Trump International Hotel and Tower

Design and construction of Chicago's concrete colossus

BY WILLIAM BAKER, STAN KORISTA, ROBERT SINN, KARL PENNINGS, AND DANE RANKIN

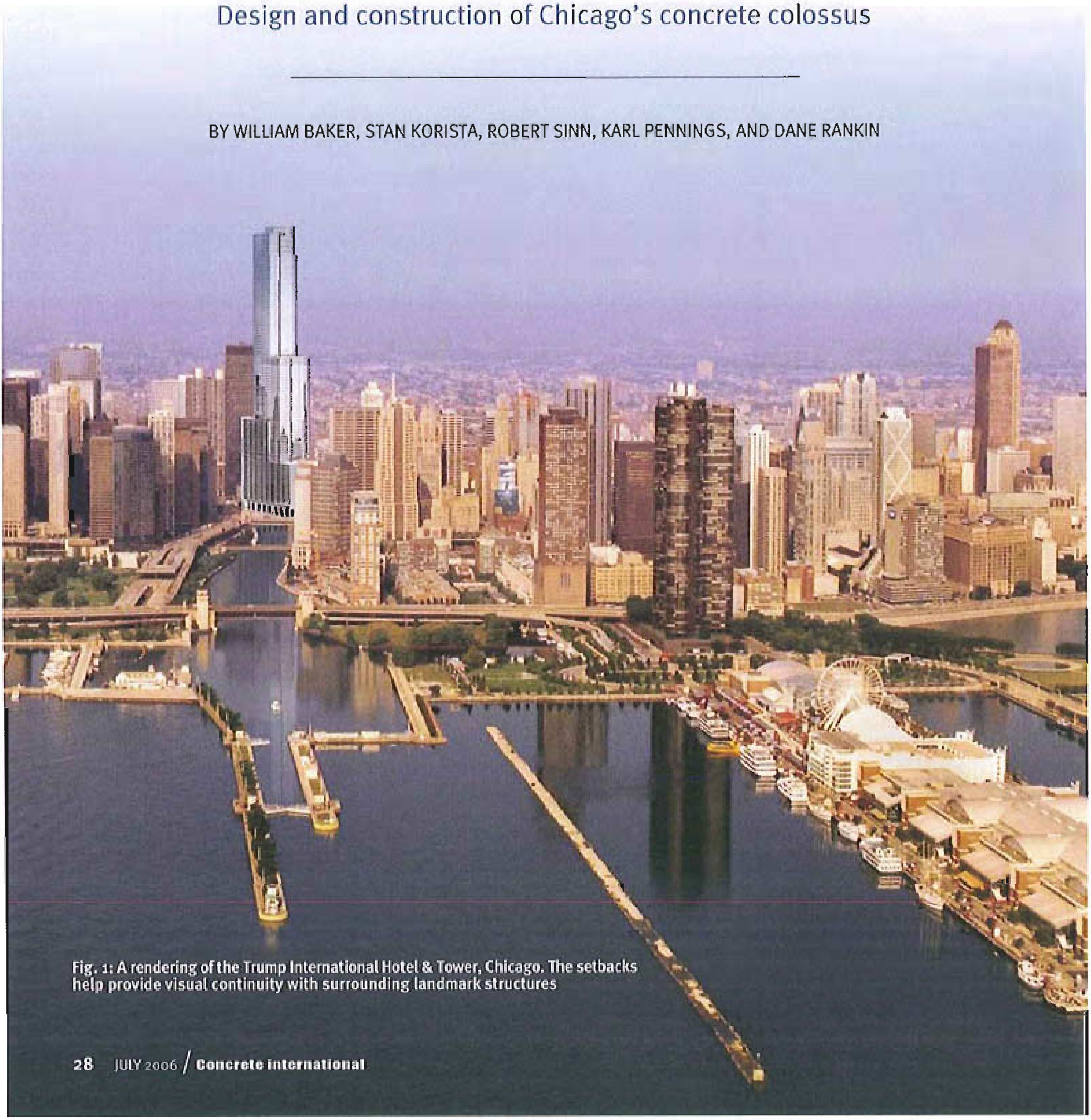

Fig. 1: A rendering of the Trump International Hotel & Tower, Chicago. The setbacks help provide visual continuity with surrounding landmark structures

When completed in 2009, the Trump International Hotel and Tower® in Chicago, IL, will rise to a height of 1134 ft (345.6 m). Including the spire, the structure will be 1362 ft (415.1 m) tall. The building is currently being constructed on the north side of the Chicago River, between Wabash Avenue and Rush Street, at the site of the recently-demolished Chicago Sun-Times building.

Designed by Skidmore, Owings & Merrill LLP (SOM), the 92-story structure will not only be the tallest reinforced concrete building in the U.S., it will be the tallest building built in North America since the completion of the Sears Tower in 1974. The tower's 2.6 million ft^2 (240,000 m^2) of floor space will incorporate 472 condo units, 286 hotel units, a health club, parking for 1000 cars, and 100,000 ft^2 (9300 m^2) of retail space. Four levels of the structure will be below grade (the two lowest levels will be below the level of the directly-adjacent Chicago River) and will contain retail and mechanical space.

Encased in stainless steel and glass, the tower shaft will rise from a newly landscaped plaza that will include a new riverwalk that will link the pedestrian level with the retail shops. The building will feature setbacks at Levels 16, 29, and 51 that correspond to the top elevations of prominent neighboring buildings, providing visual continuity with the building's surroundings (Fig. 1). These buildings include the historic Wrigley Building to the east, Bertrand Goldberg's Marina City to the west, and Mies van der Rohe's IBM Building located directly across Wabash Avenue.

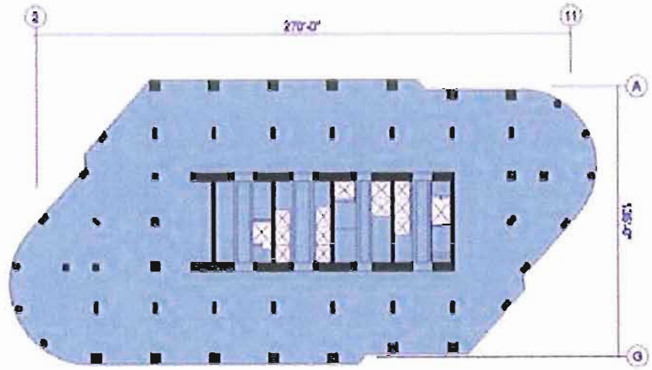

Fig. 2: The building core measures 49 and 197 ft (15 and 60 m) in the north-south and east-west directions, respectively

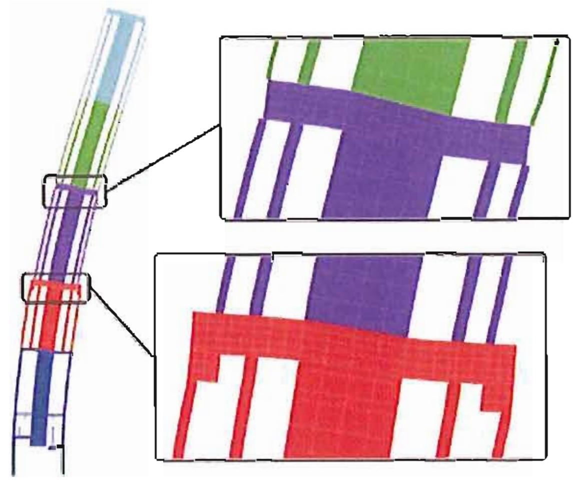

Fig. 3: The outrigger wall-beams engage perimeter columns to significantly increase the effective width of the lateral system

STRUCTURAL SYSTEMS

A core and outrigger system provides the lateral stability for the Trump Tower. Large outrigger elements tie the concrete core to perimeter columns, significantly increasing the building's lateral stiffness as well as its resistance to overturning due to wind.

The core is located at the center of the building and consists of I-shaped and C-shaped walls (Fig. 2). The webs of these I- and C-sections are oriented in the north-south direction, are 18 in. (460 mm) thick, and are 41 ft (12.5 m) long. The flanges of the sections are oriented in the east-west direction, are 48 in. (1.2 m) thick, and range from 9 to 22 ft (2.7 to 6.7 m) in length. Above the entries to the elevator cores at each level, 48 in. (1.2 m) wide by 30 in. (0.8 m) deep reinforced concrete link beams connect the flanges of adjacent walls.

The outrigger effect is most pronounced in the narrow direction of the building (north-south), as the width of the lateral system increases from 49 to 140 ft (15 to 43 m) when the perimeter building columns are engaged. The outriggers are massive reinforced concrete wall-beams (up to 66 in. [1.7 m] wide and 17.5 ft [5.3 m] deep) that extend from the wall flanges to the exterior columns at three of the double-height mechanical floors in the tower (Levels 28-29, 50-51, and 90-91 [Fig. 3]). In addition to their function as key components in the lateral system, the outriggers also serve as transfer girders, as the columns are shifted at the façade setbacks. Although they don't serve as outriggers, transfer girders at the double-height mechanical floor located at the lowest building setback (Levels 15-16) allow for a column-free space in the 10 parking levels. Perimeter belt walls at the roof and the three setback levels provide additional torsional stiffness and redundancy, as well as serving to equalize column loads along the perimeter.

Tower columns are typically 2 x 4 ft (600 x 1200 mm) rectangular sections at the top of the building and 6 ft (1800 mm) diameter circular sections at the base. With the exception of the columns above and below the outrigger levels, which experience large shear forces and bending moments due to compatibility with the outrigger walls (Fig. 3), the columns typically have ACI code minimum reinforcing levels.[1]

Typical residential floors are 9 in. (230 mm) thick flat plates spanning up to a maximum of 30 ft (9.1 m) without perimeter spandrel elements. This construction minimizes the structural depth of the floor, allowing for higher ceiling heights. A slab-and-beam system carries floor load within the core for the elevator and stair lobbies. In the parking levels, a 14 in. (360 mm) thick slab spans the 40 ft (12.2 m) between the core wall and the exterior columns. The lower levels (Level 2 and below) are a mixture of flat slab and slab-and-beam construction.

A 10 ft (3 m) thick concrete mat under the core walls transfers enormous loads into a grid of 10 ft (3 m) diameter drilled-shaft rock caissons that extend about 80 ft (25 m) down where they are socketed 6 ft (1.8 m) into solid Chicago bedrock.[2] The tower columns are also supported by rock caissons up to 8 ft (2.4 m) in diameter and stabilized by a series of caisson caps and grade beams.

OUTRIGGER STUDIES AND DESIGNS

Because of the scale of the outrigger elements and the magnitude of the applied loads, the structural engineering design for these elements was unique and extremely challenging. The outriggers are deep elements, and the locations of column loads relative to the outrigger supports therefore made it necessary to design the wall-beams using strut-and-tie models.

Large tie forces are resisted by top and bottom longitudinal reinforcing and vertical ties. The heavy longitudinal reinforcing steel must pass from the thicker outrigger through the thinner core wall web to transfer forces between the columns and core. To reduce congestion, all primary reinforcing bars in the outrigger levels are Grade 75 (Grade 520).[3] Further, in three especially-tight locations, Grade HPS 70W (Grade HPS 485W) structural steel plates[4] with welded shear studs are used in lieu of reinforcing bars to transfer the necessary force through the core wall web. Large compressive and tensile forces from the bending of the outriggers at the face of the core walls are transferred through the core wall web, resulting in large "panel zone" shear forces in the core wall web over the depth of the outrigger. A strut-and-tie model was used for the design of the core wall in these panel zones (the analogy is similar to the beam-column intersection in a welded steel frame [Fig. 4]).

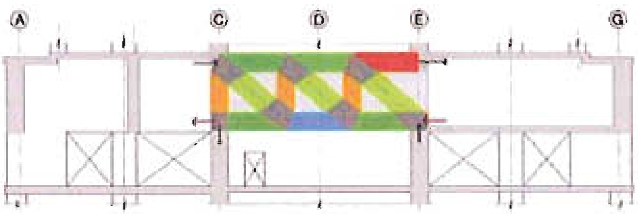

Fig. 4: A strut-and-tie model was used for design of the shearwall web at the outrigger connection

The outriggers are also significantly affected by differential shortening of the concrete columns and core walls resulting from creep and shrinkage. The columns typically have higher axial stresses, and therefore shorten more than the core walls, transferring load through the outriggers into the core walls.

A special analysis was used to account for time-dependent effects, including creep, shrinkage, construction sequencing, and the variation of material properties. This analysis included eight different finite element models of the building, each representing a different period in time during and after construction. The calculated forces in the outriggers and walls were taken into account in the forces applied to the strut-and-tie model for the design of the outriggers and were also incorporated into the design of all elements of the lateral system.

PERCEPTIBLE MOTION UNDER WIND

Trump Tower is not only a very tall building, it's quite slender, as the aspect ratio of the tower (measured as the overall height divided by the smaller base dimension) exceeds 8 to 1. Such slender buildings are known to be significantly influenced by the dynamic nature of the wind and its interaction with the building structure. It's particularly important for structural designers to consider the amount of motion that will be perceived by building occupants over time—especially in residential buildings such as the Trump Tower. The tall-building design community long ago established that residential buildings should be designed to a somewhat more stringent motion performance criterion than office or hotel buildings.[5] The prediction and evaluation of the suitability of the structural design as it relates to building motions are today facilitated through wind tunnel testing, using the guidance provided in ISO 6897[6] regarding the acceptable level of predicted acceleration for various magnitudes of windstorms (Fig. 5).

Movements under wind load are affected by a building's stiffness, mass, and damping as well as the local wind environment and geometry of the tower shaft. Concrete was chosen as the primary structural material for the Trump Tower to take advantage of its ability to provide a highly massive frame with high damping. Inherent damping of the designed concrete frame is on the order of 50% higher than in a comparable steel scheme. Further, these benefits were intentionally enhanced by maintaining the full thickness of the core walls over the full building height. The high lateral stiffness of the tower was accomplished by using high modulus of elasticity concrete in the massive column, wall, and outrigger elements. All of these factors resulted in predicted peak accelerations at the topmost occupied floors that are comfortably within the ISO criteria applied to residential buildings.

Torsional motions have historically been suggested as some of the most troubling for building occupants.

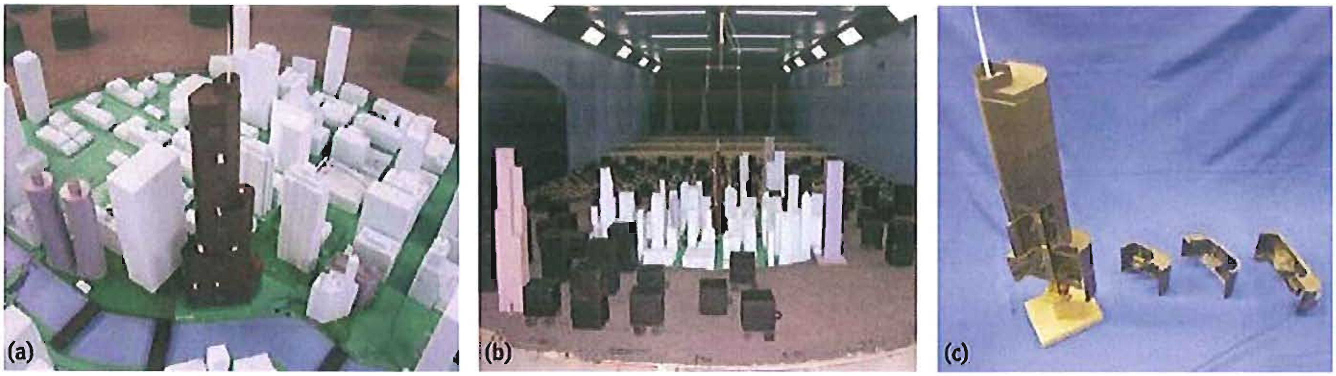

Fig. 5: Wind tunnel studies were used to evaluate the building's dynamic response: a) an aeroelastic model of the tower was mounted among scale models of existing buildings; b) models were mounted on a carrousel so that wind direction could be varied; and c) the partially assembled model shows the sophisticated fabrication required for aeroelastic modeling *(Photos courtesy of Rowan Williams Davies & Irwin, Inc.)*

Predicted peak torsional velocities were also determined to be quite low and well within tentative guidelines suggested in the literature and generally followed by the wind tunnel industry.[7] In fact, the building will require no auxiliary damping devices that are often employed in comparable-height structures to meet these guidelines.

HIGH-PERFORMANCE CONCRETE

A series of high-performance concrete mixtures, designed by Prairie Material Sales, Inc., are advancing the state-of-the-art. Up to Level 51, concrete strengths of 12,000 psi (83 MPa) at 90 days have been specified for all vertical column and wall elements. Local areas in the outrigger zones, however, require 16,000 psi (110 MPa) concrete at 90 days. Because the 16,000 psi (110 MPa) concrete is located in areas with high reinforcement congestion, self-consolidating concrete (SCC) with a minimum flow spread of 24 in. (610 mm) has been specified. Further, to reduce the heat gain in the massive elements, the high-performance SCC incorporates slag cement, fly ash, and silica fume as well as portland cement. We believe this will be the first application of 16,000 psi (110 MPa) SCC that will be pumped and placed at an elevation up to 650 feet (200 m) above grade.

To meet the occupant motion perception criteria, the stiffness of the concrete is critical. The modulus of elasticity of the high-strength concrete was therefore specified to at least achieve the modulus of elasticity values indicated in ACI 318 equations. To meet this as well as the minimum strength requirements, the producer is using dense limestone coarse aggregate, with a maximum aggregate size of 1/2 in. (13 mm).

In contrast to the stringent minimum strength requirements in ACI 318, concrete modulus of elasticity may be specified on an average basis. Somewhat lower modulus values in local areas are therefore acceptable as long as the average value remains as specified. Further, such modulus values may be obtained at a much later date—for example, 180 or 365 days—as the motion perception criteria are long-term serviceability issues and won't be critical until the building is completed. To date, testing for the 12,000 psi (83 MPa) concrete in the lower story walls and columns indicates that the modulus of elasticity is somewhat higher than predicted using equations from ACI 318.

Fig. 6: As of May 2006, construction had progressed to the fourth parking level. The 6 ft (1800 mm) diameter exterior columns signal the scale of the structure to follow

MILESTONES

Project completion is scheduled for spring of 2009. Based upon the phased-occupancy plan, however, the hotel will be operational in late 2007—well before the scheduled topping out of the structure in mid 2008. To date, project milestones have included the demolition of the existing Sun-Times Building in March 2005, completion of the rock caissons in August 2005, and the 4400 yd^3 (3360 m^3) continuous 22-hour placement of SCC for the core mat on September 29, 2005.[8] Also, as part of the development, the Trump Organization replaced the adjacent 1920's era Wabash Viaduct, completed on November 19, 2005. As of May 2006, the Trump Tower structure had risen to the fourth parking level (Level 6), the ninth framed level (Fig. 6).

References

1. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (318R-05)," American Concrete Institute, Farmington Hills, MI, 2005, 430 pp.

2. Schock, B., "Rock Caisson Foundations for the World's Tallest Concrete Building," *Foundation Drilling*, Mar.-Apr. 2006, pp. 10-14.

3. ASTM A 615/615M-06, "Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement," ASTM International, West Conshohocken, PA, 2006, 6 pp.

4. ASTM A 709/709M-06, "Standard Specification for Structural Steel for Bridges," ASTM International, West Conshohocken, PA, 2006, 8 pp.

5. Isyumov, N., "Criteria for Acceptable Wind-Induced Motions of Tall Buildings," *International Conference on Tall Buildings*, Council on Tall Buildings and Urban Habitat, Rio de Janeiro, May 1993.

6. ISO 6897, "Guidelines for the Evaluation of the Response of Occupants of Fixed Structures, Especially Buildings and Off-Shore Structures, to Low-Frequency Horizontal Motion (0,063 to 1 Hz)," 1984, 6 pp.

7. Isyumov, N., "Criteria for Acceptable Wind-Induced Motions," *Structures Congress XII*, N.C. Baker and B.J. Loodno, eds., American Society of Civil Engineers, Atlanta, Apr. 1994, pp. 642-647.

8. Nasvik, J., "First Stage of a Landmark Building: Trump International Hotel & Tower, Chicago," *Concrete Construction*, Nov. 2005, p. 42.

Selected for reader interest by the editors.

PROJECT TEAM

Developer:
401 North Wabash Venture LLC (The Trump Organization)

Structural Engineer:
Skidmore, Owings & Merrill LLP

Architect:
Skidmore, Owings & Merrill LLP

Geotechnical Consultant:
STS Consultants Ltd.

Wind Tunnel Consultant:
Rowan Williams Davies & Irwin Inc. (RWDI)

Construction Manager:
Bovis Lend Lease LMB, Inc.

Concrete Contractor:
James McHugh Construction Co.

Caisson Contractor:
Case Foundation Co.

ACI member **William Baker** graduated from the University of Illinois, Urbana, IL, with an MS in civil engineering and is the Partner in charge of structural and civil engineering at SOM. His work at SOM has encompassed a wide range of engineering projects including the Burj Dubai, currently under construction and soon to be the world's tallest building, and the 63-story AT&T Corporate Headquarters in Chicago.

ACI member **Stan Korista** graduated from the University of Illinois with an MS in civil engineering and is a Director in structural/civil engineering at SOM. Throughout his career at SOM, he has been involved in a variety of building projects including the Hubert H. Humphrey Metrodome in Minneapolis, MN; the 57-story Three First National Plaza in Chicago; the 88-story Jin Mao Tower in Shanghai; and the Burj Dubai tower.

ACI member **Robert Sinn** graduated from the Massachusetts Institute of Technology with an MS in civil engineering and is an Associate Partner and Senior Strutural Engineer at SOM. His work at SOM has included the Hotel Arts Tower in Barcelona, Spain; the Guggenheim Museum in Bilbao, Spain; the Atlantico Stadium in Lisbon, Portugal; and Millennium Park in Chicago. He is a member of ACI Committee 363, High-Strength Concrete.

Karl Pennings graduated from the University of Texas at Austin, Austin, TX, with an MS in civil engineering and is a Structural Engineer at SOM. He is a member of the American Society of Civil Engineers and led the computer-based structural analysis and design team for the Trump International Hotel and Tower.

Dane Rankin graduated from Purdue University, West Lafayette, IN, with an MS in civil engineering and is an Associate and Project Engineer at SOM. He is a member of the American Society of Civil Engineers and the Structural Engineers Association of Illinois and served as Project Structural Engineer on the Trump International Hotel and Tower.