CHAPTER 1

Design Considerations for Tall and Supertall Buildings

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1.1 Introduction

The structural design of tall and supertall buildings is as much an art as a science. First and foremost, a profound respect for the forces of nature is required. These forces, induced by gravity, wind, seismic effects, thermal conditions, and settlement, are extraordinary and must be carefully managed. Great skill is required in the arrangement and proportioning of the structural system so that the resulting building performs as intended and meets the owners' and occupants' expectations of safety and efficiency.

To achieve an efficient structural design, close collaboration with the architect and mechanical/electrical engineers is required. Although it may be possible to simply "apply" a structural design to a set architectural vision, the resulting building will likely be inefficient in the management of forces and distribution of materials. Close collaboration with the design team so that the structural concepts become integral with the architecture and functions of the building will lead to the best overall outcome (which resulted in economical structure and LEED platinum award). (See Fig. 1.1.)

Figure 1.1 300 North LaSalle. (*Photo by Magnusson Klemencic Associates.*)

1.2 Codes and Standards of Practice

Building codes around the world are generally developed with modest-scale buildings in mind. These codes do not directly address the unique aspects of tall buildings, and, in some instances, current code provisions may not be appropriate for application to tall buildings.

One of the most significant design considerations for most tall buildings is the response to wind. Although building codes stipulate minimum forces to be considered, most stop short of requiring that any other specific performance criteria be satisfied. For tall buildings, interstory drift and occupant comfort are generally the controlling design limits.

The minimum wind forces specified in most codes do not consider the potential dynamic response of a tall tower and may therefore grossly underpredict demand levels. In some tall, slender structures, vortex shedding can lead to very high crosswind effects that are many times the force levels stipulated by any code. In addition, wind buffeting from adjacent tall buildings may also increase demands. For these reasons, wind tunnel studies are generally appropriate to better characterize the response of a tall building to wind.

Few local jurisdictions have any set guidelines as to when a wind tunnel study is required, leaving this decision instead to the judgment of the design professional. Care must be exercised in determining whether a wind tunnel study is warranted because building height is not the only consideration. A very slender building of more modest height or a building with a unique geometry or offsets may be equally susceptible to the effects of dynamic amplification of the wind.

Several resources are available to design professionals to guide decisions relating to wind loading and recommendations for appropriate building performance acceptance criteria. A few of these resources are:

> "Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10)" (Reston, VA: ASCE, 2010).
>
> Nicholas Isyumov, "Criteria for Acceptable Wind-Induced Motions of Tall Buildings" (Paper presented at the International Conference on Tall Buildings, Rio de Janeiro, May 17–19, 1993).
>
> Parker D and Wood A. eds. Tall Building Reference Book New York, Routledge 2013.
>
> "Wind Actions on Structures," International Organization for Standardization, ISO 4354:1997(E), July 2007.

In regions of moderate to high seismicity, most building codes do not adequately address the unique aspects of tall buildings. In particular, tall buildings respond to ground shaking in a complex manner, where the fundamental mode of vibration is not necessarily the controlling response. Higher modes of vibration, excited by violent ground shaking in a period range of 1–3 seconds, may dominate the seismic response of a tall tower. Flexural and shear demands can be much greater than those envisioned by code provisions, and the distribution of these demands can be wholly inconsistent with the typical first mode response inherent in prescriptive building code provisions.

In recognition of the unique response of tall buildings, performance-based seismic design (PBSD) has become more prevalent in the last decade. With PBSD methodology, site-specific seismic demands are more rigorously defined at two or more levels of ground shaking. The structural design of a tall tower is then proportioned and detailed to meet specific performance objectives when subjected to each level of seismic ground shaking. Rather than hoping to meet performance objectives through prescriptive code provisions, a much more explicit and direct confirmation of performance is achieved through rigorous computer simulation. The resulting designs achieve a level of safety and reliability superior to that of a similarly designed structure following prescriptive code provisions.

The body of knowledge and experience supporting PBSD is still expanding, and refinements are ongoing. Several resources are available to guide the design professional, including:

> "Guidelines for Performance Based Seismic Design of Tall Buildings, Version 1.0, November 2010" (Pacific Earthquake Engineering Research Center Report No. 2010/05).

"An Alternate Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region, 2011 Edition" (Los Angeles Tall Buildings Structural Design Council).

"Recommendations for the Seismic Design of High-Rise Buildings" (Council on Tall Buildings and Urban Habitat, 2008).

1.3 Structural Systems

Structural systems used in the construction of tall buildings have evolved over the decades and can be very broadly categorized by type and era.

Early tall buildings were constructed as bearing-wall buildings. The Monadnock Building in Chicago (Fig. 1.2) is one of the most famous, with laid-in-place exterior brick walls upward of 6 feet thick supporting a 16-story, 150-foot-tall building.

With the advent of structural steel came a series of taller buildings that included three-dimensional frames of beams and columns such as Comcast Center, Philadelphia, Pennsylvania (Fig. 1.3). Many times, portions of the frames were in-filled with brick, clay tile, or concrete to provided added stiffness.

In the early 1960s and 1970s, a class of taller buildings evolved that incorporated exterior bracing systems. For the first time, the architecture of tall buildings was very expressive of the underlying structural system. Fazlur Khan was one of the most influential leaders in developing efficient structural systems coincident with the architecture of a tall tower. The John Hancock Building (Fig. 1.4) and Willis (Sears) Tower (Fig. 1.5), both located in Chicago, are two of the more recognizable towers of this era.

Figure 1.2 Monadnock Building (1893). (*Photo by Aric Austermann*.)

Figure 1.3 Comcast Center, Philadelphia, Pennsylvania. (*Photo by Vakaris Renetskis/Thornton Tomasetti*.)

Figure 1.4 John Hancock Building. (*Photo by Marshall Gerometta*.)

Figure 1.5 Willis (Sears) Tower. (*Photo by Marshall Gerometta*.)

Pressures in the real estate market to maximize efficiencies and provide unencumbered views for tenants caused engineers to turn away from external bracing systems in favor of core-based structural systems. A stiff, strong, central core surrounding the elevators, stairs, and support spaces of a tower provides maximum planning flexibility and completely unencumbered views. An example of this can be found in 111 South Wacker, located in Chicago (Figs. 1.6 and 1.7).

A core-based bracing system, however, is efficient only to a certain height (for reasons related to aspect ratio) due to the core's limited width. When a core alone does not provide enough stiffness to efficiently manage the forces and sway of a tower, outrigger systems are added, which effectively broaden the tower's stance (Fig. 1.8). To be effective, outriggers must engage perimeter columns, which can be quite large. This has resulted in series of towers that include mega columns, such as Taipei 101 in Taiwan (Figs. 1.9 and 1.10).

The most recent wave of tall buildings reflects a resurgence of some of the earlier structural concepts. The popularity of the so-called extreme architecture has resulted in the reintroduction of exterior bracings systems, with the CCTV Tower in Beijing a prime example (Fig. 1.11) or, in the case of supertall buildings, the Burj Khalifa in Dubai (Fig. 1.12), with a return to bearing-wall systems.

Figure 1.6 111 South Wacker. (*Photo by Magnusson Klemencic Associates*.)

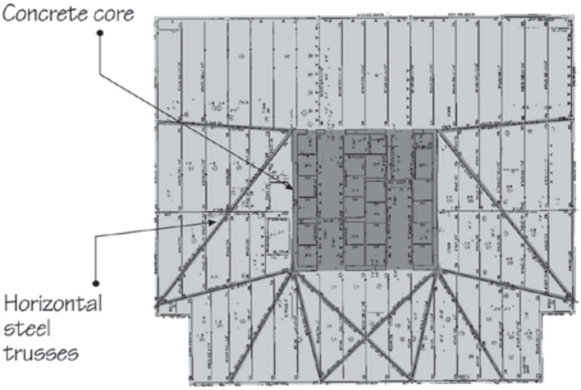


Figure 1.7 Floor plan, 111 South Wacker. (*Photo by Magnusson Klemencic Associates*.)

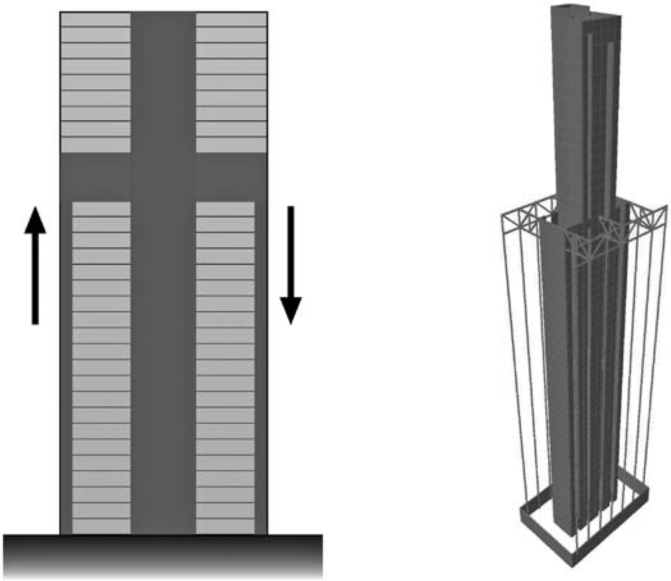


Figure 1.8 Outrigger system. (*Photo by Magnusson Klemencic Associates*.)

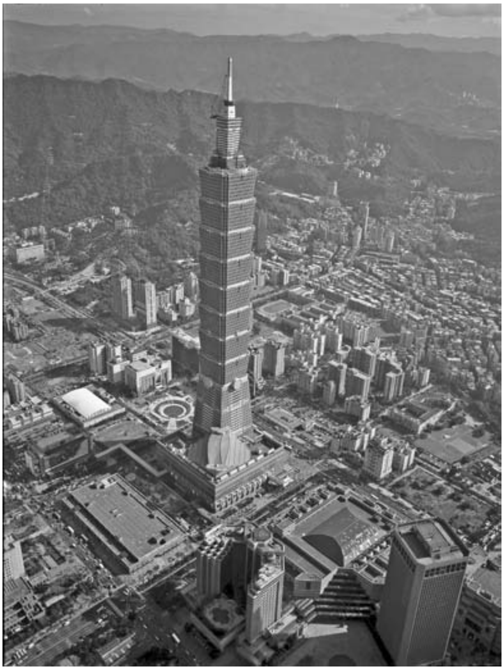


Figure 1.9 Taipei 101. (*Photo by Dugald MacKay*.)

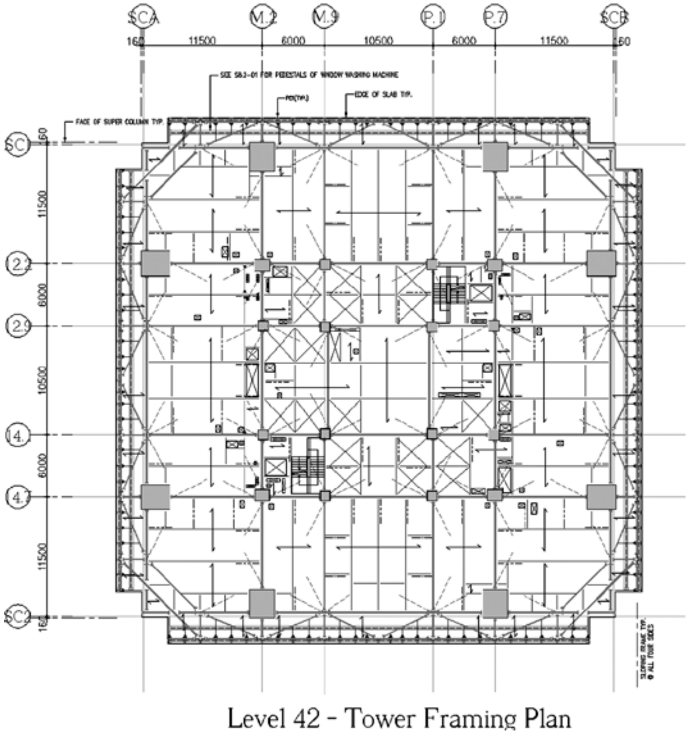


Figure 1.10 Floor plan, Taipei 101.

Figure 1.11 CCTV Tower. (*Photo by ARUP*.)

Figure 1.12 Burj Khalifa. (*Photo by SOM/Nick Merrick © Hedrich Blessing*.)

1.4 Wind Engineering

Wind, in many instances, is the dominant lateral force acting on a tall building. Even in earthquake-prone areas such as California and Southeast Asia, wind demands and considerations of occupant comfort may very well control the required strength and stiffness of a tower. Interestingly, though, building codes around the world generally address only strength requirements. Building codes generally do not regulate service-level performance related to the effects of building movements on architectural finishes and façades and the effects of building accelerations on occupant comfort. Defining and controlling specific performance objectives for building movements and accelerations are left to the discretion of the design professional.

Safety is, of course, first and foremost. Tall buildings can often experience dynamic wind-loading effects well in excess of those stipulated by prescriptive building code provisions due to potential dynamic interaction with the wind. To study and quantify the possible dynamic amplification of wind-loading effects, wind tunnel studies are commonly conducted.

1.4.1 Wind Tunnel Testing

Wind tunnel testing to determine the structural response of a tall tower can play a critical role in determining both the required strength and serviceability performance. Wind effects can be quantified in the wind tunnel based on the specific location, orientation, shape, and dynamic properties of the structure. These building-specific responses can then be directly addressed by arranging and proportioning the structure for a more effective and efficient design. In many instances, wind effects can be reduced through the consideration of alternate tower orientations, shapes, or structural systems.

1.4.2 Orientation and Shaping

The orientation and shaping of a high-rise structure can play an important role in the resulting response of the tower to wind. In some locations, a dominant wind direction exists. By rotating the orientation of the tower with respect to the dominant wind direction, the forces and resulting actions of the tower can be effectively managed and minimized.

Further, the shape of a tall tower can also play a critical role in managing wind effects. Prismatic shapes extending over significant heights can lead to the formation of vortices because the wind tends to "organize" around regular shapes with sharp corners. By altering the shape of the tower in plan or tapering the tower over the course of its height, wind effects can be profoundly reduced. Rounded building corners, reentrant corners, and the tapering of a tower with height all represent strategies to minimize the potential for the wind to organize in the form of significant vortices (Figs. 1.13, 1.14, and 1.15).

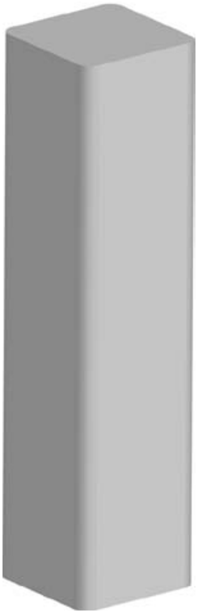


Figure 1.13 Rounded corner. (*Courtesy of RWDI.*)

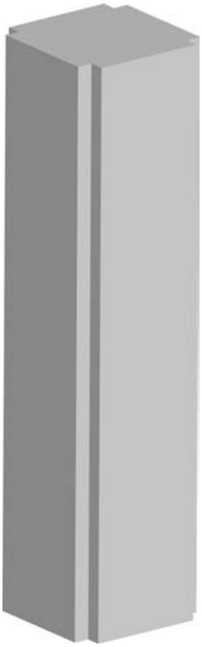


Figure 1.14 Reentrant corner. (*Courtesy of RWDI.*)

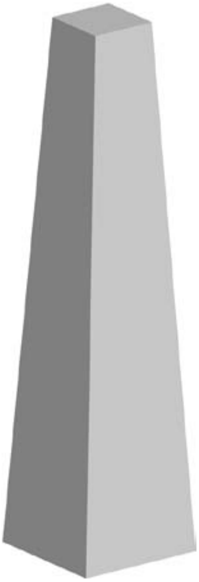


Figure 1.15 Tapering tower. (*Courtesy of RWDI.*)

1.4.3 Drag and Crosswind Effects

It is intuitive that wind acting on a surface causes pressure that, in the case of a tall building, results in the swaying of the tower along the direction of the wind (drag). What is less intuitive is that the same wind direction can actually cause the tower to sway about an axis parallel to the wind direction. This phenomenon is called a *crosswind effect*. The sway of the tower perpendicular to the wind direction is a result of the differential pressures created by vortex shedding. In some instances, this crosswind effect can result in demands on the structure significantly greater than the effects of drag.

1.4.4 Vortex Shedding and Buffeting

All buildings have dynamic properties directly related to their mass, stiffness, and inherent damping. In tall buildings, the dynamic response of the tower can interact with the wind at various speeds, resulting in the formation of vortices as the wind flows past the tower (Fig. 1.16). If the formation and subsequent shedding of these vortices become resonant with the dynamic properties of the tower, significant amplification of wind-induced actions can occur. Buffeting from adjacent tall buildings in dense urban environments can also significantly influence the forces acting on a tower (Fig. 1.17).

1.4.5 Interstory Drift

Typically, one of the controlling design parameters for a tall tower is interstory drift. Excessive interstory drift can have adverse impacts on architectural finishes and building façade systems. Limiting tower drifts to acceptable levels is important to the overall performance of the tower. However, most building codes do not prescribe specific drift limits, leaving their definition and application to the discretion

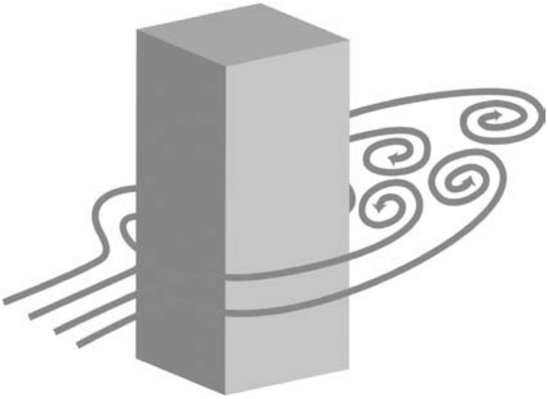


FIGURE 1.16 Vortex shedding. (*Courtesy of RWDI.*)

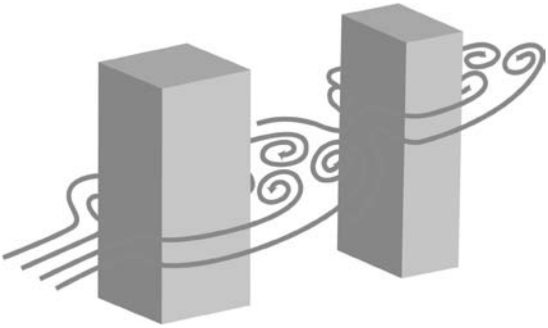


Figure 1.17 Buffeting. (*Courtesy of RWDI.*)

of the design professional. As a result, a wide range of demand levels and acceptable drift limits have been utilized.

Wind demand levels that are commonly considered in assessing interstory drift are 50-year, 20-year, and sometimes even 10-year return intervals. Fifty-year winds have been commonly considered because they are consistent with traditional code-based prescriptive force requirements. However, in many instances, this demand level has been deemed to be excessive, with 20- or 10-year winds considered instead.

Traditional interstory drift limits associated with these demand levels have typically been accepted as H/400 to H/500, where H is the story height. A much more thorough treatment of this subject can be found in "Serviceability Limit States Under Wind Load" (L. G. Griffis, *AISC Engineering Journal*, First Quarter, 1993).

1.4.6 Building Accelerations

Building accelerations due to the dynamic actions of a tower and the resulting impacts on occupant comfort are also often a controlling design consideration. Through wind tunnel studies, building accelerations can be predicted and compared to commonly agreed-on acceptance criteria. Traditionally, these acceptance criteria have been associated with the consideration of 10-year return period winds and defined as follows:

Office towers	20–25 mg
Residential and hotel towers	15–18 mg

More recently, acceptance criteria have emerged focused on more frequent 1-year return interval winds. In addition, research has suggested that occupant comfort is related to building frequency, resulting in a more complex range of acceptance criteria. A reference for further detail on this topic is "Basis for Design of Structures—Serviceability of Buildings and Walkways Against Vibration" [ISO 10137:2007(E), November 2007].

1.5 Seismic Engineering

The seismic engineering of tall buildings has advanced significantly in the last decade. In recognition of the unique response of tall structures to strong ground shaking, a design methodology based on PBSD principles has developed. PBSD considers directly and rigorously the site-specific seismic demands at two or more levels of ground shaking. The structural design of a tall tower is then proportioned and detailed to meet specific performance objectives when subjected to each level of seismic ground shaking. Rather than hoping to meet performance objectives through prescriptive code provisions, a much more explicit and direct confirmation of performance is achieved through rigorous computer simulation. The resulting designs achieve a level of safety and reliability superior to that of a similarly designed structure following prescriptive code provisions.

Some of the unique features of tall buildings that are better and more directly addressed through PBSD include the following:

- Complex dynamic behavior
- Axial forces
- Size effects
- Damping

1.5.1 Complex Dynamic Behavior

It is common for the response of a tall building to be heavily influenced by complex dynamic behavior, including the impacts of higher modes of vibration when subjected to strong ground shaking. Traditional engineering practice has focused on only the first translational mode of vibration when setting strength requirements and lateral force distributions. For tall buildings, the second or even third mode of vibration can be equally, if not more, important to the overall design.

The influence of these higher modes of vibration can result in significantly higher flexural demands that are well above a building's base (Fig. 1.18), as well as shear demands three to four times greater than those anticipated by a typical prescriptive design (Fig. 1.19). Failing to recognize and incorporate these demands into a tower's design can lead to undesirable and potentially unsafe results.

1.5.2 Axial Forces

In tall buildings, due to the significant number of floor levels, axial forces in supporting columns and walls typically grow to very high values. To support these tremendous forces, columns and walls can be quite large. As these elements grow larger and larger, they tend to attract additional axial forces due to their interaction with the floor framing system and/or bracing system. The accumulation of these effects can be significant. Great care must be taken in the structural design

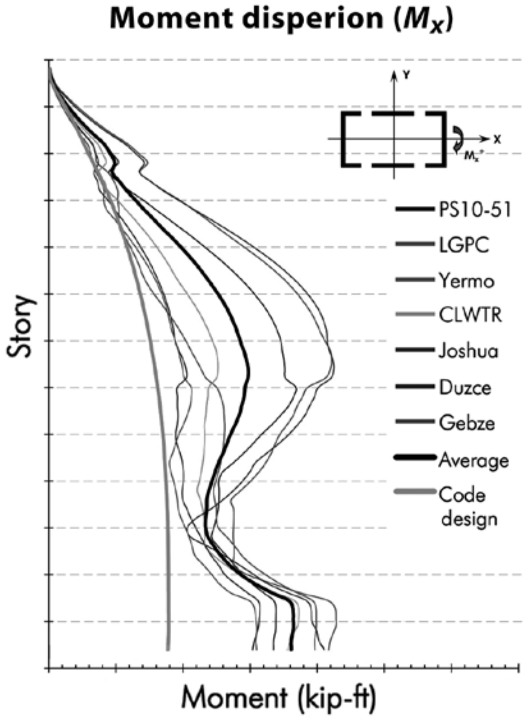


Figure 1.18 Flexural demands related to higher modes of vibration. (*Courtesy of Magnusson Klemencic Associates*.)

of the tower to adequately address this possibility and to protect columns against axial failure, which could prove to be catastrophic.

1.5.3 Size Effects

As buildings grow taller, the size of columns, walls, and foundations tend to grow proportionally. Most of the existing research forming the basis of design provisions in building codes for steel and concrete is the result of small-scale testing. As structural elements grow to enormous sizes, extrapolating the research results and associated code provisions becomes questionable. Consider, for instance, a column at the base of a tall building that is 3.0 m sq, with a story height of 4.0 m. Code provisions and the underlying research clearly do not contemplate such proportions.

1.5.4 Damping

A modest amount of data exists regarding the natural damping inherent in a tall building. Unfortunately, there is not a great deal of instrumentation of tall buildings, especially those subjected to strong ground shaking. Data that is available suggests that the amount of

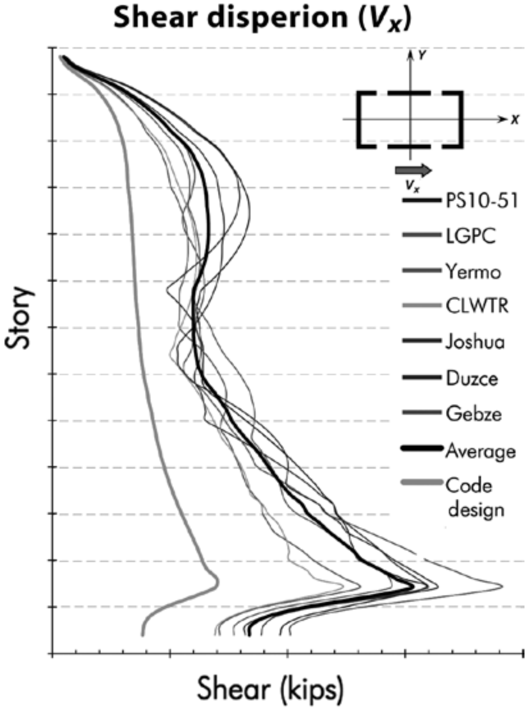


Figure 1.19 Shear demands related to higher modes of vibration. (*Courtesy of Magnusson Klemencic Associates*.)

natural damping inherent in tall buildings is modest, in the range of 2–3%; that is much lower than the traditional value of 5% normally considered in seismic design. Lower amounts of natural damping can lead to higher seismic demand levels throughout the height of the tower. Careful consideration of the amount of damping assumed in linear elastic analysis or calculated in nonlinear response history analysis must be carefully considered.

1.5.5 Guidelines on Performance-Based Seismic Design

Guidelines and recommendations for the appropriate and consistent application of PBSD have been published by a number of structural engineering groups, including the following:

- Structural Engineers Association of Northern California
- Department of Building Inspection, City and County of San Francisco
- Los Angeles Tall Buildings Structural Design Council
- Pacific Earthquake Engineering Research Center
- Council on Tall Buildings and Urban Habitat

Although there are some differences in the specific recommendations offered by each of these groups, the consensus view is that PBSD allows structural engineers to more appropriately and directly address the unique aspects of the seismic design of tall buildings.

1.6 Elastic Shortening, Creep, and Settlement

Elastic shortening and the long-term effects of creep of the vertical supporting elements and the potential foundation settlement of a high-rise building are important design considerations. The distribution of stresses throughout the tower and the general levelness of floor slabs are directly impacted by each of these effects.

Although it may seem obvious and even somewhat trivial to calculate the effects related to elastic shortening. However, it has measurable impact on structure of buildings. In fact, the management of vertical shortening of a tall tower is one of the most difficult challenges faced by the design professional. Many variables influencing the outcome enter the picture, including:

- Construction sequence.
- Temperature.
- Humidity.
- Actual material properties.
- Actual loads imposed on the building.

Considering these variables, predicting vertical building movements is not an exact calculation with only one outcome. Sensitivity analysis to the variables leads to a range of possible outcomes. The most rigorous analysis considers all of the topics previously mentioned in a sequential computer simulation of the planned construction schedule. A range of possible outcomes must be carefully assessed for any possible adverse effects.

In addition to elastic shortening and creep of vertical supporting elements, foundation settlement can also contribute to an adverse distribution of stresses and/or building movements. It is critical that the structural engineer work in close collaboration with the project's geotechnical engineer to understand and quantify the effects of the interaction between the building's structure/foundation and the underlying soil/rock. Vertical movements due to foundation settlement can equal or sometimes exceed the movements due to vertical shortening and creep.

To adequately assess the likely performance of a tower's foundation, an iterative analysis may be necessary to achieve conformance between the load distribution predicted by the structural engineer and the settlement predictions calculated by the geotechnical engineer.

Combining engineering predictions with careful monitoring during construction allows for the possibility of making corrections during construction. These corrections may include constructing the tower to initially higher elevations or occasionally overpouring, shimming, or trimming the vertical supporting elements of the tower. Although the goal is to build the tower floors as closely as possible to the so-called design elevation, it is likely that the floor elevations will ultimately not coincide with theoretical. To allow for this reality, adequate tolerances must be thoughtfully introduced into all of the tower detailing.

1.6.1 Analysis

Powerful computer programs are available today that "automate" much of the structural design process. In the case of tall buildings, great care must be exercised in the analytical approach and in the assumptions made in the analysis.

Analytical Approach and Elastic Analysis

Most elastic analysis computer programs first assemble the complete stiffness matrix for the structure from the foundation to the roof. The completed stiffness matrix is then combined with the loading matrix to calculate the resulting stresses and deformations. Postprocessing programs are then sometimes used to complete the structural member selection and/or design without any review or interaction by the design professional. Although this process can be quite efficient, especially given the scale of tall buildings, it can also be fraught with erroneous results.

Tall buildings are typically built from the foundation to the roof, experiencing loading incrementally. Depending on the arrangement of the structural system, significant fictitious stresses due to gravity may be reported by a simple computer analysis. Thoughtful consideration of this possibility is required. In many instances, gravity and lateral loading analyses are completed separately, and the results are superimposed to avoid such issues. In other instances, a more rigorous sequential analysis is conducted wherein the structure is actually built and loaded incrementally as part of a computer simulation. This latter approach is numerically intense and not commonplace.

In addition to thoughtfully considering the overall computer modeling approach, great care must be exercised in modeling assumptions regarding:

- Design versus actual (predicted) material properties.
- Effective stiffness parameters considering the effects of concrete cracking.
- Boundary conditions.
- Diaphragm stiffness.
- Damping values.

Nonlinear Analysis

In recent years, nonlinear analysis has become more popular as computer software has become more readily available and user-friendly.

This is particularly true for seismic design in which nonlinear response is fundamental to the overall design philosophy. Although these computer programs are powerful in their capabilities, even greater care needs to be exercised in developing the nonlinear response parameters for various building elements. Further, the interpretation of analytical results, as judged against research and testing outcomes, requires insight and a broad understanding of the sensitivities.

1.7 Exterior Façades

The support of exterior wall systems is a critical consideration in the design of tall buildings. Vertical shortening of the tower due to gravity, differential floor deflections, and interstory drift due to wind or seismic actions all impact the design and detailing of the exterior façade. The many types of exterior wall systems can be grouped generally into two categories:

1. Curtain wall systems, wherein the façade system is continuous and external to the structural floor system (Fig. 1.20)
2. Window wall systems, wherein the façade system is not continuous but instead rests atop each floor (Fig. 1.21)

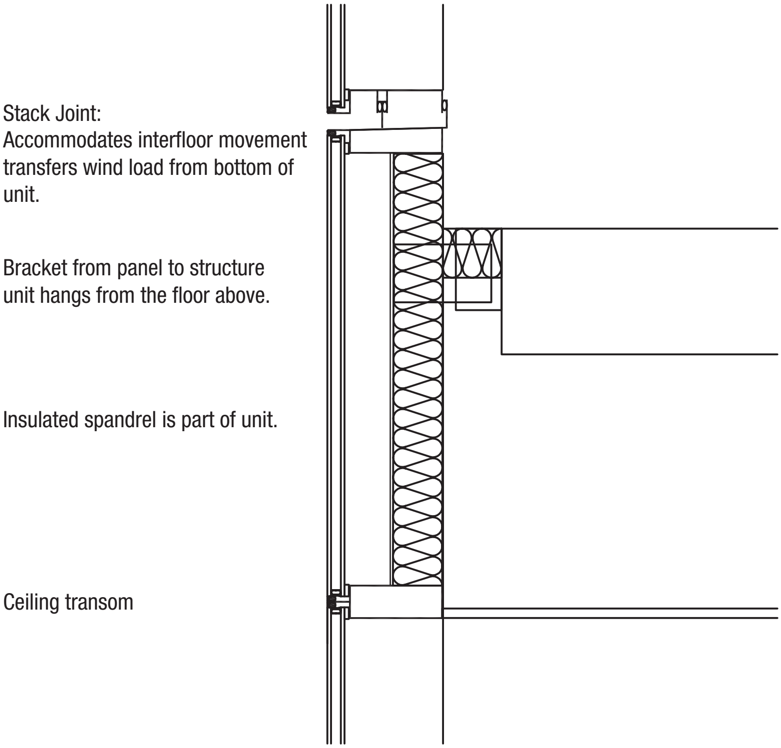
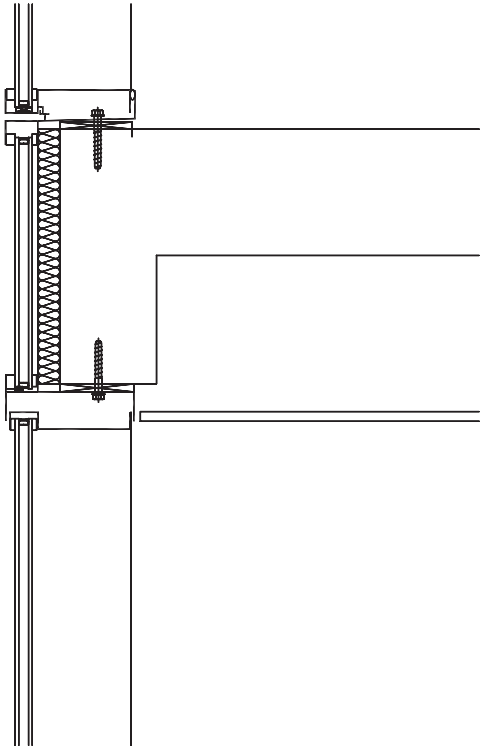


FIGURE 1.20 Curtain wall system. (*Courtesy of Front, Inc.*)



Sill Track:
Supports base of panel
and top of slab edge cover
fixed directly to slab.

Slab Edge Cover:
May be insulated metal panel or
opacified glass, in some climates slab
edge is exposed.

Head Track:
Accommodates inter-floor movements
and top of panel wind load.

Figure 1.21 Window wall system. (*Courtesy of Front, Inc.*)

In either case, the ability of the wall system to respond to the anticipated movements of the structure is critical. These movements include:

- Vertical shortening of the tower due to gravity loads.
- Differential movement of one floor adjacent to the next.
- Interstory drift (sway), resulting in horizontal movement across the plane of the façade.

These various movements must be thoughtfully accommodated in the connections and jointing of the façade to avoid undesirable actions or damage. In addition, tolerance must be built into the various connection locations because it is unlikely that the floor slabs will be in their precise design location.

1.8 Summary

The design of tall buildings is very much a specialty. Although powerful graphical and analytical tools exist today that allow one to imagine and design increasingly complex towers, these tools cannot replace the decades of practical experience and knowledge gained through the construction of countless high-rise towers. The very best designs take full advantage of this experiential knowledge, combining it with the powerful tools available today to envision the towers of tomorrow.

1.9 References

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