DEVELOPMENT AND APPLICATION EXAMPLE OF ROTATIONAL INERTIA MASS DAMPER

M. Okamoto [1], Y. Tsuyuki [1], K. Matsui [1]

[1] *KAYABA SYSTEM MACHINERY CO.,LTD.*

Abstract

It resulted a large and long-time shaking in the high-rise buildings of Osaka plain and Tokyo metropolitan area, which made many people felt great fear by The 2011 off the Pacific coast of Tohoku Earthquake. After that, we had feared a massive earthquake in Nankai Trough. We also supposed this massive earthquake might cause serious shaking to more high-rise buildings that we never expected before. Therefore, it's necessary to establish an effective method for upgrade the damping performance of buildings for reducing magnitude and shortening shaking time of building during earthquakes.

Recently years, by rotating the spindle using a ball screw mechanism, equipment (Rotational Inertia Mass Damper) has been put into practical use large inertia mass effect resulting in several thousand to several hundred times of mass of the weight. Using this principle of rotational inertia mass damper can be greatly reduced the seismic displacement of the building compared with conventional vibration-control-devices.

Rotational Inertia Mass Damper is expected to able to build vibration control system with high mass ratio for the mass of the building due to large inertia mass effect. Furthermore, this damper is possible to shorten the construction period because it has high effect of vibration-control with per damper and number of installation location can be reduced compared with conventional vibration-control-devices. In addition, this damper has an overload protector as fail-safe mechanism to cut off the power of the damper burden of an unexpected [1].

In this paper, we report the principle and application example of Rotational Inertia Mass Damper.

Keywords: Inertia mass; Ball screw; Overload prevention mechanism; Vibration control system

1. Introduction

It resulted a large and long-time shaking in the high-rise buildings of Osaka plain and Tokyo metropolitan area, which made many people felt great fear by The 2011 off the Pacific coast of Tohoku Earthquake. In the massive earthquake typified by Nankai Trough earthquake that occurred is feared, the high-rise buildings are quite likely to suffer a serious shaking. Therefore, it's necessary to establish an effective method for upgrade the damping performance of buildings for reducing magnitude and shortening shaking time of building during earthquakes.

The oil dampers produced by Kayaba System Machinery Co., Ltd (KSM) are widely used in many buildings for vibration-control and seismic isolation system. Moreover, we also have kept developing various dampers with special functions. However, it will cost huge expense if we install the conventional vibration-control-devices in a common building according to an existing design method. The reason is not only the expense of the vibration-control-devices, but also the increase of the installation charge. In order to decrease the cost, we have to reduce number of installation vibration-control-devices compared with conventional ones.

Because Rotational Inertia Mass Damper can reduce the installation number as compared with the conventional vibration-control-devices by using a large inertia mass, it is expected to shorten a construction period and reduce a construction cost. In this paper, we describe the structures, the characteristics, and the results of performance evaluation test of Rotational Inertia Mass Damper, and we introduce vibration control effects of using this damper as an application example.

This damper was developed jointly with NSK Ltd., Shimizu Corporation, and KSM.

2. Structure of Rotational Inertia Mass Damper

Figure 1 shows appearance of Rotational Inertia Mass Damper. There are vibration-control-devices that have been used a lot conventionally as hysteretic dampers represented by a yield-point steel and viscous dampers represented by an oil damper. These dampers reduce earthquake response by using a rigid or a viscous term in a motion equation. There is Tuned Mass Damper (so-called TMD) as a device by using a mass term in the motion equation. Recently, large-typed TMD have been developed for improving seismic safety. However, there is a limit to mass capacity of conventional TMD, and the main target was often limited to livability measures against wind shaking. On the other hand, Rotational Inertia Mass Damper which converting linear motion into rotational motion is the device that produces large inertia mass of several thousand times of actual mass. Since producing large inertia mass, this damper reduces vibration of the building by utilizing mass effect.

Fig. 1 – Appearance of Rotational Inertia Mass Damper

2.1 Equivalent inertia mass

Figure 2 shows internal structure of Rotational Inertia Mass Damper. Rotational Inertia Mass Damper converts linear motion into rotational motion by utilizing the mechanism of nut-rotation-typed ball screw. It is composed a ball screw which rotational motion is constrained and a ball nut which linear motion is constrained and four bearings which hold the ball nut, when the ball screw is in linear motion, the ball nut is in rotational motion, torque is transmitted to the weight through the friction plate, and the cylindrical weight is in rotational motion with the ball nut.

Assuming an internal cylindrical weight of the damper as inertia mass, the outer diameter of the cylindrical weight of the damper is *D*, the internal diameter is *d*, moment of inertia is *I* and actual mass is *m*. When axial displacement of the ball screw is *x*, the cylindrical weight is rotated θ, and axial load of the ball screw will be generated by this displacement is *F*. Eq. (1) shows relationship of *F* and *x*. *Ld* is pitch of the ball screw this time.

$$F = \frac{I\ddot{\theta}}{L_d/(2\pi)} = (\frac{2\pi}{L_d})^2 I\,\ddot{x} = \frac{\pi^2(D^2+d^2)}{2L_d^{\ 2}} m\ddot{x} = \psi\ \ddot{x} \tag{1}$$

Ψ is equivalent inertia mass in the axial direction of the ball screw at Eq. (1), it is possible to enlarge value several thousand times of actual mass *m*. This force (inertial force) *F* is found to be proportional to (relative acceleration of the ball screw and the ball nut) acceleration in the axial direction.

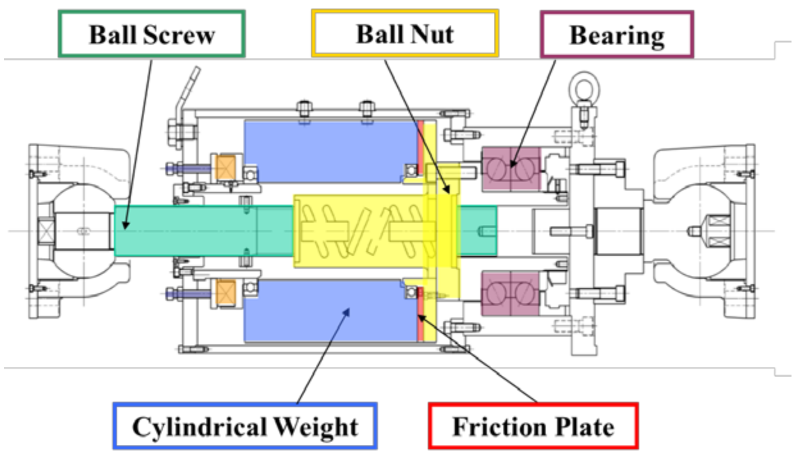


Fig. 2 – Internal structure of Rotational Inertia Mass Damper

2.2 Overload prevention mechanism

If the inertia mass load exceeds more than the limit, slip occurs between the weight and the friction plate, and rotational motion will be limited to transmit from the ball nut to the cylindrical weight. According to this mechanism, it is possible to control maximum axial load of the damper as relief load, and it can avoid the transmission of excessive reaction force to building structural flames.

In order to realize this mechanism, some coil springs that pressing force is variable are placed on one side of the cylindrical weight, the amount of deflection of the springs controls surface pressure of the friction plate which is placed on the other side. By setting the transmission of torque moment with surface pressure of the friction plate, it is possible to control operation of overload prevention mechanism. At the same time, it is possible to prevent damage of Rotational Inertia Mass Damper.

3. Product Specification

Table 1 shows specification of Rotational Inertia Mass Damper. The lineup of products has three types by equivalent inertia mass (6,500, 4,000, 2,500[ton]). Actual mass that produces equivalent inertia mass 6,500[ton] is 880[kg], it can be seen that amplified about 7,000 times by converting into rotational motion. Furthermore, installation environment is indoor in principle.

Table 1 – Specification of Rotational Inertia Mass Damper

Model name	BDM6500	BDM4000	BDM2500
Equivalent inertia mass [ton]	6,500	4,000	2,500
Equivalent inertia mass of weight [ton]	6,121	3,609	2,113
Relief load [kN]	800～1,200	600～1,100	500～1,000
Maximum axial load [kN]	2050	2050	2050
Actual mass of cylindrical weight [ton]	0.88	0.64	0.46
Mass amplified ratio of weight [-]	6,955	5,640	4,594

4. Performance Evaluation Test

Rotational Inertia Mass Damper generates inertial force that is proportional to relative acceleration between both sides of the damper. Therefore, when the damper is vibrated by a sine wave, relative acceleration is in the opposite phase with respect to displacement, and negative gradient appears in relationship of load and relative displacement of the damper. Using this characteristic, we evaluated the performance on the basis of relationship of load and relative displacement obtained from the vibration test with actual devices.

Figure 3 shows the performance evaluation test on the electric-testing-machine. We used the electric-testing-machine of ball screw type what our company owned on the vibration test. Table 2 shows specification of electric-testing-machine. Figure 4 shows relationship of load and relative displacement of the damper when we input the sine wave of 0.5 [Hz]-±10 [mm] to the damper. Since load is proportional to relative acceleration, the slope of the line connecting maximum and minimum points of displacement (red line in Fig. 4) becomes downward-sloping. Now, when relative displacement is x and relative acceleration is $\ddot{x}$, input frequency is f, equivalent inertia mass is Ψ, and axial load is F. F/x equals numeric value what is read from the slope of the vibration test, and we can calculate equivalent inertia mass using Eq. (2.4). Moreover, when the area surrounded by the loop in Fig. 4 is ΔW, equivalent viscous damping coefficient Ceq is represented by Eq. (3). Eq. (4) and (5) show the calculation examples at the case of 0.5 [Hz]-±10 [mm].

$$x = A\sin\omega t \ , \ (\omega = 2\pi f\ ) \tag{2.1}$$

$$\ddot{x} = -\omega^2 A\sin\omega t = -\omega^2 x \tag{2.2}$$

$$F = \psi \cdot \ddot{x} \tag{2.3}$$

$$\psi = \frac{F}{\ddot{x}} = -\frac{1}{\omega^2}\cdot\frac{F}{x} \tag{2.4}$$

$$Ceq = \frac{\Delta W}{2(\pi A)^2 f} \tag{3}$$

Calculation example:

Equivalent inertia mass

$$\frac{F}{x} = -64.12 \quad [kN/mm], \qquad \psi = -\frac{1}{2\pi\cdot 0.5}\cdot -64.12 = 6497 \quad [ton] \tag{4}$$

Equivalent viscous damping coefficient

$$A = 0.0098 \quad [mm]、\ \Delta W = 3.66 \quad [kN\cdot m]$$

$$Ceq = \frac{3.66}{2\pi^2\cdot 0.0098^2\cdot 0.5} = 3{,}861 \ [kN\cdot s/m] \tag{5}$$

It is considered that equivalent viscous damping coefficient *Ceq* of Rotational Inertia Mass Damper is generated by viscous resistance of grease which sealed between the ball screw and the ball nut or the bearings. In the damper of three types, from the vibration test results with the parameter of frequency and damper amplitude, it is confirmed that the damper has frequency dependability of what equivalent viscous damping coefficient increases with a rise of frequency. On the other hand, it is considered that the damper does not have dependence of damper amplitude at same frequency. Figure 5 shows frequency dependability of viscous damping coefficient of BDM- 6500 based on the vibration test results with the actual devices.

Table 2 – Specification of electric-testing-machine

Load capacity [kN]	±2000
Stroke [mm]	±150
Waveform	Sine, Random
Frequency [Hz]	0.02～4.00

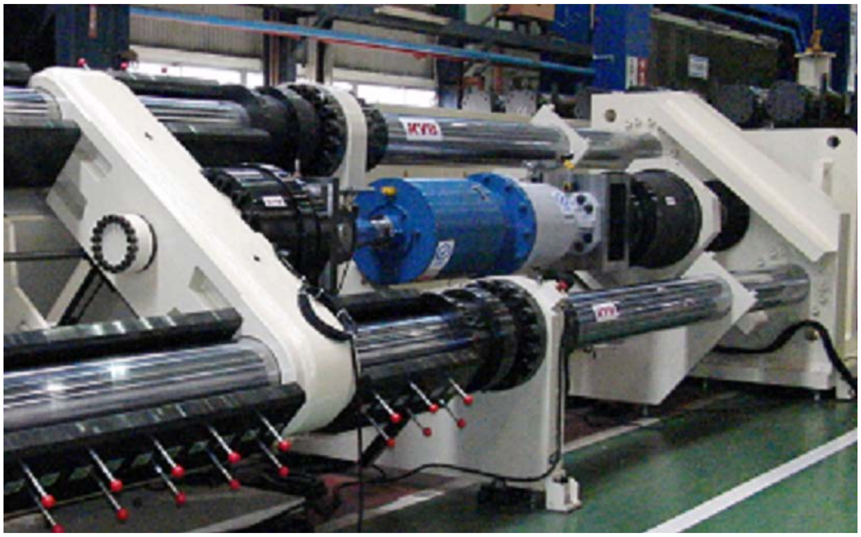


Fig. 3 – Performance evaluation test on electric-testing-machine

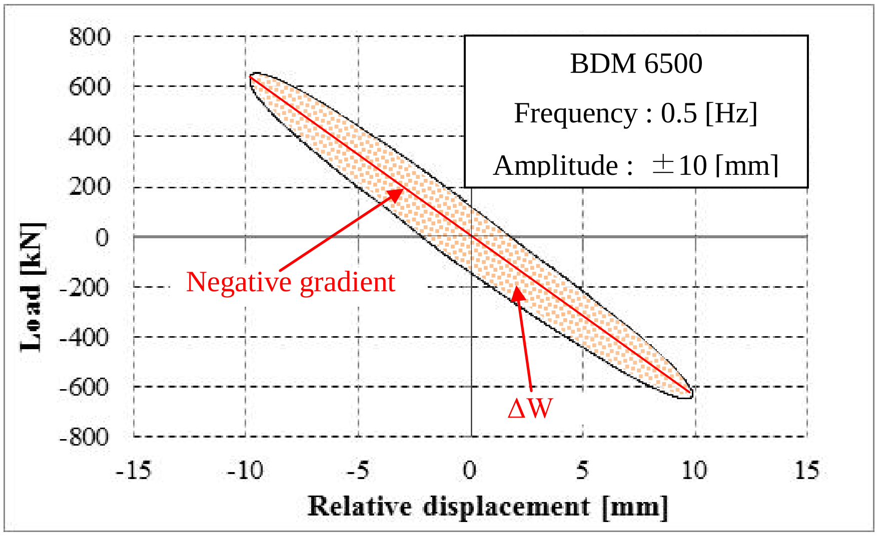


Fig. 4 – Relationship of the load and relative displacement

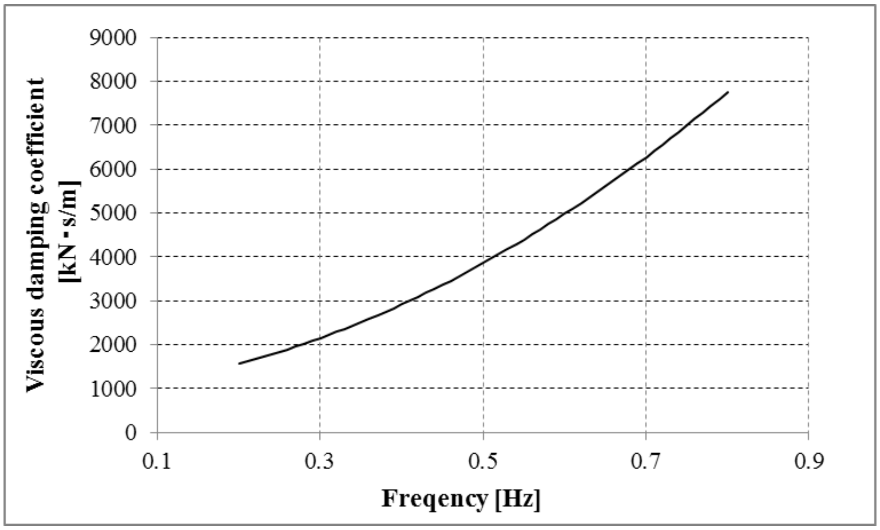


Fig. 5 – Freqency dependability of viscous damping coefficient of BDM6500

5. Installation Method and Mechanism of Response Reduction

Figure 6 shows vibration control system conceptual model using Rotational Inertia Mass Damper. This is a kind of TMD system (Tuned Mass Damper) to demonstrate the vibration control by using mass effect. As mentioned previously, since large equivalent inertia mass can be obtain from small actual mass, this damper can realize the TMD which controls the structural response for earthquake with large mass ratio while reducing load to the building structure.

For conventional vibration control devices, it's the common method in high-rise building to distribute the devices into from middle floors to upper floors. However, Rotational Inertia Mass Damper, it can be controlled shaking of the whole building due to be placed intensively only in lower floors. Figure 7 shows the placement method of Rotational Inertia Mass Damper to the buildings. In general, mass and stiffness of the building structures are different in each building. By tuning the period of additional vibration control system (Equivalent inertia mass of Rotational Inertia Mass Damper, additional damping, and additional stiffness) and the period of main frame, it is possible to obtain reasonable vibration control system. If necessary, using the oil damper as additional damping and the axle spring device with disc springs or damper mounting braces as an additional stiffness.

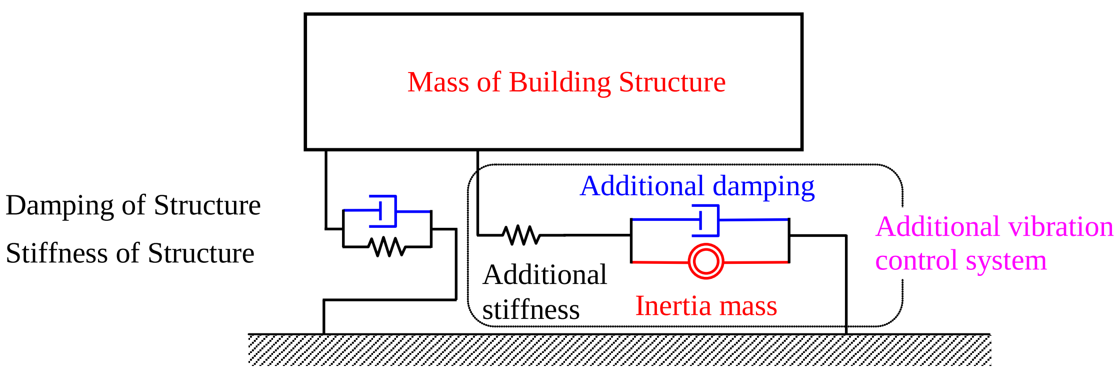
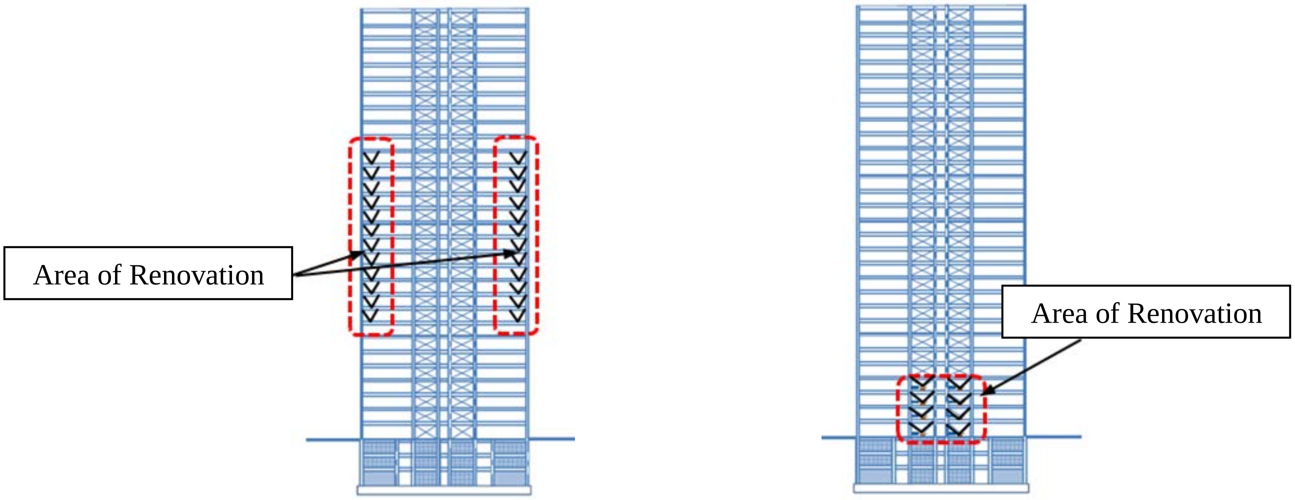


Fig. 6 – Vibration control system conceptual model



The traditional installation method by using conventional vibration control devices

A new installation method by using Rotational Inertia Mass Dampers (Place centrally on lower floors)

Fig. 7 – Renovation construction example of Rotational Inertia Mass Damper

6. Application Example

As an application example of Rotational Inertia Mass Damper, we examine vibration control effect of using this damper in the virtual building with analysing.

6.1 Analysis Model and Analysis Condition

The target building is steel frame office building what has 20 floors above ground and the height 80 [m].

Analysis model is 20 degree-of-freedom systems, and the structural damping ratio which is proportional to the stiffness is 2% at primary natural period. Relationship of story shear force and story drift at each floor applied Normal Tri-Linear model based on the incremental loading analysis result. 8 Rotational Inertia Mass Dampers what equivalent inertia mass is 6,500[ton] were placed only on the first floor. Figure 8 shows analysis model, and figure 9 shows relationship of story shear force and story drift at each floor. Table 3 shows specification of analysis model, and table 4 shows input seismic motions. Now, compared the response analysis of with dampers or without, we examined the effect of response reduction of the damper.

6.2 Decision Procedure of Damper Specification

We set the Rotational Inertia Mass Damper which effective mass ratio was aiming for 5%. According to the fixed-point theory, as tuning the period of additional vibration system and the natural period in elastic range of the building, we determined the equivalent mass and stiffness. Table 5 shows natural period of the building, figure 9 shows the curve of amplification ratio of displacement. The optical value of additional damping can be determined theoretically, but due to using damper which viscous damping coefficient confirmed experimentally is 3,850 [kN･s/m] , it is slightly larger to the optimum value. As a result, effective mass ratio became 5.2 [%] of primary natural period of building because of placed the 8 dampers which has inertia mass of 6,500 [ton]. Then, equivalent damping factor was increased to 6.4 [%] from 2 [%] of only structural damping.

6.3 Result of Analysis

Figure 11 show maximum response displacement of the building, and figure 12 shows maximum story drift. In the figures, solid line shows the case with the dampers, while broken line shows the case without the dampers. In input seismic motions of El-Centro NS and Long-Distance Phase of public notice, maximum story drifts are over

1/100 in the case of without the dampers, while maximum story drift were able to less than 1/100 in the case of with the dampers. The rate of response reduction was 24.1 [%] at maximum. In response displacement, it is seemed similarly reduction, it can be reduced about 20 [%] in Long-Distance Phase of public notice. From these result, intensively placed Rotational Inertia Mass Damper in only first floor, reduction effect of displacement and story drift were confirmed.

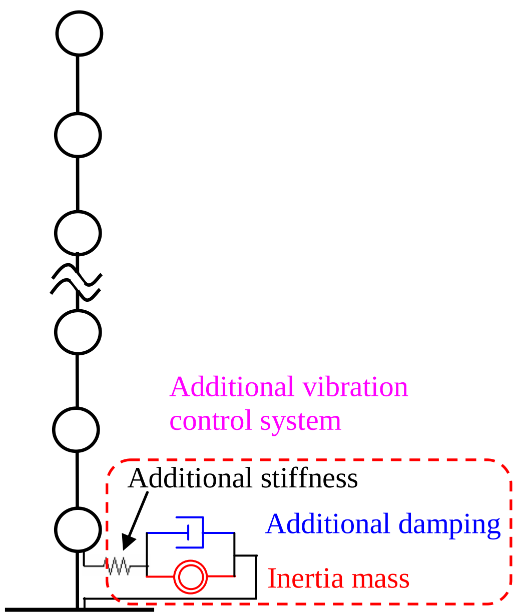


Fig. 8 – Analysis model

Table 3 – Specification of analysis model

Floor	Mass[ton]	Horizontal Stiffness[kN/m]
RF	144	
20	360	66,500
19	480	190,000
18	600	285,000
17	780	427,500
16	780	617,500
15	780	646,000
14	780	665,000
13	780	674,500
12	780	703,000
11	780	722,000
10	780	741,000
9	780	769,500
8	780	798,000
7	780	832,600
6	780	880,000
5	780	910,000
4	780	950,000
3	780	1,045,000
2	840	1,187,500
1	960	1,425,000

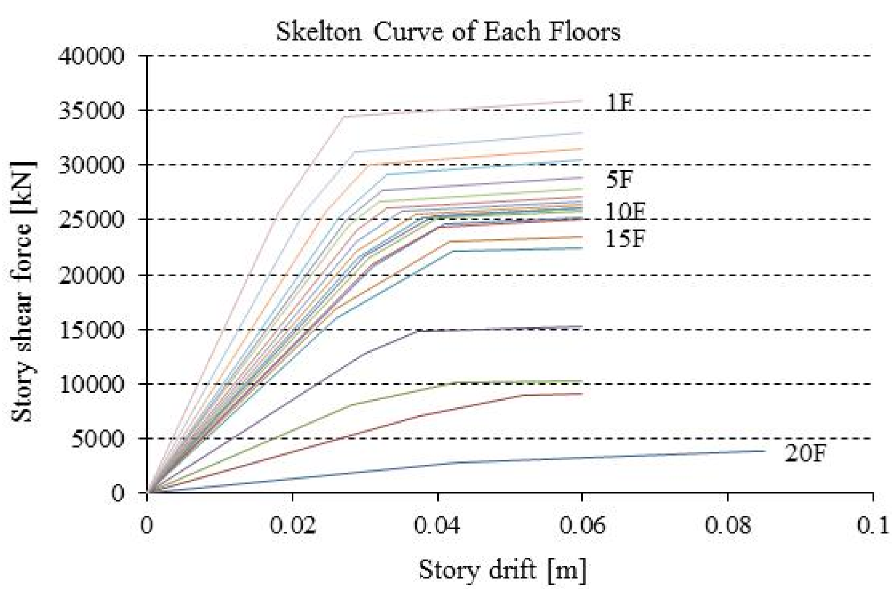


Fig. 9 – Relationship of story shear force and story drift

Table 4 – Input seismic motions

Seismic motion	Abbreviation	Maximum acceleration [cm/s^2]	Duration [s]
EL-CENTRO 1940 NS	EL	511(50cm/s fitting)	53
TAFT 1952 EW	TA	497(50cm/s fitting)	53
HACHINOHE 1968 NS	HA	337(50cm/s fitting)	53
short-range phase of P.N.※	KS	424	82
long-distance phase of P.N.※	KL	440	200

※ Ground motion based on the velocity response spectrum stipulated in building standard law of Japan

P.N. : Public Notice

Table 5 – Natural period of analysis model

	Natural period [s]
Primary	2.19
Secondary	0.80
Tertiary	0.52

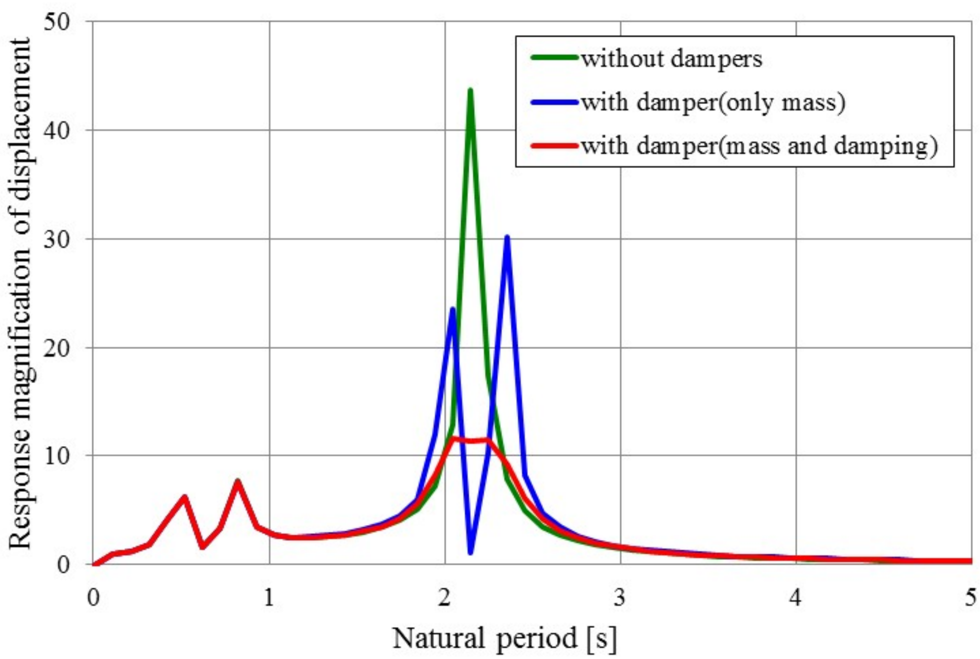


Fig. 10 – Response magnification of displacement

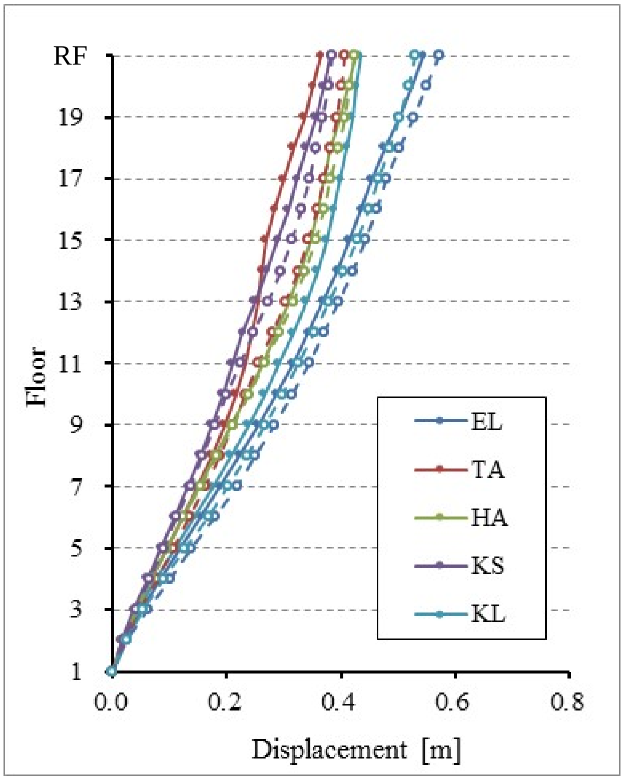


Fig. 11 – Maximum response displacement

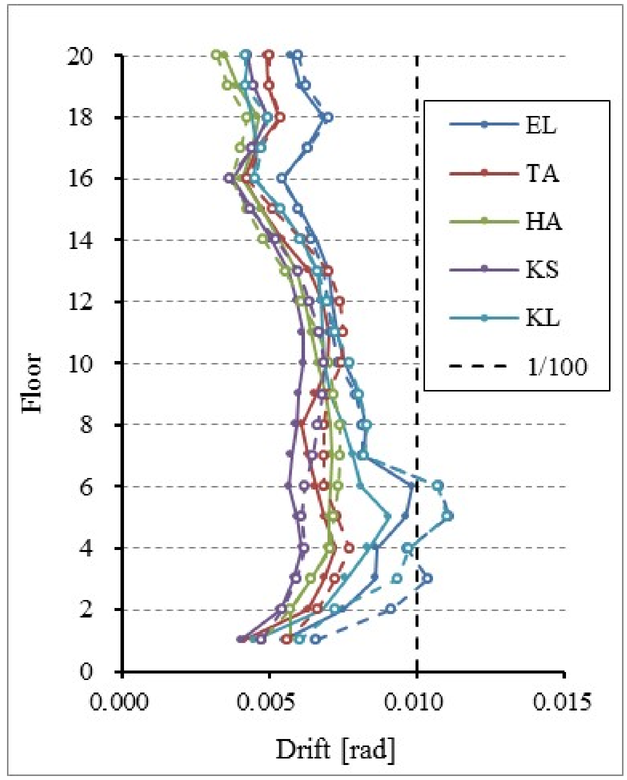


Fig. 12 – Maximum story drift

7. Conclusion

We describe the structures, the characteristics, and the performance evaluation test results, and more of Rotational Inertia Mass Damper. In addition, we introduced about reducing number of the damper compared with conventional dampers. As a result, it is expected the advantages of cost reduction, shortening construction term, and improving width of building plan. In this paper, Rotational Inertia Mass Damper was used only in the application example, but it need the installation of the oil damper if the damping of Rotational Inertia Mass Damper is greatly smaller than optimum additional damping or it is significant impact to higher-order mode.

Since The 2011 off the Pacific coast of Tohoku Earthquake, it is growing need for improving seismic performance of the existing building for massive earthquake. However, in renovation of improving seismic control performance, since there are people in the building, it is often required the renovations that has many restrictions. For installation location is less, vibration control system of Rotational Inertia Mass Damper has many advantages of shortening construction term including cost reduction for owner of the building. In addition, reduction of number of vibration control devices will be improving the width of the building plan in new buildings.

In Japan after The 2011 off the Pacific coast of Tohoku Earthquake, it has started to be reconsidered input seismic motions in structural design. To massive earthquake that greatly exceeds conventional input seismic motions, in the situation which seismic performance is required, we hope that our method will be one of countermeasure.

In the future, we will keep effort to disseminate Rotational Inertia Mass Damper with compactification and to increase the capacity of inertia mass.

8. References

[1] Isoda K, Hanzawa T, Hukukita A, Hukasawa, T (2010): *Development of Inertia Mass Damper with Overload Prevention Function. Part 1. Purpose of Development and Summary of the Damper.* Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, Hokuriku,2010, B-2 Structure 2 453-454.