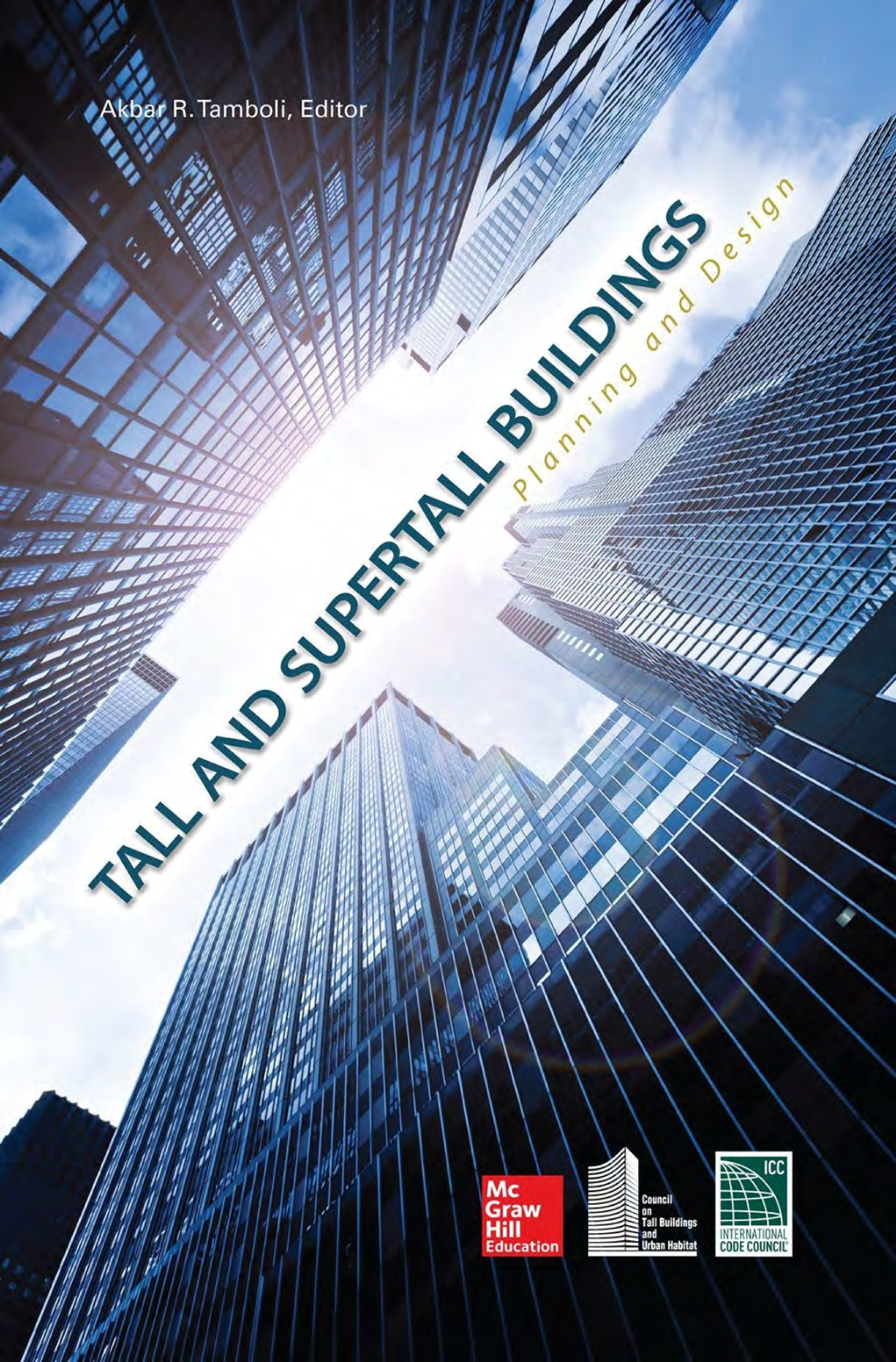

Akbar R. Tamboli, Editor

TALL AND SUPERTALL BUILDINGS

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Tall and Supertall Buildings: Planning and Design

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Contents

Contributors

William F. Baker, P.E., S.E., F.ASCE *Partner, Skidmore, Owings & Merrill LLP, Chicago, Illinois* (CHAP. 7)

Melissa Burton, Ph.D. *Regional Manager North America, BMT Fluid Mechanics, New York, New York* (CHAP. 11)

Volker Buttgereit, Ph.D. *Managing Director, BMT Fluid Mechanics, Teddington, Middlesex, U.K.* (CHAP. 11)

Stefano Cammelli, P.E., M.S. *Head of Civil Structures, BMT Fluid Mechanics, New York, New York* (CHAP. 11)

Anton Davies, Ph.D., P.Eng., FCAE *Chairman, Rowan, Williams, Davies & Irwin Inc., Guelph, Ontario, Canada* (CHAP. 10)

Khaldoun Fahoum, Ph.D. *Senior Associate/Vice President, Langan Engineering & Environmental Services and Langan International, Abu Dhabi, Dubai* (CHAP. 9)

Rudolph Frizzi, P.E. *Managing Principal/Executive Principal/Vice President, Langan Engineering & Environmental Services and Langan International, Elmwood Park, New Jersey* (CHAP. 9)

Marc Gallagher, P.E. *Principal/Vice President, Langan Engineering & Environmental Services and Langan International, New York, New York* (CHAP. 9)

Jon K. Galsworthy, Ph.D., P.Eng. *Principal/ General Manager—Loads & Effects, Rowan, Williams, Davies & Irwin Inc., Guelph, Ontario, Canada* (CHAP. 10)

Mike Gibbons, M.E.Sc. *Technical Coordinator/Wind Climate Specialist, Rowan, Williams, Davies & Irwin Inc., Guelph, Ontario, Canada* (CHAP. 10)

Ramin Golesorkhi, Ph.D., P.E., G.E. *Principal/Vice President, Langan Engineering & Environmental Services and Langan International, San Francisco, California* (CHAP. 9)

Peter A. Irwin, Ph.D., P.Eng. *Senior Executive Consultant/Past President, Rowan, Williams, Davies & Irwin Inc., Guelph, Ontario, Canada* (CHAP. 10)

Leonard M. Joseph, P.E., S.E. *Principal, Thornton Tomasetti, Irvine, California* (CHAPS. 4 AND 5)

Ron Klemencic, P.E., S.E. *Chairman, Magnusson Klemencic Associates, Seattle, Washington* (CHAP. 1)

George Leventis, P.E. *President, Langan Engineering & Environmental Services and Langan International, New York, New York* (CHAP. 9)

Bujar Morava, Ph.D., P.Eng. *Technical Director/Associate, Rowan, Williams, Davies & Irwin Inc., Guelph, Ontario, Canada* (CHAP. 10)

James J. Pawlikowski, S.E., LEED AP *Associate Director, Skidmore, Owings & Merrill LLP, Chicago, Illinois* (CHAP. 7)

Alan Poeppel, P.E. *Senior Principal/Senior Vice President, Langan Engineering & Environmental Services and Langan International, New York, New York* (CHAP. 9)

Dennis Poon, P.E. *Vice Chairman, Thornton Tomasetti, New York, New York* (CHAP. 6)

Frank Rollo, CEL, LGE *Senior Consultant, Langan Engineering & Environmental Services and Langan International, San Francisco, California* (CHAP. 9)

Valerie Sifton, P.Eng. *Specialist—Wind Climatology, Rowan, Williams, Davies & Irwin Inc., Guelph, Ontario, Canada* (CHAP. 10)

Robert Sinn, P.E., S.E., F.ASCE *Principal, Thornton Tomasetti, Chicago, Illinois* (CHAP. 8)

Asif Syed, P.E., LEED AP BD+C *Partner, STE Engineering, New York, New York* (CHAP. 2)

Vincent Tang, M.A.Sc. *Ventilation Modeling Specialist, Rowan, Williams, Davies & Irwin Inc., Guelph, Ontario, Canada* (CHAP. 10)

Billy Tse, P.E. *Senior Associate, Thornton Tomasetti, New York, New York* (CHAP. 6)

Peter Weismantle, F.AIA, RIBA *Director of Supertall Building Technology, Adrian Smith + Gordon Gill Architecture, Chicago, Illinois* (CHAP. 8)

Hanqing Wu, Ph.D., P.Eng. *Technical Director/Principal, Rowan, Williams, Davies & Irwin Inc., Guelph, Ontario, Canada* (CHAP. 10)

Hadi Yap, Ph.D, P.E., G.E. *Senior Associate/Vice President, Langan Engineering & Environmental Services and Langan International, San Francisco, California* (CHAP. 9)

John Zils, P.E., S.E., F.ASCE, F.AIA *Associate Partner Emeritus, Skidmore, Owings & Merrill LLP, Chicago, Illinois* (CHAP. 3)

Preface

This is a book that assembles and explains the planning and design and construction of tall and supertall buildings.

It is intended to help architects and engineers and students of civil engineering, mechanical engineering, and architecture with an authoritative reference work on tall and supertall buildings. Among the buildings covered are most of the state-of-the-art tall and supertall buildings from Sears Tower (Willis Tower) to Kingdom Tower.

The design chapter is devoted to loading criteria used, including seismic and other environmental considerations.

Wind forces have the greatest impact on the design of supertall buildings. In two chapters, this is covered in detail by leading experts.

Because each project site is faced with special situations on foundation design, the foundation chapter deals with how various types of foundations could be used in different situations.

Mechanical systems impact greatly on the structural aspects; therefore, a special chapter explains the most efficient way to deal with this situation.

Architectural interaction in minimizing wind loading impact is explained in many chapters where it had a very large impact on the design.

The 11 chapters have been written by 30 contributors chosen for their eminence and wide experience in tall and supertall building projects. They have presented their material in ready-to-use form.

Each chapter treats very large projects big enough to fill a book in itself. The contributors had to select material that, in their judgment, is likely to be most useful to the greatest number of users. However, sources for additional material are noted for most of the topics that could not be treated in sufficient detail.

The concepts and methods explained in these chapters will be helpful in guiding design and planning decisions for tall and supertall buildings. This book will serve as a working manual for engineers, architects, government officials, and others whose duties require them to make decisions about the planning and design of tall and supertall buildings.

Each chapter was carefully arranged to minimize duplication of the content and to see that important topics were fully covered.

The editor gratefully acknowledges all the contributors' painstaking efforts to prepare quality manuscripts, their cooperation in editing their work, and their patience during the time it has taken to bring the book to completion.

If users find any errors in the book, the editor will be grateful for having these called to his attention. Such errors will be corrected in the next printing.

In closing, the editor hopes that all users worldwide will find this book helpful in their planning and design of tall and supertall buildings.

Akbar R. Tamboli, P.E., F.ASCE

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The editor would like to acknowledge the input and help received from many people, specifically those listed here, for the time and encouragement they provided.

- Charles Thornton, founding principal, Thornton Tomasetti
- Richard Tomasetti, founding principal, Thornton Tomasetti

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The editor would also like to acknowledge the help and assistance provided by Michael McCabe, senior editor; Stephen Smith, editing manager; and Bridget Thoreson, associate editor, who put forth invaluable support during the process of preparing the manuscript. Also, thanks go to many other individuals at McGraw-Hill Education and MPS Limited who were responsible for bringing the book to press, including Fred Dahl, copy editor; A. Nayyer Shamsi, proofreader; Robert Swanson, indexer; and Charu Khanna, project manager.

Thanks also go to Antony Wood, executive director of the Council on Tall Buildings and Urban Habitat, for providing encouragement for the book, and to John Henry, P.E., for his technical review of the codes and standards sections on behalf of the International Code Council.

Finally, the editor wishes to extend his thanks and appreciation to his wife Rounkbi and to his children Tahira, Ajim, and Alamgir for their patience and understanding during the preparation of this book.

About the Editor

Akbar R. Tamboli, P.E., F.ASCE, is senior vice president and principal at Thornton Tomasetti structural engineers, one of the foremost structural engineering firms. He was formerly vice president and project manager with Cantor Seinuk consulting engineers in New York, where he was responsible for several major projects. A fellow of the American Society of Civil Engineers and a professional engineer, Mr. Tamboli is the editor of *Steel Design Handbook: LRFD Method* and *Handbook of Structural Steel Connection Design and Details*, now in its second edition.

CHAPTER 1

Design Considerations for Tall and Supertall Buildings

Ron Klemencic

Magnusson Klemencic Associates

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).

CHAPTER 5

Taipei 101

Leonard M. Joseph

Thornton Tomasetti

The Taipei 101 complex has numerous special and unique features, as befits an iconic skyscraper breaking the building height record in 2004 by reaching 508 m (1667 ft) into the sky. The unique features start with the 30,277-m^2 (326,000 ft^2) site, which was developed under a 70-yr Build-Operate-Transfer agreement signed in 1997 between the Taipei City Government and Taipei Financial Center Corporation (TFCC). TFFC had 11 businesses as backers and 14 shareholders, all major domestic companies. In the early planning stages, office space demand at the site was projected to be up to 200,000 m^2 (2.15 million ft^2). Groundbreaking occurred at the start of 1999, and steel erection began 18 months later. The completed project of 374, 220 m^2 (4 million ft^2) includes roughly equal areas for retail/parking space, which opened in November 2003, and tower space, which opened at the end of 2004 (see Fig. 5.1).

5.1 Architectural Design Features

Although the site could have held several smaller towers with the same cumulative office space, a single tall tower provides all tenants with the benefit of the same landmark address, justifying the cost premium associated with supertall construction. A height of roughly 100 stories was determined by dividing the desired gross office area by the size of a commercially preferred office floor plate. A count of 101 stories was selected to represent a goal of excellence.

The tower profile envisioned by architect C. Y. Lee reflects local cultural touchstones. Pagodas and bamboo stalks are referenced by having stacked vertical modules. The symmetry of even numbers, and lucky number 8 (that number and the word "wealth" sound the same when spoken) are expressed by placing eight modules of eight stories each, atop level 26 of a truncated pyramidal base over a five-story deep basement. Each upper module becomes wider as it rises, creating an impression of opening flowers. The resulting outward-leaning perimeter

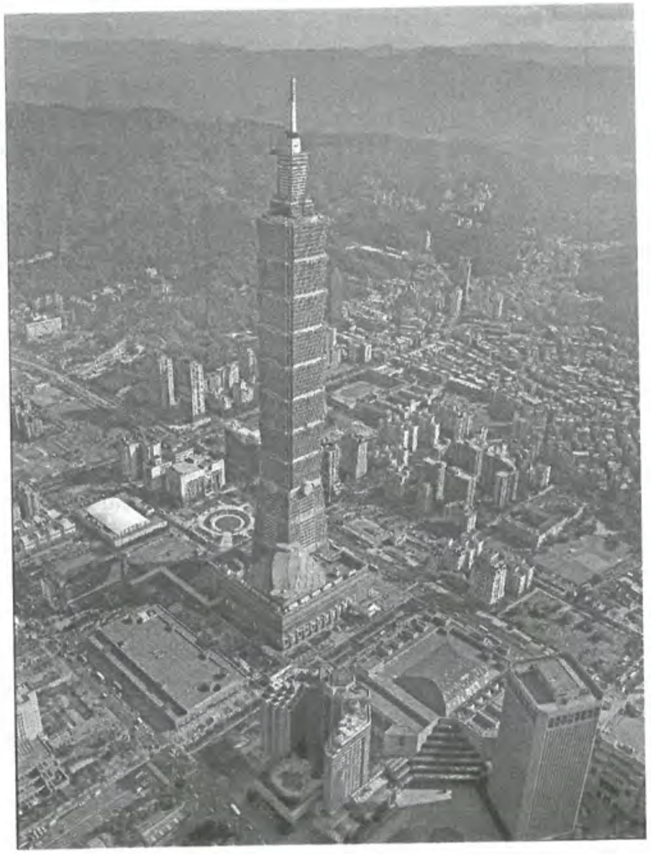

Figure 5.1 Aerial view of the Taipei 101 tower rising above its podium from the southeast corner of the site. *(Courtesy C Y Lee & Partners.)*

walls also provide windows a degree of self-shading against solar gain. Above a roof deck at level 91, one more module, with matching wall slopes but a smaller footprint, encloses the elevator overruns, machine rooms and other functions. A spire with communications equipment and aviation warning lights completes the tower composition.

The architect, structural engineer of record Evergreen Consulting Engineering, Inc., and structural consultant Thornton Tomasetti worked closely at key points in the design and approval process. The building MEP systems were designed by Continental Engineering Consultants and peer reviewed by Lehr Associates. Key roles were played by Sino Geotechnology, Inc. as the geotechnical consultant, RWDI as the wind consultant, and Motioneering as the damping consultant.

Project management was performed by Turner Steiner International, and the General Contractor was KTRT Joint Venture, including Kumagai Gumi, Taiwan Kumagai, RSEA Engineering Corp., and Ta-Yo-Wei Construction Company.

5.2 Design Criteria and Material Selection

The general structural design approach followed U.S. practice, for example, using American Institute of Steel Construction LRFD design criteria for the concrete-filled steel box columns. The Taiwan concrete code also followed the American Concrete Institute ACI-318 standard. Taiwan seismic provisions were consistent with the seismic design philosophy of codes in the United States such as the Uniform Building Code.

The extensive use of steel framing for this tower—107,000 tons (118,000 T) of steel members and connections, including SM570M (60-ksi yield) high-strength, high-ductility steel plate in box columns—was practical because Taiwan has an advanced, competitive structural steel fabrication and erection industry. The use of steel framing was helpful to minimize building mass, which is beneficial both to reduce seismic demands on the structure and to minimize gravity demands on the foundations. Because the tower foundation was expected to require long piles to reach good bearing strata, a reduction of tower weight offered a clear economic benefit. In addition, steel framing can be erected rapidly—using four cranes on the tower and four on the podium—and concrete for slabs can be placed when convenient rather than in a particular sequence. For all these reasons, the preferred floor system consisted of concrete-filled metal deck slabs on composite steel beams (see Fig. 5.2).

Figure 5.2 Construction photo during erection of the lower portion of the tower shows multiple cranes for tower and podium, two supercolumns on each face, and two supplementary supercolumns on each face.

CHAPTER 7

Burj Khalifa

William F. Baker, James J. Pawlikowski

Skidmore, Owings & Merrill LLP

7.1 Overview

The intention of the Burj Khalifa is not simply to be the world's highest building; it is to exemplify the world's highest aspirations. At 828 m, the Burj Khalifa is the world's tallest structure, passing all previous height records. Designing and constructing such an ambitious project required a combination of reliable methodologies, repetitive forms, technological advances, and innovating thinking. However, because its building stature has never been attempted, before it was necessary to use technologies and methods that were of sound development and practice. The designers sought to be able to use conventional systems, materials, and construction methods, modified and utilized in new capacities, to achieve such a visionary goal.

Construction of the Burj Khalifa, the centerpiece of a $20 billion development located just outside of downtown Dubai, began in January 2004 and concluded in January 2010. The assignment consisted of the tower itself as well as an adjacent podium structure, a separate six-story office annex, and a two-story pool annex. The 280,000-m², reinforced-concrete multiuse tower is designed predominantly not only for residential and office use, but it also contains retail stores and a Giorgio Armani hotel (Fig. 7.1). The tower and podium structure have a combined area of 465,000 m².

7.2 Design Concept

From the start, the owner, Emaar Properties PJSC (Dubai), desired the tower to be the world's tallest. The initial concept was 518 m high but grew during the design process to 828 m.

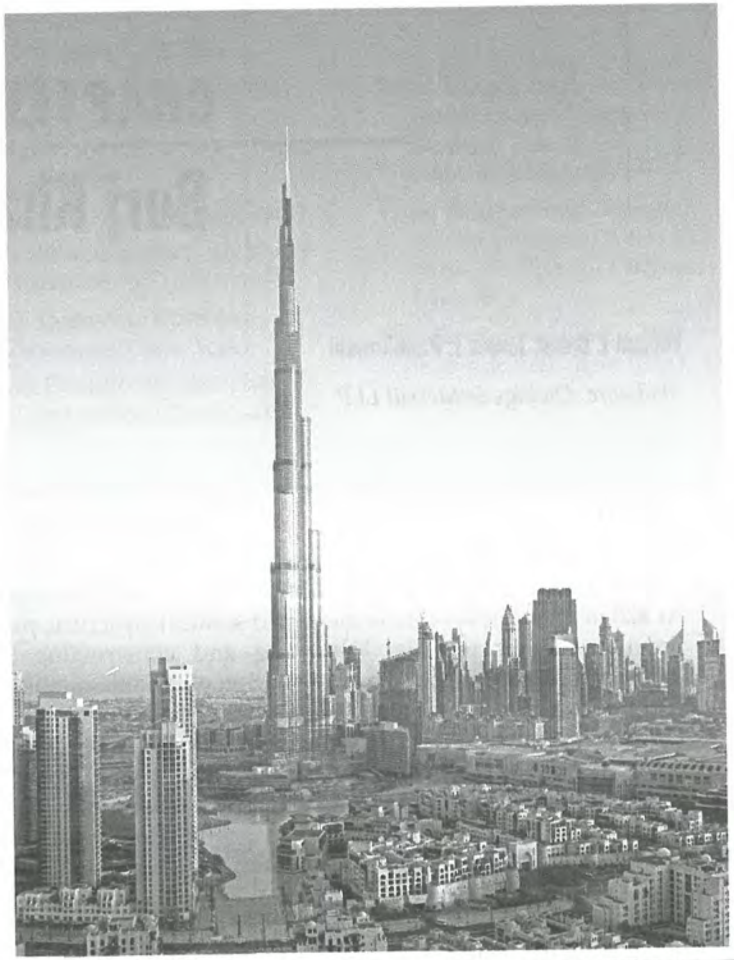

Figure 7.1 Dubai skyline.

7.3 Architectural Design

The principal design concept of the tower is an organic form with triaxial geometry and spiraling growth that can be easily seen in the final design. The floor plan of the tower consists of a triaxial, Y-shaped plan, formed by having three separate wings connected to a central core (Fig. 7.2). As the tower rises, one wing at each tier sets back in a spiraling pattern, further emphasizing its height. The Y-shape plan is ideal for residential and hotel use in that it allows the maximum views outward without overlooking a neighboring unit. The wings contain the residential units and hotel guest rooms, with the central core housing building services and all of the elevators. The tower is serviced by five separate mechanical zones, located approximately 30 floors apart over the height of the building. Situated above the occupied reinforced concrete portion of the building are the structural steel spire, housing communication, and mechanical floors, and a large open void, completing the architectural form of the tower. The result is an efficient building in terms of its functionality, structural system, and response to wind, while maintaining the integrity of the initial design concept.

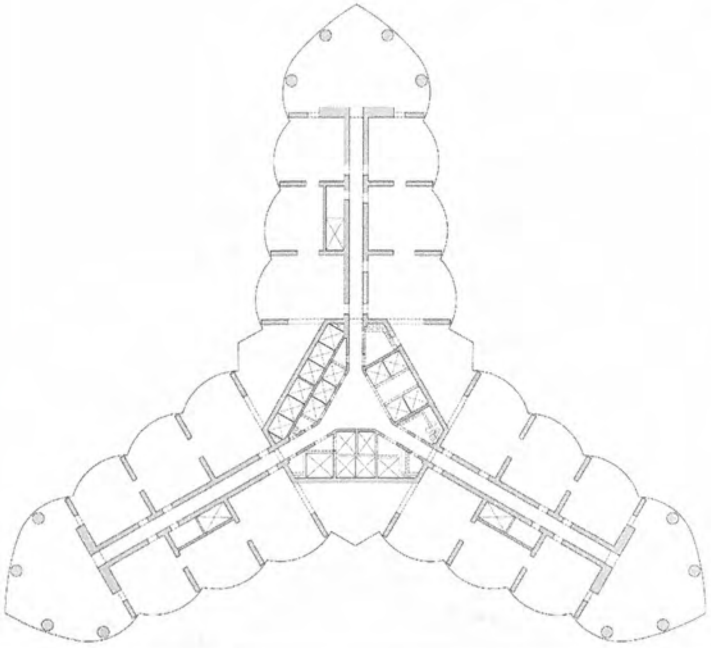

Figure 7.2 Typical floor plan.

7.4 Engineering the Y: The Buttressed Core

In the initial stages of the project, architects and engineers worked closely to determine the shape of the tower so that its structural system and wind responses would be efficient and well behaved. Their close collaboration is exhibited in the final spiraling shape of the tower. In addition to its aesthetic and functional advantages, the spiraling Y serves to reduce the wind forces on the tower.

To accomplish this, a new structural system was developed. Named the "buttressed core," the system consists of high-performance concrete walls used to create three wings that buttress one another via a six-sided central core, or hexagonal hub (Fig. 7.3). The premise is simple: The central concrete core provides torsional resistance. It acts as an axle that encloses the elevators and resists the twisting of