SEISMIC VIBRATION CONTROL OF A HIGH-RISE R.C. BUILDING BY A LARGE TUNED MASS DAMPER UTILIZING WHOLE WEIGHT OF THE TOP FLOOR

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ABSTRACT :

This paper outlines the design of the high-rise R.C. building whose top floor is isolated and utilized as the mass of a large-scale mass damper, and describes the effect of the vibration control system realized by the design.

In many cases, conventional mass dampers with additional weight on the building tops have been installed for the purpose of improving the habitability against strong wind. However, it has been rare for mass dampers to be used as countermeasures against earthquakes.

We have developed a large-scale vibration control system utilizing the whole weight of building top floors to serve as mass dampers. The building used for our study on mass dampers is a high-rise R.C. structure, about 162 meters high at the highest point, with forty-three stories above the ground.

Based on the seismic response analysis using the artificial earthquake waves, the natural vibration period of the mass damper was tuned so as to decrease the story drift of the whole building remarkably. If the building is assumed to be elastic, the optimum frequency of the mass damper is 3.8 sec., equivalent to the theoretically estimated from the primary natural frequency of the building. On the other hand, if the building is assumed to be elasto-plastic, the damper becomes the most effective when the frequency is tuned to about 8.0 sec. With the mass damper, the maximum story drift of the building is reduced by about 20%.

KEYWORDS: Mass damper, Vibration control system, Seismic isolation, High-rise R.C. building

1. INTRODUCTION

This paper outlines the design of the high-rise building whose top floor is isolated and utilized as the mass of a large-scale mass damper, and describes the effect of the vibration control system realized by the design. The building used for our study on mass dampers is a high-rise reinforced concrete structure, about 162 meters high at the highest point, with forty-three stories above the ground (refer to Figure 1). The lower part of the building from the first to the fourth floor, with plane area of about 100m×42m, houses a shopping mall, a life support center for the elderly people, and a broadcasting station. The high-rise part of the building from the fifth to the 42nd floor, with the plane area of about 37m×33m, has condominiums. There is a view lounge on the top floor, above which a helideck is located on the rooftop. There are seismic isolation floors underneath the view lounge and helideck, the weights of which are utilized for mass dampers.

2. STRUCTURAL OUTLINE

Figure 2 shows the framing plan of the typical high-rise floors of the building. The framing work is in a pure rigid-frame RC structure, and the floors of the dwelling units are made of flat slabs (PC panel hybrid slabs). A double tube structure is used, where columns are intensively laid out along the perimeter and around the center core. The natural periods of the building are 3.7 sec. in the X direction, and 3.6 sec. in the Y direction respectively.

3. OUTLINE OF LARGE-SCALE MASS DAMPER

Figure 3 and Figure 4 show the floor plan of the view lounge and the cross section of the mass damper, respectively. The view lounge and helideck are individually base-isolated, which forms a dual structure of seismic isolation. The weight of the view lounge accounts for about 2.2% of the building weight above the ground, and the weight of the helideck accounts for about 0.2%.

The operational stroke of the mass dampers is ±one meter. The larger mass and longer operational stroke than those of the conventional mass dampers against wind enable the system to work effectively against large earthquakes.

As a part of the residential area, the view lounge (19,071kN in weight) is usually fixed to the main building, but if a strong earthquake hits the building, the lounge will be released to operate as a mass damper system. The automatic control system to operate the view lounge as a mass damper is as follows: The view lounge fixed will be automatically released by the signals of 80cm/s^2 or more from the sensor installed on the first floor of the building. The helideck (1,862kN in weight), which is not a part of the residential area, is always in service as the measure against more moderate earthquakes.

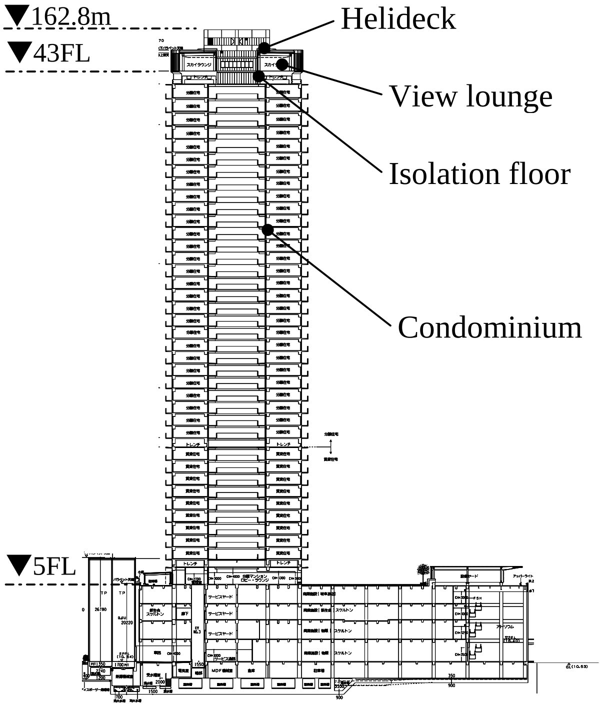


Figure 1 Building section

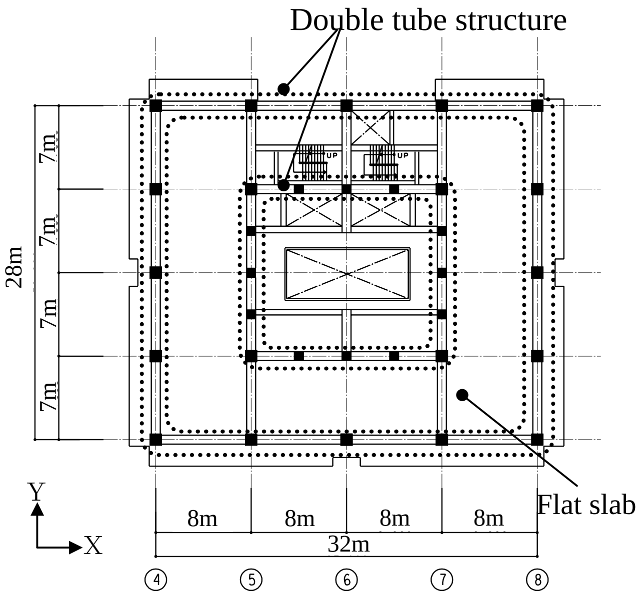


Figure 2 Framing plan of typical floor

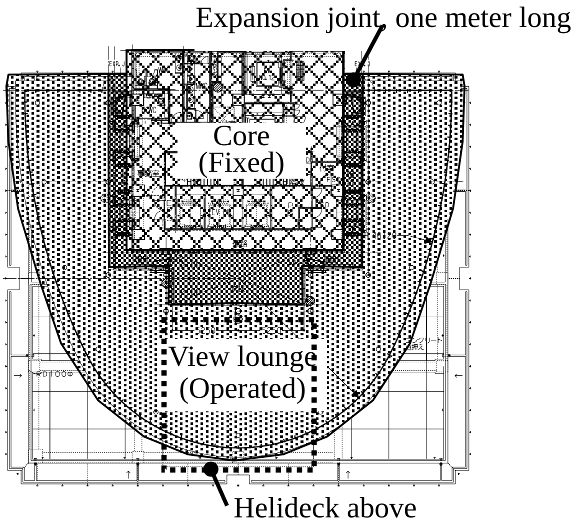


Figure 3 Floor plan of view lounge

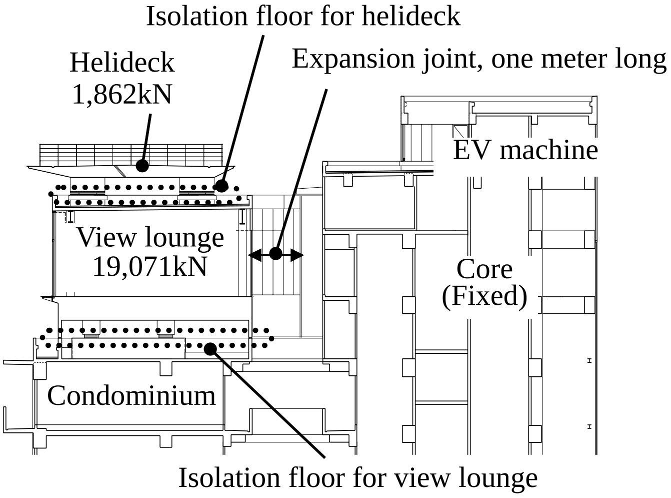


Figure 4 Cross section of mass damper

4. OUTLINE OF ISOLATION SYSTEM

Figure 5 shows the plan of the isolation floor for the view lounge. The isolation system under the view lounge consists of the following 5 elements:

1. Sixteen (16) sheets of steel ball bearing panels to serve as a supporting element;
2. Eight (8) isolators of laminated rubber bearings, each piled up double to serve as a restoring element;
3. Eight (8) oil dampers to serve as a damping element;
4. Eight (8) oil dampers to control the view lounge floor; and
5. Eight (8) oil buffers to protect against collisions at velocities up to 60cm/s.

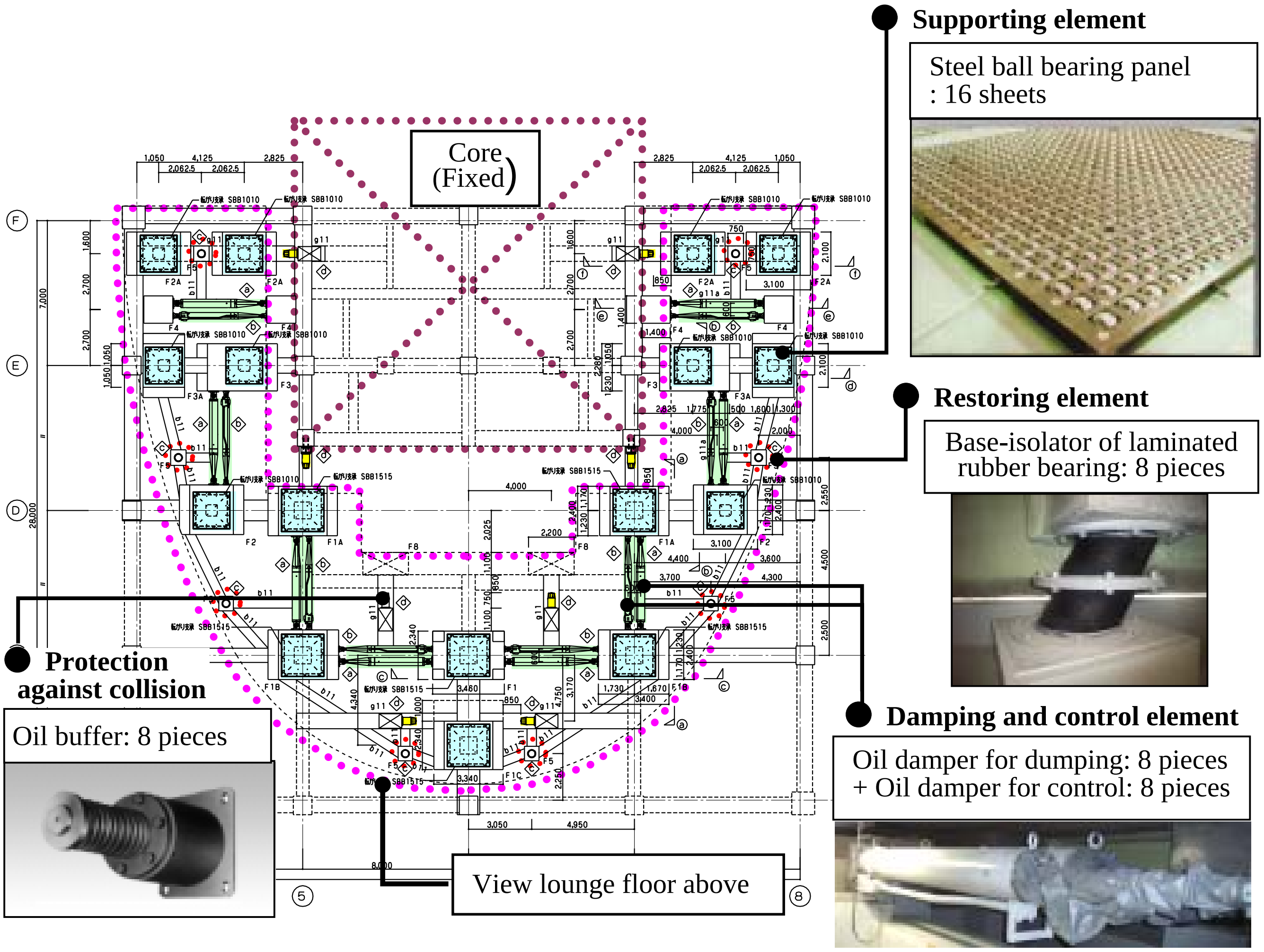


Figure 5 Floor plan of view lounge

As the operational stroke of the mass dampers in this system is set to ±one meter, longer than that of the conventional mass dampers against wind, we have developed a long-stroke oil damper that can follow large displacements [1]. The rubber bearings are used only as a restoring element: Each isolator consists of two piled-up bearings for longer stroke. The exterior walls are controlled, synchronized with the view lounge floor: They are normally fixed to resist the strong wind, but the locked condition will be automatically released in a large earthquake.

Table 1 shows the restoring force characteristics and damping characteristics of the seismic isolation floor under the view lounge. Their natural vibration periods, 8.05 sec. for the view lounge floor and 4.9 sec. for the helideck floor, are set to achieve the maximum damping effect based on the preliminary response analysis. As shown in Figure 6 the damping factor of the oil dampers is proportional to the square of the velocity. The factor becomes closer to the theoretically optimum damping factor of a mass damper in a low velocity region, but increases in a high velocity region to control the maximum stroke of the damper.

Table 1 Characteristics of seismic isolation floors under view lounge and helideck

	View lounge	Helideck
Weight (kN)	19,071	1,862
Natural vibration period (sec.)	8.05	4.90
Coefficient of viscous damping (kN・s^2/cm^2)	0.42	0.10

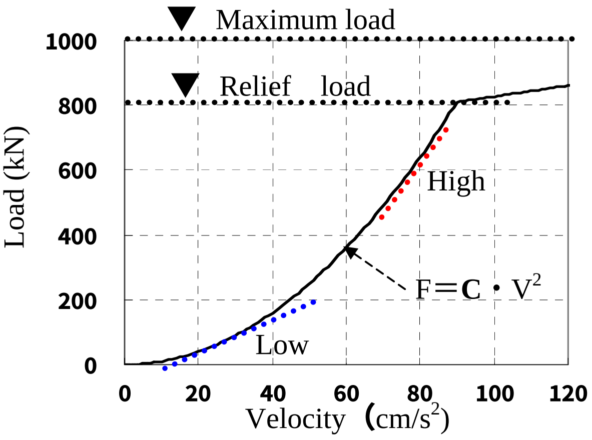


Figure 6 Damping factor of the oil damper

5. SEISMIC RESPONSE ANALYSIS

5.1. Outline of analytical modeling and earthquake wave inputs

Figure 7 shows the building model for the seismic response analysis. We prepared a flexure-shear model of point masses to analyze the main building, and used an elasto-plastic model to analyze the restoring force characteristics of the building. The seismic isolation floors were modeled so as to be subject to torsional vibration.

Table 2 shows the maximum acceleration and maximum velocity of the earthquake waves used for the response analysis. We used two levels of artificial seismic waves to simulate the moderate and large-scale earthquakes, according to the acceleration response spectra on the engineering bedrock given by the Building Standard Law of Japan (refer to Figure 8), using the two phase characteristics. We made adjustment for moderate earthquakes: The acceleration of the input wave was set to such a level that the fixed view lounge floor starts to be released.

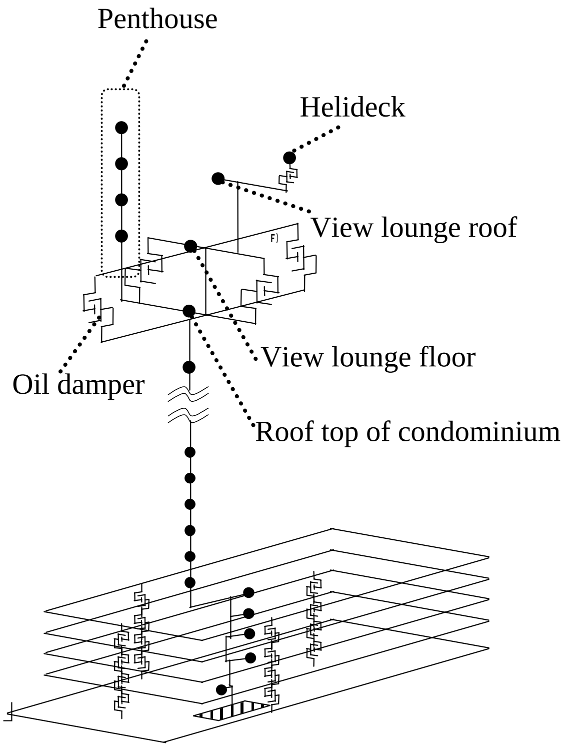


Figure 7 Building model for seismic response analysis

Table 2 Maximum Acceleration and Maximum Velocity of Earthquakes Used for Response Analysis

Wave No.	Phase Characteristics	Moderate earthquake		Large Earthquake	
		ACC (cm/s^2)	VEL (cm/s)	ACC (cm/s^2)	VEL (cm/s)
1	Random	80.0	7.1	586.3	49.9
2	Observed[*1]	80.0	5.7	607.8	57.4

[*1] Observed in Kushiro, Japan in 1993

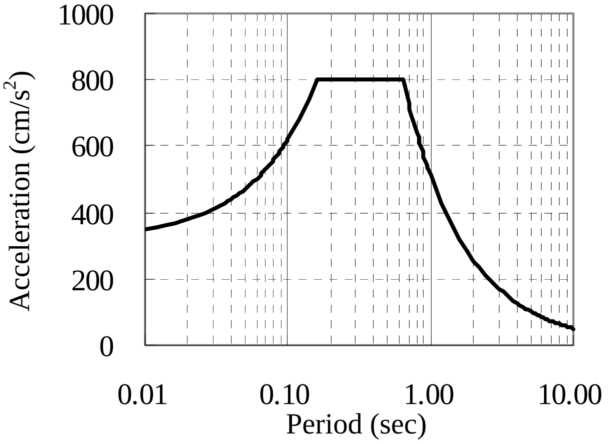


Figure 8 Acceleration response spectra on engineering bedrock given by Building Standard Law of Japan (Large Earthquake)

5.2. Response of seismic isolation floor

Table 3 shows the maximum response of the seismic isolation floor under the view lounge and their design criteria against large earthquakes. To satisfy the design criteria, the maximum inter-story displacement should not exceed 85cm, and the maximum inter-story velocity should not exceed 100cm/s.

Figure 9 shows the graph of the literature-based critical accelerations of an overturning action of furniture [2]-[3], and we plotted the maximum acceleration of the view lounge floor in case of large earthquakes.
As the natural frequencies are long, the acceleration levels are low enough to prevent an overturning action of three meter high furniture at the aspect ratio(H/B) of about 6.

Table 3 Maximum responses of seismic isolation floor under view lounge and their design criteria

	Response		Criteria
	Wave No.1	Wave No.2	
Displacement (cm)	62.3	68.5	85.0
Velocity (cm/s)	87.2	93.6	100.0

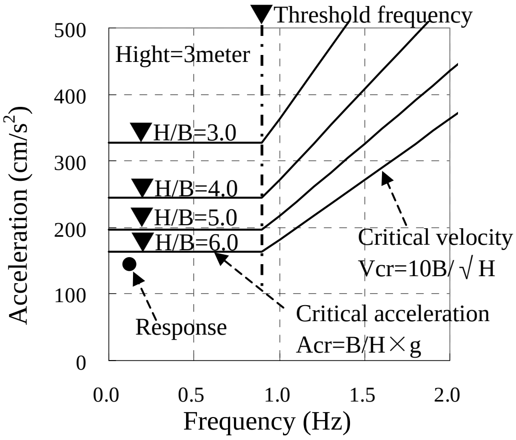
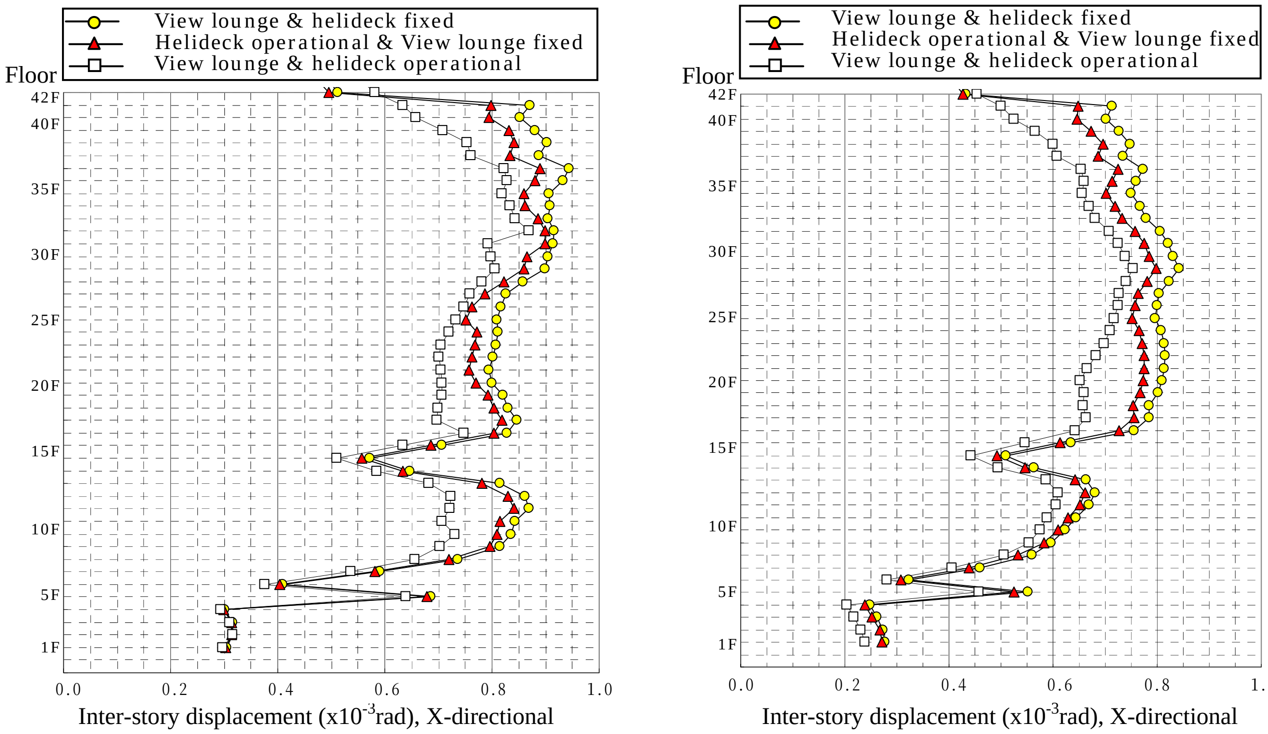


Figure 9 Critical acceleration of furniture overturning action vs. max. acceleration

5.3. Effect of mass damper in modetate earthquake

Figure 10 shows the effects of the mass damper on the X-directional inter-story drift angle during a moderate earthquake. The case of the mass damper remaining non-operational is also shown in the charts. The inter-story drift angle can be reduced by at maximum about 7%, if only the helideck floor is operating, and by at maximum about 20% if the view lounge floor is also operating.

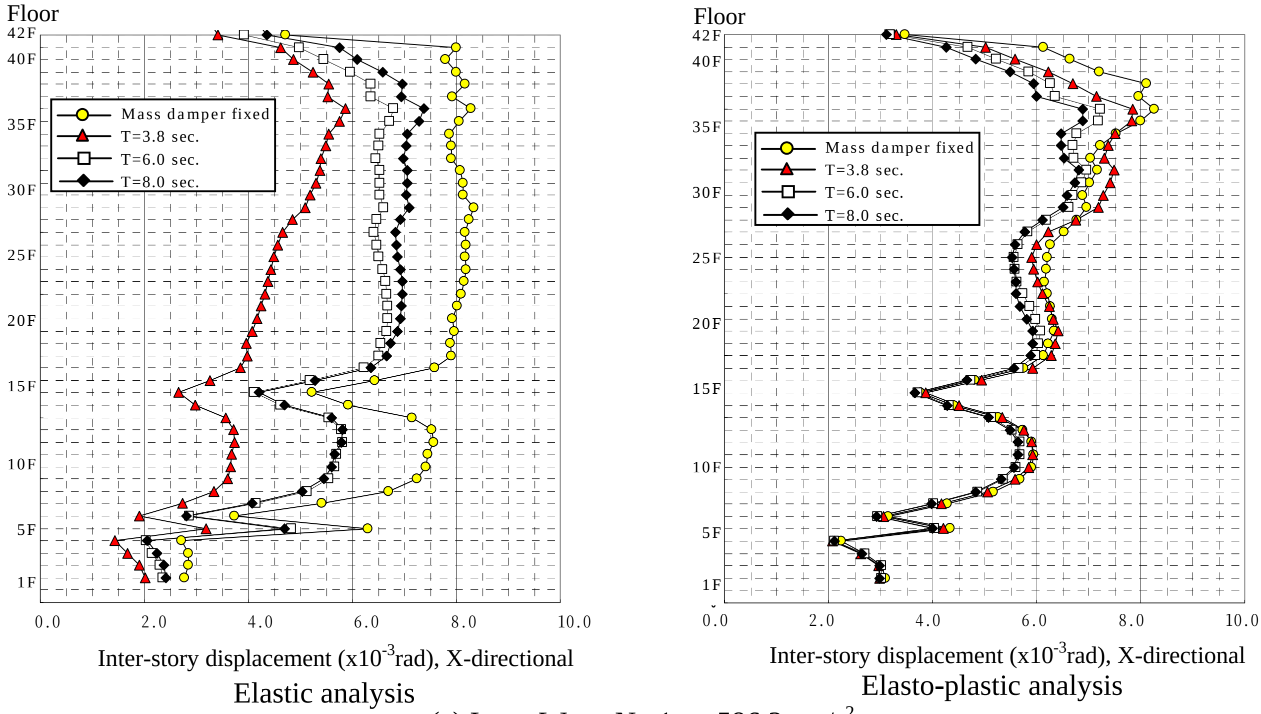


(a) Input Wave No.1 80cm/s^2 (b) Input Wave No.2 80cm/s^2

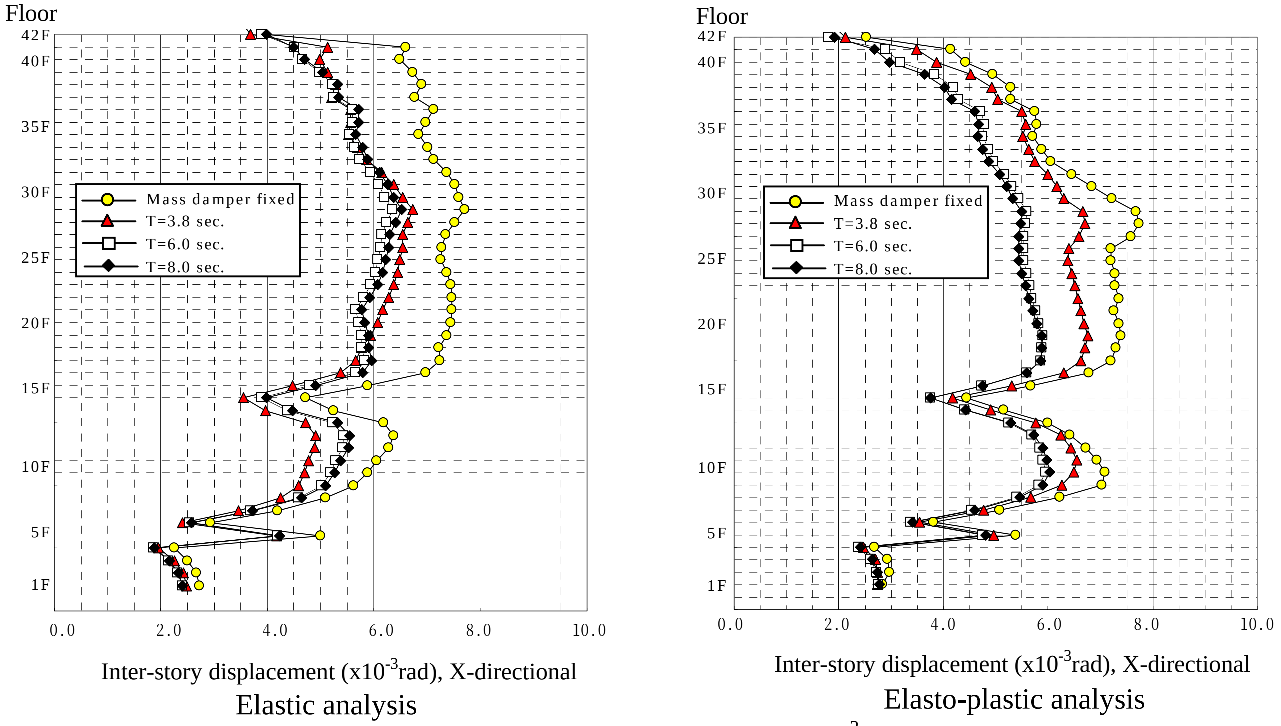
Figure 10 Effect of mass damper on inter-story displacement (Moderate earthquake)

5.4. Effect of mass damper in large earthquake

Figure11 shows the effects of the mass damper with different natural periods on the X-directional inter-story drift angle during a large earthquake. The effect of the mass damper on the response varies considerably, according to the phase characteristics of earthquakes and the natural vibration periods of the mass damper.



(a) Input Wave No.1 586.3 cm/s^2



(b) Input Wave No.2 607.8 cm/s^2

Figure 11 Effect of mass damper on inter-story displacement (Large earthquake)

In the analysis on an elastic building, the damper is the most effective when the natural vibration period of view lounge's mass damper is set to 3.8 sec., that is equal to the optimum natural vibration period, theoretically estimated from the primary natural vibration period of the building. On the other hand, when the skeleton curve of the building is elasto-plastic, the natural vibration period of the damper will have to be as longer as about 8 sec. to attain a sufficient damping effect.

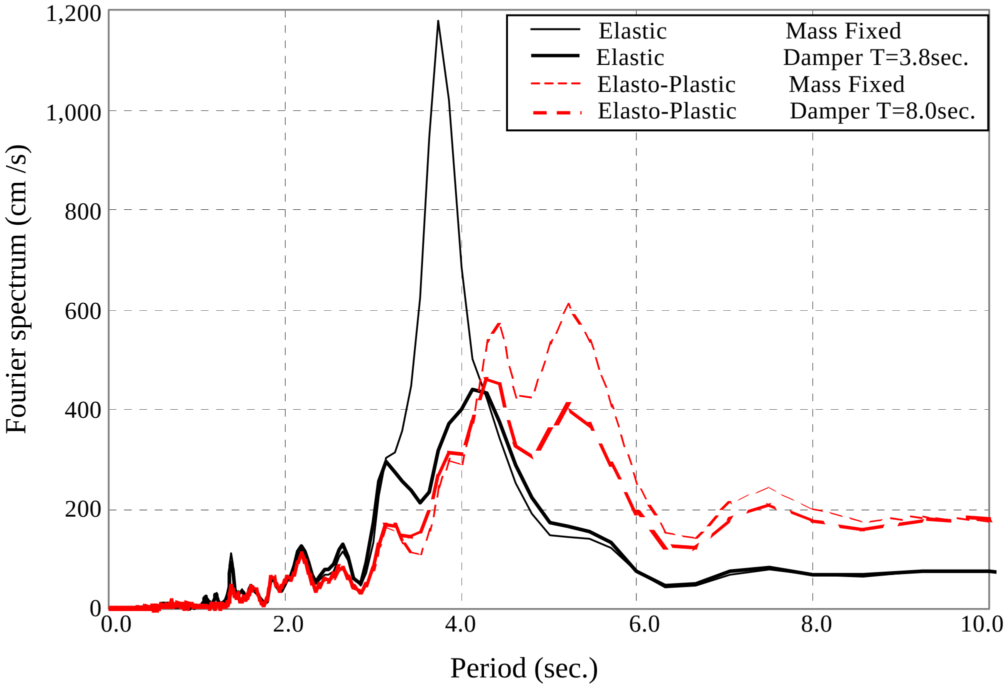
Also, as can be seen in the figures, the damping effects in an elasto-plastic building are not so good as those in an elastic building when the natural vibration periods are set to be optimum. In an elasto-plastic building, however, the responses still can be reduced by 20 - 40% at the floors with larger inter-story drift angles, and therefore the mass dampers are fully effective in practical use.

Moreover, the mass dampers with natural vibration periods of 6 and 8 sec., do not show any significant difference in damping effects. Therefore, no strict tuning is required for elasto-plastic buildings.

5.5. Fourier spectrum of response on building top

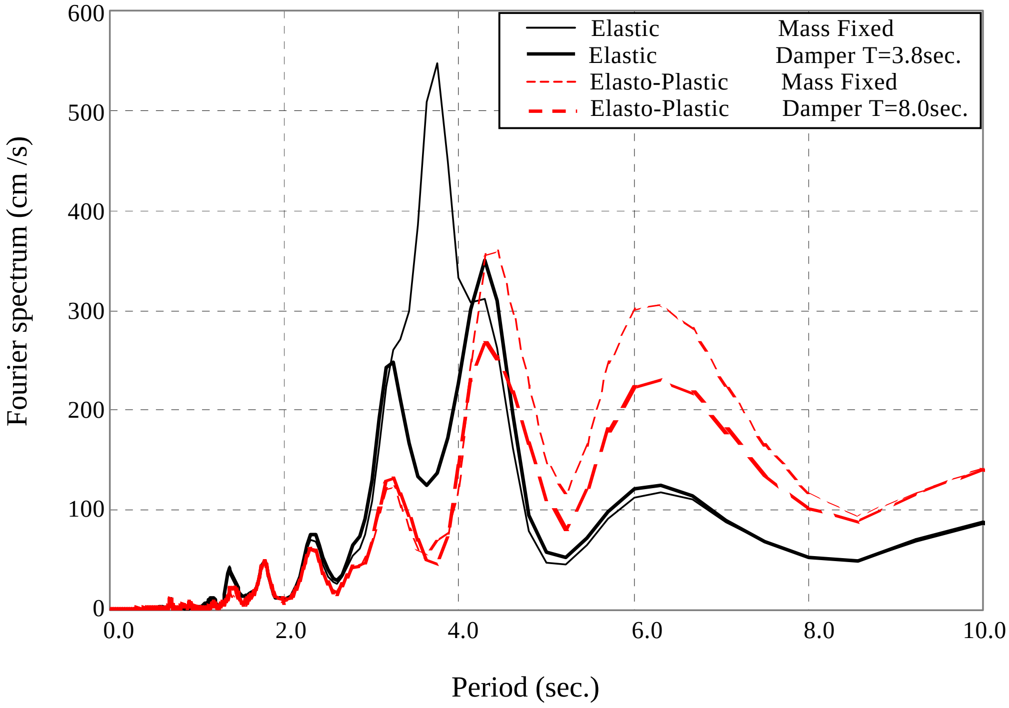
Figure 12 shows the Fourier spectra of response waves on the building top (the lower side of the seismic isolation floor). In case of the elastic responses as shown by the solid lines below, the distinct peak in the natural vibration period disappears due to the mass damper effects.

On the other hand, in case of the elasto-plastic responses as shown by the dashed lines, each spectrum has no distinct peak frequency, but the whole energy is increased in a longer period range than the elastic natural vibration period of the building. Accordingly, the mass dampers in an elasto-plastic building are also effective in reducing the energy not partially but throughout the long period range.



(a) Input Wave No.1 586.3 cm/s^2

Figure 12(a) Fourier spectrum of response waves on building top(Large earthquake)



(b) Input Wave No.2 607.8 cm/s^2

Figure 12(b) Fourier spectrum of response waves on building top(Large earthquake)

6. CONCLUSION

The effect of a large mass damper utilizing the building top floor weight isolated from a high-rise R.C. building is studied in this paper on the basis of the earthquake response analysis. As a R.C. structure behaves elasto-plastically, the vibration of the building is not simple natural frequency vibration. Accordingly, the effect of the mass damper is not so remarkable as that on elastic vibration. However, sufficient mass and a long stroke enable the mass damper to be practically effective enough. The natural vibration period of the mass damper should be set by considering the nonlinearity of the building appropriately.

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