The Analysis of Irregular Shaped Structures

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The Analysis of Irregular Shaped Structures

Wood Diaphragms and Shear Walls

R. Terry Malone, P.E., S.E.
Scott E. Breneman, Ph.D., P.E., S.E.
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Second Edition

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Library of Congress Cataloging-in-Publication Data

Names: Malone, R. Terry, author. | Breneman, Scott E., author. | Rice, Robert W., author.
Title: The analysis of irregular shaped structures : wood diaphragms and shear walls / R. Terry Malone, P.E., S.E., Scott E. Breneman, Ph.D., P.E., S.E., Robert W. Rice, CBO.
Description: Second edition. | New York : McGraw Hill, [2022] | Includes bibliographical references and index. | Summary: "This is a second edition of a popular guide for professionals in need of solutions for lateral load path problems in wood building construction and design. This edition is updated to include newly developed structure types and new design solutions. It is co-branded with The International Code Council (ICC) and incorporates up-to-date structural codes, as well all other requirements and standards"—Provided by publisher.
Identifiers: LCCN 2022014767 (print) | LCCN 2022014768 (ebook) | ISBN 9781264278824 (hardcover) | ISBN 9781264278831 (ebook)
Subjects: LCSH: Structural design. | Shear walls—Design and construction. | Diaphragms (Structural engineering)—Design and construction.
Classification: LCC TA658.4 .M35 2022 (print) | LCC TA658.4 (ebook) | DDC 624.1/7—dc23/eng/20220509
LC record available at https://lccn.loc.gov/2022014767
LC ebook record available at https://lccn.loc.gov/2022014768

The Analysis of Irregular Shaped Structures: Wood Diaphragms and Shear Walls, Second Edition

1 2 3 4 5 6 7 8 9 LHN 27 26 25 24 23 22

ISBN 978-1-264-27882-4
MHID 1-264-27882-9

This book is printed on acid-free paper.

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

To our families, especially our wives:

Jerri
Courtney
Lisa

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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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9. American Wood Council, *Special Design Provisions for Wind and Seismic with Commentary*, Leesburg, VA, 2021.

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)
$d_{req,d}$	depth required (ft)
E	modulus of elasticity (psi, ksi)
$EI_{eff,f}$	flatwise effective bending stiffness of CLT (lb-in^2/ft)
e	eccentricity (in, ft)
e_n	nail deformation (in)
e_f	fastener deformation (in)
$e_{f\parallel}$	fastener deformation on panel edges parallel to applied load (in)
$e_{f\perp}$	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_bS_{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
$R_{2\text{L}}$	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

The Analysis of Irregular Shaped Structures

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

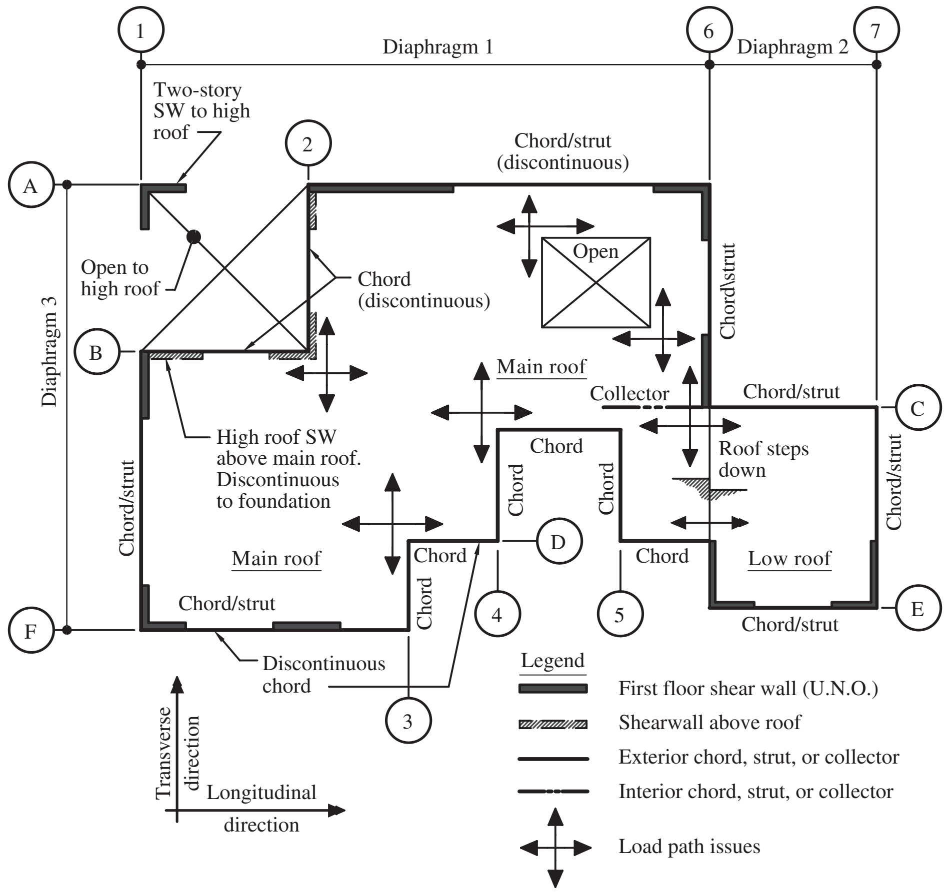

Figure 1.2 Continuous load path issues.

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

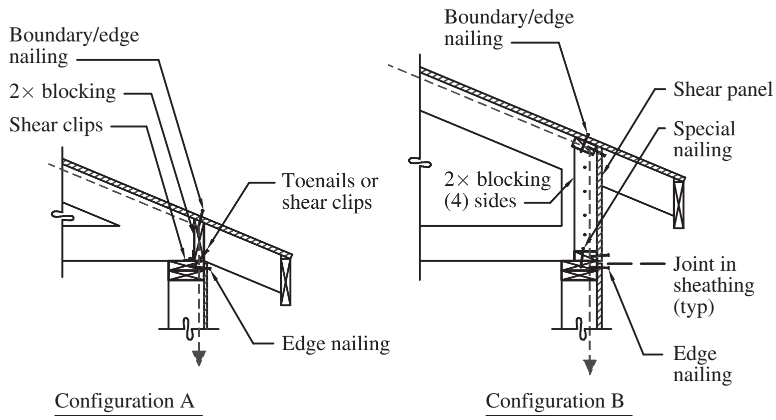

Figure 1.3 Example complete load paths—roof sections.

Figure 1.4 Photo of incomplete load path—blocking issue.

be installed. In addition, the roof sheathing in Fig. 1.4 is not supported by the blocking at the wall location to prevent its buckling under lateral shear forces (in-plane axial force applied to the sheathing). It should also be pointed out that code does not allow the diaphragm sheathing to act as the boundary element or to act as the splice for a boundary element. Under the blocking configuration shown in the figure, boundary nailing cannot be installed to transfer the shear forces into the wall top plate so the diaphragm shears would have to be transferred into the truss top chord at the first nail located back from the blocking. The effective nail spacing at that location would be one nail at 24″ o.c. parallel to the shear wall. It should be obvious that this excessive nail spacing would not be capable of resisting the applied shears. Therefore, a complete load path does not exist and the transfer of diaphragm shears into a boundary element cannot be obtained. The structural detailing for the shear transfer at this location was correctly shown on the drawings but was ignored or overlooked during construction.

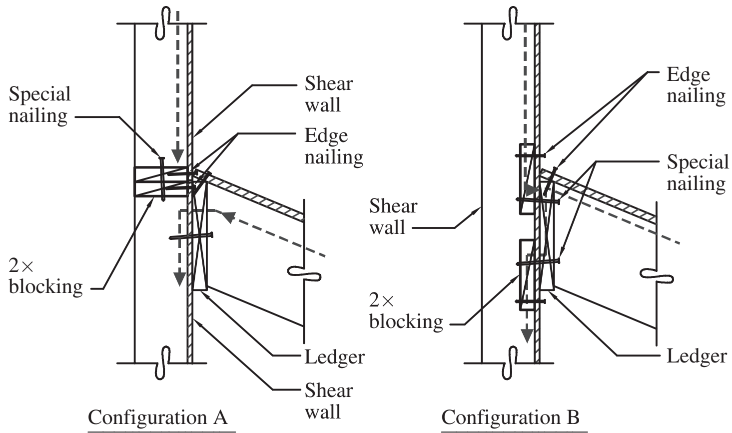

Figure 1.5 Example complete load paths—low roof sections.

There have been many debates on the necessity of full depth blocking at exterior wall lines, especially in areas of low to moderate seismicity. Some stakeholders are pushing for partial height blocking or to eliminate the blocking entirely. These efforts are not consistent with the goal of providing a complete lateral load path and should be scrutinized for rationality and substantiation. Attempting to transfer diaphragm

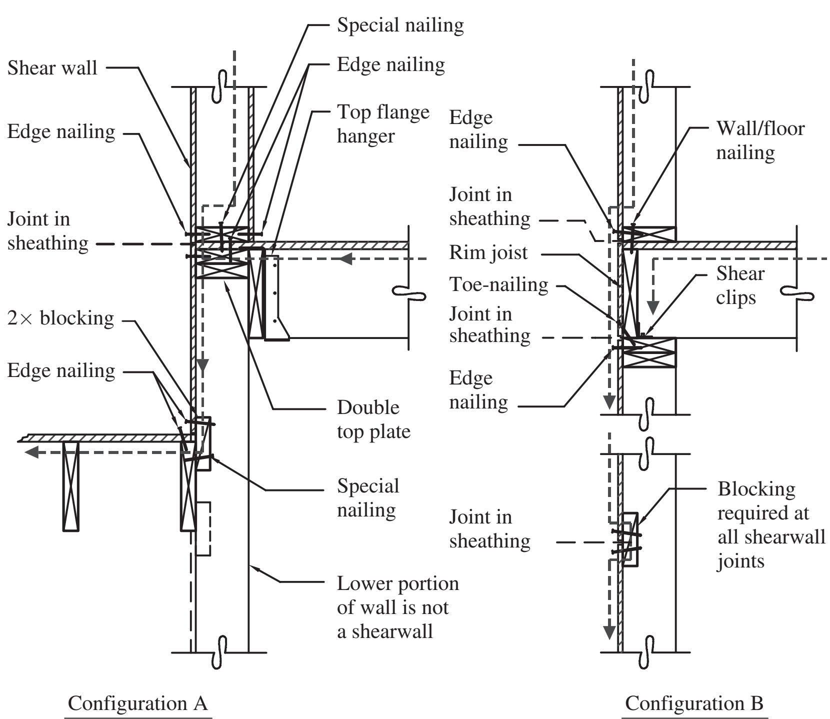

Figure 1.6 Example complete load paths—floor/roof sections.

shears through the truss top chord would put the truss top chord in cross-grain bending at the truss heel joint if partial-height blocking was used and could potentially pull off the gang-nail plate. This type of failure has been observed in the field. In the case where blocking is eliminated, the truss would have to transfer the shears into the wall top plate by roll-over action. Substantial testing for gravity plus roll-over forces or gravity plus cross-grain bending forces should be evaluated on gang-nail trusses before serious consideration can be given to reducing the full depth blocking requirements. Also, trusses would have to include these rotational forces in their design.

The APA has conducted tests on sloped mobile home roof diaphragms, which demonstrated the need for a complete diaphragm load path. An interesting mode of failure was that the gang-nail plates at the ridge line joint of the trusses were pulled apart by opposing shear forces in the diaphragm sheathing because blocking was not provided for the sheathing at the ridge joint.

In configuration B of Fig. 1.3, a prefabricated shear panel consisting of 2× members with plywood sheathing replaces the solid blocking. The load path is the same regardless of the blocking material installed, transferring the diaphragm shears down to the top plate. Larger vent holes can be cut in the shear panel sheathing to allow for ventilation. This condition accommodates the use of deep heel trusses that have become popular for creating roof overhangs and for energy purposes allowing deeper insulation. Recent editions of the IBC and IRC now show a deep heel truss condition in Figures 2308.6.7.2(2) and R602.10.8.2(3), respectively.

Figure 1.5 shows the condition at walls where low roofs frame into the walls at mid-height of the studs. The lateral load path is defined by the dashed arrows. Configuration A shows the condition where the ledger is attached directly to the wall sheathing. The exterior wall sheathing can be terminated at the low roof elevation if the wall is not acting as a shear wall. If the wall is acting as a shear wall, the sheathing should be installed full height of the wall. The lower roof shears are transferred from the diaphragm sheathing into the ledger and double wall blocking, into the sheathing and then down to the foundation. Condition B shows the condition where the wall sheathing is disrupted at the interface of the wall and low roof ledger. The shear from the upper wall sheathing is transferred into the blocking, into the ledger, back into the lower blocking and then back into the wall sheathing. The low roof shears are transferred into the ledger, then into the lower blocking and wall sheathing.

Figure 1.6 shows two floor framing sections. Joints in the wall sheathing can occur at many locations in the floor framing area. There are no guarantees where these joints will occur unless the joint locations are specifically detailed in the drawings. The nailing required to establish a complete load path should be based on the worst-case scenario assuming that the joints will fall at the locations shown in configuration B; and that, the sheathing will not be lapped onto the rim joist and blocking, unless specifically detailed on the drawings. Configuration A shows a condition where the upper floor joists are hangered off the wall in a semi-balloon framing condition instead of platform framing as shown in configuration B. The wall shear is transferred from the upper wall into the wall double top plate below and then back into the outer sheathing. The floor shears are transferred from the floor sheathing into the double top plate of the wall below, then back out into the wall sheathing. The low floor or roof sheathing is nailed to the edge joist. These shears are then transferred from the lower floor or roof through the blocking that is nailed to the edge joist, then down into the wall sheathing below as required. Configuration B represents the common method of platform framing a floor onto a bearing wall. Since sheathing joints usually occur at the upper wall bottom plate and lower wall top plate locations, the upper wall and floor shears must be transferred by nailing into the rim joist, then down into the lower wall top plate by toe nailing or shear clips. All of these figures should callout the complete nailing, clip, splice straps, and blocking necessary to provide a continuous load path. Calculations should be completed to verify the adequate transfer of all forces and shears. A mistake commonly made occurs when a detail is taken from a "Typical Detail Book" and is applied to a set of drawings without verifying that the capacity of the connections will actually meet or exceed the applied shears. It is sometimes assumed that the detail will work for any load that is applied. When applying a typical detail developed in-house or by others, it is the responsibility of the engineer to understand the load capacity of the detail and to be able to recognize when the capacity is exceeded.

Figure 1.7 is a typical interior or exterior shear wall elevation along a line of lateral-force resistance. In this case, the load path under discussion is the transfer of shears and lateral forces from the roof diaphragm down to the soil. The continuous rim joist or wall top plates and beams can be used as the diaphragm boundary elements (drag struts). If blocking occurs between the joists in lieu of a continuous rim joist, the diaphragm shears are transferred through the blocking into the drag members and shear wall at the wall top plate level. All the nailing, clips, splice straps, and blocking necessary to provide a complete continuous load path along the drag line must be detailed and installed correctly. The wall shears are transferred through the wall, into the bottom plate, and then into the foundation by anchor bolts. The wall overturning forces are resisted by dead loads and/or hold downs that are embedded into the foundation. The foundation

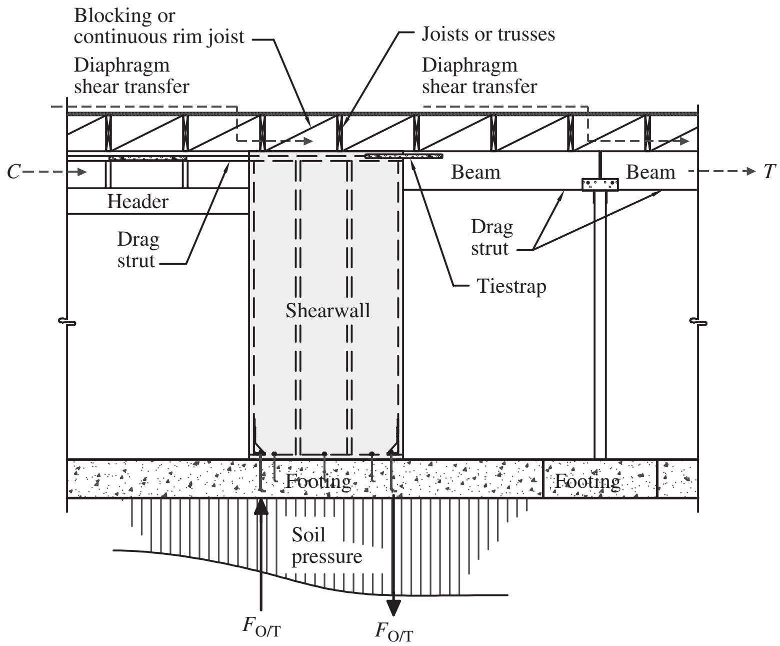

Figure 1.7 Complete load path to foundation—roof at same elevation.

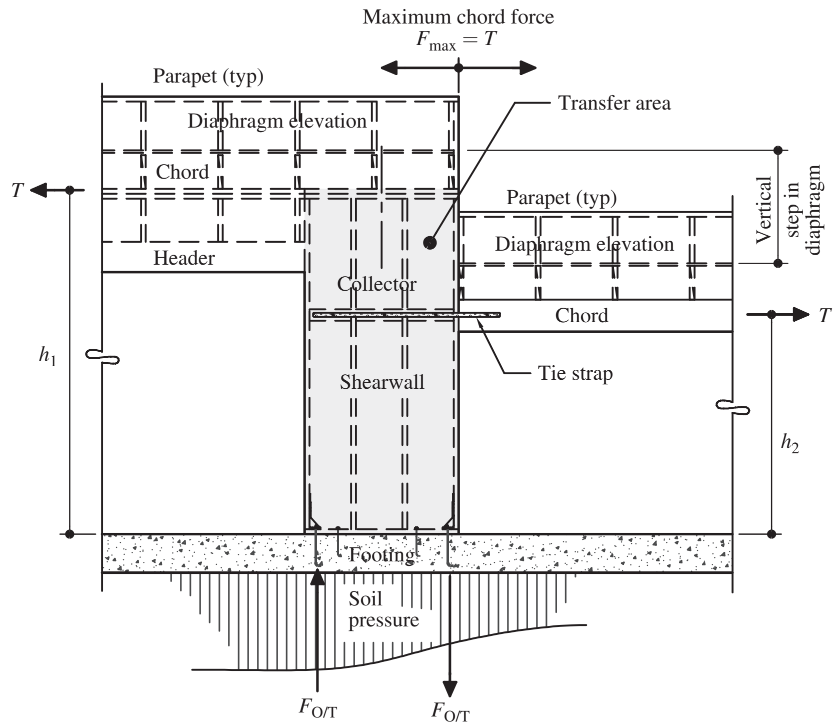

Figure 1.8 Complete load path to foundation—roof at different elevations.

must be designed to have the strength necessary to transfer all these forces plus gravity loads into the soil without exceeding the allowable soil bearing pressures. The load path is not complete until the forces are completely transferred into the soil. Figure 1.8 shows the condition where the roof diaphragms are vertically offset. If drag forces are applied in the same direction along the line of lateral resistance, the shear and overturning moments caused by the upper and lower roofs are additive to the transfer shear wall. When loads are applied to the diaphragm perpendicular to the wall line, the boundary members act as a diaphragm chord. Under this loading condition, a transfer wall is required to connect the vertically discontinuous chords. Figure 1.8 shows chord forces applied to the wall at the offset. The chord forces are equal in magnitude but act in opposite directions, occurring at different heights. This causes a counterclockwise moment that is larger than the clockwise moment. A net moment will result acting in the counterclockwise direction, which must be resisted by a hold down anchor.

Assuming no dead load (for simplicity):

$$M_1 = T(h_1)$$
$$M_2 = T(h_2)$$
$$F_{O/T} = \frac{M_1 - M_2}{L_{wall}}$$

The actual force transfer through this wall is somewhat complicated and will be addressed in detail in Chap. 7.

It is important to provide documents that can verify that a complete load path has been provided. Experience has shown that lateral load paths are occasionally framed incomplete in the field because details have not been completely or clearly defined in the drawings, assuring that a complete lateral system can be provided. Structural drawings can vary widely from region to region and from firm to firm depending on the prevalent lateral force in the area and individual office practices. Although not specifically required, the lateral drawings should include a simple key plan to show the diaphragm boundaries and required nailing, all drag struts/collector locations, special nailing requirements, shear walls and/or frame locations, and necessary structural sections. Defining collectors on the drawings assures that these members are highlighted as important lateral elements requiring special load path transfer of diaphragm shears down into the collector beam or truss. Whenever a preengineered truss is used as a strut or collector, it is also important to add the truss elevation with the applied forces and its location on the truss on the plans, so that the truss manufacture can properly design the truss for those forces. Grid lines are often convenient for ease of communication over the phone or in written forms to identify specific locations. Wall elevations should be provided when walls contain openings that require special force transfer connections, anchoring, or special nailing requirements.

1.7 Methods of Analysis

The examples in this book provide methods of analyzing complex diaphragms and shear walls. Each chapter contains one or two examples that demonstrate the method or methods being discussed in the chapter. Problems are located at the end of the chapter that are variations of the examples, each of which have a special lesson or point of interest. As shown in those examples, the relocation of a single shear wall can significantly change the distribution of forces through a structure. Unless noted otherwise, the lateral loads used in the examples are generalized and can represent wind, seismic, or soil loads at either an allowable stress (ASD) or strength (LRFD) design level. The applied loads are assumed to be the results of the individual's generation of forces to the structure, which are appropriately factored up or down to fit the load combination and design method being used. Some of the examples are carried out using more decimal places than would normally be used in common practice. The intent is to provide better closure of the diaphragm chord and collector force diagrams.

The typical sign convention used in this book is shown in Fig. 1.9. One-foot by one-foot square sheathing elements are used to show the direction of the shears acting on the sheathing elements or collectors and chords. The figure shows typical positive and negative sheathing elements when loaded in the transverse and longitudinal directions. The figure also shows representative portions of force diagrams for collectors, struts, and chords. For transverse loading, a positive force is drawn above the line representing tension. A negative force is drawn below the line representing compression. In reality, it does not make a difference which side of the line the forces are drawn as long as the construction of these diagrams is consistent throughout the analysis. This is because the force in a member will change from tension to compression upon the reversal of the direction of the loads.

As a prerequisite, the reader should have a working knowledge of the analysis and design of simple rectangular diaphragms, simple shear walls, and should know how to calculate wind and seismic forces to structures. The methods for calculating wind and

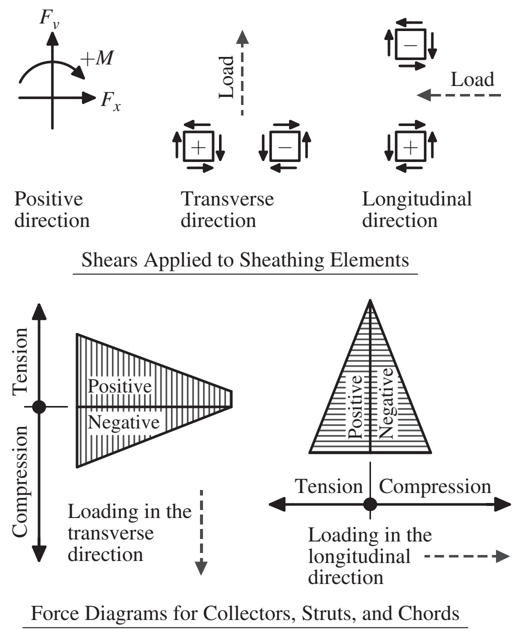

FIGURE 1.9 Standard sign convention.

seismic forces are not included in this book. A cursory review on the analysis of simple diaphragms and shear walls is presented as an introduction or refresher before reviewing the more advanced examples contained in this book.

The examples and methodology presented should be verified by the reader for its accuracy and applicability prior to use on a project.

1.8 References Containing Analysis Methods for Complex Diaphragms and Shear Walls

1. *Design of Wood Diaphragms*[6] by Edward F. Diekmann, *Journal of Materials Education*, University of Wisconsin, Madison, August 1982

   This paper is one of a set of modules on Wood: Engineering Design Concepts that was prepared for the Fourth Clark C. Heritage Memorial Workshop at the University of Wisconsin, Madison, August 1982, published seriatim in the *Journal of Materials Education*. The paper is a very important document, which provides a fairly comprehensive coverage of basic diaphragm and shear wall analysis and connection design. Of greater importance and relevance to this book are the presentations on the following:

   - Diaphragm continuity issues
   - Diaphragms with openings
   - Diaphragms with horizontal offsets (notches)

- Diaphragms with vertical offsets
- Collector analysis at diaphragm discontinuities
- Transfer of disrupted chord forces within the diaphragm
- Shear walls with openings

The examples are clear and easy to follow. It is surprising, and at the same time unfortunate, that this paper was not provided in a major publication where it could have been more readily accessed by the engineering community.

2. *Diaphragms and Shear Walls*[8] by Edward F. Diekmann, S.E., *Wood Engineering and Construction Handbook*, Chapter 8, 3rd ed.

Chapter 8 of the book is devoted to simple diaphragms and shear walls. Most of the material on basic diaphragms and shear walls that was included in reference 1 has been repeated here. Diaphragms with openings covered in reference 1 have also been included in the chapter. The information provides a comprehensive coverage of simple systems but is limited with regard to complex systems.

3. *ATC-7-1 Proceedings of a Workshop on Design of Horizontal Diaphragms*[6] 1980

The objective of the workshop was to evaluate current knowledge and practice in the design and construction of horizontal wood diaphragms, examine the needs and priorities for immediate and long-range research required to minimize gaps in current knowledge, to improve current practice, and to provide state-of-the-art practice papers for the development of a guideline for the design of horizontal wood diaphragms. The document included several case studies on (1) the field performance of wood diaphragms subjected to wind and seismic loading conditions, (2) the performance of mechanical fasteners in wood diaphragms, (3) analysis methods for horizontal diaphragms, (4) a very basic discussion of irregular shaped diaphragms, and (5) details for the transfer of forces from the diaphragm to the vertical force-resisting elements. A final list of some of the recommendations developed from the workshop included the following:

- Develop mathematical models and analysis methods to predict the inelastic response of diaphragms
- Develop a simplified analytical model to predict deflections of diaphragms
- Perform additional dynamic tests using either cyclic loads or input from realistic earthquake motions
- Determine what, if any, size effects exist in the performance of diaphragm tests
- Determine, by tests, distances required for ties and collectors to spread loads into the diaphragm
- Evaluate, by tests, current assumptions associated with sub-diaphragms
- Determine the effects of the size and location of openings on the force distribution and deformation of diaphragms
- Determine the necessity of code enforced aspect ratios

4. *ATC-7 Guidelines for the Design of Wood Sheathed Diaphragms*[5] by the Applied Technology Council, Berkeley, California, September 1981

   The guideline was prepared by H.J. Brunnier Associates and guided by an advisory panel comprised of Noel R. Adams, Edward F. Diekmann, Byrne Egg-enberger, Ronald L. Meyes, Roland L Sharpe, and Edward J. Teal.

   The document was considered to be the state-of-the-art at the time of publication. Most of the information contained in the guideline continues to be of value and relevance today. Twelve design examples are included in the guide, in addition to discussions on the topics listed below. Some of the concepts are not fully developed; however, there is a considerable amount of information contained therein for the novice and the experienced professional.

   - Basic diaphragm discussions
     a. Basic components and stresses
     b. Girder analogy
     c. Truss analogy
     d. Moment couple series
   - Diaphragms with openings
   - Continuous diaphragms
   - Sub-diaphragms
   - Irregular diaphragms
   - Diagonal and straight sheathed diaphragms
   - Diaphragm deflections
   - Load transfer through the diaphragm

5. *APA Research Report 138*[9] by John R. Tissell, P.E. and James R. Elliott, P.E., Technical Services Division

   The report included eleven tests of diaphragms on panelized systems, high load diaphragms, diaphragms with openings, field glued diaphragms, and diaphragms with framing spaced at 5 ft. Of particular interest is Appendix E, which provided an example on the analysis of a diaphragm with openings. The example was based on the design method described in ATC-7, which was developed by Edward F. Diekmann, S.E.

6. *Design of Wood Structures*[10] by D.E. Breyer, J.F. Fridley, D.G. Pollock, and K.E. Cobeen

   This book is perhaps the best known and most widely used book on the design of wood members, connections, diaphragms, and shear walls. It provides a very comprehensive coverage on the design of simple wood structures.

7. *2018 IBC Structural/Seismic Design Manual, Volume 2*[11] by SEAOC

   Volume 2 provides one of the most comprehensive and state-of-the-art coverages on the analysis and design of light framed structures, and masonry and concrete tilt-up walls with flexible diaphragms. All of the design examples are located in high seismic zones.

8. *Diaphragms and Diaphragm Chords*[12] by Uno Kula, P.E., C.E., S.E., SEAOC 2001 70th Annual Convention Proceedings

   The paper was a short abstract on the analysis of irregular shaped diaphragms containing openings and horizontal offsets of the diaphragm chords. Although the number of examples was limited, the method described for analyzing chord and collector forces was fairly clear and complete. The analytical method was consistent with the method developed by Edward F. Diekmann, S.E., as presented in ATC-7.

9. *Guide to the Design of Diaphragms, Chords, and Collectors*[13]

   The guide provides examples for the analysis and design of multistory rectangular diaphragms with cantilever sections and interior openings.

   - Four-story concrete diaphragms with concrete collectors
   - Three-story wood diaphragms with wood collectors
   - Four-story flexible steel deck diaphragm with steel beam collectors
   - Four-story concrete filled steel deck diaphragm with steel beam collectors

   Clear, thorough examples are provided for the design of the chords and collectors. The guide is based on the 2006 IBC and ASCE/SEI 7-05.

10. NEHRP Seismic Design Technical Brief No. 10[14]—*Seismic Design of Wood Light-Frame Structural Diaphragm Systems: A Guide for Practicing Engineers* by Kelly Cobeen, J. Dan Dolan, Douglas Thompson, John W. van de Lindt

1.9 References

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11. Structural Engineers Association of California (SEAOC), IBC Structural/Seismic Design Manual, Volume 2, SEAOC, CA, 2018.
12. Structural Engineers Association of California (SEAOC), SEAOC 2001 70th Annual Convention Proceedings, Diaphragms and Diaphragm Chords, Uno Kula, SEAOC, CA, 2001.
13. *Guide to the Design of Diaphragms, Chords and Collectors Based on the 2006 IBC and ASCE/SEI 7-05*, Dr. Timothy Mays, National Council of Structural Engineers Association (NCSEA), 2009.
14. National Institute of Standards and Technology (NIST), NEHRP Seismic Design Technical Brief No. 10, *Seismic Design of Wood Light-Frame Structural Diaphragm Systems, A Guide for Practicing Engineers*, U.S. Department of Commerce, 2014.

CHAPTER 2
Diaphragm Basics

2.1 Introduction

The methods for analyzing and designing simple rectangular box systems have been common knowledge for decades. A number of publications and textbooks that have been written to date provide a fairly complete coverage on the topic. However, a natural progression of architectural creativity has taken structures from simple rectangular floor plans to ones that contain horizontal and vertical offsets and other irregularities that complicate load paths. Due to time constraints, the length of undergraduate classes on wood design often limits the coverage of diaphragms to basic simple rectangular systems. The extent of mentoring after graduation varies greatly, and because there are very few books or examples that explain how to analyze complex diaphragms and structures, some individuals may not have an in-depth understanding how complex diaphragms and their components really work. This may cause some engineers to approach the analysis and design of these irregular shaped structures as though they are still rectangular diaphragms. A cursory review of simple diaphragms and their components will be provided here as a base from which to extend the discussion into irregular shaped diaphragms.

2.2 The Basic Lateral-Force-Resisting System

The structure shown in Fig. 2.1 represents a typical bearing wall system, also known as the box system. Lateral forces are resisted by the flexible wood roof diaphragm and light-framed shear walls at the upper level and by the flexible wood floor diaphragm and concrete or masonry shear walls at the lower level. Wind loads are typically transmitted to the roof diaphragm as a uniform load by wind pressure imposed on the vertical studs. Seismic forces are transmitted through the roof diaphragm by inertial forces on the mass of the diaphragm and tributary height of the walls. These loads are resisted by the roof diaphragm which acts like a horizontal beam, or deep girder. Girder analogy, as described in ATC-7,[1] assumes that the flanges of the diaphragm only take tension and compression forces due to bending and the web takes the entire shear. Plywood diaphragm testing has indicated that the girder analogy is an acceptable predictor of the performance of wood sheathed diaphragms; and that, the use of the analogy for the determination of the chord forces is conservative. Figure 2.2 shows the resulting shear and moment diagrams for a uniformly loaded rectangular diaphragm. Plywood diaphragms behave slightly different from shallow beams due to the width of the diaphragm and the jointed construction. The APA noted that it has been shown that shear

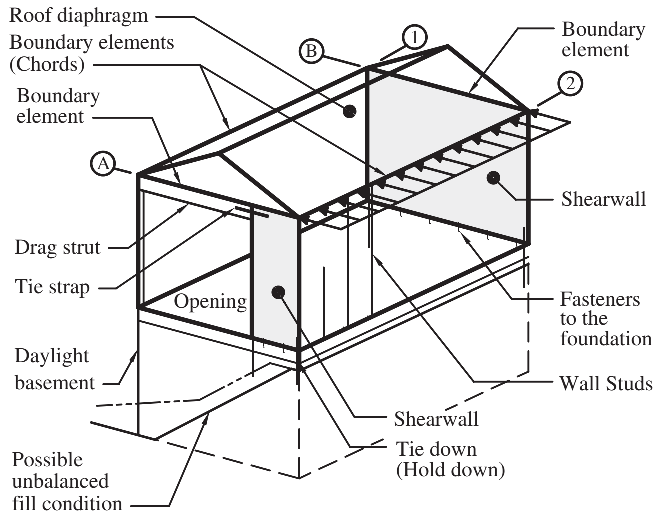


Figure 2.1 Typical box system loaded in the transverse direction.

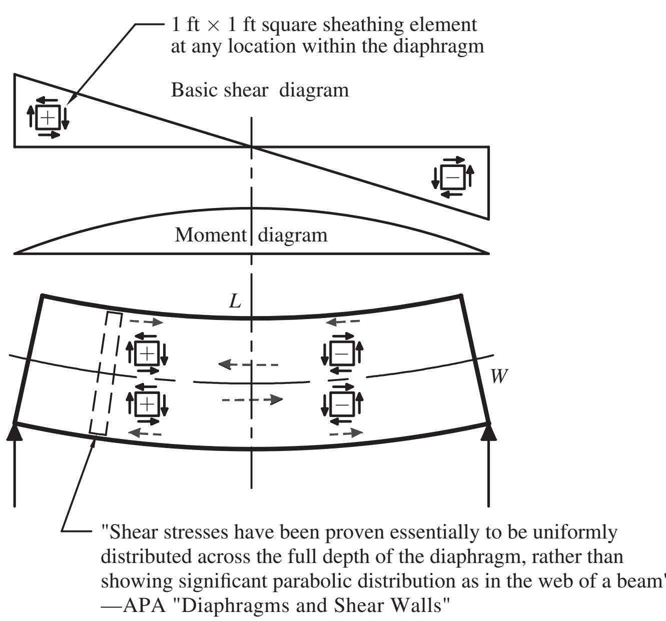


Figure 2.2 Shear distribution into a simple diaphragm.

stresses have been proven to be essentially uniform across the full width of the diaphragm, rather than showing significant parabolic distribution as in the web of a shallow solid beam. Other publications have also noted the same observation, citing the tests were not set up in a manner to accurately record the exact distribution. The assumption of uniform shear distribution is widely accepted in the engineering community as a useful assumption for design. The basic shear diagram for a diaphragm under uniform loads is plotted as shown in the figure, positive shears occurring on the left side of mid-span of the diaphragm and negative shear occurring on the right side. A symbol representing 1×1 ft^2 pieces of sheathing, referred to as "sheathing elements," has been added to the basic shear diagram to show the direction of the unit shear forces (plf) acting on the edges of the sheathing elements. The maximum moment occurs at the point on the shear diagram where the unit shear is zero. A simple rectangular diaphragm uniformly loaded is analyzed as follows:

w = uniform distributed load

L = length of diaphragm

W = width of diaphragm (often referred to as "b or d")

x = distance from support under consideration

$$R = \frac{wL}{2} = V = \text{diaphragm reaction at the support}$$

$$v = \frac{V}{W} = \text{diaphragm unit shear at the support}$$

$$V_x = R - wx = \text{shear at any distance } x \text{ from the support}$$

$$M_{\max} = \frac{wL^2}{8} = \text{maximum moment}$$

$$M_x = Rx - \frac{wx^2}{2} = \text{moment at any distance } x \text{ from the support}$$

$$F_{\text{chord}} = \frac{M}{W} = \text{chord force}$$

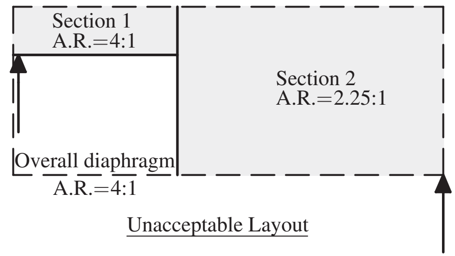
Code limits the maximum length to width aspect ratios of flexible wood and untopped steel deck diaphragms. Two tables regarding allowable aspect ratios for wood diaphragms and steel deck diaphragms have been included in Fig. 2.3 for the convenience of the reader. The limitations were established based on tests conducted on diaphragms by the APA and by the Steel Deck Institute. The limitations on aspect ratios apply to simple rectangular diaphragms as a whole. Currently, there are no guidelines or limitations for complex, irregular shaped diaphragms. Similar limitations could be applied to the diaphragm as a whole and to each individual section of the diaphragm that has been broken down into simple rectangular sections for the ease of analysis (e.g., segments around an opening in the diaphragm, sections near offsets, transfer diaphragms). The schematic plan in the upper right of Fig. 2.3 demonstrates a condition where all individual sections of the diaphragm and the diaphragm as a whole complies with the allowable aspect ratios listed in the tables, but by observation, this configuration would make the diaphragm far too flexible. The diaphragm must be stiff enough to prevent stability problems in the members supporting the diaphragm, prevent excessive shear and forces within the diaphragm, and limit drift in accordance with code allowable. Sound engineering judgment should be used when checking allowable aspect ratios.

Code requires that all boundaries of a diaphragm be supported by struts, chords, shear walls, frames, or other vertical lateral-force-resisting elements. Although vertical

4.2.2 Maximum Diaphragm Aspect Ratios

Diaphragm Sheathing Type	Maximum *L/W* Ratio
Wood structural panel, unblocked	3:1
Wood structural panel, blocked	4:1
Single-layer straight lumber sheathing	2:1
Single-layer diagonal lumber sheathing	3:1
Double-layer diagonal lumber sheathing	4:1

Courtesy, American Wood council, Leesburg, VA.



NDS-SDPWS Table 4.2.2
Maximum Diaphragm Aspect Ratios
(Horizontal or sloped diaphragm)

Steel Deck Diaphragms

Flexibility category	*F* Flexibility factor	Maximum span in feet for masonry or concrete walls	Allowable Aspect Ratio			
			Rotation not considered in diaphragm		Rotation considered in diaphragm	
			Masonry or concrete walls	Flexible walls	Masonry or concrete walls	Flexible walls
Very flexible	More than 150	Not used	Not used	2:1	Not used	1.5:1
Flexible	70 – 150	200	2:1 or as required for deflection	3:1	Not used	2:1
Semi-flexible	10 – 70	400	2.5:1 or as required for deflection	4:1	As required for deflection	2.5:1
Semi-rigid	1 – 10	No limitation	3:1 or as required for deflection	5:1	As required for deflection	3:1
Rigid	Less than 1	No limitation	As required for deflection	No limit	As required for deflection	3.5:1

Courtesy, ICC Evaluation Services, LLC, Whittier, CA.

Table 3 - Diaphragm Flexibility Limitation
ER-3056

See latest Evaluation Report for applicable footnotes and limitations.

Figure 2.3 Allowable diaphragm aspect ratios for flexible diaphragms.

lateral-force-resisting elements are not present at the end of cantilever diaphragms, a boundary member is required to act as a diaphragm chord when loads are applied parallel to the cantilever length. When the structures shown in Figs. 2.1 and 2.4 are loaded in the transverse direction by wind, or by seismic loads as shown in Fig. 2.5, both longitudinal walls at grid lines 1 and 2 act as diaphragm chords that serve as boundary elements. In accordance with the definitions included in Section 2.2 of SDPWS[2] and Section 11.2 of ASCE 7,[3] boundary members and boundary elements are elements that are parallel to the applied load that collects and transfers diaphragm shear forces to the vertical elements of the lateral-force-resisting system. Collectors and struts function in the same manner and are basically interpreted as being the same thing. It is the authors' preference to designate a drag strut as a perimeter boundary element that collects shears from one side only. A collector is an interior boundary element that collects shear from both sides. The full-length shear wall at grid line B is a boundary element which serves to support one end of the diaphragm. The partial length shear wall at grid line A also serves as boundary members and provides the support for the other end of the diaphragm. The wall at grid line A receives uniformly distributed diaphragm shears along the full width of the diaphragm. Since the wall

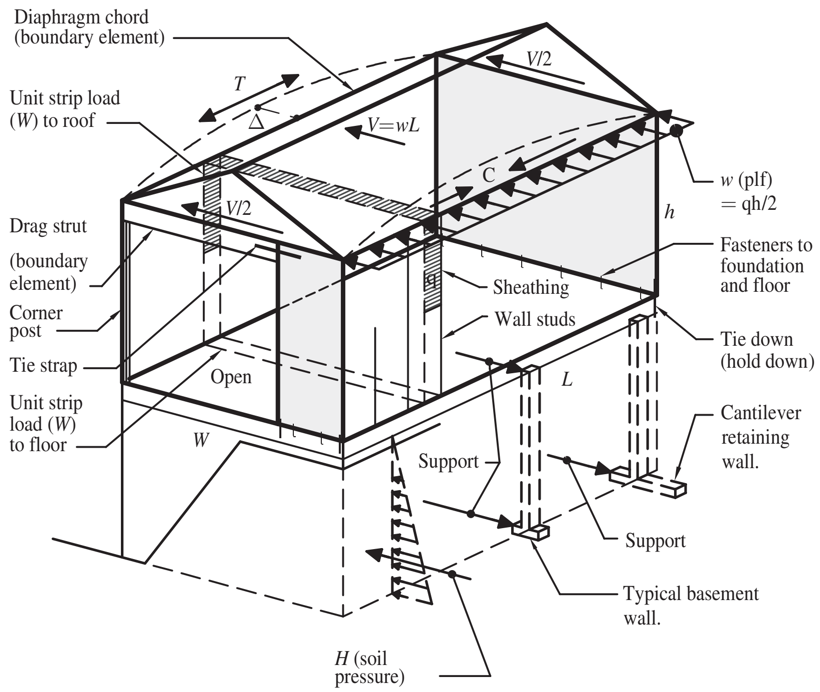


Figure 2.4 Wind load distribution into a diaphragm.

extends only a short distance across the width of the diaphragm, a boundary member known as a drag strut must be installed to support the remainder of the diaphragm and transfer the collected shears back into the top of the shear wall. Both shear walls act like vertical cantilever beams or diaphragms that resist the reactions of the diaphragm and keep the diaphragm from sliding off the structure. The diaphragm forces at the top of the walls cause overturning and sliding forces in the walls, which are transferred into the foundation for stability.

Figure 2.6 shows the elevations of the walls located at grid lines A and B. Boundary members are also required for shear walls, as shown in the figure. Overturning can be resisted by the dead load that is applied to the wall. Additionally, hold downs are required at each end of the shear wall if the dead load is not large enough to resist the overturning moment. Sliding is resisted by nailing or other method of connection of the wall to the floor and/or foundation. The floor diaphragm and its connection to the foundation must be designed to resist the tributary wind or seismic loads from the walls above plus soil loads in accordance with IBC[4] Section 1610 and ASCE 7 Sections 11.7 and 11.8. The foundation must be designed to safely transfer the lateral-forces into the soil without exceeding the allowable soil bearing pressure.

2.2.1 Shear Capacity of Nailed Sheathing

Once the diaphragm and shear wall forces and shears have been calculated, the sheathing and nailing requirements must be determined. Diaphragm and shear wall unit shear capacities are calculated from tabulated values using SDPWS Section 4.1.4. The

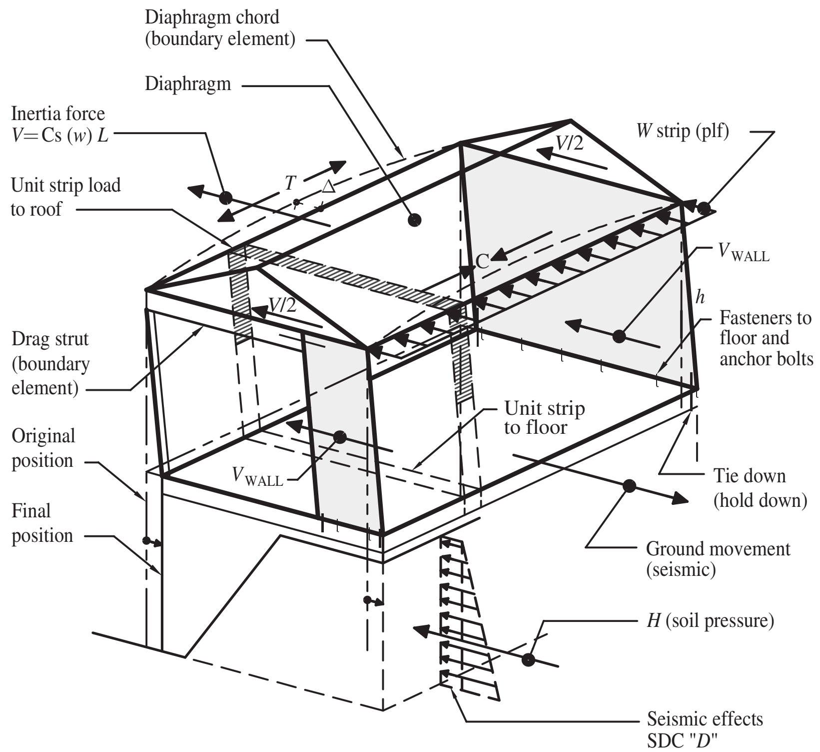


Figure 2.5 Seismic load distribution into a diaphragm.

shear capacities provided in SDPWS Tables 4.2A through 4.2D for diaphragms and Tables 4.3A through 4.3D for shear walls are nominal unit shear capacities, which must be reduced for ASD or LRFD unit shear capacities. Prior editions of the tables broke the nominal shear values down into two columns, one for seismic (column A) and one for wind (column B). The 2021 SDPWS has combined seismic or wind design into a single nominal shear value, typically equal to the older wind nominal value. ASD and LRFD capacities are determined by reduction factors as noted in Section 4.1.4.1 for seismic and Section 4.1.2 for wind.

For seismic design of diaphragms and shear walls, the ASD allowable shear capacity shall be determined by dividing the nominal shear capacity by the ASD reduction factor of 2.8 and the LRFD factored shear resistance shall be determined by multiplying the nominal shear capacity by a resistance factor of 0.50. For wind design of diaphragms and shear walls, the ASD allowable shear capacity shall be determined by dividing the nominal shear capacity by the ASD reduction factor of 2.0 and the LRFD factored shear resistance shall be determined by multiplying the nominal shear capacity by a resistance factor of 0.80. No further increases are permitted. Further decreases may be required per the footnotes of the tables, particularly when using framing other than Doug-Fir Larch or Southern Pine with a moisture content equal or less than 19 percent at the time of construction.

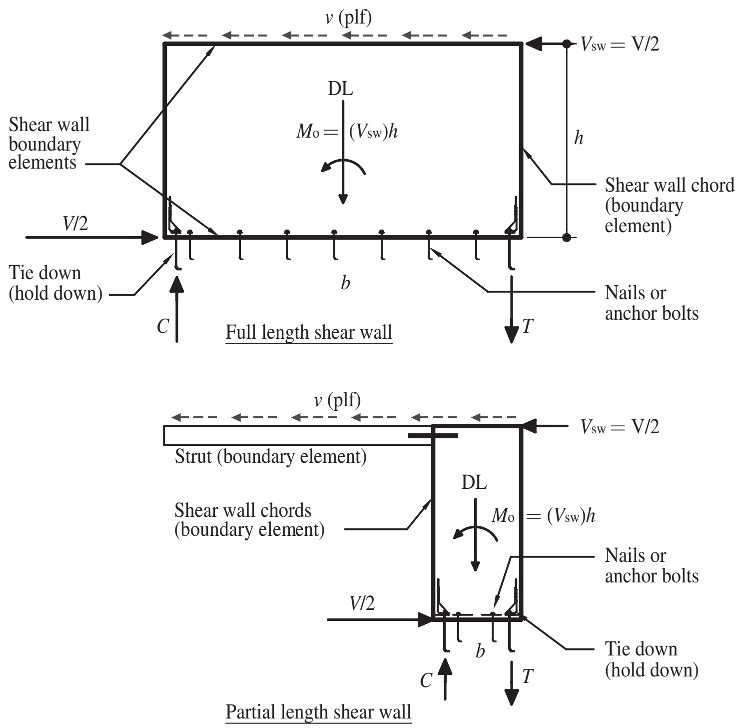


Figure 2.6 Shear wall boundary elements.

Occasionally, the question is asked if a higher shear can be obtained by using a thicker sheathing. SDPWS commentary notes that the use of "minimum nominal panel thickness" in the tables is to accommodate use of the tabulated nominal unit shear capacities. Structural panels of greater thickness can be used provided nails with the prescribed dimensions are used and that bearing length of the nail into framing exceeds the prescribed minimum bearing length. This allowance recognizes that greater structural panel thickness will also develop the strength of the prescribed nailing upon which the nominal capacities are based. However, a greater shear capacity will not be developed because the nails control the shear capacity by bending and nail slip.

2.3 Load Distribution into a Diaphragm

Wind pressure and seismic forces are the primary lateral forces that are applied to roof and floor diaphragms and their supporting shear walls. IBC Section 1609.1.1, with some exceptions, requires the determination of wind loads to be in accordance with ASCE 7 Chapters 26 through 30. Any method can be used provided the method is applicable to irregular shaped structures and separates the wind loads onto the windward, leeward, and side walls of the building and properly accesses the internal forces in the main wind-force-resisting system (MWFRS). The wind pressure on the sheathing is transferred uniformly into the supporting studs as shown in Fig. 2.4. The combined internal and external pressures multiplied by half of the stud height (qh/2) plus the wind pressures acting on the roof surface apply a uniform strip load (plf) to the roof and floor diaphragm.

Seismic forces are applied to the diaphragms of a structure when the ground moves laterally under the structure, causing inertia forces proportional to the mass of the structure to resist the resulting acceleration, as shown in Fig. 2.5. For a single story, the seismic force applied to the roof diaphragm and shear walls is usually based on 1-ft wide strips, in which the seismic weight consists of the dead load of the upper half of each wall that occurs across the section plus the roof dead load of the unit strip. The seismic weight of the unit strip is multiplied by the seismic response coefficient, C_s, and is applied as a uniform lateral load to the roof diaphragm. For multistory buildings, the diaphragm inertial design forces developed in the roof or floor diaphragms are calculated by ASCE 7 Section 12.10.1.1, Eq. 12.10-1. The dynamic response of multistory buildings is a complex multi-modal response. The diaphragm design force for a floor, F_{px}, can be higher than the vertical distribution of seismic forces F_x, because the peak diaphragm acceleration does not necessarily coincide with the peak shear in the story below. The in-plane seismic shear resulting from the self-weight of end walls should be included when calculating the end wall overturning. This in-plane load is often ignored for light-framed walls; however, exterior walls can have significant self-weight. The seismic weight tributary to the floor diaphragm is also broken down into 1-ft wide strips, which consists of the dead load of the lower half of the upper walls across the section plus the floor dead load of the unit strip. If half of the weight of the walls above the floor are included in the seismic weight of the level above that under consideration, then half, not all, of the weight of these walls above need to be included in the seismic weight. This seismic diaphragm design forces calculated per ASCE Section 12.10.1.1 are then applied as a uniform lateral load to the floor diaphragm.

The distribution of wind and seismic forces into and out of the diaphragm have identical load paths. Soil loads applied to the floor diaphragm are commonly ignored at the first floor if the backfill acts at full height on opposing walls of the foundation, creating a balanced condition, with the logic that the diaphragm is restrained from movement. However, for conditions of unbalanced backfill or first floors with daylight basements loaded on one side only, the soil pressures must also be applied to the floor diaphragm in addition to the wind and seismic forces.

Typically, two types of foundation walls are used for below grade walls, cantilever retaining walls and typical (standard) basement walls as shown in Fig. 2.4. The stability of cantilevered retaining walls is provided by the weight of the soil over the extended footing (heel) and increased soil pressure on the interior (toe) side of the footing. The weight of the soil pushing down on the heel of the footing resists overturning of the wall. Out-of-plane lateral support at the top of a cantilever wall is not required and transmission of soil pressures into the diaphragm does not occur. In contrast, the standard basement wall has a narrow continuous footing at the base of the wall that cannot resist overturning due to the small projection of the footing edges beyond the face of the wall. Stability of this wall is provided by the lateral support of the floor diaphragm at the top of the wall and by the concrete slab on grade at the bottom of the wall. This type of wall is a restrained wall that is designed for at-rest soil pressures, except as noted below in high seismic areas. The force applied to the floor diaphragm in this case would be equal to the reaction of the upper floor wall studs caused by wind pressure or seismic forces plus the reaction of the basement wall from the soil pressure, or the seismic strip load plus the reaction of the basement wall from the soil pressure. Additionally, for seismic design categories (SDCs) D through F, dynamic lateral soil pressures because of earthquake motion must also be applied in accordance with ASCE 7 Sections 11.8.3 and 12.1.5. As an example, assume the following:

Given: Assume wind controls the design.

The addition of dynamic soil pressures is not required.

h_1 = 10 ft upper story plus 1 ft of projected area for the width of the floor
h_2 = 9 ft basement
p = 18 psf, wind pressure
q = 65 psf, soil equivalent fluid pressure (at-rest)

Uniform load to the diaphragm from the soil and wind pressure:

$$w = p\left(\frac{h_1}{2}+1\right)+\frac{q(h_2)^3}{6h_2} = p\left(\frac{h_1}{2}+1\right)+\frac{q(h_2)^2}{6}$$

$$= 18\left(\frac{10}{2}+1\right)+\frac{65(9)^2}{6} = 985.5 \text{ plf}$$

This is a significant load which would make it difficult to provide a reasonable diaphragm design. The ASD of the connections for shear transfer from the diaphragm to the foundation walls must include the load duration factor of $C_D = 0.9$, because soil pressure is a permanent load, in accordance with the NDS.[5,6] The shear per linear foot in the diaphragm and connections will be very high given the calculated load in the example unless special detailing and framing is considered.

Many structures have interior shear walls which break the diaphragm into separate sections or multiple spans. Interior shear walls are usually added when the allowable aspect ratio of the diaphragm is exceeded, when the demand on a wall line is too high, or when additional redundancy is desired. Traditionally, the approach used to analyze this condition has been to treat each span as a simply supported diaphragm, ignoring any continuity of the flange at the interior supports. History has shown that diaphragms have performed satisfactorily using the simple span beam analogy. Figure 2.7 shows a single and a multiple span diaphragm. Based on the simple span diaphragm analogy where the diaphragm is idealized as flexible, the force to each wall line will be distributed in accordance to its tributary width as shown in the figure.

Single-span diaphragm:

$$R = \frac{wL_1}{2} = V_{SW1} = V_{SW2}$$

Two-span diaphragms:

$$V_{SW1} = \frac{wL_1}{2}$$

$$V_{SW2} = \frac{w(L_1+L_2)}{2}$$

$$V_{SW3} = \frac{wL_2}{2}$$