

DESIGN AND PERFORMANCE OF TALL BUILDINGS FOR WIND

ASCE MANUALS
AND REPORTS ON
ENGINEERING PRACTICE
NO. 143

EDITED BY PREETAM BISWAS
JOHN PERONTO

TASK COMMITTEE FOR THE
DESIGN AND PERFORMANCE OF
TALL BUILDINGS FOR WIND

ASCE



STRUCTURAL
ENGINEERING
INSTITUTE

ASCE Manuals and Reports on Engineering Practice No. 143

Design and Performance of Tall Buildings for Wind

Edited by Sreetam Biswas and John Peronto

Prepared by
Task Committee for the Design and Performance of Tall Buildings for
Wind of the Structural Engineering Institute of the
American Society of Civil Engineers



Published by the American Society of Civil Engineers

Library of Congress Cataloging-in-Publication Data

Names: Biswas, Preetam, editor. | Peronto, John, editor. | Task Committee for the Design and Performance of Tall Buildings in Wind author.

Title: Design and performance of tall buildings for wind / prepared by Task Committee for the Design and Performance of Tall Buildings in Wind; edited by Preetam Biswas, P.E., and John (Sp.) - Peronto.

Description: Reston, Virginia : American Society of Civil Engineers, [2020] | Series: ASCE manuals and reports on engineering practice ; no. 143 | Includes bibliographical references and index. | Summary: "Design and Performance of Tall Buildings for Wind, MOP 143 provides a framework for the design of tall buildings for wind, based on the current state-of-practice in tall building structural design and wind tunnel testing"— Provided by publisher. | Identifiers: LCCN 2020033269 | ISBN 9780784415658 (paperback) | ISBN 9780784433121 (adobe pdf)

Subjects: LCSH: Tall buildings—Aerodynamics. | Wind resistant design.

Classification: LCC TH891 .D37 2020 | DDC 690/.21—dc23

LC record available at <https://lccn.loc.gov/2020033269>

Published by American Society of Civil Engineers

1801 Alexander Bell Drive

Reston, Virginia 20191-4382

www.asce.org/bookstore | ascelibrary.org

Any statements expressed in these materials are those of the individual authors and do not necessarily represent the views of ASCE, which takes no responsibility for any statement made herein. No reference made in this publication to any specific method, product, process, or service constitutes or implies an endorsement, recommendation, or warranty thereof by ASCE. The materials are for general information only and do not represent a standard of ASCE, nor are they intended as a reference to purchase specifications, contracts, regulations, statutes, or any other legal document. ASCE makes no representation or warranty of any kind, whether express or implied, concerning the accuracy, completeness, suitability, or utility of any information, apparatus, product, or process discussed in this publication, and assumes no liability therefor. The information contained in these materials should not be used without first securing competent advice with respect to its suitability for any general or specific application. Anyone utilizing such information assumes all liability arising from such use, including but not limited to infringement of any patent or patents.

ASCE and American Society of Civil Engineers—Registered in US Patent and Trademark Office.

Photocopies and Permissions. Permission to photocopy or reproduce material from ASCE publications can be requested by sending an email to permissions@asce.org or by locating a title in the ASCE Library (<https://ascelibrary.org>) and using the "Permissions" link.

Errata. Errata, if any, can be found at <http://dx.doi.org/10.1061/9780784415658>.

Copyright © 2020 by the American Society of Civil Engineers.

All Rights Reserved.

ISBN 978-0-7844-1565-8 (soft cover)

ISBN 978-0-7844-8312-1 (PDF)

Manufactured in the United States of America.

25 24 23 22 21 20 1 2 3 4 5

MANUALS AND REPORTS ON ENGINEERING PRACTICE

(As developed by the ASCE Technical Procedures Committee,
July 1930, and revised March 1935, February 1962, and April 1982)

A manual or report in this series consists of an orderly presentation of facts on a particular subject, supplemented by an analysis of limitations and applications of these facts. It contains information useful to the average engineer in his or her everyday work, rather than findings that may be useful only occasionally or rarely. It is not in any sense a "standard," however, nor is it so elementary or so conclusive as to provide a "rule of thumb" for nonengineers.

Furthermore, material in this series, in distinction from a paper (which expresses only one person's observations or opinions), is the work of a committee or group selected to assemble and express information on a specific topic. As often as practicable the committee is under the direction of one or more of the Technical Divisions and Councils, and the product evolved has been subjected to review by the Executive Committee of the Division or Council. As a step in the process of this review, proposed manuscripts are often brought before the members of the Technical Divisions and Councils for comment, which may serve as the basis for improvement. When published, each manual shows the names of the committees by which it was compiled and indicates clearly the several processes through which it has passed in review, so that its merit may be definitely understood.

In February 1961 (and revised in April 1982), the Board of Direction voted to establish a series titled "Manuals and Reports on Engineering Practice" to include the manuals published and authorized to date, future Manuals of Professional Practice, and Reports on Engineering Practice. All such manual or report material of the Society would have been refereed in a manner approved by the Board Committee on Publications and would be bound, with applicable discussion, in books similar to past manuals. Numbering would be consecutive and would be a continuation of present manual numbers. In some cases of joint committee reports, bypassing of journal publications may be authorized.

A list of available Manuals of Practice can be found at <https://www.asce.org/bookstore>.

This page intentionally left blank

AUTHORS

Preetam Biswas, Skidmore, Owings & Merrill

Preetam Biswas is a director of structural engineering at Skidmore, Owings & Merrill (SOM). He has led the design of multiple tall buildings, airports, stadiums, and convention centers around the globe. He has authored many technical papers focusing on tall buildings and other structural system innovations and served as the chair for the task committee that authored this Manual of Practice.

John Peronto, Thornton Tomasetti, Inc

John Peronto is a senior principal at Thornton Tomasetti and has led the design of many tall-to-megatall buildings, as well as unique and iconic structures around the world. He is highly published and a leader in professional organizations such as ASCE, ACI, ASCE, ICE, CTBUH, CCHRB, and has served as the chair for the Tall Buildings Committee of SEI since 2016.

Kevin Aswegan, Magnusson Klemencic Associates

Kevin Aswegan is an associate with Magnusson Klemencic Associates (MKA) in Seattle, where his design experience focuses on tall buildings in areas of high wind and seismicity in the United States and around the world. He is actively involved in wind-related research, has authored many articles on performance-based wind design, and is an active member of the Standard ASCE 7 update process.

Loy Denoon, CPP Wind Engineering

Loy Denoon is vice president of CPP Wind Engineering and has been involved in wind tunnel testing for 30 years, during which time he has worked on many globally iconic buildings and structures. He is a member of the ASCE 7 Wind Load Subcommittee, a contributing author to the *ASCE/SEI Prestandard for Performance-Based Wind Design*, a co-author of

the *CTBUH Technical Guide on Wind Tunnel Testing of High-Rise Buildings* and is a CTBUH Fellow.

John Kilpatrick, RWDI

John Kilpatrick is a principal at RWDI. John is currently Wind Engineering Practice Leader at RWDI, a former chair of the UK Wind Engineering Society, and is a contributing author to the *ASCE/SEI Prestandard for Performance-Based Wind Design* and *ASCE 49 Standard for Wind Tunnel Testing for Buildings and Other Structures*.

Sami Matar, LERA Consulting Structural Engineers

Sami S. Matar is an associate partner with LERA Consulting Structural Engineers (LERA). Since joining LERA in 1995, he has built extensive experience in a variety of projects and has participated in or led the design of several of the firm's high-rise building projects.

Brian McElhatten, Arup

Brian McElhatten is an associate principal in Arup's Chicago office and leads the structural engineering group there. He has extensive knowledge of tall building systems, analysis, and design. During his time at both Arup and SOM, he has worked on and led the structural design of numerous tall and supertall buildings around the world. In addition to the Tall Buildings Committee of SEI, he is actively involved in CTBUH.

Patrick Ragan, WSP

Patrick Ragan is an associate principal at WSP in Chicago. His design experience includes towers in the United States, China, and the Middle East, with a primary focus on the lateral system design and optimization of high-rise structures. He has authored papers on various subjects including statistical methods for estimating wind turbine design loads, form-finding analysis of shell-shaped roof structures, and fluid viscous damper alternatives to conventional steel frame outrigger systems.

CONTRIBUTOR

Alexander W. Jordan, Skidmore, Owings & Merrill

Alex Jordan is an Associate at Skidmore, Owings & Merrill (SOM). He has experience in the design of tall buildings and airports, and he specializes in digital design practices.

CONTENTS

PREFACE	xi
ACKNOWLEDGMENTS	xiii
1 INTRODUCTION	1
1.1 Purpose	1
1.2 Scope	1
1.3 Use of This Manual	2
1.4 Historic General Design Requirements	3
1.5 Stakeholders	3
1.6 Nature of Wind	5
1.7 Limitations	6
2 DESIGN PROCESS	7
2.1 Overview	7
2.2 Establish Performance Objectives	7
2.3 Preliminary Structural Design	8
2.4 Wind Climate Assessment	8
2.5 Wind-Induced Loads and Responses	9
2.6 Structural Modeling and Analysis	10
2.7 Comparison of Results to Acceptance Criteria	10
2.8 Wind Optimization Program	10
2.9 Final Design	10
3 PERFORMANCE OBJECTIVES AND ACCEPTANCE CRITERIA	13
3.1 Introduction	13
3.2 Mean Recurrence Intervals	13
3.2.1 Strength: Foundation and Lateral System (Main Wind Force Resisting System)	14
3.2.2 Serviceability: Drift and Displacement	14
3.2.3 Serviceability: Accelerations and Motion Perception	15

3.3	Stability	16
3.3.1	P-Delta (Second Order) Effects	16
3.3.2	Story Stability Coefficient	17
3.3.3	Stability Evaluation with P-Delta Analysis	17
3.3.4	Global Stability and Story Stability	18
3.3.5	Stability Acceptance Criteria	19
3.4	Strength Evaluation of the Lateral Force-Resisting System	19
3.5	Building Displacements	20
3.5.1	Overall Building Deflection	20
3.5.2	Story Drift	20
3.5.3	Drift Measurement Index	22
3.5.4	Recommended Drift Criteria	22
3.6	Nonstructural Elements	23
3.7	Occupant Comfort	25
3.7.1	Acceleration	25
3.7.2	Visual and Auditory	27
3.8	Project-Specific Performance	27
4	PRELIMINARY STRUCTURAL DESIGN	29
4.1	Purpose	29
4.2	Preliminary Wind Estimates	29
4.2.1	Along-Wind Response	29
4.2.2	Crosswind Response	30
4.3	Estimation of Building Performance	30
4.3.1	Preliminary Structural Analysis	31
4.3.2	Strength Checks	32
4.3.3	Building Periods and Mode Shapes	32
5	WIND CLIMATE ASSESSMENT	35
5.1	Overview	35
5.2	Davenport Wind Loading Chain	35
5.3	Wind Climate: Storm Types and Data Sources	36
5.3.1	Wind Storm Types	36
5.3.2	Data Sources	37
5.4	Influence of Terrain	38
5.5	Extreme Value Analysis	39
5.6	Design Criteria: Mean Recurrence Intervals	40
6	WIND TUNNEL TESTING	41
6.1	Overview	41
6.2	Triggers for Testing	41
6.3	Types of Wind Tunnel Tests	42
6.3.1	High-Frequency Balance	43
6.3.2	High-Frequency Pressure Integration	44
6.3.3	Aeroelastic Method	45

6.4	Physical Testing versus Computational Estimates	47
6.5	Testing Procedure	47
6.5.1	Timeline and Type for Testing	47
6.5.2	Inclusions and Exclusions	48
6.5.3	Required Input Information	48
6.6	Combining Climate and Wind Tunnel Data	48
6.7	Typical Outputs	49
6.8	Additional Considerations	51
6.8.1	Shielding and Influence from Surrounding Buildings	51
6.8.2	Design Evolution	51
6.8.3	Minimum Thresholds	51
7	DAMPING	53
7.1	Overview	53
7.2	Inherent Damping	53
7.3	Aerodynamic Damping	54
7.4	Supplemental Damping	54
7.4.1	Direct Damping Systems	55
7.4.2	Indirect Damping Systems	56
7.5	Supplemental Damping: Strength and Seismicability	58
8	STRUCTURAL MODELING AND ANALYSIS	59
8.1	Structural Modeling	59
8.1.1	Strength-Level and Serviceability-Level Analysis	60
8.1.2	Primary Lateral Load-Resisting System and Nonparticipating Elements	60
8.1.3	Building Mass	61
8.1.4	P-Delta (Second Order) Effects	62
8.1.5	Diaphragms	62
8.1.6	Foundation Flexibility	63
8.1.7	Panel Zone Deformations	64
8.2	Special Considerations for Reinforced Concrete Structures	65
8.2.1	Expected Strength and Modulus of Elasticity of Concrete Materials	65
8.2.2	Stiffness Modifiers and Behavior of Cracked Reinforced Concrete Structures	66
8.2.3	Simplified Method for Selecting Stiffness Modifiers	67
8.2.4	Detailed Method for Selecting Stiffness Modifiers	67
	WIND OPTIMIZATION PROGRAM	71
9.1	Introduction	71
9.2	Building Orientation	71
9.3	Building Geometry	72
9.4	Holistic Optimization	73

10 CONCLUDING REMARKS	77
10.1 Design Validation	77
10.2 Peer Review	77
10.3 Concurrent Research and Future Directions	78
10.3.1 Monitoring	78
10.3.2 Performance-Based Design	79
10.3.3 Computational Wind Engineering	79
10.3.4 High-Performance and New Materials	79
10.4 Closing Remarks	80
REFERENCES	81
INDEX	85

PREFACE

The Tall Buildings Committee of the Structural Engineering Institute of the American Society of Civil Engineers comprises senior leaders active in the field of tall buildings from both industry-leading professional consulting firms and academic institutions. The goal of this committee is to publish an industry consensus manual of practice that provides guidelines on the design and performance of tall buildings for wind effects. This publication provides recommendations and guidance on tall building design industry standard practice and approaches to complement current literature, model codes, and other standards. This publication should be used in conjunction with local building codes and considered a current consensus document developed by industry leaders for the design and performance of tall buildings for wind effects. However, it is the opinion of the committee that this consensus will evolve over time and as the industry advances.

*Preetam Biswas, P.E., LEED
Director of Structural Engineering
Skidmore, Owings & Merrill*

Task Committee Chair—Design and Performance of Tall Buildings for Wind

*John Peronto, P.E., S.E., C.Eng, EUR ING, FStructE, FICE, SECB, LEED AP
Senior Principal
Thornton Tomasetti, Inc.
Technical Activities Division Chair—Tall Buildings*

This page intentionally left blank

ACKNOWLEDGMENTS

To all the individuals who contributed to the discussion on content:

Maryam Asghari	Ramon Gilsanz	Viral Patel
Mooneghi	Jennifer Goupil	Karl Rubenacker
Andrew Bartolini	Jeremy Hasselbauer	Rob Smith
Audrey Bentz	Johnn Judd	Seymour Spence
Manotapa Bhaumik	Hessam Kazemzadeh	John Tessem
Melissa Burton	Tracy Kijewski-Correa	May Thu Nwe Nwe
Finley Charney	Jordan Komp	Un Yeong Jeong
Jon Galsworthy	Michael Montgomery	
Mike Gibbons	Deepak Pant	

To members of institutes and firms that contributed to the discussion on content:

Arup	Kinetica	University of Michigan
ASCE/SEI	LERA	University of Notre Dame
BCE	McNamara Salvia	University of Wyoming
CPP	MKA	Virginia Tech
DCI	Rad Urban	Walter P Moore
GMS	RWDI	WSP
Gradient Wind	SOM	
JHU	TT	

A special acknowledgement to the members of the Blue Ribbon Panel for their thorough and detailed review of the contents of this manual:

Abbas Aminmansour, Ph.D.
William F. Baker, P.E., S.E., F.ASCE
Daryl Boggs, Ph.D., P.E.
David Farnsworth, P.E.
William Faschan, P.E., S.E., F.ASCE

Robert A. Halvorson, P.E., S.E.

Peter Irwin, Ph.D., P.Eng.

Ahsan Kareem, Ph.D., Dist.M.ASCE

Ron Klemencic, P.E., S.E.

Robert Sinn, P.E., S.E.

CHAPTER 1

INTRODUCTION

1.1 PURPOSE

This Manual of Practice is intended to provide best-practice guidelines for the design of tall buildings for wind. Current building codes and design standards focus primarily on strength design for ultimate wind loads, offering little guidance related to the evaluation and establishment of acceptance criteria for tall building performance under varying levels of wind effects. As such, current design practice varies widely across the industry. The goal of this document is to promote consistency and best practices within the industry for the design of tall buildings for wind. It is envisioned to apply to buildings with height greater than 120 m (400 ft) and/or a height to width aspect ratio greater than 5:1.

1.2 SCOPE

The design recommendations provided in this manual are primarily focused on the wind design of building structures that are especially tall, slender, and/or prone to wind-induced movement. A discussion of both static and dynamic approaches to wind design are presented in subsequent chapters. Wind design performance objectives are achieved by

- Ensuring structural integrity under ultimate loads;
- Limiting lateral deflections under service loads to prevent permanent deformations, damage to nonstructural elements, or adverse effects on the serviceability of the building's services and vertical transportation systems;