

second edition

design of buildings for wind

a guide for
ASCE 7-10
Standard users
and designers
of special
structures

EMIL SIMIU, PE, PhD

DESIGN OF BUILDINGS FOR WIND

Second Edition

DESIGN OF BUILDINGS FOR WIND

A Guide for ASCE 7-10 Standard
Users and Designers of Special
Structures

Second Edition

EMIL SIMIU, P.E., Ph.D.



WILEY

JOHN WILEY & SONS, INC.

This book is printed on acid-free paper. (∞)

Copyright © 2011 by John Wiley & Sons, Inc. All rights reserved
Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 646-8600, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at www.wiley.com/go/permissions.

Limit of Liability/Disclaimer of Warranty: While the publisher and the author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor the author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information about our other products and services, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Simiu, Emil.

Design of buildings for wind : a guide for ASCE 7-10 standard users and designers of special structures / Emil Simiu. – 2nd ed.

p. cm.

Includes index.

Originally published under title: Design of buildings and bridges for wind. 2006.

ISBN 978-0-470-46492-2 (hardback); 978-1-118-07735-1 (ebk); 978-1-118-07736-8 (ebk); 978-1-118-07737-5 (ebk); 978-1-118-08613-1 (ebk); 978-1-118-08622-3 (ebk); 978-1-118-08623-0 (ebk)

1. Wind-pressure. 2. Buildings—Aerodynamics. 3. Bridges—Aerodynamics. 4. Wind resistant design. I. Simiu, Emil. Design of buildings and bridges for wind. II. Title.

TA654.5.S54 2011

624.1'75—dc23

2011013566

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

CONTENTS

PREFACE	xi
PART I INTRODUCTION	1
1 OVERVIEW	3
PART II GUIDE TO THE ASCE 7-10 STANDARD PROVISIONS ON WIND LOADS	7
2 ASCE 7-10 WIND LOADING PROVISIONS	9
2.1 Introduction / 9	
2.2 ASCE 7-10 Standard: An Overview / 10	
2.3 Organization of the Guide: Chapters 3 to 9 / 19	
3 REGULAR AND SIMPLIFIED APPROACH: RISK CATEGORY, BASIC WIND SPEED, ENCLOSURE, EXPOSURE, TOPOGRAPHIC FACTOR	21
3.1 Risk Category (ASCE Table 1.5-1) / 21	
3.2 Basic Wind Speed V (ASCE Sect. 26.5, ASCE Figs. 26.5.-1a, b, c) / 22	
3.3 Enclosure Classification (ASCE Sects. 26.2 and 26.10) / 23	

3.4	Exposure Category (ASCE Sect. 26.7) / 24	
3.5	Topographic Factor K_{zt} (ASCE Sect. 26.8, ASCE Fig. 26.8-1) / 27	
4	REGULAR APPROACH: STEPS COMMON TO ALL BUILDINGS/OTHER STRUCTURES (MWFRS AND C&C)	31
4.1	Introduction / 31	
4.2	Regular Approach: Steps Common to All Buildings and Other Structures (MWFRS and C&C) / 32	
5	REGULAR APPROACH: BUILDINGS, PARAPETS, OVERHANGS (“DIRECTIONAL” PROCEDURE), MWFRS	37
5.1	Introduction / 37	
5.2	Regular Approach: Enclosed or Partially Enclosed Buildings of All Heights, MWFRS / 37	
5.3	Regular Approach: Roof Overhangs and Parapets, MWFRS / 53	
5.4	Regular Approach: Open Buildings with Monoslope, Pitched, or Troughed Free Roofs, MWFRS / 55	
6	REGULAR APPROACH: LOW-RISE BUILDINGS, PARAPETS, OVERHANGS (“ENVELOPE” PROCEDURE), MWFRS	57
6.1	Net Pressures on Walls and Roof / 57	
6.2	Comparison Between Results Based on ASCE Sects. 27.4.1 and 28.4.1 / 62	
6.3	Regular Approach: Parapets and Roof Overhangs, MWFRS / 63	
7	REGULAR APPROACH: STRUCTURES OTHER THAN BUILDINGS, MWFRS	65
7.1	Solid Freestanding Walls and Solid Signs / 65	
7.2	Open Signs, Lattice Frameworks, Trussed Towers / 69	
7.3	Chimneys, Tanks, Rooftop Equipment, and Similar Structures / 74	
7.4	Solid Attached Signs / 75	
7.5	Rooftop Structures and Equipment on Buildings / 77	

8	SIMPLIFIED APPROACH: ENCLOSED SIMPLE DIAPHRAGM BUILDINGS, PARAPETS, OVERHANGS (MWFRS)	81
8.1	Simplified Approach: Class 1 Buildings, Walls and Roof, MWFRS / 81	
8.2	Simplified Approach: Parapets, MWFRS / 85	
8.3	Simplified Approach: Roof Overhangs, MWFRS / 85	
8.4	Simplified Approach: Class 2 Buildings, Walls and Roof, MWFRS / 86	
8.5	Simplified Approach: Simple Diaphragm Low-Rise Buildings, MWFRS / 90	
9	REGULAR AND SIMPLIFIED APPROACHES: C&C	95
9.1	Introduction / 95	
9.2	Regular Approach / 95	
9.3	Simplified Approaches / 105	
PART III WIND ENGINEERING FUNDAMENTALS		107
10	ATMOSPHERIC CIRCULATIONS	109
10.1	Atmospheric Hydrodynamics / 109	
10.2	Windstorms / 113	
11	THE ATMOSPHERIC BOUNDARY LAYER	117
11.1	Wind Speeds and Averaging Times / 118	
11.2	Wind Speed Profiles / 121	
11.3	Atmospheric Turbulence / 130	
12	EXTREME WIND SPEEDS AND WIND-INDUCED EFFECTS	137
12.1	Wind Speed Data / 138	
12.2	Cumulative Distributions, Exceedance Probabilities, Mean Recurrence Intervals / 141	
12.3	Parametric Estimates of $\overline{N}$ -Year Wind Speeds; Closed Form Estimators; Software / 143	
12.4	Probabilistic Estimates of Wind Effects Based on Nondirectional and Directional Wind Speed Data / 149	

12.5	Development of Directional Databases of Hurricane Wind Speeds / 153	
12.6	Development of Directional Databases of Non-Hurricane Wind Speeds / 155	
12.7	Non-Parametric Statistics, Application to One-Dimensional Time Series / 157	
12.8	Error Estimates / 159	
13	BLUFF BODY AERODYNAMICS BASICS; AERODYNAMIC TESTING	163
13.1	Introduction / 163	
13.2	Bluff Body Aerodynamics / 163	
13.3	Aerodynamic Testing / 173	
13.4	Low-Frequency Turbulence and Aerodynamic Pressures on Residential Homes / 183	
14	STRUCTURAL DYNAMICS	185
14.1	Introduction / 185	
14.2	The Single-Degree-of Freedom Linear System / 186	
14.3	Continuously Distributed Linear Systems / 190	
14.4	Time Domain Solutions for Three-Dimensional Dynamic Response / 199	
15	AEROELASTICITY	203
15.1	Introduction / 203	
15.2	Vortex-Induced Oscillations / 205	
15.3	Galloping / 206	
15.4	Flutter / 210	
16	STRUCTURAL RELIABILITY UNDER WIND LOADING	217
16.1	Introduction / 217	
16.2	First-Order Second-Moment Approach, Load and Resistance Factors / 220	
16.3	Dependence of Wind Effects on Wind Directionality / 225	
16.4	Structural Strength Reserve / 226	
16.5	Design Criteria for Multi-Hazard Regions / 228	
16.6	Individual Uncertainties and Overall Uncertainty in the Estimation of Wind Effects / 229	
16.7	Calibration of Design MRIs in the Presence of Dynamic Effects or of Large Knowledge Uncertainties / 232	

17	LOSS ESTIMATION	237
17.1	Introduction / 237	
17.2	Elements of Damage Estimation Procedures / 238	
17.3	Loss Estimation / 245	
PART IV	WIND EFFECTS ON BUILDINGS	247
18	RIGID BUILDINGS	249
18.1	Introduction / 249	
18.2	Database-Assisted Design (DAD) / 252	
18.3	Wind Directionality Effects / 258	
18.4	Uncertainties in the Estimation of Wind Effects / 259	
19	TALL BUILDINGS	261
19.1	Introduction / 261	
19.2	High-Frequency Force Balance Approach (HFFB) / 263	
19.3	Aeroelastic Effects. Testing Based on Strain Measurements / 265	
19.4	Database-Assisted Design / 269	
19.5	Serviceability Requirements / 278	
19.6	Preliminary Estimates of Flexible Building Response / 279	
PART V	APPENDICES	287
APPENDIX A1	RANDOM PROCESSES	289
A1.1	Fourier Series and Fourier Integrals / 290	
A1.2	Parseval's Equality / 291	
A1.3	Spectral Density Function of a Random Stationary Signal / 292	
A1.4	Autocorrelation Function of a Random Stationary Signal / 293	
A1.5	Cross-Covariance Function, Co-Spectrum, Quadrature Spectrum, Coherence / 295	
A1.6	Mean Upcrossing and Outcrossing Rate for a Gaussian Process / 296	
A1.7	Probability Distribution of the Peak Value of a Normally Distributed Random Signal / 297	
A1.8	Probability Distribution of the Peak Value of a Non-Gaussian Random Signal / 298	

APPENDIX A2 MEAN WIND PROFILES AND ATMOSPHERIC BOUNDARY LAYER DEPTH	301
A2.1 Equations of Balance of Momenta within the Atmospheric Boundary Layer / 301	
A2.2 The Turbulent Ekman Layer / 302	
APPENDIX A3 SPECTRA OF TURBULENT VELOCITY FLUCTUATIONS, KOLMOGOROV HYPOTHESES	307
APPENDIX A4 WIND DIRECTIONALITY EFFECTS, OUTCROSSING AND SECTOR-BY-SECTOR APPROACHES	311
A4.1 Approach Based on the Outcrossing of the Limit-State Boundary / 311	
A4.2 The Sector-By-Sector Approach [18-10] / 313	
APPENDIX A5 REPORT ON ESTIMATION OF WIND EFFECTS ON THE WORLD TRADE CENTER TOWERS	315
REFERENCES	323
INDEX	333

PREFACE

For most common types of structure, standard provisions on wind loads are in principle adequate for design purposes. The ASCE 7-10 Standard, among other standards, has incorporated a great deal of wind engineering knowledge accumulated within the last half-century. However, because the Standard has been developed by successive accretions, not always smoothly, its previous versions have been perceived by some practitioners as complicated and unwieldy. In an effort to respond to the demand for a clearer document, the ASCE 7-10 version of the Standard has been substantially expanded and revised. However, difficulties remain.

One of the main objectives of this book is to help the reader better understand the ASCE 7-10 Standard provisions for wind loads and apply them with confidence and ease. To this end, the book presents a guide to the Standard that explains the rationale of the provisions and illustrates their use through a large number of detailed numerical examples. Particular attention is given to the numerous changes made in the 2010 version of the ASCE Standard. Comparisons are presented between—or among—results of alternative provisions specified by the Standard for the same type of building. The comparisons show, for example, that for low-rise buildings, the so-called envelope procedure does not necessarily yield the lowest wind loads, as the Standard asserts. They also show that wind loads yielded by alternative regular methods, by regular and simplified methods, or by alternative simplified methods, can exhibit significant differences.

Wind loads and effects on special structures cannot in general be estimated by using standard provisions based on tables and plots. Rather, they need to be based on aerodynamic testing in the wind tunnel or larger facilities, and

on information on the extreme wind speeds at the site. The Standard's provisions on the wind tunnel method are still vague and incomplete. In particular, they contain little or no material on dynamic analyses, the dependence of the response on wind directionality, and the calibration of the design mean recurrence intervals to account for larger-than-typical errors and uncertainties in the parameters that govern the wind-induced demand.

Some design offices have a policy of requiring wind effects estimates from more than one consultant. This is prudent, and justified by the fact that, owing to the lack of adequate standard provisions on the wind tunnel procedure, estimates by various laboratories can differ significantly. For example, recent estimates of the New York World Trade Center towers response to wind, performed by two well-known consultants, were found to differ by over 40%.

Consultant reports need, therefore, to be carefully scrutinized, and the need for transparency in their presentation cannot be overemphasized. The book includes as an appendix a report by Skidmore Owings & Merrill LLP, which presents a practitioner's perspective on the current state of the art in wind engineering and is a testimony to the need for transparent, traceable, and auditable procedures. Material presented in the book enables structural engineers to "ask the right questions," scrutinize effectively wind engineers' contributions to the determination of wind effects, and determine wind effects efficiently and accurately on their own, just as structural engineers do for seismic effects. This requires the use by the structural engineer of aerodynamic or aeroelastic data supplied by the wind engineer in standard, electronic form, and of directional extreme wind speed data obtained from wind climatological consultants. The wind effects of interest include internal forces, demand-to-capacity indexes for individual member design, as well as deflections and accelerations needed to check serviceability requirements. The book describes in detail modern, effective, and transparent methods for estimating such wind effects for any specified mean recurrence interval.

Wind effects on individual members are functions of influence coefficients that differ from member to member. In the past, the lack of sufficiently powerful computer resources did not allow this dependence to be taken into account accurately. The capability to do so is now routinely available. It has created a bridge between the wind engineer and the structural engineer that makes it possible to integrate the wind and structural phases of structural design more clearly and accurately than was heretofore possible. Public domain database-assisted design software referenced in the book allows the effective implementation of this capability.

Until about two decades ago, the time domain solution of large systems of differential equations posed insurmountable computational problems, and dynamics calculations were performed by using the spectral (frequency domain) approach, which transforms the differential equations of motion into algebraic equations. This approach is not always transparent and intuitive, and in practice suppresses phase information needed to correctly add wind effects from various sources (e.g., from two perpendicular lateral motions).

Computational capabilities and measurement technology developed in last two decades have made it possible to replace the frequency domain approach by the typically more effective time domain approach. The time domain approach, used in publicly available software referenced in the book, is not limited to the estimation of loads through the summation of pressures measured at large numbers of ports. Rather, in the integrated format known as database-assisted design, it can be directly and effectively applied to the design or checking of individual member strength, and can thus substantially improve structural design accuracy. In particular, the time domain approach eliminates the need for large numbers of cumbersome load combinations, based on guesswork—the method currently being used—and performs the requisite combinations through simple algebraic addition of time series of load effects. The improvements inherent in the use of time domain rather than frequency domain methods can be compared to those inherent in the calculation of structural response by finite element rather than by slide-rule based techniques.

The book contains material on structural reliability under wind loads that provides, among other matters, a perspective on the limitations of the Load and Resistance Factor Design (LRFD) approach, and a procedure for the calibration of design mean recurrence intervals. The calibration is required to ensure adequate safety levels if uncertainties in the determination of wind effects exceed typical uncertainties assumed in the ASCE 7 Standard. To date, the role of errors and uncertainties in the specification of design mean recurrence intervals has not been addressed by the ASCE 7 Standard provisions for the wind tunnel procedure, with the result that some designers and wind engineers resort to “magic numbers” that may be inadequate. For example, the same design mean recurrence interval is implied in the Standard for ordinary buildings and for tall buildings, whose response depends on dynamic parameters, including damping, which may exhibit large uncertainties. A reliability-based approach that takes into account such uncertainties can yield, for some tall buildings, longer mean recurrence intervals and hence larger wind effects than those specified in the ASCE Standard.

Structural reliability is also useful because it helps engineers design structures that do not consume more material and do not contain more embodied energy than necessary to ensure adequate safety levels. Inadequate safety levels can result in wind-induced losses, which are visible and costly. On the other hand, the cost of unnecessary materials—of “fat,” as opposed to “muscle”—is much less visible to the public eye, but is nonetheless real, in monetary, energy consumption, and carbon footprint terms.

The book addresses incipient efforts to estimate ultimate capacities under fluctuating wind loads, aimed to achieve designs that are safer, more economical, and less demanding of embodied energy than those based on linear methods of analysis. The book also addresses wind-induced loss estimation, a topic fraught with difficulties, owing to the nonlinearities typically associated with the analysis of failures. Finally, in response to requests by students and