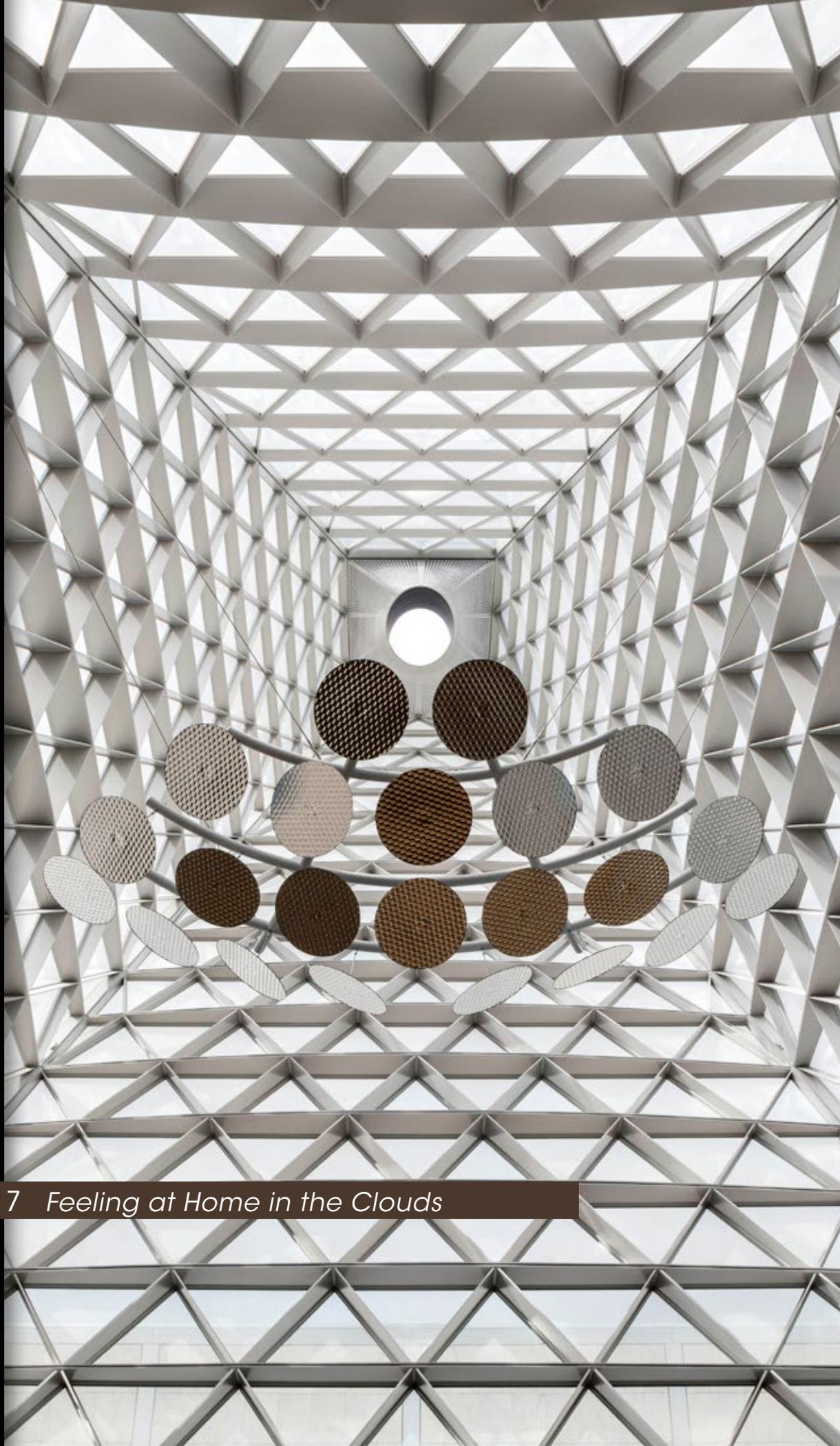


# STRUCTURE®

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December 2017 *Feeling at Home in the Clouds*



# STRUCTURAL PERFORMANCE

performance issues relative to extreme events

## Feeling at Home in the Clouds

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Modern engineering tools and techniques enable structural engineers to continually redefine the limits of possibility. Nowhere is this more evident than in supertall buildings, where controlling wind-induced sway has become a critical aspect of project success.

The use of tuned mass damping systems has become a mainstay in attaining this control, in large part because each custom-designed system can be tuned to match the as-built characteristics of the building. They also provide a much more efficient solution than adding more mass or stiffness.

One recent example is the Shanghai Tower which, when it opened in 2014, became China's tallest building and the second tallest building in the world. Even though the design of the 2,073-foot (632-meter) tower was optimized to reduce wind effects, the developer also chose to include a tuned mass damper (TMD) to reduce accelerations further and eliminate any feeling of structural movement. The resulting 1,100-ton system is the world's largest eddy current TMD, discussed in more detail below.

### Problems

As buildings are designed to be taller and more slender, they also are designed to be lighter and, relatively speaking, not as stiff. As a result, wind tends to cause much more flexure in these structures than in shorter, more squat buildings. To put it another way, the taller and more slender a modern building is, the more lively it is likely to be.

If left uncontrolled, excessive wind-induced building movement can cause various problems. For example, large oscillatory displacements may make it necessary to reduce the speed of elevators during strong wind events. Displacements can

also damage more brittle secondary elements such as partitions, glazing, and the façade. Beyond any noticeable harm caused by a single large displacement, the accumulation of many cycles of amplitude can also cause fatigue failures.

Wind-induced movement can cause two other significant problems that affect a building's usability. The first, audible creaking and groaning, seems to be especially prevalent where there is the greatest amount of relative motion between building parts as the building deflects. Often occurring on the lower levels, these potentially loud noises can make even a new building sound like a rickety old ship.

The most common problem, however, is the perception of movement that comes from the acceleration of the building as it sways back and forth. This is an issue that designers must address to ensure occupants remain comfortable even as the building moves. Although their homes can be literally in the clouds, people want to feel like they are on solid ground.

The inherently low structural damping in modern high-rise structures is a significant factor in managing occupant perceptions of movement. The challenge is made even more problematic because of the relatively high uncertainty in assuming an appropriate level of inherent structural damping.

### Challenges

Adding movement criteria to the building design process increases the complexity of coming up with a good design. Fortunately, a structure's dynamic characteristics can be estimated using the structural engineer's computer model through a back-and-forth approach.

Many years ago, wind tunnel testing on an instrumented flexure was used principally to come



*Wind tunnel testing of the tall and slender 432 Park Avenue played a key role in evaluating the effects of vortex shedding created by its very uniform shape.*



*Located within blocks of New York's Central Park, 432 Park Avenue is more than twice the height of any of its nearby neighbors, leaving the upper portion of the structure fully exposed to the wind.*

up with foundation loads to determine the building's overturning moment. However, in more recent times, it was realized that the test data already being collected could also be used to estimate accelerations. This is now a routine activity.

For many current projects, the structural engineer begins by laying out the structural system to resist the gravity loads vertically and the wind loads laterally – and sometimes earthquake loads, as applicable – based on the selected primary structural materials (which is to say concrete and steel) and their configuration. This initial layout includes the lion's share of what determines the building's mass and stiffness.

This typically leads to an initial design based on a finite element model. The output from that model provides the dynamic characteristics of the building. Using that information coupled with wind tunnel data and analysis, the structural engineer is given a set of equivalent distributed static wind loads, based on the specific dynamic characteristics of the building and local meteorological climate. This data can be put back into the same finite element model to confirm the adequacy of all structural members for the ultimate design. Another check is conducted to ensure serviceability requirements are met during regularly occurring wind events.

All of the secondary members in buildings – everything from the glazing to the interior drywall and partitions – also contribute to building stiffness in minor ways, but these additions are not taken into consideration by the structural engineer, making the findings a bit conservative with regard

to safety. Conventional thinking is that, as far as loads are concerned, more stiffness is almost always better.

Researchers have gleaned a significant amount of data on building performance characteristics, including damping ratios as a function of height and building type. These characteristics help to estimate structural performance. However, data is less prevalent for a supertall building's inherent damping except to know that it is going to be very low. In fact, the trend is that the typical amount of inherent damping is decreasing in new buildings as designs get leaner and more efficient, which brings us back to the observation that new buildings tend to be more lively. So, what are the

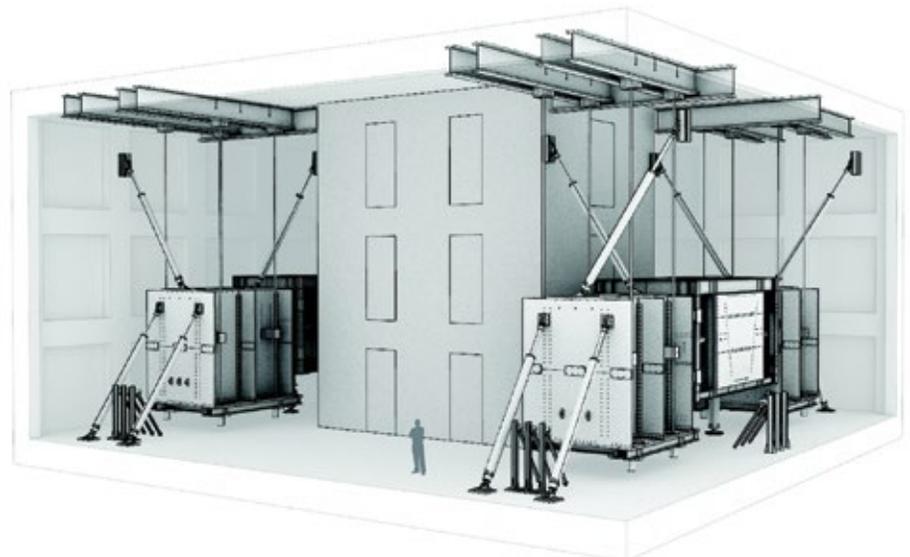
implications when you know you cannot expect much damping from the building structure, but you are going to reach for the sky anyway?

## Setting Limits

How people feel about perceived movement and acceleration is highly subjective, so trying to define how much acceleration is too much yields only a fuzzy threshold. However, there is a consensus that building occupancy type and anticipated return periods (or mean recurrence intervals) factor into setting a reasonable range of such limits.

Residential buildings have tighter limits on movement than other buildings, such as offices or commercial space. People in a condominium or apartment are going to be much more particular about how comfortable their residence is, on an around-the-clock-basis, than the same people would be in an office building. When acceleration guidelines for buildings are set, they also include an anticipated recurrence interval. For example, larger accelerations that the majority of people would sense might be acceptable if they occur only infrequently, such as once a year or once every 10 years. For weekly or monthly occurrences, however, the acceleration would be limited to a much smaller value that ideally should be imperceptible to most people.

Traditionally, the industry has found that keeping residential building accelerations below about 18 milli-g for the worst storm expected only once every 10 years heads off most complaints. For office towers, accelerations of 25 milli-g might be acceptable. That



*Two 660-ton opposed pendulum tuned mass dampers (TMDs), located near the top of the tower on the east and west sides of the core, provide supplemental damping for 432 Park Avenue.*

means, essentially, that weather patterns could be expected to produce building swaying that would be noticeable and uncomfortable on the uppermost floors – causing chandeliers or draperies to move, or doors to swing on their hinges – once in 10 years.

Although 10-year acceleration targets have proven to be useful guideposts for designers over the years, here again the liveliness of newer buildings comes into play. Whereas, for older buildings, most plots of peak acceleration versus average time between occurrences typically had roughly the same slope, such plots for lighter, more flexible structures can have much flatter slopes. In these cases, it is not unusual for the 1-month and 1-year accelerations to govern. Further complicating the picture, the cyclic frequency of the building's sway also affects occupant sensitivity. One level of acceleration that is acceptable on a very slow swaying, low-frequency building may be objectionable on a higher frequency building.

This type of limit is reflected in the International Standards Organization's standard ISO 10137: 2007, which provides acceleration criteria for residential and office structures at the 1-year return period across

a range of frequencies. By aligning these limits with logarithmic graphs showing a building's total peak accelerations plotted against the typical mean time between these occurrences, when and to what extent structural performance improvements are necessary can be determined. (This is a very simplistic description of the process, as several key assumptions go into the actual plot generation.)

## Resisting Wind Loads

The process of determining appropriate wind loads for tall and supertall buildings is quite complex. It involves historical weather data, usually from a nearby airport, which may require interpretation to be more site-specific. Further extrapolation is necessary because weather data typically are collected close to the ground. The most critical wind speeds for a supertall building occur several hundred yards above the ground surface.

When determining how much a high-rise building will oscillate in the wind, the controlling factor is damping. At one extreme, there is little or no resistance to oscillation and the building continues to sway back

and forth indefinitely, unable to dissipate the energy that the wind transferred into it. The opposite behavior, known as *critical damping*, results in no oscillation at all, and the building simply returns to its at-rest position after any perturbation, in the shortest interval of time. Neither of these is the case in real-world tall buildings.

The amount of damping inherent in a tall or supertall building is impossible to predict with any certainty. In fact, inherent damping is the most uncertain structural variable. It, therefore, requires significant judgment and should be viewed together with other material behavior design assumptions. Observed damping ratios for scores of buildings confirm that the damping is very low, and trends lower with every story closer to the sky. A range of inherent damping, typically from 1% to 2% of critical, is used in the design.

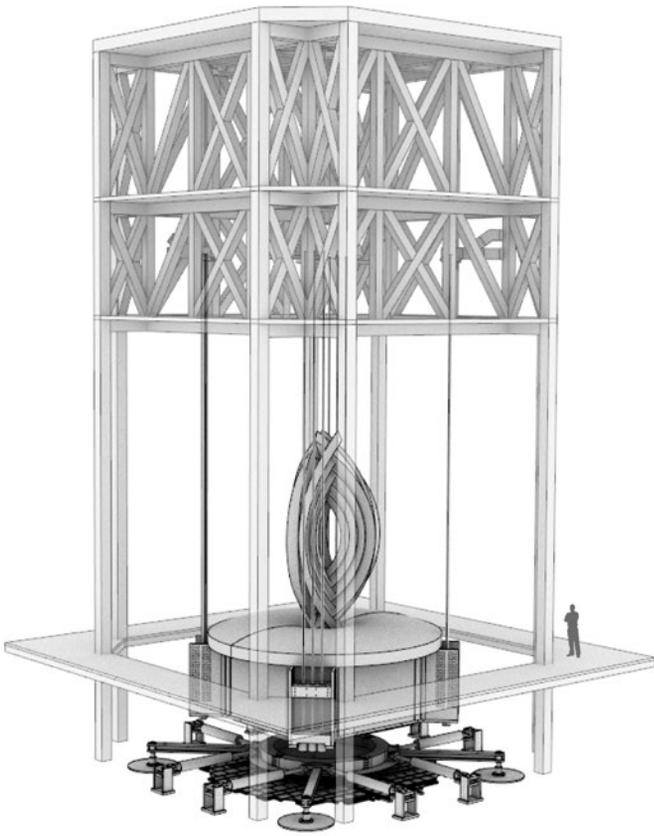
It turns out that the challenge of designing a building to stay below specific acceleration targets is very sensitive to the as-built damping level in the structure, and that is not known until the building has been constructed.

By way of example, if the assumption is 1.5%, it could easily be as high as 1.8% or as low as 1.2%. That sounds like an insignificant absolute difference, but it can make a 20% relative difference in the acceleration

*NOTE – The accelerations experienced in a swaying building are most frequently expressed in thousandths of a G, the constant acceleration due to gravity, which is 9.81 meters per second squared. Applying the metric prefix milli yields the term milli-g.*



Visitors to the observation area at the top of the Shanghai Tower can see the slow movements of a 70-ton jade sculpture mounted atop the tower's pendulum-like tuned mass damper.



*Supported by the crown structure of the tower, the simple pendulum of the tuned mass damper at the top of the Shanghai Tower is suspended over an eddy current damping system by 12 cables, three on each of four corners.*

levels. Instead of the target 18 milli-g at a 10-year return period, it could end up being as high as 22 milli-g or as low as 14.5 milli-g, which is quite a wide range of response. So, even though it is understood that the damping levels are low, the uncertainty in predicting real-world accelerations is still very significant.

## Staying in Control

This essential uncertainty concerning a structure's damping characteristics can be greatly reduced with the addition of a tuned mass damping system. Engineered to operate passively in response to building movement, these types of damping systems exert forces opposing the building's movement.

A TMD system should be as high up in the building as possible to be most effective. Most damping systems are designed to be adjusted, or tuned, once the building is substantially complete to accommodate the uncertainty of the structure's as-built sway frequency(ies).

These TMDs consist primarily of a large mass, either liquid or solid, some means of

dissipating the energy, and an appropriate system of attachment to the structure. The mass is specifically sized for each building according to the demand for improved performance; for supertall buildings, this is typically several hundred tons.

Liquid dampers use a mass of moving water in various configurations, including tuned liquid column dampers and tuned sloshing dampers. Although water dampers are usually somewhat less expensive than their solid counterparts, they take more space and are not as high performance per ton of installed mass.

Solid TMDs usually consist of multiple steel plates that are transported to the TMD location and assembled in place. The mass can be suspended by cables, much like a simple pendulum, or supported by other low friction means. Other configura-

tions in common use include a dual-stage pendulum, which requires only about half the vertical clearance, and an arrangement of opposing pendulums. In the latter case, one mass held aloft by struts is linked to a second mass supported pendulum-style. This configuration can be used to create a long period set up in the relatively low headspace.

After the building is structurally complete, the TMD must undergo a tuning and commissioning phase. With the TMD locked out, the final as-built frequency of the building must be measured. The TMD is then tuned to best interact with that frequency and release it to do its work of steadying the tower, keeping even its highest occupants feeling as stable and sure-footed as if they were on solid ground.

## TMDs at Work

Selecting a specific type of TMD for a given building is accomplished through an implementation assessment. Primary considerations include the force required and space constraints, although other factors also come into play.

### 432 Park Avenue

This slender, taller-than-all-neighbors residential tower in the heart of New York City offered an extreme challenge in managing wind effects. Despite extensive attempts to reduce wind effects through reshaping, which led to including wind floors at several levels of the structure, the need for a supplemental damping system was a foregone conclusion. The building's long period, together with the required large movement of the damper mass, eliminated sloshing damper technology from consideration. To meet the space constraints, two 660-ton opposed-pendulum TMDs, one on each side of the building core, were ultimately used.

### Shanghai Tower

This tower was one of those rare cases with accelerations below the ISO standards to begin with, but the owner wanted them to be even lower – and was prepared to spend significantly more to achieve that. The goal was to give the impression that the structure simply does not move.

That led to the installation of a 1,100-ton TMD, which the owner also wanted to display as an architectural feature visible within the observation levels. Also, a unique form of damping was added to the system. Typically, TMDs have sizeable viscous damping devices (VDDs), similar to shock absorbers, which are used to drain energy from the TMD and also control its response in high winds. For the Shanghai Tower, a large array of rare earth magnets was attached to the pendulum, and a layer of copper plate was fixed to the floor. As the TMD travels back and forth, electrical eddy currents are passively formed that create a force that resists the motion of the pendulum mass relative to the tower. This system replaced the eight large, inclined VDDs that otherwise would have been used, making the installation much more aesthetically pleasing. This installation is the world's largest eddy current TMD.

## Conclusion

Supplemental damping technology is something that should be in every tall building designer's toolbox. Especially when used in conjunction with shaping techniques that reduce wind effects, TMDs can make living and working in high-rise buildings every bit as comfortable as more traditional, shorter buildings. And that allows people to relax and enjoy the spectacular view.