Challenging Vibration in Engineered Structures

by Brian Breukelman, P. Eng.

Cutting-edge structures require innovative solutions to manage structural vibrations for safety and serviceability.

Structural engineering is seeing a fascinating revival. Super-tall buildings, extremely long bridges, and ultra-slender monuments are being designed and constructed, due in part to recent advances in computing and materials. However, vibration due to human activity and environmental factors is increasingly the dominant design issue facing these structures. A few notable projects have had severe vibration concerns. Understanding these and making appropriate changes has accelerated the knowledge base and the possibility of pushing the envelope further.

Issue and Causes

From an historical perspective, fluid flow was the first mechanism that caused vibration problems for civil structures. It could be said that earthquakes contributed to vibration problems, but this has been a more recent phenomenon from a vibration perspective. There are many historical references to the phenomenon called *vortex shedding*. In the 15th century, Leonardo Da Vinci sketched the vortices behind a pile in a stream. In wind, this phenomenon combined with other aerodynamic processes to cause a variety of vibration problems.

With increasing height of buildings and slenderness of bridges, fluid flow in the form of wind has become a major contributor to structural vibration problems. The desire for architectural details like pinnacles, spires and signs also has added areas where wind-induced vibrations can exist.

Earthquakes have caused destruction ever since man began constructing permanent shelter. For modern buildings, bridges and dams, amplification of the ground motion in upper levels is a threat, but the study of the dynamics of civil structures under seismic excitation has become relatively mature, especially with alternative design approaches, such as base isolation and energy dissipation.

Pedestrians cause vibration problems, especially for bridges and long-span floors. The old tenet of requiring troops to break step before crossing a bridge comes to mind; this adage supposedly came from a number of actual experiences in Europe in the first part of the 19th century. Another source of human-caused vibration comes from coordinated fitness activities such as aerobics or dancing in multi-use structures, a relatively new phenomenon.

Mechanical systems are connected to and supported by civil structures, like HVAC units, generators and other motors. Any system that involves rotating components has the possibility of causing vibrations in a structure. Historically, most mechanical installations performed acceptably, but with today's lightweight and efficient structural design and construction, problems continue to crop up.

Advanced materials, like "exotic" carbon-fibre composites and high-strength steel and concrete, have been a real boon to the construction industry. Structures that in the past could not have been built can now be constructed cost-effectively. In most instances this has led to more slender and lighter structures. From a seismic-vibration perspective, this has been helpful, since the tendency to reduce mass reduces possible seismic forces. However, for other vibration sources, especially wind, vibration issues are growing in number and complexity.

For some advanced materials, the manufacturing process requires extremely low levels of vibration. The quality and possibility of micro-electronic components and future nanotechnology depend on near-impossible requirements for manufacturing precision. Even low levels of vibration in these facilities, from someone walking down a corridor, could seriously affect the outcome of the manufacturing processes.

In addition to advanced materials, engineers have better design tools. A variety of FEA (Finite Element Analysis) packages allow engineers to accurately determine the load distribution in a

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structure and optimize the overall demand on the structural system. These developments also have lead to a revolution in the architectural design practice. As materials and computer technology advance, the envelope of aesthetic possibilities also are growing. Architects are leading the way with increasingly complex and ground-breaking designs. The Guggenheim Bilbao, the Quadracci Pavilion at the Milwaukee Museum of Art or the Glasgow Science Centre "Wing" are some examples.

Many design states can be affected by vibration, including safety, fatigue, deflection and comfort. Historically the primary consideration for the structural engineer and architect was the structural safety and deflection. But recently, vibration is challenging almost every design state, including comfort and fatigue. This trend has forced the structural engineering community to adapt its historical approach to include a significant focus on vibration in general and on methods of reducing the impact that these vibrations have.

Traditional engineering approaches to reduce vibration remain cost effective. This includes making stiffness or mass changes, or modifying the shape of a bridge or building section. Some new solutions are still price competitive. A source of this newer technology is mechanical and automobile engineering, where much has been developed to solve vibration problems. Many approaches are making their way into the sphere of structural engineering.

The Dublin Spire.

Spire Section showing tuned mass dampers.

Dublin Spire

Design issues: safety and aerodynamic stability

A fascinating new monument was commissioned in July 2003 on the site of the former Nelson Pillar in Dublin, Ireland. It is likely the most slender structure to have been constructed to date. Its height soars to 120 m from a 3 m-diameter base, and is the world's tallest sculpture. The outcome of a competition for the project, called the O'Connell Street Monument, is the spire designed by British architectural firm, Ian Ritchie. The structural engineer was Ove Arup and Partners of London, UK.

Of particular concern for the stainless steel structure was aerodynamic stability. For some structures with low levels of damping, and especially those that are very slender, the stability during certain wind events can become a dominant design issue. For this structure, it was expected that the inherent damping levels (rate of energy dissipation) could be low, even down to 0.2%, which during a wind event, would cause concern for the spire's safety. As a reference, most steel high-rise structures are assumed to have about 1.0% inherent damping.

Traditional engineering approaches could have included reducing the height, increasing the mass, or changing the shape. But the project was intended to be a sculpture, and architecture prevented most changes. Only increasing the mass would have had a beneficial effect, but it would have come with significant increases in fabrication and supply costs, and it would have impacted the foundation design.

The solution to this potential vibration problem was to install two Tuned Mass Dampers (TMD), which dissipate dynamic energy from the two modes of vibration that were the cause of concern to the structural engineer. The two TMD masses, weighing 800 kg (1760 lb) and 1250 kg (2750 lb), were suspended as natural pendulums at approximately two-thirds the height of the spire. Combined with appropriately specified viscous dampers, these TMDs increase the equivalent damping to well above 1%, ensuring the aerodynamic stability of the spire in all wind conditions.

The TMDs were constructed entirely of stainless steel components to match the materials of the spire itself. This was done to ensure that corrosion would not be a problem through the design life of the spire. A specially designed monitoring system is being installed to ensure that the TMDs are continuously operational.

Bloomberg Building

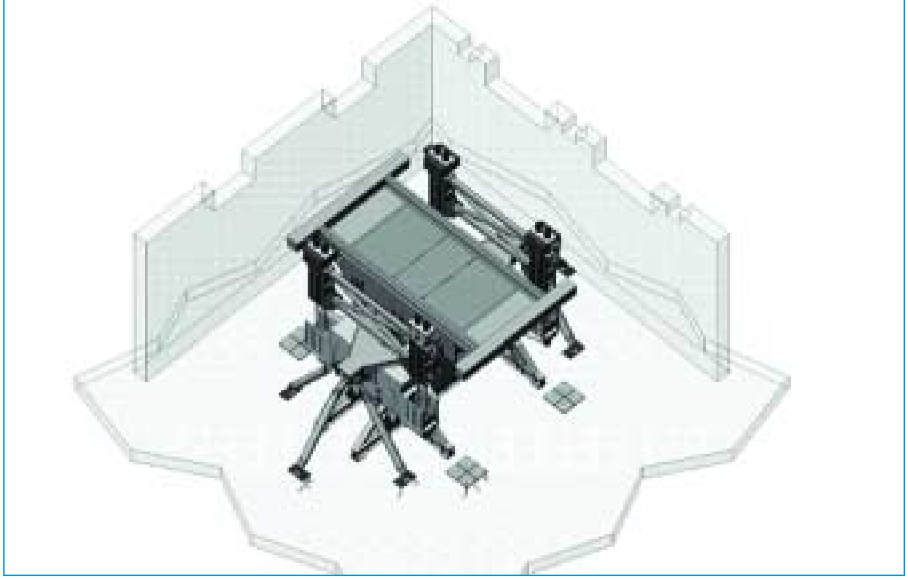
Design Issue: occupant comfort

Designing a mixed-use building is a challenge in most environments—designing a high-rise in New York City can be nightmarish. The Bloomberg building, designed by architect Cesar Pelli and under construction since 2001, is a case in point. The building's lower floors, for retail and office occupancy, are constructed of steel, and the upper portion, a high-rise luxury condominium development, is constructed of reinforced concrete.

Wind engineering studies by Rowan Williams Davies & Irwin Inc. demonstrated to structural engineers Thornton Tomasetti that lateral accelerations on the building's top levels would be higher than desirable for luxury condominiums. Structural iterations were performed to optimize the structure and reduce the predicted motion. The developer also considered a shorter building: A very effective method of reducing vibration, but one that could critically diminish the viability of the development project, since the most valuable real estate is the top portion of the tower.

The structural optimization studies performed indicated that due to the multiple structure types and materials, the motion at the top of the building would be difficult to control from a purely structural approach. Since the development

Bloomberg Building, New York City.



Bird's eye view of Bloomberg Building TMD.

program required a less-than-ideal structural system, designers chose to implement a damping system solution to reduce the vibration.

Two different types of damping systems were considered: a TMD and Tuned Liquid Column Damper (TLCD). A TLCD works similarly to a TMD except it dissipates energy internally in the liquid (water in this case) and the mass is a large "U"-shaped tank of water. Due to the lower density of water compared to steel, a TLCD takes up substantially more space. TMD was chosen, since the space required for TLCD installation in the Bloomberg building was beyond what was available. The TMD weighs 545 tonnes (600 tons) and installation was planned by Motioneering in early February 2004.

Las Vegas Footbridges

Design Issue: pedestrian comfort and deflection

While investigating expected accelerations of proposed pedestrian bridges in Las Vegas, it became clear that under certain occupant/event conditions, the bridges could have vibrations of a magnitude that would cause concern for the structural performance.

To date, three slender footbridges with clear spans ranging from 40 m (130') to 49 m (160') have been constructed in Las Vegas. The depth of the span was limited to 1.5 m (5'), which led to vertical frequencies in the 1.7Hz to 2.2Hz range. In this range, typical pedestrian vertical excitation is possible, and if the damping of the bridge is low, uncomfortable vibration levels are possible.

Also, if pedestrians could coordinate their activities, sufficiently large deflections of the bridges were possible. The structural engineers, Martin & Peltyn of Las Vegas, considered structural solutions, including making the bridges very heavy and increasing the stiffness. However, the spans were simply supported, making this approach inefficient and costly.

The solution for both pedestrian comfort and possible deflections was to add damping. By implementing a system of six TMDs, weighing approximately 8000 kg (9 tons) in total, the effective damping of the bridges was increased by more than an order of magnitude.

Layout of TMDs on pedestrian bridge in Las Vegas.

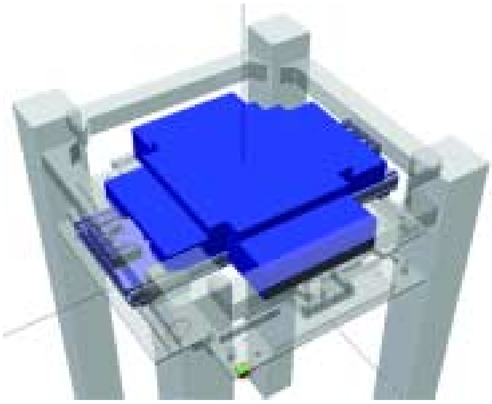
Taipei 101 Pinnacle

Design Issue: wind-induced fatigue

Late in 2003, the newest entrant in the "worlds tallest" building list became a reality. The 508 m-high Taipei 101 located in Taipei, Taiwan with a 60 m pinnacle, surpassed the Petronas Towers, which have held the distinction of world's tallest since their completion in 1998.

Located in an adverse construction environment, with significant seismic activity and constant typhoons in season, the Taipei 101 structure required a considerable engineering effort to ensure life safety and comfort. The pinnacle structure demanded the most innovative solution, due to the potential for fatigue damage.

The first approach was to keep the pinnacle structure as light as possible, in order to minimize demands due to seismic responses for both the pinnacle and



CAD rendering of TMD mass and pinnacle structure for Taipei 101.

the tower structure. With a light pinnacle, the wind-induced vibration and the resultant fatigue from many cycles of this vibration became the dominant design issue. The traditional approach of increasing the mass of the pinnacle would have caused serious implications for the overall tower design with respect to seismic loading. The owner and architect also considered changing the shape to reduce wind effects.

Due to the overall structural system for the building, several modes of vibration also included motion of the pinnacle. Three modes (six if counting the perpendicular direction) were found to be affected by vortex-induced vibration; however, only two were found to be significant relating to fatigue damage.

To reduce fatigue damage in the pinnacle, a system of two TMDs was designed and installed by Motioneering. The TMDs will be tuned to provide the most benefit to the structure, and they can obtain a significant amplitude reduction in modes 10 and 12. Each TMD weighs 4,500 kg (9,900 lb). They are located near the tip of the pinnacle. ★

This paper has been edited for space considerations. To learn more about vibration, read the complete text online at ***www.modernsteel.com*** *or in the 2004 NASCC Proceedings.*