COST-EFFECTIVE SOLUTION

Controlling Perception of Wind-Induced Motion in Slender Buildings

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Satisfying occupant comfort criteria is a common challenge in the design of slender high-rise buildings. When wind-induced accelerations exceed the acceptable limits for human comfort, structural engineers typically try to increase building mass or stiffen the building. Nevertheless, this approach may not be a cost effective or feasible option, especially when the structural system has already been determined and the option of introducing additional structural components is limited.

When a project is initiated, structural engineers estimate wind loads in compliance with building codes and standards and adjust them, if necessary, based on their past experience and knowledge of the area. In New York City, it is not uncommon to find wind loads for a nearby building of similar scale. However, when it comes to wind loads, often the information from neighboring buildings is not applicable to the building under design due to the complex nature of wind-structure interaction. In addition, even though design standards are available to structural engineers to compute wind loads, these standards are not sufficient to predict all possible issues discovered after wind tunnel testing is completed.

Two slender towers, Building A, (the real name of Building A is not identified, per the request of the building owner), and W New York Downtown Hotel and Residence (referred to as the W Downtown Hotel in this article), recently built in New York City, exemplify the aforementioned cases.

Structural System

Building A is a 60-story, 650-foot tall residential building. The building footprint at the typical floors is 150 feet by 65 feet, and the building slenderness ratio is 10:1. A dual system, combining moment frames using a typical 10-inch thick flat plate slab with columns and shear walls, is used as a lateral load resisting system to resist wind and seismic loads. In order to maximize the efficiency of each structural component, shear walls extend the full 65-foot width in the north-south direction at the base of the building and a thicker 12-inch thick flat plate slab is used at the 35th floor and above, where their frame action is more effective. This enabled engineers to increase the stiffness and mass of the building to a certain extent without elongating the building periods, which generally increase the resonance portion of wind induced responses.

The W Downtown Hotel is a 57-story, 627-foot tall mixed-use building (*Figures 1* and *2*) with a slenderness ratio of 11:1, located one block south from the World Trade Center site. The footprint of the typical floors is 124 feet by 57 feet. The top 24 floors are high-end condominium units and the bottom 30 floors are occupied by amenities, mostly hotel rooms and furnished residences. Two mechanical floors are strategically used for lodging full height belt walls (full height reinforced concrete spandrel beams connecting exterior columns) at the 31st floor and 100-inch deep belt beams at the 57th floor. These belt walls and beams supplement the framed tube action initially provided by the exterior columns and flat plates but reduced by transfers at the 6th floor.

Figure 1: W New York Downtown Hotel and Residence.

Figure 2: Construction of W New York Downtown Hotel and Residence.

Wind Responses Obtained from Wind Tunnel Testing

Wind responses under two configurations of the surroundings were studied to predict the most critical wind loads for designing the structure and evaluating the serviceability performance. In both cases, the future neighboring buildings provided a shielding effect, and benefits from the future adjacent buildings turned out to be more significant in the east-west direction. Despite these benefits, both towers were designed for wind loads under the present configuration, since it resulted in the most critical wind responses.

For the initial study, stiffness of the structures under two different return periods (50 year and 10 year) were estimated based on the modified code specified wind loads (knowing that code specified wind loads do not include cross wind responses and torsional responses). After the initially estimated wind loads were provided by a wind tunnel lab, a more precise analysis was preformed to estimate cracked sections. Then the corresponding structural dynamic properties under these estimated wind loads were sent back to the wind tunnel testing lab. The final wind loads for the design of structural members and evaluation of serviceability performance were established after several iterations, in order to reach compatible results between the wind responses and the stiffness of the structures corresponding to estimated cracked conditions.

The W Downtown Hotel was initially designed as a 55-story building, and the peak acceleration of this structure was estimated to be 17.4 mg (milli-g: 1/1000th of gravity acceleration) at the 53rd floor. By the end of the design development phase, the owner decided to add two more floors to the building. Assuming a damping ratio of 2% of the critical damping for the selected structural system of the tower, which are comprised of flat plates and shear walls coupled with shallow link beams at every level, the peak acceleration of the taller building excluding influence of hurricanes was estimated to be 19.4 mg at the top occupied residential floor (55th floor). For Building A, the peak acceleration of the 650-foot tall structure was estimated to be 22.4 mg at the topmost occupied residential floor.

Acceptable Limit in Accelerations

For both Building A and the W Downtown Hotel, the wind studies indicated that accelerations were excessive at the floors where long-term occupants will reside. The commonly acceptable range for 10 year peak accelerations is 15 mg to 18 mg for residential towers and 18 mg to 20 mg for office towers. This acceptable range can be varied depending on the natural frequencies of the structure, as occupant's sensitivity to motion decreases when the natural frequencies of buildings are lower. Therefore, buildings with longer periods can generally allow larger accelerations in terms of perception to motion.

As the initial studies indicated that the accelerations of both buildings were excessive, the structural modifications, such as increasing the stiffness and increasing the general mass, were investigated. According to the engineer's study in cooperation with the wind tunnel testing lab, adding massive shear walls at the base of the building for Building A and improving frame tube action by enlarging exterior columns and reducing exterior spans for the W Downtown Hotel would have produced the targeted accelerations. However, these modifications would have required architectural compromises and reduction of valuable space. As an alternative option, introducing supplementary damping systems to improve the performance of both structures under the 10 year return period wind loads was explored.

Supplementary Damping Systems

Various types of supplementary damping systems (SDS) were considered: a tuned mass damper (TMD), a deep tuned sloshing damper (DTSD), a shallow tuned sloshing damper (STSD) and a tuned liquid column damper (TLCD). For both towers, a TLCD was not a feasible option because of space limitations. A tuned mass damper was also excluded due to the higher cost and maintenance requirement in comparison with a deep tuned sloshing damper (DTSD) which was eventually selected. Two levels of target performance were investigated during an initial study for the W Downtown Hotel. Level 1 performance aimed for 2.0 mg of reduction in the peak acceleration and Level 2 performance aimed for 3.0 mg to 4.0 mg of reduction. In the end, Level 2 performance was achieved.

Tuned Sloshing Damper (TSD)

A tuned sloshing damper utilizes liquid waves to absorb energy from vibrating structures through wave travel and viscous action in a partially filled tank of liquid. The tank is designed so that the liquid surface wave has a frequency "tuned" to be near the fundamental frequency of the building for the optimal performance of a tuned sloshing damper. The frequency of the liquid is determined by the density, length, width and depth of the liquid.

During the initial wind study, it was found that the majority of the excessive peak acceleration of Building A was in the north-south direction. The W Downtown Hotel was somewhat different from Building A. The acceleration in the north-south direction was also the primary contributor to the large acceleration but, due to mainly

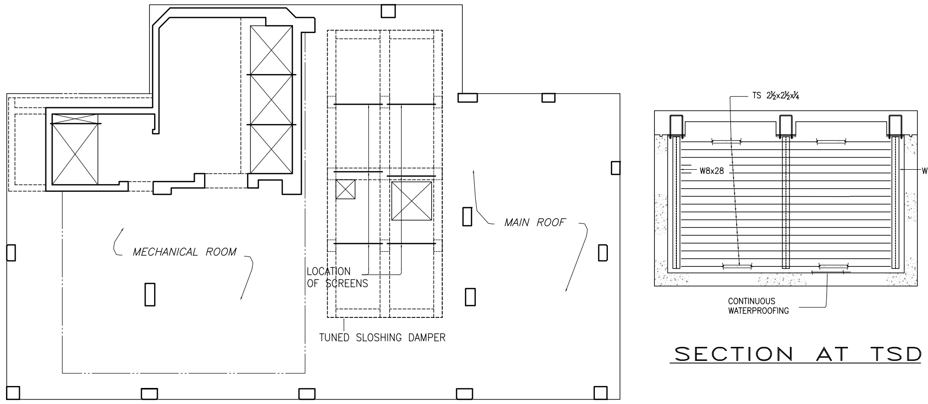

Figure 3: TSD location plan and section (Builindg A–58th floor plan).

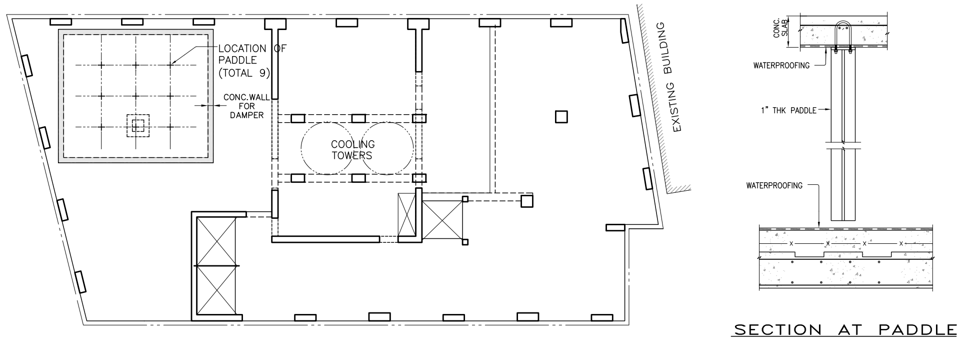

Figure 4: TSD location plan and section (W Downtown Hotel -56th floor).

across wind responses, the acceleration in the east-west direction was not negligible. Therefore an effort was made to reduce accelerations in both directions. Considering the contribution of accelerations in each direction, a one-directional-tuned-deep-sloshing damper (18 feet x 45 feet x 11.6 feet high) (*Figure 3*) and a bi-directional-tuned-deep-sloshing damper (27.25 feet x 23.16 feet x 8 feet high) (*Figure 4*) were evaluated to be the most cost-effective and space-optimal option for Building A and the W Downtown Hotel respectively.

Construction of Dampers

A tuned sloshing damper consists of a damper tank, liquid and screens or vertical hangers generating turbulence of water in motion. When a wind event begins, the liquid resonates out of phase with the structure and energy is dissipated from the liquid by flowing through these devices. For Building A, three slat screens parallel to the short direction of the damper tank (*Figure 5*) were installed in the tank. Similarly, for the W Downtown Hotel, nine paddles were hung from the ceiling of the concrete tank (*Figure 6*). Each paddle consists of 1-inch thick by 10-inch wide galvanized steel plates welded to two 1-inch thick by 4½-inch wide plates to a create cross shape section. These paddles work in both directions to provide additional damping and ultimately result in reduced peak accelerations. The total construction cost of a damper for the W Downtown Hotel was estimated to be less than $200,000.

Frequency Measurement and Tuning

Construction of the damper tanks, made of cast-in-place concrete, needed to proceed with the rest of the concrete construction. Hence it was important to confirm the pre-determined dimensions of the damper tanks prior to their construction based on the measured building frequencies. These measured building frequencies were compared with the estimated building frequencies using FEM (Finite Element Method) analysis. Considerations for the in-situ conditions at the time of measurement had to be taken into account. Non-cracked sections were assumed under the ambient wind loads. A reduced building mass, which excluded the weight of the missing mechanical equipment, was used. Lastly, the higher strength of the tested and in-place concrete in some vertical members was incorporated in the structural model.

For both towers, the measured building frequencies were in a range of 10% of their estimated building frequencies (*Table*). The concrete damper tank for each damper was built per the original design without any modifications.

For the W Downtown Hotel equipped with the bi-directional-tuned-sloshing damper, the water depth was primarily tuned for the natural frequency of the building in the north-south direction. The dimension of the damper tank in the east-west direction was left

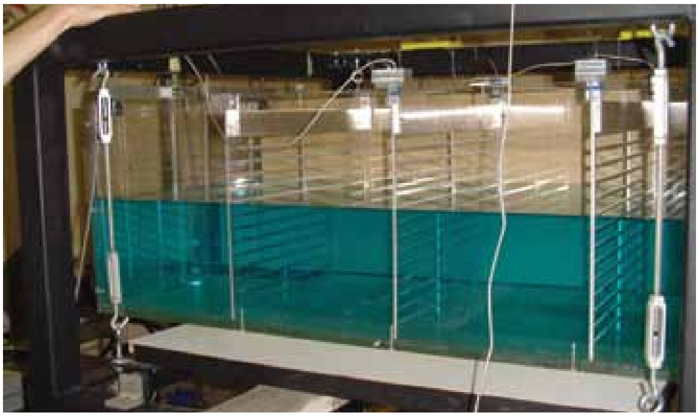

Figure 5: Scale model of one-directional TSD (Building A) for shake table performance test. Courtesy of RWDI and Motioneering Inc.

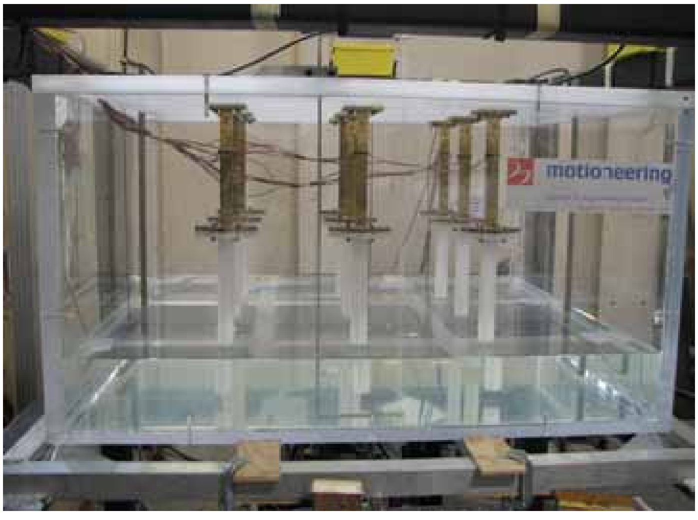

Figure 6: Scale model of bi-directional TSD (W Downtown Hotel) for shake table performance test. Courtesy of RWDI and Motioneering Inc.

Table: Summary of estimated and measured building frequencies of the W Downtown Hotel.

	Estimated Frequencies by FEM (Finite Element Method) analysis		Measured Frequencies by Monitoring	
Condition	Design phase (Assume completed structure and cladding)	As built-condition (reduced mass and 90% completion of cladding)	Interim monitoring under as-built-condition (reduced mass and 90% completion of cladding) Oct 2009	Final monitoring under as-built-condition (after completion of structure and cladding) June 2011
Purpose	Evaluate serviceability performance in terms of motion perception during an initial study	Ensure dimensions of a damper tank for construction	Ensure dimensions of a damper tank for construction	Establish frequencies of the building and the damper for tuning
Frequencies (Periods)				
X-direction (E-W)	0.208 Hz (4.8 sec)	0.253 Hz (3.9 sec)	0.278 Hz (3.6 sec)	0.266 Hz (3.8 sec)
Y-direction (N-S)	0.185 Hz (5.4 sec)	0.208 Hz (4.8 sec)	0.192 Hz (5.2 sec)	0.183 Hz (5.4 sec)
Torsion	0.322 Hz (3.1 sec)	0.377 Hz (2.6 sec)	0.418 Hz (2.4 sec)	0.402 Hz (2.4 sec)
Estimated Peak Accelerations				
Without a tuned sloshing damper	19.4 mg (2% of inherent damping)		18.1 mg (2% damping) – 20.9 mg (1.5% of inherent damping)	
With a tuned sloshing damper			15.6 mg (2% damping) – 17 mg (1.5% of inherent damping)	

flexible for future adjustments, which would consist of constructing additional layers of concrete masonry unit walls at the north wall or at the south wall of the damper tank. However, interim monitoring results indicated that adjustments in the tank dimensions of the damper basin were not necessary.

After construction of the W Downtown Hotel was completed, the final monitoring was performed to ensure the performance of the TSD that was filled with 36 inches of water, predetermined from the initial study. This final monitoring indicated that the measured frequency of the damper was slightly different from the measured frequencies of the completed structure. As a result of this measurement, the water level of the damper was adjusted to 27 inches.

Design Team

Building A

Structural Engineer: Rosenwasser/Grossman Consulting Engineers, P.C.
Wind Engineering Consultant: Rowan Williams Davies & Irwin Inc. / Motioneering, Inc.

W New York Downtown Hotel & Residence

Structural Engineer: Rosenwasser/Grossman Consulting Engineers, P.C.
Developer: The Moinian Group
Wind Engineering Consultant: Rowan Williams Davies & Irwin Inc. / Motioneering, Inc.

Summary

Within the last five years, more buildings have been equipped with supplementary damping systems. Since buildings are getting taller and more slender, conventional methods to improve their performance in terms of motion perception may no longer be cost-effective. These traditional methods such as increasing stiffness or generalized mass without negatively affecting building frequencies, result in increased construction costs and loss of valuable space. From two buildings recently designed and built in New York City, engineers have learned that a tuned sloshing damper can be a competitive alternative to those traditional means. Also, this system can be fitted to the buildings not only to decrease accelerations but also to reduce wind loads, as long as the supplementary damping system is properly tuned for the building frequencies under the considered wind loads.▪

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