Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VIII)

SE-5

DESIGN AND ANALYSIS OF A TOWER STRUCTURE WITH A TUNED MASS DAMPER

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SUMMARY

Chiba Port Tower is a steel structure 125m high which has a tuned mass damper on the top floor in order to reduce vibrations caused by strong winds and earthquakes. This paper reviews the design and analysis of the tower structure with the tuned mass damper. Analyses of the behavior of the tower in earthquakes using data measured were carried out and the effect of the tuned mass damper was confirmed.

INTRODUCTION

Tuned mass dampers have been used for vibration damping in mechanical systems for a long time. However, in Japan, this type of damper has not been applied to tower structures and tall builidngs. Chiba Port Tower is the first tower equipped with a tuned mass damper in Japan.

FUNDAMENTAL DYNAMIC PROPERTIES OF A TOWER STRUCTURE WITH A TUNED MASS DAMPER

Fundamental dynamic properties of a tower structure with a tuned mass damper were studied for sinusoidal ground motions using a two-mass model. The model is shown in Fig. 1, where D represents a tuned mass damper and S represents a tower structure. The displacement amplification curves are shown in Fig. 2 for the 2-mass model in the case of a mass ratio $M_D/M_S=1/100$, a frequency ratio $\omega_D/\omega_S=1.0$, and a structure damping factor $h_S=0.02$. When a damping factor of the tuned mass damper h_D is small, the amplification curves have two peaks, but when h_D is large, they have one peak. Though the resonance amplification of the structure without a tuned mass damper is 25 times the ground motion, the amplification of the structure with the tuned mass damper becomes remarkably smaller when a proper value of h_D is chosen, because of the interaction of the tuned mass damper and the structure. If h_D is too large, the effect of the tuned mass damper is reduced. Therefore, an optimum damping factor value exists.

For the purpose of studying the influences of M_D/M_S and h_D on the structure response, the maximum amplifications of the structure are plotted in Fig. 3

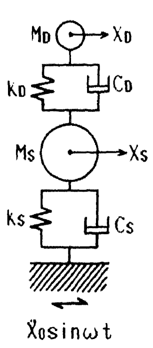

Fig. 1 Analytical model

for ranges of M_D/M_S=1/1000~1/10 and h_D=0.01~1.0 where ω_D/ω_S=1.0 and h_S=0.02.

Figure 3 shows that the minimum amplification of the structure for each value of M_D/M_S decreases with increased M_D/M_S, and the optimum value of h_D for each of M_D/M_S increases with increased M_D/M_S. From these results it is concluded that M_D/M_S of a value greater than 1/100 is necessary to reduce the amplification of the structure to a half of that in the case without a tuned mass damper.

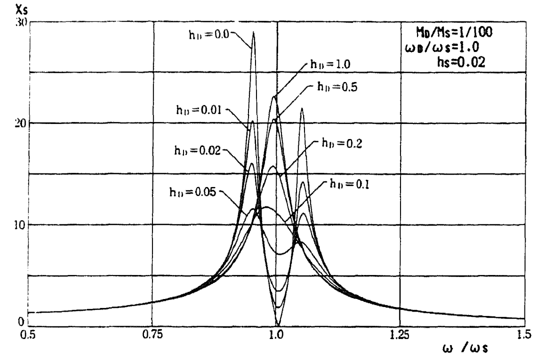

Fig. 2
Amplification curves of the 2-mass model

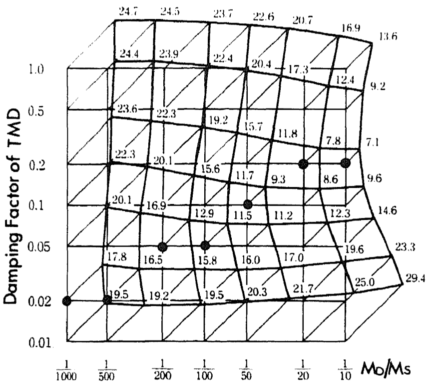

Fig. 3
Maximum amplifications vs h_D and M_D/M_S

TUNED MASS DAMPER DEVELOPED

<u>Mechanism of a Tuned Mass Damper Developed</u> A tuned mass damper developed is shown in Photo 1 and its mechanism in Fig. 4. The damper consists of a mass and two frames overlapped at right angles which can move in X and Y directions respectively. The mass, therefore, can move in any horizontal direction without rotation. Each frame is equipped with coil springs and damping devices. The slide mechanism reduces friction force by roller bearings. The damping device has a rotator in a high viscosity liquid and produces a damping force by shearing the liquid. Through this mechanism, the period of the damper can be matched with that of the tower according to X and Y directions respectively, by changing the number of the springs and adjusting a weight of the mass. The damper was developed by the authors in collaboration with Mitsubishi Steel Mfg. Co., Ltd.

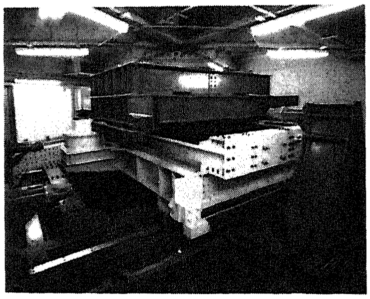

Photo 1 View of the tuned mass damper

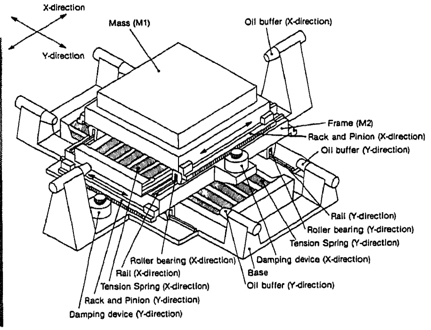

Fig. 4 Mechanism of the tuned mass damper

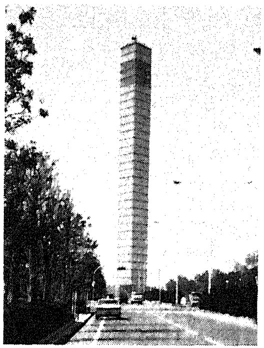

Photo 2 Full view of Chiba Port Tower

<u>Specifications of the Tuned Mass Damper</u> The specifications of the tuned mass damper were decided considering the fundamental properties mentioned in the preceding. The damper weight was set to about 1/100 of the 1st mode effective weight of the tower, in consideration of the limited installation area and easy construction of the sliding mechanism. In the actual damper, the weight in X

direction M_{DX} was set to 10t (=M1) and that in Y direction M_{DY} to 15t (=M1+M2), resulting in the mass ratios of $M_{DX}/M_S=1/120$ and $M_{DY}/M_S=1/80$ where the 1st mode effective weight of the tower $M_S=1200$t (total weight of the tower is 1950t). The acceptable range for the damping factor of the tuned mass damper is $h_D=0.05\sim0.3$, and $h_D=0.2$ was adopted as the standard value in consideration of temperature dependency of the viscous materials used in the damping devices. The maximum amplitude of the tuned mass damper was set to ±1.0m.

APPLICATION OF THE TUNED MASS DAMPER TO CHIBA PORT TOWER

The tuned mass damper was installed on the top floor of Chiba Port Tower (Photo 2) in Chiba, Japan. The tower has a rhombus shaped plan with a side length of 15m. The main frame of the tower is a hexagonal tubed structure with vertical bracing on all sides, so that the tower has similar properties of stiffness and strength in all directions and stability against torsional force. The tower has observatories on the upper floors. All of the surfaces are covered with half mirror glass. Therefore, the tower has a large surface area and is a fairly sensitive structure with respect to wind. The purpose of the tuned mass damper is to increase damping of the 1st mode vibration and to improve the dynamic response properties of the structure.

Effect of the Tuned Mass Damper in the Design Analysis Earthquake response analyses of the tower with and without the tuned mass damper were carried out and the effect of the damper was confirmed. As shown in Fig. 5, the analysis in the case with the damper used a 19-mass tower model, which was provided with one mass representing the tuned mass damper at P2 Floor. The natural periods of the tower are 1st mode one of 2.25 sec and 2nd mode one of 0.51 sec. The damping factor of the tower is 0.02 constant irrespective of frequency. The damping factor of the tuned mass damper is 0.2.

The input seismic motion used was EL CENTRO NS 1940.5.18, with the maximum velocity of 50cm/sec (the maximum acceleration of 518cm/sec^2), and the analysis duration was 30 sec. The maximum relative displacement of the top floor was 62.8cm in the X direction without the damper, but with the damper it was reduced about 40% to 37.1cm. In the Y direction that of the tower without the damper was 68.2cm but with the damper was reduced about 30% to 48.7cm. Story shear forces were almost unchanged at the upper stories in X and Y directions but at middle and lower stories those of the tower with the damper were 5 ~ 30% smaller than those without the damper. Overturning moments were reduced about 30%, from 45800tm without the damper to 32800tm with the damper in the X direction, and in the Y direction they were reduced about 30% from 41200tm to 29200tm. Tuned mass damper displacements were 96.2cm in the X direction and 122.9cm in the Y direction.

Measurement of Earthquake and Wind Actions The authors and others organized the "Research Committee for Full Scale Measurement of Earthquake and Wind Actions on Chiba Port Tower" and started the measurement in August/1987 in cooperation with Chiba Prefecture and Chiba City. The members of the Committee are Takafumi Fujita, Assoc. Prof., Univ. of Tokyo (Chairman); Takeshi Ohkuma, Prof., Kanagawa Univ.; Jun Kanda, Assoc. Prof., Univ. of Tokyo; and five private companies, Nikken Sekkei, Takenaka Corporation, Nippon Sheet Glass Co., Ltd., Mitsubishi Steel Mfg. Co., Ltd., and Sankyo Aluminium Industry Co., Ltd. The locations of the measuring devices are shown in Fig. 6. Accelerometers were located on the

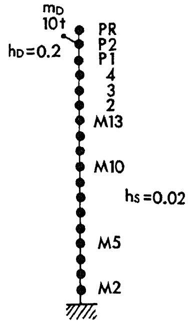

Fig. 5 Analytical model for the Tower

top and 1st floor, displacement transducers on the damper, an anemometer at 7m above the roof level, and wind pressure transducers at 90m above the ground level at 10 points on the facade. The measured data are recorded by digital data recorders. The recordings are made by automatic measuring equipment and remotely monitored.

DYNAMIC RESPONSE ANALYSIS USING MEASURED DATA OF AN EARTHQUAKE

Using date of an offshore earthquake east of Chiba Pref. (Dec. 17/1987), which is the strongest earthquake measured until now, dynamic response analysis was carried out. The measurement location, the epicenter, the depth, and the magnitude of the earthquake are shown in Fig. 7. Time histories of acceleration measured are shown in Fig. 8 and their response spectra in Fig. 9.

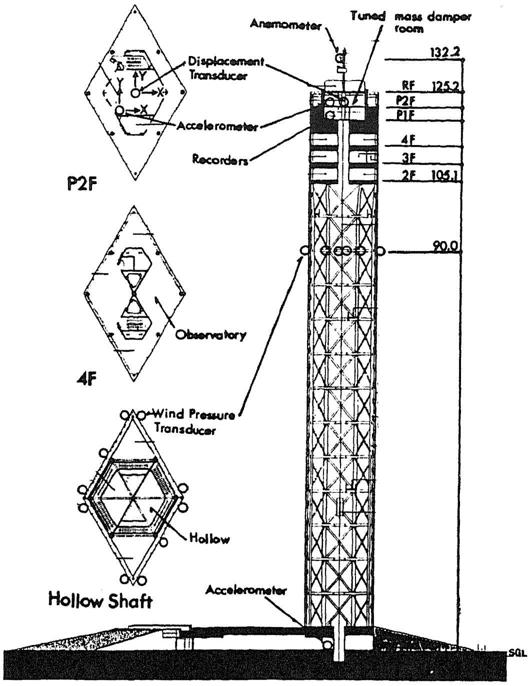

Fig. 6
Locations of measuring devices

This earthquake was a strong earthquake with an intensity of 5 on the Japanese Meteorological Agency scale (8 on M.M.I. scale). However, the tower received no damage in spite of the flexible structure covered with glass.

The same analytical model as shown in Fig. 5, was used. For the period, the damping factor and the spring constant of the model, values obtained from performance tests at the completion were used, which are shown in Table 1. For the damping factors of the tower, a value of 0.5% was adopted for the 1st period and values proportioned to the frequencies for the higher periods. A comparison between the measured time histories and analysed time histories for the acceleration and the displacement on the top of the tower are shown in Fig. 10 together with the displacement of the damper.

A comparison for the maximum values is shown in Table 2. The results of the seismic response analysis coincided with the measured data. For a simple and regular structure like this tower, it was confirmed that the behavior of the structure under an earthquake could be predicted accurately using an analytical model for the design.

Using this analysis model, the top floor displacements of the tower with and without the damper were calculated for this earthquake. A comparison between the displacements is shown in Fig. 11. The maximum response values are shown in Table 3. The top floor displacement of the tower became smaller by virtue of the damper. After the occurrence of the maximum displacement, the damping due to the damper became large and the vibration was reduced quickly. From these results the effect of the damper was confirmed. However, the acceleration at the top floor was little changed, because the 2nd mode was dominant in the acceleration although the damper was designed to increase the damping of the 1st mode.

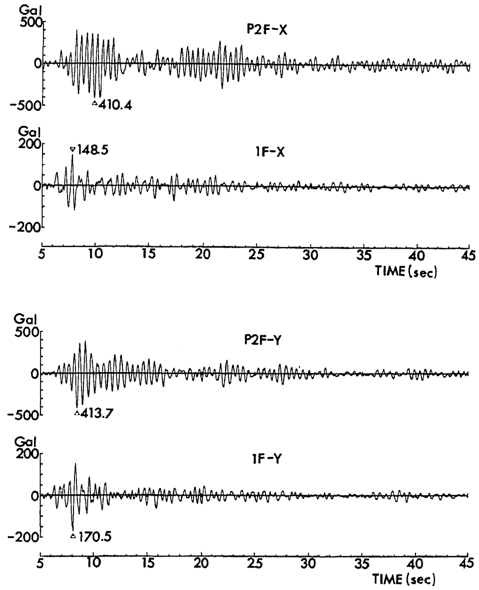

Fig. 8 Time histories of acceleration measured

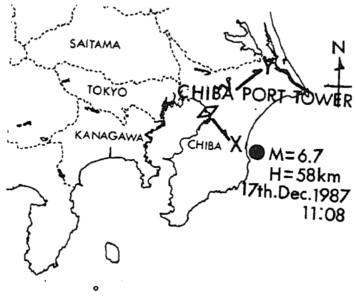

Fig. 7 Measurement location and epicenter of the earthquake used for the analysis

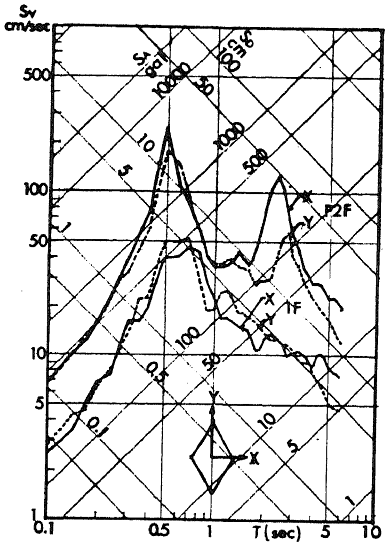

Fig. 9 Response spectra

Table 1 Constants of the analytical model

			X direction	Y direction
Structure	1st mode effective weight (t)		1200.	
	Period	1st mode (sec)	2.25	2.70
		2nd mode (sec)	0.51	0.57
	Damping factor (%)		0.005	
TMD	Weight (t)		10.0	15.4
	Period (sec)		2.24	2.72
	Spring constant (t/cm)		0.080	0.084
	Friction force (t)		0.045	0.045
	Damping factor (%)		0.15	

Table 2. Comparison between measured and analysed values

	X direction			Y direction		
	P2F Disp. (cm)	P2F Acc. (cm/sec2)	TMD Disp. (cm)	P2F Disp. (cm)	P2F Acc. (cm/sec2)	TMD Disp. (cm)
Meas.	10.20	410.	–	8.25	414.	–
Cal.	8.77	373.	25.8	8.85	416.	12.4
Meas. /Cal.	0.86	0.91	–	1.07	1.00	–

Table 3. Comparison between the maximum values with and without TMD

	X direction		Y direction	
	P2F Disp. (cm)	P2F Acc. (cm/sec2)	P2F Disp. (cm)	P2F Acc. (cm/sec2)
Without TMD	10.28	368.	10.14	423.
With TMD	8.77	373.	8.85	416.
With /Without	0.85	1.01	0.87	0.98

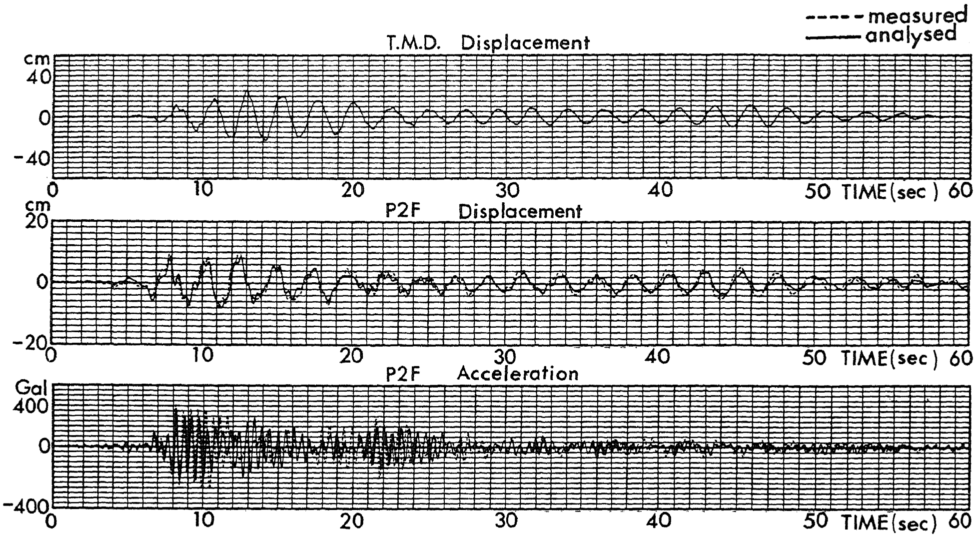

Fig. 10 Comparison between the measured and analysed time histories

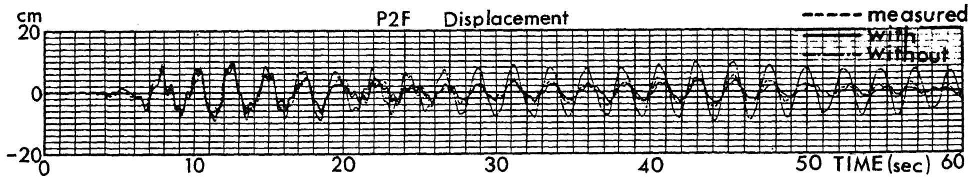

Fig. 11 Comparison between the time histories with and without TMD

CONCLUDING REMARKS

This paper discussed various subjects investigated for application of a tuned mass damper to Chiba Port Tower. Though a tuned mass damper in the theory was just a simple one-mass system, various problems had to be solved to implement it to the structure. These included decision of the specifications of the damper, installation of the damper in the restricted space, development of the damper mechanism to enable the 10 or 15t weight to oscillate in plane with a large amplitude of ±1m. The authors hope this paper will serve as useful reference for the implementation of tuned mass dampers in the future.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of Chiba Prefectural and Chiba City Officials which made the measurement possible. The measured data belongs to the Research Committee for Full-Scale Measurement of Earthquake and Wind Actions on Chiba Port Tower and the analysis of the measured data was made in cooperation with Yasuhiko Abe, Technical Research Laboratory, Takenaka Corporation, who is a member of the Committee.

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