Innovative Solutions for Acoustic Challenges in Tall Slender Skyscrapers

Bonnie Schnitta and Sean Harkin

Introduction

During hurricanes, news stations broadcast astonishing live scenes, with a meteorologist showing the dramatic and often devastating effects of the wind. As the storm approaches, images of trees swaying due to these conditions are shown to illustrate the force of that wind speed. If you have ever sheltered from a windstorm in your home, you are likely to be familiar with the sounds the structure begins to create as it is moved by the force of the wind. Fortunately, for those in tall skyscrapers, these structures are designed to move with not only the force of the wind but also with the force of earthquakes. However, although these building designs keep their occupants safe, if the interior partitions, such as walls, floors, and ceilings, are not designed to be adaptable to the motion of the skyscraper, then the language of building sounds at higher floors associated with weather conditions, particularly on windy days, can be unsettling.

Today, skyscrapers not only are taller than their twentieth-century predecessors, but advances in structural engineering have made it possible for architects to achieve soaring heights with a remarkably small base area on the ground. Most people are familiar with the Empire State Building in New York, New York, which is 1,250 feet tall. Comparably, buildings of this new class of tall skyscrapers are as tall as 1,776 feet, as is the case of the new One World Trade Tower (NY). The Empire State Building has a height-to-base ratio of 3:1. The typical height-to-base ratio of these tall slender buildings is 10:1, although buildings built in the last decade have included such ratios as 13:1 and greater for height-to-width ratio. There were buildings completed in 2022 that have a ratio of 24:1 (Dreith, 2022), challenging what many would have ever conceived to be possible. An example of one such building can be found in **Figure 1**.

As the base-to-height ratio increases, the impact caused by the wind on the building's interior partitions and the potential for partition sounds also increases. This article explores the movement of these new tall skyscrapers and the potential disruptive noises that can occur during high winds unless careful design considerations are made and innovative solutions are engineered and implemented.

Tall Skyscraper Sounds

All buildings are designed to endure the impact of environmental phenomena. The motion of a tall building in high-wind conditions produces movement where the top of the structure moves more than its base. This simple law of physics then tells us that if the top of a building is moving more than its base, then the ceiling of a room will move more than the floor. This movement in tall

Figure 1. *Photograph of a tall slender skyscraper in New York City. Courtesy of Victor Salcedo of Gerb USA.*

https://doi.org/10.1121/AT.2023.19.2.53

skyscrapers can create a vibratory response within the partitions of a building that then become airborne sounds, much like the vibrating strings of a guitar creating sound. The science to solve this problem is fascinating and is presented in this article.

An Overview of the Solution

Ultimately, the goal is to determine a solution to create a quiet environment within a building. Once the potential noises are understood, the next step would be to analyze the movement of the building and how that movement will impact an individual floor. Ideally, each floor of a building should be analyzed because each is different in how it will respond to building movement. If untreated, this wind impact causes exterior motion and interior movement of the partitions, which, in turn, generates audible sounds of what we call "snap, creak, and pop" in standard construction. The three main steps taken to mitigate the potential sounds are to (1) determine the acceptable noise level for the client, who could be the architect, building owner, or individual residence owner; (2) measure the baseline motion and sounds of the building; and (3) engineer and finalize the solution set to bring the noise levels down to acceptable levels.

Although it is well-documented and researched that the senses are a key factor in how one feels in a room from sounds and vibrations in general (Harris, 1998; Tamura et al., 2006; Keith, 2008; Kwok et al., 2009; ANSI/ASA, 2012; Waddington et al., 2014; Kowalska-Koczwara and Stypula, 2020), the reverse is also true. That is, if someone categorizes an auditory or vibratory experience as unpleasant, then the space with those auditory or vibratory sounds will also be considered unpleasant. This was expanded on in Heshmati's PhD dissertation (2022). A summary of the experiments performed and his thesis is the question: "What vibrations outweigh the amazing and breathtaking view of a city skyline and make the residence feel unpleasant?" With this research in mind, we ask and answer in this article "What acoustic treatment is required and confirmed to work in the construction of a room, apartment, or home to make the space feel as wonderful as the majestic city views?"

The acoustic treatment solution set used to bring a residence in a tall skyscraper that is subject to high winds to a state of quietude requires thorough acoustic testing and analysis. This testing and analysis generate construction specifications for consideration during the design phase of the building. Actual testing to date shows that wind tunnel tests have the potential to be a good estimate, but there is nothing that leads to a more successful solution set as the actual site vibration and airborne readings. Also, it is critical to remember that each floor often has a different movement and therefore a potentially different solution set to the building noise.

Some of the basic solution sets to address building movements provide important guidelines and are presented in this article. The procedure of measuring sound and vibration in tall slender buildings during high-wind conditions is also included because it is critical to engineering a solution with optimum efficacy. After a building is constructed, a very critical point is that airborne acoustic readings alone typically do not provide sufficient data that will lead to the correct solution set. Vibration readings must also be taken. Case studies are provided in this article to provide some examples of how novel techniques and solution sets have successfully been installed in even the most challenging environments.

Gaspar (2017) of the Brewer Smith Brewer Group, Abu Dhabi, United Arab Emirates, identified that, in strong winds, building movement can be nearly three feet on each side during strong winds. Gasper went on to state that despite this building movement, the building is structurally fine.

To address wind-induced movement of the structure, a tuned mass damper (TMD), or "harmonic absorber" is

Figure 2. *Photograph of a tuned mass damper installed in a tall slender skyscraper. Courtesy of Victor Salcedo of Gerb USA.*

commonly included in the building design. Frahm (1911) received a United States patent for a Dynamic Vibration Absorber, which today is known as a TMD. The TMD helps reduce the perception of the movement, although it does not eliminate the movement entirely. An excellent overview of how a TMD works in skyscrapers is provided by Gasper (2017). The full video is found on the Practical Engineering YouTube channel (Hillhouse, 2016). An example of a TMD installed in a skyscraper can be seen in **Figure 2**.

The engineering to specify the TMD that is used to create this counterweight is performed by a structural engineer. It is a beautiful sight to see a multi-ton object move in response to environmental conditions. With that TMD dance comes sounds from the TMD movements. Although minor sounds, readings of these sounds must be taken by the acoustic engineer to ensure that sounds from the TMD movement do not travel through the partitions where the TMD is located or through other possible conduits, such as HVAC ducts. This could result in acoustic issues in any space connected through shared ductwork.

Next Step: Treating Interior Sound Sources in a Residence of a Tall Skyscraper

Acoustic and Vibration Readings for Design-Phase Acoustic Engineering

After the TMD has done its magic, there remains the critical step in the solution set: treating the remaining sounds and vibrations that result from building movement. These remaining sounds must be addressed by acoustically treating the interior partitions with an innovative solution set because standard construction typically fails to meet the demand of the structure movement. Additionally, the movement of the building systems, such as the pipes or the ducts for the heating or cooling, and those movements against rigid clamps or surfaces, such as the drywall, also contributes to the movement sounds and must be addressed.

There are examples that easily demonstrate how rigidity where movement is needed create acoustic problems and give a hint to the solution set. The first example of how the rigid wall contributes to the noise source is to think of children making a telephone using two cups and a string. When a cup is placed to their ear, the voice of their friend on the other end can be heard if the string is taut. If there is slack to the string, the only sound heard is that of frustration because the "phone" did not work. This illustrates that the solution for this rigid wall noise is "loosening" these taut lines or making the partitions resilient. This same analogy will help for understanding later sections.

The other important fact to remember in the solution set is that sound travels much further than its point of origin when given the right set of circumstances. This is easily explained by how the earth's motion from an earthquake in one part of the world will register on seismic graphs in the United States. A fascinating article with further detail on this phenomenon is "The Unheard Symphony of the Planet" (Morley, 2023). If a vibration can travel from Los Angeles, California, to New York, a vibration can also easily travel along the walls of a building. Therefore, the solution set needs to "cut the string of the telephone cup" wherever possible.

Indeed, although it may seem like the building sounds are from the movement of the building and nothing can be done, a successful solution set comes from addressing standard rigid construction. The ground movement and the typical and maximum winds that influence the building movement contribute to engineering the solution set.

It is critical to understand the amount of sound created within the building during windy conditions as well as the natural frequency response of the partitions creating noise while impacted by building movement. This can be accomplished by monitoring both airborne noise levels with a spectrum analyzer and simultaneously vibration levels with an accelerometer attached to a partition within the room.

Depending on the building, wind speeds that induce noise can be as low as 10-15 mph sustained winds at ground level to create meaningful building noise the interior partitions are not acoustically treated. Moreover, it is imperative to know that this can vary from floor to floor. That is, even if readings are used to engineer a successful innovative installation on one floor, those readings and that solution set may not work as well for another floor. Fortunately, once the solution set has been engineered for one floor, it can be used in any future renovation at that specific floor. Also, if there are changes to the buildings around the new tall skyscraper, they typically create a buffer and may reduce the wind effects. Furthermore, there is enough of a margin in the design for each floor that if one nearby building comes down, it will not cause a problem.

Acoustic Readings of Building Noise with Typical Construction

Acoustic readings were taken in a residence that was built using conventional construction methods of rigid walls, preventing them from moving with the building structure so that a solution could be determined. Results of the airborne acoustic readings showed that wind events generated sound levels from the partitions that were significantly above ambient sound levels. Ambient and building movement noise data are provided in **Figure 3.**

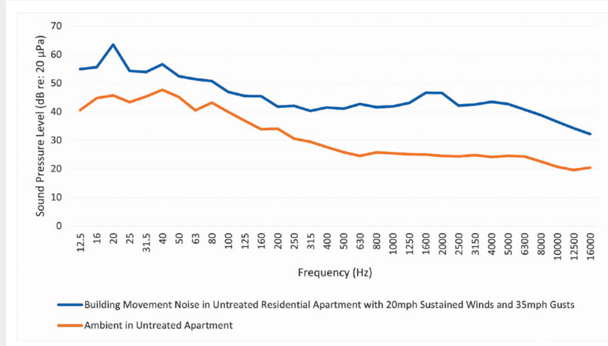


Figure 3. *Acoustic data collected within an untreated apartment showing background sound levels, and sound levels due to building movement.*

The data collected showed that ambient-sound levels were exceeded by as much as 20 dB in select one-third octave bands around 2,000 Hz. To put this into perspective, speech frequencies typically range from 125 to 2,000 Hz.

Engineering a Quiet Space on a Floor or Room of a Tall Building

With data collected for airborne and structure-borne vibrations, solution sets can be engineered. Just as tall needle buildings are novel in some aspects of their design, the construction that results in a quiet and comfortable space for typical weather as well as in high-wind conditions must include some novel acoustic engineering and construction. This is true for residences as well as for office spaces. As these are explained, remember the analogy of the two cups with the string in-between. The string needs to be cut or loosened to minimize the movement of the building from transferring into the partition. Consequently, it is now clear that successful installations have all included the following:

- Resilient connections (remember the two telephone cups with the string in-between)
- Eliminating metal-on-metal connections and structure selection
- Expansion joints; and
- Increasing the transmission loss of partitions to contain any residual noise.

These additions may initially appear to be significant additions to the construction strategy. However, they are not that different from the requirements for an acoustically correct home or workspace. The difference in construction requirements is only a few novel acoustic materials and installation requirements with diligent construction administration.

As noted in the **Introduction**, an acoustic consultant starts the architectural design and associated construction process first with an interview or survey of the client's noise sensitivities (Schnitta and Carter, 2017) and vision of the acoustic outcome. After the engineering is performed, it is followed by a discussion of the recommended acoustic treatment and associated costs. Whether the client is the architect, the owner of the building, or the individual residence owner, decisions are made based on the interview and survey. In the case of the tall skyscraper, some of the requirements are not optional for an ideal living or working environment (Cerrato and Goodes, 2011). It has been stated by professionals in the construction field that even when evaluating simple improvements to the acoustics of a project that sound treatment can have a minimal impact on the budget at the early design stages. As construction begins, the cost to make those same improvements can be significant and is often done with compromises due to other design constraints. This is a fact that permeates into every aspect of construction but especially for acoustics.

Resilient Connections

In concrete buildings, the walls, ceilings, pipes, ductwork, and any building materials within the apartment are typically attached to the concrete at the top and bottom, typically referred to as the top slab and bottom slab. Resilient connections of building elements that are connected to the concrete at the ceiling and floor of a residence in the building are essential. Including resilient connections not only allows the partitions and mechanical equipment to have a small amount of travel movement but also allows for the movement in the resilient component to be spread out evenly over the partition rather than showing an immediate deformation or shift that is characteristic of a rigid connection. Remember the two cups with the string in between. We do not want a taut or rigid connection.

Further emphasis on the importance of engineering the specifications for these resilient connections and allowing movement is that there is some torque in the building movement. Although it is not the intent of this article to explain these movements, it should be noted the importance of knowing that (1) these movements occur and must be part of engineering the solution set and (2) they put emphasis on the importance of airborne and vibration readings. The resilient connection of floors and ceilings is necessary to inhibit tall skyscraper sounds on a windy day. These resilient connections also help reduce sound transmission between apartments of people talking/listening to TV as well as people walking around. Resilient connections of ductwork and piping are just as essential. The solution set includes acoustic resilient underlayments under the floors to be installed as well as using a decoupler or resilient clips within the ceiling construction.

Because the walls connect the top and bottom concrete slabs, which move in different amounts, thoughtful selection of the attachment methods is critical. One solution is to use resilient bushings with elastomeric materials. An example of one of the bushing assemblies creating a connection between the wall and bottom slab is shown in **Figure 4**. This type of assembly is critical to allow the structure to move ever so slightly with the building without resistance.

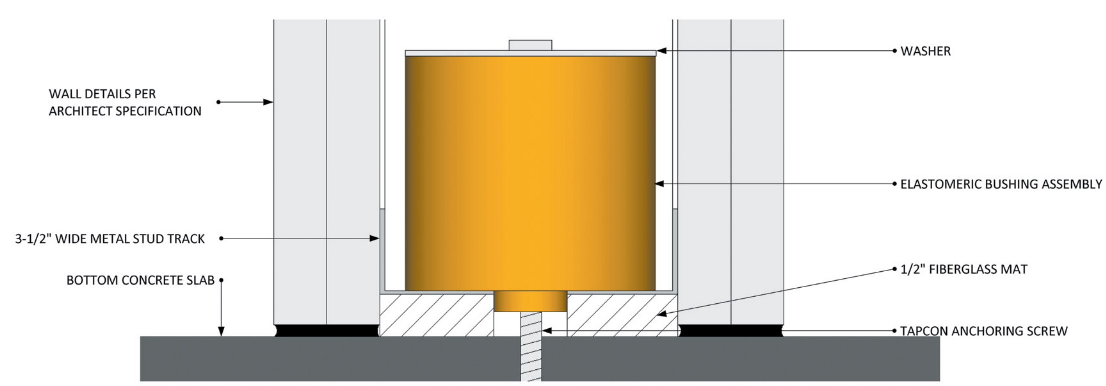
Although the bushing assembly shown in **Figure 4** functions similarly to readily available rubber products, it is a custom-engineered component that must be tailored to the application. Although the same or similar bushing designs have been able to be used in multiple floors of the same building or in a couple of different buildings, it is unknown if they can be used across all slender building applications. It probably would not provide the optimum efficacy. This is why acoustic testing for each application is critical so that the design can be reevaluated to determine if the same dimensions and stiffness of elastomeric materials are acceptable or if a different design is necessary.

To isolate ductwork and piping, rubber or elastomeric hangers are used when connecting ductwork and piping to a concrete slab. For example, resilient clips or equivalents could be used instead. A typical application of a resiliently hung pipe is shown in **Figure 5**.

Elimination of Metal-on-Metal Connections and Structure Selection

During building movement, the framing for the partitions and their connections will shift against one another, causing any metal-on-metal connections to create noises. This type of movement is necessary within the dynamics of the building but needs to be appropriately treated so that additional noise is not created from metal rubbing against metal. Thus, any metal-on-metal connections should be eliminated. This can be accomplished through several different means, including introducing layers of

Figure 4. *Example of an elastomeric bushing assembly for wall connection.*



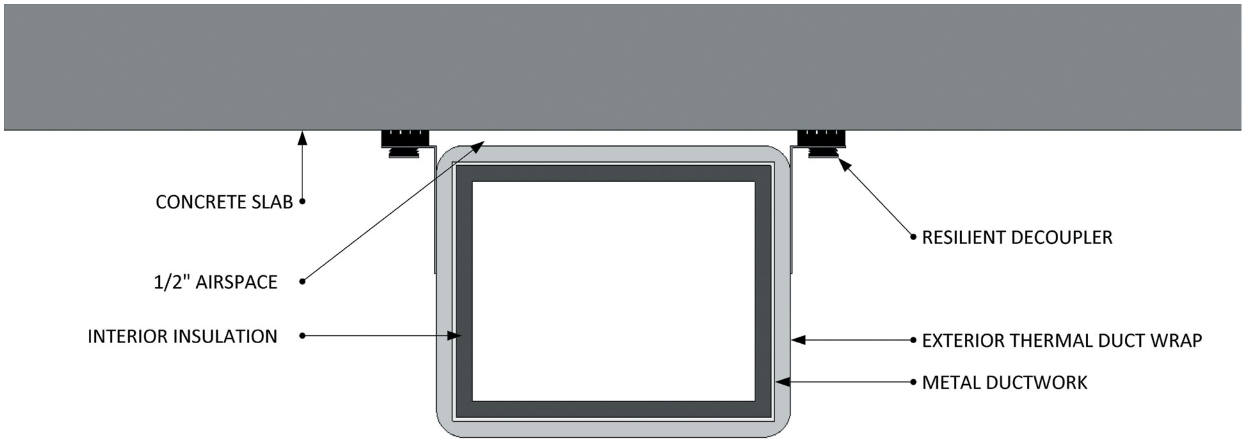


Figure 5. *Example of a resilient ductwork connection to a concrete slab.*

materials between the metal. Some companies have also developed products to break up these connections.

In addition to the connections of the framing to each other as well as the structure, it is important that the framing of the wall be thoughtfully selected so that it can remain strong even under the motion of the building while also providing resiliency and freedom of motion where possible. In addition to the elastomeric bushings described in ***Resilient Connections***, the metal studs of the wall normally sit in a rigid track. Using a track in which the studs reside allows for vertical movement between the stud and the track, or a slip track, at the top track of the structure, allowing for some movement between the wall and top concrete because, as mentioned in **Tall Skyscraper Sounds**, the ceiling of an apartment moves more than the floor. Although the actual dynamics of the situation are more complicated, the motion can be likened to an object under a force that creates torque. The differential of movement between the top and bottom slab of each floor provides the torque, whereas strengthening the wall assembly helps to increase the wall's "moment of inertia." Since the original applications of this work, some manufacturers have come up with additional solutions, allowing for drift in multiple axes, not just one.

Expansion Joints

Along the same lines as using framing assemblies to allow for drift, expansion joints are also a key component of successful solutions. Using an expansion joint, particularly at the ceiling, allows for some movement of the wall relative to the ceiling, which helps to reduce the risk of cracking finishes during movement as well as deformation at these connections. The installed expansion joints can be covered with molding details and a small gap.

Transmission Loss Increase on Each Side of a Wall

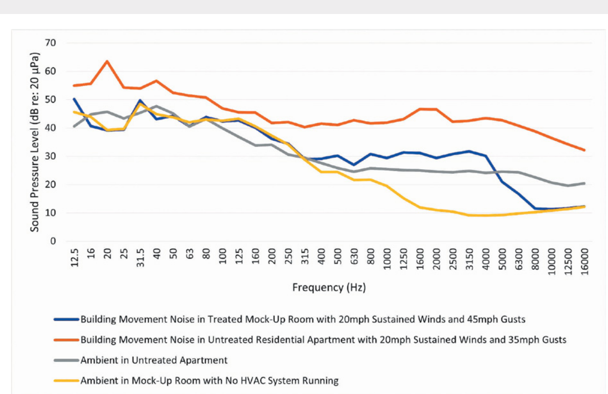
During design, it was assumed that some noise on the interior of the wall could still be possible. Therefore, the transmission loss on each side of the wall was increased. Because this had to be done in as little space as possible, mass-loaded vinyl was included in wall configurations to be able to provide an airtight acoustic barrier into the wall cavity while also providing a break between the metal studs and gypsum board that introduced a small amount of resiliency.

Mock-Up Testing with Solutions Installed

In most instances, mock-up testing is critical to ensure that the solution set will meet the satisfaction of all project stakeholders, even if the building is being designed from the start of construction instead of a renovation. During one project that was associated with the data collected in an untreated unit presented in ***Acoustic Readings of Building Noise with Typical Construction***, the outlined solutions provided there were implemented to measure the residual sound levels within the mock-up room. A significant amount of flanking or acoustic leakage was observed because of unsealed ductwork penetrations and no acoustic gaskets on the temporary doors installed into the room. These paths were identified and tested through visual inspection as well as utilizing a recently patented device, the dB Focus Tube (Schnitta and Israel, 2018), to test and identify the severity of such acoustic leakage paths. This led to conditions that were corroborated by the project team where noise was occasionally slightly audible within the mock-up room but was clearly emanating from a wall outside the room and sound was entering through the doorways. Although it was not a perfect environment for full evaluation, it was the best that could be achieved at a minimal cost and built expeditiously.

Over the course of three months, noise and vibration measurements were collected within the mock-up room. The sound level meter was configured to capture audio recordings for sound levels higher than the background sound level of 38 dB(A). Any recordings reviewed during the monitoring were inaudible until one sample recorded in the third month of monitoring. This sound above 38 dB(A) was attributed to something within the room instead of to noise outside the room. The results of this sample can be found in **Figure 6,** which shows the data collected in the untreated portion of the building presented in ***Acoustic Readings of Building Noise with Typical Construction*** as well as inside the mock-up room. It should also be noted that since the heating, ventilation, and air conditioning (HVAC) equipment was not operational in the mock-up room, ambient-sound levels were extremely low and lower than what would occur after project completion. Therefore, the ambient-sound level with an operational HVAC system has also been provided as a point of reference.

Figure 6. *Measured sound levels in the mock-up room and untreated apartment.*



The results of the mock-up testing showed that, in similar wind conditions, a 10-15 dB reduction was observed. Compared with the ambient-sound levels measured within the untreated apartment with an operational HVAC system, sound levels were only 5-7 dB above ambient levels, which is a significant reduction.

Despite the known acoustic leakage into the room as described at the beginning of this section, the lack of any absorptive finishes within the mock-up room and the low ambient sound, there was no or minimal audible sound during typical wind conditions. The apartment was built using the mitigation measures implemented in the mock-up room. The emphasis in the construction ensured that all acoustic leakage points were resolved in each room being constructed.

Sound will travel through any weak or incomplete junctions of a partition. For example, the sound through a wall can be 10 dB greater when there is something as seemingly minor as a 1-inch square gap, such as a 1/8-inch space between the bottom of a wall where the wall meets the floor (Gover and Bradley, 2006), or a lack of complete caulking at partition perimeters. For this reason, acoustic leakage paths such as doors, outlets, plumbing penetrations, shared chases, conduits, ceiling/wall, or floor/wall points of intersection in construction should be addressed so the wall or other partitions perform up to their engineered ability to stop sound.

More importantly, the partitions for tall skyscrapers contain some residual noise from building movement. Just like perimeter seals keep the cold from coming into a warm house, acoustic leakage treatment of partitions will keep the residual sounds in a wall, ceiling, or floor from entering a room. The locating and treating of acoustic leakage is a significant step in a successful solution set. This can be performed with products such as an ultrasound camera or dB Focus Tube.

In addition to resolving acoustic leakage, addressing reverberation was a key component to the project moving forward. Excessive reverberation reduces the intelligibility of speech, corrupts the music within a room, or can amplify sounds in a room. This becomes problematic when a slight sound (1-2 dB above ambient) from building movement becomes amplified to 4-5 dB or more due to a high reverberation time within the room and results in a disturbance. Acoustically absorbing or diffusive surfaces were integrated where possible because they should be in any home, office, or hospital.

In addition, HVAC systems were specifically designed so that they would provide a small amount of sound masking to ensure that ambient sound levels were not too low so that a larger differential between ambient and residual noise did not present itself. A true sound-masking system was proposed to be integrated into the speaker system of the residence. Due to the success of the innovative solution set, this was never installed.

Conclusion

Although noises in buildings, and especially in skyscrapers, are normal due to the motion of the buildings, they can create disturbance to occupants, whether in a residence or an office space. With careful structural and acoustic design as well as treatments such as elastomeric bushings, framing selection, resilient partition connections, elimination of metal-on-metal connections, expansion joints, and mass-loaded vinyl, builders can help to mitigate these noises. Although the noises during high-wind conditions may not be able to be eliminated in all circumstances, thoughtful selection of target background noise levels, mock-up testing, reverberation analysis, and construction administration help bring the solution set to a successful outcome. All of this helps to create a reduction in noise to ensure the quietude of these amazing apartments will be as pleasurable and exciting as the views afforded by the advances in structural technology.

References

ANSI/ASA (American National Standards Institute/Acoustical Society of America). (2012). *Guide to the Evaluation of Human Exposure to Vibrations in Buildings*. ANSI/ASA S2.71-1983, ASA, Melville, NY.

Cerrato, G., and Goodes, P. (2011). Practical approaches to solving noise and vibration problems. *Sound and Vibration,* 45(4), 18-22. Available at http://www.sandv.com/downloads/1104cerr.pdf.

Dreith, B. (2022). Seven super-skinny skyscrapers changing New York City's skyline. *Dezeen*. April 13, 2022. Available at http://bit.ly/40q21IK.

Frahm, H. (1911). *Device for Damping Vibrations of Bodies.* US Patent 989958, April 1911.

Gaspar, M. (2017). *The Mechanism and Applications of a Tuned Mass Damper* (*TMD*). Technical Report, Brewer Smith Brewer Group, Abu Dhabi, UAE. Available at http://bit.ly/3zaFBPX.

Gover, B., and Bradley, J. (2006). *Detection of Localized Sound Leaks or "Hot Spots" and Their Effects on Architectural Speech Privacy.* Institute for Research in Construction, National Research Council of Canada, Ottawa, Quebec, Canada. https://doi.org/10.4224/20377775.

Harris, C. (1998). *Handbook of Acoustical Measurements and Noise Control,* reprint of 3rd ed. American Institute of Physics, College Park, MD, pp. 26.1-26.17.

Heshmati, K. (2022). *Acceptability of Wind-Induced Vibrations in Tall Buildings' Office Environments.* PhD Dissertation, University of Bath, Bath, UK. Available at https://bit.ly/3JVCpwe.

Hillhouse, G. (2016). What is a tuned mass damper? *Practical Engineering,* Available at bit.ly/3z8P3mR.

Keith, R. (2008). *Noise Control for Buildings and Manufacturing Plants.* Hoover and Keith, Inc.. Houston, TX, pp. 3-1-3-10.

Kowalska-Koczwara, A., and Stypula, K. (2020). A comparative analysis of two methods for determining the influence of vibrations on people in buildings. *Sciendo* 114 (1), 53-64. https://doi.org/10.4467/2353737XCT.17.004.6101.

Kwok, K. C. S., Hitchcock, P. A., and Burton, M. D. (2009). Perception of vibration and occupant comfort in wind-excited tall buildings. *Journal of Wind Engineering and Industrial Aerodynamics* 97, 368-380.

Morley, M. (2023). The unheard symphony of the planet. The *New York Times* January 3, 2023. Available at http://bit.ly/3K03izw.

Schnitta, B., and Carter, S. (2017). Frequency tones and elevated decibel level that are indicators of ill health or a state of health with associated pain. *The Journal of the Acoustical Society of America* 141(6), 95. Available at https://bit.ly/40lZcbG.

Schnitta, B., and Israel, M. (2018). *Sound Focusing Mechanism and Method of Estimating Acoustical Leakage of an Object and Method of Estimating Transmission Loss of an Object.* Patent 10,013968, July 2018. Available at https://patents.google.com/patent/US7908924/en.

Tamura, Y., Kawana, S., Nakamura, O., Kanda, J., and Nakatà, S. (2006). Evaluation perception of wind-induced vibration in buildings. *Structures and Buildings* 159, 1-11.

Waddington, D. C., Woodcock, J., Peris, E., Condie, J., Sica, G., Moorhouse, A. T., and Steele, A. (2014). Human response to vibration in residential environments. *The Journal of the Acoustical Society of America* 135, 182-193.

Contact Information

Bonnie Schnitta
bonnie@soundsense.com
SoundSense, LLC
39 Industrial Road, Unit 6
PO Box 1360
Wainscott, New York 11975, USA

Sean Harkin
sean@soundsense.com
SoundSense, LLC
39 Industrial Road, Unit 6
PO Box 1360
Wainscott, New York 11975, USA

For author bios, please go to acousticstoday.org/bios-19-2-6