

The luxury Stella development in California includes four and five stories of wood-frame construction over a shared concrete pool-level podium. It was designed to meet requirements for Seismic Design Category D.



Photo: Lawrence Anderson, www.lawrenceanderson.net

Designing for Earthquakes

Wood is a proven choice for seismic-resistive construction

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Earthquakes cannot be prevented but sound design and construction based on research and compliance with building code requirements can reduce their effects. Worldwide, it is estimated that several million earthquakes occur each year,¹ but most are too small to be felt. They can occur anywhere; however, the likelihood of earthquakes strong enough to threaten buildings is especially high in certain geographic areas. Areas of particularly high seismic hazard in the U.S., for example, are shown in Figure 1 on page 3.

In North America, where wood-frame construction is common, loss of life due to earthquakes has been relatively low compared to other regions of the world.² The relative good performance of wood buildings is often attributed to the following characteristics:

- ▶ **Lightweight.** Wood-frame buildings tend to be lightweight, reducing seismic forces, which are proportional to weight.
- ▶ **Ductile connections.** Multiple nailed

connections in framing members, shear walls and diaphragms of wood-frame construction exhibit ductile behavior (the ability to yield and displace without sudden brittle fracture).

▶ **Redundant load paths.** Wood-frame buildings tend to be comprised of repetitive framing attached with numerous fasteners and connectors, which provide multiple and often redundant load paths for resistance to seismic forces. Further, when structural panels such as plywood or oriented strand board (OSB) are properly attached to lumber floor, roof and wall framing, they form diaphragms and shear walls that are exceptional at resisting these forces.

▶ **Compliance with applicable codes and standards.** Codes and standards governing the design and construction of wood-frame buildings have evolved based on experience from prior earthquakes and related research. Codes also prescribe minimum fastening requirements for the interconnection of repetitive wood framing members; this

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Learning Objectives

After reading this article, you should be able to:

1. Discuss seismic-resistive design requirements for wood-frame buildings with a focus on compliance with the 2015 IBC and ASCE 7-10.
2. Explain the analysis procedure commonly used for determining seismic design loads of wood-frame buildings in the U.S.
3. Describe the two most common wood-frame seismic force-resisting systems.
4. Describe the role of structural configuration and redundancy in seismic design.

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BUILDING CODE REQUIREMENTS

Building codes address the probability and severity of earthquakes by providing design requirements relevant to the site-specific seismic hazard and the building’s risk category. Although codes accept that some non-structural and structural damage will occur, they seek to limit the likelihood of structural collapse in general and to ensure the superior performance of critical and essential facilities such as hospitals and fire stations relative to other structures. These performance expectations recognize that it is not economically feasible to prevent all damage in all buildings when designing for infrequent, large-magnitude earthquakes.

is unique to wood-frame construction and beneficial to a building’s seismic performance.

In addition to their other advantages—such as cost-effectiveness and sustainability—properly designed and constructed wood buildings complying with building code requirements help make communities more resilient to seismic hazards, because they are proven to perform well during seismic events. In California, for example, where wood-frame construction is common for public schools, an assessment of the damage to school buildings in the 1994 Northridge earthquake was summarized as follows: “Considering the sheer number of schools affected by the earthquake, it is reasonable to conclude that, for the most part, these facilities do very well. Most of the very widespread damage that caused school closure was either non-structural, or structural but repairable and not life threatening. This type of good performance is generally expected because much of the school construction is of low rise, wood-frame design, which is very resistant to damage regardless of the date of construction.”²³

This continuing education course provides an overview of seismic-resistive design issues in wood-frame buildings with a focus on compliance with the 2015 *International Building Code (IBC)* and *American Society of Civil Engineers/Structural Engineering Institute Minimum*

Table 1		
Summary of Risk Category for Buildings and Other Structures		
Descriptions of IBC and ASCE 7 Risk Categories	Importance Factor for Seismic I_e	Allowable Story Drift ^{a,b} (% story height)
RISK CATEGORY I buildings represent a low hazard to human life in the event of failure, such as agricultural facilities and storage buildings.	1.0	2.0% – 2.5%
RISK CATEGORY II buildings are those not defined as Risk Category I, III or IV, which would include houses, apartment buildings, offices and stores.	1.0	2.0% – 2.5%
RISK CATEGORY III buildings represent a substantial hazard to human life, such as schools and assembly buildings with an occupant load greater than 300.	1.25	1.5% – 2.0%
RISK CATEGORY IV buildings are designated as essential facilities intended to remain operational in the event of extreme environmental loading such as power-generating stations, police and fire stations, and other structures having critical functions.	1.5	1.0% - 1.5%

Note: In the 2015 IBC, the term “Risk Categories” is used to categorize buildings and structures based on their importance, which includes considerations such as risk to human life and societal need of the building or structure to function during and following an extreme event.

- a. There is no drift limit for single-story structures with interior walls, partitions, ceilings and exterior wall systems that have been designed to accommodate the story drifts.
- b. The larger value of story drift is applicable for wood-frame structures four stories or less above the base where interior partitions, ceilings and exterior wall systems have been designed to accommodate the story drifts.

Equation 1

$$V = \frac{S_{DS}}{\left(\frac{R}{I_e}\right)} W$$

W = effective seismic weight
 R = response modification factor (see Table 3)
 I_e = importance factor that accounts for the degree of risk to human life, health and welfare associated with damage to property or loss of use or functionality
 S_{DS} = design, 5% damped, spectral response acceleration parameter at short periods
 $= 2/3(F_a)(S_s)$
 F_a = short-period site coefficient (at 0.2-second period) to account for ground motion amplification based on soil type
 S_s = mapped spectral response acceleration parameter for short periods

Design Loads for Buildings and Other Structures (ASCE 7-10). The information on code-conforming wood design contained in this course is based on the American Wood Council’s (AWC’s) 2015 *National Design Specification® (NDS®) for Wood Construction*, and 2015 *Special Design Provisions for Wind and Seismic (SDPWS)*.

The NDS and SDPWS are adopted by reference in the 2015 IBC.

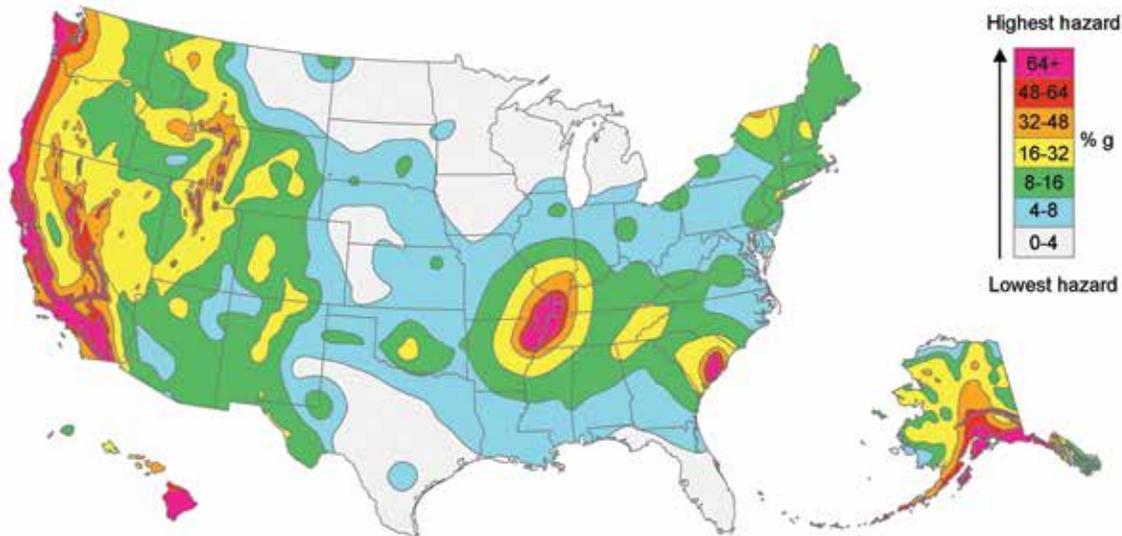
DESIGNING WOOD BUILDINGS TO WITHSTAND SEISMIC FORCES

Seismic design forces are specified in the building code to allow for proportioning of strength and stiffness of the seismic force-

Source: U.S. Geological Survey

Figure 1

The U.S. Geological Survey (USGS) National Seismic Hazard Map



Values of mapped acceleration parameters and other seismic design parameters can be found on the U.S. Geological Survey website at http://earthquake.usgs.gov/hazards/products/conterminous/2014/HazardMap2014_lg.jpg.

Photo: VanDorpe Chou Associates



Structures with ductile detailing, redundancy and regularity are favored for seismic force resistance. This structure includes repetitive wood framing and ductile nailed wood structural panel shear walls and diaphragms.

Equation 2

$$T_a = C_t h_n^x$$

WHERE:

h_n = the structural height

C_t = 0.02 for all other structural systems in Table 12.8-2 of ASCE 7

x = 0.75 for all other structural systems in Table 12.8-7 of ASCE 7

resisting system. Structures with ductile detailing, redundancy and regularity are favored for seismic force resistance. These beneficial characteristics are specifically recognized in the seismic design requirements.

The IBC establishes the minimum lateral seismic design forces for which buildings must be designed primarily by reference to ASCE 7. While ASCE 7 allows use of a number of analysis procedures, the equivalent lateral force (ELF) procedure is most commonly used for seismic design of buildings in the U.S. This is particularly true for low-rise, short-period, wood-frame buildings. The ELF procedure

TERMINOLOGY ADAPTED FROM ASCE 7-10

EFFECTIVE SEISMIC WEIGHT, W : The effective seismic weight, W , of a structure includes the dead load above the base and other loads above the base as follows:

- ▶ In areas used for storage, a minimum of 25% of the floor live load. Exceptions: a) Where the inclusion of storage loads adds no more than 5% to the effective seismic weight at that level, it need not be included in the effective seismic weight, and b) floor live load in public garages and opening parking structures need not be included in the effective seismic weight.
- ▶ Where provision for partitions is required in the floor load design, the actual partition weight or a minimum weight of 10 pounds per square foot (psf) of floor area, whichever is greater
- ▶ Total operating weight of permanent equipment
- ▶ Where the flat roof snow load, P_f , exceeds 30 psf, 20% of the uniform design snow load, regardless of actual roof slope
- ▶ Weight of landscaping and other materials at roof gardens and similar area

STRUCTURAL HEIGHT, h_n : The vertical distance from the base to the highest level of the seismic force-resisting system of the structure; for pitched or sloped roofs, measured from the base to the average height of the roof

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

SHEAR PANEL:

A floor, roof, or wall element sheathed to act as a shear wall or diaphragm

LIGHT-FRAME WOOD

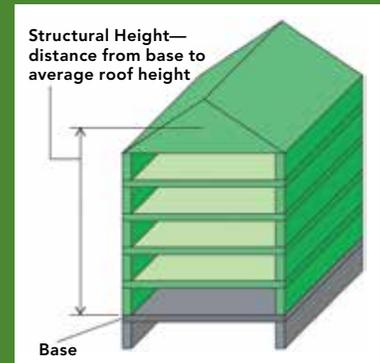
SHEAR WALL: A wall constructed with wood studs and sheathed with material rated for shear resistance

BEARING WALL: Any

wood stud wall that supports more than 100 pounds per linear foot (plf) of vertical load in addition to its own weight

BUILDING FRAME SYSTEM: A structural system with an essentially complete space frame providing support for vertical loads; seismic force resistance is provided by shear walls or braced frames

INVERTED PENDULUM-TYPE STRUCTURES: Structures in which more than 50% of the structure's mass is concentrated at the top of a slender, cantilevered structure and in which stability of the mass at the top of the structure relies on rotational restraint to the top of the cantilevered element



relies on seismic force-resisting system design coefficients such as the response modification coefficient, R (often referred to as the R-factor), deflection amplification factor, C_d , and overstrength factor, Ω_o . The R-factor is essential for determining design seismic base shear, V , which is used in the design of elements of the seismic force-resisting system. For short-period, wood-frame structures, seismic base shear, V , is calculated in accordance with Equation 1.

Design seismic base shear is proportional to effective seismic weight, W , the seismic hazard at the site represented by the spectral response acceleration parameter, S_{DS} , response modification coefficient, R , and the importance factor, I_e . Since the R-factor is found in the denominator of the seismic base shear equation, as the R-factor increases for systems being considered, the seismic base shear forces decrease. For wood-frame buildings, values of the R-factor cover a wide range from $R=1.5$ to $R=7.0$ depending on the type of wood-frame seismic force-resisting

system. (See Table 1.)

For proper design, it is critical to identify the risk category of the building or structure. Detailed descriptions of buildings and structures associated with Risk Category I, II, III and IV are described in IBC Table 1604.5. (For a summary, see Table 1.)

The value of design seismic base shear increases with increasing values of the importance factor, which range from 1.0 for Risk Category I and II structures to a maximum value of 1.5 for Risk Category IV structures. (See Table 1.) The importance factor is equal to 1.25 for Risk Category III structures. Requirements for drift control are also linked to building risk category. Reduced values of permissible drift are associated with higher risk category structures. For example, allowable story drifts range from a maximum of 2.5% of the story height for Risk Category I or II structures to a minimum of 1.0% of the story height for Risk Category IV structures. More stringent drift requirements for higher

risk category structures are expected to limit structural and non-structural damage associated with building deformation relative to lower risk category structures.

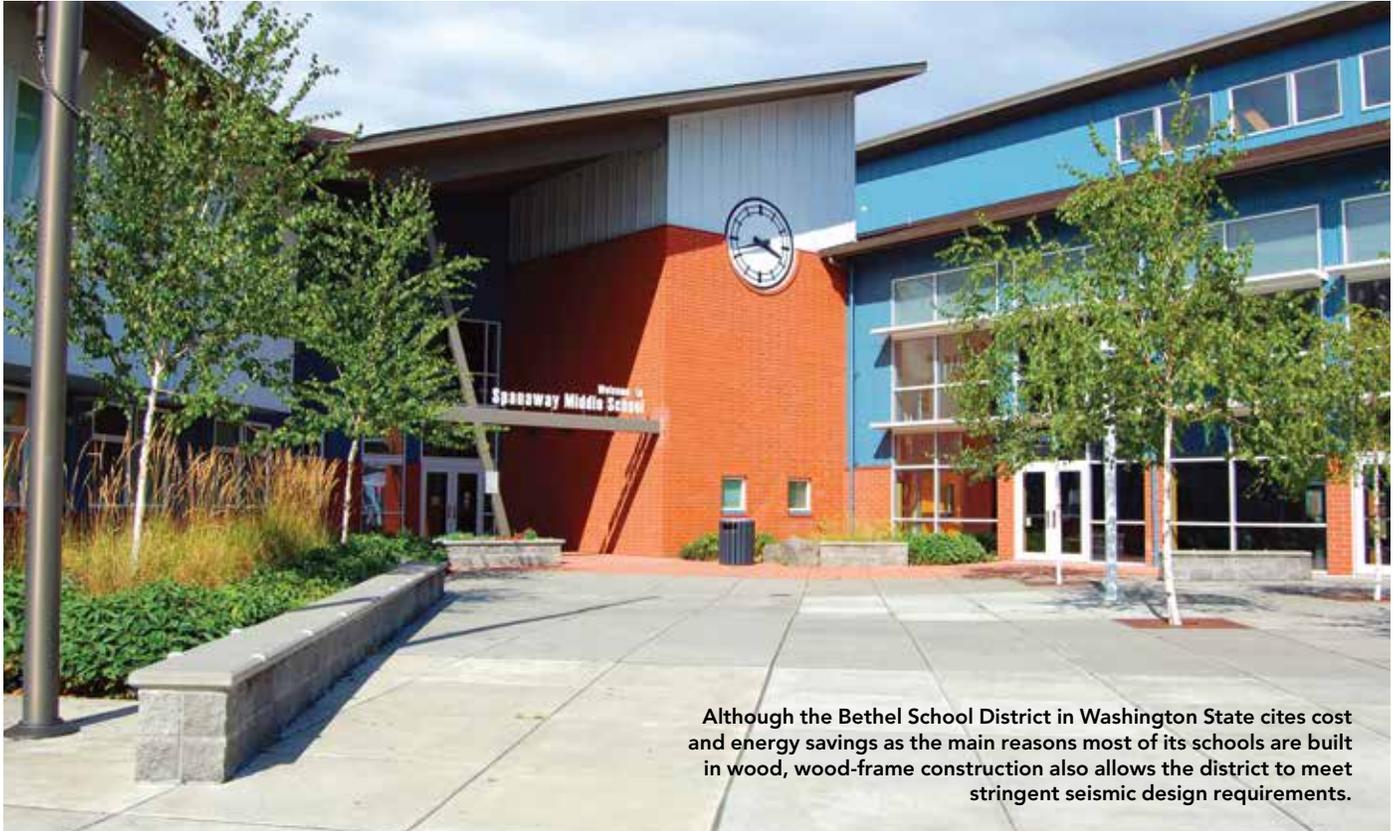
All except the tallest wood-frame shear wall buildings will be classified as short-period buildings due to the stiffness inherent in wood-frame shear wall structures coupled with the ASCE 7 maximum structural height of 65 ft for wood-frame construction. Within ASCE 7, the applicable equation for determining the approximate fundamental period, T_a , for a wood-frame building is shown in Equation 2.

From Equation 2, values of approximate fundamental period are observed to vary by structural height. The relationship between height and approximate fundamental period is shown in Table 2.

ALTERNATIVE SIMPLIFIED PROCEDURE

An alternative simplified version of the ELF procedure is provided in ASCE 7-10 for Risk Category I or II buildings three stories or less

Photo: Erickson McGovern Architects, Bethel School District



Although the Bethel School District in Washington State cites cost and energy savings as the main reasons most of its schools are built in wood, wood-frame construction also allows the district to meet stringent seismic design requirements.

Table 2
Relationship between Approximate Fundamental Period, T_a , and Structural Height, h_n

h_n (feet)	T_a (seconds)
15	0.15
25	0.22
35	0.29
45	0.35
55	0.40
65	0.46

ADHESIVE USE IN WOOD-FRAME SHEAR WALL SYSTEMS

Because of limited ductility and brittle failure modes observed in testing of rigid adhesive shear wall systems, such systems are limited in SDPWS to seismic design categories A, B, and C and the values of R and Ω_o are limited to $R=1.5$ and $\Omega_o=2.5$ unless other values are approved. The use of adhesives in combination with nailing for mitigating floor vibration, increasing floor stiffness for gravity loading, and reducing the potential for squeaking in horizontal wood floor diaphragms is associated with beneficial contribution to diaphragm strength over that provided by nailing alone and is not subject to limitations on use for seismic.

in height, including building configuration limits to avoid a significant torsional response. The simplified procedure is not applicable in Site Class E or F (e.g., soft clay soils, peats and/or highly organic clays, very high plasticity clays, and very thick soft/medium stiff clays). The design base shear is roughly equivalent to that derived from the full ELF procedure for one-story structures, but results in a slightly more conservative first-story design base shear in multi-story structures. Features of the simplified procedure are: 1) a simplified story shear distribution assumption—e.g., story shear

is taken as proportional to the effective seismic weight at each level, 2) omission of requirements to check story drift, and 3) use of seismic R-factors associated with the full ELF procedure.

WOOD-FRAME SEISMIC FORCE-RESISTING SYSTEMS

Specific wood-frame seismic force-resisting systems recognized in ASCE 7 are listed in Table 3. In accordance with ASCE 7, each seismic force-resisting system is associated with seismic design coefficients (R , C_d and Ω_o) and height

limitations based on seismic design category (SDC). For wood-frame seismic force-resisting systems, listed seismic design coefficients are applicable for systems designed in accordance with the SDPWS for wood-frame shear walls and diaphragms and with the NDS for wood member and connection design. In typical wood-frame platform construction, the bearing wall system category is generally applicable because shear walls used for seismic force resistance also function to support gravity loads of the building. While slightly larger R-factors

Table 3

Wood-Frame Seismic Force-Resisting Systems^a Extracted from ASCE 7-10 Table 12.2-1

				Structural system and height, h_n , limits (ft)			
				Seismic Design Category			
Seismic Force-Resisting System	R	C_d	Ω_o	B	C	D	E,F
A. Bearing wall systems							
15. Light-frame (wood) walls sheathed with wood structural panels rated for shear resistance	6½	3	4	NL	NL	65	65
17. Light-frame walls with shear panels of all other materials	2	2½	2	NL	NL	35	NP
B. Building frame systems							
22. Light-frame (wood) walls sheathed with wood structural panels rated for shear resistance	7	2½	4½	NL	NL	65	65
24. Light-frame walls with shear panels of all other materials	2½	2½	2½	NL	NL	35	NP
G. Cantilevered column systems detailed to conform to the requirements for:							
6. Timber frames	1½	1½	1½	35	35	35	NP

NL – Not Limited, NP – Not Permitted
^aFor wood-frame systems designed in accordance with applicable provisions for ASCE 7, SDPWS, and NDS

are associated with shear walls in building frame systems in which gravity loads are carried by a separate structural system (such as a structural frame of beams and columns) and the shear walls resist seismic shear loading only, this type of structural system is less prevalent than standard platform construction. The slight increase in R-factor recognized for building frame systems is based largely on the judgment that the shear walls providing shear resistance in such systems are less susceptible to strength and stiffness degradation from combined gravity and seismic shear loading than shear walls in bearing wall systems.

As defined in ASCE 7-10, the most common seismic force-resisting systems employed in wood-frame platform construction are A15 and A17. The design requirements and construction details for wood-frame shear walls used in those systems for seismic force resistance are

contained in the SDPWS. Specific details for each system include the following:

SDPWS 4.3: Wood-frame wood structural panel shear walls (applicable for bearing wall system A15 and building frame system B22 per ASCE 7-10)

► This system includes wood structural panels conforming to the requirements of the U.S. Department of Commerce/National Institute of Standards and Technology documents, *PS 1-09 Structural Plywood* or *PS 2-10 Performance Standard for Wood-Based Structural-Use Panels*.

► All framing members and blocking are 2-in. nominal or greater except that 3-in. nominal or greater framing is used at adjoining panel edges for closely spaced nails, larger-diameter nails or higher-strength shear walls.

► Nails are located at least 3/8 in. from panel edges and fastener spacing at panel edges is not less than 2 in. on center (o.c.).

► Foundation anchor bolts have a steel plate washer under each nut not less than 0.229 in. x 3 in. x 3 in. in size except where standard cut washers are explicitly permitted.

► Design for shear and overturning provides for properly sized tension and compression chords and shear and overturning anchorage.

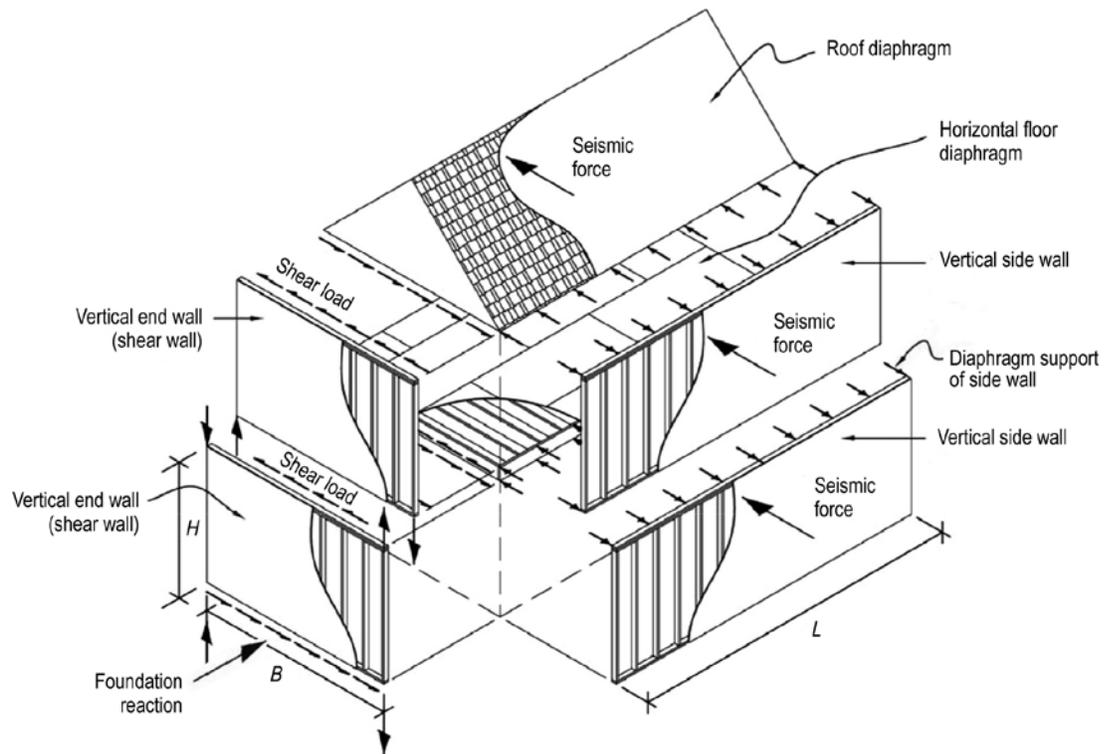
► Maximum shear wall aspect ratio (e.g., height-to-length ratio) is 3.5:1.

► Allowable unit shear strengths range from 200 plf (3/8-in. rated sheathing on one side, 6d common nails and 6 in. o.c. nail spacing at panel edges) to 1,740 plf (19/32-in. rated sheathing on two sides, 10d common nails and 2 in. o.c. nail spacing at panel edges).

LOAD PATH IN LIGHT-FRAME WOOD BUILDING

This Figure illustrates the load paths for resistance to seismic forces. When structural panels such as plywood or oriented strand board (OSB) are properly attached to lumber floor, roof and wall framing, they form diaphragms and shear walls that are exceptional at resisting these forces.

Source: FEMA (2006). *Homebuilders' guide to earthquake-resistant design and construction, FEMA 232, Federal Emergency Management Agency, Washington, D.C.*



- This system is permitted in seismic design categories A, B, C, D, E and F.

SDPWS 4.3: Wood-frame shear walls sheathed with other materials (applicable for bearing wall systems A17 and building frame system B24 per ASCE 7-10)

- This system includes shear panels of particleboard, structural fiberboard, gypsum wallboard, gypsum base for veneer plaster, water-resistant gypsum backing board, gypsum sheathing board, gypsum lath and plaster, and Portland cement plaster, or lumber sheathing with fastening and shear wall aspect ratio varying by shear panel type.

- All framing members and blocking used for shear wall construction are 2-in. nominal or greater.

- Foundation anchor bolts have a steel plate washer under each nut not less than 0.229 in. x 3 in. x 3 in. in size except in some cases where standard cut washers are explicitly permitted.

- Design for shear and overturning provides for properly sized tension

Example calculations of seismic base shear for wood-frame wood structural panel shear walls (A15), wood-frame shear walls with other sheathing materials (A17) and cantilevered column systems (G6) are summarized in Table 4. The seismic base shear calculation assumes all buildings are located at the same site with mapped values of $S_s=1.0g$, site coefficient=1.0 and Importance Factor, $I_e=1.0$. As would be expected, the A15 system employing wood-frame and wood structural panels (i.e., $R=6.5$) results in the lowest design seismic base shear equal to 0.154 W or approximately 15% of the effective seismic weight. In contrast, the A17 system employing wood-frame and shear panels of other materials (such as gypsum wallboard or structural fiberboard with $R=2.0$) results in design seismic base shear equal to 0.50 W or approximately 50% of the effective seismic weight. In lower seismic regions, the significance of lower R-factor systems is often negligible as requirements for wind design will produce greater design forces than even the lowest R-factor systems. In cases where seismic forces do govern design of shear walls, use of systems associated with larger values of design seismic base shear is generally associated with increased required lengths of shear walls for shear resistance, increased number and/or size of connections and anchorage to the foundation, and increased foundation size.

and compression chords and shear and overturning anchorage.

- Allowable unit shear strengths span a wide range across different sheathing materials. For 1/2-in. gypsum wallboard, allowable unit shear strengths range from 75 plf (sheathed on one side, unblocked panel edges, and 7-in. fastener spacing

at panel edges) to 360 plf (sheathed on two sides, blocked panel edges, and 4-in. fastener spacing at panel edges). Particleboard, structural fiberboard, horizontal lumber and vertical board shear walls are permitted in seismic design categories A, B and C.

- Gypsum wallboard, gypsum base for

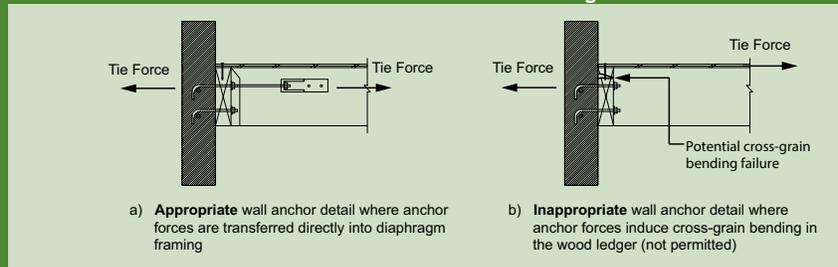
ANCHORAGE OF CONCRETE OR MASONRY STRUCTURAL WALLS TO WOOD DIAPHRAGMS

Although special design criteria for anchorage of concrete or masonry structural walls to wood diaphragms have been in place for decades, some designers are unaware of these requirements. In fact, they exist both in ASCE 7 and building codes, having been developed to address instances where tall, single-story concrete and masonry structural walls became detached from supporting roofs, resulting in collapse of walls and supported bays of framing. The intent is to prevent the diaphragm from tearing apart during strong shaking by requiring transfer of wall anchorage forces across the complete depth of the diaphragm.

These special criteria, which are applicable in Seismic Design Categories C, D, E and F, include designing concrete or masonry structural wall anchorage to wood diaphragms for forces in accordance with ASCE 7 Section 12.11.2 and additional criteria for seismic detailing for transfer of anchorage force that includes:

- Use of continuous ties between diaphragm chords to distribute concrete or masonry structural wall anchorage forces into the diaphragm
- Permitted use of sub-diaphragms to transmit concrete or masonry structural wall anchorage forces to main continuous cross-ties

Figure C4.1.5B from SDPWS



- Restriction on use of toe-nailed connections and nails subject to withdrawal for transfer of concrete or masonry structural wall anchorage forces
- Restriction on use of framing loaded in cross-grain bending or cross-grain tension

Details commonly employed for transfer of wall anchorage forces into the diaphragm use mechanical attachment between the wall anchor and wood framing oriented perpendicular to the wall (Figure C4.1.5B), avoiding direct loading of wood framing in cross grain bending. Special detailing provisions for wood diaphragms consistent with those in ASCE 7 have been added to 2015 SDPWS in Section 4.1.5.

veneer plaster, water-resistant gypsum backing board, gypsum sheathing board, gypsum lath and plaster, or Portland cement plaster, and diagonal lumber shear walls are permitted in seismic design categories A, B, C and D.

Wood-frame wood structural panel shear walls are prevalent in high seismic areas where lateral forces from seismic loading control the required length of shear walls. Relatively large design strengths and permitted use of up to 3.5:1 aspect ratio wood structural panel shear walls provide design flexibility to accommodate building configurations where total length of wall or aspect ratio of wall portions available for seismic force resistance is limited. Additionally, wood-frame wood structural panel shear walls are permitted for use in all SDCs and, in SDC D, E and F, are permitted with structural height of 65 ft. In contrast, wood-frame shear walls sheathed with other materials are generally associated

Table 4		
Example Calculation of Seismic Base Shear for Different R-Factor Systems		
Seismic Force-Resisting System	R	Design seismic base shear as a ratio of effective seismic weight ($I_e=1.0, F_a=1.0, S_s=1.5$)
A. Bearing wall systems		
15. Light-frame (wood) walls sheathed with wood structural panels for shear resistance	6½	$V = W/6.5 = 0.154 W$
17. Light-frame walls with shear panels of all other materials	2	$V = W/2.0 = 0.50 W$
G. Cantilevered column systems detailed to conform to the requirements for:		
6. Timber frames	1½	$V = W/1.5 = 0.67 W$

with smaller values of design strength, most commonly used where large lengths of shear wall are available, not permitted in SDC E and F, and limited to a structural height of 35 ft in SDC D. In some cases, such as for structural fiberboard shear walls and particleboard shear walls, use of such shear walls for seismic force resistance is limited to SDC A, B and C only with a structural height of 35 ft in SDC C.

For inverted pendulum structures of timber frames (e.g., system *G6. Timber Frames*), seismic design coefficients ($R=1.5$, $\Omega_o=1.5$, and $C_d=1.5$) are applicable. Such systems include wood pile-supported structures where the wood member and its connections are designed in accordance with member and connection provisions of the NDS.

SEISMIC DESIGN CATEGORY

The seismic design category for the structure at the site is critical for proper application of requirements for seismic design. The SDC is used as a trigger for permitted use of seismic systems and structural height limitations as seen in Table 3. It is also used to trigger applicability of special requirements associated with structural redundancy and structural irregularities in the building system. SDC is determined based on several factors:

- ▶ Soil properties at the site, or site class, which range through site class A, B, C, D, E and F. Site class A is associated with presence of hard rock. Site class F is associated with peats and/or highly organic clays, very high plasticity clays and very thick soft/medium stiff clays.
- ▶ Mapped values of seismic hazard
- ▶ Risk category of the structure

For short-period structures, such as most wood-frame structures, ASCE 7 allows determination of the seismic design category based on value of S_{DS} and risk category alone (see Table 5) provided alternative criteria are met for structure period and diaphragm flexibility and for sites where mapped values of S_i are less than 0.75. Seismic design categories A, B, C, D, E and F reflect the range of possible categories under ASCE 7. They are similar to seismic zones found in previous codes; however, seismic design categories are more representative of the risk to a particular building because they incorporate the structure's risk category, site conditions and mapped seismic hazard at the

EXPERIENCE FROM PAST EARTHQUAKES

In 2002, the California Department of Government Services completed a legislated inventory and earthquake worthiness assessment of schools. School buildings that were constructed of steel, concrete, reinforced masonry or mixed systems designed between 1933 and July 1, 1979 were required to be evaluated. Older wood-frame schools were exempted on the basis that "wood-frame buildings are known to perform well in earthquakes."⁴

Following is a brief summary of the way wood-frame buildings have performed in North American earthquakes:⁵

San Leandro earthquake, 1971: The earthquake affected commercial buildings and many single-family homes as well as hospitals. Many masonry buildings with design faults collapsed or were severely damaged and had to be demolished. This shows that buildings that appear to be "solid" are subject to damage if their design and construction does not meet modern code requirements. Wood-frame houses performed well, especially from the standpoint of life safety.

LOMA PRIETA EARTHQUAKE, 1989:

The earthquake caused the collapse of a number of engineered structures including the double deck freeway in Oakland that resulted in the death of 49 motorists. Houses at the epicenter—most of which were wood-frame construction—were subjected to high peak ground accelerations and performed well unless they were located where ground fissures developed or had large openings in lower story walls.

NORTHRIDGE EARTHQUAKE, 1994:

Though moderate in size (magnitude 6.7 on the Richter scale), the peak ground accelerations were among the highest ever recorded and significantly higher than those specified in building codes at the time. There were numerous building collapses, including many large structures. At a hearing before the U.S. House of Representatives by the Committee on Space, Science and Technology, one of the reasons given for the limited deaths and injuries was: "The earthquake occurred at 4:31 a.m., when the majority of people were sleeping in their wood-frame, single-family dwellings, generally considered to be the safest type of building in an earthquake.

site.

SDC A represents a very low seismic hazard for which there are no seismic-specific limits on structural height, system type, structural redundancy or structural irregularities. Structures located in this category are not subject to design forces determined in accordance with the ELF. Beginning with SDC B, seismic forces in accordance with ELF are applicable and consideration must be given to special requirements for structural irregularities. Special requirements and limitations become increasingly significant beginning in SDC C. As can be seen in Table 3, as seismic design category increases, structural height limitations apply as well as limitations on the use of particular systems.

STRUCTURAL REDUNDANCY

The arrangement of structural elements within the building structure is recognized as significant to seismic performance.

Buildings with a high degree of redundancy tend to perform better than those where structural resistance is concentrated in just a few elements. The goal of redundancy requirements in the code is to encourage redundant layouts of seismic force-resisting system elements. The redundancy factor, ρ , varies from 1.0 to 1.3 and has different criteria based on judgment applied to the various system configurations. The redundancy factor equals 1.0 in SDC B and C. For wood-frame shear walls in higher seismic design categories, use of a redundancy factor equal to 1.0 can often be accomplished for plans that have a regular layout and resistance provided at building perimeters, where aspect ratio (height-to-length ratio) of shear walls providing shear resistance is 1.0 or less, or, for cases where aspect ratio of shear walls is greater than 1.0, the minimum length of wood structural panel shear wall equals or exceeds the story height.

Photo: Dreamstime



When structural panels such as plywood or oriented strand board (OSB) are properly attached to lumber floor, roof and wall framing, they form diaphragms and shear walls that are exceptional at resisting seismic forces.

STRUCTURAL IRREGULARITIES

Structural irregularities are formed when the load path for strength or stiffness of a structure is interrupted thus concentrating demand on certain elements of the structure. Structural irregularities have been observed in prior earthquakes to cause a variety of problems that can range in seriousness from localized failure to an undesirable overall response causing total collapse. Irregularities are categorized in two groups: horizontal and vertical. Horizontal structural irregularities include: torsional irregularity, re-entrant corner irregularity, diaphragm discontinuity irregularity, out-of-plane offset irregularity and nonparallel system irregularity. Vertical structural irregularities include: soft story irregularity, weight irregularity, vertical geometric irregularity, in-plane discontinuity irregularity and discontinuity in lateral strength irregularity (e.g., weak story). Examples of common irregularities are shown in Figure 2.

BUILDINGS WITH COMBINATIONS OF FRAMING SYSTEMS

Buildings typically have only one structural system and associated R-factor in each principal axis and vertically. However, in cases where more than one R-factor system

is utilized horizontally or vertically, special rules of ASCE 7 apply. In general, design forces and limitations associated with the lower R-factor system are applicable for design in the direction of each principal axis under consideration. There are three common exceptions worthy of mention.

Vertical combinations: Where a building transitions from one system to another vertically through the height of the building structure, system height limits are imposed for the entire structure based on the most restrictive system used. When the upper portion of the structure has a larger R-factor, the upper portion is permitted to be designed for the R-factor associated with that system. The forces imposed from the upper portion onto the lower portion are required to be multiplied (increased) by the ratio of R-factors.

Horizontal combinations: For one- or two-story Risk Category I or II buildings of light-frame or flexible diaphragm construction, the lowest R-factor in any independent line of resistance may be utilized as long as the diaphragm is designed for the lowest R-factor in the overall direction.

Two-stage analysis procedure: This procedure applies when the upper portion of a structure is relatively flexible compared

to a rigid lower portion. In this case, the interface between the upper and lower portions is considered to be the base of the upper structure from which structural height of the upper portion is measured. For these structures, the overall building height equals the structural height for the upper portion added to the height of the lower portion. The most common application of the two-stage analysis procedure for wood-frame construction utilizes an upper portion constructed of wood-frame wood structural panel shear walls (structural height limited to 65 ft maximum above the top of the lower portion in SDC D, E, and F) constructed on top of a Type IA concrete podium. Several requirements must be met in order to comply with requirements of the two-stage analysis procedure:

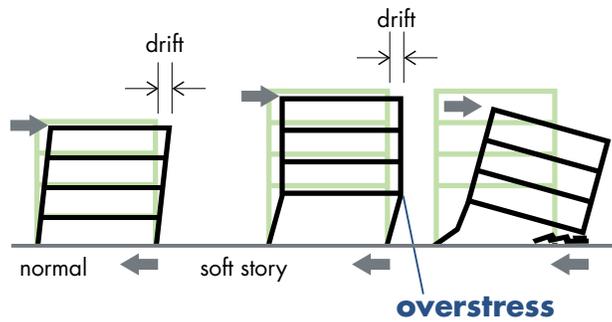
- ▶ The lower structure must be at least 10 times as stiff as the upper structure.
- ▶ The period of the entire structure shall not be greater than 1.1 times the period of the upper portion considered as a separate structure supported at the transition from the upper to the lower portion.
- ▶ The upper portion shall be designed as a separate structure using the appropriate

Source: FEMA

Figure 2

Soft or weak stories

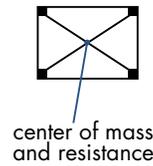
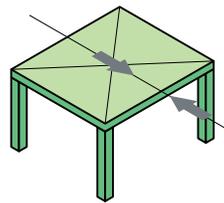
This figure shows a possible failure mechanism associated with a soft or weak story. A soft story is one in which there is less stiffness in the story below and a weak story is one in which there is less strength in the story below. See ASCE 7-10 for specific descriptions for soft and weak story irregularity.



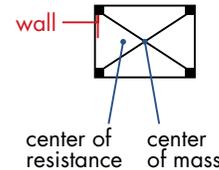
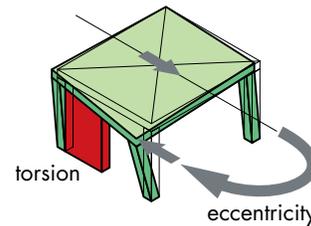
Torsional forces

This figure shows how torsion occurs. If the center of mass and center of resistance do not coincide, the building tends to rotate around the center of resistance. See ASCE 7-10 for specific descriptions of torsional irregularity.

Balanced Resistance

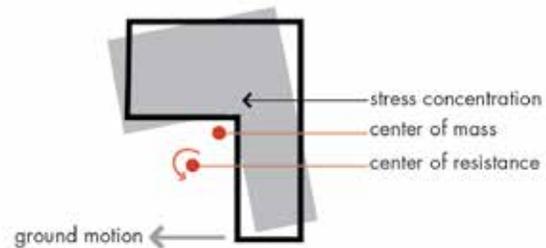
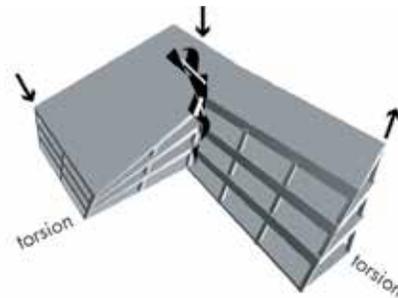


Unbalanced Resistance



Re-entrant corner

In addition to the torsional response created by the offset between center of mass and center of resistance, this figure shows area of possible failure due to stress concentrations at the re-entrant corner. See ASCE 7-10 for specific descriptions of re-entrant corner irregularity.



Examples of structural irregularities from *FEMA 424 – Design Guide for Improving School Safety in Earthquakes, Floods and High Winds*. Another good reference is *FEMA 454 – Designing for Earthquakes – a Manual for Architects*.

values of R and ρ .

► The lower portion shall be designed as a separate structure using the appropriate values of R and ρ . The reactions from the upper portion shall be those determined from the analysis of the upper portion amplified by the ratio of the R/ρ of the upper portion over R/ρ of the lower portion. This ratio shall not be less than 1.0.

► The upper portion is analyzed with the equivalent lateral force or modal response spectrum procedure, and the lower portion is analyzed with the equivalent lateral force procedure.

In SDC D, E, and F, the two-stage procedure can be used over a 20-ft-high Type IA podium allowing the overall building construction height of up to 85 ft maximum prescribed in the height and area provisions of the IBC. In addition, to allow the design to structurally achieve height limits associated with height and area provisions, the two-stage procedure allows the upper portion to have the maximum permitted number of stories and area while being considered a separate structure for IBC height and area purposes (with the overall building height measured from the ground).

NONSTRUCTURAL COMPONENT BRACING

Higher performance for critical and essential facilities is accomplished, in part, by designing for higher forces associated with application of the Risk Category Importance Factor and more stringent drift criteria (mentioned previously). It is also achieved through requirements for bracing of nonstructural components within the building. Examples include bracing of fire sprinkler lines, gas supply

Table 5 Seismic Design Category Based on Short-Period Response Acceleration Parameter <small>(Adapted from Table 11.6-1 of ASCE 7-10)</small>		
Value of S_{DS}	Risk Category	
	I, II or III	IV
$S_{DS} < 0.167$	A	A
$0.167 \leq S_{DS} < 0.33$	B	C
$0.33 \leq S_{DS} < 0.50$	C	D
$0.50 \leq S_{DS}$	D	D

lines, critical equipment, egress stairways and any other component needed for continued operation of a Risk Category IV structure. While requirements for bracing of nonstructural components are the most extensive for Risk Category IV buildings, they are also applicable in varying degrees to other structures based on factors such as seismic design category, structure type and weight, and importance factor assigned to the component.

CONCLUSION

Years of research and building code development have proven that wood-frame buildings can be designed to meet or exceed the most demanding earthquake requirements. As discussed in this course, wood buildings offer a number of advantages that contribute to their relative good performance in

seismic events. Among other things, they tend to be lightweight, reducing seismic forces (which are proportional to weight). Multiple nailed connections in framing members, shear walls and diaphragms offer ductility, meaning they have the ability to yield and displace without sudden brittle fracture. Repetitive members and multiple connections create redundant load paths, which effectively transfer lateral loads. And, when structural panels such as plywood or oriented strand board are properly attached to lumber floor, roof and wall framing, the resulting diaphragms and shear walls offer exceptional seismic force resistance.

For more information on code conforming wood design, please visit www.awc.org.

This article also appears online at ce.enr.com

ENDNOTES

1. U.S. Geological Survey, <http://earthquake.usgs.gov/earthquakes/search/>
2. U.S. Geological Survey, <http://earthquake.usgs.gov/earthquakes/?source=sitenav>
3. *The January 17, 1994 Northridge, CA Earthquake An EQE Summary Report*, March 1994, www.lafire.com/famous_fires/1994-0117_NorthridgeEarthquake/quake/00_EQE_contents.htm
4. *Seismic Safety Inventory of California Public Schools*, California Department of Government Services, 2002
5. *Wood-frame construction in past earthquakes*, Rainer, J. Hans, Karacabeyli, E., FPInnovations (Forintek)

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