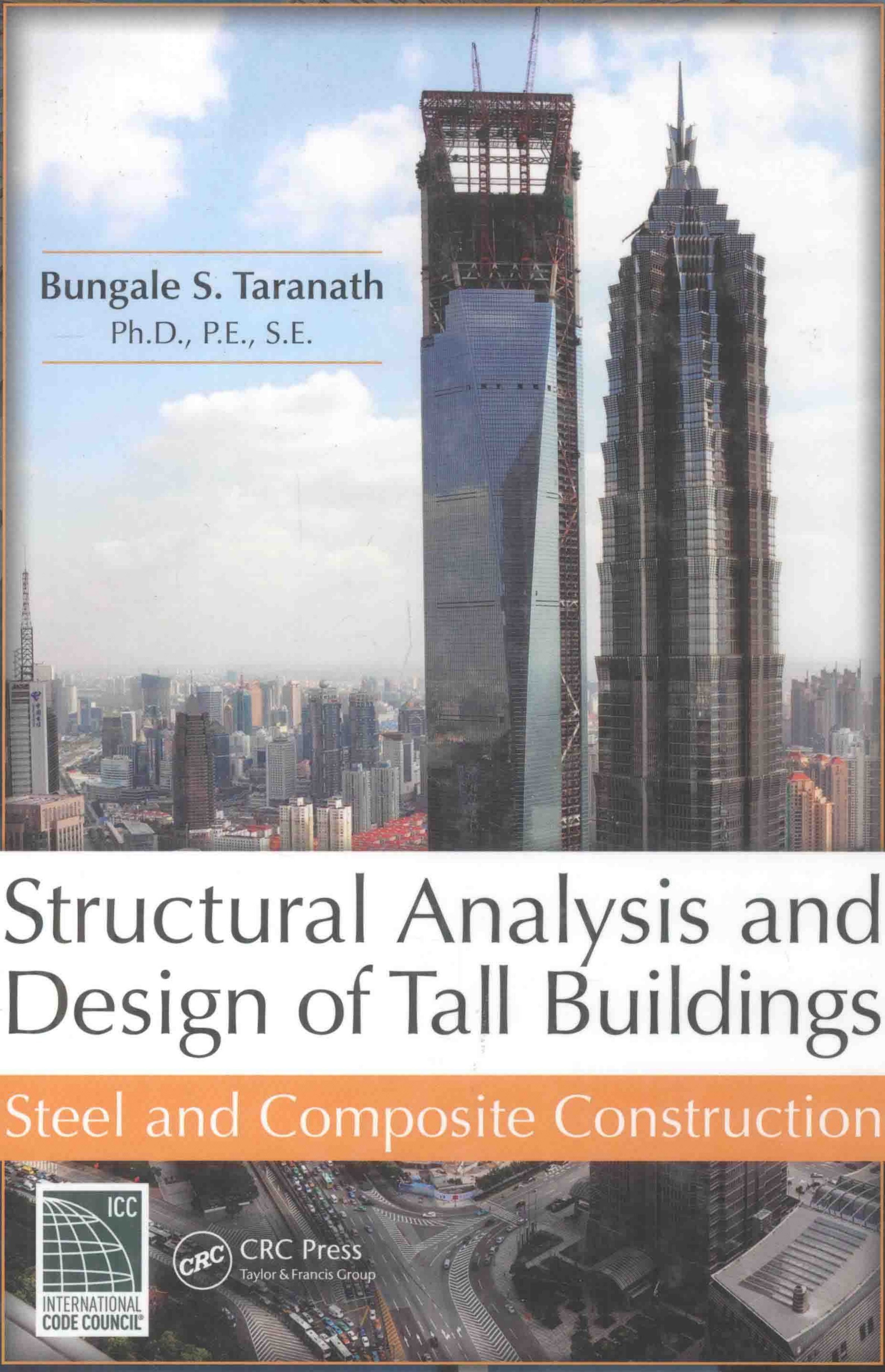

Bungale S. Taranath
Ph.D., P.E., S.E.

Structural Analysis and Design of Tall Buildings

Steel and Composite Construction

ICC
INTERNATIONAL CODE COUNCIL®

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This book is dedicated to my wife

Saroja

my dearest and best friend, whose considerable expertise and interest in all aspects of life has influenced my entire existence including my book-writing avocation.

Foreword

Dr. Taranath has produced a serious state-of-the art book on tall steel and composite structures. As with his phenomenally successful text *Reinforced Concrete Design of Tall Buildings*, this new book should be titled "all you ever wanted to know about steel structures including composite." The good doctor does not cheat the reader by taking shortcuts. His text is truly a magnificent effort by a highly intelligent engineer with a purpose of teaching all he has accumulated in his illustrious career of designing and teaching. This book is not a thin publication or a die-fast text; it is truly a labor of love. Each of the chapters in this book clearly identifies the benefits, shortcomings, and range of applicability of alternate high-rise structural systems, along with the way these systems respond to changing functional and architectural demands.

The first two chapters (Chapters 1 and 2) are on lateral load resisting structures. Logically, the next two (Chapters 3 and 4) are on gravity load systems for steel and composite. The next five chapters (Chapters 5 through 9) are on the evolution of more and more complex concepts such as determination of along-wind and across-wind response, inelastic cyclic behavior of buildings during earthquakes, seismic rehabilitation, and preliminary analysis techniques. The final chapter (Chapter 10) deals with the nonautomatic phase of design—the art of connection design.

One of the underlying philosophies of the author is his humorous and yet serious concern about the brain damage inflicted on engineers who have a slavish adherence to computers. His writing attempts to create a balance between what we should know intuitively and the technical results perfected by the computer.

Structural steel is a complex building material which is the product of an advanced techno society. The infrastructure to produce steel and fabricate it is exceedingly complex. To produce it, you need iron ore, limestone, blast furnaces, pig iron, and open-hearth furnaces.

Steel in structures was initially utilized in America. Steel was responsible for the transition to high-rise structures with elegant members. The advent of the elevator made it possible to go higher and faster, creating the modern skyscraper. To this day, a valued mentor of the author, Dr. Fazlur Kahn, holds the record of the tallest steel structure in the world: the Sears Tower (now the Willis Tower), in Chicago, Illinois.

The steel structures of the Empire State Building, as well as the Humana Headquarters Building, shroud the steel in stone; nonetheless, the interior columns are space-saving and thin.

The first composite structure, believe it or not, was cast iron with masonry backup for stability. This cast iron façade became decorative art and was related to the robust cast iron columns on the interior. The use of composite structures today includes using steel deck composite with studded beams as well as the filling in or concrete encasement around steel members. The tallest composite structure in the world is the Taipei 101.

One of the challenges of using steel is the relative loss in strength with temperature increase. This challenge has been overcome with the modern use of spray or troweled fireproofing, as well as tnemec paints which expand in fire and protect the members.

Why steel? One has just to see the lightness of the Eiffel Tower filigree, suspension bridges, and the exquisite slenderness of modern curtain wall façades to appreciate a material which produces such lightness and grace.

Our field has had a generational crisis of sorts, between those who champion the elegant and intuitive solutions and those who solely rely on the lightning-speed output of computers. However, in order to conceive a structure and give it meaningful proportions, one must follow both the intuitive and the mathematical paths. Only then can we, structural engineers who are trained to be thrifty, fulfill our cherished goal of designing for "the most with the least."

That said, Taranath's abiding engagement and contribution to the structural engineering community has been to develop structural systems for tall buildings that are at once economical and elegant. Take, for example, the belt and outrigger system that has become the workhorse of lateral bracing for tall and ultra-tall buildings. Almost all tall buildings built around the world in the past two decades have used this system in one form or another. In 1974, while employed with the Chicago Office of Skidmore, Owings & Merrill, SOM, Taranath wrote a historic paper that offered for the first time an insight into the behavior of outrigger-braced tall buildings. Using a classic approach that could be literally performed on the back of an envelope, he provided general guidance in locating single and multiple outriggers in tall building structures. Since then, his recommendations have been used in the bracing of tall and super-tall buildings around the world.

Dr. Taranath's intuitive techniques presented in this book extend to several other practical aspects unique to the construction and design aspects of tall buildings, such as

- Structural concepts for super-tall buildings using concrete cores, megaframes, supercolumns, and double-outrigger and belt truss systems
- Response spectrum and design charts for determining seismic base shears in buildings located in selected cities in the United States
- Effect of panel zones in determining lateral stiffness of moment frames
- Differential shortenings of tall steel building columns and how to compensate for their effects
- Comparison of structural schemes for tall buildings including impact of column sizes on architectural layouts
- Unit quantity of materials for preliminary cost comparison
- Details for improving seismic safety of buildings

As an intellectual discipline and applied field, structural engineering's contributions to the lives of the individuals and society are indirect. We rarely directly interact with the generations of people who will inhabit the buildings we design, and yet our expertise and dedication are imprinted throughout.

Within this context, Taranath strives to zero in on the most economical system that simultaneously satisfies the owners' cost concerns and the architects' dreams. Additionally, to assist engineers in arriving at preliminary cost comparisons, he has developed graphs and charts that give unit quantities of materials such as structural steel and mild steel reinforcement in tall and ultra-tall steel and composite construction.

In addition to being an accomplished structural engineer, Taranath is also a gifted educator, passionate to share his enthusiasm with engineers entering the profession as well as seasoned specialists. Five of his books have been published thus far, and the sixth is on its way; all attest to his talent as a practitioner who is able to lucidly and engagingly explain the practice. The topic of each book varies, but the overreaching themes of all his publications bridge the gap between the structural intuition we humans have and the results obtained by using rigorous analytical techniques.

Few engineers have had a career both as a practicing engineer and educator as Dr. Taranath. Fewer, if any, have at the same time made such a prodigious contribution in sharing that knowledge with the profession at large, both in the United States and internationally.

It is indeed my distinct privilege and honor to write this foreword. This book is a must for any serious engineer who truly wants to understand the gestalt of steel and composite tall building design.

Vincent J. DeSimone
Chairman
DeSimone Consulting Engineers

ICC Foreword

It was a great honor when Dr. Taranath asked me to contribute the foreword to his latest work, *Structural Analysis and Design of Tall Buildings: Steel and Composite Construction*. His intentional reliance on intuitive concepts rather than a rigorous analytical approach helps to facilitate an understanding of the many complex ideas involved in tall building design. Although most modern structures eventually do become abstract computer models for purposes of analysis, all structures usually start out as simple concepts, sometimes even a rough sketch on a napkin in a coffee shop. As Dr. Taranath suggests in the preface, his approach is intended to bridge the gap between conceptual design and computer analysis. I was both impressed and amused by his comments regarding Chapter 5 on seismic design, "The primary emphasis is on visual and descriptive analysis. The engineering mechanics are kept to a basic level, and the mathematics to a slide rule accuracy. The highlight of this chapter, perhaps, is the presentation of structural dynamics in which differential equations and esoteric jargon are conspicuously and purposely absent." Basic conceptualization and intuition lies at the very foundation of structural engineering and design. Going back to basics and relying on fundamentals often leads to discoveries that can be masked by abstract computer analysis and reams of abstruse calculations. This is reminiscent of the late great Cal Tech physicist and Nobel Laureate Richard Feynman who has been called a "Babylonian Thinker" because he was an empiricist who favored intuitive conceptual thinking, and not a "Greek Thinker"—a rationalist who prefers rigorous, analytical thinking. We all recall the famous demonstration on television when Professor Feynman placed a small O-ring in a glass of ice water before a congressional committee investigating the Shuttle *Challenger* disaster and showed that the O-ring lost its elasticity at cold temperatures. This simple demonstration ultimately led to the conclusion that the failure of an O-ring seal was due to brittleness caused by cold weather prior to the launch. It was old-fashioned intuition that discovered the problem, not reams of abstract equations and computer analysis.

In this modern digital world of high-speed computers, we engineers need to remind ourselves that many of the world's greatest structures, such as the Golden Gate Bridge, were designed during the era of the slide rule. In the "good ole days" engineers only "estimated" the loads, forces, stresses, and strains that act on structures. The limited precision of the slide rule was a constant reminder that we only know the numbers to three significant figures, which kept us from confusing accuracy with precision. In fact, because the slide rule has no decimal point, the user had to determine where the decimal point belonged, based on mental estimation. This mental estimation forced us to keep track of the order of magnitude our numbers. We had to have a cognitive expectation of the answer we were seeking: would it be 5.5, 55, 550, or 5500? The German rocket scientist Wernher von Braun brought two Nestler slide rules with him when he came to the United States after World War II, and throughout his life he never used any other calculating devices. Slide rule accuracy was sufficient for this famous rocket scientist to *estimate* a host of rocket design parameters. In today's modern era of high-speed computers, it is easy to express numbers with great (misleading) precision, and with modern software such as spreadsheets, PowerPoint presentations, and laser printers, we can produce a dazzling array of beautifully formatted numbers, precise to 12 significant figures and yet be completely wrong!

I am sure the reader will agree that getting back to basics using intuition and conceptualization is the best way to present this subject matter, and Dr. Taranath has done an outstanding job of accomplishing that goal in this comprehensive tall building design guide. He has a perspicuous writing style with a flair for lucidity rather than obscurity, and on occasion even highlights it with some engineering humor. Saying that earthquake engineering is to engineering as psychiatry is to medicine clearly elucidated the point for me. Or saying that ductility is like money—you can never have too much of it—is a perfect way to emphasize that seismic design is all about ductility, and bigger (stronger and stiffer) is not always better.

I am confident that all kinds of engineers, from students to young graduates, from seasoned practitioners to academics, will appreciate Dr. Taranath's conceptual approach to the subject with no need for rigor. The rigor comes later, after the conceptual ideas have coalesced. After all, one man's rigor is quite possibly another man's rigor mortis.

John R. Henry

Preface

Throughout my career as a practicing engineer, I have seen the ways that the field has shifted and transformed. Many changes certainly move us as practitioners toward greater accuracy, detail, and accountability. Other changes, in my view, seem to diminish our ability to identify key elements in structural design. The last 20 years, in particular, have witnessed tremendous evolution in how structural engineers work in design offices. Software navigating skills have come to the forefront of design concerns, and in so doing, have relegated the very art of structural conceptualization to the backseat. Engineering, of course, is the marriage of artistic and intuitive designs with mathematical accuracy and detail, and I see the latter overshadowing the former in the ways we teach the new generations. Training in the art of conceptualization is not offered in design offices except perhaps for teaching navigating skills through commercial software and in-house spreadsheets. Such training is deemed to be of low value to business balance sheets, yet would encourage us to preserve the conceptual knowledge that seems to belong to an older generation of practitioners.

In a world of high expectations, we seem to place less and less emphasis on learning the fundamentals of conceptual thinking. If we retained these skills as a profession, we engineers could be more adept at identifying what is critical for capturing the 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, if we remain convinced that the output of voluminous calculations of every structural member is proof of good design.

Mine is not the only voice airing these concerns. A plethora of published journal articles address this ever-increasing gap between the conceptual approach and the computer analysis justified typically by endless tabulation of demand–capacity ratios for each and every structural member. Certainly, there is no doubt that software navigating skills are critical and necessary. My sense, however, is such skills are more useful if built upon solid foundation of engineering principles and conceptual knowledge. As these thoughts occur to me in my day-to-day engineering practice, and more so as I prepare this manuscript, I have set for myself a challenge to bridge the gap between these two approaches: the software operating skills and conceptual design. The very magnitude of this challenge begs for a communal effort on a national scale, and the work presented in this book is but a modest attempt by a single author to address these concerns.

Using conceptual thinking and basic strength of material concepts as foundations, the book attempts 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. The emphasis in this book is on steel and composite building 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 used in 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.

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, it is only recently that its use has been officially formalized by the AISC 341-05/10. Now we can, with equal assurance, design composite buildings in areas of high seismic risk.

The behavior and design of lateral load–resisting systems of structural steel and composite buildings is the subject of Chapters 1 and 2. Traditional as well as relatively recent bracing systems are discussed, including outrigger and belt truss systems that have become the bracing workhorse of super- and ultra-tall buildings. Also included are steel and composite concentric and eccentric braced frames, composite moment frames, and composite shear walls.

Chapters 3 and 4 are dedicated to gravity design of steel and composite floors and columns. In addition to traditional beam-and-girder framing systems, novel floor framing systems such as haunch and stub girders are also discussed.

In Chapter 5, we discuss methods of determining design wind loads using the provisions of ASCE 7-05 and 7-10. Wind-tunnel procedures are discussed, including analytical methods for determining along-wind and across-wind response.

The behavior of buildings and their components subject to inelastic cyclic deformation during large earthquakes is discussed in Chapter 6. The first part of this chapter explains the complex field of structural dynamics in a simple manner so as to make it comprehensible to anyone concerned with the seismic design of buildings. The primary emphasis is on visual and descriptive analysis. The engineering mechanics are kept to a basic level, and the mathematics to a slide rule accuracy. Design requirements of ASCE 7-05 and 7-10 that implicitly provide for acceptable performance beyond elastic range are discussed using equivalent static, dynamic, and time-history procedures. The highlight of this chapter, perhaps, is the presentation of structural dynamics in which differential equations and esoteric jargon are conspicuously and purposefully absent.

Chapter 7 focuses on the anatomy of seismic provisions for structural steel and composite buildings (ANSI/AISC 341-05 and 10). Also presented in this chapter are the designs of special moment frames, braced frames, shear walls, buckling-restrained brace frames, and special plate shear walls.

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

Chapter 9 deals with special topics and starts with a description of tall-building structural systems using case studies that range from the run-of-the-mill bracing techniques to systems that are more appropriate for ultra-tall buildings. I concentrate on actually built or proposed systems using plans, elevations, and three-dimensional schematics. Preliminary analysis techniques using examples are discussed as are graphical approaches for determining wind and seismic loads. The chapter continues with a discussion of human tolerance to wind-induced dynamic motions of tall buildings. Also explained in this chapter are the U.S. and International design guidelines for limiting building motion perception and the effect of structural damping in determining the serviceability limit state. Next, we consider the fundamental aspects of performance-based design (PBD), which has become the cutting-edge technology in building design. Owners like PBD buildings because they cost less, architects love it 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 materials. The chapter concludes with a discussion of analytical methods for determining axial shortening of tall-building columns. Also presented are graphical aids for estimating unit-quantity of structural steel for purposes of conceptual estimates.

The final chapter, Chapter 10, deals with the nonquantifiable, nonautomatic phase of design—what engineers call their art, the art of connection design. Many of the special requirements for joints and connection materials as regulated by the AISC 360-05, AISC 358-05 and AISC 341-05/10, are discussed along with suggested typical details.

This book integrates the design aspects of steel and composite buildings within a single text. It is my hope that 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 opportunities.

Bungale S. Taranath
Corporate Consultant
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Las Vegas, Nevada

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Author

Dr. Bungale S. Taranath, PhD, PE, SE, is a corporate consultant to DeSimone Consulting Engineers, a consulting firm, with offices in New York, Miami, San Francisco, New Haven, Las Vegas, Hong Kong, and Abu Dhabi. He has extensive experience in the design of concrete, steel, and composite tall buildings and has served as principal-in-charge for many notable high-rise buildings. He has 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 has also served as a senior project manager with a consulting firm in Los Angeles, California. Dr. Taranath is a member of the American Society of Civil Engineers and the Concrete Institute, and a registered structural and professional engineer in several states. He has conducted research into the behavior of tall buildings and shear wall structures and is the author of a number of published papers on torsion analysis and multistory construction projects. He has previously published four 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*; and *Reinforced Concrete Design of Tall Buildings*. Three of his books were translated into Chinese and Korean and are widely referenced throughout Asia. Dr. Taranath has 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 has never waned. Today, his greatest joy is sharing that enthusiasm with owners, architects, and fellow structural engineers to develop imaginative solutions for seemingly impossible structures.

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