CASE STUDY OF TUNED MASS DAMPER AT TAIPEI WORLD FINANCIAL CENTER TAIWAN

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Abstract*At 101 stories and 508 m above grade, the Taipei 101 tower is the newest World's Tallest Building. Collaboration between architects and engineers satisfied demands of esthetics, real estate economics,construction, occupant comfort in mild-to-moderate winds, and structural safety in typhoons and earthquakes. Its architectural design, eight eight-story modules standing atop a tapering base, evokes indigenous jointedbamboo and tiered pagodas. Building shape refinements from wind tunnel studies dramatically reduced acceleration and overturning forces from vortex shedding. The structural framing system of braced core and multiple outriggers accommodates numerous building setbacks. A secondary lateral load system of perimeter moment frames and special core connections adds to seismic safety. Column axial stiffness for drift controlwas made practical through steel boxes filled with high-strength concrete. Occupant comfort is improved by amassive rooftop pendulum Tuned Mass Damper. Pinnacle framing fatigue life is enhanced by a pair of compactspring-driven tmds. The soft soil subgrade required mat foundations on bored piles, slurry walls, and a mix oftop-down and conventional bottom-up construction with cross-lot bracing. The project illustrates the large andsmall design decisions in both architecture and engineering necessary to successfully complete a major building in a challenging environment.*

Keywords: **vortex shedding, high-strength concrete, tuned mass damper, outrigger, fatigue.**

INTRODUCTION

During earthquake structural performance of Reinforced Concrete (RC) buildings always play crucial roles in losing of life, injuries, economic losses etc. But to a certain extend structures already built are vulnerable to future earthquakes. Earthquake risk is associated with seismic hazard and vulnerability of building. Therefore, to protect such civil structures from significant damage one of the way is to increase flexibility of structures. But will affect the comfortability of people inside the building. So the response reduction of civil structures during dynamic loads such as severe earthquakes and strong winds has become an important topic in structural engineering. A number of methods have been developed to reduce the structural response due to lateral excitations. Tuned Mass Damper (TMD) is one of the device that is the most popular one due to its simple principle that have been utilized to control the behavior of tall structure subjected to excitations. It is a passive control system which consist of a mass, and spring that is attached to a structure in order to reduce the dynamic response of the structure. The idea behind a tuned mass damper is that if a multiple-degree-of-freedom system has a smaller mass attached to it, and the parameters of the smaller mass are tuned precisely, then the oscillation of the system can be reduced by the smaller mass.

LITERATURE REVIEW

[1]**Ali Ajilian Momtaz, Mohamadreza Akhavan Abdollahian, Anooshiravan Farshidianfar. Study of wind-induced vibrations in tall buildings with tuned mass dampers taking into account vortices effects, 15 November 2017:**In recent years, construction of tall buildings has been of great interest. Use of lightweight materials in such structures reduces stiffness and damping, making the building more influenced by wind loads. Moreover, tall buildings of more than 30 to 40 stories, depending on the geographical location, the wind effects are more influential than earthquakes. In addition, the complexity of the effects of wind flow on the structure due to the interaction of the fluid flow and solid body results in serious damages to the structure by eliminating them. Considering the importance of the issue, the present study investigates the

phenomenon of wind-induced vibration on high-rise buildings, taking into account the effects of vortices created by the fluid flow and the control of this phenomenon. To this end, the governing equations of the structure, the fluid flow and the tuned mass damper (TMD) are first introduced, and their coefficient values are extracted according to the characteristics of ACT skyscraper in Japan. Then, these three coupled equations are solved using a program coded in MATLAB. After validation of the results, the effects of wind loads are analyzed and considered with regard to the effects of vortices and the use Of TMD, and are compared with the results of the state where no vortices are considered. Generally, the results of this study point out the significance of vibrations caused by vortices in construction of engineering structures as well as the appropriate performance of a TMD in reducing oscillations in tall buildings

[2] Jorge Eliecer Campuzano Carmona, Suzana Moreira Avila, Graciela doz. Proposal of a tuned mass damper with friction damping to control excessive floor vibrations, 23 June 2017:A numerical and experimental study is carried out for a tuned mass damper (TMD) to control excessive floor vibrations. To verify the performance of this control device, free and forced vibration experiments were performed on the platform for dynamic tests located at the University of Brasilia Structure Laboratory. The platform and the TMD were previously modeled via the finite element method using ANSYS software for harmonic and transient analysis, varying damper parameters to find design values for TMD mass, damping and stiffness. The control device was constructed so that it could be installed above the platform. Experimental tests were performed on the platform by people doing rhythmic activities of continuous jumping, walking randomly and synchronized movements with semi bended knees. The results of the tests verified the reduction of the response acceleration of the structure with TMD installation. This control system is of simple construction and maintenance, and has a low manufacturing cost.

[3] Nam Hoanga,Yozo Fujinoa, Pennung Warnitchaib. Optimal tuned mass damper for seismic applications and practical design formulas, 26 June 2007: In seismic retrofit of a long-span truss bridge in Japan, a new retrofit scheme was applied in which the existing bearings of the bridge were replaced by a new floor deck isolation system. The floor decks and isolation system together can be viewed as a giant tuned mass damper (TMD) to reduce the seismic force of the truss. This motivates a study on the optimal design of a TMD for a single-degree-of-freedom structure under seismic loads in this paper. Kanai–Tajimi spectrum is selected to model the earthquake excitation. It is shown that, when ratio of the characteristic ground frequency in the Kanai–Tajimi spectrum to the structural frequency is above three, the ground motion can be assumed to be a white noise to design TMD. For a smaller ground frequency ratio, simple formulas of the optimal TMD parameters are obtained. The dependence of optimal TMD parameters on mass ratio especially for large TMD is highlighted. It is found that the optimal TMD has lower tuning frequency and higher damping ratio as the mass ratio increases. For a large mass ratio, TMD becomes very effective in minimizing the primary structure response and robust against uncertainties in the parameters of the system.

[4] Said Elias, Vasant Matsagar. Wind response control of tall buildings with a tuned mass damper, 08 November 2017: Wind response control of tall buildings installed with a tuned mass damper (TMD) is investigated. The performance of a TMD installed at the topmost floor of a 76-storey benchmark building is compared with the TMD installed at different floors (locations) of the building. The TMD is placed where particular mode shape amplitude of the building is largest or larger. At each location, the performance of the TMD is examined by tuning it to the first few modal frequencies. The coupled differential equations of motion for the building without/with the TMD are derived and solved by employing Newmark's integration method. Variations in the normalized response of the controlled building under wind forces are computed to study the effectiveness of using different TMD schemes. Placement, tuning frequencies, mass and damping ratios of the devices are the parameters investigated to compare the effectiveness of these different TMD schemes. It is concluded that placement of the TMD shows a significant influence in improvement of the performance of the TMD, especially if it is tuned to the corresponding modal frequency. In addition, the optimally determined damping ratio reduces for the TMD tuned to the higher modal frequencies.

[5] Chi-Chang Lin, Jin-Min Ueng, Teng-Ching Huang. Seismic response reduction of irregular buildings using passive tuned mass dampers, 24 April 1998: This paper illustrates the practical considerations and vibration control effectiveness of passive tuned mass dampers (PTMDs) for irregular buildings, modelled as multi-storey torsionally coupled shear buildings, under bi-directional horizontal earthquake excitations. The PTMD is designed to control the mode which makes most contribution to the largest response of the building. Its optimum installation location and moving direction are determined from the controlled mode shape values. The optimal system parameters of PTMD are then calculated by minimizing the mean-square modal displacement response ratio of controlled mode between the building with and without PTMD under earthquake excitation from critical direction. As two PTMDs are used to reduce both translational responses, this study arranges the two mass dampers to achieve the largest vibration reduction. Numerical and statistical results from a long and a square five-storey torsionally coupled buildings subjected to five real earthquakes from different incident angles verify that the proposed optimal PTMDs are able to reduce the building responses effectively.

[6]**Z. Guenidia, M. Abdeddaima, A. Ounisa, M.K. Shrimalib, T.K. Dattab. Control of Adjacent Buildings Using Shared Tuned Mass Damper, 1017:** Seismic control of adjacent buildings has received considerable attention in recent years because of two reasons: i) for the control of the response of the two buildings simultaneously by a single control device and ii) for the reduction of the possibility of interaction between the two buildings. Various types of coupling devices have been introduced and their effectiveness in controlling the responses of the adjacent building is studied. Out of the different types of the coupling devices, MR damper is one which is widely investigated. In this paper, the responses of the two buildings are controlled by using two strategies: i) a shared tuned mass damper (TMD) and ii) a hybrid system using both a TMD and a MR damper. The shared TMD is mounted such that it can effectively control the responses of both buildings and it is tuned to the fundamental frequencies of (i) the coupled structure and (ii) the two adjacent buildings vibrating separately. The shared TMD has the obvious advantage that the two separate TMDs are not required to control the two buildings separately. The response control includes the control of the top story displacement, base shear and maximum drift. Results of the study show that i) a shared TMD can provide adequate response reduction compared to that obtained by using two TMDs separately, ii) the frequency ratio between the two adjacent building is the most important parameter which dictates the response reduction, iii) the hybrid control provides a significant improvement in response reduction over that obtained by a shared TMD alone.

[7] Tat S. Fu, Erik A. Johnson. Control Strategies for a Distributed Mass Damper System, June 10-12, 2009: Recent developments of a distributed mass damper (DMD) system integrate structural and environmental control systems for buildings. External shading fins are used as mass dampers such that they can (*i*) control building energy consumption by adjusting the fins and, thus, the amount of sunlight coming into the building and (*ii*) control structural movements by dissipating energy with the dampers during strong motions due to wind or earthquakes. Shading fins are placed along the height of the building, distributing the mass along the building instead of being concentrated in a few locations like traditional tuned mass dampers (TMDs). This eliminates any large damper mass on the top of the building that can be a structural and architectural challenge to design. The DMD system is formulated, simulated and analyzed with passive, active and semiactive control strategies. The passive DMD is shown to be as effective in response mitigation as a conventional TMD; active and semiactive strategies give further improvements. The building energy consumption using the movable shading fins is also briefly presented in this paper.

[8] Ging-Long Lin, Chi-Chang Lin, Bo-Cheng Chen, Tsu-Teh Soong. Vibration control performance of tuned mass dampers with resettable variable stiffness, 22 November 2014*:*Vibration control of civil engineering structures using tuned mass dampers (TMDs) is a widely acknowledged control strategy based on numerous analytical and experimental verifications. Although the design and application of traditional linear TMD systems are well established, nonlinear TMD systems that may have better control performance remain in the developmental stage. The TMD systems have two main problems, i.e. detuning effect and excessive TMD's stroke. To improve the overall performance of TMD systems, a novel semi-active TMD named resettable variable stiffness TMD (RVS-TMD), is proposed. The RVS TMD consists of an undamped TMD and a resettable variable stiffness device (RVSD). This RVSD is composed of a resettable element and a controllable stiffness element. By varying the stiffness of controllable stiffness element in the RVSD, force produced by the RVSD can be controlled smoothly through a semi-active control law. By operating the resettable element, the hysteretic loops of the RVSD can cover all four quadrants in the force–deformation diagram and, thus, increases energy dissipation. In other words, both stiffness and damping of the RVS-TMD are adjustable via only the RVSD device. The harmonic and seismic responses of a building equipped with the RVS-TMD were investigated. Numerical results show that the proposed RVS-TMD system can avoid detuning effect automatically and assure the optimal control performance as desired when the frequency of primary structure is changed.

[9] Saman Bagheri, Vahid Rahmani-Dabbagh. Seismic response control with inelastic tuned mass dampers, 21 June 2018: An elasto-plastic spring is utilized in a tuned mass damper (TMD) with eliminating its viscous damper to establish a new seismic response control system. A novel method to find the most appropriate parameters of the proposed elasto-plastic TMD (P-TMD) including its initial stiffness/frequency and yield strength is presented so as to reduce the seismic response of the main system with the P-TMD to a level of that obtained with a previously suggested optimum TMD. The parameters are used to compute the responses of several main structures in the form of single-degree of freedom systems with the proposed P-TMD under different earthquake excitations. To evaluate the effectiveness of the proposed device and tuning method, maximum displacements and accelerations are compared to those of optimum TMD systems as well as those obtained from uncontrolled ones. The numerical results show that the proposed device, when using the introduced procedure for selecting its design parameters, reduces the seismic responses significantly and can be used instead of the optimum TMD without the need for a viscous damper.

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1. The Taipei 101 uses a 800 ton TMD which occupy 5 of its upper floors (87 – 91).
2. The ball is assembled on site in layers of 12.5-cm-thick steel plate. It is welded to a steel cradle suspended from level 92 by 3” cables, in 4 sets of 2 each.
3. Eight primary hydraulic pistons, each about 2 m long, grip the cradle to dissipate dynamic energy as heat.
4. A roughly 60-cm-dia pin projecting from the underside of the ball limits its movement to about 1 m even during times of the strongest lateral forces.
5. The 60m high spire at the top has 2 smaller ‘flat’ dampers to support it.

Seismic DesignIssues

While wind is an ever-present environmental condition, Taiwan’s geology also mandated that earthquake resistance must be considered. A structural system stiff enough to limit wind drift does not automatically have the overload behavior desired for seismic ductility. But frames specifically designed for seismic ductility can be too flexible for wind conditions. The solution here was to design for stiffness and then check for seismic ductility and seismic strength. For example, where braces are ‘opened’ (work points do not coincide), in a seismic-controlled design they might be treated as ductile Eccentric Braced Frames with beam sections selected to meet specific proportions that force web shear to control over beam flexure. But such members would introduce undesirable flexibility for wind conditions.Instead,theopen‘link’portionofthebea m is strengthened by side plates to maintain stiffness and ensure the link is not controlling strength across the eccentric links. At the same time, where flexure was inherent in the design and large rotations were anticipated during seismic events, such as the deep beams crossing core corridors to link braced bays, ductility was provided by a Reduced Beam Section or ‘dogbone’ detail using proportions developed at the localuniversity.Inaddition,adualsystemwas applied steel moment frames along each sloping face of the building work in parallel with the braced core and outriggers.

Energy Conservation Analogy

With a string length of 14.7 m and a mass of 660,000 kg hanging from 90th floor to The 87th floor to provide a offset of movement of about 1.3 m. Shown in fig 3a

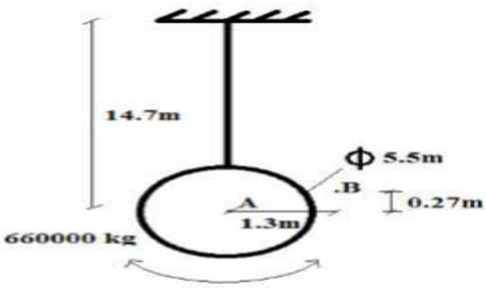


Figure 3 (a) Energy conservation analogy of taipei 101 damper.

The energy gained by the pendulum in raising its center of mass to a height of 0.27 m
Is purely gravitational potential energy. The gyroscopic damper should have an Equivalent energy range and capacity to store such energy to compensate for the Energy transferred to the building.

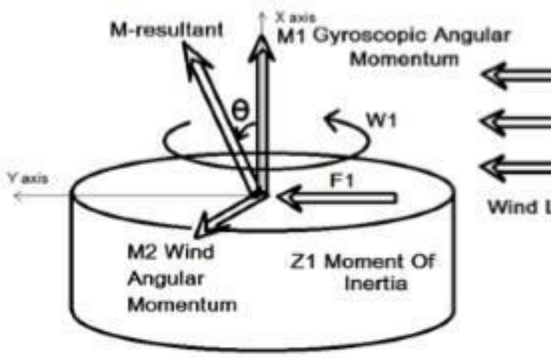


Figure 3 (b)
Gyroscope Subjected To High Wind Loads

The above figure shows a gyroscope subjected to high wind loads. The M1 represents The flywheel angular momentum, while M2 represents the wind angular momentum By the Wind Load-F1. The resultant caused by these two combination is inclined at an Angle from the vertical axis. Z1 represents the moment of inertia of the flywheel. W1 Is the anticlockwise angular velocity of the flywheel. Due to rotation kinetic energy An angular momentum M1 is induced in the gyroscope. This axis of rotation is now With an extra inertia or resistance towards any external force. With Rw as rotational Energy stored.

Momentum Conservation Analogy

The swinging of pendulum causes the gain of potential energy and is acted upon by the force of gravity at its most peak position which results in generation of a restoring Angular momentum. This restoring momentum cases the damping effect of windVibrations and increases the stability of the structure against such vibrations.The**Analogy**is shown in fig 3 c

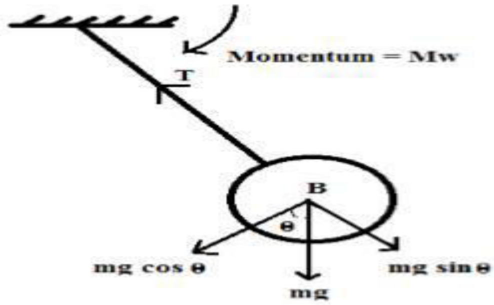


Figure 3 c Momentum Conservation Analogy

Finite Element 3d Model
Based on the design drawings, a detailed 3D-FEM model of Taipei 101 Tower is established by using ANSYS12.0. The FEM model uses beam elements, shell elements, link elements and mass elements to model the structural system of the Taipei 101 Tower and the TMD. The amplitude-dependent damping character of the TMD is considered as equivalent viscous damping. The TMD system is modelled using two spring systems in both X and Y directions, located at the centroid of the 88th floor. Constrain equations are also used to combine the TMD system with the Taipei 101 Tower. The wind loads on the tall building are determined by a large eddy simulation (LES) and typical examples of the simulated wind forces are shown in Figure 3 (f). The earthquake record, measured at the lowest floor of the basement in the Taipei 101 Tower during the Wen Chuan earthquake are used to the 3D-FEM model incorporating with the TMD, for dynamic analysis. The completed model is illustrated in Figure 3 (d) and (e)

Modal Analysis

As an effective passive control device, the major contribution of the TMD is to reduce The dynamic responses of the structure by altering the fundamental frequency (first Mode) of the structure, so that the acceleration of the top residential floors can be Controlled to satisfy the safety criterion as well as the serviceability criterion for Human comfort. In order to achieve this goal, the optimal parameters of the TMD Were derived, as shown in Table 1. It is also listed in Table 2 the results from equation (27) and the natural frequencies of the building (with and without TMD). The modal Analysis results are shown in Figures Table 2. Due to the symmetry feature of the Building, the first two frequencies are identical. As the TMD is installed, the first Mode in the X and Y directions becomes two modes. This situation is similar to the SDOF system. This is the expected way that the TMD is to perform.

Result

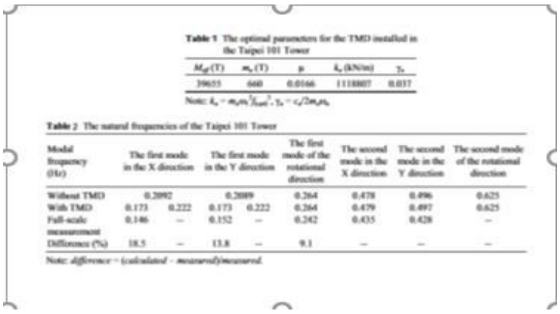


Table 1 The optimal parameters for the TMD installed in the Taipei 101 Tower

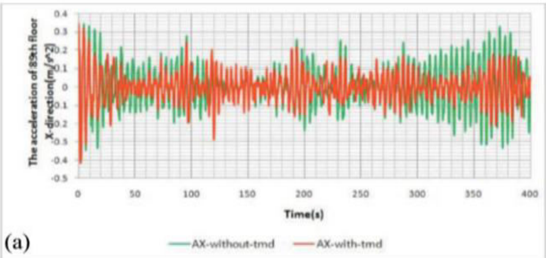
M_{eff} (T)	m_d (T)	μ	k_d (kN/m)	γ_d
39655	660	0.0166	1118807	0.037

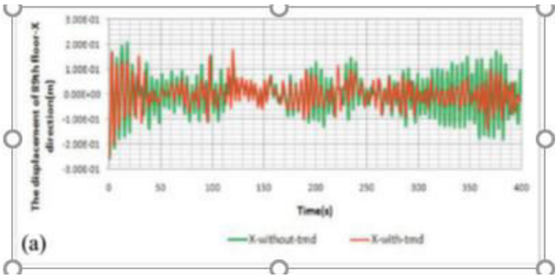
Note: $k_d = m_d \omega_1^2 f_{opt}^2$, $\gamma_d = c_d / 2 m_d \omega_d$

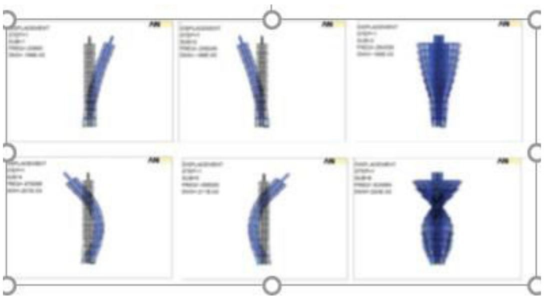
Table 2 The natural frequencies of the Taipei 101 Tower

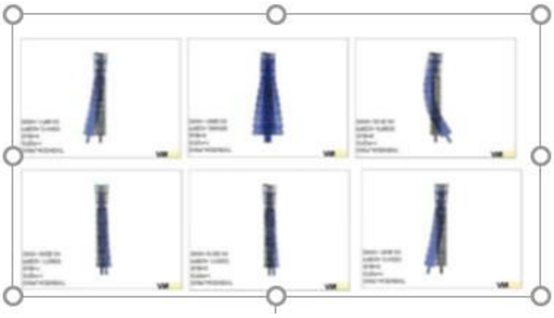
Modal frequency (Hz)	The first mode in the X direction		The first mode in the Y direction		The first mode of the rotational direction	The second mode in the X direction	The second mode in the Y direction	The second mode of the rotational direction
Without TMD	0.2092		0.2089		0.264	0.478	0.496	0.625
With TMD	0.173	0.222	0.173	0.222	0.264	0.479	0.497	0.625
Full-scale measurement	0.146	–	0.152	–	0.242	0.435	0.428	–
Difference (%)	18.5	–	13.8	–	9.1	–	–	–

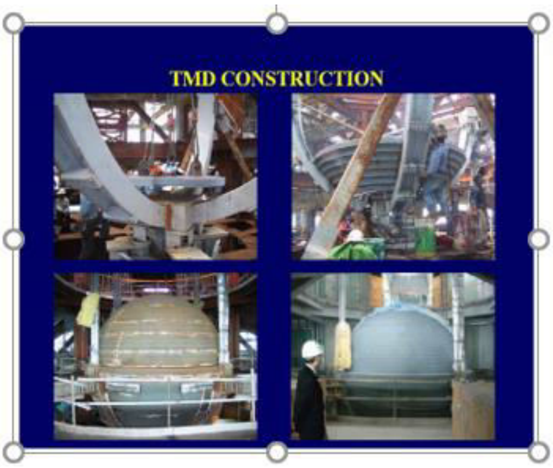
Note: difference = (calculated − measured)/measured.











CONCLUSION

- TMD is effective for controlling structural response to harmonic base excitation.
- TMD is most effective for lightly damped structure, and its effectiveness decreases as with increase in structural damping.
- TMD is more effective for long duration earthquake ground motions.
- TMD is most effective when the structural frequency is close to the central frequency of ground motion.
- TMD is reasonably effective for broad banded motions across the spectrum of structural frequencies. However, TMD is also effective for narrow banded motions, if the structure and ground motion frequencies are close to each other.
- Effectiveness and optimum parameters of TMD does not get affected with increasing peak ground acceleration values, keeping all other parameters constant.

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