Monograph on

Planning and Design of Tall Buildings

Volume SC

Tall Building Systems and Concepts

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Group Coordinators

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Foreword

This is one volume of a multivolume Monograph bringing together current knowledge about tall buildings themselves and about their interactions with the urban environment. Topics covered in the Monograph include structural and service systems, foundation, loadings and structural safety, structural design methods, architecture and urban planning, related cultural, social, and political factors, and the management and operation of buildings in use.

The entire Monograph consists of 52 chapters arranged in the following five volumes:

Volume PC: Planning and Environmental Criteria for Tall Buildings
Volume SC: Tall Building Systems and Concepts
Volume CL: Tall Building Criteria and Loading
Volume SB: Structural Design of Tall Steel Buildings
Volume CB: Structural Design of Tall Concrete and Masonry Buildings

This particular volume (SC) deals with the structural, mechanical, and electrical systems of the tall building, and with its foundation, its construction, its cladding, and with its internal subdivision.

Volume SC concentrates on the systems; and in the case of loading and structural design, it provides the concepts that are the basis for much of the material contained in Volumes CL, SB, and CB. On the other hand, the system considerations, as well as the design concepts with regard to the mechanical, electrical, service, and vertical transportation aspects are self-contained within this particular volume. The work rests on the premises and understanding of the planning and environmental criteria that are contained in Volume PC; and there is frequent reference thereto.

The Monograph as a whole should be of value to all those with major responsibilities for planning and deign practice. In addition to its function to communicate to knowledgeable persons the state-of-the-art and the most advanced knowledge in the field, the text on a given topic may well be most useful to those in *other* disciplines. The Council has seen considerable benefit accrue from the mix of professions, and this is no less true in the Monograph itself. In keeping with this, and to af-

ford such benefit to all appropriate professionals, every effort has been made to provide a comprehensive glossary for each volume.

In the same vein, where more than one point of view is appropriate, those views are set forth. Since there are several instances in which there is no final answer, there are numerous points of controversy; and such controversy has not been avoided.

Tall Buildings

What is a tall building? The important criterion is whether or not the design is influenced by some aspect of "tallness." A tall building is *not* defined by its height or number of stories. A suggested definition, then, might be "a building in which 'tallness' strongly influences planning, design, and use"; or "a building whose height creates different conditions in the design, construction, and use from those that exist in 'common' buildings of a certain region and period."

As a consequence, there is some variation among chapters on this matter of tallness. Each one has proceeded on the basis that "tall" constitutes whatever creates the "tall building problem" for that particular subject. Topics are not included in the Monograph simply because they pertain to buildings in general. If, on the other hand, a topic is particularly important for a tall building, then the objective has been to treat that topic even if it is also a problem for all buildings

A "building" is a structure that is designed essentially for residential, commercial, or industrial purposes. other categories include institutional, public assembly, and multiple-use structures. An essential characteristic of a building is that it has floors. Structures designed for entertainment, such as towers, monuments, and "space needles," generally are excluded from consideration.

The Council

This Monograph has been prepared by the various topical and advisory committees of the Council on Tall Buildings and Urban Habitat. The Council is an activity sponsored by engineering, architectural, and planning professionals throughout the world, and was established to study and report on all aspects of the planning, design, construction, and operation of tall buildings.

The Professional Society sponsors are the International Association for Bridge and Structural Engineering (IABSE), the American Society of Civil Engineers (ASCE), the American Institute of Architects (AIA), the American Planning Association (APA), the International Federation for Housing and Planning (IFHP), and the International Union of Architects (UIA). The particular contribution of several of these are described further in the Foreword of Volume CL.

The Council does not take an advocacy role for tall buildings. Rather, its premise is that in those situations in which they are viable, it seeks to encourage the use of the latest knowledge in their implementation.

Direct contributions to the Monograph have come from many countries and many people. One further notable characteristic is that much of the material has been prepared by practicing designers. Members of design and industrial firms account for nearly two-thirds of the 175-member editorial team. The wide mix of disciplines has also been notable—right from the initial planning phase to the final reviews of the written contributions. To this the Monograph owes its unusually broad perspective.

In addition to the editorial committee, more than 800 individuals supplied specific contributions. All told, about 1300 committee members from 78 countries had opportunity to review at least one chapter.

The idea of developing a Monograph was part of the original concept when the Council was formed ten years ago as the "Joint Committee on Tall Buildings." In 1968 there developed an awareness of the significant amount of research information—and design approaches as well—that were not documented in a form that was useful in advanced design work. There was a need for a comprehensive examination of all aspects of the topic, and the Monograph was envisioned as the mechanism for disseminating as much of the results of that study as practicable. The urgency of meeting that need stemmed from the exploding urban population creating increasing demand for tall buildings, the requirement for economy of construction, and the evident neglect of human factors in urban design at the expense of livability and quality of life.

The major steps that were then followed by the Council in the production of the Monograph are described in the Foreword of Volume CB. In the early days both the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT) approaches were tried. With respect to forcing a careful development of all the steps involved, the effort was most successful. But as a method of assuring that deadlines were met, it did not work—largely because a project such as this depends so much upon volunteer effort. In such a case the best deadline still remains a conference or meeting.

High-Rise Building Data Base

Where are the tall buildings in the world? What are their heights? Of what material are they built? How are they used? What has been the record of their skyward climb? This is the subject of the "High-Rise Building Data Base" that is included as an appendix to this volume. It consists of a tabular presentation of the answers to the above questions, covering the tallest buildings in each country as well as the tall buildings in the major cities of the world.

The data are only as up-to-date (and as accurate) as our advisors could provide from each city. In some parts of the world tall building construction is very active. In other parts it is slow or nonexistent. Consequently, in those cases where the reader has information available that is not included, the data should be forwarded to Headquarters for incorporation in the computer data base and for later publication.

The following classifications of the use of high-rise buildings have been adopted:

1. Commercial: office, store and shops, bank, public utility.
2. Residential: apartment (rental and condominium), hotel, dormitory, hostel.
3. Industrial: warehouse, manufacture ("flatted factory"), material processing.
4. Institutional: school, hospital (health care facility), laboratory, library, museum, correctional institution, court of law, religious edifice.
5. Public Assembly: theater, hall and auditorium (meeting rooms), restaurant, observation.
6. Special Purpose: transport interface (air, rail, bus, ship), garage (parking deck), mausoleum.
7. Multiple Use (megastructures that are various combinations of the above).

Units, Symbols, and References

With regard to the units, it will be evident to the reader that complete uniformity in the text was not achieved. The general guideline was to use SI units first, followed by American units in parentheses and metric when necessary. A conversion table for units is supplied at the end of the volume. Because of the extensive amount of new artwork that otherwise would have been involved (and the consequent delay), many previously existing drawings and tables remain with their original units. However, enough conversions are given throughout to enable a proper interpretation.

A list of symbols appears at the end of the volume. Because of variations among chapters the chapter number is identified with each citation.

The spelling was agreed at the outset to be "American" English. An early decision relating to the method of citing and arranging the references and bibliographical material was made. The following format is suggested for those who wish to refer to a chapter, to a volume, or to the Monograph as a whole in their own publications:

To refer to a chapter:

Council on Tall Buildings, Committee 2C, 1980
ELECTRICAL SYSTEMS, Chapter SC-3, Vol. SC of Monograph on Planning and Design of Tall Buildings, ASCE, New York.

To refer to a particular volume:

Council on Tall Buildings, Group SC, 1980
TALL BUILDING SYSTEMS AND CONCEPTS, Volume SC of Monograph on Planning and Design of Tall Buildings, ASCE, New York.

To refer to the entire Monograph:

Council on Tall Buildings, 1978-1981
PLANNING AND DESIGN OF TALL BUILDINGS, a Monograph in 5 volumes, ASCE, New York.

The Monograph has been, from the start, the prime focus of the Council's activity, and it is intended that its periodic revision and the implementation of its ideas and recommendations should be a continuing activity on both national and international levels. Readers who find that some topic is inadequately treated or calls for further thought are invited to bring that fact to our attention. Perhaps they also can draw our attention to publications or recent research results that have been overlooked. It is planned that periodically a "Monograph Update" containing new information about tall buildings and the urban habitat will be collected and disseminated. Every reader is urged, therefore, to submit any new material for inclusion in future revisions and addenda. Each committee will then have an opportunity to update its material.

As one of the Committee leaders said, "We never can reach the 'perfect' Monograph. A Monograph as it is at this moment, published as soon as possible, is much better than the perfect Monograph never published at all."

Acknowledgment

This work would not have been possible but for the financial support of our major sponsor, the National Science Foundation, which supported the program out of which the Monograph developed. The understanding and support of Dr. Michael Gaus of NSF has been most appreciated. In addition, the following individuals and

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Next, tribute is due the Chairmen and Vice-Chairmen who provided leadership to the committee. To the Committee Editors fell the major burden of writing, editing, adjusting, and rewriting. Their contributions have been most significant. All of these are identified on the title page of the respective chapters.

The true "authors" of the Monograph were sometimes the committee editors, but in most cases they were the contributors and reporters whose papers formed the essential first drafts—the starting point. These are identified in the acknowledgment page that follows the title page for each chapter.

The coordinating and editing effort on the volume as a whole has been the work of the Group Coordinators, Fazlur R. Khan and John Rankine, and the Group Editors, Walter P. Moore, Jr., Howard D. Eberhart, and Henry J. Cowan. "Jack" Cowan applied his skills not only from his experience in Australia as educator in both structural engineering and architecture, but also from his extensive experience as an author in his own right. Howard Eberhart similarly contributed from his wide-ranging experience at the University of California, Berkeley. Walter Moore, as a practicing engineer in Houston, Texas, brought to the effort his considerable experience in the design of tall buildings, especially in that unique city. The Council is equally indebted to John Rankine whose wide design experience in Australia and other parts of the world has made him well qualified in his role as a group leader.

The Council has been most fortunate to have the leadership of Fazlur R. Khan, who has been responsible for the structural design of some of the world's tallest buildings and of many innovations in approach. Not only that, his grasp of the interaction between engineering, architecture, and planning has played no small role in the development of this volume and in the progress the Council has made over the years. He currently serves as Chairman of the Council.

The Council acknowledges, with sincere gratitude, the contributions of all of these leaders.

Lehigh University
Bethlehem, Pennsylvania
1980

Lynn S. Beedle
Editor-in-Chief

Preface

Skyscrapers first appeared in a number of urban centers in the United States nearly 100 years ago. Since that time, steady advances have been made in the application of technical principles to the construction of tall buildings. The period of the 1930s made its mark with the construction of the 102-story Empire State Building in New York. After World War II the population explosion, in combination with rapid urbanization, provided the impetus for the development of new and improved systems and concepts for tall buildings.

Although tall buildings are a relatively recent development, it is certainly true that monuments and edifices of considerable height were built in much earlier times. The pyramids of Giza in Egypt, the Mayan temples in Tikal, Guatemala, the Kutab Minar in India are but a few examples of man's desire to reach for the sky. Tall buildings are first of all tall structures and as such have interested the structural engineer. Dr. Leo Finzi at the 1973 Italian National Conference on Tall Buildings underlined this special interest when he said, "For the structural engineer, the tall building has a fascination in itself because the design of the structure raises, and in a way that cannot be denied, all the more up-to-date and difficult problems concerned with conceiving, calculating, making and erecting these structures." Building tall buildings and towers has fascinated mankind from the beginning of civilization. In August, 1973, at the National Conference on the Planning and Design of Tall Buildings in Tokyo, Japan, Professor Yasumi Yoshitake began his talk with a biblical passage in Genesis about the Tower of Babel. "Come," they said, "let us build ourselves a city and a tower with its top in the heavens, and let us make a name for ourselves, lest we be scattered abroad upon the face of the whole earth." He further states that this story "seems to reveal the innate human desire for a tall structure . . . (but) also implies the dream and the fear which architects and architectural engineers in Japan now have at the coming of the age of tall buildings."

The practicality of the tall building requires the consideration of many other technological and planning factors beyond those essential to the character of the structure itself. It should be recalled that the first system which allowed the structural engineer to develop the modern skyscraper was the invention by Elisha Otis in

the 1850s of the first safe vertical transportation system. That breakthrough set the stage for other planning and technological systems to be brought to bear to meet the challenges of buildings of even greater height. Vertical transportation is an essential part of the tall building; but as buildings get taller, special considerations need to be given in many other areas. The internal environment, the fire safety needs, and other emergency requirements for tall buildings require the compatible development of their own system. Even the architectural elements, which for a short building are left entirely to traditional architectural detailing, need to be carefully analyzed in terms of such factors as building movement and the long-term effects of deflection, so that all doors, partitions, windows, and exterior cladding will perform satisfactorily through seasonal changes over a long period of time.

Whereas the structural system remains dominant, there is an increasing awareness that the success of the tall building architecturally, functionally, and economically very much depends on the innovative development of compatible systems of all elements of the building, including, for example, fire fighting, communicating, heating, ventilating, air conditioning, plumbing, partitions, walls, and cladding. In fact, all systems should go hand in hand in the total design process for a tall building. Indeed there have been occasions on which the important service systems have had to be fitted into a building only after its structure was designed and finalized. Speaking as a building services engineer, Mr. R. Banbam at the Regional Conference on Tall Buildings in Bangkok, Thailand, commented that "Regrettably, in Asia, all too often he (the building services engineer) is required to design systems around an architectural plan and a structural system which have been developed to a point where modifications cannot be made to either." This statement truly represents the thrust and purpose of this volume on Systems and Concepts.

The need to work as a team in the early formulation of the building design is a necessity all over the world. Every professional working on the complex problems involved in the tall building needs to realize the impact that his concepts will have on other members of the team. Building systems are not independent, but rather they are interrelated beginning with the foundation systems and ending with the construction systems. As such, even in this age of specialization, everyone needs to understand and appreciate this interrelationship of systems from the very beginning of the project.

This volume tends to treat the various systems independently by chapters; but because of their interdependence, they are grouped together in this one volume. They represent the current state-of-the-art of tall buildings systems around the world and should serve to stimulate the imagination of the reader to develop even more advanced systems. The search for better, newer, and more efficient systems and concepts will continue throught the coming years, and we hope that this volume of the Monograph will act as important source material for the present design of tall buildings, and that it will be a foundation for future innovation.

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1980

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Tall Building Systems and Concepts

Chapter SC-1

Structural Systems

Prepared by Committee 3 (Structural Systems) of the Council on Tall Buildings and Urban Habitat as part of the Monograph on the Planning and Design of Tall Buildings.

John V. Christiansen Chairman
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The following is a complete list of those who have submitted written material for possible use in the chapter, whether or not that material was used in the final version. The Committee Chairman and Editor were given quite complete latitude. Frequently length limitations precluded the inclusion of much valuable material. The Bibliography contains all contributions. The contributors are: H. Bandel, J. F. Brotchie, R. J. Brungraber, Yu. D. Bychenkov, J. V. Christiansen, R. O. Disque, R. Dziewolski, I. Erenyi, T. Hisatoku, M. Kavyrchine, G. F. König, J. Kozák, R. E. Lewis, L. W. Lu, K. G. Martin, N. G. Matkov, W. P. Moore, Jr., J. Nasser, A. F. Nassetta, F. Nishikawa, Z. Pawlowski, P. Pun, F. K. Reinitzhuber, L. E. Robertson, R. A. Sofronie, A. G. Sokolov, H. Sontag, A. P. Vasiliev, A. H. Yorkdale, U. Yuceoglu.

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SC-1 Structural Systems

1.1 INTRODUCTION

In general, the structural system of a building is a three-dimensional complex assemblage of various combinations of interconnected structural elements. These may be discrete members or they may be continuous assemblages. The primary function of the structural system is to carry effectively and safely all the loads acting on the building, and eventually to transmit them to the foundation. A structural system is therefore expected to:

1. Carry dynamic and static vertical loads.
2. Carry horizontal loads due to wind and earthquake effects.
3. Resist stresses caused by temperature and shrinkage effects.
4. Resist external or internal blast and impact loads.
5. Resist and help damp vibrations and fatigue effects.

In addition, a structural system is usually subject to the following constraints:

1. It should conform with the architectural requirements and those of the user or owner, or both.
2. It interacts with and facilitates an appropriate solution to the service systems, such as heating, ventilating, and air conditioning, horizontal and vertical transport, and other electrical and mechanical systems.
3. It facilitates simple and fast erection of the building.
4. It is resistant to fire.
5. It enables the building, the foundation, and the ground to interact properly.
6. It is economical.

In the process of selecting the most suitable structural system for a tall building, several factors have to be considered and optimized in addition to the height of the