducted rotary deformation test on laminated rubber bearings under high and low axial load.

I use natural rubber bearing (NRB) as specimen. Diameter is 500mm and shear modulus of rigidity is 0.39MPa. Specimen for rotary deformation test is shown in figure 4. NRB has high durability against compressive force, but durability against tensile force is low. Therefore, it is necessary to control the tensile deformation caused by rotary deformation. Then, downside flange is not connected to base concrete to accept the floating of flange edge.

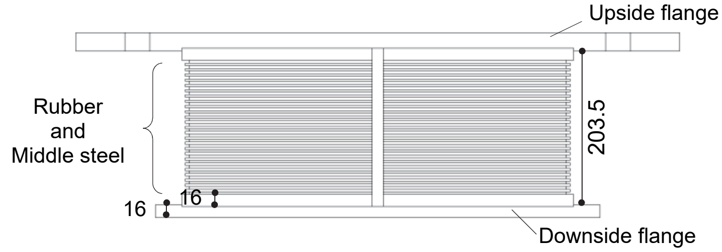


Figure 4. Specimen for rotary deformation test.

Loading equipment is shown in figure 5. Center jacks give constant compressive force. Outer jacks give an inverse direction force each other to rotate specimen. Lateral jack keeps the point (figure 5 ●) fixed horizontally. Strength of concrete is 80MPa.

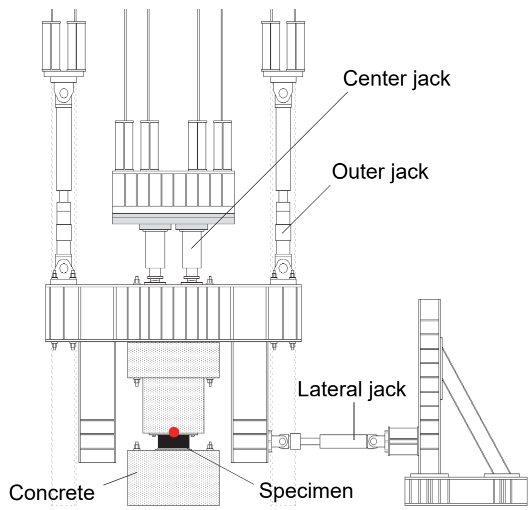


Figure 5. Loading equipment.

There are three types of loading patterns to confirm rotary stiffness, durability of rotary deformation and ultimate state. First, to confirm rotary stiffness, specimen is deformed 3 cycles at each angle from rotary angle 1/800 to 1/50rad. Second, to confirm durability of rotary deformation, under constant contact pressure, specimen is deformed 200 cycles at rotary angle 1/100rad and 100 cycles at rotary angle 1/50rad. Finally, to confirm ultimate state, specimen is deformed 5 cycles at rotary angle 1/33rad. Loading parameters are shown in table 1.

Table 1. Loading Parameters

Confirming content	*Contact pressure (MPa)*	*Rotary angle (rad) x number of cycles*
Stiffness	8, 15, 1	1/800, 1/400, 1/200, 1/100, 1/50 Every 3 cycles
Durability	1	1/100 x 200 cycles, 1/50 x 100 cycles
Ultimate state	1	1/33 x 5 cycles

Bending moment–rotary angle relation is shown in figure 6. As the contact pressure gets smaller, the liner area becomes narrower. But bending moment-rotary angle relation is stable regardless of contact pressure, despite large deformation. By the way, influence of p-delta effect and friction is eliminated from the figure.

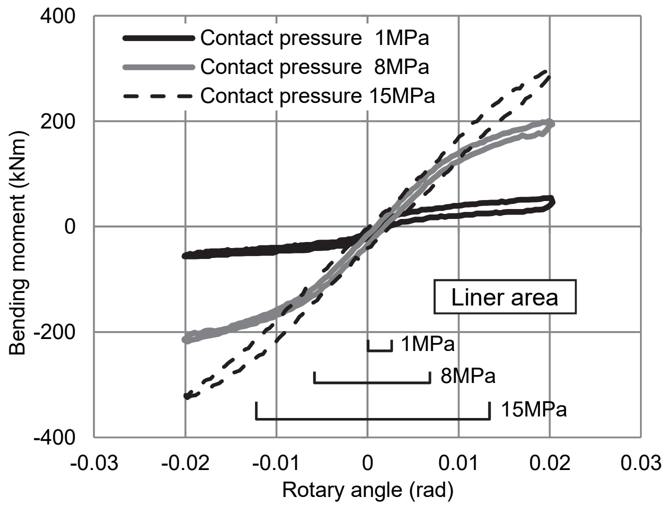


Figure 6. Bending moment–rotary angle relation.

Transition of rotary stiffness in durability confirming test is shown in figure 7. Rotary stiffness is determined by liner approximation using least-square method at each cycle and is standardized to result of stiffness confirming test. The transition of rotary stiffness under repeatedly rotary deformation is few.

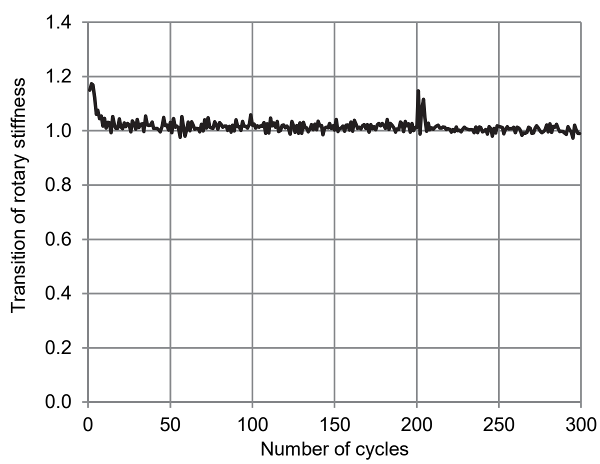


Figure 7. Transition of rotary stiffness (contact pressure: 1MPa).

Cyclic Loading Test of RC Wall-Damper Connection

For the system I developed, it is important to carefully design the damper connections between different materials (steel and concrete). However, many experiments show that cyclic loading causes stiffness reduction of RC element. To evaluate stiffness and durability of wall-damper connection under long-period ground motion, I conduct cyclic loading test on T-shape specimen. Specimen for cyclic loading test is full-scale for maximum damping force 1500kN and is shown in figure 8.

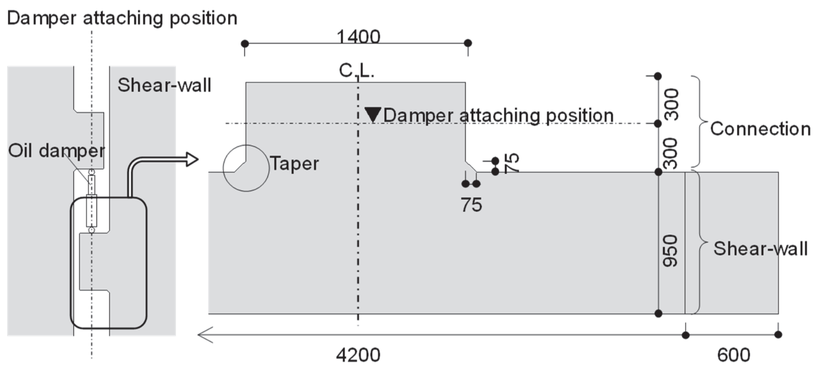


Figure 8. Specimen for cyclic loading test.

There are three types of loading patterns to confirm stiffness, durability against cyclic loading and property after maximum loading. First, to confirm stiffness, specimen is loaded 3 cycles at each loading force from 250kN to 1500kN. Second, to confirm durability against cyclic loading, specimen is loaded 100 cycles at loading force 1500kN. Finally, to confirm property after maximum loading, specimen is loaded 5 cycles at loading force 1800kN. Loading program is shown in table 2.

Table 2. Loading Program

No.	*Confirmation content*	*Loading pattern*
1	Stiffness	±250, 500, 1000,0 1500kN each 3 cycles
2	Durability	±1500kN 100 cycles
3	Property after maximum loading	±1800kN 5 cycles

Force–lateral displacement relations are shown in figure 9. As the loading force gets larger, the lateral stiffness becomes smaller. But force–lateral displacement relations are stable even if loaded repeatedly and overloaded.

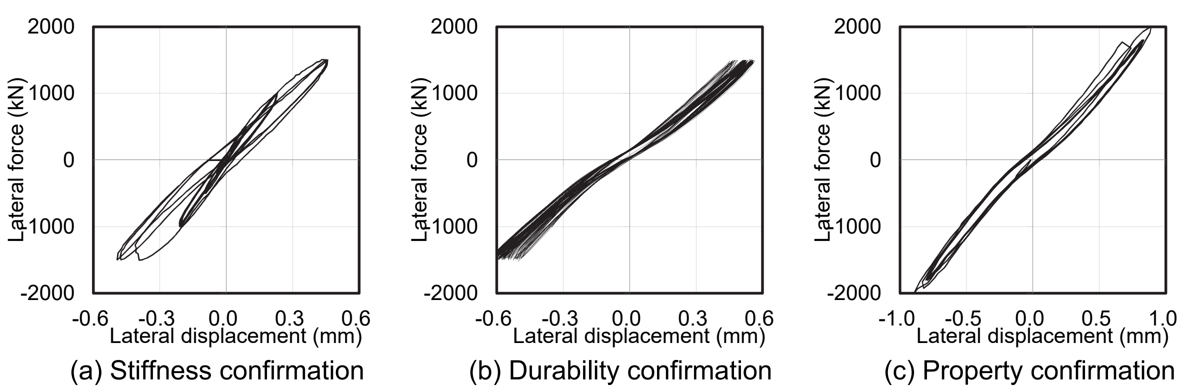
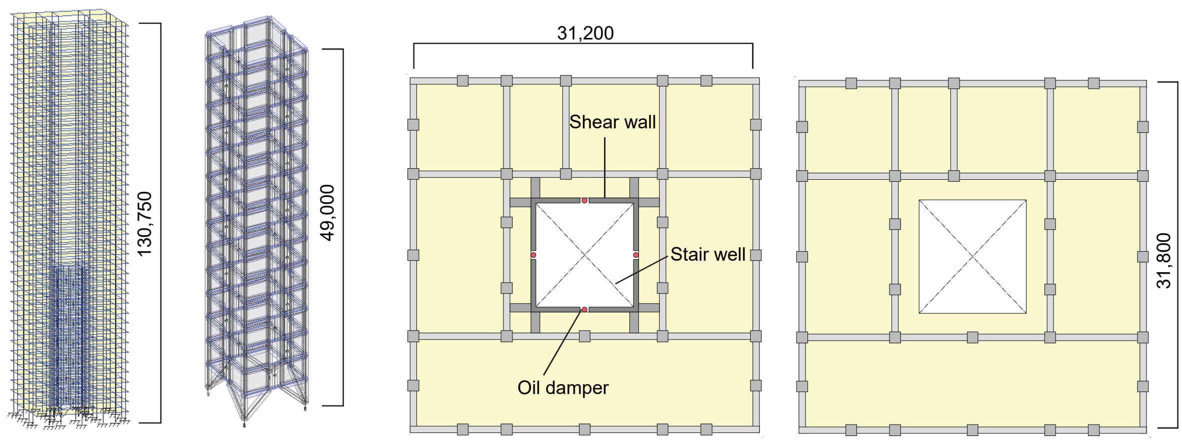


Figure 9. Force-deformation relations.

Case Study Using Detailed 3-Dimension Model

Analysis model. Supposing general high-rise apartment in Japan, I set plan, floor height, mass and so on. Framing elevation and beam plan of analysis model are shown in figure 10. It has 40 stories, building height is 130.75m, and floor height of ordinal floor is 3.25m.



(a) Whole model (b) Shear wall (c) Beam plan at lower floor (d) Beam plan at uper floor

Figure 10. Analysis model.

I design the building without oil damper and shear wall (model N). After that, I also design the building with oil damper and shear wall (model OS) based on the specification of the model N. As a model for comparison, the building with oil damper, without shear wall (model O) is considered, too.

Model N is designed to satisfy the term below: Maximum story drift angle is almost less than 1/100. Column section is 1m square. Bending yield is allowed, but shear fracture is not allowed.

Model O is the model added oil damper to model N. 4 oil dampers are set to each floor from 6th to 30th, so total number of oil dampers are 100. Maximum damping force is 1000kN and it is common to all floors. Oil dampers are settled through steel columns.

Model OS has multi-story shear walls from 1st floor to 15th floor. The walls have 7 oil dampers with maximum damping force 1500kN at its each aspect, so total number of oil dampers are 28. It is equivalent to 42% of model O's total damping force.

Input ground Motions. Input ground motions are 4. Pseud velocity spectrum of input ground motions are shown in figure 11. It depends on Japanese building law and the return period of those ground motions are around 500years. In the case of high-rise buildings (over 60 meter high) and base-isolation buildings, it is obliged in Japan to vindicate that they can withstand those ground motions.

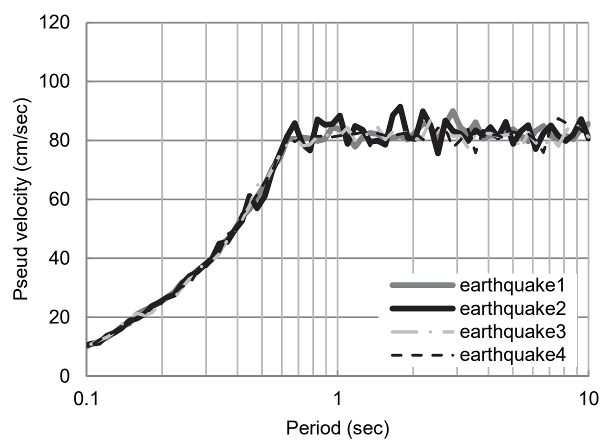


Figure 11. Pseud velocity spectrum of input ground motion.

Results of Analysis. Envelope of maximum story drift angle against all ground motions is shown figure 12. In spite of fewer numbers of dampers, response of model O and model OS are similar. In the case of model OS, oil dampers work more effectively than that of model O.

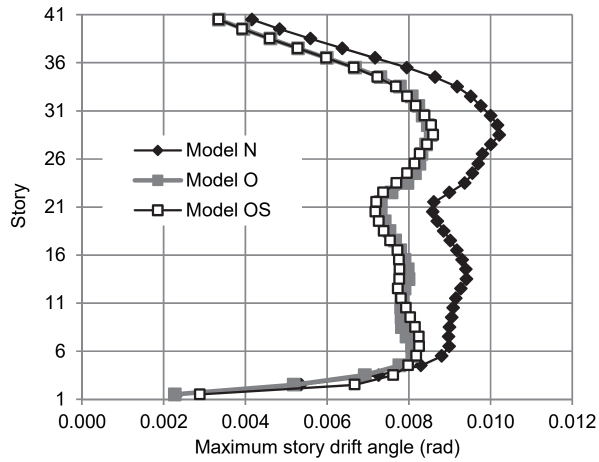


Figure 12. Maximum story drift angle.

Conclusion

A new vibration control system was presented. It is composed of three parts: lower layers with lowered stiffness, pairs of rocking-walls with semi-rigid connection using laminated rubber bearings, and oil-dampers settled between rocking-walls. This system can reduce the maximum story drift even if number of dampers is few in comparison with conventional vibration control system.

Laminated rubber bearing has a high durability against rotary deformation. The rotary stiffness of laminated rubber bearing is not deteriorated sharply under the repeated rotary deformation.

RC wall-oil damper connection has enough stiffness and durability against cyclic loading. So the system can demonstrate its effectiveness under long-period ground motion.

References

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