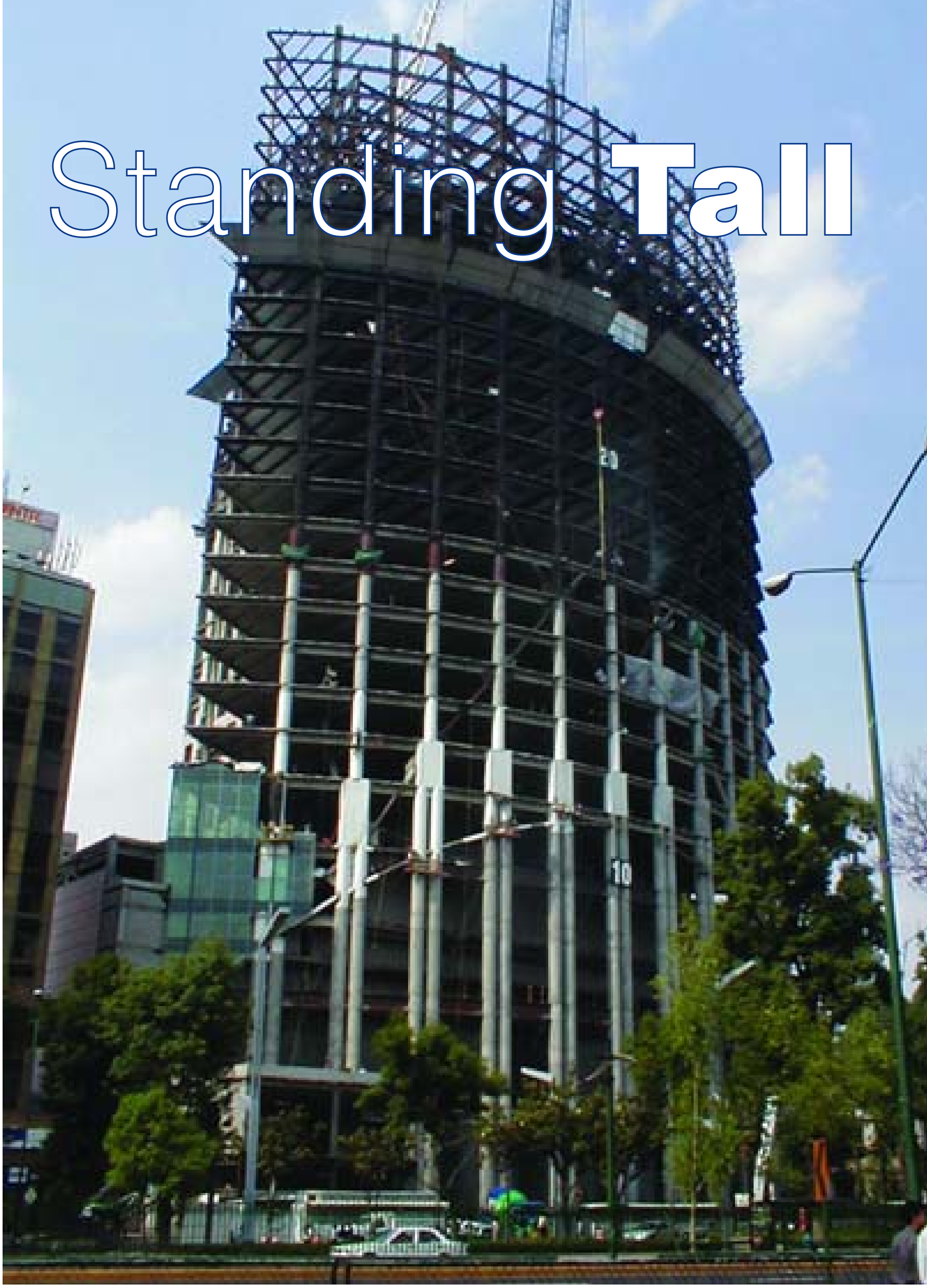


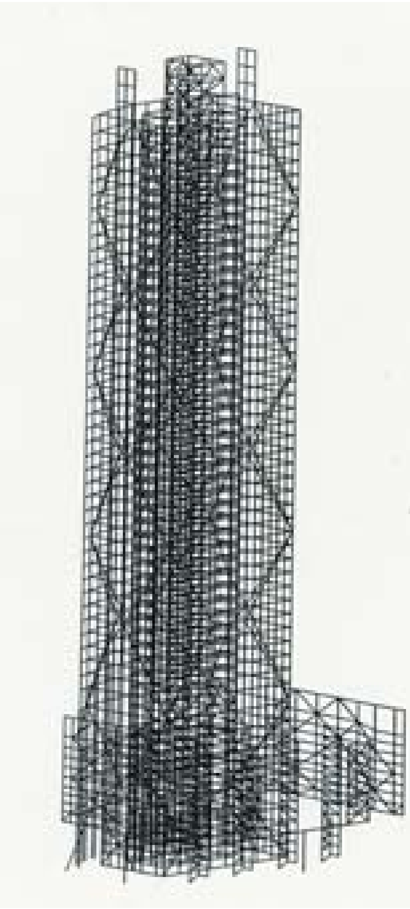
Standing Tall

Ahmad Rahimian, S.E., P.E. and Enrique Martinez Romero, P.E.

The tallest building in the Americas south of Texas, Torre Mayor stands up to Mexico City's tough seismic conditions.

Torre Mayor is a 57-story office tower to be completed this summer in Mexico City, Mexico. The $250-million project reaches a height of 225m above ground and is the tallest building in Mexico and Latin America. The seismic design approach utilized in this project offers an innovative concept in absorption of seismic energy for tall buildings. Soil-structure interaction analysis and site-specific spectral analysis were performed to obtain realistic information with respect to seismicity and building response. A three-dimensional computer model using non-linear viscous supplemental damping elements was created to obtain structure response to time-history ground excitation as well as spectral analysis.

Nine above-ground parking levels are provided in addition to four below-ground parking levels. The tower is de-



A three-dimensional computer model of the lateral system was generated using SAP2000 structural analysis software.

signed according to the Mexico City Building Code (MCBC)[1,2], and its seismic provisions are among the most stringent requirements worldwide. It also complies with the Uniform Building Code-1994 (UBC-94)[3], and several of the latest FEMA-267[4] provisions proposed after the Northridge Earthquake in California.

The building has an 80 m-by-80 m footprint at below-grade levels and it reduces to an 80 m-by-65 m footprint from the fourth level to the 10th level. Above the 10th level the tower plan is further reduced to its typical tower size of 48 m by 36 m. The tower floor plate is a geometric combination of a rectangle merged with an arch segment at the south side of the building, forming a curved façade at the south face. Office floors are located at levels 11 to 53. The tower also houses a heliport at the main roof.

Seismic forces are obtained according to the Mexico City Building Code (MCBC) regulations for site seismicity Zone II/III and building classification Type B. A Site Specific Response Spectra study was performed at the Instituto de Ingenieria (UNAM)[5,6]. The final seismic design of the building was according to the Site Specific Response Spectra, developed in compliance with the MCBC.

STRUCTURAL SYSTEM

The building's superstructure is primarily a steel structure. The columns at the interior and perimeter of the tower are encased in reinforced concrete for the lower half of the tower for added stiffness, strength, and economy.

Typical floor framing is comprised of 3″-deep composite metal deck with 2½″ of concrete supported on steel framing connected via shear studs. Thicker slabs are used at mechanical floors and ceiling to carry higher loads and to improve sound insulation. Electrified metal deck is specified for electrical wiring. A special detail at the trench header was required to ensure adequate diaphragm action in this weakened zone. The tower's steel columns are encased in concrete up to the 30th floor at the perimeter and up to the 35th floor in the core area.

The project has a four-story underground parking structure, placing the lowest level 15 m below grade. A flat slab system with reinforced concrete and composite columns (steel columns encased in concrete) is utilized for the below grade structure.

FOUNDATION

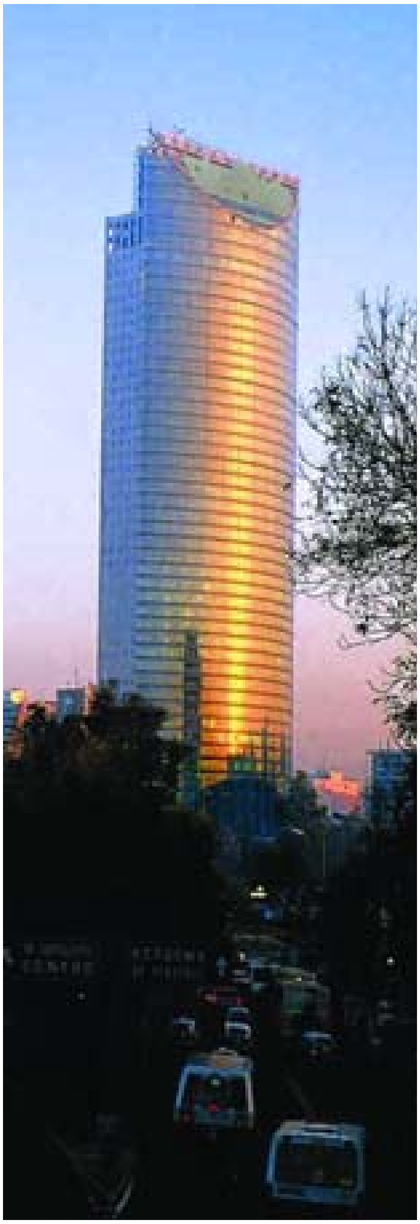
The foundation for the tower is a combination caisson/mat system. The building is founded on caissons of up 1.2 m in diameter reaching 40 m down to the hard rock layer of "depositos profundos" existing below the soft deposit layers typically found in Mexico City.

The reinforced concrete mat system connects all the caissons and a 800 mm foundation wall at the lowest basement level. The design incorporates a degree of redundancy to ensure uniform action under the most severe earthquake forces. The concrete mat thickness varies from 1.0 m to 2.5 m thick under the tower core columns where load concentration is the highest. Slurry foundation walls are specified for the project due to the poor soil condition and high water table. The 600 mm slurry walls are to be placed prior to the site excavation and are augmented by a 200 mm concrete liner wall to be placed during the construction of the underground structure.

LATERAL SYSTEM

The lateral system selected for this project evolved from a series of studies of alternate structural concepts. More than 25 different structural systems were studied during the preliminary phase of the project in order to establish the merits of each structural system under the severe seismic conditions of Mexico City.

The selected structural system is based on a redundant multiple system, which is a further enhancement of the "dual" concept recommended by seismic codes worldwide. This is accomplished by introducing a "dual"



Torre Mayor, near completion, towers over Mexico City.

conventional (deflection sensitive) lateral-force resisting system in combination with a supplemental damping system (velocity sensitive). In effect, a "trio" system is provided to respond to the seismic energy from an earthquake.

The "trio" system is composed of a primary super braced frame at the perimeter of the tower coupled with a perimeter moment frame forming a tube system, and a trussed tube at the core of the building. The bracing connecting the composite core columns creates a structural spine in the building core. The perimeter frame and the powerful super-diagonal system create an efficient tube structure joining the spine in resisting the seismic forces. This system is augmented by a series of supplemental viscous dampers placed in north-south and east-west directions.

Various studies were performed for the selection of the dampers with respect to the type of damper as well as the capacity and location of the dampers. In the north-south direction, a total of 72 dampers are placed within the core truss system. A total of 24 dampers are placed as part of the perimeter bracing system. In the east-west direction, dampers are placed at the north and south perimeter of the tower. Dampers are placed in such a configuration as to optimize their performance. The theory and concept behind the optimization of the proposed damping system is explained elsewhere[7]. This optimization attempts to improve the effectiveness of the dampers by increasing the dampers' differential velocity for a given interstory sway and velocity. This is accomplished by reversing the orientation of axial velocity of the columns adjacent to the dampers. This increases the net differential velocity of the damper. This could be physically achieved by modifying the placement of the dampers by placing them between two lateral systems comprised of truss system, frame system or wall system or any combination of them. This unique application resulted in a US Patent grant.

The selected structural system incorporates supplemental damping devices that are highly effective in reducing the impact of seismic motion on the structure as well as on the non-

Above. The $250-million Torre Mayor project reaches a height of 225 m and is the tallest building in Mexico and Latin America.

Left and below. Supplemental dampers reduce building sway interstory drift.

Lateral bracing forms a super-X configuration on the east and west faces, where the X covers the entire width of the tower. On the north and south faces, two sets of super-Xs were introduced.

structural elements (i.e. architectural and mechanical components). The supplemental damping reduces the overall and inter-story sway of the tower, as well as the vibration and the seismic forces of the structural elements.

The damping elements reduce the building response by absorbing and dissipating a significant portion of the seismic energy transmitted to the building and consequently reducing the ductility demand on the steel framing. They also add to occupants' comfort level against sway perception, during either high wind or moderate levels of earthquake shaking.

The stiffness and load carrying capacity of the tower columns is enhanced by encasing them in concrete up to mid-height of the tower where demands on strength and stiffness are higher. The concrete encasement of core columns extends five floors above the perimeter columns in order not to create a sudden change in inter-story floor stiffness.

SUPPLEMENTAL DAMPING

During the schematic phase, the structure was studied with and without the supplemental damping system in order to ascertain quantitatively the advantages of the supplemental damping system with respect to building performance under a seismic event. For example, designers studied the sway response of the tower under a seismic excitation with Richter magnitude of 8.2 for the structure with and without the supplemental damping system.

Viscous damping units made by Taylor Devices, Inc. were selected after studying various damping systems for this project. The structure, using the supplemental viscous damping elements produces equivalent damping ratios (as percentage of critical damping) of 8.5 percent in the north-south and 12 percent in the east-west direction for the fundamental modes of vibration.

Time-history analysis, using impulse excitation, was used to evaluate the equivalent damping of the system. Damping ratios were obtained by evaluating the decay function of the response time history, such as the response of the tower to an impulse loading in both primary directions. As a crosscheck, the damping calibration was verified by comparing time-history responses of the structure with dampers with that of a system with equivalent modal damping.

Bracing of the structure follows a super-X configuration at the east and west faces where the X covers the entire width of the tower. At north and south faces, two sets of super-Xs were introduced. No bracing is placed within the two center bays, except at three locations where a set of diagonals forms a diamond shape connecting the super-X systems. The dampers in the north and south faces are placed at these diamond-bracing locations. This in effect enhances the damping system's performance by creating a damped link between the super-X systems. Additional fine-tuning of the secondary link element was necessary to emphasize the basic concept of damped link element[7].

SOIL-STRUCTURE INTERACTION

The building is located in seismic zone II, at the border between seismic zone II and seismic zone III, as defined by the Mexico City Building Code. Zone III is the MCBC's most severe seismic zone.

A site-specific spectral analysis and soil-structure analysis were performed at the Instituto de Ingenieria UNAM[5,6] to establish a more accurate design spectra reflecting the nature of the site and its interaction with the proposed structure. The code-specified spectra are free field, while the site-specific spectra are based on the soil structure interaction result. Site-specific spectra were obtained at the surface level and at the foundation level. Also, a free-field spectrum was obtained as a source of comparison with the code spectra. Design spectra were obtained for the damping ratios of 8.5 percent and 12 percent.

SEISMIC ANALYSIS

A three-dimensional computer model of the lateral system was generated using SAP2000 structural analysis software. This model included the steel and composite members as well as the damper elements for the time-history analysis.

The analysis and design were performed based on spectral analysis using damped design spectra. However, an independent design check was made using the seismic forces obtained for time-history analysis to reveal areas with higher seismic force demand. In effect, the envelope of the forces from spectral and time-history analysis was used for design of the structure. Seven series of time-history ground accelerations were generated using the SIMQKE program[9] from the site-specific spectrum obtained from the soil-structure study.

Time-history analysis with viscous damping elements was performed with the SAP2000 program, using the Ritz vector approach and including 365 mode shapes. Sufficient mode shapes were provided to capture the activities of all 96 dampers in the structure. A study of the distribution of the energy between various components of elastic, kinetic, and damping energies during a seismic event demonstrated the significant contribution provided by the supplemental dampers.

SEISMIC DESIGN

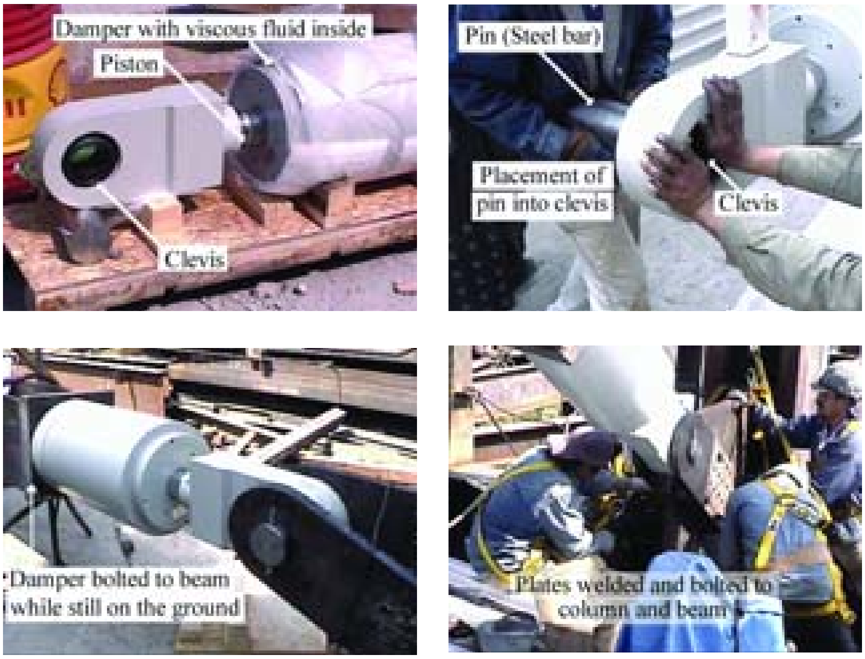
A ductility factor of one ($R = 1$) was used throughout the study for both spectral and time-history analyses and design. Joint size effect as well as panel zone deformation was considered in the frame analysis. The flexibility of beam, column and panel-zone assembly was studied using an in-house program[8]. The sizes of equivalent rigid offsets are obtained and input in the SAP2000 model,[10] considering the panel-zone shear deformation. The structural elements were designed to satisfy strength and stiffness (sway criteria) as per MCBC.

While the seismic design concept of this project did not rely on the ductility of the system, numerous measures were taken to enhance the ductility of the structure as a result of findings after the Northridge Earthquake of 1985. Measures were taken to enhance the performance of the connections, such as using electrodes with better material ductility that had a minimum CVN of 20 lb-ft at 70 degrees F; increasing access holes beyond the minimum requirement of AISC; removing the backer bar at the bottom flange, and grinding the full penetration welds smooth.

SPECIAL FEATURES

A special floor diaphragm system was designed at the 10th level, where the structure's footprint increases to include the low-rise parking structure. The paths for the lateral force transfer between tower lateral system and additional low-rise lateral systems were studied and designed to accommodate the diaphragm action.

The floor plates below level 10 are set back to allow for an open space plaza and lobby entrance at the south side of the building. This is done in such a way as to form an arch with its apex at the 10th level. The free standings columns and beams in this zone were sized to maintain a similar stiffness and strength to the floors above and the frame at the north face of the tower. A set of detailed computer models was generated to provide a tool for the calibration of the sizes of the beams and columns. Column elements are comprised of two coupled circular composite columns providing sufficient strength and stiffness to span vertically between the bracing levels.



Viscous damping units are assembled for the project. The damping elements absorb and dissipate a significant portion of the seismic energy transmitted to the building, and consequently reduce the ductility demand on the steel framing.

SEISMIC STUDY FOR CONSTRUCTION PHASE

Dynamic studies were performed to verify the structural performance at various stages of construction under the design seismic event. Site-specific seismic studies were performed for building constructed to the 10th level and the 23rd level. Obviously, the period of the building at these stages is shorter than the final condition. Also, the effect of supplemental dampers was not considered for the building reaching up to the 23rd level. However, the partial mass associated with the constructed portion would compensate the impact from the change in period.

WIND STUDY

The building is also designed to resist wind loads as specified by the Mexico City Building Code (MCBC). Additional safety and occupants' comfort were ensured by performing a wind tunnel test. The result of the wind tunnel test provided detailed wind load information by modeling the microclimate of the site. The wind tunnel study was conducted at the University of Western Ontario's Boundary Layer Wind Tunnel Laboratory[11]. ★

Ahmad Rahimian, Ph.D., S.E., P.E. is a design principal at Cantor Seinuk Group, New York, NY. Enrique Martinez Romero, P.E. is the general director of engineering firm Enrique Martinez Romero, SA, Mexico City, Mexico.

DESIGN ARCHITECT

Zeidler Grinnel Partnership, Toronto, Canada

EXECUTIVE ARCHITECT

Adamson Associates, Toronto, Canada
IDEA Asociados de México, S.A. de C.V., Mexico City

No bracing is placed within the two center bays, except at three locations where a set of diagonals forms a diamond shape connecting the super-X systems. The dampers on the north and south faces are placed at these diamond-bracing locations. This enhances the damping system's performance by creating a damped link between the super-X systems.

STRUCTURAL ENGINEERS

The Cantor Seinuk Group, New York, NY

Enrique Martinez Romero, S.A., Mexico City

STRUCTURAL ENGINEERING SOFTWARE

SAP 2000

GEOTECHNICAL ENGINEERS

Mueser Rutledge Consulting Engineers, New York, NY

TGC Geotecnia, Mexico City

REFERENCES

1. *Reglamento de Construcciones Para el Distrito Federal*, Centro de Actualizacion Perofesional. (1987). Mexico, D.F.
2. *Normas Technicas Complementarias del Reglamento de Construccion Para el Distrito Federal*, Centro de Actualizacion Perofesional. (1987). Mexico, D.F.
3. *Uniform Building Code*, UBC-1994, International Conference of Building Officials, CA.
4. Federal Emergency Management Agency *Interim Guidelines and Advisory No. 1*, FEMA 267 and FEMA 267A, 1997.
5. Romo M. P. (1994). *Espectros de Campo Libre Para el Sitio del Proyecto Chapultepec*. Instituto de Ingenieria UNAM, Mexico, D.F.
6. Romo M. P. Ovando E. (1994). *Propiedades Dinamicas y Estaticas de Los Suelos del sitio Proyecto Chapultepec*. Instituto de Ingenieria UNAM, Mexico, D.F.
7. Rahimian A. (1997). *Coupled Truss Wall with Damped Link Elements*. Proceeding of International Conference on High Technology Buildings, Sao Paulo, Brazil.
8. Rahimian A. (1986). *Panel Joint Size Effect*, The Cantor Seinuk Group, P.C., NY.
9. *SIMQKE User's Manual and Documentation.* (1976). Department of Civil Engineering, Massachusetts Institute of Technology, MA.
10. *SAP2000 User's Manual. Analysis Reference.* (1996). Computer and Structures, Inc., CA.
11. Isymov N. Mikitiuk M. (1997). *Wind Engineering Studies for the Chapultepec Office Tower*, The Boundary Layer Wind Tunnel Laboratory, The University of Western Ontario, Report No. BLWT-SS32-1997.
12. Rahimian A. (2002). US Patent No. 6,397,528 B1, Coupled Truss Systems with Damping for Seismic Protection of Buildings