



Bungale S. Taranath, Ph.D., P.E., S.E.

TALL BUILDING DESIGN

Steel, Concrete, and Composite Systems



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Preface

Tall buildings have a unique appeal, even an air of romance and mystery associated with their design. The adoration that super- and ultratall buildings command lies in their apparent freedom from gravity loads—they do not just stand tall, they seem to do so effortlessly resisting gravity as well as laterally directed force generated by wind gusts and seismic ground motions.

Tall buildings have fascinated humans from the beginning of civilization—the primary motivation was to create monuments rather than human habitats. Today's structures, on the other hand, are human habitats—not allowed by economics and design to be nearly as simple, heavy, stiff, and robust as their relatively recent counterparts such as the Empire State Building of the 1930s.

Although tall buildings are unique from certain aspects such as consideration of lateral deflection, their design, in a manner of speaking, is similar to the design of their lower brethren. Thus the material presented in this book applies equally to not-so-tall buildings as well.

This book is an outgrowth of my previous publications. It attempts to maintain the same basic approach: first to establish a firm understanding of the behavior of structural members and systems and then to develop proficiency in the methods used in current design practice with particular reference to the provisions of the following publications:

- Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-10 Specifications
- Specifications for Structural Steel Buildings, ANSI/ASCE 360-10
- Seismic Provisions of Structural Steel Buildings, ANSI/AISC 341-10
- Pre-qualified Connections for Special and Intermediate Steel Moment Connections for Seismic Applications, ANSI/AISC 358-10
- Building Code Requirements for Structural Concrete, ACI 318-11
- Seismic Rehabilitation of Existing Buildings, ASCE/SEI 41-06

Much of the present-day design is carried out using commercially available computer software or spreadsheets written by individuals for their particular needs. It is generally recognized that mere proficiency in navigating through computer software is inadequate, and often dangerous, for successful professional practice. Moreover, code provisions and procedures are subject to change periodically, oftentimes too frequent for the comfort of design professionals. To understand and keep abreast of these rapid developments is no small task. To do so successfully, the engineer needs a thorough grounding in the behavior of structural components and systems. Familiarity in the present-day methodology is essential to design structures that comply with legally adapted standards and to do so safely, economically, and efficiently.

The fundamental laws governing the static and dynamic analysis of structures subjected to the forces of nature are over 150 years old. Therefore, anyone who claims that they have invented a new fundamental principle is a victim of their own knowledge gap. The real challenge in writing a text in the structural engineering field, then, is to describe in physical and practical terms the underlying theory and how it relates to the modern world, where structural analysis and even the interpretation of analysis results are typically done by the computer.

Thus, the foremost objectives of this book are as follows:

- To promote a better understanding of the structural behavior of steel, concrete, and composite members and systems.
- To develop a cohesive wind- and earthquake-resistant design procedure for tall building structures and their lower brethren.

- To bridge the gap between two design approaches, one based on skill and experience and the other that relies upon computer skills, to imagine the design possibilities when that wonderful ability—the intuition we humans have—marries unfathomable precision and numerical accuracy.
- To cultivate imaginative approaches by presenting examples, and where appropriate relate these specific examples to building codes and standards that are essential and mandatory tools of the trade.
- To address the question frequently proposed to the designer by architects: “Can we do this?” In tackling this seemingly simple question, we need to acknowledge that in the fast paced world we live in, the time frame for answering such questions is measured in days and even in hours. What is needed at this juncture is the proverbial back-of-the-envelope analysis that confirms the applicability and efficiency of a concept, which would then also serve as a check of computer solutions.
- To promote the idea that design is a creative process as opposed to a mere execution of framing proposals.
- To reiterate the adage that computers assist us in the analysis phase, but it is the designer who harmonizes system components so as to optimize both cost and behavior.

Utilizing the aforementioned goals as a guide, I have set for myself a challenge to prepare a comprehensive text that will explore the world of steel, concrete, and composite materials as applied to the construction of buildings, particularly those that are super- and ultratall.

Using conceptual thinking and basic strength of material concepts as foundations, I have ventured to show how to use imperfect information to estimate the answer to much larger and complex design problems. To do so requires a certain intuitive feel for numbers as well as an appreciation of the fact that the “right answer” in this context is only of an order of magnitude of a more precise computer solution, but good enough to put us on the right track. The whole idea is to break seemingly intractable problems down to more manageable pieces that can be quickly approximated. Thus, I attempt to base the entire text on that wonderful ability of intuition we humans have developed in visualizing and realizing economical structural systems.

Developments in the last decade have produced many slender high-rise buildings, demanding that particular attention be paid to their complex behavior under lateral loads. Economic considerations routinely call for leaner and sparser designs that increasingly challenge the design professional to come up with safe and economical structural solutions.

In today’s engineering practice, it is obligatory to prepare several schematic options before a final scheme is selected. Even experienced engineers find it difficult to readily come up with diversified structural schemes because, other than their own library of experience, very little reference material is available. This book attempts to alleviate this problem by providing a systematic basis for arriving at preliminary structural schemes.

The trend in building design today is for the architect to define the building shape while the structural engineer, as a facilitator, comes up with a structural system that fulfills the architect’s dream within the owner’s budget requirements. This trend has resulted in innovative and daring structural schemes. Fortunately for the layperson, the result has been an interesting, varied, and flamboyant architecture that adds to the variety and interest of the skyline in urban cities.

Therefore, there is a need today for the structural engineer to be familiar with the run-of-the-mill design as well as with the less usual structural solutions. To this end, emphasis is placed in this book on the state-of-the-art solutions that have evolved as a natural extension of the proven systems.

Structural steel, as we know today, has been with us for well over a hundred years. It was in the year 1894 that the first specification for structural steel was published, and an examination of test results of that era suggests that the properties of this early steel were not very different from the A36 steel of the 1950s and 1960s. The first design specifications for steel buildings published by the

American Institute of Steel Construction (AISC) in the 1920s firmly established steel as a building material, and ever since its growth has been phenomenal in the construction of buildings and bridges.

Reinforced concrete has been known to humans for over two hundred years. However, its recognition as a viable product for seismic areas and loads is relatively recent. In fact, it was at an American Concrete Institute (ACI) convention held in San Francisco in 1980 that reinforced concrete was presented as a modern, earthquake-resistant material capable of being at once strong and ductile. Since then, we have witnessed a phenomenal increase in its load-resisting and ductile properties.

At first glance, composite construction may appear to be a new, emerging technology, but in reality it has been with us also for over a hundred years. However, only recently has its use been officially formalized by the AISC. We can now design, with equal assurance, composite buildings in areas of high seismic risk.

In today's world of high expectations, we seem to place less emphasis on learning the fundamentals of conceptual thinking. If we were to retain these skills as a profession, we engineers would be more adept at identifying what is critical for capturing essential behavior of the structural system instead of addressing every component of design independently. Computer analysis, then, works to solidify and extend the creative idea or concept that might have started out as a sketch on the proverbial back of the envelope. Our unique gift as engineers is our critical thinking, and we risk shortchanging ourselves and our field, in general, if we remain convinced that the output of voluminous calculations of every structural member is proof of good design.

When designing buildings in accordance with the ASCE 7-10 Minimum Loads Standards, considerations of wind- and seismic-resistant design is required for most building structures in the United States. The use of these documents can be daunting, particularly for those engineers that have little formal training in seismology, seismic hazard analysis, structural dynamics, and inelastic behavior. Given this perspective, this book has been designed to provide guidance on how to use code-based procedures while at the same time providing sufficient technical background to explain why the provisions are written the way they are. Where possible, the technical background is presented simultaneously with the explanation of the building code provisions. In many cases, such explanations are presented as part of a series of detailed numerical examples that are presented throughout the book. Information is provided on the wind and seismic detailing requirements of structural steel, reinforced concrete, and composite structures in the context of building system selection and behavior.

The first three introductory chapters present a discussion of various loads and load combinations typically used in building design. Tall buildings, like their lower brethren, are utilitarian creations. Out of all concerns related to structural design, that of safety is paramount as it is directly related to the loads. If the earth did not pull, the wind did not blow, the earth's surface did not sink or shake, and the air temperature and humidity did not change, loads would not exist, and a formal structural design would be unnecessary. We would all be out of work. This, however, is not the case.

In Chapter 1, we discuss basic dead and live loads, the two types of loads that exert gravitational loads on buildings. Dead loads are the self-weight components that make up the building, while live loads determined on the basis of statistic probabilities include all the loads that are variable within the operation cycle of a building.

Chapter 2 discusses the wind forces that must be accounted for in a properly engineered lateral force resisting system, regardless of building size or magnitude of load. Special emphasis is on the technical background to explain why the code provisions are written the way they are. Methods for assessing wind loads to examine building performance in severe windstorms are also discussed.

In Chapter 3, we discuss the ground and building characteristics so essential to give designers a *feel* for how their building will react to ground shaking. The chapter emphasizes the fact that in spite of the complexity of the interactions between the building and the ground during the first few seconds of shaking, there is ample evidence from extensive observations of buildings in earthquakes worldwide as to how different building types will perform under different shaking conditions.

Chapter 4 deals with methods for determining design wind loads using the provisions of ASCE 7-10. Wind tunnel procedures are discussed, including analytical methods for determining along-wind and across-wind response.

Conceptual seismic design, defined here as the avoidance or minimization of problems created by the effects of seismic excitation, is discussed in Chapter 5. From the analysis of general equations for predicting earthquake response, it becomes clear that to overcome the detrimental effects of many of the uncertainties in the predictions, one needs to apply a two-pronged approach: (1) control or decrease the demand as much as possible and (2) be generous in the supply of capacity, particularly by providing large ductility with stable hysteretic behavior, also called toughness. Using this philosophy as a basis, the first part of this chapter translates the complex field of structural dynamics into a simplified language that will be comprehensible to anyone concerned with the seismic design of buildings. The primary emphasis is on visual and descriptive analysis. The engineering mechanics is kept to a basic level and the mathematics to slide rule accuracy. Design requirements of ASCE 7-10 that implicitly provide for acceptable performance beyond elastic range are discussed using static, dynamic, and time-history procedures.

In Chapter 6, we introduce the concept of performance-based design (PBD). Although not revolutionary, it represents an evolution in design thinking that is in tune with the increasing complexity of today's buildings and also takes advantage of development and innovations in building technology. PBD suggests that rather than relying on the building code for protection against seismic hazards, a more systematic investigation is conducted to ensure that the specific concerns of building owners and occupants are addressed. Building codes focus on providing life safety, and property protection is secondary; PBD provides additional levels of protection that cover property damage and avoidance of functional interruption within a financially feasible context.

PBD has become the high-end, cutting-edge technology in building design. In lieu of prescriptive provisions that tend to discourage innovation required of ever more complex buildings, PBD provides analytical tools to assist in the earthquake design assurance process. It is expected that the profession will be able to avail itself of PBD techniques within this decade. This is so because owners like them for they are likely to cost less if designed only for traditional code compliance, architects love them because it offers more design freedom, and engineers being thrifty go for it because it can result in higher quality structures with the least amount of material.

Chapter 7 presents preliminary analysis and design techniques. Approximate methods are developed using fundamental principles of mechanics because it is only through sound understanding of these principles that engineers can successfully perform preliminary designs without resorting to full-blown computer analysis. The chapter concludes with a discussion of preliminary methods for determining axial shortening of tall steel building columns, and graphical aids for estimating unit quantity of structural materials for the purpose of conceptual estimates.

Chapter 8 is devoted to the structural rehabilitation of seismically vulnerable steel and concrete buildings. Design differences between a code-sponsored approach and the concept of ductility trade-off for strength are discussed, including seismic deficiencies and common upgrade methods. The ASCE standard, *Seismic Rehabilitation of Buildings*, ASCE/SEI 41-06, forms the basis of this chapter.

In Chapter 9, we address a number of topics, including serviceability considerations, prediction of tall building motions, damping devices, seismic isolation, blast-resistant design, and progressive collapse. The structural systems for selected tall buildings are also described.

Chapter 10 covers warping torsion, as it applies to open-section shear walls and wide flange sections. It includes worked examples to give the readers a feel of the magnitude of axial stresses resulting from warping torsion.

Chapter 11 is somewhat unique in that we attempt to capture the essence of seismic design using only illustrations with elaborate captions where necessary.

Finally, Chapters 12 and 13 are dedicated to explaining gravity and lateral systems for steel, and composite buildings, respectively. Also discussed in these chapters is the nonquantifiable, nonautomatic phase of design that engineers call their art—the art of connection design.

It is of interest to recognize that the debate over the perceived inadequacies of structural engineering graduates has reached fever pitch. Few deny that engineers today are faced with more information than they did even five years ago. Building information modeling and sustainability are just a few of the new design paradigms, and globalization, intelligent technology, digital fabrication, and self-consolidating concrete are just a few of the new industry standards.

Additionally, the codified laws by which we create structures have also expanded and sharpened. The bureaucratic, legalistic, rule-fixated viewpoint of our society has given rise to building codes and design guidelines that are voluminous and complex without precedent. Gone are the old days when an entire code book was no more than an inch thick, while the rest of the design process was left to the engineer's specific principles and experience.

To be sure, today's flamboyant architecture does not allow—by design and economics—structures that are simple, heavy, stiff, and robust as were the buildings of the 1930s and 1940s. However, even in today's computer age, the same timeless principles of engineering judgment apply as much now as ever before, demanding that we perform *back-of-the-envelope* decision-making calculations based on intuition and engineering judgment.

No one really starts with intuition, but cultivates it slowly over time. Computers can in fact help the engineer develop understanding because it challenges one's conventional thinking. The trick is to establish a link between those who *have* knowledge and those young engineers who simply run analytical models. Thus a business office, as I see, also becomes a place of continuing education between masters and apprentices.

What else can we do to prepare tomorrow's engineers to design safe, cost-effective projects, accounting for greater complexity and uncertainty with less formal education? The answer is by motivating them to cultivate engineering judgment and intuition with a constant objective of educating oneself. Every moment of every workday can be a learning experience practically regardless of the actual task: every drawing glanced at, or an engineering conversation overheard, can be another bit of experience gained, with the right attitude.

Another avenue is to have available—out of books, notes, and individual experience—all the *rules of thumb* and *reality checks* engineers have acquired over the years. No matter how complicated an analysis becomes, it is practically guaranteed that at some point in the process you will need to *prove* your design succinctly, in the space of a single page or two, to someone who has a stake in the project, but, above all, to your own conscience. When faced with these challenges, one learns what cannot be taught.

The very magnitude of efforts required to achieve the said goals begs for a communal effort on a national scale. The work presented in this book is but a modest attempt by a single author.

Design specifications for steel, concrete, and composite construction get more and more complicated with each edition, and there seems to be no let up in the drive of code writing agencies to increase the complication. Every expert in the field wants to incorporate what he or she considers to be the proper structural action, typically resulting in long and barely understandable formulas. It has gotten so that in many cases it is not possible to understand the rationality behind these equations.

How far should we go to increase the complications? What have the super specifications accomplished? Do we have better structures? Are there fewer failures? Have we balanced the complications against the need to maintain simplicity so that we will always understand the structure?

We need to stop and take a hard look at what the so-called increased precision has accomplished. If we feel that the specifications are not accomplishing their purpose, then we should make our opinions known. It seems there is no real input from practicing engineers to the decision of code writing authorities.

One answer to this problem is perhaps for someone to write a simple specification that will satisfy the intent of the code, equations. In some cases, it may be necessary to be much more specific, particularly in areas that are fundamental to the stability of structures. Some of the ideas in the commentary to the specifications could be incorporated with much more discussion.

No committee could do this. If done by an individual, such a document would not have the voice of authority, but if it was well done it would be used with confidence by practicing engineers.

The most important duty of engineers is to understand the structure they are designing. If this is not accomplished, then there is a risk that there will be mistakes that will cause problems. Specifications ought to help rather than hinder this process.

Tall Building Design: Steel, Concrete, and Composite Systems addresses the foregoing anxieties while integrating the design aspects of building structures within a single text. It is my hope that a commonsense approach for the modern world presented in this book will serve as a comprehensive design guide and reference for practicing engineers and educators, and more importantly, as a welcome mat for recent graduates entering the structural engineering profession by assuring them that they have discovered an exciting world of challenges and opportunity.

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Dr. Bungale S. Taranath, PhD, PE, SE, was a structural consultant based in Chino Hills, California. He had extensive experience in the design of concrete, steel, and composite tall buildings and served as principal-in-charge for many notable high-rise buildings. He held positions as a senior project engineer in Chicago, Illinois, and as vice president and principal-in-charge with two consulting firms in Houston, Texas. He also served as senior project manager with a consulting firm in Los Angeles, California. Dr. Taranath was a member of the American Society of Civil Engineers and the Concrete Institute and a registered structural and professional engineer in several states. He conducted research on the behavior of tall buildings and shear wall structures and authored a number of published papers on torsion analysis and multistory construction projects. He has published five other books: *Structural Analysis and Design of Tall Buildings*; *Steel, Concrete, and Composite Design of Tall Buildings*; *Wind and Earthquake Resistant Buildings: Structural Analysis and Design*; *Reinforced Concrete Design of Tall Buildings*; and *Structural Analysis and Design of Tall Buildings: Steel and Composite Construction*. Three of his books were translated into Chinese and Korean and are widely referenced throughout Asia. Dr. Taranath conducted seminars on tall building design in the United States, China, Hong Kong, Singapore, Mexico, India, and England. He was awarded a bronze medal in recognition of a paper presented in London, when he was a fellow of the Institution of Structural Engineers, London, England. Taranath's passion for tall buildings never waned. His greatest joy was sharing that enthusiasm with owners, architects, and fellow structural engineers to develop imaginative solutions for seemingly impossible structures. Dr. Taranath passed away as this book was being produced.

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