An Introduction to High-Rise Design

By John Zils and John Viise

The structural system of a high-rise building often has a more pronounced effect than a low-rise building on the total building cost and the architecture. As a result, those faced with an initial venture into tall building design need to be aware of concepts that are not emphasized for low-rise design.

High-rise design comes into play when a structure's slender nature makes it dynamically sensitive to lateral loads, such that a premium is associated with its *lateral system* development (*Figure 1*). The simplified model for the behavior of a tall building is a vertical cantilever out of the ground. In this model, the moment of inertia of the cantilever is calculated considering each of the vertical elements, such as core walls and perimeter columns, active in the lateral system. Deflection is due primarily to axial shortening and elongation of these elements.

Due to **shear deformation**, this idealized stiffness is not fully achievable. A measure of how closely a system can approach the idealized model is reported as a ratio of deflection of the ideal cantilever system to the actual deflection, and is referred to as the building's cantilever efficiency. It is important when selecting a system to realize where shear deformation loss occurs and to ensure that analytical modeling techniques accurately account for it (*Figure 2*).

Each lateral system choice brings its own practical limits. For the two main structural materials, steel and reinforced concrete, suggested practical ranges are illustrated in *Figure 3*. While steel systems offer speed in construction and less self-weight, thereby decreasing demand on foundations, reinforced concrete systems are inherently more resistant to fire and offer more damping and mass, which is advantageous in combating motion perception by occupants. Composite systems can exploit the positive attributes of both.

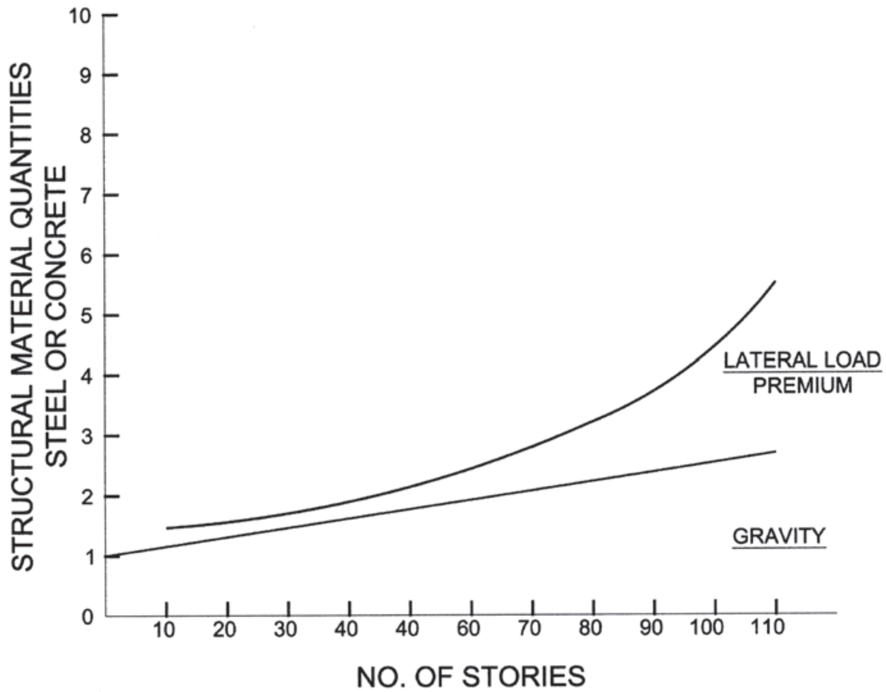

Figure 1: High Rise Premium

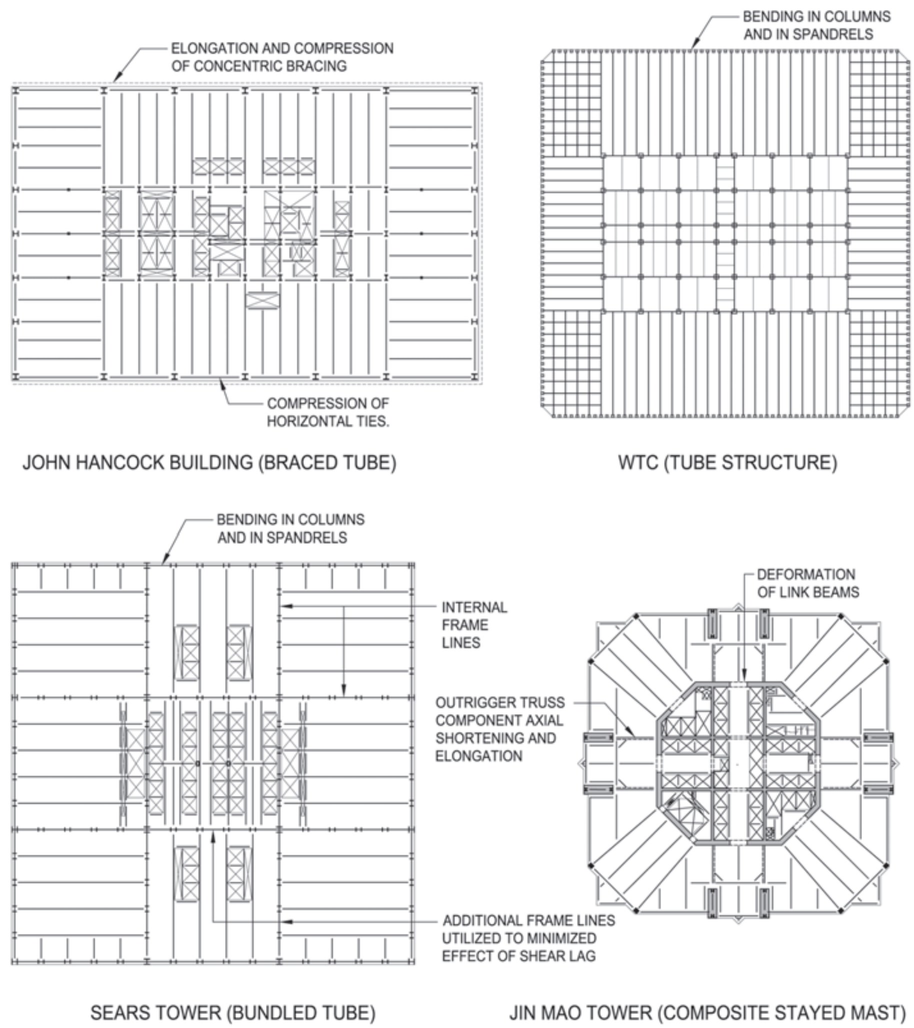

Figure 2: Shear Deformation Effects

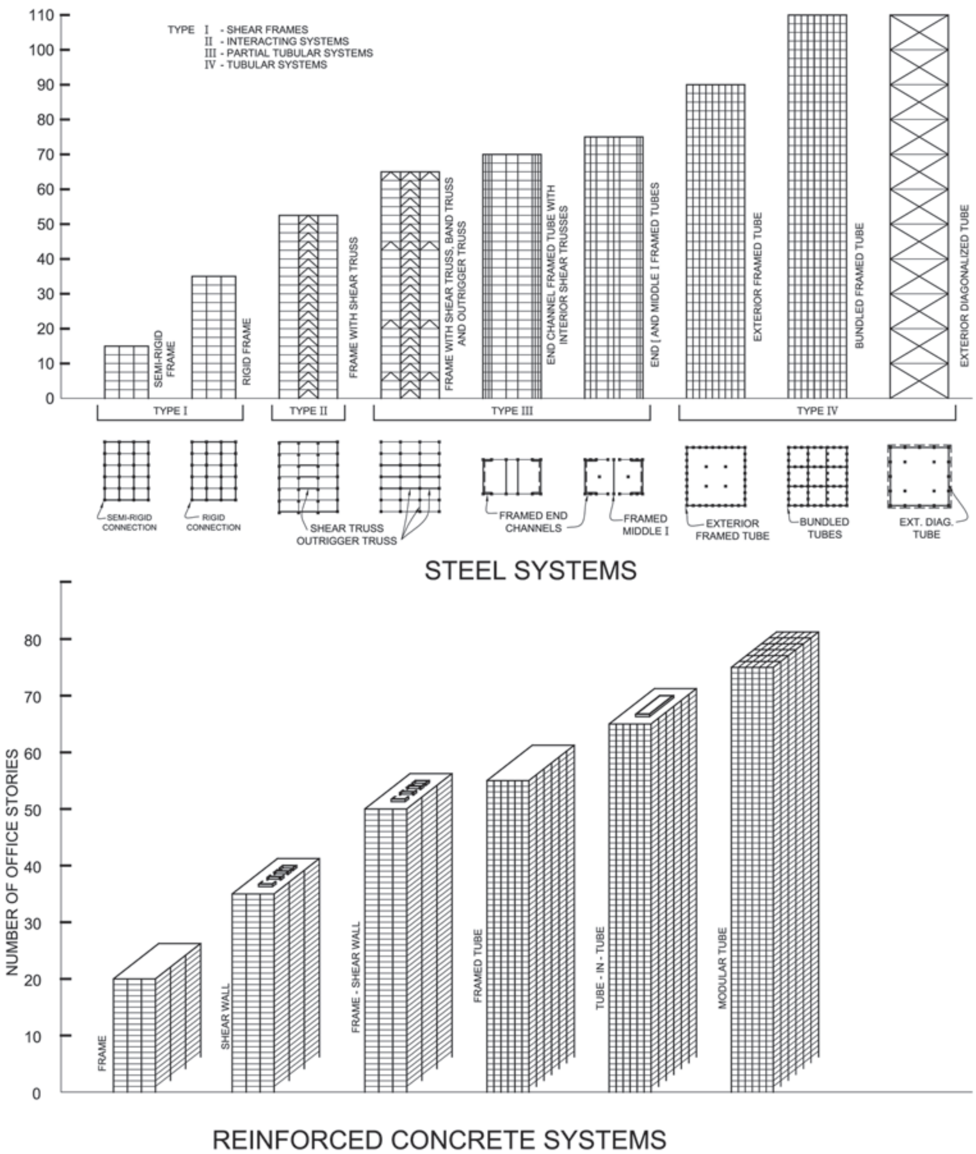

Figure 3: Practical Limits of Lateral Systems

Along with a system's material choice, the issue of slenderness must also be considered. A measure of a building's slenderness is the **aspect ratio**. For core wall only lateral systems, ratios typically range from 10:1 to 13:1. For lateral systems that engage exterior elements, an aspect ratio up to 8:1 is feasible. Pushing this ratio up to 10:1 can result in the need for special damping devices to mitigate excessive motion perception.

Wind loading is normally the governing loading in design of high-rise lateral systems. Conventionally, a maximum wind drift criteria of H/500 is used. Drift is more important with a tall building due to significant second-order effects it can produce (the additive overturning effect of the building mass applied in its deflected shape). In a low-rise building, these effects may be negligible. However, in tall building design the impact on deflection and overturning moment can not be overlooked. When considering P-delta effects for strength checks of the system, total factored gravity loads are used. When considering impact on deflections, all self-weight, cladding, actual superimposed dead load and a percentage of live load, 10psf minimum, is considered.

See the Wind Tunnel Testing article on page 24 of this issue.

Because code prescribed equivalent static wind loading cannot accurately predict the gust effect on tall buildings or turbulence created by adjoining buildings, wind tunnel tests are routinely conducted. Gusting effects become especially problematic and pronounced when pulsating transverse loading, called **vortex shedding**, is created in tune with fundamental periods of the building (*Figure 4*).

Wind tunnel testing considers appropriate loading for overall lateral system design and cladding design, and predicts motion perception and pedestrian level effects. In a wind tunnel test, block models, scaled 1:300 to 1:600, are incorporated into a proximity model on a turntable which includes buildings and other obstructions from 300m to 800m around the building site. The turntable is adjusted to measure wind effects on the building model for a full 360 degrees, taking into account site specific directional behavior of the winds.

Commonly, a high frequency force-balance test is used to assess proper design wind loads for overall system design. This test measures base overturning and torsional moments by modeling the building as a rigid element, taking into account its fundamental sway and torsional modes of vibration. Intrinsically, the test assumes that the lowest sway modes of the building are linear up the height of the building. Where this is not the case, analytical adjustments are made to test results. Ultimately, the test yields a series of wind loads (x, y and torsional) at each floor, and loading direction cases that take into account dynamic effects for all wind directions.

Although wind tunnel testing offers more accurate results, approximate wind and cross wind acceleration equations are included in the Canadian National Building Code. Generally, horizontal accelerations vary inversely proportional to generalized mass, inversely proportional to the square root of damping, and are less significantly correlated to the

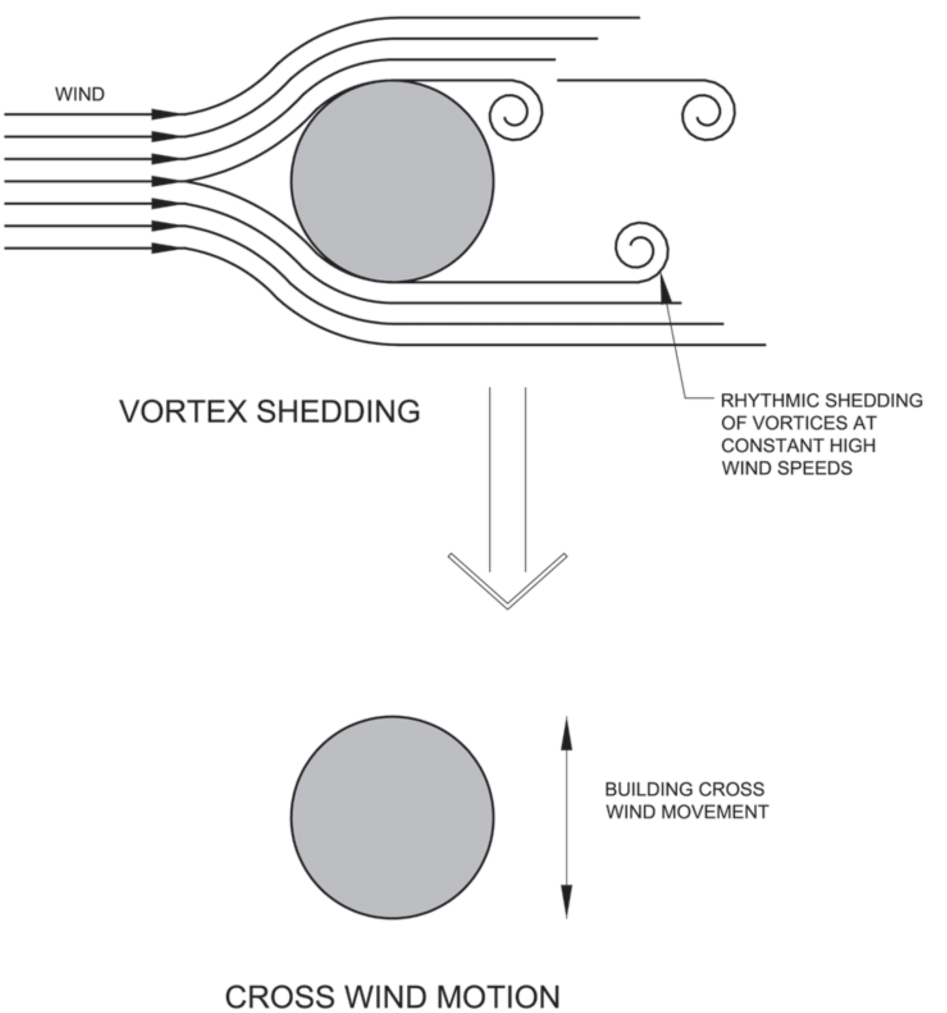

Figure 4: Vortex Shedding Forces

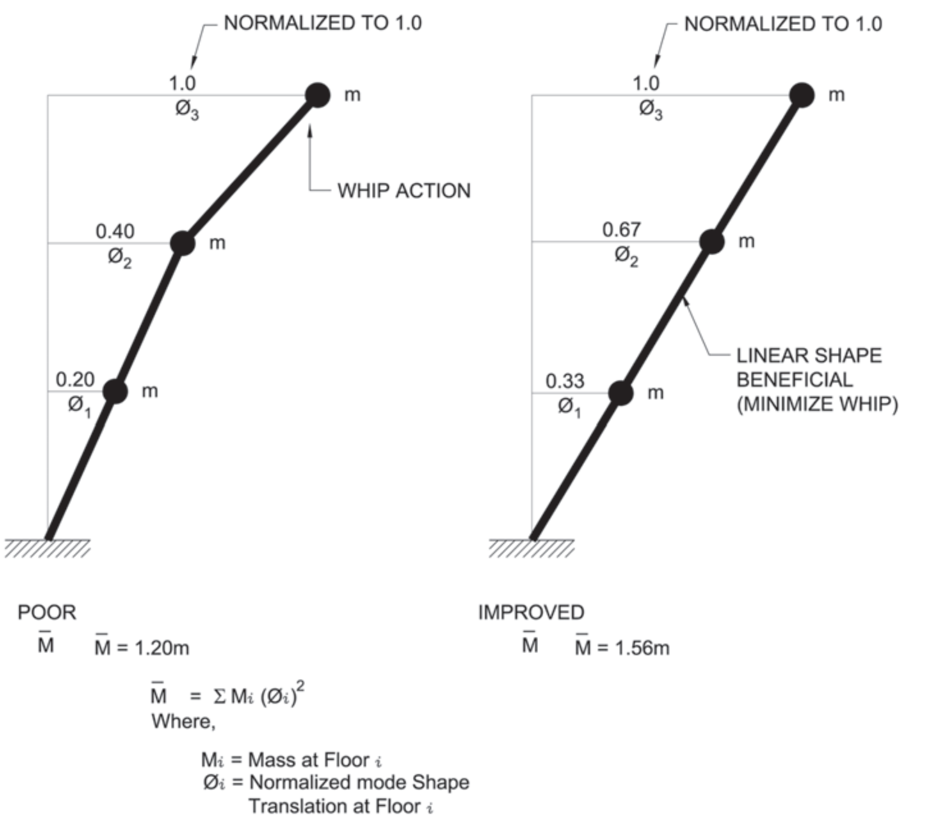

Figure 5: Maximizing Generalized Mass

stiffness and the period of the structure. As a result, often the most cost-effective way to reduce building accelerations is by maximizing generalized mass (*Figure 5*).

Higher return periods, the average time between the magnitude of event considered, are investigated for each component tested based on the consequence of failure to meet the design criteria. For example, in the overall system strength design, a 100 year wind may be used while in the case of checking motion perception, a 10 year wind may be used.

The effects of wind can be minimized by aerodynamic shaping of the building. In the case of the proposed 2000' tall 7 South Dearborn building in Chicago, the impact of dynamic loads due to organized vortex shedding was reduced by rounding building edges, varying floor plate size, and introducing building set-backs. One distinctive feature of the design introduced building slot discontinuities resulting in a reduction of overturning moments by approximately 15% (*Figure 6*).

Intrinsically, tall buildings have longer periods and are not as sensitive as low-rises to high frequency seismic loading. A response spectrum analysis is usually performed, regardless of the site seismic zone. In higher seismic zones special care is devoted to detailing to ensure system ductility.

Once the conceptual lateral system is laid out and governing load cases are established, optimization methods can be employed to ensure that structural material is distributed efficiently to lateral system components. Typically building elements are optimized to meet a given drift target or to tune the building to meet a target sway period[1,2].

Due to the heavier loading, high-rise foundations are a major component of the design. Where possible, high-rise foundations consist of piles or caissons founded in solid rock or sub grade layers. Where soil conditions are poorer, special attention must be made to ensure differential settlement values will not have a detrimental effect. Differential settlement in high-rise foundations is especially problematic because base rotations produce P-delta effects up the height of the building. Pile stiffness, used in design, should accurately account for pile axial shortening, pile creep and shrinkage effects for sustained loads, and soil settlement. Foundation stability checks for sliding and overturning should confirm a minimum factor of safety of 1.5. In these checks, stabilizing effects of basement walls and passive soil pressure against foundation elements and basement walls are taken into account.

A specified lease span, the distance from the core face to the inside face of building enclosure, will often be part of a tall building's design brief. Defined lease spans

Glossary

Lateral System	Structural elements which resist seismic, wind and eccentric gravity loading.
Braced Tube	Distributes gravity and lateral loads along perimeter columns through the use of concentric bracing.
Bundled Tube	System of inter-locking frames consisting of closely spaced columns and deep girders sized to behave as a tube and to limit impact of shear lag.
Shear Lag	(In a tube system) Loss of effective uniform stress distribution along perimeter frame line flanges as distance from shear frame line increases.
Composite Stayed Mast	Interior reinforced concrete core tied to perimeter columns to increase structural overturning stiffness.
Core Wall	Reinforced concrete walls that enclose interior circulation core and resist seismic, wind and eccentric gravity loads.
Shear Deformation	(In the context of a building lateral system) Any deformation which reduces the stiffness of the system from the ideal cantilever model.
Aspect Ratio	Measure of lateral system slenderness. For core wall only systems, measured as the ratio of the building height to minimum dimension of the core wall. For systems that engage perimeter columns, ratio of height to the minimum out-to-out of perimeter columns.
Ceiling Sandwich	Floor-to-floor section, produced in the conceptual phase, which identifies required allowance zones for architectural, structural, and building services.
Outrigger Trusses/Walls	Trusses/walls which link interior core with perimeter lateral system elements. Usually coupled with belt trusses / walls at double story mechanical levels.
Gust Effect	Exciting effect on a building due to turbulent wind.

are beneficial because they ensure that cores will have long faces with aligned walls, thereby offering maximum depth for lateral core bracing or core wall lines. Once the lease span is established, optimization of the structural framing system is important because any reduction in the structural zone of the **ceiling sandwich** translates to significant savings over the height of the building. In addition to efforts to reduce framing depths, options that incorporate building service allowances within the structural zone (such as steel cellular beams and composite steel floor trusses) are often pursued.

Unlike most low-rise design, construction schedules and sequencing can significantly impact design assumptions. A good example is the phenomenon of creep and shrinkage in reinforced concrete columns and walls. In reinforced concrete high-rises, an effort is made to equalize stress level to minimize this effect. Design must take into account adjustments and phasing that will be required, during construction, to ensure a defined design load flow and ultimate floor levelness.

Issues of robustness and redundancy of a high-rise building system are generally left to the discretion of the designer[3]. In British Standards and other codes such as the New York City building code, provisions to prevent progressive collapse are included. Redundancy is addressed by provisions that attempt to develop alternate load paths in extreme events. Robustness is addressed by identification of system key elements and specification of an extreme loading to be considered in their design.

Though this article is not long enough to address all of the issues that one might face in high-rise design, it offers a brief summary to get such projects started successfully. A number of good additional resources are available for those interested in more information[4,5]. Because tall building design results in larger computer analysis models as compared to low-rise design, the most important thing to keep in mind is fundamental behavior and to provide "sanity checks" along the way that ensure analytical modeling is accurately depicting the real structural behavior.

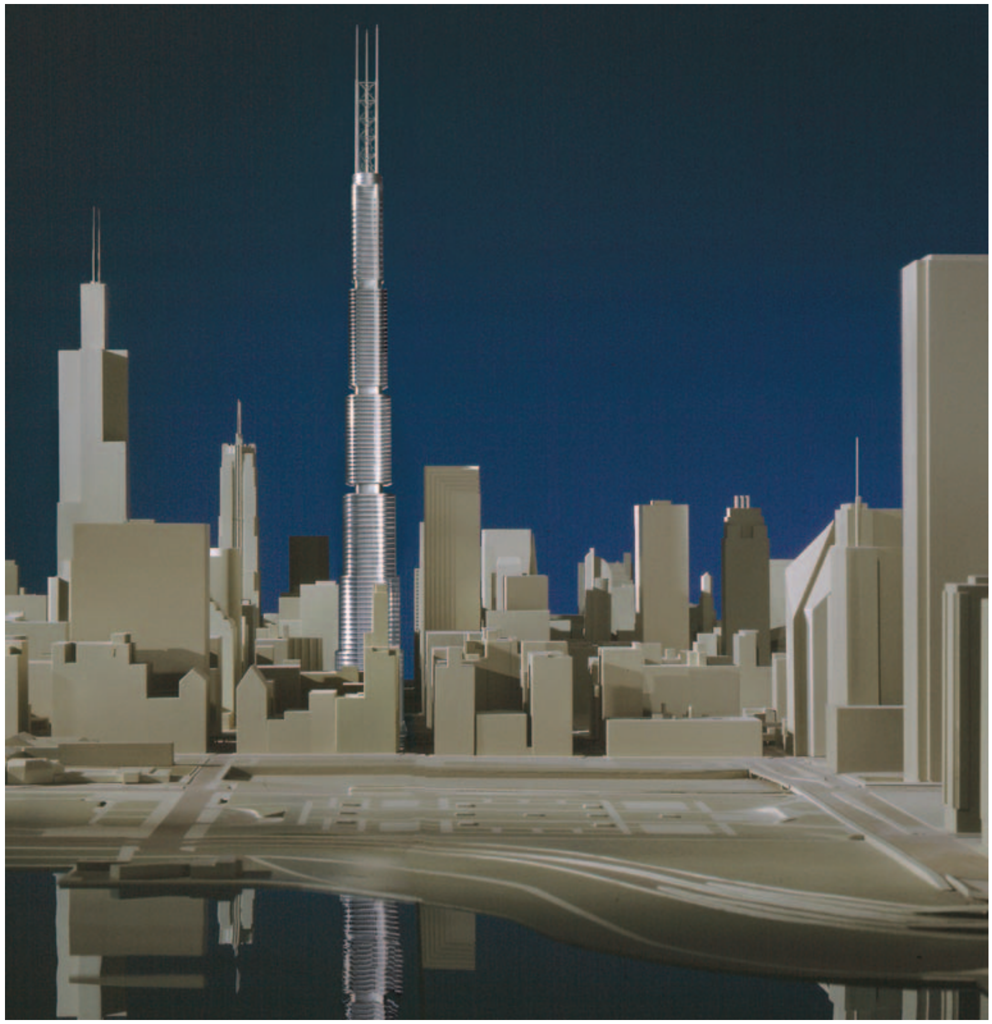

Figure 6: Aerodynamic Shaping of Buildings
(Courtesy of Skidmore Owings & Merrill, LLP & James Steinkamp, Steinkamp Ballogg)

John Zils, FAIA, SE, PE, is an Associate Partner with the firm Skidmore, Owings and Merrill LLP in Chicago. John has been with the firm since 1966. John Viise, SE, PE, is an Associate with Skidmore, Owings, and Merrill LLP, and has been with the firm since 1993.

References

1. Baker, W.F., 1992 Structural Engineering International, Published by IABSE, May 1992, "Energy-Based Design of Lateral Systems", pp. 99-102.

2. Baker, W.F., Novak, L.C., Sinn, R.C. and Viise, J.R., ASCE Structures Congress 2000, "Structural Optimization of 2000' Tall 7 South Dearborn Building".

3. Abdelrazaq, A.K., Sinn, R.C., ASCE Structures Congress 2000, "Robustness and Redundancy Design for Tall Buildings".

4. Taranath, B.S., 1998, 2nd Edition, Steel, Concrete, & Composite Design of Tall Buildings.

5. Smith, B.S., Coull, A., 1991, 1st Edition, Tall Building Structures: Analysis and Design.