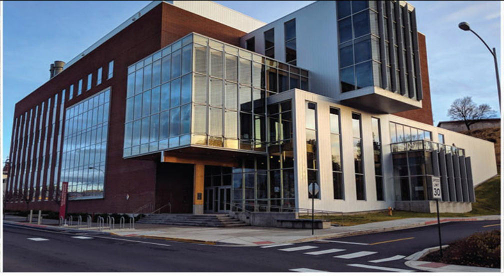
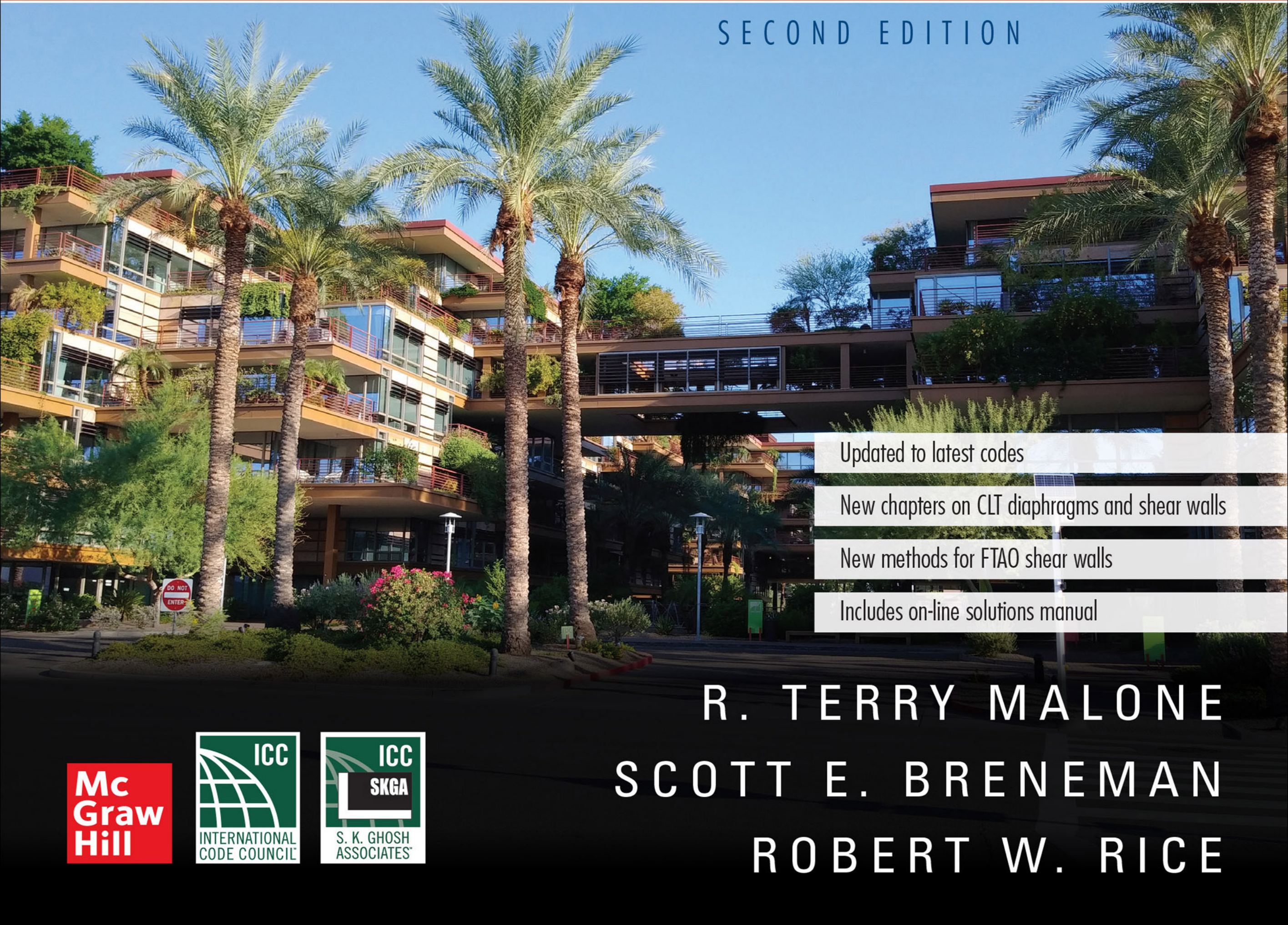


THE ANALYSIS OF IRREGULAR SHAPED STRUCTURES

WOOD DIAPHRAGMS AND SHEAR WALLS

SECOND EDITION



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The Analysis of Irregular Shaped Structures

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Wood Diaphragms and Shear Walls

R. Terry Malone, P.E., S.E.

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Robert W. Rice, CBO

Second Edition

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Dedicated to, and in appreciation of, those who inspire us.

To our families, especially our wives:

Jerri
Courtney
Lisa

About the Authors

R. Terry Malone, P.E., S.E., is a licensed structural engineer in Washington, Oregon, and Arizona and senior technical director of the Project Resources and Solutions Division of WoodWorks. He provides project support and education to architects, engineers, and design professionals regarding designing and constructing wood buildings, oversees the development of technical educational content, and is involved in professional standards committees through the American Wood Council. Prior to joining WoodWorks, Mr. Malone was a principal in consulting structural engineering firms in Washington and Oregon and also conducted third-party structural plan reviews. He previously served as a faculty member at St. Martin's College in Lacey, Washington. He has over 45 years of wood design experience and experience with lateral-force-resisting systems.

Scott E. Breneman, Ph.D., P.E., S.E., is a licensed structural engineer and professional engineer in the State of California, is a licensed professional engineer in the State of Washington, and is experienced with structural design, seismic rehabilitation, and peer review of building projects of all shapes and materials. He received bachelor's and master's degrees from the University of Florida and a doctorate from Stanford University. As a senior technical director at WoodWorks, Dr. Breneman currently provides project support and education to AEC professionals constructing wood buildings, oversees the development of technical educational content, and generally tries to stay knowledgeable on the rapidly progressing field of mass timber. He is a past president of the Structural Engineers Association of Central California and is involved in numerous professional standards committees through the American Society of Civil Engineers, American Wood Council, and APA—The Engineered Wood Association.

Robert W. Rice, CBO, is operations manager/chief building official for Northwest Code Professionals, which provides building department services for jurisdictions throughout Oregon and Washington. Following 10 years of work as a structural designer for engineering firms in Southern Oregon, and a developing interest in building codes, he worked as building official for Josephine County. Oregon and assistant state building official for the State of Oregon. He is also actively involved in code development with ICC and the State of Oregon and is a past member of ICC's Building Code Action Committee. Mr. Rice is a past president of Oregon Building Officials Association and the Southern Oregon Chapter of ICC. He was also a part-time instruction for the construction technology program at Rogue Community College.

For instructors of classes using this book as a text, a solutions manual for the end-of-chapter problems is available at www.mhprofessional.com/AnalysisofIrregularShapedStructures2E.

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Preface

Residential and commercial buildings have become more complex than structures built only a few decades ago. To create architecturally appealing structures, horizontal and vertical offsets in the diaphragms, multiple reentrant corners, multiple irregularities, and fewer vertical lateral-force-resisting elements have become commonplace. The structural configurations of many modern buildings require very complex lateral load paths. Most texts and publications available only address simple rectangular diaphragms and shear walls. Methods of analysis for these simpler diaphragms and shear walls do not easily adapt to complex diaphragms and shear wall layouts in irregular shaped structures.

Calculating the forces that are to be transferred across multiple discontinuities and detailing the design requirements on the construction documents can be very challenging and time consuming. Various methods of analyzing the distribution of lateral loads in complex structures were developed in the early 1980s, based largely on work done by the Applied Technology Council (ATC-7),[1] the APA—The Engineered Wood Association,[2] and by Edward F. Diekmann[3] among others. But the distribution of this information has been limited, making some of the material hard to find. Innovations in wood construction have also introduced cross-laminated timber (CLT) into wood roof, floor, and wall constructions. While basic load path analysis is material independent, the use of CLT in lateral-force-resisting diaphragms and shear walls brings in new design considerations for practicing engineers.

The purpose of this publication is to consolidate information into one source to provide a comprehensive coverage of the analysis of modern irregular shaped structures through numerous step-by-step examples, and to bring it to the forefront of the engineering and code official communities. A secondary objective is to demonstrate how to achieve the *necessary* complete lateral load paths through shear wall and diaphragm discontinuities. The complex diaphragm, shear wall, and load path issues addressed in this book are representative of today's demand on design professionals and code officials. Most of the examples in this book are based on light-frame wood construction using diaphragms that can be idealized as flexible. Shear walls are typically considered to be rigid bodies using wood or cold-formed steel framing with wood sheathing but vary in stiffness due to larger openings.

The information presented in this book is intended to serve as a guideline for recognizing irregularities and developing the procedures necessary to resolve the forces along complicated load paths. The examples provide a progressive coverage of basic to very complex illustrations of load paths in the complicated structures. The benefits of the methods presented herein allow creation of complete lateral load paths when none appear to be possible. Most of the examples presented throughout the book and in the solutions manual show shear wall and diaphragm configurations that would be considered minimal lateral-force-resisting systems, without redundancy and under maximum demand. This has been done to simplify the examples. Reducing the number of vertical lateral-force-resisting elements, combined with multiple complicated load paths, and then designing to the maximum element capacity is neither suggested nor encouraged by the authors. In most cases, more direct, conservative, and simpler solutions to load paths are available. The methods and examples included are intended to provide the design professional with reasonable and rational analytical tools that can be used to solve complex problems, but do not represent the only methods available.

It has been the authors' experience from private design practice, teaching, and plan reviews that the knowledge in the engineering and code administration communities regarding the analysis of wood diaphragms and shear walls varies greatly. Design professionals need to learn and mentor the art of understanding and establishing complete load paths. This is increasingly important due to an increased reliance on structural analysis programs in the design process. Although it is helpful to have a basic understanding of simple shear walls and diaphragms prior to reading this book, enough fundamental information is provided for the laymen to follow the complex examples.

This book is based on the 2021 IBC,[4] ASCE7-16,[5] the 2018 NDS,[8] and the 2021 edition of the Special Design Provisions for Wind and Seismic (SDPWS).[9] It is assumed that the reader has a working understanding of and access to these design codes and standards, including the applicable loads, load combinations, allowable stresses, and adjustment factors. Publications covering the basic concepts and methods of addressing analysis and design of wood structures can be referenced in *The Design of Wood Structures*[6] and SEAOC's *Structural/Seismic Design Manual, Vol. 2*,[7] which provide a comprehensive coverage of fundamentals of wood lateral-force-resisting system analysis and design. The opinions and interpretations are those of the authors, based on experience, and are intended to reflect current structural practice. Engineering judgment and experience has been used in establishing the procedures presented in this book when there was an absence of documentation or well-established procedures available. Although every attempt has been made to eliminate errors and to provide complete accuracy in this publication, it is the responsibility of the design professional or individual using these procedures to verify the results. Users of this information assume all liability arising from such use.

Comments or questions about the text, examples, or problems may be addressed to any of the authors through this address: malone.breneman.rice@gmail.com.

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Nomenclature

Organizations

AF&PA
American Forest and Paper Association
1111 19th St., NW
Suite 800
Washington, District of Columbia 20036

APA
APA—The Engineered Wood Association
PO Box 11700
Tacoma, Washington 98411-0700

ASCE
American Society of Civil Engineers
1801 Alexander Bell Dr.
Reston, Virginia 20191

ATC
Applied Technology Council
2471 E. Bayshore Rd.
Suite 512
Palo Alto, California 94303

Building Seismic Safety Council (a council of the National Institute of Building Safety)
Washington, District of Columbia 20005

ICC
International Codes Council
3060 Saturn Street,
Suite 100, Brea, California 92821

AWC
American Wood Council
22 Catoctin Circle, SE, Suite 201
Leesburg, Virginia 20175

SEAOC
Structural Engineers Association of California
555 University Ave., Suite 126
Sacramento, California 95825

USDA
US Department of Agriculture
Forest Products Laboratory
Madison, Wisconsin 53726

WPC
Wood Products Council
WoodWorks
1101 K St NW Ste 700
Washington, District of Columbia 20005

Abbreviations

Allow.	allowable
ASD	allowable stress design
Bm.	beam
Blk'g.	blocking
CLT	cross laminated timber
Discont.	discontinuous
Diaph.	diaphragm
Ecc.	eccentricity, eccentric
FS	factor of safety
Flr.	floor
Hdr.	header
I.P.	inflection point
Lds.	loads
LRFD	load and resistance factor design
LFRS	lateral force resisting system
max.	maximum
min.	minimum
MLFRS	main lateral-force-resting system
MSFRS	main seismic force-resisting system
MWFRS	main wind force-resisting system
N.A.	neutral axis
N.G.	no good
o.c.	on center
o.k.	okay
OSB	oriented strand board
PW	plywood
req'd.	required
SDC	seismic design category
SDS	short period design spectral acceleration parameter
Shr.	shear
SFRS	seismic force-resisting system
Sht'g.	sheathing
STR	strength, strength design
SW	shear wall
Trib.	tributary
UNO	unless noted otherwise
Unif.	uniform
WSP	wood structural panels

Units

ft	foot, feet
ft^2	square foot, square feet
in	inch, inches
in^2	square inch, square inches
k	kip, kips, 1000 lb
ksi	kips per square inch
ksf	kips per square foot
pcf	pounds per cubic foot
plf	pounds per lineal foot
psf	pounds per square foot
psi	pounds per square inch

Symbols

A	area (in^2, ft^2)
A_{net}	net area (in^2, ft^2)
A.R.	aspect ratio (length to width or length to depth)
ATS	automatic tensioning system anchor, shrinkage compensating
A_x	torsional amplification factor

b	length of shear wall parallel to lateral force, distance between chords of shear wall (in, or ft)
b_{eff}	effective width of moment-resisting arm between centerline of hold-down rod and centerline of compression boundary member of the shear wall used to determine the overturning force (ft)
b_i	individual full height section of perforated shear wall
b_s	width (breadth) of a CLT shear wall panel
b', d'	shallower width or depth of diaphragm (ft)
C	compression force (lb or kips)
C.M.	center of mass
C.R.	center of rigidity
C_{b}	bearing length (in)
C_{D}	load duration factor
C_{di}	diaphragm factor for nail connections
C_{eg}	end grain factor for wood connections
C_{f}	size factor for sawn lumber
C_{G}	CLT shear wall capacity adjustment factor for specific gravity
CL	distance from face of hold-down to the centerline of the anchor bolt (in)
C.L.	centerline
C_{s}	seismic response coefficient
D	dead load (lb, k, plf, klf, psf, ksf)
D	depth (ft)
d	depth of solid wood section (in)
d_{a}	vertical elongation of overturning anchorage (in)
d_{e}	depth of member less the distance from the connector to the unloaded edge (in)
Diaph 2	diaphragm 2
DL	dead load (lb, k, plf, klf)
$d_{\text{req,d}}$	depth required (ft)
E	modulus of elasticity (psi, ksi)
$EI_{\text{eff,f}}$	flatwise effective bending stiffness of CLT (lb-in^2/ft)
e	eccentricity (in, ft)
e_{n}	nail deformation (in)
e_{f}	fastener deformation (in)
$e_{\text{f}\,\parallel}$	fastener deformation on panel edges parallel to applied load (in)
$e_{\text{f}\,\perp}$	fastener deformation on panel edges perpendicular to applied load (in)
f_{a}	axial stress (psi, ksi)
f_{b}	bending stress (psi, ksi)
F_{b}'	allowable bending stress, adjusted (psi, ksi)
$F_{\text{b}}S_{\text{eff}}$	flatwise reference flexural design capacity of CLT (lb-ft/ft)

F_{9B}	the force at grid line 9B (lb, k)
f_c	compression stress (psi, ksi)
F_{CL}	force at centerline (lb, k)
$F'_{c\perp}$	allowable bearing stress perpendicular to the grain, adjusted (psi, ksi)
F_{chord}	chord force (lb, k)
$F_{collector}$, $F_{coll.}$	collector force (lb, k)
F_{max}	maximum force (lb, k)
$F_{o/t}$	overturning force (lb, k)
F_{strut}	strut force (lb, k)
F_T	torsional force (lb, kips)
ft	feet
ft-lb	foot-pounds
ft-k	foot-kips
F'_v	allowable shear stress, adjusted (psi, ksi)
f_v	horizontal shear stress (psi)
F_V, F_H	vertical or horizontal force (lb, k)
F_x, F_y	force along the x or y axis (lb, k)
F_x	axial force (lb, k)
F_y	steel yield strength (psi, ksi)
$F_{v,e}$	edgewise (in-plane) reference shear stress of CLT (psi)
G_a	apparent diaphragm or shear wall shear stiffness from nail slip and panel shear deformation
$GA_{eff,f}$	flatwise effective shear stiffness of CLT (lb/ft)
G_t	panel rigidity through the thickness, in lb per inch of panel width
H	horizontal force (lb, k)
h	height of shear wall (ft)
h_1	height of 1st story (ft)
h_{sx}	the story height below level x
I	moment of inertia (in^4)
I_E, I_e	importance factor for seismic
I_o	moment of inertia of individual element about itself (in^4)
I_T	the total moment of inertia (in^4)
I_w	importance factor for wind
J	polar moment of inertia (in^4)
k	kips, 1000 lb
K	rigidity, stiffness
L	length of diaphragm or shear wall (in, ft)
L'	length of cantilever diaphragm (ft)
LL	live load (lb, k, plf, klf)
L_1	length of section 1 (ft)

$L_{1\text{–}3}$	length of section from grid line 1 to 3 (ft)
l_{brg}	length of bearing (in)
L_{embed}	length of embedment (ft)
L_{hdr}	length of header (ft)
L_{r}	roof live load (psf)
L_{sw}	length of shear wall (ft)
L_{TD}	length of transfer diaphragm (ft)
l_{u}	unbraced length of bending member (in, ft)
L_{wall}	length of wall (ft)
L/W, L/d, L/b	length to width (or depth) ratio
M	bending moment (in-lb, in-k, ft-lb, ft-k)
M_{max}	maximum bending moment (in-lb, in-k, ft-lb, ft-k)
M_{net}	net bending moment (in-lb, in-k, ft-lb, ft-k)
M_{o}, $M_{\text{o/t}}$	overturning moment (ft-lb, ft-k)
M_{R}	resisting moment (ft-lb, ft-k)
M_x	bending moment at distance x (in-lb, in-k, ft-lb, ft-k)
M_1	bending moment at grid line 1, or moment 1 (in-lb, in-k, ft-lb, ft-k)
n	number of fasteners in the same plane
n	number of connectors per panel at base of CLT shear wall
$n_{\parallel}$	number of slip planes at a CLT diaphragm connection parallel to the applied loads
$n_{\perp}$	number of slip planes at a CLT diaphragm connection perpendicular to the applied loads
o/t	overturning
P	concentrated load (lb, k)
$P_{\parallel}$	panel length parallel to the applied load (ft)
$P_{\perp}$	panel length perpendicular to the applied load (ft)
p, q	wind pressure (psf)
R	reaction (lb, k)
R	generic reference design value calculated following the NDS
R'	generic adjusted design capacity calculated following the NDS
R_{2L}	reaction on the left side of grid line 2 (lb, k)
R_{A}	reaction at grid line A (lb, k)
R_{L}, R_{R}	left or right reaction (lb, k)
S	regular spacing of fasteners in a CLT diaphragm (in)
S, SL	snow load (lb, k, plf, klf)
S, S_{x}	section modulus (in^3)
SBP	soil bearing pressure
SDC	seismic design category
SW1	shear wall 1

T	tension force (lb, k)
T	fundamental period of vibration of structure (sec)
TA	transfer area
TD1	transfer diaphragm 1
TD	transfer diaphragm
t_e	effective shear thickness of plywood
Typ	typical
V	shear force (lb, k)
V	vertical force (lb, k)
V_V, V_H	vertical or horizontal shear force (lb, k)
V_{max}	maximum shear force (lb, k)
V_n	the average uniform load per nail (lb)
V_n	the nominal shear capacity of a fastener or connector (lb)
V_n'	the average non-uniform load per nail (lb)
V_{sw2}	shear force applied to shear wall 2 (lb, k)
V_s	flatwise reference shear capacity of CLT (lb/ft)
V_{TL}, V_{total}	total shear force (lb, k)
V_u, V_{uom}	ultimate (nominal) shear (lb, k)
V_{wall}	shear force applied to a wall (lb, k)
V_x	total shear force at distance x (lb, k)
V_{2L}	shear force on the left side of grid line 2 (lb, k)
v_{3AB}	uniform unit shear at grid line 3, from A to B (plf, klf)
v	uniform unit shear (plf, klf)
v_{diaph}	uniform unit shear in the diaphragm (plf, klf)
$v_{d,ASD}$	ASD unit shear demands in the diaphragm (plf, klf)
$v_{d,LRFD}$	LRFD unit shear demands in the diaphragm (plf, klf)
v_{max}	maximum uniform unit shear (plf, klf)
v_{net}, v_n	net uniform unit shear (plf, klf)
v_n	nominal diaphragm or shear wall shear capacity (plf)
V_r'	adjusted design shear based on effective depth (lb, k)
v_{sw2}	uniform unit shear in shear wall 2 (plf, klf)
v_x	uniform unit shear at distance x (plf, klf)
v_{2L}	uniform unit shear on the left side of grid line 2 (plf, klf)
W	width of diaphragm, opening (ft)
W'	width of cantilever diaphragm (ft)
w	lateral uniform load, wind or seismic (plf, klf)
w_{lw}	lateral uniform load due to wind, leeward pressures (plf, klf)
W_{TD}, w_{TD}	Width of transfer diaphragm (ft)
w_{ww}	lateral uniform load due to wind, windward pressures (plf, klf)
w_{3-5}	uniform load from grid line 3 to 5 (plf, klf)

w_E	lateral uniform load due to seismic (plf, klf)
w_{strip}	uniform load applied to a 1 ft wide strip across the structure (plf, klf)
w_x	uniform load applied along a distance x (plf, klf)
x	distance x (ft)
$\bar{\bar{x}}$	distance to the neutral axis from base line (in, ft)
Z	reference shear capacity of a single fastener per NDS (lb)
Z'	adjusted allowable shear capacity of a single nail per NDS (lb)
Z^*	adjusted allowable short-term shear capacity of a single fastener per NDS (lb)
γ_D	force amplification factor for CLT diaphragm components
Δ	deflection (in)
Δ_{ADVE}	average displacement of vertical force-resisting elements
Δ_a	total vertical elongation at wall anchorage
Δ_{aeff}	total effective vertical elongation at wall anchorage
Δ_B	deflection at grid line B (in)
Δ_b, Δ_B	deflection due to bending (in)
Δ_c, Δ_{cs}	deflection due to chord slip (in)
Δ_e	deflection due to elongation of steel strap (in)
Δ_{max}	maximum deflection (in)
$\Delta_{rot.}$	deflection due to rotation (in)
Δ_{ns}	deflection due to nail slip (in)
Δ_s	deflection due to shear (in)
Δ_{strap}	deflection due to strap elongation and nail slip (in)
Δ_T, Δ_{TL}	total deflection (in)
δ_{diaph}	diaphragm displacement (in)
δ_{MDD}	maximum diaphragm displacement (in.)
δ_{RH}	horizontal rotational displacement
δ_{RV}	vertical rotational displacement
δ_{slip}	diaphragm and shear wall deflection component resulting from fastener slip (in)
δ_x	story drift at level x (in)
δ_{xe}	deflection at the location required determined by an elastic analysis (in)
ρ	redundancy factor
θ	stability coefficient for P-delta effects
ϕ_D	LRFD resistance factor for diaphragms
Ω_o	overstrength factor
Ω_D	ASD reduction factor for diaphragms

CHAPTER 1

Code Sections and Analysis

1.1 Introduction

For centuries, building codes have been developed to define the standards for the design and construction of structures. Opinions are often expressed that code requirements have become too complex; however, from the earliest of codes to our current standards, codes have changed in response to our increased understanding of materials and methods as well as our knowledge of the forces that are imposed on structures, particularly wind and seismic forces. This understanding has been greatly increased by past structural failures and from current state-of-the-art testing, research, and a better understanding of how buildings respond in an extreme loading event. In addition, changes to the code have been brought about by the reality that structures have become increasingly more complex as compared to structures previously built.

The most widely used and accepted code for building design standards in the United States is the International Building Code (IBC) published by the International Code Council (ICC).[1] The document references a compilation of design standards that have been developed through an open and transparent consensus process that represents all interested parties and stakeholders. ASCE/SEI 7-2016, *Minimum Design Loads for Buildings and Other Structures,* is published by the American Society of Civil Engineers and the Structural Engineering Institute[2] and is referenced from the 2021 IBC. Wood lateral-force-resisting systems are addressed in *National Design Specification for Wood Construction* (NDS-2018) and *Special Design Provisions for Wind and Seismic* (SDPWS-2021), which are both published by the American Wood Council.[3] The IBC-21, ASCE 7-16, NDS-18, and SDPWS-21 are codes and standards that will be discussed in the chapters that follow. Relative sections and definitions from these codes and standards are provided for quick reference and comparisons. The following code sections and definitions are not direct quotes and can contain additional clarifications and authors' comments.

1.2 IBC 2021 Code Sections Referencing Wind and Seismic[1]

Chapter 2

202.1 Definitions

Diaphragm: A horizontal or sloped system acting to transmit lateral forces to vertical elements of the lateral force-resisting system. When the term "diaphragm" is used, it shall include horizontal bracing systems.

Collector: A horizontal diaphragm element parallel and in line with the applied force that collects and transfers diaphragm shear forces to the vertical elements of the lateral force-resisting system or distributes forces within the diaphragm, or both. [Authors' note: Collectors are also used at areas of discontinuity in diaphragms and shear walls and can be oriented in the direction within the diaphragm or shear wall.]

Seismic Design Category: A classification assigned to a structure based on its risk category and the severity of the design earthquake ground motion at the site.

Seismic Force-resisting System: That part of the structural system that has been considered in the design to provide the required resistance to the prescribed seismic forces. [Authors' note: This term is synonymous with "lateral-force-resisting system," under wind or seismic forces.]

Chapter 16

1604.4 Analysis

This section requires that load effects on structural members and their connections shall be determined by and take into account equilibrium, general stability, geometric compatibility and both short- and long-term material properties; and that any system or method of construction used shall be based on a rational analysis in accordance with well-established principles of mechanics. Such analysis shall result in a system that provides a complete load path capable of transferring loads from their point of origin to the load-resisting elements.

Lateral forces shall be distributed to the various vertical elements of the lateral-force-resting system in proportion to their rigidities, considering the rigidity of the horizontal bracing system or diaphragm.

Chapter 23

2305 General design requirements for lateral force resisting systems.

2305.1 General:

Structures using wood-framed shear walls or wood-framed diaphragms to resist wind, seismic or other lateral loads shall be designed and constructed in accordance with AWC SDPWS and the applicable provisions of Sections 2305, 2306 and 2307.

2305.1.1

Openings in shear panels that materially affect their strength shall be fully detailed on the plans and shall have their edges adequately reinforced to transfer all shearing stresses.

2306.2 and 2306.3

Wood frame diaphragms and shear walls shall be designed and constructed in accordance with AWC SDPWS and the provisions of IBC Sections 2305, 2306 and 2307.

Also see Section 2308.4.4.1—openings in diaphragms in SDC B-F, and Section 2308.4.4.2—vertical offsets in diaphragms in SDC D and E.

1.3 ASCE 7-16 Sections Referencing Seismic[2]

Chapter 11

11.2 Definitions

The following definitions are provided for comparison to other code or standards definitions.

Boundary Elements: Portions along wall and diaphragm edges and openings for transferring or resisting lateral forces. Boundary elements include chords and collectors at diaphragms and shear wall perimeters, edges of openings, discontinuities, and re-entrant corners.

Diaphragm Boundary: A location where shear is transferred into or out of the diaphragm element. Transfer is either to a boundary element or to another lateral force-resisting element.

Diaphragm Chord: A diaphragm boundary element perpendicular to the applied load that is assumed to take axial stresses caused by the diaphragm moment.

Collector (Drag strut, tie, diaphragm strut): A diaphragm or shear wall boundary element parallel to the applied load that collects and transfers diaphragm shear forces to the vertical elements of the seismic force-resisting system or distributes forces within the diaphragm or shear walls. [Authors' note: A collector can also resist wind or other lateral forces.]

Chapter 12

12.1.3 Continuous Load Path and Interconnection (partial quote)

A continuous load path, or paths, with adequate strength and stiffness shall be provided to transfer all forces from the point of application to the final point of resistance. [Authors' note: Connections are considered as part of the complete load path.]

12.3 Diaphragm Flexibility, Configuration Irregularities, and Redundancy.

12.3.1 Diaphragm Flexibility.

The structural analysis shall consider the relative stiffnesses of diaphragms and the vertical elements of the lateral force-resisting system. The structural analysis shall explicitly include consideration of the stiffness of the diaphragm (i.e., semi-rigid modeling assumption).

12.3.1.1 Flexible diaphragm condition
12.3.1.2 Rigid diaphragm condition
12.3.1.3 Calculated flexible diaphragm condition

12.10 Diaphragm Chords and Collectors

12.10.1 Diaphragm design:

Diaphragms shall be designed for both shear and bending stresses resulting from design forces. At diaphragm discontinuities, such as openings or reentrant corners, the design shall assure that the dissipation or transfer of edge (chord) forces combined with other forces in the diaphragm is within the shear and tension capacity of the diaphragm.

12.10.2 Collector elements.

Collector elements shall be provided that are capable of transferring the seismic or wind forces originating in other portions of the structure to the elements providing resistance to those forces.

1.4 Important AWC-SDPWS-2021 Sections[3]

2.2 Terminology

Boundary Element: Diaphragm and shear wall boundary members to which sheathing shear forces are transferred. Boundary elements include chords and collectors at diaphragm and shear wall perimeters, interior openings, discontinuities, and reentrant corners.

Diaphragm Boundary: A location where shear is transferred into or out of the diaphragm sheathing. Transfer is either to a boundary element or to another lateral force-resisting element.

Collector: A diaphragm or shear wall boundary element parallel to the applied force that collects and transfers diaphragm shear forces to the vertical lateral force-resisting elements or distributes forces within the diaphragm or shear wall.

Chord: A diaphragm boundary element perpendicular to the applied load that resists axial stress due to the induced moment.

Diaphragm: A roof, floor or other membrane bracing system acting to transmit lateral forces to the vertical resisting elements. When the term "diaphragm" is used, it shall include horizontal bracing systems.

4.1.1 Design requirements.
The proportioning, design and detailing of engineered wood systems members, and connections in lateral force-resisting systems shall be in accordance with

- Reference documents in Section 2.1.2 and the provisions of this chapter and standard.
- Applicable building code, and ASCE 7.
- The seismic shear capacity shall be determined in accordance with Sections 4.1.4.1 and 4.1.4.2 for wind.

Structures resisting wind and seismic loads shall meet all applicable drift, deflections, and deformation requirements of this standard. A continuous load path, or paths, with adequate strength and stiffness shall be provided to transfer all forces from the point of application to the final point of resistance.

4.1.9 Boundary elements.
Shear wall and diaphragm boundary elements shall be provided to transfer the design tension and compression forces. Diaphragm and shear wall sheathing shall not be used to splice boundary elements. Diaphragm chords and collectors shall be placed in, or tangent to, the plane of the diaphragm framing unless it can be demonstrated the moments, shears, and deformations, considering eccentricities resulting from other configurations, can be tolerated without exceeding the framing capacity and drifts limits.

4.2 Sheathed wood frame diaphragms

4.2.1 Application Requirements
Wood-framed diaphragms shall be permitted to be used to resist lateral forces provided the in-plane deflection of the diaphragm, as determined by calculations, tests, or analogies drawn therefrom, does not exceed the maximum permissible deflection limit of attached load distributing or resisting elements. Framing members, blocking, and connections shall extend into the diaphragm a sufficient distance to develop the force transferred into the diaphragm. [Authors' opinion: The development length should be verified by calculation as demonstrated in this book or by other equivalent method.]

4.2.2 Diaphragm Aspect Ratios.
Size and shape of diaphragms shall be limited to the aspect ratios in Table 4.2.2.

4.2.3 Deflections
Alternatively, for wood structural panel diaphragms, deflection shall be permitted to be calculated using a rational analysis where apparent shear stiffness accounts for panel deformation and non-linear nail slip in the sheathing-to-framing connection.

4.3 Sheathed wood framed shear walls

4.3.3.1 Shear Wall Aspect Ratios.
The size and shape of shear walls shall be limited to the aspect ratios in Table 4.3.3 and Figure 4C for segmented shear walls, Figure 4D for FTAO shear walls and Figure 4E for perforated shear walls. [See Chap. 10 for suggested shear wall header, sill, and transfer diaphragm aspect ratio limits.]

4.5 CLT diaphragms (new in SDPWS 2021)

4.6 CLT shear walls (new in SDPWS 2021)

1.5 Sections Specifically Referencing Structural Irregularities

It is important to recognize and understand structural irregularities. A large portion of this book provides guidance on how to identify and solve force transfer across areas of discontinuities in irregular structures. The following sections are presented to show agreement between the codes and standards with regard to lateral-force-resisting systems that resist wind and seismic forces. These sections have been selected for their relevance to this book. These sections should be reviewed in their entirety when reading each chapter of the book.

1.5.1 ASCE 7-16

12.3.2.1 and Table 12.3-1 Horizontal structural irregularities
12.3.2.2 and Table 12.3-2 Vertical structural irregularities
12.3.3 Limitations and additional requirements for systems with structural irregularities
12.3.3.3 Elements supporting discontinuous walls or frames
12.3.3.4 Increase in forces caused by irregularities for seismic design Categories D through F
12.8.4.1 Inherent Torsion
12.8.4.2 Accidental Torsion

1.5.2 SDPWS-21

4.1.7 Horizontal distribution of shear
4.1.8 Vertical distribution of seismic force resisting systems strength
4.2.5.1 Torsional Irregularity
4.2.6 Open-front Structures

1.5.3 2018 IRC[4]

R301.2.2.6 Irregular Buildings

- Shear wall or braced wall offsets out-of-plane
- Lateral support of roof and floors. Edges not supported by shear walls or braced wall lines (cantilevers)
- Shear walls or braced wall offsets in plane
- Floor or roof opening
- Floor level offset—vertically
- Perpendicular shear wall and bracing—do not occur in two perpendicular directions.
- Wall bracing in stories containing masonry or concrete construction.

1.6 Complete Load Paths

Most of the texts and publications available today only address simple rectangular diaphragms, the analysis of which does not easily adapt to complex diaphragm and shear wall layouts. The layout of the lateral-force-resisting system shown in Figs. 1.1 and 1.2 demonstrate these types of problems. The vertical and horizontal offsets shown in the figures create discontinuities in the diaphragm, which require special collector and drag strut elements to establish complete load paths. Collectors and drag strut elements in diaphragms and in shear walls are a critical part of complex lateral-force-resisting systems. The analysis and design requirements for diaphragms under wind or seismic loading is a complicated topic that is prone to being misunderstood. Some of the confusion has been brought about by the location of lateral-force-resisting systems requirements within ASCE 7-16. Chapters 11 and 12 of that standard, which address seismic design, provide a complete and organized coverage of lateral-force-resisting systems, components, and requirements under seismic loading conditions. Chapters 26 through 31 address the analysis and application of wind loads and pressures on structures and on components and cladding. It does not, however, cover lateral resisting elements or systems or their design requirements in as much detail as seismic design section does. Some designers may interpret the lack of discussion of structural systems or elements in the wind chapters to imply that drag struts and collectors are not required for wind design; and that, diaphragm discontinuities do not have to be addressed if wind controls. Section 1604.9 of the 2021 IBC addressing wind and seismic detailing says, "Lateral-force-resisting systems shall meet seismic detailing requirements and limitations prescribed in this code and ASCE 7, excluding Chapter 14 and Appendix 11A, even when wind load effects are greater than seismic load effects." Diaphragms, drag struts, collectors, and shear walls function the same way regardless of if loads applied to the diaphragm are from wind, seismic, soil, or other pressures. All irregularities and/or discontinuities within a system of diaphragms and shear walls should be addressed. It is easy to overlook the definitions section when thumbing through the codes and standards, believing that the contents therein are already understood. A quick review will show that the definitions actually set the criteria and requirements for diaphragms, chords, collectors, and their design. In practical terms, all diaphragms must have boundary members consisting of drag struts, chords, collectors, or other vertical lateral-force-resisting elements. Collectors are required at all offsets and areas of discontinuity within the diaphragm, including at openings. These requirements also apply to shear walls. Forces at all discontinuities and openings must be dissipated or transferred into the diaphragm or shear wall without exceeding its design capacity. The codes and standards specify that the sheathing shall not be used to splice boundary elements or collectors. Furthermore, all diaphragms and shear walls shall contain continuous load paths along all boundaries and lines of lateral-force-resistance and across all discontinuities.

Irregular shaped structures similar to the one shown in Fig. 1.1 are commonly designed without properly addressing the irregularities contained therein. The structure exhibits multiple vertical and horizontal offsets in the diaphragm, cantilever diaphragms, few opportunities for shear walls at the exterior wall line and multiple vertical and horizontal discontinuities in the lateral load paths of the lateral-force-resisting system. Some designers may intuitively place tie straps with blocking throughout the structure without explicit purpose, in an ambiguous attempt to address discontinuities with no rationalization or supporting calculations. Such a judgment-based approach will easily miss connections that are required to develop a complete load path, even along straight lines of lateral force resistance. ATC-7 noted that failures have occurred because of the following[5]:

- Connection failures caused by incomplete load paths, incomplete designs, inadequate detailing, and inadequate installation (construction). Often, the size of wood chords for tension and compression forces is also ignored in the design, which can lead to failures.
- Designs included diaphragm shears and chord forces only, connection designs were not addressed.
- Designs did not include load paths that continued down to the foundation and into the soil.
- Designing to the maximum diaphragm and shear wall capacity (close nailing), while limiting the number of shear walls to a minimum (no redundancy) provides no room for substandard workmanship. This puts a high demand on diaphragms, shear walls, and connections.

Figure 1.1 Irregular shaped structure.

- Splitting, using smaller nails than specified, using different species of wood than specified, over-driving nails, and slack in light-gage metal straps.

Edward F. Diekmann provided an interesting note in his engineering module "Design of Wood Diaphragms"[6] regarding a misconception for the requirement of wood diaphragms and shear walls. He noted that it was unfortunate that interest in diaphragms and shear walls was developed primarily on the West Coast, which gave rise to an impression that they were required only because of the earthquakes that occur in that region. Because of this misconception, it appears that a large number of wood framed structures in many other regions of the country are apparently erected without thought as to how they are to be braced against wind forces. Another problem noted in ATC-7-1[7] was the lack of complete load paths and detailing. Engineering has become a highly competitive business. ATC-7-1 noted "Nothing is more discouraging to the conscientious engineer endeavoring to deal with lateral forces with all the detailing requirements on diaphragms and shear walls than to contemplate the absence of attention paid by some of his fellow engineers to the most basic shear transfer problems. It is a sobering experience to see structural plans for a wood framed apartment complex without a single wood-framing detail and to realize that you were not given the job because your proposed fee was too high." It is hoped that the information provided in this book will provide clarity to the importance of complete load paths and designs.

The diaphragm and shear wall layout shown in Fig. 1.2 is a good example of structures currently being designed and built. The code and standards definitions should be

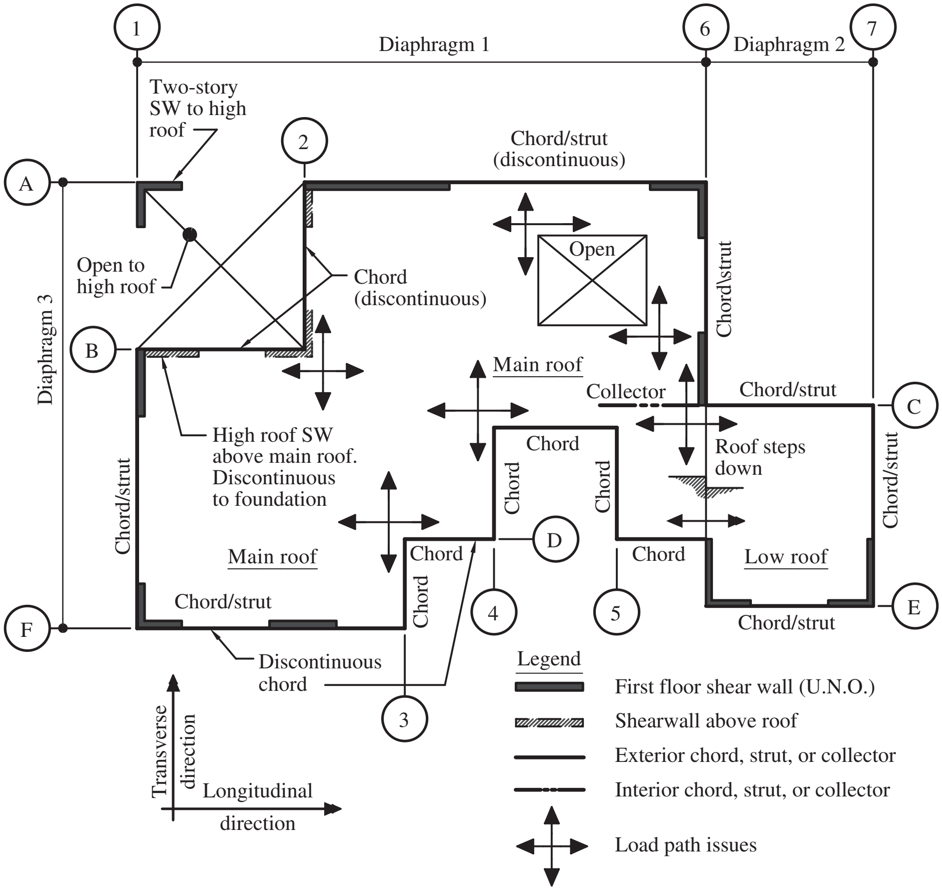

FIGURE 1.2 Continuous load path issues.

carefully reviewed for applicability to each irregularity discussed for this structure. In the transverse direction, two diaphragms exist. The main diaphragm is supported by the first-floor shear walls along grid lines 1 and 6. The low roof diaphragm is supported by the shear walls located at grid lines 6 and 7. The main diaphragm has multiple discontinuities and irregularities within the span which must be resolved. Starting at grid line 1A, it can be seen that a two-story entry condition exists, which is typical in many offices or shopping center complexes. The upper level is usually an architectural feature commonly referred to as a pop-up. The shear walls at grid line 1A are two stories in height and support the pop-up roof. The walls at grid line 2 and grid line B also support the pop-up roof but are discontinuous shear walls because they are supported by the main roof and do not continue down to the foundation. The pop-up section should be designed as a second story that transfers its forces as a concentrated load into the main diaphragm. The diaphragm sheathing and framing is often omitted below the pop-up section at the main roof level. Diaphragm boundary members are not allowed at the main diaphragm level at grid line A from 1 to 2 or at line 1 from A to B, due to architectural constraints. This condition creates a horizontal offset in the roof diaphragm in the transverse and longitudinal directions. The offset disrupts the diaphragm chords, creating an offset diaphragm. Because of the offset, a question arises on how to provide continuity in the chord members and transfer its disrupted force across the offset. It also raises a question on how to dissipate the disrupted chord force into the main diaphragm, at grid line 2B. Creating complete load paths to transfer all the discontinuous forces into the main diaphragm can be very complicated and challenging. There are multiple offsets at grid lines C, D, and F between 3 and 6. These offsets also cause a disruption in the diaphragm chords and struts and must also have their disrupted chord forces transferred into the main diaphragm by special means. The large opening in the diaphragm in-line with grid line 5 causes a disruption in the diaphragm web and requires the transfer of concentrated forces into the main diaphragm at each corner of the opening. The opening as well as the multiple offsets reduce the stiffness of the diaphragm. Diaphragm shears will increase at all areas of discontinuities because of the additional shears that are created by the transfer of the disrupted chord forces into the main diaphragm. The low roof diaphragm which is located between grid lines 6 and 7 from C to E is offset vertically from the main diaphragm. The low roof is supported on three sides by shear walls. The diaphragm boundary along grid line C is unsupported unless the boundary element along that line is transferred into the main diaphragm by a vertical collector in bending that extends into the main diaphragm. This example may appear to be extreme to some; however, such structures are becoming more commonplace in current practice and design.

The establishment of a complete load path does not end by providing boundary element along the entire length of the lateral-force-resisting line. It must also include all the connections necessary to make members in the line of lateral-force-resistance act as a unit and transfer the shears and forces from the diaphragm sheathing into the boundary elements, then into the vertical force-resisting elements and finally down into the foundation. The lateral forces must then be transferred safely into the soil without exceeding the soil capacity. The drawings and calculations must be complete and clear so that the engineer can assure that the load paths are complete from the point of application of the loads to the foundation. In addition, to a clearly defined load path, supporting calculations and drawings should be developed to assist the plans examiner in an efficient and accurate review of the documents. The drawings provide the contractor with the details necessary to construct the structure per the design, and the building inspector to verify compliance with the construction documents. Clear and thorough documentation of load paths can save countless hours of misunderstanding, construction errors, and revisions. In some cases, those errors may not even be realized because of the lack of clarity and the final product may not meet the intended design.

Figures 1.3 through 1.6 provide examples of maintaining complete load paths through various framing configurations. Figure 1.3 shows sloped roof trusses connected to exterior wood bearing walls. In configuration A, the diaphragm shears are transferred into full depth solid blocking installed between the trusses, then into the double top plate of the wall by shear clips and/or toenailing, then from the double top plate into the wall sheathing. As can be seen in Fig. 1.4, a common complaint for this configuration is the difficulty of providing for ventilation through the solid blocking. Figure 1.4 is a photograph of framing that is similar to configuration A. The photo shows that the blocking between the trusses is not the full depth of the trusses at the point of bearing. This is often done to provide roof ventilation. However, this prevents the installation of the boundary nailing for the diaphragm because the nails at this location cannot transfer shear across the air gap. Boundary nailing is required by code for all engineered diaphragms, as verified by diaphragm testing and the principles of mechanics and must