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Recently, Mr. Tamboli managed several high-profile institutional projects, including the new John Edward Porter Neuroscience Research Center for the National Institutes of Health in Bethesda, Md., and the Janelia Farms Research Campus for Howard Hughes Medical Institute in Leesburg, Va. Another notable project was the Random House World Headquarters and Park Imperial high-rise building in New York City.

A resident of Princeton Junction, N.J., Mr. Tamboli received his Master of Science in Civil Engineering from Stanford University. He is active in various professional organizations, including the American Society of Civil Engineers. He has published two engineering handbooks: *Steel Design Handbook LRFD Method* and *Handbook of Structural Steel Connection Design and Details*, both for McGraw Hill.

Manhattan's Mixed Construction Skyscrapers with Tuned Liquid and Mass Dampers

This presentation is based on a paper by the presenter; Chris Christoforou, P.E.; Aine Brazil, P.E.; Len Joseph, P.E., S.E.; Umakant Vadnere, P.E.; and Brad Malmsten, EIT.

1. Random House, 1745 Broadway, Manhattan, N.Y.
Ever-increasing heights of modern-day skyscrapers often require supplementary damping devices for occupant comfort in wind. The 675-foot- (205-meter-) high Random House Tower exemplifies this challenge and its innovative solution. The top 25 stories use concrete floors for apartments, while the bottom 25 stories are relatively flexible steel-framed office spaces. Structural engineers included a Tuned Liquid Column Damper in their design for the residents' comfort. This was the first TLCD used in a high-rise building in the United States.

This presentation will discuss the important details, layout, design considerations, commissioning, operation guidelines, and benefits of the TLCDs at the Random House Tower. These details can provide other engineers with insights on using TLCDs on high-rise projects. Studies show that a reduction in the maximum wind response of up to 40% can be achieved by using a TLCD.

2. Mixed-Use Tower, 731 Lexington Avenue, New York, N.Y.
The commercial levels in the lower 30 floors are framed entirely in steel and support the cast-in-place flat plate residential levels above. A tuned mass damper housed at roof level controls tenant comfort criteria. The TMD, which is a steel ball constructed of flat plates, sways out of phase with the tower creating large displacements. Dashpot "shock absorbers" are pushed and pulled, converting kinetic energy into heat.

MANHATTAN'S MIXED CONSTRUCTION SKYSCRAPERS WITH TUNED LIQUID AND MASS DAMPERS

By Akbar Tamboli, P.E., FASCE, Chris Christoforou, P.E.
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ABSTRACT

Keywords: Building lateral system; vibrations, damping, cost effectiveness, residential occupancy, tall buildings.

Random House at 1745 Broadway

Ever increasing heights of modern day skyscrapers can often require supplementary damping devices for occupant comfort in windy conditions. The 675 feet high Random House Tower in Manhattan, New York exemplifies this challenge and its innovative solution. The top 25 stories use concrete floors for residential apartments, supported on a relatively flexible 25 story steel framed office structure below.

This paper presents important details, layout, design considerations, commissioning, operation guidelines and benefits of the Tuned Liquid Column Dampers (TLCDs), water-filled custom-shaped tanks, used at Random House Tower. These details can provide other engineers with insights on making use of TLCDs on their high-rise projects. The dynamics and practical functional aspects of TLCDs are presented. Structural response with and without a TLCD is compared. Studies show that a reduction in the maximum wind response of up to 40% can be achieved by using a TLCD.

731 Lexington Avenue

To accommodate the tower's mixed use, the commercial levels in the lower 30 floors are framed entirely in steel that then support a cast-in-place flat plate structure used for the 24 residential levels above. Two outrigger floors with a system of belt trusses positioned at the mechanical levels, together with a braced core and shear wall with many unique features, provide the needed stability. A tuned mass damper (TMD) to satisfy tenant comfort criteria, housed at roof level, has a unique low-headroom design. This TMD has two linked systems: a steel plate mass on a short pendulum, and a second mass on pivoting legs as an 'inverted pendulum.' The linked masses sway out of phase with the tower, creating large differential displacements. Dashpot "shock absorbers" are pushed and pulled to convert kinetic energy into heat.

INTRODUCTION

There are several methods available to control the motion of tall buildings for occupant comfort in windy conditions. A traditional solution to the problem of excessive accelerations at the upper floors of tall buildings is to add more structure. Structural material can be used to stiffen the building, reducing its displacement; to increase its mass, yielding a longer sway period for the same building stiffness; or both. However, to achieve significant improvements in occupant comfort, structural approaches can be relatively costly. Another approach is to supplement the damping of the structure. Tall buildings typically have inherent damping levels of one or two percent of critical (i.e., once started, oscillations will continue for many cycles). Damping can be increased several ways. One way is to add friction or viscous damping to selected building joints. But any single joint moves only slightly as building sways, so this treatment must be applied to a large number of joints within the structure. Another way to add overall building damping is often more cost-effective: installing a Tuned Mass Damper (TMD). The tallest building in the World, Taipei 101, has a TMD with a pendulum mass weighing a record 680 tonnes installed near the top to provide occupant comfort. The previous tallest buildings, Petronas Towers in Kuala Lumpur, Malaysia, include TMDs for a different reason. Three small spring-driven TMDs are installed in each of the four skybridge legs to reduce wind-induced leg oscillations. Reduction of oscillations greatly extends the fatigue life of the welded steel leg connections.

While TMDs based on swaying pendulums are widely used, they require very tall spaces for mounting and operation, and additional structure for support of their great weight. Tuned Liquid Column Dampers (TLCDs) are special types of dampers relying on the motion of a column of liquid in a U-shaped container to counteract the forces acting on the structure. Damping is introduced in the oscillating column through an orifice in the liquid passage. The additional space needed for this type of damper is minimal, if located where storage tanks would be needed anyway. Similarly, the additional structure is minimal since the weight of tank and contents would be present anyway.

This paper discusses implementations of TMDs and TLCDs in two recent tall buildings constructed in New York City. First, TLCDs atop the Random House Tower is presented followed by a discussion of the Tuned Mass Damper in the tower at 731 Lexington Avenue.

RANDOM HOUSE - 1745 BROADWAY

Project Description

The $170-million, 840,000 square-foot building rises 675 feet above street level. It includes a 25-story concrete, luxury residential building, The Park Imperial, atop transfer trusses of the steel-framed 25-story headquarters for Random House, as well as ground floor retail space and two levels of underground parking. Structural engineers Thornton-Tomasetti included a TLCD system high in the building to reduce wind-induced motion at upper residential floors. It is not relied on for structural stability. This is the first application of a TLCD in a building in the U.S.

Figure 1. Random House - 1745 Broadway, New York

The TLCD system consists of two U-shaped, water-filled tanks with 16” thick concrete walls on the 50th floor mechanical room. One tank runs north-south direction and the other runs east west. Each is approximately 20’ wide, 70’ long and 12’ tall. Steel framing spans over the space to simplify concrete forming, expedite roof erection and accommodate any future changes needed.

The TLCD is a passive device. Its natural frequency is close to the fundamental frequency of the building, causing water to oscillate in response to wind-induced building sway. Adjustable louver blades in the tank convert the energy of moving water into heat that is then exhausted from the building. Using this system, rather than increasing member sizes throughout the structure or using a traditional pendulum tuned mass damper, resulted in sizeable cost savings.

Figure 2. Construction of Random House

Selection of Design Parameters for a TLCD

The mass ratio μ should be determined based on the trade-off between the desired reduction in the response and the cost, space, and weight of the dampers. Once the mass ratio is selected, the tuning ratio f and the head-loss coefficient δ, which depends on the expected acceleration of the building floor, can be determined. The tuning ratio is used to find the liquid length L and the head loss coefficient is used to obtain the orifice opening. Optimal value of α (where α = B/L is the ratio of the tube width to liquid length) is determined from parametric studies. Studies show that α varies from 0.75 to 0.8 for moderate to strong floor motions (acceleration up to 0.7g). Using the appropriate vale of α, the tube width B can be determined.

Commissioning of TLCD in Random House Project

Unlike TMDs, the damping in TLCDs is amplitude dependent, and thus the TLCD dynamics are non-linear. Parametric studies need to be carried out to approximate the frequency and damping characteristics of the TLCDs. During the week of Feb 6th 2004, engineers from Motioneering Inc. conducted a series of tests at the Random House building. The oscillation frequency of water in a TLCD is determined primarily by the tank dimensions and, to a lesser extent, the water height. Damping within a TLCD is related to frictional resistance as water moves along the U-shaped tank. The amount of damping provided by the TLCD can be changed by varying the louver blade positions to alter the orifice openness ratio.

The testers forced the water to oscillate in the TLCD. During each test, one end of the tank was sealed and pressurized, which caused water to displace from the pressurized side to the non-pressurized side. When the water level was displaced 12 inches from equilibrium, the chamber was rapidly depressurized and the water oscillated back and forth until motion died out. Water motion in the tank also excited building vibration. Simultaneous measurements of water level and building acceleration were recorded. The measurements were repeated for different louver blade positions. The gathered data were analyzed to extract the properties of the building and the TLCDs, including as-built fundamental sway frequencies of the building, TLCD frequencies and the relationship between damping coefficients and with louver blade angles were obtained.

Dynamic analysis of the building was carried out using SAP2000. Various stages of the building were considered, including Incomplete Construction at 45th Floor, Complete Uncracked Building, Complete Moderate Event Exposure and Complete Severe Event Exposure. Building frequencies for various modes were obtained for all stages. Due to the short service of the structure at the time of TLCD commissioning, the Complete Uncracked Building frequencies were used to tune up the TLCDs. The effectiveness of the TLCDs will actually increase as the building becomes less stiff.

Table 1. Frequencies of the Building in various stages

Mode	*Predicted Uncracked frequencies (Hz)*	*Measured Frequencies (Hz) (Uncracked Building condition)*	*Predicted frequencies (Hz) for Complete Moderate Event Exposure*	*Predicted frequencies (Hz) for Complete Severe Event Exposure*
E_W sway mode	0.1468	0.1682	0.1427	0.1369
N_S sway mode	0.1679	0.2125	0.1623	0.1516

Tuned Liquid Column Dampers Details

This passive damping system is a variation of the TMD. Whereas a spring and a viscous damper are combined with a mass block (usually concrete or steel) in the TMD, water or other liquid is used in a TLCD, combining the functions of the mass, spring and viscous damping elements. The geometry of the tank that holds the water is determined by theory to give the desired natural frequency of water motion. A gate, set of louver blades, or other similar device is used to dissipate the energy in the moving water.

Table 2. Frequencies of the TLCD

TLCD	*Measured Freq. (Hz)*
X tank (E-W)	0.1682
Y tank (N-S)	0.2125

The plan and sections of the TLCD installed in the Random House Project are shown below.

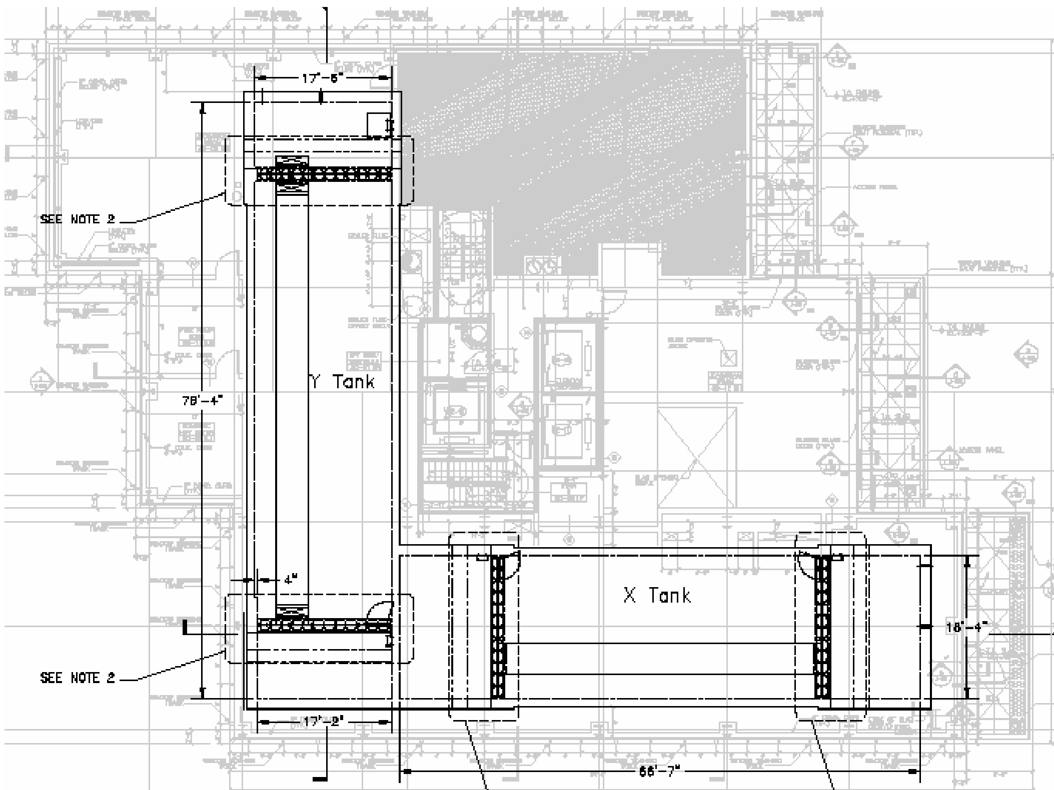


Figure 3. 50th Floor Plan

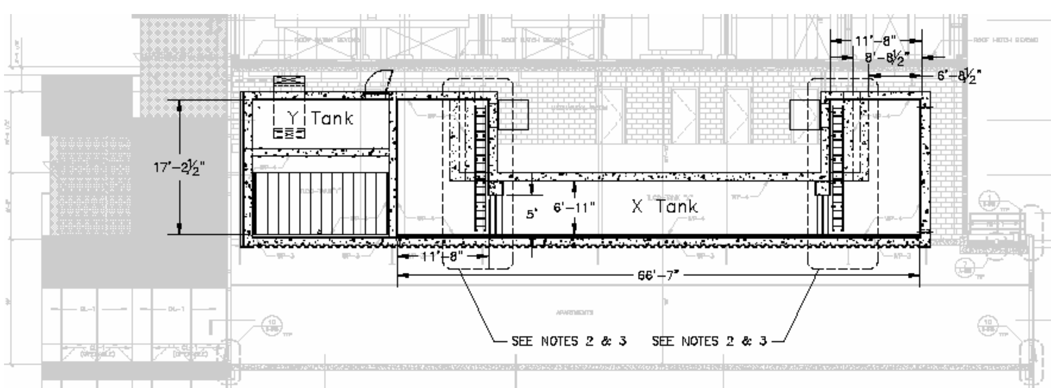


Figure 4. East-West Section through Building Top

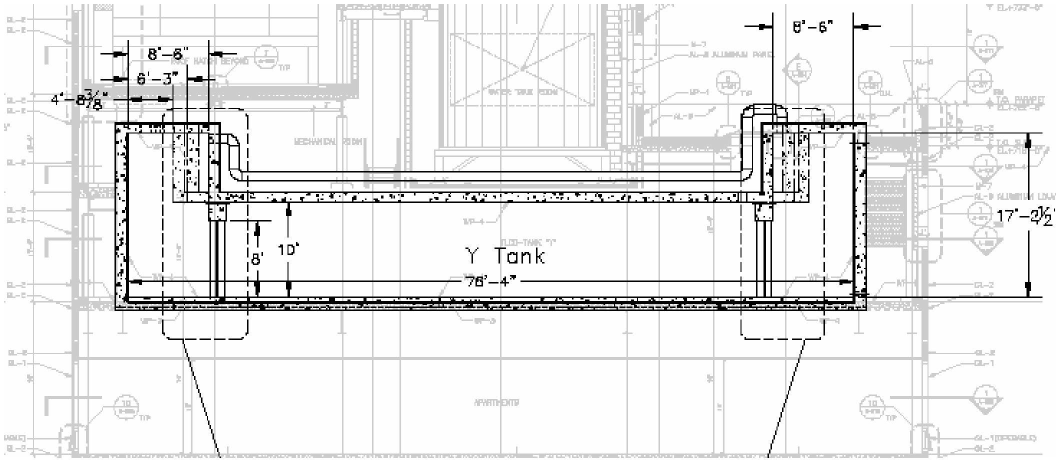
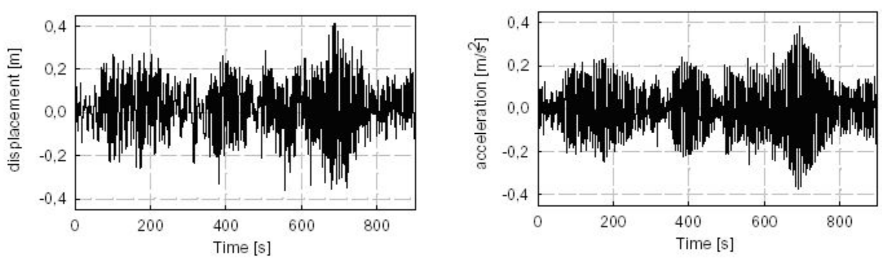


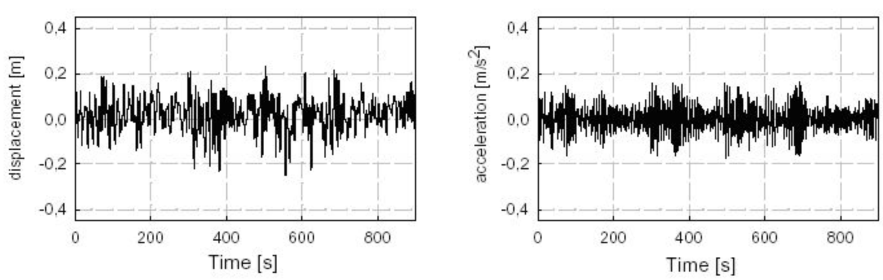
Figure 5. North-South Section through Building Top

Comparison With and Without TLCDs
Without a damping device the deflections at the top floors of the building would have been high enough to cause discomfort to the occupants. The use of TLCD resulted in restricting the interstory deflections to less than H/350 or 1/2" in the case of Random House building.

Following is a comparison study of a building with and without the TLCD. The building is a 76-story 306 meters concrete office tower (Yang, 2000). This reinforced concrete building is slender with a height to width ratio of 7.3; and thus wind sensitive. The building has a square cross-section, and a total mass of 153,000 metric tons. Analysis of the model revealed, that the first mode response dominated the building dynamics. Thus, a TLCD with a liquid mass of 500 metric tons was installed on the top floor. This is about 45% of the top floor mass, which is 0.327% of the total mass of the building. Graphs below show that a good structural response reduction can be achieved by the use of TLCD.



Top floor displacement and acceleration of the original building



Top floor displacement and acceleration of the building with a passive TLCD

Figure 6. Top floor displacement and acceleration of the building with passive TLCD.

Operational Recommendations

- Air trapped between the bulkheads in the horizontal portion of the TLCDs significantly reduces their effectiveness. When the tanks have to be drained and refilled, care must be taken to completely remove the trapped air. An air venting system or equivalent solution should be installed prior to the next tank re-filling.
- The water level must be maintained at a height established by the Supplier. TLCD performance is insensitive to minor changes in water level, so inspection of water level every 3 months, and refilling if required, should be satisfactory. Attach a marker (pipe clamp) on the maintenance ladder as a visual indicator of the proper water level.
- Exercise the louver dampers on the maintenance schedule issued by the Supplier, to avoid possible seizing of the mechanism. The blade position must be reset to the position stated by the Supplier to assure continued optimal operation.
- It is recommended that the Supplier have a representative present whenever tanks are drained and refilled or when the louver blades are exercised to insure the louver blades are reset to the proper position, the water level is at the proper height, and the air is completely removed from the horizontal portion of the TLCDs.
- The supplier of waterproofing material should be contacted regarding the water treatment. Whatever compound is used should not chemically interact with the waterproofing.

Project Conclusion

The following are benefits of using a TLCD to reduce the motions of a building:

- Helps in reducing building accelerations
- Water in the tank can also be used for fire fighting purposes
- In some instances, water in the tank can be used for chilled water storage
- Effectiveness of TLCDs actually increases as the building becomes less stiff over a period of time due to cracking, wear of nonstructural elements, etc.
- TLCD systems have low costs and maintenance requirements
- A TLCD system is capable of providing control in multiple directions simultaneously
- Studies have shown that maximum wind response can be reduced 40% by using a TLCD

A possible limitation of TLCDs is that there might not be enough space available at the top of the building where TLCD tanks could be installed. Small density of water or other liquids in TLCDs relative to those of steel, concrete or lead in TMDs necessitates large spaces to produce the same mass ratio and thus the same damping effect.

731 LEXINGTON AVENUE

Project Description

A dramatic transformation of an entire city block at 731 Lexington Avenue between 58th and 59th Streets in New York City has reached completion. The1,400,000 sq.ft. mixed-use development features an 815’ tall, 55-story tower at its west end, an 11-story low-rise at its east end, and a spectacular plaza and atrium in the center connecting the two components and the six-story podium. The 55-story tower which was topped out in the spring of 2004 includes retail floors at its base, three below-grade floors, 26 stories of office space, a portion of which will house the world headquarters of Bloomberg LLP, and 24 stories of luxury condominiums at the top.

Figure 7. 731 Lexington Avenue, New York City

This tight urban site is between two streets that lead to a bridge with extremely heavy traffic volumes at all times. Pedestrian traffic was also a big factor, since the site is located in one of the busiest retail sections of midtown Manhattan. Both factors added to the complications and logistics of the project, forcing all loading and unloading zones to occur within the footprint of the new construction. The subway tube located at the western boundary of the site also had a major impact on the foundations of the new building. Foundation walls were stepped several times in order to avoid interferences.

To accommodate the tower's mixed use, a unique structural system was employed. The commercial levels in the lower 30 floors are framed entirely in steel that then support a cast-in-place flat plate structure used for the residential levels above. Two outrigger floors with a system of belt trusses positioned at the mechanical levels, together with a braced core and shear wall with many unique features, provide the needed stability. The second outrigger level also serves as the transfer floor, where all concrete columns and walls of the high-rise concrete frame above transfer onto the steel core and columns of the steel frame below via a series of plate girders, transfer trusses and belt trusses.

Building a luxury condominium tower atop a steel high-rise structure created various design challenges, which made excellent coordination among the design team crucial. Innovative design and construction methods resulted in a cost-effective fast-track design project that was successfully completed on time.

Figure 8. 731 Lexington under construction

The use of concrete in the residential floors accommodated story heights varying from 10'-9" to 14'-9", resulting in more apartment floors and units within the zoning requirement. The typical residential floor structure is a 9" thick reinforced concrete flat plate allowing for easier forming, pouring and finishing. It also permitted a three-day construction cycle, thus significantly reducing the construction schedule with the help of excellent cooperation and coordination between all parties in the design and construction teams.

The design and positioning of columns and shear walls allowed for an open residential floor layout. Concrete columns varied in size and shape, typically from 20"x 30" to 40"x18", as was necessary for strength and to fit into the architectural layouts. Column transfers were required at the 48th floor building setback, with loads transferred through the flat slab that was 21" thick with 8000 psi strength. Shear reinforcing in the form of stud-rails was provided where necessary. This approach kept the thickness of construction at the transfer floor to a minimum, thus maximizing the ceiling height at the floor below. The lateral system for the concrete portion of the structure consisted of concrete shear walls located within the core varying in thickness from 24" to 16", and column-slab moment frames.

One of the most critical and challenging aspects of the design was how to transfer the gravity and the lateral loads from the concrete structure above the 30th floor, to the steel frame below. This task was further complicated by two geometry issues: the concrete shear wall was completely misaligned with the steel braced core below, and the building massing had a major setback at the north and south elevations so that the steel perimeter columns were outboard of the concrete ones. Both issues prohibited a more direct transfer of the loads. A unique system of outrigger trusses, belt trusses and transfer trusses was provided between the 29th and 30th floors. The outrigger system consists of four north-south and two east-west trusses engaging the steel core and the perimeter steel columns. It significantly reduces overturning moment in the core while increasing the building's lateral stiffness. These outrigger trusses also support a series of transfer trusses and plate girders used to pick-up the residential concrete columns. In all, 46 concrete columns were transferred onto the steel frame below.

The concrete shear walls were also picked up on secondary steel trusses that were then delivered onto the steel core bracing bays. In order to develop the wall reinforcing into the steel truss elements, as well as achieve good continuity between the two systems, the concrete core was overlapped with the steel trusses by encasing the trusses with concrete and extending the reinforcing within the height of the 30th floor. Reinforcing bars terminated on steel members via welded Lenton couplers. An economical and efficient building emerged from the coordinated use of concrete and steel where each was most suitable.

Tenant comfort at the top residential floors was also a major concern. The structure would not be economical if designed stiff enough to keep wind-induced accelerations within acceptable limits. Additional damping to the building was provided by a 600-ton roof-top tuned mass damper (TMD), which was supported by a concrete box structure consisting of 18” thick walls and a 24” thick base slab. The selection and the design aspects of the TMD are described below.

Selecting the TMD System

Meeting occupant comfort criteria was a constant goal throughout the design process. Very elaborate and detailed parametric studies were carried out in order to determine the effectiveness of increasing the building stiffness by adding structural material, increasing the building’s mass by using thicker floors, and changing the building’s mode shapes by altering its mass distribution with height through varying slab thicknesses. These options were available because wind governed the lateral design of the main tower; the seismic requirements were moderate. However, wind tunnel model testing at Rowan Williams Davies & Irwin, Inc. (RWDI) revealed that local conditions create a power spectrum, or graph of wind energy versus the building’s period, that is flat in the range of lowest-mode periods. This meant that modifying the tower’s dynamic properties by changing stiffness, mass, or mode shape would do little to affect the building’s response and occupant comfort levels in windy conditions. Some changes could even worsen the response. In addition, any of these modifications would be cost-prohibitive.

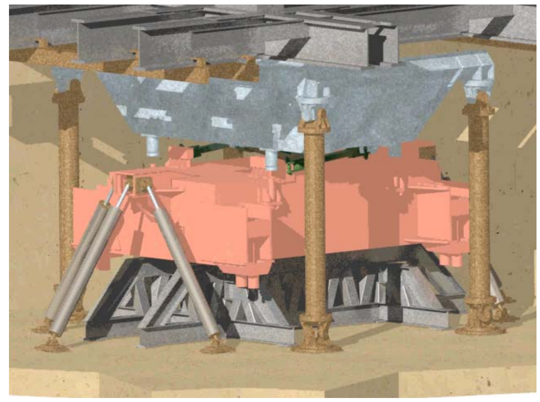


Figure 9. Primary mass (bottom) and secondary mass (top) of TMD

Given this situation, supplementary damping was found to be the most effective way to meet comfort criteria. Two possible options for providing additional damping to the structure were studied: a Tuned Mass Damper (TMD) or a Tuned Liquid Column Damper (TLCD).

After careful consideration of advantages and disadvantages for both systems, such as cost, size, future adjustability and more, a passive TMD system was selected by the owner and the design team. Once the system was selected, the design effort was then focused on how to optimize the TMD and minimize the height of the pendulum.

The Mechanics of the Unique TMD System

A tuned mass damper (TMD) at the top of a building moves out of phase as the building sways, driving dashpots, large “shock absorbers” that convert a portion of the kinetic energy of building motion into heat. A passive TMD was selected because it needs no outside energy source, making it reliable and easy to maintain. The simplest TMDs are pendulums whose free length is varied to match the building period, just as the length of the pendulum in an old-fashioned clock is adjusted to better keep time.

The natural period of a single degree of freedom mass-and-spring system in radians/sec is (mass/spring stiffness)$^{0.5}$. A pendulum is a stable oscillator independent of mass. A pendulum with length L has an equivalent period of $(L/g)^{0.5}$. So in order to match the tower’s longest periods (6.5 and 7.9 seconds) the pendulum would have to be about 51 ft long within a space about 60 ft high. This would require additional costs for framing and cladding the TMD enclosure, and for resisting the greater wind loads created by making the building taller for the additional room. So the design team was challenged to keep the pendulum height to a minimum.

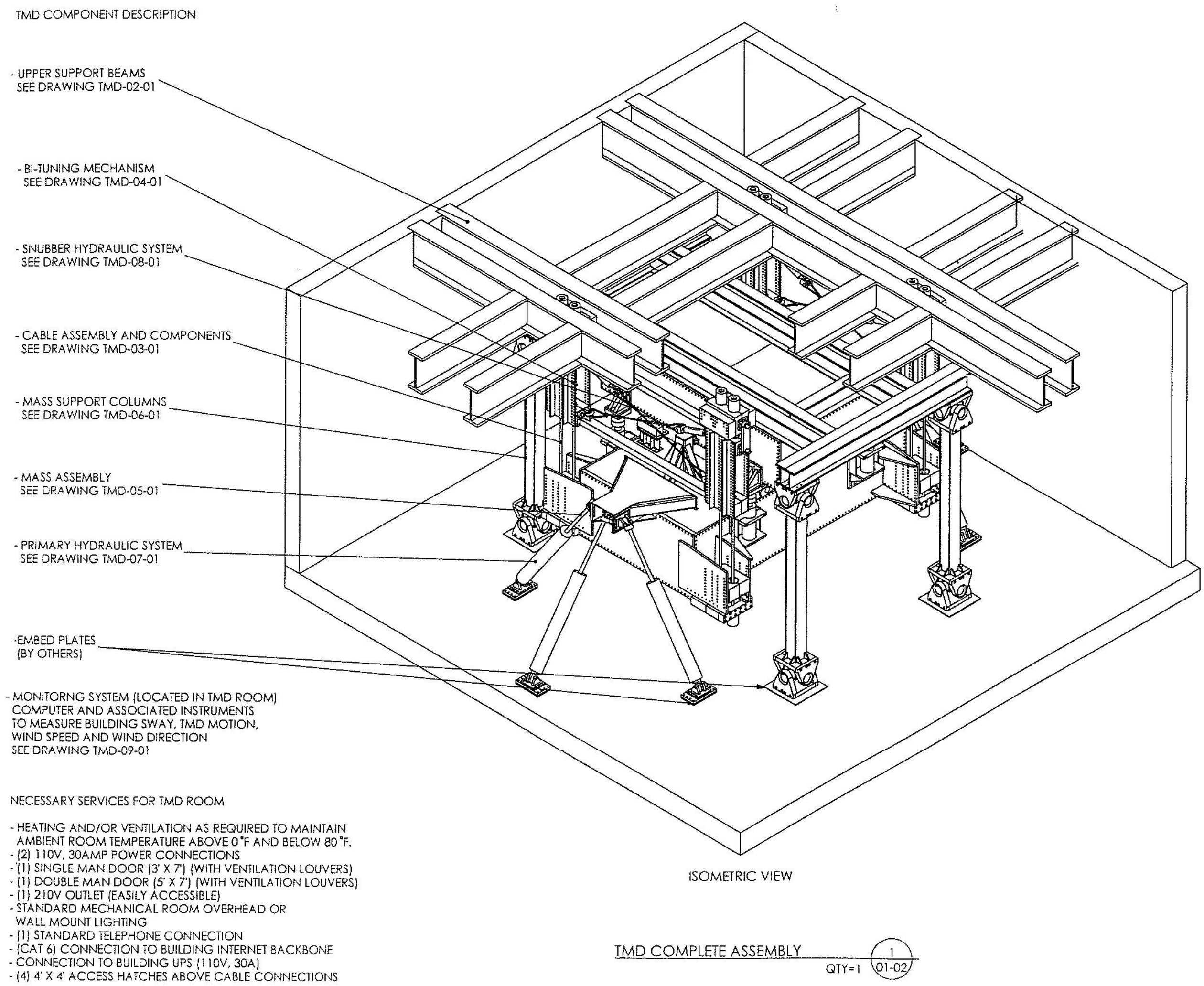


Figure 10. Overall isometric view of 731 Lexington Avenue TMD

The 731 Lex TMD uses the principle of linked stabilizing/destabilizing forces to match building periods in a low-headroom space. An inverted pendulum is a "lollipop" balanced on its lower tip. As it leans, it generates a destabilizing force of magnitude exactly opposite to that of a pendulum of the same mass and length. Without a restoring force the "lollipop" would flop over and stay there. For large masses, single-point systems are not practical, so a 'loose-jointed table top' is used instead. If two equal masses, one a pendulum of length L and the other a table top with leg length L are linked together, the destabilizing and restoring forces would be equal and opposite. The masses could be pushed sideways and released, and they'd stay put. By making the pendulum length a bit shorter than the table top, or by making the pendulum heavier than the table top, a small net restoring force is left to act on the two large linked masses. The resulting system frequency is very low and the period is very long.

The resulting innovative two-mass system can be tuned to long building periods but only requires a room 25 ft high. An upper 220 ton steel block stands on jointed legs. It is linked to a lower 380 ton steel block suspended from short pendulum cables. As a result, the mass is the sum of the two blocks, but the spring stiffness is established by the difference between the destabilizing effect of the upper mass and the restoring force of the lower mass. The high mass and low spring stiffness results in periods long enough to match building behavior.

The Required Mass and Damping

The whole point of a TMD of course is the damping. The TMD swings the opposite way the building moves, but it's not a 'counterbalance.' It is a convenient way to magnify building motions and drive damping devices (dashpots). When the mass is tuned to match the building it swings out of phase and with larger amplitude than the building. Dashpots or 'shock absorbers' between building floor and TMD mass are pushed and pulled, absorbing energy. Enough mass is needed so that the force of its swing will be able to push and pull the dashpots. The force required depends on the amount of damping needed.

Damping for buildings is described as % of critical damping. Critical damping is the least amount of energy absorption needed so that, if displaced, the structure would just return to its original position without swinging through zero. For most tall buildings, having 2 to 3% of critical damping is sufficient for good comfort, but in some cases more damping may be required, depending on:
a) usage (permissible acceleration is less for quiet residences than for busy offices)
b) wind conditions (design for steady moderate winds, hurricanes)
c) building shape (curves that act like a wing; chimneys and sharp corners that shed vortices)
d) dynamic properties (building mass distribution, periods for main modes, mode shapes).

A concrete-framed building is usually assumed to have up to 2% damping inherent in the structure (rubbing across natural microcracks in the concrete). A steel-framed building may be assumed to have about 1% inherent damping thanks to rubbing of partitions. If additional damping is needed in order to satisfy occupant comfort, and knowing the dynamic properties, the needed amount of energy absorption (damping) can be determined.

For many skyscraper TMDs, where the TMD is at the highest floor possible, the optimal mass is about 3% of the 'generalized' mass. For a straight-line mode shape (a good approximation when both flexure and shear are considered) and uniform floor masses and story heights, the modal mass is 1/3 of total building mass. So commonly the TMD weighs about 1% of the building weight.

This was the case for the 731 Lexington project. The final TMD weight was approximately 600 tons and the provided total damping was approximately 6% of critical. The TMD reduced the building accelerations (for wind storms with a 10-year return period) from 21.1 milli-g to just below 15 milli –g.

Project Conclusions

A uniquely designed double-stacked pendulum was successfully implemented at one of Manhattan's newest skyscrapers. Not only did it improve residential tenant comfort without the need for additional costly stiffening of the supporting frame, but its unique design fit in the shallowest height possible, resulting in additional savings in enclosure costs.

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