Innovation and resourcefulness in the engineering of tall buildings are one of the cornerstone requirements of building resilient cities and communities. Successful performance of these structures during extreme natural events is living proof of the value of design that targets resilient performance, enhancing the confidence of the stakeholders and the public for the engineering and technologies used. Mexico City is a mega-city where performance-based design using cutting-edge technologies in the past two decades has been tested repeatedly by large earthquakes, floods, and winds. This city has evolved from the ancient Aztec capital to one of the most prominent modern metropoles of Latin America. The economic growth in recent years has resulted in an increase of the city's footprint by a factor of 100 to accommodate the millions of people that have moved into Mexico City from rural areas, generating an ever-increasing demand for taller buildings and deeper basements.

The design and construction challenges that the City of Mexico presents are multi-faceted due to its location in one of the most adverse geologic and tectonic environments in the world, as described in Part 1 of this article (STRUCTURE, December 2018). This article discusses specific challenges that continue to grow with the increasing demand, and design solutions that are also advancing with time. Key seismic features of several iconic high-rise buildings are presented, and their performance in recent major earthquakes are discussed by the designers and co-authors. The overall resilient behavior of these structures can be attributed to two fundamental factors: (i) enforcement of higher code design and construction standards following the devastating 1985 Michoacán M8.0 Earthquake, a major event exactly 32 years prior to the 2017 M7.8 Puebla-Morelos Earthquake, and (ii) advancements in the state of practice for tall buildings using performance-based engineering that go beyond the minimum code requirements, integrate geotechnical and structural performance objectives, and incorporate seismic protective technologies.

Higher Heights and Deeper Depths

Development of tall buildings over the past two decades has increased exponentially to accommodate the rapid social and economic growth of Mexico City. The complex architecture of the city is a mix of colonial architecture, modern high-rises, and its grand Paris-style boulevard, Paseo de la Reforma, where the national stock market resides (Figure 9). This wide downtown avenue that runs diagonally across the city serves as one of its “arteries” and is one of the first and oldest city avenues that have been home to tall buildings since the 1990s with the development of Torre Mayor, the tallest building at the time of its construction until recently. The opulent urban landscape reflects the city’s position as the financial center of Latin America and one of the largest economic powers worldwide.

In this continuously evolving city, tall buildings are towers that feature deep basements to accommodate parking spaces and mechanical, electrical, and plumbing demands. It is not uncommon for a modern tall building in Mexico City to have 9 to 10 underground levels which, in combination with the city’s unique geology and seismic hazard exposure, imposes its own challenges in design and construction. Specifically, as described in detail in Part 1 of this article, a large portion of Mexico City is built on a basin formerly occupied by the ancient Lake Texcoco. The subsurface conditions are largely comprised of extremely soft and compressible lacustrine clay deposits, with unusually high plasticity and natural water content, and low seismic shear waves velocity of propagation. Since the beginning of the 20th century, these saturated soft deposits have settled approximately 9 meters (30 feet) because of their consolidation due to continuous water pumping and exploitation of the aquifers underlying those soil strata, and loading from new construction. These factors caused the city to continue to sink with damaging differential deformations of many of the monuments and structures built in the former lake area, affecting the city’s architectural heritage.

In Mexico City, the preferred foundation system is a combination of perimeter slurry walls (known as “Milán” walls that are used during construction and later become permanent support elements) and deep
Seismic Resilience – Design Examples 20-Years Apart

Over the past two decades, multi-hazard resilience considerations have been integrated into the structural design of numerous tall buildings spread across the Mexico City area. Two signature project examples, Torre Mayor and Torre Cuarzo on Paseo de la Reforma, were designed and constructed within this period. Both projects incorporate seismic protective systems and were designed after the devastating 1985 Michoacán M,8.0 Earthquake that resulted in a toll of more than 39,000 deaths and nearly 10,000 building collapses. Since that event, combined with the historic high seismic activity in the region, there have been significant changes in design criteria and a shift in the philosophy of developers and design professionals in applying cutting-edge advancements in earthquake engineering, analytical tools, and protective technologies to safeguard lives and properties.

The first tower that went beyond conventional prescriptive building code objectives, by following a Performance-Based Design (PBD) approach, is the 55-story, 235-meter (774-foot) tall office tower Torre Mayor (Figure 11). From its completion in late 2002 until 2010, Torre Mayor was the tallest building in Latin America. Viscous damper technology, originally developed for military use, was used for the design of a patented diamond configuration (Post, 2003), rather than the typical X pattern that greatly improved the seismic performance of the tower. The lateral force-resisting system of Torre Mayor is equipped with 96 viscous dampers, effectively dissipating seismic energy and minimizing inelastic demands to structural components. Strategically located in an overlapping diamond-shaped array, four mega trusses with large-stroke energy dissipation devices enhanced the lateral-force-resisting system (Rahimian, 2007). The innovative diamond-shaped layout is more efficient, resulting in using less steel to achieve the performance objectives.

This seismic protective system proved its worth immediately after completion of the tower as the M,7.5 Tecóman, Colima earthquake shook the city in January 2003, merely a month after it was occupied. Not only did the building survive undamaged, but the occupants at the time of the event did not realize a tremor had occurred. The same was reported during later events, including the recent 2017 M,7.1 Puebla-Morelos earthquake. The creative engineering solution applied in Torre Mayor was far ahead of its time and pioneered the implementation of a PBD philosophy for tall buildings in Mexico City, while comprehensive PBD seismic guidelines for tall buildings in the U.S. were developed a half decade later (FEMA, 2006; TBI, 2010). To this date, Torre Mayor is a celebrated iconic tower that is a real-life example of seismic resilience and has enhanced the people’s confidence in engineering ingenuity. It is known as the building that people run into, rather than out of when an earthquake strikes (Popular Science, 2003).

The successful implementation of high-performance design elements in Torre Mayor was followed by advancements in seismic design guidelines that took into consideration the response characteristics of tall buildings. One of the latest towers, the Cuarzo Reforma, located prominently along Paseo de la Reforma, was completed in 2017 (Figure 12). This new development is comprised of two buildings connected with a common base: an iconic 40-story mixed-use tower and a 27-story hotel. The design combines experience with tall buildings in the area with PBD developments and the latest technology in seismic energy dissipation systems. Friction dampers were designed and installed along the building height. The lateral force-resisting system features...
Evolution of Local Code and PBD Criteria

The prescriptive local building code and construction requirements have historically evolved over the years, incorporating lessons learned from actual events such as the 1985 M8.0 Michoacán earthquake. The 2017 M7.1 Puebla-Morelos earthquake also influenced Mexico City officials to release the most recent edition of the local Building Code (Reglamento de Construcciones del Distrito Federal, OGDF, 2017) and its corresponding design and construction standards (Normas Técnicas Complementarias, OGDF, 2017). A comparison between characteristic records from the 1985 and 2017 events is shown in Figure 6 of Part I of this article for selected strong motion locations and site conditions. The updated design standards mark a significant technical development with respect to the previous 2004 edition. Specifically, the 2017 standards have incorporated explicit performance objectives for different seismic hazard levels, allowing for alternative structural systems that meet the intent of the standards and are approved by the building code enforcement officials in a similar approach to contemporary United States building codes.

The aspect of functionality and immediate occupancy is also addressed in the 2017 standards, with specific requirements for continued functionality and maintenance of occupancy under frequent events of low to moderate intensity that may occur more than once during the design life of the structure. For the Design Base Earthquake (DBE or DE), no major structural failures or loss of life should occur; however, significant damage or deformations may arise that could affect functionality and may require significant repairs. Foundation systems are generally expected to behave within the elastic range for the frequent events, essentially being designed for higher seismic loads than that of the superstructure, recognizing that structural systems can develop higher forces due to inherent system redundancy and material over-strength.

In applying an alternative Performance-Based Design approach based on international developments for tall buildings (TBI, ASCE41), a wider range of seismic hazard demands is incorporated, from high probability and low intensity to very low probability and high intensity, with associated performance targets. This PBD approach addresses the additional layer of a rare Maximum Considered Earthquake (MCE) for which the performance objective is within the life safety-to-collapse prevention range, depending on the structural occupancy or importance of the structure. Figure 13 depicts the local code seismic performance objectives as they relate to the PBD methodology with explicit and implicit underlain assumptions in both approaches.

Going beyond the above standards, special aspects related to the Mexico City environment should be considered, including: (i) levels of differential and total settlements and lateral deformations; (ii) Soil-Structure Interaction (SSI) – parameters and soil and foundation testing needed to derive and incorporate them into the structural model while addressing strain dependency; (iii) depth at which the input ground motions will be derived from (e.g., at the ground surface or lower) and applied to the structural model, (iv) drainage or corrosive soils issues that may affect the foundation materials,
such as the pile wall thickness; and (v) interaction with existing adjacent structures, underground structures, or utilities. To address these challenges, a synergy among involved disciplines is needed, as well as the implementation of state-of-the-art PBD methodologies, protective technologies, and analytical tools, all combined with global experience in the design of unique high-performance tall structures. Participation of the designers in the development of codes and guidelines both in Mexico and the United States benefits the advancement of seismic design practice. The Mexican high-rise structures presented in this article, along with over thirty more structures that the authors contributed to the design of, have proven seismically resilient in the past two decades. This is a direct result of compliance with improved local regulations coupled with advances in seismic engineering and ingenuity.

Conclusions

Unique geologic conditions and exposure to the high earthquake hazard of Mexico City require rigorous and holistic approaches to the seismic design of tall building structures and considerations that go beyond minimum code requirements. Close collaboration between structural and geotechnical disciplines during the very early design stages has become one of the main cornerstones of building design in Mexico City. The growing complexity of structural systems requires the utilization of state-of-the-art analysis and design techniques to allow better prediction and an overall understanding of building performance for seismic events of varying intensities. Local code, with explicitly stated performance objectives and allowance for alternative analysis and design procedures that meet the intent of the code, provides a framework for implementation of Performance-Based Design philosophy. This leaves room to integrate international experience and technological developments to offer the best engineering practice for finding innovative solutions for the numerous challenges of the Mexico City environment and to reach greater heights and deeper basements. The real-life testing of this approach with multiple frequent moderate seismic events and the recent 2017 major Puebla-Morelos earthquake has proved the resilience of these tall structures, with minimal or no damage and without functionality interruption. For designers, enhanced public trust is a significant benefit; conversations about community resilience now include specific examples of the efficacy of engineering advancements for high-performance building structures, making stakeholders feel safer and more comfortable about future developments.

The online version of this article contains references. Please visit www.STRUCTUREmag.org.
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