SIMPLIFIED BUILDING DESIGN FOR WIND AND EARTHQUAKE FORCES

Second Edition

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DIMITRY VERGUN

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PREFACE

This edition constitutes a considerable expansion of the topic over that presented in the first edition, which was published in 1980. Design examples have been extended to cover a wider range of building types and situations, more discussion of general building design issues has been added, and considerable new material on design of foundations for lateral loads has been included. Still, the general concept and basic style are the same as for the first edition. The book is intended primarily for persons with an interest in building design but who lack extensive training in engineering investigation and structural theory.

A major incentive for producing a new edition at this time was the publication of the 1988 edition of the *Uniform Building Code* (*UBC*). This edition of the *UBC* contains a major expansion and revision of requirements for seismic design, much of which is aimed at architectural design issues regarding materials and building form. Since an earlier edition of the *UBC* also made major changes in wind design requirements, the combination made much of the material in the first edition out of date. As the book has continued in use, the authors felt an obligation to produce a new edition.

Bringing the work into line with the new *UBC* is a major issue in the presentations in this edition. However, the *UBC* is not really the original source of the work on which its requirements are based, but simply reflects current directions in research, experiences gathered from recent major disasters (windstorms and earthquakes), and developments in design by leading professionals and firms. The presentations in this book, while intended to help explain some of the new *UBC* requirements, are really aimed at ideas of fundamental concern and general interest related to the topics of design for wind and seismic effects on buildings.

Both authors have experience in teaching these subjects to architecture and engineering students and in working as structural designers with architects—the latter in many cases also representing a teaching involvement. This book is extensively illustrated and contains basic explanations of concepts and problems that are aimed specifically at persons with a general interest in building design. In many situations, equal time is given to discussions of general design concerns for the building, as well as to concerns for structural behavior.

A new section has been added to this edition containing study materials, which should be of special value to persons using the book in a self-study situation. Both authors have also had recent experience in helping to develop materials for the state board examinations for architectural registration, and feel that these study materials should be useful for preparation for those exams.

We are grateful to the International Conference of Building Officials, publishers of the *Uniform Building Code*, for their permission to reprint major portions of the 1988 *UBC* in Appendix C of this book. Reference to these materials is made repeatedly throughout this book, and the reader should thus be able to gain considerable familiarity with the code.

We are also grateful to the Masonry Institute of America for their permission to reprint the materials presented here in Appendix D. Use of these materials is demonstrated in design examples.

Finally—as always—we are grateful to the many students and fellow designers whose difficulties in dealing with these subjects has steadily developed our need and concern for explaining things in as simple and clear a manner as possible.

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Los Angeles, California
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INTRODUCTION

The purpose of this book is to provide a source of study and reference for the topics of wind and earthquake effects as they pertain to the design of building structures. The treatment of these subjects is aimed at persons not trained in structural engineering but who have some background experience in the analysis and design of simple structures. Material presented includes the development of background topics, such as basic aspects of wind and earthquake effects and fundamentals of dynamic behavior, as well as the pragmatic considerations of design of structures for real situations.

As implied by the title, the scope of the work is limited. This limitation is manifested in the level of complexity of the problems dealt with and in the techniques used, principally with regard to the degree of difficulty in mathematical analysis and the sophistication of design methods. In order to set these limits we have assumed some specific minimal preparation by the reader, and individual readers should orient themselves with regard to these assumptions. For those with some lack of preparation, the list of references following Chapter 6 may be useful for supplementary study. For the reader with a higher capability in mathematics or a more intensive background in applied mechanics and structural analysis, this work may serve as a springboard to more rigorous study of the topics.

The majority of the mathematical work, especially that in the applied design examples in Chapter 5, is limited to relatively simple algebra and geometry. In the treatment of the fundamentals of dynamics and in the explanation of some of the formulas used in analysis and design it is occasionally necessary to use relationships from trigonometry, vector analysis, and calculus. The reader with this level of mathematical background will more fully appreciate the rational basis for the formulas, although their practical application will usually involve only simple algebra and arithmetic. Persons expecting to pursue the study of these topics beyond the scope of this book are advised to prepare themselves with work in mathematics that proceeds to the level of advanced calculus, partial differential equations, and matrix methods of analysis.

A minimal preparation in the topics of applied mechanics and structural analysis and design is assumed. This includes the topics of statics, elementary strength of materials, and the design of simple elements of wood, steel, and concrete structures for buildings. The general scope of the work in the design examples is limited to that developed in *Simplified Engineering for Architects and Builders* by Harry Parker and James Ambrose (Ref. 18). When some of the examples involve the analysis of indeterminate structures, the work presented is done with simplified, approximate methods that should be reasonably well understood by the reader with the previously described minimal background. For a more rigorous and exact analysis of such problems, or for the study of more complex problems, the reader is advised to pursue a general study of the analysis of indeterminate structures.

A third area of assumed background knowledge is that of the ordinary materials and methods of building construction as practiced in the United States. It is assumed that the reader has a general familiarity with the ordinary processes of building construction and with the codes, standards, and sources of general data for structures of wood, steel, masonry, and concrete.

A major reference used for this work is the 1988 edition of the *Uniform Building Code* (Ref. 1), hereinafter called the *UBC*. The design examples in this book use the general requirements, the analytical procedures, and some of the specific data from this reference. Much of the material from the *UBC* that relates directly to problems of wind and earthquakes is reprinted in Appendix C of this book. It is recommended, however, that the reader have a copy of the entire code available because it contains considerable additional material pertinent to the use of specific materials, to structural design requirements in general, and to various problems of building planning and construction.

In real design situations individual buildings generally fall under the jurisdiction of a particular local code. Most large cities, many counties, and some states have their own individual codes. In many cases these codes are based primarily on one of the so-called "model" codes, such as the *UBC*, with some adjustments and additions for specific local conditions and practices. The reader who expects to work in a particular area is advised to obtain a copy of the code with jurisdiction in that area and to compare its provisions with those of the *UBC* as they are used in this work.

Building codes, including the *UBC*, are occasionally updated to keep them abreast of current developments in research, building practices, analytical and design techniques, and so on. The publishers of the *UBC* have generally followed a practice of issuing a new edition every three years. For reference in any real design work the reader is advised to be sure that the code he is using is the one with proper jurisdiction and is the edition currently in force. This precaution regarding use of dated materials applies also to other reference sources, such as handbooks, industry brochures, detailing manuals, and so on.

Use of the word *simplified* does not mean to imply that all design for wind and earthquakes can be reduced to simple methods. On the contrary, many problems in this area represent highly complex, and as yet far from fully understood, situations in structural design, situations that demand considerable seriousness, competency, and effort by professional engineers and researchers. We have deliberately limited the material in this book to that which we believe can be relatively easily understood and mastered by persons in the beginning stages of study of the design of structures. For those whose work will be limited to the relatively simple situations presented by the examples in this book, mastery of this material will provide useful working skills. For those who expect to continue their studies into more advanced levels of analysis and design, this material will provide a useful introduction.

Computations

In professional design firms, structural computations are most commonly done with computers, particularly when the work is complex or repetitive. Anyone aspiring to participation in professional design work is advised to acquire the background and experience necessary to the application of computer-aided techniques. The computational work in this book is simple and can be performed easily with a pocket calculator. The reader who has not already done so is advised to obtain one. The "scientific" type with eight-digit capacity is quite sufficient.

For the most part, structural computations can be rounded off. Accuracy beyond the third place is seldom significant, and this is the level used in this work. In some examples more accuracy is carried in early stages of the computation to ensure the desired degree in the final answer. All the work in this book, however, was performed on an eight-digit pocket calculator.

Symbols

The following "shorthand" symbols are frequently used:

Symbol	Reading
$>$	is greater than
$<$	is less than
$\geqslant$	equal to or greater than
$\leqslant$	equal to or less than
6′	six feet
6″	six inches
Σ	the sum of
ΔL	change in L

Notation

Use of standard notation in the general development of work in mechanics and strength of materials is complicated by the fact that there is some lack of consistency in the notation currently used in the field of structural design. Some of the standards used in the field are developed by individual groups (notably those relating to a single basic material, wood, steel, concrete, masonry, etc.) which each have their own particular notation. Thus the same type of stress (e.g., shear stress in a beam) or the same symbol (f_c) may have various representations in structural computations. To keep some form of consistency in this book, we use the following notation, most of which is in general agreement with that used in structural design work at present.

a	(1) Moment arm; (2) acceleration; (3) increment of an area
A	Gross (total) area of a surface or a cross section
b	Width of a beam cross section
B	Bending coefficient
c	Distance from neutral axis to edge of a beam cross section
d	Depth of a beam cross section or overall depth (height) of a truss
D	(1) Diameter; (2) deflection

e	(1) Eccentricity (dimension of the mislocation of a load resultant from the neutral axis, centroid, or simple center of the loaded object); (2) elongation
E	Modulus of elasticity (ratio of unit stress to the accompanying unit strain)
f	Computed unit stress
F	(1) Force; (2) allowable unit stress
g	Acceleration due to gravity
G	Shear modulus of elasticity
h	Height
H	Horizontal component of a force
I	Moment of inertia (second moment of an area about an axis in the plane of the area)
J	Torsional (polar) moment of inertia
K	Effective length factor for slenderness (of a column: KL/r)
M	Moment
n	Modular ratio (of the moduli of elasticity of two different materials)
N	Number of
p	(1) Percent; (2) unit pressure
P	Concentrated load (force at a point)
r	Radius of gyration of a cross section
R	Radius (of a circle, etc.)
s	(1) Center-to-center spacing of a set of objects; (2) distance of travel (displacement) of a moving object; (3) strain or unit deformation
t	(1) Thickness; (2) time
T	(1) Temperature; (2) torsional moment; fundamental period of vibration of building
V	(1) Gross (total) shear force; (2) vertical component of a force
w	(1) Width; (2) unit of a uniformly distributed load on a beam
W	(1) Gross (total) value of a uniformly distributed load on a beam; (2) gross (total) weight of an object
Δ (delta)	Change of
θ (theta)	Angle
Σ (sigma)	Sum of
μ (mu)	Coefficient of friction
ϕ (phi)	Angle

Special notation is used in every field of engineering. The special notation used in the areas of wind and seismic design is generally reflected in the building codes. We use here the notation from the *UBC* in these areas, which is explained in the chapters that deal with the topics of design for wind and seismic effects.

1

WIND EFFECTS ON BUILDINGS

Wind is moving air. The air has a particular mass (density or weight) and moves in a particular direction at a particular velocity. It thus has kinetic energy of the form expressed as

$$E = \tfrac{1}{2}mv^2$$

When the moving fluid air encounters a stationary object, there are several effects that combine to exert a force on the object. The nature of this force, the many variables that affect it, and the translation of the effects into criteria for structural design are dealt with in this chapter.

1.1 WIND CONDITIONS

The wind condition of concern for building design is primarily that of a wind storm, specifically high-velocity, ground-level winds. These winds are generally associated with one of the following situations.

Tornadoes

Tornadoes occur with some frequency in the midwest and occasionally in other parts of the United States. In coastal areas they are usually the result of ocean storms that wander ashore. Although the most violent effects are at the center of the storm, high-velocity winds in a large surrounding area often accompany these storms. In any given location the violent winds are usually short in duration as the tornado dissipates or passes through the area.

Hurricanes

Whereas tornadoes tend to be relatively short-lived (a few hours at most), hurricanes can sustain storm wind conditions for several days. Hurricanes occur with some frequency in the Atlantic and Gulf coastal areas of the United States. Although they originate and develop their greatest fury over the water, they often stray ashore and can move some distance inland before dissipating. As with tornadoes, the winds of highest velocity occur at the eye of the hurricane, but major winds can develop in large surrounding areas, often affecting coastal areas some distance inland even when the hurricane stays at sea.

Local Peculiar Wind Conditions

An example of wind conditions peculiar to one locality are the Santa Ana winds of Southern California. These winds are recurrent conditions caused by the peculiar geographic and climatological conditions of an area. They can sometimes result in local wind velocities of the level of those at the periphery of tornadoes and hurricanes and can be sustained for long periods.

Sustained Local Wind Conditions

Winds that occur at great elevations above sea level are an example of sustained local wind conditions. Such winds may possibly never reach the extremes of velocity of storm conditions, but they can require special consideration because of their enduring nature.

Local and regional meteorological histories are used to predict the degree of concern for or likelihood of critical wind conditions in a particular location. Building codes establish minimum design requirements for wind based on this experience and the statistical likelihood it implies. The map in the *UBC* Fig. 1 (Appendix C) shows the variation of critical wind conditions in the United States.

Of primary concern in wind evaluation is the maximum velocity that is achieved by the wind. Maximum velocity usually refers to a sustained velocity and not to gust effects. A gust is essentially a pocket of higher velocity wind within the general moving fluid air mass. The resulting effect of a gust is that of a brief increase, or surge, in the wind velocity, usually of not more than 15% of the sustained velocity and for only a fraction of a second in duration. Because of both its higher velocity and its slamming effect, the gust actually represents the most critical effect of the wind in most cases.

Winds are measured regularly at a large number of locations. The standard measurement is at 10 meters (approximately 33 ft) above the surrounding terrain, which provides a fixed reference with regard to the drag effects of the ground surface. The graph in Fig. 1.1 shows the correlation between wind velocity and various wind conditions. The curve on the graph is a plot of a general equation used to relate wind velocity to equivalent static pressure on buildings, as discussed in Sec. 1.3.

Although wind conditions are usually generalized for a given geographic area, they can vary considerably for specific sites because of the nature of the surrounding terrain, of landscaping, or of nearby structures. Each individual building design should consider the possibilities of these localized site conditions.

1.2 GENERAL WIND EFFECTS

The effects of wind on stationary objects in its path can be generalized as in the following discussions (see Fig. 1.2).

Direct Positive Pressure

Surfaces facing the wind and perpendicular to its path receive a direct impact effect from the moving mass of air, which generally produces the major portion of force on the object unless it is highly streamlined in form.

Aerodynamic Drag

Because the wind does not stop upon striking the object but flows around it like a liquid, there is a drag effect on surfaces that are parallel to the direction of the

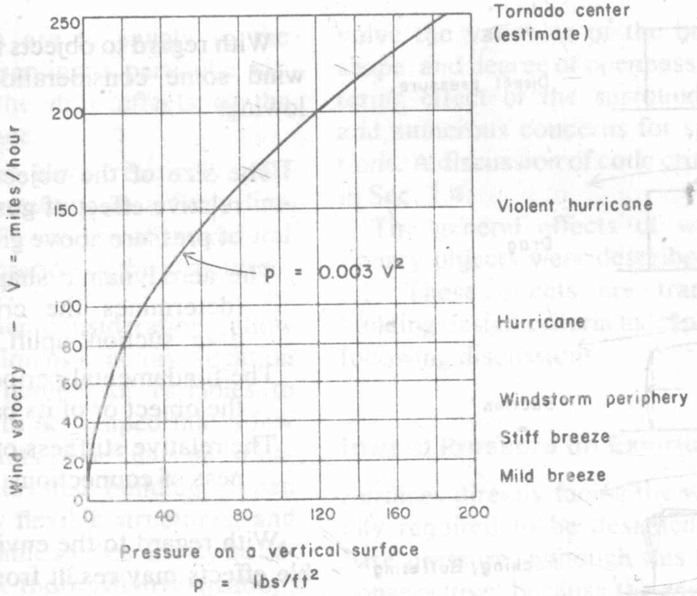

FIGURE 1.1. Relation of wind velocity to pressure on a stationary object.

wind. These surfaces may also have inward or outward pressures exerted on them, but it is the drag effect that adds to the general force on the object in the direction of the wind path.

Negative Pressure

On the leeward side of the object (opposite from the wind direction) there is usually a suction effect, consisting of pressure outward on the surface of the object. By comparison to the direction of pressure on the windward side, this is called *negative pressure*.

These three effects combine to produce a net force on the object in the direction of the wind that tends to move the object along with the wind. In addition to these there are other possible effects on the object that can occur due to the turbulence of the air or to the nature of the object. Some of them are as follows.

Rocking Effects. During wind storms, the wind velocity and its direction are seldom constant. Gusts and swirling winds are ordinary, so that an object in the wind path tends to be buffeted, rocked, flapped, and so on. Objects with loose parts, or with connections having some slack, or with highly flexible surfaces (such as fabric surfaces that are not taut) are most susceptible to these effects.

Harmonic Effects. Anyone who plays a wind instrument appreciates that wind can produce vibration, whistling, flutter, and so on. These effects can occur at low velocities as well as with wind storm conditions. This is a matter of some match between the velocity of the wind and the natural period of vibration of the object or of its parts.

Clean-Off Effect. The friction effect of the flowing air mass tends to smooth off the objects in its path. This fact is of particular concern to objects that protrude from the general mass of the building, such as canopies, parapets, chimneys, and signs.

The critical condition of individual parts or surfaces of an object may be caused by

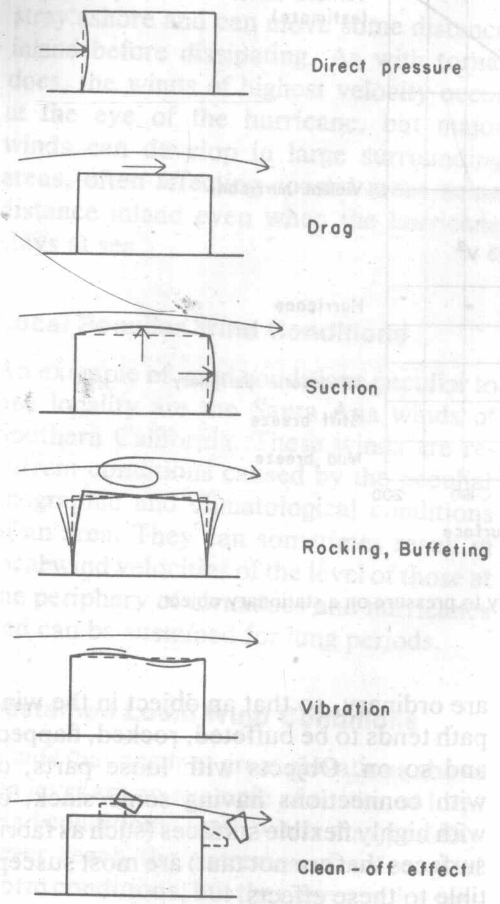

FIGURE 1.2. General effects of wind.

any one, or some combination, of the above effects. Damage can occur locally or be total with regard to the object. If the object is resting on the ground, it may be collapsed or may be slid, rolled over, or lifted from its position. Various aspects of the wind, of the object in the path of the wind, or of the surrounding environment determine the critical wind effects. With regard to the wind itself some considerations are the following:

- The magnitude of sustained velocities
- The duration of high-level velocities
- The presence of gust effects, swirling, and so on
- The prevailing direction of the wind (if any)

With regard to objects in the path of the wind some considerations are the following:

- The size of the object (relates to the relative effect of gusts, to variations of pressure above ground level, etc.)
- The aerodynamic shape of the object (determines the critical nature of drag, suction, uplift, etc.)
- The fundamental period of vibration of the object or of its parts
- The relative stiffness of surfaces, tightness of connections, and so on

With regard to the environment, possible effects may result from the sheltering or funneling caused by ground forms, landscaping, or adjacent structures. These effects may result in an increase or reduction of the general wind effects or in turbulence to produce a very unsteady wind condition.

The actual behavior of an object during wind storm conditions can be found only by subjecting it to a real wind situation. Wind tunnel tests in the laboratory are also useful, and because we can create the tests more practically on demand, they have provided much of the background for data and procedures used in design.

1.3 CRITICAL WIND EFFECTS ON BUILDINGS

The major effects of wind on buildings can be generalized to some degree because we know a bracketed range of characteristics that cover the most common conditions. Some of the general assumptions made are as follows:

- Most buildings are boxy or bulky in shape, resulting in typical aerodynamic response.
- Most buildings present closed, fairly smooth surfaces to the wind.

Most buildings are fit snugly to the ground, presenting a particular situation for the drag effects of the ground surface.

Most buildings have relatively stiff structures, resulting in a fairly limited range of variation of the natural period of vibration of the structure.

These and other considerations allow for the simplification of wind investigation by permitting a number of variables to be eliminated or to be lumped into a few modifying constants. For unusual situations, such as elevated buildings, open structures, highly flexible structures, and unusual aerodynamic shapes, it may be advisable to do more thorough investigation, including the possible use of wind tunnel tests.

The primary effect of wind is visualized in the form of pressures normal to the building's exterior surfaces. The basis for this pressure begins with a conversion of the kinetic energy of the moving air mass into an equivalent static pressure using the basic formula

$$p = Cv^2$$

in which C is a constant accounting for the air mass, the units used, and a number of the assumptions previously described. With the wind in miles per hour (mph) and the pressure in pounds per square foot (psf), the C value for the total wind effect on a simple box-shaped building is approximately 0.003, which is the value used in deriving the graph in Fig. 1.1. It should be noted that this pressure does not represent the actual effect on a single building surface, but rather the *entire* effect of all surface pressures visualized as a single pressure on the windward side of the building.

Building codes provide data for establishing the critical wind velocity and for determining the design wind pressures for the investigation of wind effects on a particular building. Considerations involve the variables of the building size, shape, and degree of openness, of the sheltering effect of the surrounding terrain, and numerous concerns for special situations. A discussion of code criteria is given in Sec. 1.4.

The general effects of wind on stationary objects were described in Section 1.2. These effects are translated into building design criteria as explained in the following discussions.

Inward Pressure on Exterior Walls

Surfaces directly facing the wind are usually required to be designed for the full base pressure, although this is somewhat conservative, because the windward force usually accounts for only about 60% of the total force on the building. Designing for only part of the total force is, however, partly compensated for by the fact that the base pressures are not generally related to gust effects which tend to have less effect on the building as a whole and more effect on parts of the building.

Suction on Exterior Walls

Most codes also require suction on exterior walls to be the full base pressure, although the preceding comments about inward pressure apply here as well.

Pressure on Roof Surfaces

Depending on their actual form, as well as that of the building as a whole, nonvertical surfaces may be subjected to either inward or suction pressures because of wind. Actually such surfaces may experience both types of pressure as the wind shifts direction. Most codes require an uplift (suction) pressure equal to the full design pressure at the elevation of the roof level. Inward pressure is usually related to the actual angle of the surface as an inclination from the horizontal.