Case Study of Tuned Mass Damper At Taipei World Financial Center

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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 jointed bamboo 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 control was made practical through steel boxes filled with high-strength concrete. Occupant comfort is improved by a massive rooftop pendulum Tuned Mass Damper. Pinnacle framing fatigue life is enhanced by a pair of compact spring-driven TMDs. The soft soil subgrade required mat foundations on bored piles, slurry walls, and a mix of top-down and conventional bottom-up construction with cross-lot bracing. The project illustrates the large and small design decisions in both architecture and engineering necessary to successfully complete a major building in a challenging environment*

Keywords- Vibration Control, Tuned Mass Damper (TMD), Structure-TMD Interaction, Dynamic Analysis, Wind Effect, Earthquake Excitation, FEM, Wind Tunnel Testing, Field Measurement, vortex shedding, high strength concrete, outrigger, fatigue.

I. INTRODUCTION

Every project has a list of challenges, but for Taipei 101, the new world's tallest building, that list is longer than size alone would imply. Starting with a design height of 508 m [check], it also includes the overall and localized load effects from frequent and extreme typhoons; potentially severe earthquakes; and difficult subsurface conditions, including an inactive fault through the site. Occupants must be both physically and psychologically comfortable with the design, even during high winds and extreme events. Rising from a dramatic, landmark-quality retail mall, the tower has a profile unlike that of any previous skyscraper: a tapering base topped by a series of flared segments. And a couple of temblors rattled the partially-completed structure, reminders of the challenges the design must address. Meeting all these challenges through studies, design and construction was an unforgettable experience for all involved.

A tuned mass damper (TMD) is a large, massive block, which is usually mounted on the top or near the top of a tall building. The system consists of a mass, springs and damping devices. Its frequency can be tuned to match the predominant vibration frequency (usually the first modal frequency) of the main structure. So that the structural dynamic responses caused by environmental excitations, such as strong winds and earthquakes, can be significantly reduced. The 508-m tall Taipei 101 Tower is a primary example, which has the world's largest TMD (660 tons) system for the control of structural vibrations.

Design of most modern buildings considers dead and live loads, since these loadings always act on constructions. Load magnitudes can be easily determined from dimensions of structural elements, material characteristics, and occupancy needs. Another type of loading that has to be taken into account is dynamic excitations. For example, design of structures subjected to excitations from human activities, such as running, jumping and dancing, should consider these loadings. Modern structures are increasingly more slender, flexible, with higher spans having ever lower natural vibration frequencies. More flexible structures imply higher amplitude vibrations that are transmitted to people that use these spaces, causing discomfort and interference in human activities, for example, damaging vision and inhibiting the movement of hands and feet. In cases of strong vibrations, changes can occur in physiological functions such as increased heart rate, neuromuscular disorders, cardiovascular, respiratory, endocrine and metabolic disorders, sensory disturbance and the central nervous system; they can also cause risk of spinal cord injuries. It is important to know that these vibrations rarely affect the safety of the structure and are therefore usually treated as a serviceability problem. Movements of the human body when performing rhythmic movements, such as walking, running, jumping and dancing, cause some of the common problems that show up in structures due to severe vertical vibrations. Induced vibration caused by moving people can interfere with the operation of constructions. Examples of structures that are subjected to vibrations caused by people practicing some sort of rhythmic activity are footbridges, stairs, floors and buildings, stadiums, etc. To solve this kind of problem for structures such as offices, shopping areas, gyms, dance studios, laboratories, theatres and walkways, structural control devices such as tuned mass dampers (TMD) can be used. Tuned mass dampers (TMD) reduce energy dissipation of structural members subjected to dynamic loads. This reduction occurs because part of the energy is transferred to the TMD, a spring mass damper system that vibrates out of phase with the main structure.

It is one of the oldest devices of structural control, proposed for the first time by Frahm in 1909. Later, Den Hartog published a more detailed study on this subject. In the beginning the use of TMD was limited to mechanical engineering systems. It was in the 60s that it became common on civil engineering applications such as high buildings, bridges, towers and industrial chimneys. Another successful application of this device is the installation of TMDs in building floors for improved comfort by reducing excessive man-induced vibrations. Following are some studies among others in the literature that concern vibration control in building floors using TMD: Allen and Pernica developed a dynamic absorber to reduce the vibrations of floors with large spans. The authors used an experimental platform, where they performed studies to compare the graphical response curves of the structure with and without the dynamic absorber. From these charts they provided rules and formulas to guide the construction of floor absorbers with optimal parameters.

II. IDENTIFICATION, RESEARCH AND COLLECTION OF IDEA

Types Of Tuned Mass Dampers:

On basis the absorbing method tuned mass dampers are widely classified into two:

1. Passive - Tuned Mass Damper
2. Active - Tuned Mass Damper

Passive Tuned Dampers:

Passive systems are characterized by the absence of an external source of energy. As a result overall system stability is usually not a concern. A passive TMD system is any TMD topology which does not contain any active element, such as an actuator. As a result these systems are entirely mechanical. A limitation shared by all passive TMD systems is its lack of robustness to detuning conditions. Outside of the narrow tuned frequency band of the TMD, the effectiveness of the TMD at reducing structural vibration is diminished. Even small deviations from the optimal tuning frequency can deteriorate the performance significantly. As a result the effectiveness of a passive TMD system is reliant on the accuracy of its initial tuning, and whether there is any structural detuning subsequently. Despite this significant limitation, passive TMD systems are still used because they are relatively inexpensive systems, which perform well when properly tuned. Furthermore the absence of an external actuator or energy source means that there are no additional operational costs once the system is installed. The two most common types of passive tuned mass dampers are translational TMDs and PTMDs .

a) Tuned Translational Damper
b) Tuned Pendulum Damper

Tuned Translational Damper:

Translational TMD can be either unidirectional or bidirectional systems. In unidirectional systems the motion of the TMD mass is restricted to a single direction, often by placing the mass on a set of rails or roller bearings, as depicted in Figure 2 a. In bidirectional systems, the mass can move along both coordinate axes. In either topology a set of springs and dampers are placed between the TMD mass and the supporting structure which is fixed to the structure. Translational TMD systems have been implemented in large scale structures for over 40 years. Examples of structures containing translation TMD systems include the Washington National Airport Tower, the John Hancock Tower, and the Chiba Port Tower.

Tuned Pendulum Damper:

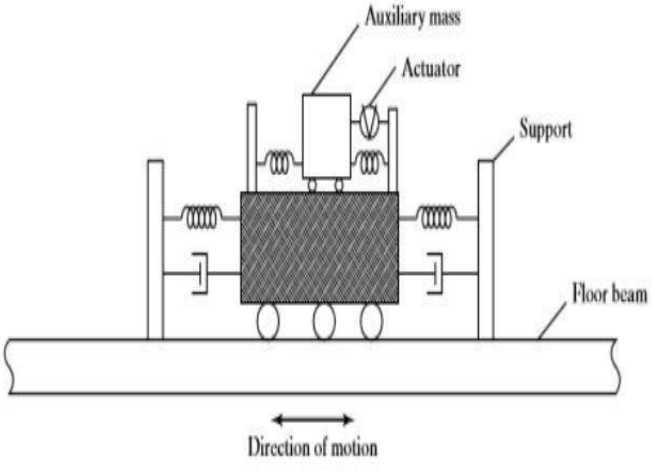
PTMDs replace the translational spring and damper system with a pendulum, which consists of a mass supported by a cable which pivots about a point, as illustrated in Figure 2 b. They are commonly modelled as a simple pendulum. For small angular oscillations they will behave similarly to a translational TMD and can be modelled identically with an equivalent stiffness and equivalent damping ratio. Hence, the design methodology for both the translational TMD system and PTMD systems are identical. A major motivating factor for using a PTMD system over an equivalent translational TMD system is the absence of any bearings to support the TMD mass. The bearing support structure used in the translational TMD assembly is expensive and susceptible to wear over the lifespan of the TMD system. As a result PTMD designs can be less expensive to manufacture and last longer.

Nearly 50% of structures in Japan that use TMD systems utilize PTMD systems. Examples include Crystal Tower in Osaka, Higashimyama Sky Tower in Nagoya, and Taipei 101 in Taipei. Studies on the use of PTMD systems generally focus on the optimization of PTMD design parameters to reduce excessive lateral deflections in structures. Gerges and Vickery utilized a nonlinear wire rope spring PTMD system in an experimental case study, concluding that their performance approaches optimal linear TMD designs while providing smaller relative displacements for lower mass ratios. presented optimization algorithms for a PTMD system induced by pedestrian loading.

Active Tuned Dampers:

Active systems contain an external energy source, often in the form of an actuator. In comparison to passive systems, which operate without an energy source and utilize an open loop control topology, active systems utilize sensors to measure system conditions and employ a closed loop control topology. An ATMD system, as shown in Figure 4, contains an actuator which drives the motion either the TMD mass or an auxiliary mass connected to the TMD mass. By 9 actively controlling the motion of an external mass, the ATMD can control the forces exerted on the structure. There are two advantages in this design. First, the performance of an ATMD system will outperform an equivalent passive TMD under detuning conditions, since any detuning is compensated by feedback control . Secondly, an ATMD system is capable of optimizing its transient performance. This is particularly useful for impact loads, such as earthquake loads. As a result ATMD systems have been implemented to reduce the lateral response of structures when induced by earthquake loads. For, example the Kyobashi Seiwa Building in Tokyo, Japan contains two ATMDs to mitigate structural vibration induced by frequent earthquakes Spencer and Sain. The installed system reduces the lateral displacement by approximately 67%. Several studies have been performed on the use and performance of ATMDs. These studies generally focus on an optimal control algorithm used to improve the ATMDs performance. Li et al. successfully applied an ATMD model to control the torsional and translational response of a 2-DOF asymmetric structure model. Nishimura et al. compared the performance of an ATMD using a set of optimized parameter equations to a passive TMD system, observing an 80% improvement at the peak frequency. Nagashima presented an optimal displacement feedback control law for an ATMD system on a SDOF system Although ATMDs can outperform their passive counterparts, they have some drawbacks. The added design, manufacturing, and instrumentation complexity results in significantly higher financial costs over passive systems. Furthermore, the addition of an actuator significantly increases the energy requirements of the system. To reduce energy demands, active systems can be converted into hybrid systems. In hybrid systems the ATMD acts as a passive system under typical loading conditions. Once the structure reaches a certain threshold, the active system is turned on. An example of a hybrid system is the Ando Nishikicho Building in Tokyo, Japan, which uses a hybrid system containing an 18 tons passive TMD and two auxiliary actuated masses weighing a combined 3.6 tunes.

Pendulum Tuned Mass Damper



Active Tuned Mass Damper

III. STUDIES AND FINDINGS

Sources of Vibration and Resonance in Structure:

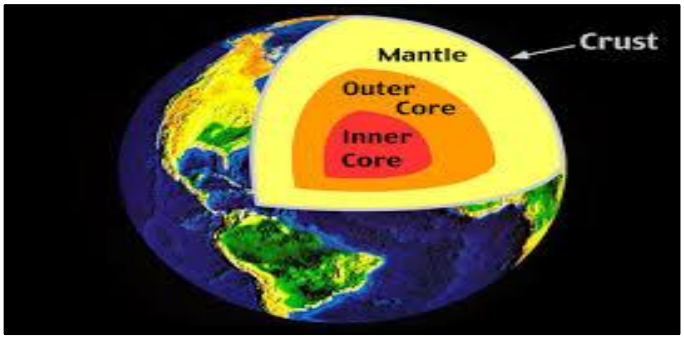
(A) Earthquakes:

The seismic waves caused by an earthquake will make buildings sway and oscillate in various ways depending on the frequency and direction of ground motion, and the height and construction of the building. Seismic activity can cause excessive oscillations of the building which may lead to structural failure. To enhance the building's seismic performance, a proper building design is performed engaging various seismic vibration control technologies. As mentioned above, damping devices had been used in the aeronautics and automobile industries long before they were standard in mitigating seismic damage to buildings. In fact, the first specialized damping devices for earthquakes were not developed until late in 1950.

What Causes Earthquakes?

(i) The Earth And Its Interior:

Long time ago, a large collection of material masses coalesced and formed the Earth. Large amount of heat was generated by this fusion, and slowly as the Earth cooled, the heavier and denser materials sank to the center and the lighter ones rose to the top. The differentiated Earth consists of the Inner Core (radius- 1290 km), the Outer Core (thickness- 2200 km), the Mantle (thickness- 2900 km) and the Crust (thickness- 5 to 40 km). Figure 1 shows these layers. The Inner Core is solid and consists of heavy metals (e.g., nickel and iron), while the Crust consists of light materials (e.g., basalts and granites). The Outer Core is liquid in form and the Mantle has the ability to flow. At the Core, the temperature is estimated to be- 2500°C, the pressure- 4 million atmospheres and density- 13.5 gm/cc; this is in contrast to- 25°C, 1 atmosphere and 1.5 gm/cc on the surface of the Earth.



The Earth And Its Interior

(ii) Plate Tectonics:

The convective flows of Mantle material cause the Crust and some portion of the Mantle, to slide on the hot molten outer core. This sliding of Earth’s mass takes place in pieces called Tectonic Plates. The surface of the Earth consists of seven major tectonic plates and many smaller ones. These plates move in different directions and at different speeds from those of the neighbouring ones. Sometimes, the plate in the front is slower; then, the plate behind it comes and collides (and mountains are formed). On the other hand, sometimes two plates move away from one another (and rifts are created). In another case, two plates move side-by-side, along the same direction or in opposite directions. These three types of inter-plate interactions are the convergent, divergent and transform boundaries, respectively. The convergent boundary has a peculiarity (like at the Himalayas) that sometimes neither of the colliding plates wants to sink. The relative movement of these plate boundaries varies across the Earth; on an average, it is of the order of a couple to tens of centimeters per year.

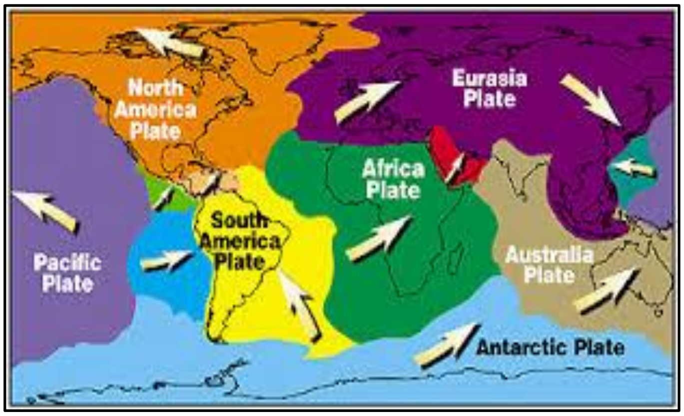


Plate Tectonics

(B) Wind:

The force of wind against tall buildings can cause the top of skyscrapers to move more than a meter. This motion can be in the form of swaying or twisting, and can cause the upper floors of such buildings to move. Certain angles of wind and aerodynamic properties of a building can accentuate the movement and cause motion sickness in people. A TMD is usually tuned to a certain building's frequency to work efficiently. However, during their lifetimes, high-rise and slender buildings may experience natural frequency changes under wind speed, ambient temperatures and relative humidity variations, among other factors, which requires a robust TMD design.

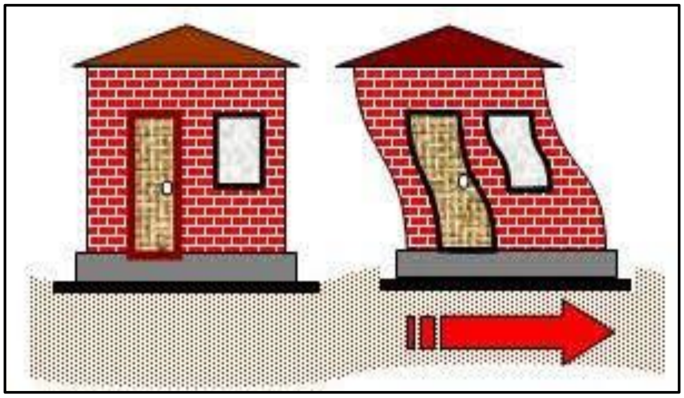
(C) Mechanical Human Sources:

Masses of people walking up and down stairs at once, or great numbers of people stomping in unison, can cause serious problems in large structures like stadiums if those structures lack damping measures.

Seismic effects On Structures:

(i) Inertia Forces in Structures:

Earthquake causes shaking of the ground. So a building resting on it will experience motion at its base. From Newton's First Law of Motion, even though the base of the building moves with the ground, the roof has a tendency to stay in its original position. But since the walls and columns are connected to it, they drag the roof along with them. This is much like the situation that you are faced with when the bus you are standing in suddenly starts; your feet move with the bus, but your upper body tends to stay back making you fall backwards!! This tendency to continue to remain in the previous position is known as inertia. In the building, since the walls or columns are flexible, the motion of the roof is different from that of the ground.

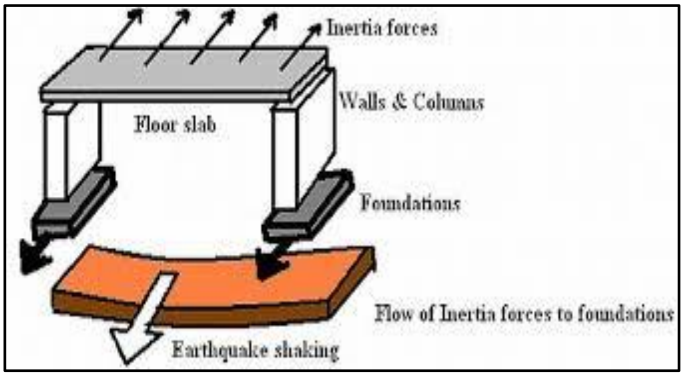


Inertia Forces On Structure

Consider a building whose roof is supported on columns. Coming back to the analogy of yourself on the bus: when the bus suddenly starts, you are thrown backwards as if someone has applied a force on the upper body. Similarly, when the ground moves, even the building is thrown backwards, and the roof experiences a force, called inertia force. If the roof has a mass M and experiences an acceleration a, then from Newton's Second Law of Motion, the inertia force FI is mass M times acceleration a, and its direction is opposite to that of the acceleration. Clearly, more mass means higher inertia force. Therefore, lighter buildings sustain the earthquake shaking better.

(ii) Flow of Inertia Forces to Foundations:

Under horizontal shaking of the ground, horizontal inertia forces are generated at level of the mass of the structure (usually situated at the floor levels). These lateral inertia forces are transferred by the floor slab to the walls or columns, to the foundations, and finally to the soil system underneath. So, each of these structural elements (floor slabs, walls, columns, and foundations) and the connections between them must be designed to safely transfer these inertia forces through them



Inertia Force To Foundation

Seismic Design Philosophy For Building:

(i) The Earthquake Problem:

Severity of ground shaking at a given location during an earthquake can be minor, moderate and strong. Relatively speaking, minor shaking occurs frequently, moderate shaking occasionally and strong shaking rarely. For instance, on average annually about 800 earthquakes of magnitude 5.0-5.9 occur in the world while the number is only about 18 for magnitude range 7.0-7.9 So, should we design and construct a building to resist that rare earthquake shaking that may come only once in 500 years or even once in 2000 years at the chosen project site, even though the life of the building itself may be only 50 or 100 years? Since it costs money to provide additional earthquake safety in buildings, a conflict arises: Should we do away with the design of buildings for earthquake effects? Or should we design the buildings to be "earthquake proof" wherein there is no damage during the strong but rare earthquake shaking? Clearly, the former approach can lead to a major disaster, and the second approach is too expensive. Hence, the design philosophy should lie somewhere in between these two extremes.

(ii) Earthquake-Resistant Buildings:

The engineers do not attempt to make earthquake-proof buildings that will not get damaged even during the rare but strong earthquake; such buildings will be too robust and also too expensive. Instead, the engineering intention is to make buildings earthquake- resistant; such buildings resist the effects of ground shaking, although they may get damaged severely but would not collapse during the strong earthquake. Thus, safety of people and contents is assured in earthquake-resistant buildings, and thereby a disaster is avoided. This is a major objective of seismic design codes throughout the world.

(iii) Earthquake Design Philosophy:

The earthquake design philosophy may be summarized as follows:

A. Under minor but frequent shaking, the main members of the building that carry vertical and horizontal forces should not be damaged; however building parts that do not carry load may sustain repairable damage.

B. Under moderate but occasional shaking, the main members may sustain repairable damage, while the other parts of the building may be damaged such that they may even have to be replaced after the earthquake; and

C. Under strong but rare shaking, the main members may sustain severe (even irreparable) damage, but the building should not collapse.

Thus, after minor shaking, the building will be fully operational within a short time and the repair costs will be small. And, after moderate shaking, the building will be operational once the repair and strengthening of the damaged main members is completed. But, after a strong earthquake, the building may become dysfunctional for further use, but will stand so that people can be evacuated and property recovered.

The consequences of damage have to be kept in view in the design philosophy. For example, important buildings, like hospitals and fire stations, play a critical role in post-earthquake activities and must remain functional immediately after the earthquake. These structures must sustain very little damage and should be designed for a higher level of earthquake protection. Collapse of dams during earthquakes can cause flooding in the downstream reaches, which itself can be a secondary disaster. Therefore, dams (and similarly, nuclear power plants) should be designed for still higher level of earthquake motion.

(iv) Buildings With Moment Resisting Frames:

Buildings with Moment Resisting Frames Smooth transfer of inertia forces in a Moment Resisting Frame (MRF) building is critically dependant on the geometry of the frame grid. Some desirable features of a frame grid include:

A. Several distinct planar, regular MRFs placed parallel to each other, in each of the two perpendicular plane directions of the building;

B. Columns running run through full height and beams through full width of the building;

C. Uniform spacing between parallel planar MRFs in each plan direction; and

D. Beams within each planar frame slender enough to deform in flexure: Concrete beams of very short span may damage in shear, which is undesirable.

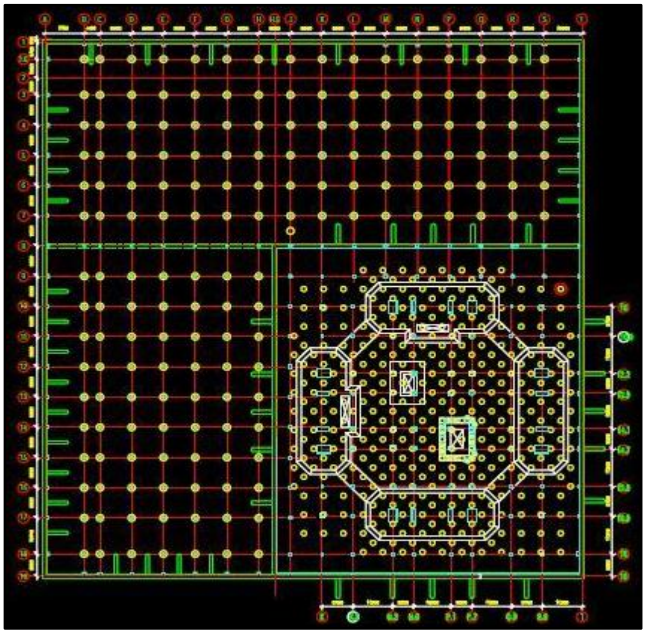
General Consideration Of Taipei 101:

Tower Height:

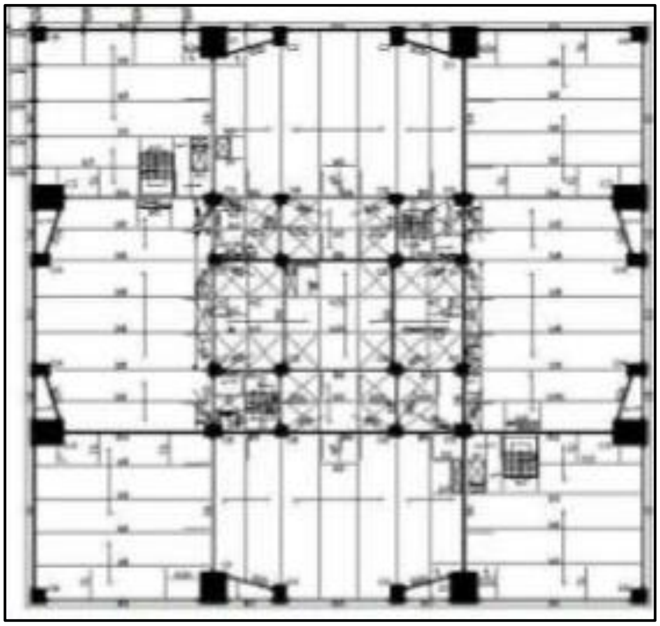
The first challenge was the height. Building stories come at an ever-increasing cost, as if the new story is added at the bottom of the building. That reflects the need for supporting all the floors above, for elevator shaft and stairwell space, and for mechanical, electrical, plumbing and fire protection risers. The economic height limit occurs where the added cost of a floor exceeds the added rent the floor will bring. Prior to Taipei 101, the tallest building on the island of Taiwan was the 85-story T&C Tower in Kaohsiung. The major jump in height resulted from the desire of project investors, several financial firms, to occupy space in a landmark building. Projected office space demand of 200,000 m2 (2.1 million square feet) [check] and individual floor areas based on general office layout standards led to a height of 101 stories. Another 200,000 m2 occurs in a podium of retail space surrounding the tower base and basement parking.

Foundation:

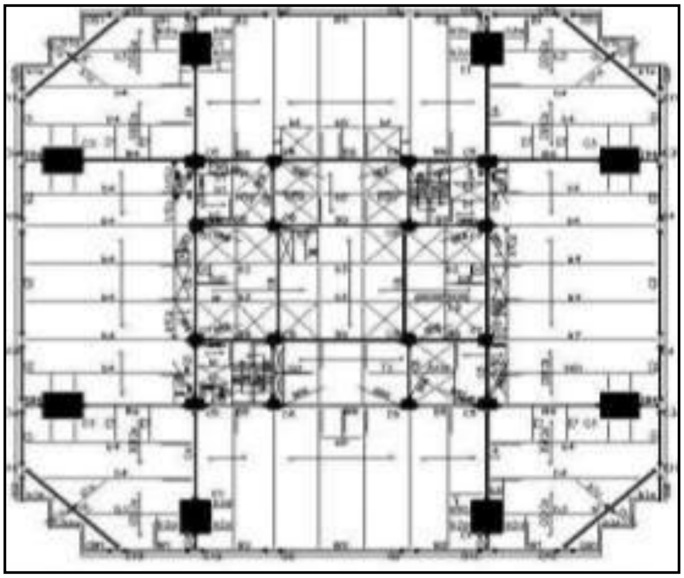
The second challenge was the site. Soft rock occurs beneath 40 to 60 m of clay and stiff colluvial soil. The design required a 21 m deep basement, while groundwater is usually 2 m below grade and potentially at grade. Based on extensive investigations by Taipei-based Sino Geotechnology Inc. And scheduling requirements, five major components were used to create two different foundation systems. One slurry wall 1.2 m (4 ft) thick surrounds both tower and podium; its 47 m (154 ft) depth cuts off ground water and provides toe embedment well below the 21.8 to 23.5 m (72 to 77 ft) excavation depth. Each podium column bears on a single 2 m (6.5 ft) diameter drilled pier. Sockets 5 to 28 m (16 to 92 ft) into bedrock resist net uplift from a podium pressure slab resisting buoyancy. The single-pier design permitted ‘top down’ basement construction: a floor was cast to brace perimeter walls, then a story of excavation proceeded below it. Superstructure framing was erected at the same time. As a result, the retail podium opened about a year before the tower topped out. A second slurry wall, enclosing just the tower footprint, was supported by steel cross-lot bracing as excavation proceeded to full depth. The walls were braced to accommodate construction sequencing. A continuous reinforced concrete mat 3 to 4.7 m (10 to 15 ft) thick transfers load from discrete column and shear wall load points to a distributed pattern of 380 drilled piers, 1.5 m (5 ft) in diameter, spaced 4 m (13.12 ft) on center in staggered rows to resist gravity loads between 10.7 and 14.2 MN (1500 and 2000 kips). Using steel framing minimized building weight, helping to reduce foundation costs.



Foundation Plan



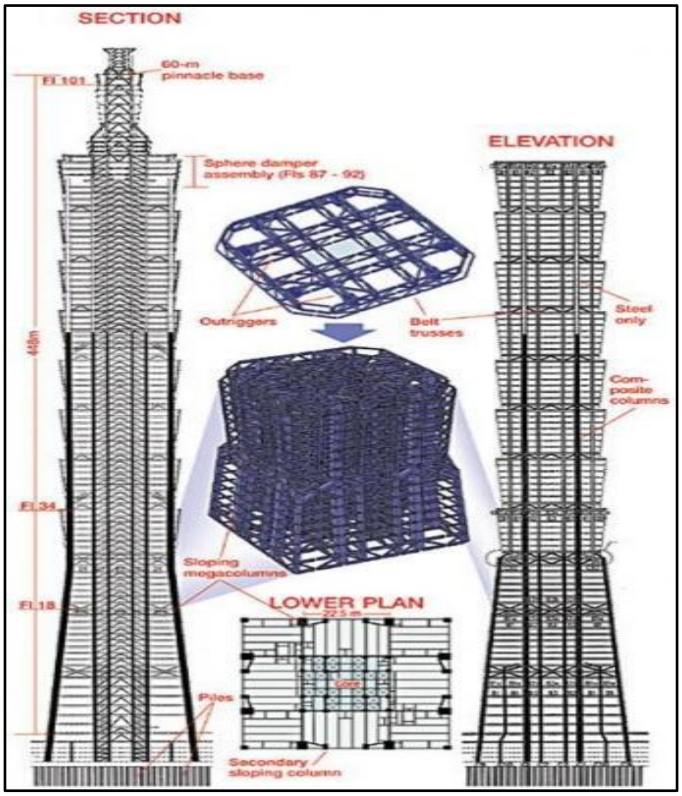
Plan Upto 26th Floor



Plan From 27th To 91st Floor

Material Analysis:

1. 380 Piles with 3 inch concrete slab.
2. Mega columns- 8 cm thick steel & 10,000 psi concrete infill to provide for overturning
3. Walls - 5 & 7 degree slope.
4. 106,000 tons of Steel of Grade fe60- 25% stronger.
5. 6 Cranes on site for Steel Placement.
6. Electrical & Mechanical



(Analysis & Design Of Project Model Taipei 101 By P. Chatupote According To ANSYS12.0)

Wind And Seismic Design Of Taipei 101

(i) Wind Design:

Results Of Wind Analysis:

- For 0.5 year return period of wind:
  Floor acceleration without damper: 7cm/sec^2
- For 50 year return period of wind:
  Max storey drift: 0.499% to 0.5% allowable
- For 100 year return period of wind:
  Max member stress ratio: 1.00

Max storey drift: 0.57%

(ii) Seismic Design:

Results Of Earthquake Analysis:

- Under Envelope Of Code Shear and Dynamic Shear:
  Max Storey Drift: 0.325% to 0.5% allowable.
- For 100 Year Of Return Period Of Earthquake:
  Stress Ratio: 1.00 by Response Spectrum Analysis.
- For 950 Year Of Return Of Earthquake:
  Ductility Demand< 2.5 by Pushover Method
  Plastic Hinge Rotation: 0.25%
- For 2500 Year Of Return Of Earthquake:
  Plastic Hinge Rotation: 4% allowable.
- If Plastic Rotation Demand: 0.5% Cut Girder Flange

IV. METHODOLOGY

The Parameter Optimization Theory for a TMD:
Over the last several decades, the parameter optimization theory for TMD's has been the subject of considerable research interest. Intensive studies have been conducted to determine the optimal parameters for a TMD under various excitations, to calculate the responses of the main structures, and to evaluate the efficiency of the TMD contributions in terms of mitigating vibration in the main structures. Warburton and his collaborators [15-17] performed systematical studies to determine the optimal parameters for a TMD. They derived the closed form expressions for the optimal parameters of an absorber, as well as for system responses. The system considered in their studies consisted of an undamped SDOF main system and an attached TMD, which was subjected to steady-state harmonic excitations and random excitations with white noise spectral density. They also extended the formulae to an elastic body without damping and one with light damping. These studies demonstrated that an elastic body can be replaced by an equivalent SDOF system, for the purpose of determining the optimal parameters of its attached TMD. Provided that the frequencies of the elastic body are well separated, and the dynamic response is majorly contributed by the fundamental mode. The results concluded that in order to minimize the fundamental resonance of an elastic body, a TMD with a small mass ratio between the absorber system and the main system is preferable. As long as the natural frequencies satisfy the condition, $\omega 1/\omega 2$ 0.5 (where $\omega 1$ and $\omega 2$ represent the first and second fundamental frequencies of the elastic body, respectively), the equivalent system yields the optimal parameters for the TMD. And the associated structural responses are minimized into an acceptable range of accuracy. As for the damping of the main system, it is suggested that limited damping of the main system has very little effect on the TMD's optimal parameters. For real systems with light damping, if this frequency condition is satisfied, it is reasonable to use the optimal parameters of the TMD for the undamped equivalent system to minimize the dynamic response of the system.

V. CONCLUSION

1. TMD is effective for controlling structural response to harmonic base excitation.
2. TMD is most effective for lightly damped structure, and its effectiveness decreases as with increase in structural damping.
3. TMD is more effective for long duration earthquake ground motions.
4. TMD is most effective when the structural frequency is close to the central frequency of ground motion.
5. 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.
6. Effectiveness and optimum parameters of TMD does not get affected with increasing peak ground acceleration values, keeping all other parameters constant.

VI. ACKNOWLEDGEMENT

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