VOLUME 4: **EARTH**

DESIGNING FOR NATURAL HAZARDS

A RESILIENCE GUIDE FOR BUILDERS & DEVELOPERS

EARTH

ACKNOWLEDGMENTS

HUD's Office of Policy Development and Research:
Government Technical Representative: Michael D. Blanford

Technical Advisory Group:
Thanks to the following subject matter experts for their contributions to this guide.

USERS
Chair: Randy Noel, MIRM
Anne Anderson, SE
Heather Anesta, PE, SE
Illya Azaroff, FAIA
Dr. Henry Burton, SE
Matthew Cooper, PE
Andrew Kollar, AIA
Darlene Rini, PE
James Williams, AIA, PE, SE

PRODUCERS
Francis Babineau, PE
Daniel Buckley
Michael Chandler
Julia Donoho, AIA, Esq.
Michael Funk
Maria Hernandez
Elizabeth Miller
William Sanderson
Lisa Stephens
Frank Thompson
Dr. Theresa Weston

PUBLIC INTEREST
Dana Bres, PE
Nicholas Crossley
Melissa Deas
Greg Grew, AIA, CBO
Dr. Therese P. McAllister, PE
Amanda Siok
Dana Sjostrom, CFM
Nancy Springer, CBO
Kristopher Stenger, AIA
Russell Strickland
Meghan Walsh, AIA

Additional Earth Task Group Members
Leader: James Williams, AIA, PE, SE
Joel Abney
Helen DiFate, AIA
Gary Ehrlich, PE
Kenneth J. Filarski, FAIA, LEED Fellow
Amanda Hickman
Fernando Pages Ruiz
Mary Uher

Illustrations by VIZ Graphics

Authored by Home Innovation Research Labs

Located in Upper Marlboro, Maryland, Home Innovation Research Labs (Home Innovation) was founded in 1964 as a wholly-owned, independent subsidiary of the National Association of Home Builders (NAHB). Originating as a small product testing laboratory, Home Innovation has since grown to become a full-service market research, building science research, consultant, product testing laboratory, and accredited third-party certification agency dedicated to issues related to the homebuilding industry.

DISCLAIMER

Visit the Disaster Recovery Tool Kit on the U.S. Department of Housing and Urban Development (HUD), Office of Policy Development and Research (PD&R) website—huduser.gov/portal/disaster-recovery.html—to find this report and other relevant resources, reports, guides, and ordinances sponsored by PD&R to aid homeowners and property owners in the disaster recovery process. Many of the reports in the kit are available in print by calling the HUD User Clearinghouse at 1–800–245–2691, option 1. As always, all reports are available as free downloads from HUD User.

FOREWORD

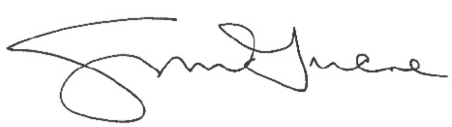
According to the National Oceanic and Atmospheric Administration, the United States spent $145 billion in 2021 recovering from natural disasters, which included wildfires, tropical cyclones, floods, tornados, drought conditions, and extreme winter storm events. To mitigate the impact of natural disasters, the U.S. Department of Housing and Urban Development (HUD) continues to develop technical guidance to improve the resilience of housing.

Resilience is characterized by a community's ability to minimize damage and recover quickly from extreme events and changing conditions.

The *Designing for Natural Hazards: A Resilience Guide for Builders & Developers* series was developed with a technical advisory group that included subject matter experts from a wide range of industry stakeholders. The experts were tasked with identifying above-code construction techniques to improve the resilience of residential buildings. A consensus process was used with the goal of creating a set of practical, actionable guidelines for builders and developers. The guidelines are intended for new construction, improvements before a natural disaster, and major reconstruction efforts after natural disasters, especially where entire communities need to be rebuilt.

The technical advisory group recognized that when natural disasters occur, certain damage is more likely than other types of damage. To address this challenge, the technical advisory group recommended a mitigation strategy that prioritizes high-frequency damage over damage that rarely occurs—based on post-disaster damage assessment reports. This novel approach encourages improving those parts of the building that typically get damaged first. It can also maximize the impact of disaster mitigation grants by preventing future damage to homes.

The resilience guides are an excellent addition to HUD's PD&R Disaster Recovery Took Kit. These guides should be updated periodically based on post-disaster damage assessment data—from future natural disasters. The resilience guides will be valuable resources to builders and developers seeking to incorporate resilience in housing.



Solomon Greene
Principal Deputy Assistant Secretary for Policy Development and Research
U.S. Department of Housing and Urban Development

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INTRODUCTION TO VOLUME 4: EARTH

Designing for Natural Hazards is a set of resiliency guides for builders and developers. It is segmented into five short volumes, each focusing on a specific natural hazard type, as illustrated below:

This guide is **Volume 4: Earth,** which highlights the damage caused by earthquakes, landslides or mudslides, soil dynamics, sinkholes, and freeze/thaw heaving; in addition, the guide identifies resilient construction practices that can eliminate or minimize earth-related damage in a meaningful way.

BACKGROUND

HUD tasked Home Innovation Research Labs (Home Innovation) to develop a set of practical, actionable guidelines for builders and developers to design and construct residential buildings, neighborhoods, and accessory structures in a manner that could improve residential resilience and integrate resiliency throughout the entire community. The ***Designing for Natural Hazards*** guides accomplish this task by providing technical content in a straightforward manner that is easy for a layperson to understand, while also providing references for design professionals, builders, developers, and public officials to dive deeper into the necessary details. These resilience guides are not intended to substitute for engineering or architectural project design work; instead, the technical guidance identifies the components that can be enhanced or improved to achieve above-code performance that should make residential buildings and other community assets more resilient.

The ***Designing for Natural Hazards*** guides focus on new construction and major reconstruction after natural disasters, especially reconstruction in areas where entire communities need to be rebuilt after catastrophic events. The guides do not focus on minor repairs or renovations that are common after typical natural disaster events and do not address commercial buildings, although many of the construction practices identified are also applicable to multifamily mixed-use buildings with wood framing.

To make the guides as practical and have as much input and buy-in as possible, Home Innovation employed many of the same approaches used to assemble the Technical Advisory Group (TAG) when helping develop the American National Standards Institute (ANSI) standards. Specifically, Home Innovation recruited a balanced number of stakeholders to reach consensus on the approach to developing content. In addition, all Task Group meetings were open to the public and input was solicited beyond the members of the TAG and its Task Groups. Although these guides were not developed in accordance with the requirements of an ANSI standard, the approach to these guides mirrored that spirit and intent of creating a voluntary consensus document.

HOW TO USE THE GUIDES

The ***Designing for Natural Hazards*** guides are intended to be used by a wide range of stakeholders, including design professionals, builders, developers, and even prospective homebuyers. The guides differ from other resiliency programs and resources because they are not a prescriptive program or list of improvements. Instead, the resilience guides are designed to be flexible and allow users to focus on either a single resilient construction practice or multiple resilient construction practices, depending on the user's specific needs.

The technical content is provided on a single, double-sided page for each resilient construction practice. These "one-pagers" are intended to be printed and used as stand-alone documents for a builder or developer to specify an above-code construction practice. The one-pagers can also be given to a prospective homebuyer or building owner as a supplemental marketing document to highlight the resilient construction features that have been included in a new building.

Each one-pager includes key information about the specific natural hazard and resilient construction practice that will minimize or eliminate potential damage. The front of each document identifies (1) the damage expected by the hazard (as shown in the photo); (2) the frequency that a specific type of damage occurs; (3) a description of the resilient construction practice that can minimize damage; (4) a description of the mitigation strategy; and (5) a summary of the cost and benefit of implementing the resilient construction practice. The back of the document provides additional design guidance details, including (1) multiple design variations and supplemental resilient construction practices; (2) the corresponding level of difficulty associated with implementing alternative resilient construction practices; (3) the relative cost of implementing the various options; and (4) technical references that provide more information for each design option.

Because the resilient construction practices summarized in these guides are intended to be implemented in areas where the building code does not specify resilient construction practices, builders cannot rely on a building code official to verify that the practices have been followed. Therefore, builders who undertake these resilient construction practices will need to either incorporate the practices into their internal quality assurance process or hire a third-party organization to confirm that the resilient construction practice(s) was appropriately included in the design and constructed per their specification, which will require some additional detail beyond the one-pagers.

Defining Earth-Related Damage and Resilient Construction

Earth-related damage can occur from a variety of events, including the most common types: earthquakes, landslides or mudslides, soil dynamics, sinkholes, and freeze/thaw heaving. The Federal Emergency Management Agency (FEMA) defines an earthquake as “a sudden release of energy that creates a movement in the Earth’s crust. Most earthquake-related property damage and deaths are caused by the failure and collapse of structures due to ground shaking. The level of damage depends upon the extent and duration of the shaking. Other damaging earthquake effects include landslides, the down-slope movement of soil and rock (in mountain regions and along hillsides), and liquefaction.” For this ***Designing for Natural Hazards*** guide, the Earth Task Group focused primarily on damage due to earthquakes and considered the other earth-related hazards as secondary because many are driven by other natural hazards. For example, a mudslide can occur after an extended drought with a period of heavy rain or after an earthquake.

The first undertaking for the Earth Task Group was to identify typical damage that happens when earthquakes occur. To that end, the group reviewed case studies of earthquake events, such as those for the Alaska earthquake on November 30, 2018, published by FEMA; and the Northridge, California, earthquake on January 17, 1994, published by HUD. The Task Group discussed the damage described in the reports, then reviewed a wide range of technical resources—for example, resources from FEMA, HUD, the United States Geological Survey (USGS), the American Society of Civil Engineers (ASCE), the International Code Council (ICC), and the National Institute of Standards and Technology (NIST)—to identify the most relevant resilient construction content to be included in the Earth one-pagers.

For those building in an area designated as at high risk for earthquakes, nearly all earth-resilient construction practices in this guide will apply, in addition to other requirements. However, this guide can also help those building earthquake-resilient residential structures in a low-risk earthquake zone to add one or more earthquake-resilient features incrementally to the building.

USGS publishes a national seismic hazard map for the United States, as illustrated in Figure 1.

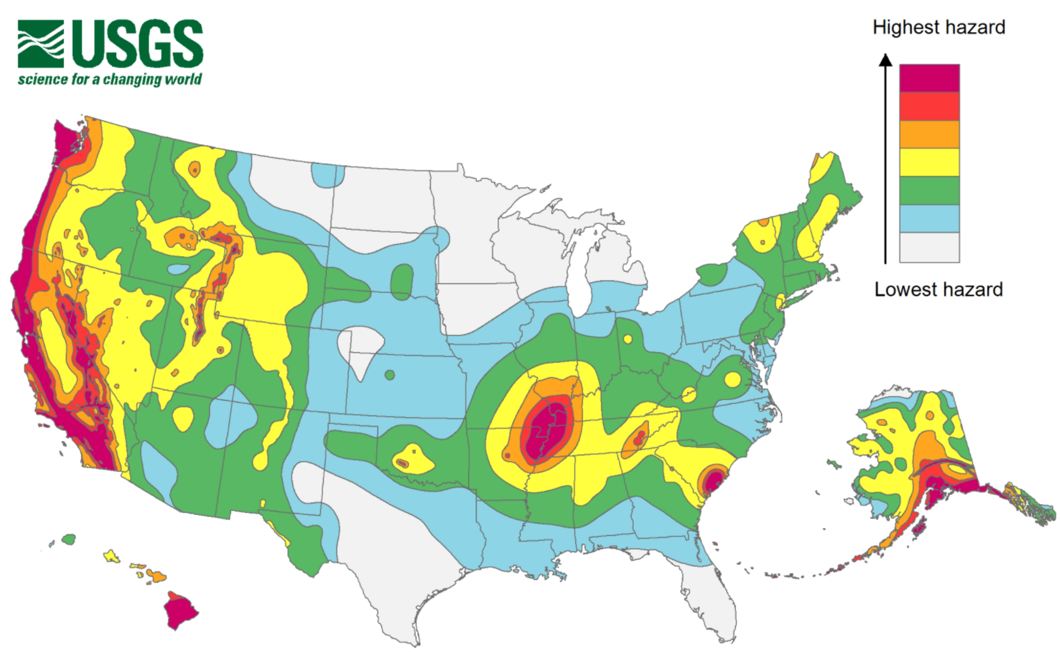


Figure 1. United States Geological Survey National Seismic Hazard Map
Source: USGS

Frequency of Damage Type

After familiarizing themselves with specific damage caused by earthquake events from various disaster reports, the Earth Task Group was asked to determine the type of damage that is most likely to occur when considering all possible damage from earth-related events. The damage is included on the one-pagers; to determine the frequency, the Earth Task Group had to infer the frequency of damage from technical reports, FEMA's *Homebuilders' Guide to Earthquake-Resistant Design and Construction*, and other mitigation programs.

Although the Structural Extreme Events Reconnaissance (StEER) Network investigates and publishes technical reports after earthquake events, the damage data available are not as extensive as their wind hazard data because earthquakes do not occur often in the United States. After the M 6.4 and M 7.1 Ridgecrest, California, earthquakes on July 4–5, 2019, StEER published a preliminary virtual reconnaissance report (PVRR) documenting the damage observed. The executive summary of the report states, "The impact of the two earthquakes on the city of Ridgecrest demonstrated its resiliency as it recovered rapidly where many restaurants and gas stations are back up and running. There was very little structural damage, even from the second stronger earthquake of M 7.1, except for the typically vulnerable buildings (e.g., unreinforced masonry structures and mobile homes). However, there were substantial non-structural and content losses. The other city that was impacted the most is Trona, which did not perform as resilient as Ridgecrest where the city remained dysfunctional up to the time of writing this report. There were more damaged structures, mostly from the effects of ground failure and possibly strong site response related to soft sediments. The town suffered from significant loss of water where its main water pipes fractured due to fault rupture and lateral spreads."

The complexity of damage is illustrated in the StEER report, varying on the basis of the soil type, age of the buildings, type of construction, and magnitude of the earthquake.

Prioritizing High-Frequency Damage for Resilience

Because these resilient construction practices are intended for low-risk areas that need additional resilience to earthquake and poor soil hazards, several participants on the Technical Advisory Group recommended prioritizing high-frequency damage areas of the building as the most practical mitigation strategy for resilience. Many were concerned that if funding for above-code practices and strategies were limited, or if a builder wanted to invest in a specific resilient construction practice above all others, knowing what was most important to do would be difficult if not for some level of prioritization. Data about the frequency of damage type are necessary for builders and developers to prioritize the resilient construction practices that will yield the greatest benefit—or the least amount of damage—to the building. The damage frequency metrics on the one-pagers are intended to provide builders and developers with a general idea of the frequency and severity of possible damage so that cost alone is not driving the mitigation strategy.

The assessment and reconnaissance reports provide some guidance, but given the complexity of the damage, the Earth Task Group—probably more than any other task group—relied on their collective judgment and expertise when determining high-, moderate-, and low-frequency damage. Additional detailed forensics data after events are needed to develop a more accurate method of prioritizing damage types.

Grouping Resilience Practices

The Earth Task Group believed that licensed design professionals and subject matter experts would be able to prioritize the resilient construction practices without much guidance. However, given the multiple options and design alternatives on the one-pagers, the Task Group thought that recommending some bundling of multiple one-pagers would still be valuable so that a builder or developer could offer a prepackaged system of resilient construction practices, similar to other resiliency programs.

The most basic prepackaged system of resilient construction practices could be as simple as selecting the basic practice for each of the one-pagers in the Earth Guide to encourage some baseline level of resilience. The Task Group also explored a "Good, Better, and Best" approach to grouping the one-pagers, in which the basic levels of resilience would be branded as "Good," the more advanced practices could be combined with those basics to offer a "Better" option, and the most comprehensively resilient practices could be considered a "Best" level of resilience. Table 1 provides an example of this type of approach for Earth Resilience, in which the one-pagers are grouped on the basis of the frequency of occurrences.

Certain resilient construction practices may be alternatives, whereas others may be additional practices to be implemented. This method allows for even further customization of a "Good, Better, and Best" approach for a builder or developer looking for this type of guidance.

Table 1. Example of "Good, Better, and Best" Approach to Resilient Construction Practices for Earth

	USING MULTIPLE 1-PAGERS		
	GOOD	**BETTER**	**BEST**
Continuous Load Path	High Frequency	High Frequency	High Frequency
Post and Beam Connections	High Frequency	High Frequency	High Frequency
Drywall (to Prevent Cracks)	High Frequency	High Frequency	High Frequency
Garage Openings	High Frequency	High Frequency	High Frequency
Exterior Wall Construction	High Frequency	High Frequency	High Frequency
Roof-to-Wall Connection	High Frequency	High Frequency	High Frequency
Cripple Wall	X	Moderate Frequency	Moderate Frequency
Floor-to-Wall Connection	X	Moderate Frequency	Moderate Frequency
Wall-to-Foundation Connection	X	Moderate Frequency	Moderate Frequency
Flatwork	X	X	Low Frequency
Bracing Water Heater	X	X	Low Frequency
Exterior Insulation Finishing System (EIFS)	X	X	Low Frequency
Slope Stability and Hillside Construction	X	X	Low Frequency
Two-Story Vaulted Area	X	X	Low Frequency
Thin Brick Veneer Exterior Cladding	X	X	Low Frequency
Drag Struts and Drag Truss	X	X	Low Frequency
Chimney Anchoring	X	X	Low Frequency
Sinkhole Mitigation	X	X	Low Frequency

NEXT STEPS AND FUTURE RESEARCH

As resilient construction practices evolve, the one-pagers within this guide should be updated to reflect improvements or modifications. To improve the damage frequency metric, additional data are necessary beyond what is currently collected.

In a few reconnaissance reports, StEER has discussed correlating damage data and the year of construction as a way to illustrate whether the building code has improved house performance over time. The data for earthquake events are not as comprehensive as those for wind events, and the data do not identify specifically if the existing building was retrofitted to improve earthquake performance before an earthquake event occurred.

The State of California's Seismic Safety Commission publishes a document titled *Expected Earthquake Performance of Buildings Designed to the California Building Code*. The document states that "the California Building Code is a minimum requirement intended to protect life safety and prevent collapse. It allows damage, which means buildings may not be habitable or functional after a moderate or large earthquake." This understanding of the building code is important to note because resilience implies that damage is minimized or prevented such that the building remains habitable or functional after a moderate or large earthquake. Future research that explores the definition of resilience may need to develop design guidance beyond what currently exists.

Failure due to lack of load path. Source: U.S. Geological Survey

Damage Frequency

HIGH

Construction Practice

Use hold-down anchors to connect the walls to foundation, and use straps to provide lateral and uplift load continuity.

Mitigation Strategy

Reinforce continuous load path connections.

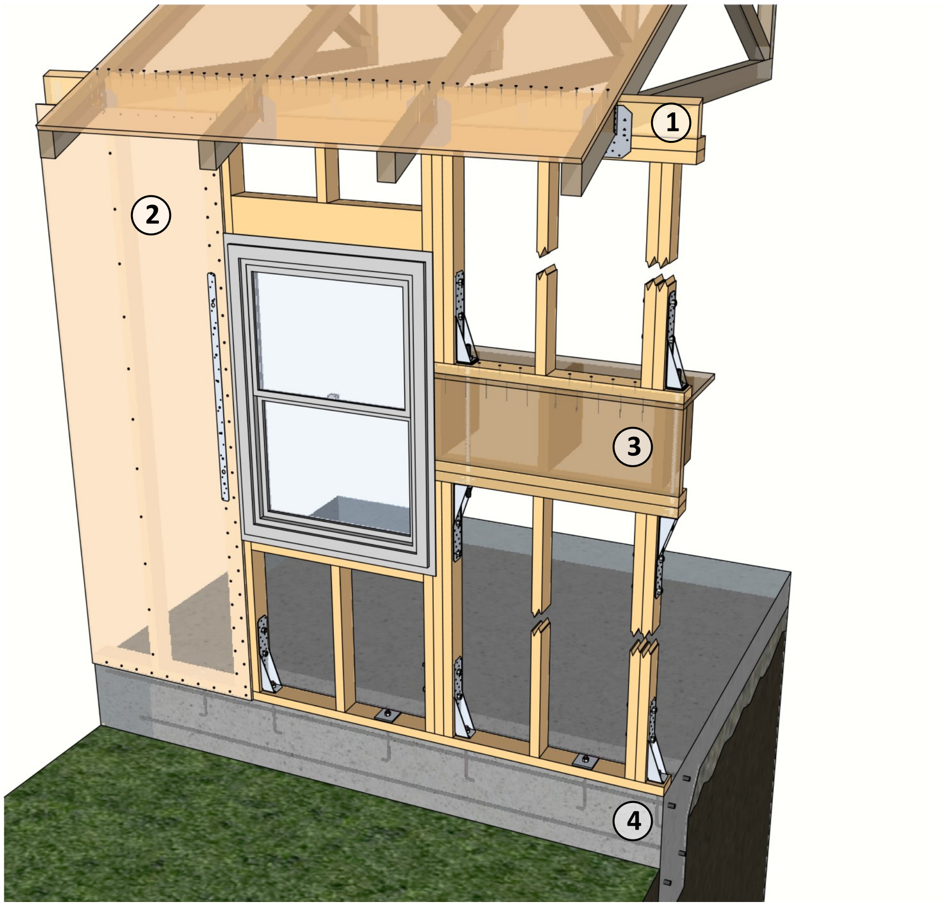
Cost & Benefit

Cost range to implement: $–$$

Benefit: Good connections that tie the floor, walls, and roof together provide continuity in the load path and more reliable building performance, therby avoiding the potential for major damage.

CONTINUOUS LOAD PATH

A continuous load path strengthens the structural components of a house by reinforcing connections. A home will fail due to earthquake at the weakest point in the load path. A continuous load path requires the following series of connections: the roof-ceiling system to the second-story bracing wall system; the second-story bracing wall system to the floor-ceiling system; the floor-ceiling system to the first-floor bracing wall system; the first-story bracing wall system to the foundation; and the foundation to the supporting soil.



1. Roof-to-wall connection
2. Sheathing reinforcement
3. Wall-to-floor connection
4. Wall-to-foundation connection

FOR SEISMIC AND WIND LOADS

GUIDANCE	DIFFICULTY	COST
Roof sheathing attachment: Increase the nailing to 4 in. at panel edges and 6 in. along intermediate supports (from a 6/12-in. pattern), and use deformed shank nails to increase withdrawal strength. [1]	Easy	$
Gable end walls bracing: Brace gable end walls at both the top and bottom, and ensure that they are properly attached to the roof and wall, respectively. [2]	Easy	$
Gable end walls sheathing: Sheathe all gable ends with wood structural panels that have the same performance category as the walls. This method helps resist wind loads and prevents projectile damage. [2]	Easy	$
Roof truss/rafter attachment: Attach roof framing member to the wall top plates with a fastener that resists loads in all three directions. Placing those fasteners on the exterior of the wall provides a more direct load path from the roof to the wall sheathing. [3,4]	Easy	$
Bracing of roof framing: Ensure that trusses and rafters, especially those with taller heels, are properly braced to transfer the loads from the roof to the walls. [5]	Easy	$
Connections between stories: Ensure that upper and lower floors are properly attached to resist uplift loads and create a solid lateral connection. Options for this detail include attaching wall sheathing from above and below to a common rim board, attaching a common sheathing panel that spans over the floor to a stud above and below, and metal strapping. [4]	Easy	$
Floor system design: Ensure that the floors are properly designed to resist all loads. Good practices include a tighter nailing pattern and sheathing all floors with plywood or oriented strand board (OSB). See the floor section for more information. [6]	Moderate	$
Wall system design: Ensure that walls are properly designed to resist all loads. Good practices include a tighter nailing pattern and sheathing all exterior walls with plywood or OSB. See the walls section for more information. [7]	Moderate	$
Wall-to-foundation connection: Attach sill plates to the foundation with ½-in. anchor bolts at 32–48 in. o.c. Provide a 3x3-in.-sq. plate washer at each anchor bolt. Ensure that the wall sheathing is attached to the properly anchored sill plate with the nailing pattern of the edge of the sheathing as required by the wall design. [4]	Easy	$
Alternate 1: See each key component for improvements.	Easy	$$
Alternate 2: Provide an engineered load path. [4]	Easy	$
Alternate 3: For overturning loads, using hold-down connectors (brackets, straps, etc.) is recommended as an above-code measure to improve load transfer and thereby decrease damage. For most of the basic IRC wall bracing types, the provisions rely on building weight and the fasteners resisting horizontal loads to also resist overturning. Wall component testing, however, indicates that this method is not as reliable in resisting overturning as using positive anchorage devices. [8]	Moderate	$$
Alternate 4: Provide engineered design per IBC, and possibly increase the importance factor to 1.5 or a fraction thereof. [9,10]	Moderate	$

RESOURCES

1. Roof Deck Sheathing and Sealing for Sloped Roofs. Building America Solution Center (BASC). 2020.
2. Lateral Bracing in Gable End Walls. BASC. 2020.
3. Table R602.3(1) Fastening Schedule. 2018 IRC.
4. Continuous Load Path Provided with Connections from the Roof through the Walls to the Foundation. BASC. 2020.
5. Section R602.10.8 Braced Wall Panel Connections. 2018 IRC.
6. Chapter 5: Floors. 2018 IRC.
7. Chapter 6: Wall Construction. 2018 IRC.
8. *Earthquake Resistant Design Concepts.* FEMA P-749. 2010.
9. ASCE 7-16 *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*.
10. Table 1604.5 Risk Category of Buildings and Other Structures. 2018 IBC.

Source: Seattle Department of Planning and Design - Earthquake Home Retrofit Handbook

POST AND BEAM CONNECTIONS

Post and beam construction is common in residential design. Typically, this term refers to where beams connect to posts or columns. Other types of post and beam connections are roof beams or girders to posts, deck beams to posts, and posts to footings. The building code requires that positive connections be "provided to ensure against uplift and lateral displacement" to minimize the chance of accidentally displacing columns that support beams or girders, which could happen during a seismic event.

Damage Frequency

HIGH

Construction Practice

Follow good framing practices to ensure that all posts have a positive anchorage to beam above and footing below, using mechanical anchors.

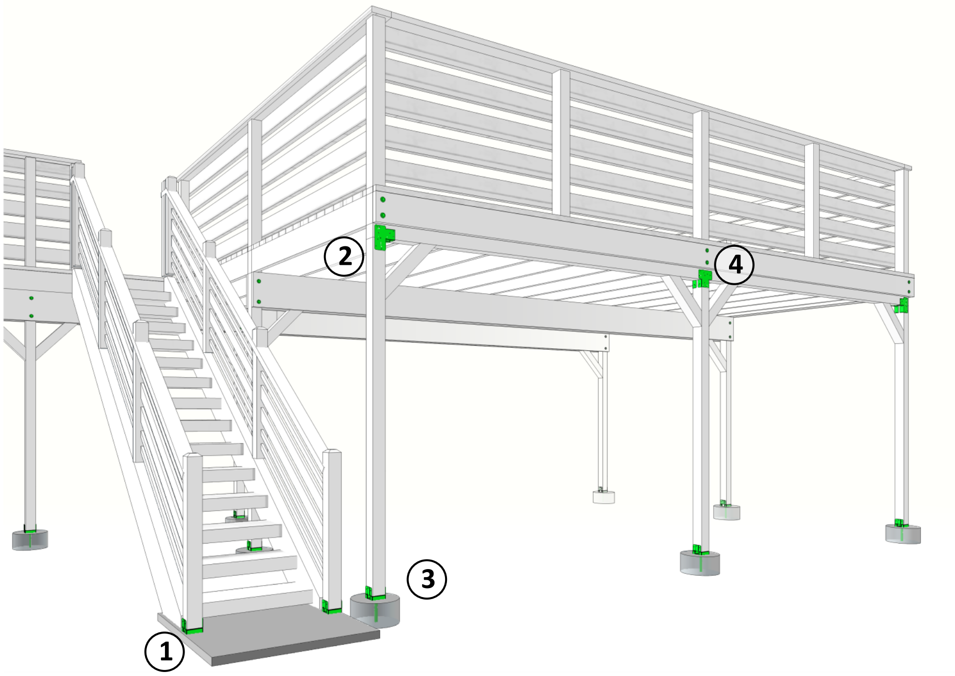
Mitigation Strategy

Provide reinforced connection for attaching beams to post, and anchor post to footing with column bases or angles for smaller posts.

Cost & Benefit

Cost range to implement: $–$$

Benefit: Ensuring that posts and beams are properly anchored together and firmly anchored to the foundation.



1. Post-to-foundation slab connector
2. Post-to-beam corner connector
3. Post-to-footing connector
4. Post-to-beam connector

GUIDANCE	DIFFICULTY	COST
Framing: Follow good framing practices to ensure that all posts have a positive anchorage to beam above and footing below. Avoid use of toenails. Use mechanical anchors, installed per the manufacturer's specifications. [1]	Easy	$
Deck ledger and rim joist connection: Anchor deck ledger to solid rim joist (do not use "I" joist as rim) at house with screws instead of nails, and provide lateral connection.	Easy	$
Post and footing connection: Anchor posts to footings with manufactured anchors, such as column bases or angles for smaller posts in crawl spaces. Deck posts may also be anchored to the foundation by embedding post in concrete. [2]	Easy	$
Attaching ledger to house: Properly attach deck ledgers that support deck to house to resist lateral and gravity loads. [3]	Easy	$
Alternate 1: Provide positive connections at all post-to-beam connections, as required by code. IRC allows no connection of posts to footings in Seismic Design Categories A, B, and C where posts are less than 48 in. in height in crawl spaces with floors fully enclosed by a continuous foundation. Construct decks per IRC. [4,5]	Easy	$
Alternate 2: Provide positive connections at all post-to-beam and post-to-footing connections. Ensure that decks are properly constructed. Ensure that patio roofs have beams anchored to house to resist loads in three directions (up, down, and pull-out or tension). [6]	Easy	$
Alternate 3: Use robust connections, such as attaching beams in walls on solid post with king stud nailed to each side of beam with six 16d nails or screws. Attach posts to bottom plates with light gauge angles. Use manufactured column caps and column bases for standalone posts and beams. Provide knee bracing or diagonals for lateral resistance at deck posts.	Moderate	$$
Alternate 4: Provide engineered design to ensure adequate connection detailing. [7]	Moderate	$

RESOURCES

1. Section R507.5 Deck Beams. 2018 IRC.
2. Section R507.3 Footings. 2018 IRC.
3. Section R507.6 Deck joists. 2018 IRC.
4. Section R407.3 and Commentary Figures R407.3 (1,2,&3). 2018 IRC.
5. Section R502.9 and Commentary Figure R502.9. R507. 2018 IRC.
6. DCA 6: *Prescriptive Residential Wood Deck Construction Guide (2015 IRC Version)*.
7. Section R301.2.2.2.6 Irregular Buildings. 2018 IRC.

Drywall crack.

DRYWALL (TO PREVENT CRACKS)

Reduce damage to drywall surfaces caused by earth movement. The practices below will reduce cracking during a mild seismic event and generally prevent cracking due to normal wood frame shrinkage and movement.

Damage Frequency

HIGH

Construction Practice

Screw and glue drywall to reduce damage caused by earth movement.

Mitigation Strategy

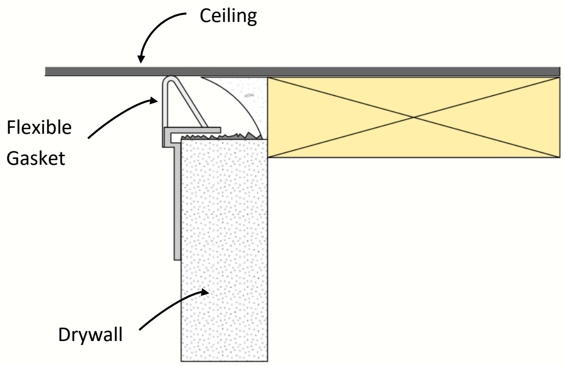
Follow proper drywall installation steps to avoid cracking due to lateral forces.

Cost & Benefit

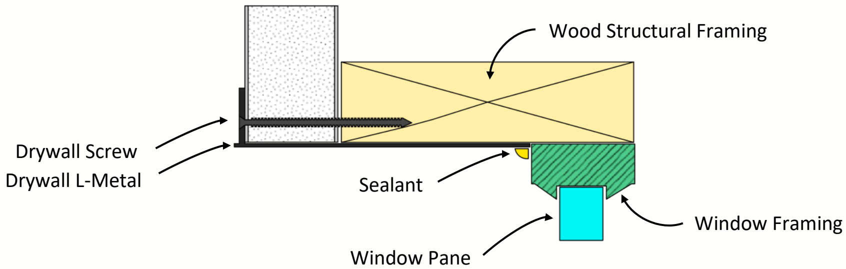
Cost range to implement: $–$$$

Benefit: Prevents excessive cracking due to seismic forces.

WALL TO CEILING



WALL TO WINDOW



GUIDANCE	DIFFICULTY	COST
Attaching drywall: Screw and glue drywall to framing. [1]	Easy	$
Openings: Avoid breaking drywall sheets at openings. Run boards across windows and openings and cut opening with a router so that no breaks occur at opening corners. At a minimum, notch drywall around doors and windows instead of breaking drywall at these movement-prone areas. If a joint must be at the corner of a window, door, or other opening, use wide mesh tape.	Easy	$
Gap: Leave a 1/8-in. gap between boards; do not butt boards tight against each other. This practice allows for minor movement between boards.	Easy	$
Gap: Leave a 1/8-in. gap between wall drywall and ceilings to fill with a flexible caulk or drywall deflection bead to absorb movement between structural components.	Easy	$
Edges: Always tape the edges of the corner bead. [2]	Moderate	$$
Flexible vinyl beads: Use a flexible vinyl bead at the apex of vaulted ceilings to prevent cracking at this susceptible location. Some products will allow as much as 3/8-in. movement without cracking.	Moderate	$$
Expansion joints: If drywall runs 15 ft. or longer, install a vinyl expansion joint. Several types exist, including fire-resistant varieties for use in rated assemblies. [3]	Moderate	$$
Drywall truss clips: At ceilings, consider using drywall truss clips or backing angle designed to pull ceiling drywall slightly down and away from trusses to minimize inside corner movement and thus prevent cracking due to both normal truss uplift and separation caused by earth movement. [4]	Moderate	$$
Surface textures: Avoiding surface textures can make repair work easier.	Moderate	$$$
Alternate 1: Consider upgrading to fiber-reinforced gypsum board or fiber tape used at joints.	Easy	$$

RESOURCES

1. Table R702.3.5 Application. 2018 IRC.
2. *Repair of Earthquake Damaged Concrete and Masonry Wall Buildings.* FEMA 308. 1998.
3. *Control Joint Placement in Gypsum Board Assemblies.* Wall and Ceiling Bureau (WCB).
4. RR-0107: Drywall, Wood and Truss Uplift, Building Science Corporation. 2001.

DESIGNING FOR NATURAL HAZARDS
A RESILIENCE GUIDE FOR BUILDERS & DEVELOPERS

Garage door damage.
Source: FEMA P-530

GARAGE OPENINGS

Portal frames for garage doors provide the added strength to resist lateral loads. They rely on robust movement-resistant connections where vertical supports connect to horizontal beams. In wood framing, the header is extended past the opening and tied to the narrow stud walls or piers. Plywood or oriented strand board (OSB) sheathing adds strength, with a tightly spaced nail pattern at the header, studs, and plates. The sill plate is anchored to the foundation with anchor bolts and hold downs to resist overturning.

Damage Frequency

HIGH

Construction Practice

Follow details in the IRC or APA construction details for Portal Frame with Hold Downs.

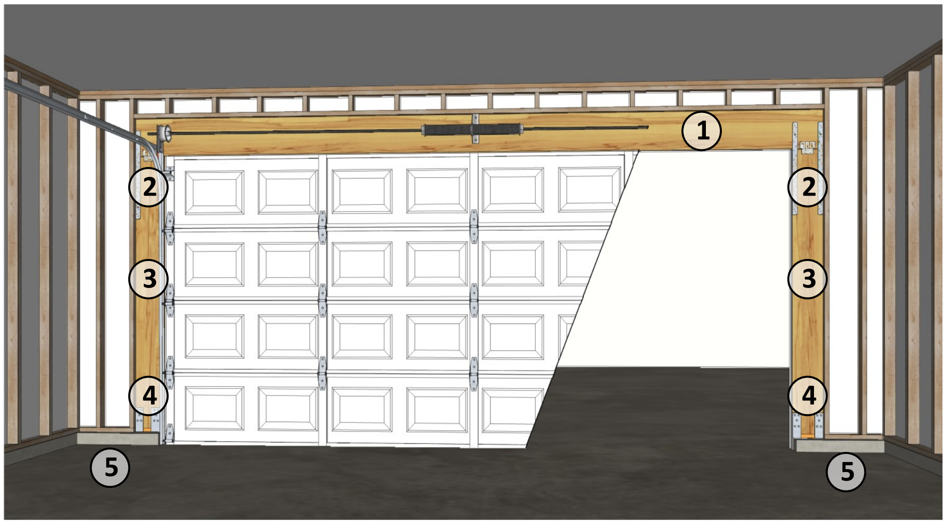
Mitigation Strategy

Proper installation of portal frame with hold downs and anchor bolts can minimize damage to a garage door.

Cost & Benefit

Cost range to implement: $–$$

Benefit: Portal frames require proper installation to perform as intended. Builders should pay attention to sheathing joints, nailing details, anchor bolts, and hold-down installation to avoid the potential for major damage.



1. Header
2. Header-to-jack stud strap
3. Portal frame
4. Foundation anchors
5. Foundation

GUIDANCE	DIFFICULTY	COST
Method PFG (Portal Frame at Garage door openings) without hold downs is allowed in Seismic Design Categories A, B, & C. [1]	Easy	$
Alternate 1: Method CS-PF (continuously sheathed portal frame) provides lateral resistance without hold downs but is limited in number of panels allowed. [2]	Easy	$
Alternate 2: Method PFH (Portal frame with hold downs) provides additional lateral resistance and is also used in engineered design. Increased strength may be achieved with wider garage piers and interior plywood or OSB sheathing. Ring shank nails may also add strength. [3,4]	Moderate	$$
Alternate 3: Wood or steel pre-engineered narrow wall solutions with calculated and tested design loads.	Moderate	$

RESOURCES

1. Section R602.10.6.3 Method PFG: Portal frame at garage door openings in seismic design categories A, B, and C. IRC 2018.
2. Section R602.10.6.4 Method CS-PF: Continuously sheathed portal frame. IRC 2018.
3. Section R602.10.6.2 Method PFH: Portal frame with hold-downs. IRC 2018.
4. *Homebuilders' Guide to Earthquake Resistant Design and Construction.* FEMA 232. 2006.

DESIGNING FOR NATURAL HAZARDS

A RESILIENCE GUIDE FOR BUILDERS & DEVELOPERS

Wall cracks.

Damage Frequency

HIGH

Construction Practice

Provide proper stud spacing, adequate nailing, continuous sheathing, and strong connection of walls to various building elements so the load can be transferred through the wall to the foundation.

Mitigation Strategy

Proper spacing, nailing, sheathing, and connection of walls to various elements of the building.

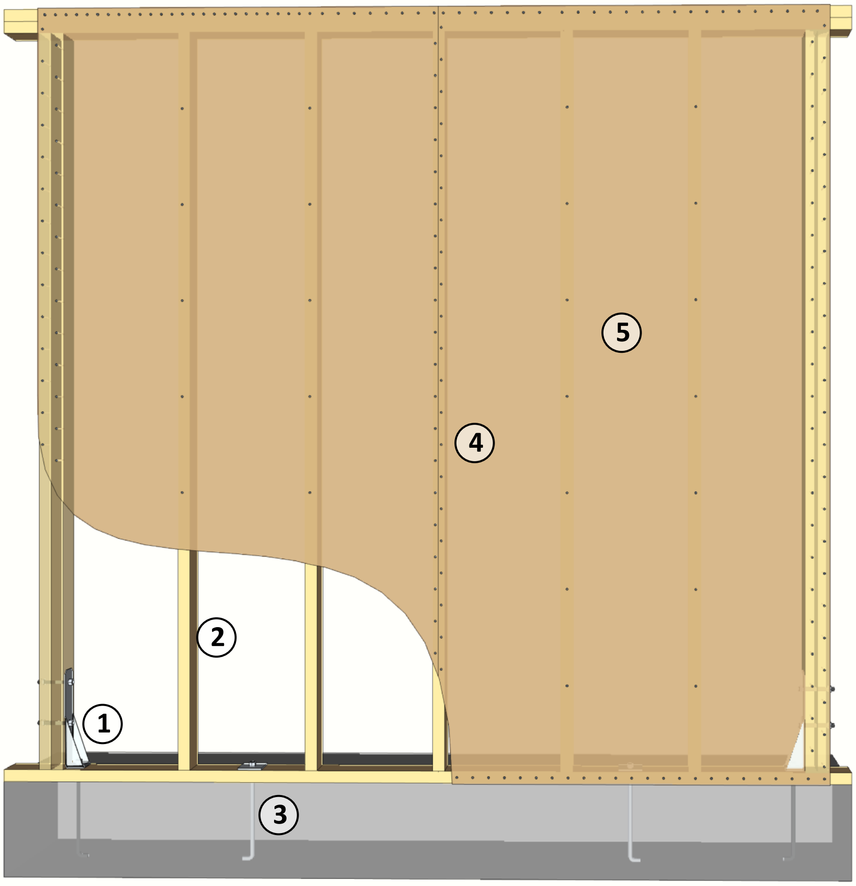
Cost & Benefit

Cost range to implement: $–$$$

Benefit: Good construction of exterior walls results in more reliable buildings that are better able to withstand seismic force.

EXTERIOR WALL CONSTRUCTION

Shear walls or braced wall panels resist the racking force that occurs during earthquakes. They transfer lateral loads or shear resulting from the weight of the roof and floors into the foundation. Shear walls or braced wall panels are walls covered with plywood or oriented strand board (OSB) sheathing. These sheathed walls resist the racking or in-plane shear forces by combining the plywood or OSB with strong nailing patterns, anchor bolts, and specialized hold-down anchors or straps at the base of the wall. These specialized anchors resist the tipping or overturning forces that occur at the ends of the braced wall panels and at the door and window jambs, and the anchor bolts transfer the shear force to the foundation.



1. Hold-down anchors
2. Wood framing
3. Base shear anchor bolts with plate washers
4. Nailing pattern
5. Wood sheathing

GUIDANCE	DIFFICULTY	COST
Wall studs: Provide studs with a maximum spacing of 16 in. o.c., and orient wall sheathing horizontally so the panels are applied with the long dimension spanning across the studs. Use ring shank nails with annular grooves to increase grip and withdrawal resistance.	Easy	$
Connection: Fasten sill plates to the foundation using anchor bolts. Provide edge nailing along the full height of studs, which are connected to hold-down anchors or straps. Provide special hold downs for narrow braced wall panels at each end to prevent them from tipping over or overturning in an earthquake. [1]	Easy	$
Sheathing: Fully sheathe the exterior walls with plywood. Sheathe interior walls, such as walls between garage and main house. [2]	Easy	$
Minimum recommendation: Use bracing requirements for Seismic Design Category C or higher. [3]	Easy	$
Alternate 1: Use bracing requirements for Seismic Design Category D. Use only the continuously sheathed wood panels method. [3,4]	Easy	$
Alternate 2: Avoid irregular building configurations, when possible, otherwise irregular buildings or irregular portions of buildings shall be an engineered design by a licensed design professional or engineer. [5]	Moderate	$$
Alternate 3: Provide engineered design using a segmented shear wall or perforated shear wall design. Use IBC and ASCE 7-16 and an importance factor of Ie = 1.0 minimum. Consider increasing the importance factor to Ie = 1.25 or Ie = 1.5 for increased seismic resistance. Note that Ie = 1.5 is equivalent to an essential facility that would remain operational after an earthquake. [6,7]	Moderate	$$–$$$

RESOURCES

1. Section 403 Footings. 2018 IRC.
2. Chapter 7 Wall Covering. 2018 IRC.
3. Section 602.10 Wall bracing. 2018 IRC.
4. Section 602.10.4.2 Continuous sheathing methods. 2018 IRC.
5. Section 301.2.2.6 Irregular buildings. 2018 IRC.
6. ASCE 7-16 *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*.
7. Table 1604.5 Risk Category of Buildings and Other Structures. 2018 IBC.

DESIGNING FOR NATURAL HAZARDS
A RESILIENCE GUIDE FOR BUILDERS & DEVELOPERS

Failure of gable wall.
Source: FEMA P-530

ROOF-TO-WALL CONNECTION

The roof-to-wall connection must resist gravity and "uplift" due to wind and sometimes earthquake thrusts. Builders can provide walls with resistance to these natural hazards through a combination of nailing and specialty framing anchors. To better understand the importance of the roof-to-wall connection, one can imagine the walls of a shoebox, which are weak and flimsy without a lid. Once the lid is placed on the shoebox, it is noticeably stronger. If one were to staple or glue the lid of the shoebox in place, the lid and the shoebox would act as a system and be even stronger. Residential roof-to-wall connections are similarly critical; if the connection fails in an earthquake, the building typically collapses.

Damage Frequency

HIGH

Construction Practice

Connect roof framing (trusses or rafters) to the walls using hurricane clips for uplift and framing anchors for lateral loads. Fasten the solid or truss blocking to wall using framing anchors.

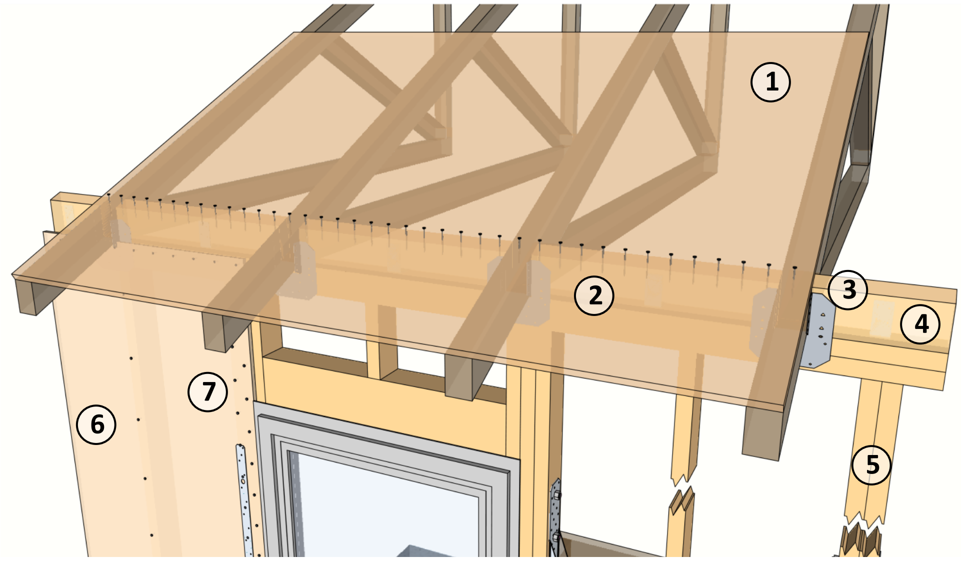
Mitigation Strategy

Enhanced connections improve structural performance.

Cost & Benefit

Cost range to implement: $–$$

Benefit: Good connections that tie the roof and walls together provide continuity in the load path and more reliable building performance, avoiding the potential for major damage.



1. Roof deck
2. Blocking between trusses
3. Roof-to-wall connector
4. Top plate
5. Wall framing
6. Wood sheathing
7. Nailing pattern

GUIDANCE	DIFFICULTY	COST
Framing connection: Connect roof framing (trusses or rafters) to walls using hurricane clips for uplift and framing anchors for lateral loads. [1]	Easy	$
Nailing: Nail the roof sheathing into solid or truss blocking located above the exterior wall and into the continuous fascia member using edge nailing. Fasten the solid or truss blocking to the wall using framing anchors. [2]	Easy	$
Sheathing: Fully sheathe gable end walls with plywood or OSB to provide load path from roof diaphragm to walls. Tie gable end walls back to structure. [3]	Easy	$
Alternate 1: Follow IRC fastening schedule, braced wall connection details, and roof uplift requirements. [4,5,6,7]	Easy	$
Alternate 2: Choose the highest seismic design category in IRC where possible. Provide a more robust connection at roof eave with solid blocking from the top plate to roof plywood and framing anchors rather than relying only on nails to transfer loads. [8]	Easy	$
Alternate 3: Some more robust hurricane clips can also resist lateral loads and uplift. Omitting the blocking might be possible. Run plywood up past the top plate and overlap with blocking to provide more direct shear transfer. This method requires a deeper heel truss and vertically placed blocking. For solid blocking, clip its corners for ventilation, drill holes, or omit every third space. Add blocking at roof diaphragm boundaries.	Moderate	$$
Alternate 4: Provide engineered design per IBC for additional strength, with increased importance factor to 1.5 equal to essential facility. [9,10]	Moderate	$

RESOURCES

1. Retrofit of Existing Roofs for Hurricane, High Wind, and Seismic Resistance. Building America Solution Center (BASC). 2021.
2. Section 802 Wood Roof Framing. 2018 IRC.
3. Framing of Gable Roof Overhangs. BASC. 2020.
4. Table R602.3(1) Fastening Schedule. 2018 IRC.
5. Section R602.10.8.2 Connections to roof framing. 2018 IRC.
6. Figures R602.10.8.2(1-3). 2018 IRC.
7. Section R802.11 Roof tie-down. 2018 IRC.
8. 2018 *International Residential Code* (IRC).
9. ASCE 7-16 *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*.
10. Table 1604.5 Risk Category of Buildings and Other Structures. 2018 IBC.

Damage to cripple wall.
Source: FEMA P-1045
Photo Credit: Estructure

Damage Frequency

MODERATE

Construction Practice

Construct cripple walls in accordance with the framed shear wall practice listed in this guide. Provide continuous sheathing and adequate nails.

Mitigation Strategy

Proper connection and continuous sheathing of cripple walls.

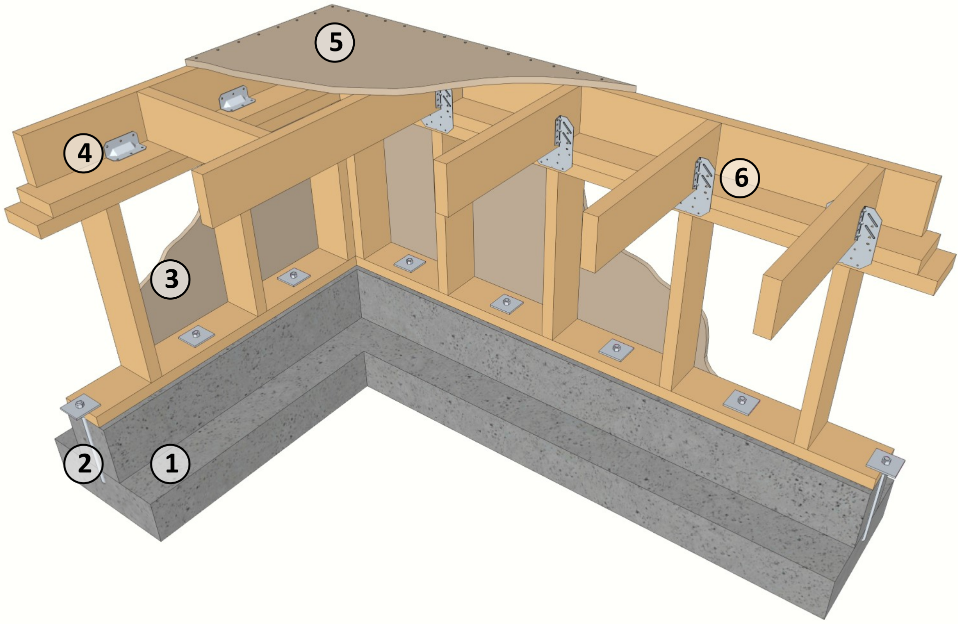
Cost & Benefit

Cost range to implement: $–$$

Benefit: Additional construction details can help prevent excessive damage.

CRIPPLE WALL

Homes may be supported by wood-framed cripple walls or pony walls on top of the foundation. Traditionally, these walls have not been fully sheathed or braced. In an earthquake, the cripple walls can rack or deflect horizontally, causing significant damage or collapse of the structure. To minimize failure of a cripple or pony wall, include sheathing, anchors to the foundation, and specialty framing connectors.



1. Foundation
2. Hold-down anchor
3. OSB or plywood sheathing
4. Sill plate-to-floor connector
5. Subfloor board
6. Floor-to-wall connector

GUIDANCE	DIFFICULTY	COST
Continuous sheathing: Construct cripple walls in accordance with the framed shear wall above. Ensure that they are fully sheathed and properly nailed. Provide continuous sheathing from the main-level walls to the sill plate below the cripple walls. If sheathing is not continuous, connect the rim joist to cripple wall top plate with properly sized and spaced framing anchors. [1]	Easy	$
Stud size and spacing: Match the size and spacing of the stud with the studs in the wall above. [1]	Easy	$
Top plate and sill plate: Provide double top plate and sill plate.	Easy	$
Anchor the sill plate to the foundation with anchor bolts that are properly sized and spaced. Use anchor bolts with plate washers to minimize cross-grain bending. [2]	Easy	$
Window and door jams: Place hold-down anchors or straps at the ends of the walls and at window and door jams.	Easy	$
Alternate 1: IRC code minimum requires cripple walls constructed with studs as framed above. Cripple wall bracing shall be as per the length and method of bracing used for the wall above. [1,3,4]	Easy	$
Alternate 2: Cripple walls should be fully sheathed with plywood or OSB on the exterior rather than just where the braced walls are above. These walls should be supported on a continuous foundation and anchored to the foundation with 5/8-in.-diameter anchors at 4 ft. o.c. min. Hold-downs should be placed at the foundation, and the cripple wall studs to which they are attached should be anchored to the studs above with straps of the same capacity to transfer the load between the cripple wall and the wall above. [5]	Easy	$
Alternate 3: Increase the number of anchor bolts and hold-down anchors. Add strength to sheathing attachment: use 10d nails at 4 in. o.c. at panel edges and 8 in. o.c. in the field.	Moderate	$$
Alternate 4: Sheathe inside face of cripple wall. [5]	Moderate	$

RESOURCES

1. Section R602.9 Cripple walls. 2018 IRC.
2. *Earthquake Safety at Home.* FEMA P-530. 2020.
3. Section R602.10.10 Cripple wall bracing. 2018 IRC.
4. Figure R602.11.2 Stepped Foundation Construction. 2018 IRC.
5. *Seismic Retrofit Guide*, Simpson Strong-Tie. 2007.

Failure of building wall and floor. Source: Mitigation Ideas (FEMA)

FLOOR-TO-WALL CONNECTION

The floor-to-wall connection must resist vertical gravity loads—such as the weight of someone standing on a floor—and the unusual stresses caused by high winds and seismic activity. Vertical loads are parallel to the wall; lateral, or horizontal, loads run perpendicular to the wall. Those forces are transferred through engineered nailing patterns to knit the wall and sometimes specialized framing anchors. These connections create a load path for both vertical and lateral forces. Once the floor-to-wall connection fails in an earthquake, the building typically collapses.

Damage Frequency

MODERATE

Construction Practice

Connect floor members to the walls using framing anchors, adequate nails with tighter spacing, and continuous sheathing.

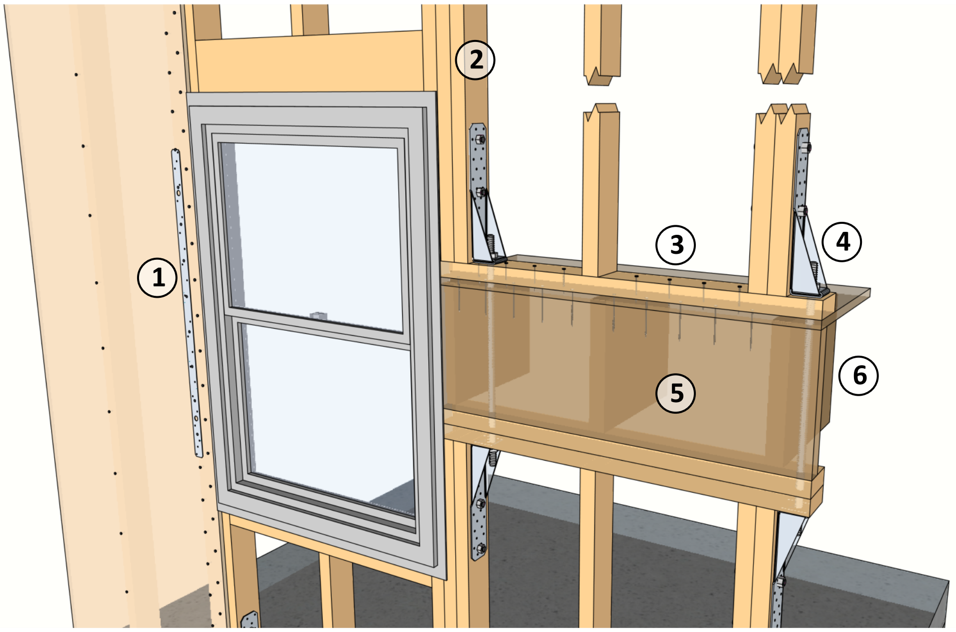
Mitigation Strategy

Provide adequate connection to floors and walls to resist vertical and lateral loads.

Cost & Benefit

Cost range to implement: $–$$$

Benefit: Good connection of floor to wall provides a continuous load path for better resistance to seismic force.



1. Hold-down strap
2. Wood framing
3. Floor sheathing edge nailing
4. Anchors
5. Band joist
6. Floor joist

GUIDANCE	DIFFICULTY	COST
Floor connection: Connect the floor joists to the walls using framing anchors to account for off-plane and lateral loads. When possible, fasten the boards to walls using specialized framing anchors that add strength. [1]	Moderate	$
Nail size and spacing: Reducing the nail spacing at a floor-to-wall connection can increase its strength, so will increasing the nail size and providing a blocked diaphragm (2x framing blocks installed between the joists to support all edges of sheathing panels) and increasing the size or type of framing anchor used. [2]	Easy	$
Sheathing joints: Run exterior wall panels, such as plywood or OSB, continuously on exterior walls, overlapping the rim board to tie the first and second story walls together. Nail the floor sheathing into blocking located above interior walls and into the continuous rim board above exterior walls. [2]	Easy	$
Minimum requirement: Follow IRC Fastening Schedule and Braced Wall Connections. [3,4]	Easy	$
Alternate 1: In the IRC, select Seismic Design Category D when possible. Provide edge nailing at all diaphragm boundaries. At exterior walls, run the sheathing continuously over rim joist. At overhangs and interior shear walls, provide framing anchors to join the floor joist or the rim to the wall's top plates. Provide a continuous load path. [5]	Easy	$
Alternate 2: Provide tighter nail spacing from floor plywood or OSB to joists. Block floor diaphragm at panel edges. [6]	Moderate	$$
Alternate 3: Provide engineered design for detailed load path connections. Use IBC to potentially increase the importance factor to 1.5. [7,8]	Complex	$$$

RESOURCES

1. *Wind Retrofit Guide for Residential Buildings.* FEMA P-804. 2010.
2. *Homebuilders' Guide to Earthquake-Resistant Design and Construction.* FEMA 232. 2006.
3. Table R602.3(1) Fastening Schedule. 2018 IRC.
4. Figures R602.10.8(1&2). 2018 IRC.
5. *Local Officials Guide for Coastal Construction.* FEMA P-762. 2009.
6. Section 2304.10 Connectors and fasteners. 2018 IBC.
7. ASCE 7-16 *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*.
8. Table 1604.5 Risk Category of Buildings and Other Structures. 2018 IBC.

Watsonville, California, 1989 Loma Prieta earthquake. Source: FEMA P-749: Figure 17

WALL-TO-FOUNDATION CONNECTION

The wall-to-foundation connections must resist gravity loads and uplift and horizontal forces due to high wind and seismic activity. In-plane forces are parallel to the wall, whereas out-of-plane forces are perpendicular to the wall. Those forces are transferred through nailing plywood or OSB panels on wall framing and into the bottom sill plate. Anchor bolts fasten the sill plate to the foundation, and specialty "hold-down" anchors or straps added next to openings and at the end of walls help to resist overturning. Once the wall-to-foundation connection fails in a high-wind event or earthquake, the building typically collapses, or the house can slide off the foundation wall.

Damage Frequency

MODERATE

Construction Practice

Connect the exterior walls to the foundation sill plate with the required nailing pattern using the prescribed wall edge nailing into the sill plate. Nailing into the treated sill plate requires fasteners that will not rust over time.

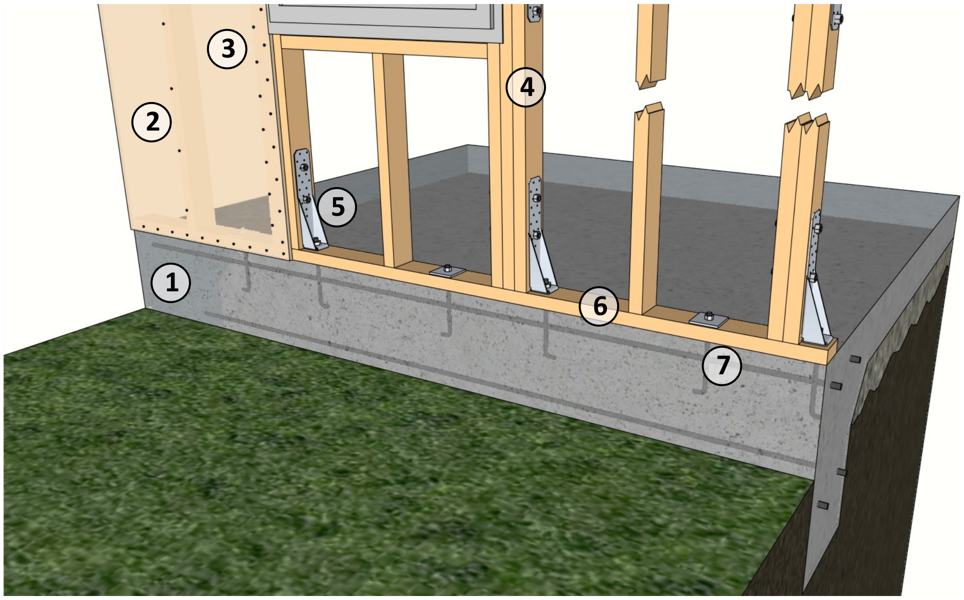
Mitigation Strategy

Connect exterior wall to foundation using hold-down anchors.

Cost & Benefit

Cost range to implement: $–$$$

Benefit: Good connections that tie the walls and foundation together provide continuity in the load path and more reliable building performance.



1. Foundation
2. Wood sheathing
3. Nailing pattern
4. Wood framing
5. Hold-down anchor
6. Sill plate
7. Hold-down anchor bolts

GUIDANCE	DIFFICULTY	COST
Nailing: Connect the shear wall to the sill plate with the required nailing pattern of the shear walls using shear wall edge nailing into the sill plate. Nailing into the treated sill plate requires fasteners that will not corrode over time. [1]	Easy	$
Anchor bolts: Use anchor bolts to fasten the sill plate to the foundation wall to prevent sliding, and use plate washers to prevent splitting. [2,3]	Easy	$
Hold-down anchors and straps: Install hold-down anchors or straps next to openings and at the end of walls to resist potential uplift. [2]	Easy	$
Alternate 1: Provide anchor bolts and hold-down anchors with the size and spacing to satisfy the IRC. Follow requirements for Seismic Design Category D. Minimum anchor bolts are typically ½-in. bolts at 4–6 ft. o.c. Hold-downs generally are required only at narrow braced walls less than 4 ft. wide and corners, as determined by prescriptive braced wall design. [4,5,6]	Easy	$
Alternate 2: Provide continuous sheathing with wood structural panels and anchor bolts with 3x3 plate washers, as required, at braced wall panels around the entire perimeter of the building. [4,5,6]	Easy	$
Alternate 3: Anchor bolt spacing, sheathing attachment. Using minimum anchor bolt spacing of 32 in. o.c., use 10d nails spaced to 4 in. o.c. at panel edges and 8 in. in the field. [7]	Easy	$
Alternate 4: Double hold-downs, bigger anchor bolts. Increase the number of hold-downs to braced wall panels that are less than 6 ft. wide. Increase anchor bolt size from 1/2 in. to 5/8 in. diameter. [8]	Easy	$$
Alternate 5: Increase the number of hold-downs and anchor bolts for 50-percent higher load, or next size up. Provide engineered design using the IBC, and select an importance factor of 1.5 or a fraction thereof. [9,10]	Easy	$$$

RESOURCES

1. Section 2304.10 Connectors and fasteners. 2018 IBC.
2. *Wind Retrofit Guide for Residential Buildings.* FEMA P-804. 2010.
3. Section 2308.3.1 Foundation plates or sills. 2018 IBC.
4. Section R403.1.6 Foundation anchorage. 2018 IRC.
5. Section R602.10 Wall bracing. 2018 IRC.
6. Section R602.10.6 Construction of Methods ABW, PFH, PFG, CS-PF, and BV-WSP. 2018 IRC.
7. Figure 2-7 Overturning Load Path Connections and Deformations. *Homebuilders' Guide to Earthquake-Resistant Design and Construction.* FEMA 232. 2006.
8. Figure R602.10.6.1 Methods ABW—Alternate Braced Wall Panel. 2018 IRC.
9. ASCE 7-16 *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*.
10. Table 1604.5 Risk Category of Buildings and Other Structures. 2018 IBC.

Flatwork cracks.

FLATWORK

Flatwork in construction refers to concrete poured on a horizontal plane and having a flat and smooth or even surface. Inside, it is the basement floor; outside, it is the patio, the walk, and the driveway. Interior and exterior, all flatwork is supported by the earth beneath, which is the vulnerability in earth-related events (sinkhole, landslide/mudslide/avalanche, erosion, liquefaction, surface rupture, settlement, collapsible soil, expansive soil, corrosive soil, freeze/thaw heaving). Concrete is good in compression but not in tension. If tension loads are a factor, welded-wire mesh or reinforcing bars can be added.

Damage Frequency

LOW

Construction Practice

Check for adverse soil condition. Compact soil, use reinforcement in slabs, and install control joints, expansion joints, and slip joints to avoid cracking.

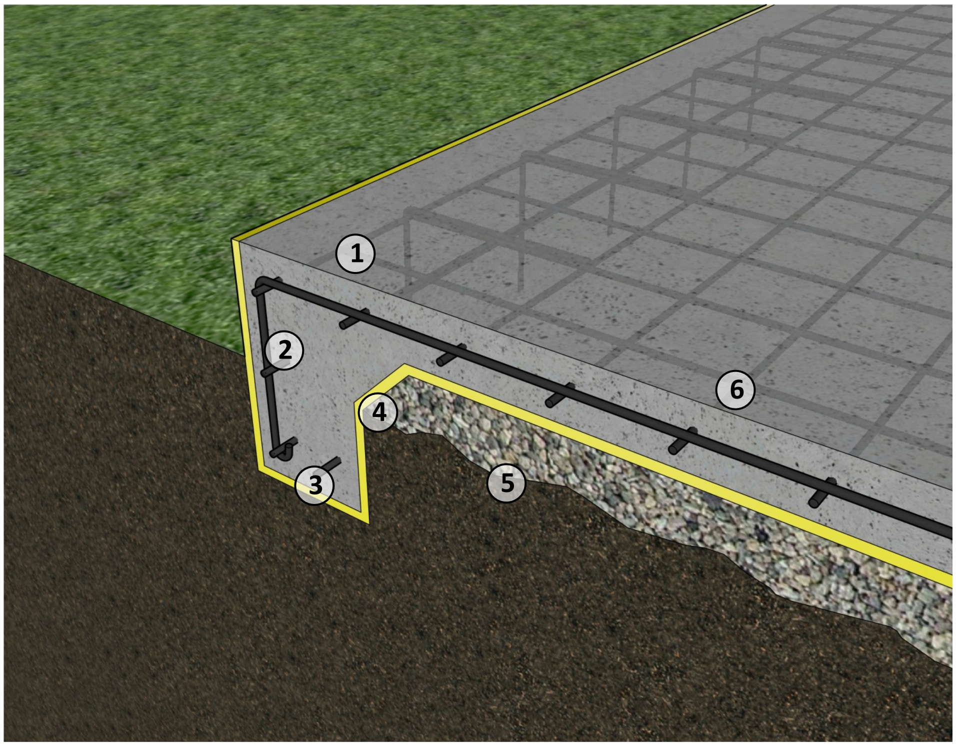
Mitigation Strategy

Compaction of soil and reinforcement of slab.

Cost & Benefit

Cost range to implement: $–$$$

Benefit: Avoids excessive cracking and appearance of large cracks due to lateral earth movements.



1. Concrete slab
2. Rebar
3. Footing
4. Vapor barrier under concrete
5. Compacted hardfill
6. Wire mesh

GUIDANCE	DIFFICULTY	COST
Soil compaction and concrete strength: Compaction of the soil, thickness of the concrete, and the compressive strength of the concrete mix are critical to the ability of the flatwork to support the weight and stresses imposed.	Easy	$
Tying slab to foundation: For interior slabs, in addition to reinforcing, consider tying the slab to the foundation walls to act as a diaphragm in an earth-related event. For exterior slabs at doors, consider tying to the foundation wall to avoid unwanted movement.	Moderate	$
Joints: Control joints, expansion joints, and slip joints may be installed to minimize the area of damage.	Easy	$
Alternate 1: Consult local officials, maps, and existing data for adverse soil conditions. [1,2]	Easy	$
Alternate 2: Consult a geotechnical engineer, and follow his or her advice. It could range from soil compaction to support piles driven to bedrock to locating elsewhere. [1,2]	Easy to Complex	$–$$$
Alternate 3: Add reinforcing to the slab, and provide connection to the foundation walls. The reinforcement could be welded-wire mesh, typically for a 4-in.-thick slab on grade, 6X6 W1.4XW1.4 placed 2 in. below the slab surface or in the upper 1/3, whichever is closer to the surface. Connect slab to foundation walls with no. 4 rebars at 48 in. o.c. [2]	Moderate	$$
Alternate 4: Engineered design for additional details and adding rebar for reinforcement. [2]	Complex	$$$

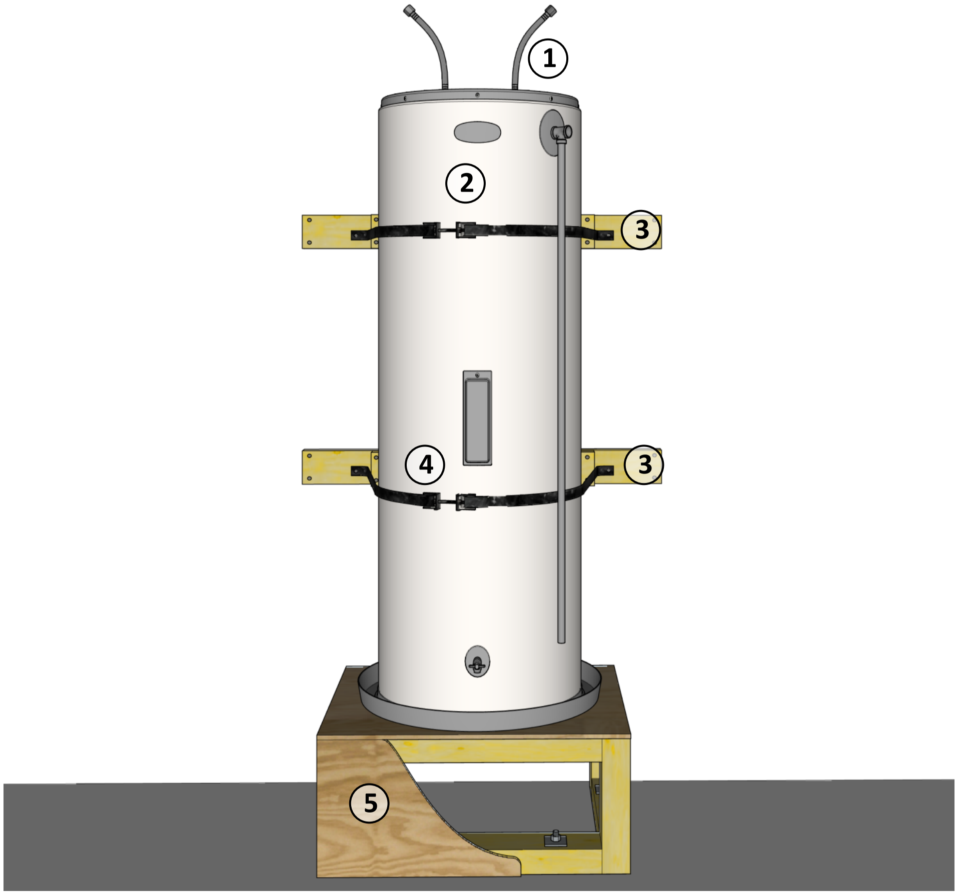
RESOURCES

1. Section R401 General. 2018 IRC.
2. *Homebuilders' Guide to Earthquake-Resistant Design and Construction.* FEMA 232. 2006.

Leakage following a water heater pipe break.

BRACING WATER HEATER

Free-standing water heaters can be damaged during an earthquake, which may result in a house fire, water damage, or carbon monoxide poisoning.



1. Flexible water connections
2. Hot water heater
3. Bracing connected to wall studs
4. ½-in.-diameter thin wall conduit with ends flattened
5. Raised support stand

Damage Frequency

LOW

Construction Practice

Anchor or strap the water heaters in the upper one-third and the lower one-third to resist a horizontal force equal to one-third of the operating weight of the water heater, acting in any horizontal direction.

Mitigation Strategy

Properly brace water heaters.

Cost & Benefit

Cost range to implement: $–$$$

Benefit: Good bracing of water heater and utilities makes them less likely to be damaged during an earthquake, which decreases the chances of house fire, water damage, and carbon monoxide poisoning.

GUIDANCE	DIFFICULTY	COST
Anchoring water heater: Anchor or strap the water heaters in the upper 1/3 and the lower 1/3 to resist a horizontal force equal to 1/3 of the operating weight of the water heater, acting in any horizontal direction. [1]	Easy	$
Alternate 1: Do not locate water heaters and critical equipment in garage or large openings that would create a significant risk of movement or collapse during an earthquake. Soft stories of the building are those with large, unreinforced building openings. Soft story is discussed in Garage Openings.	Easy	$
Alternate 2: Provide strapping and bracing. Water heaters ranging in size from 30 to 50 gallons require 2 straps. Water heaters in size from 75 to 80 gallons require 3 straps. Water heaters containing 100 gallons or more require 4 straps. Strapping must be placed properly: the top 1/3 and the lower 1/3 of the water heater must be strapped to prevent rocking and tipping. Cost range variance depends more on labor involved rather than materials. [2,3,4]	Easy to Moderate	$–$$
Alternate 3: Install a tankless hot water heater (one or several) to serve as the main hot water heater or as backup. Install close to source of use, in structurally sound location, with sufficient anchorage and bracing. [3]	Moderate	$$–$$$

RESOURCES

1. County of San Diego, Water Heater Strapping Requirements. 2014.
2. Chapter 5 Water Heaters, *California Plumbing Code* 2019.
3. *Homebuilders' Guide to Earthquake-Resistance Design and Construction.* FEMA 232. 2006.
4. *Guidelines for Earthquake Bracing of Residential Water Heaters.* Department of General Services, Division of State Architect, State of California. 2004.

Failure and damage to masonry cladding.

Damage Frequency

LOW

Construction Practice

Use metal mesh and allow base and finish coats to cure properly.

Mitigation Strategy

Use weather-resistive barrier (WRB), rigid foam, metal mesh, base coats, and finish coats.

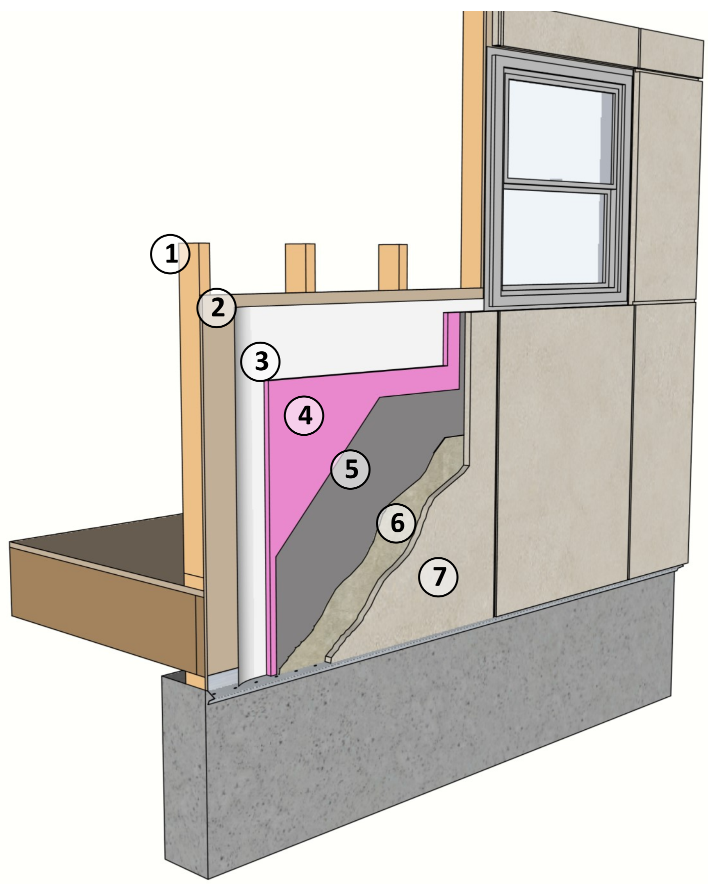
Cost & Benefit

Cost range to implement: $–$$

Benefit: An easy way to prevent extensive damage.

EXTERIOR INSULATION FINISHING SYSTEM (EIFS)

Builders can reduce damage to the exterior insulation finishing system (EIFS) caused by earth movement by adopting the following EIFS installation and finish practices. These practices will reduce cracking during a seismic event.

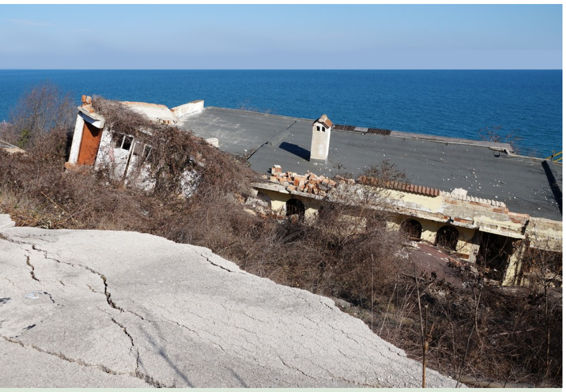


1. Wood framing
2. Wood sheathing
3. Weather barrier
4. Rigid foam insulation
5. Fiber mesh
6. Base coat
7. Finish coat

GUIDANCE	DIFFICULTY	COST
Exterior wall covering, lath, and plaster: Follow IRC 2018 R703 for base code reference. [1]	Easy	$
Framing: Strong framing techniques, including fully sheathed walls, will help prevent cracking of stucco and warping of other claddings. [2]	Easy	$
Lath: Use self-furring lath to ensure proper bedding of mortar.	Easy	$
Application: Allow scratch and brown coats to cure properly and completely between coats, especially before the color coat.	Easy	$
Curing: Damp mist walls while curing in hot weather.	Easy	$
Drainage plane: To preserve the integrity of the shear wall sheathing, apply two layers of weather-resistive barrier, the first as drainage plain and the second as a bond break. Some stucco lath comes with a double layer of paper. *Alternative:* One layer of WRB with 60-minute resistance with either an intervening draining space (3/16th) or an additional non-water-absorbing layer (10 min. grade D paper or foam sheathing). [2,3]	Easy	$$
Painting: After color coat, elastomeric paint can help bridge small cracks, with some paints capable of bridging cracks up to 0.06 in.	Moderate	$$
Casing beads: Use casing beads to isolate load bearing from non-load-bearing members, openings, and intersections between dissimilar materials. [3]	Moderate	$$
Control joints: Do not run lath across control joints; follow ASTM 1063, which states, "Lath shall not be continuous through control joints but shall be stopped and tied at each side." [4]	Moderate	$$
Control joints: Install control joints, following the recommendations of ASTM C1063, at least every 144 sq. ft. along large stucco surfaces, no greater than 18 ft. apart in any direction. [4]	Moderate	$$
Sealant gap: Provide a gap for sealants at casing bead and control joints to manage movement.	Moderate	$$

RESOURCES

1. Section R703 Exterior Covering. 2018 IRC.
2. Section R703.3 Wall covering nominal thickness and attachments. 2018 IRC.
3. Drainage for Stucco, JLC. April 2017.
4. ASTM C1063-22 *Standard Specification for Installation of Lathing and Furring to Receive Interior and Exterior Portland Cement-Based Plaster*.



Failure due to construction on an unstable slope.

Damage Frequency

LOW

Construction Practice

Conduct geological investigations, excavate, remove and recompact or import fill, and construct retaining walls where necessary.

Mitigation Strategy

Excavation and recompacting of soil where needed; if ground stability remains an issue, install retaining walls.

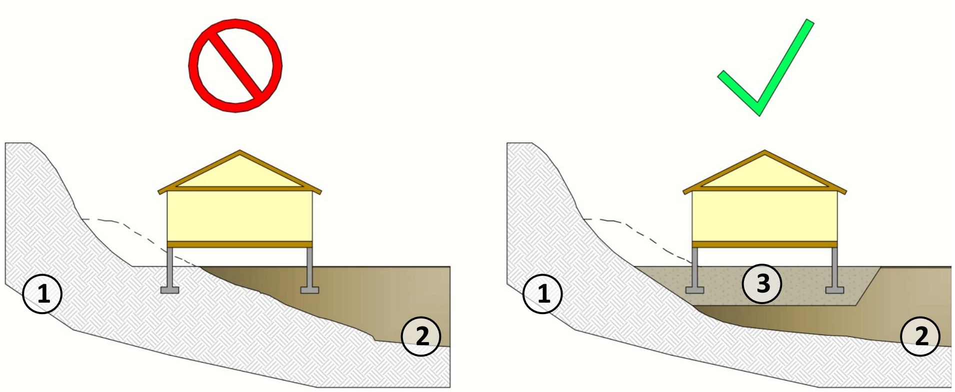
Cost & Benefit

Cost range to implement: $–$$$

Benefit: Avoids potential for major damage from ground movement.

SLOPE STABILITY AND HILLSIDE CONSTRUCTION

The most desirable building lots are often located on a hillside or sloping lot. Hillside construction poses many challenges and takes additional study, preparation, construction time, and costs. Potential problems may exist with slope stability. A home may be constructed on a slope where the ground is not stable. After the home is constructed on a sloping grade, the ground may become unstable and slide down the hill. The amount of movement depends on many variables, but even a small amount of movement can cause a significant amount of damage to a home and may even result in the site being condemned and the home having to be moved or demolished. Even if the ground under the home is stable, the sloping soil above the home may become unstable, slide, and destroy the home. Slope stability can be affected by the type of soil, the amount of slope, moisture, if the ground is disturbed by excavations, or if additional loads are added to it from construction. In some instances, entire neighborhoods have been condemned due to slope stability. Slope stability issues may not become apparent until an earthquake or heavy rain occurs. One should note that slope stability can be a localized failure confined to a smaller area, or it could be a global failure and affect a very large area, such as an entire neighborhood.



1. Cut rock
2. Existing soil material
3. Fill material

GUIDANCE	DIFFICULTY	COST
Engineered fill: If a home is to be constructed on a slope, construct the entire home on engineered fill material by over-excavating, removing and recompacting or importing fill as needed. [1]	Medium	$$
Alternate 1: Geotechnical investigations. Retain services of a geotechnical engineer to study the building lots and surrounding geological features, including hillside slopes, in conjunction with proposed construction. [2]	Easy	$
Alternate 2: Retaining walls designed to divert the mud around build site.	Complex	$$$

RESOURCES

1. *Homebuilders' Guide to Earthquake-Resistant Design and Construction.* FEMA 232. 2006.
2. Section 1803 Geotechnical Investigations. 2018 IBC.

Two-story vaulted area failure.

Damage Frequency

LOW

Construction Practice

The studs are continuous from top plate to sill plate at foundation to resist loads perpendicular to the walls. Wall sheathing is installed on the framing members.

Mitigation Strategy

Provide adequate structural design elements for tall walls.

Cost & Benefit

Cost range to implement: $–$$

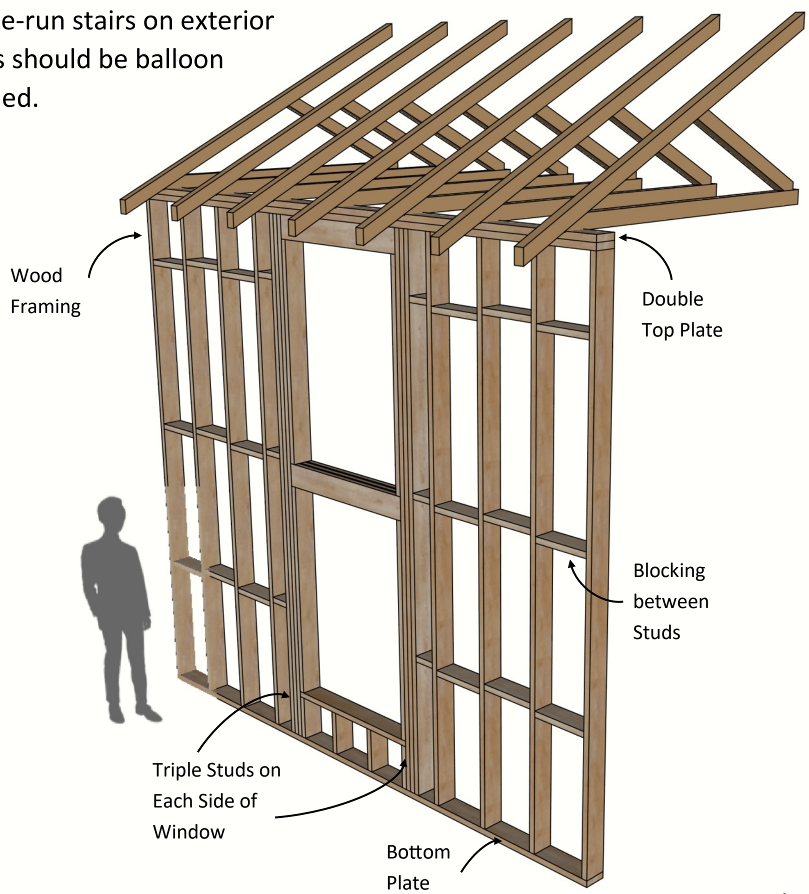
Benefit: Good connections that tie the floor, walls, and roof together provide continuity in the load path and more reliable building performance.

TWO-STORY VAULTED AREA

Two-story walls, such as those in a great room, can have a hinge point if not constructed correctly. Hinge points occur if the wall is "platform framed," similar to when a second floor is framed separately above the first floor, rather than "balloon framed." Balloon framing requires the studs to be continuous from the bottom of the wall to the top. For a vaulted area, a hinge point could also occur if the gable end wall is flat at the top rather than extending to the vaulted ceiling. Two-story walls may also occur when stairs are adjacent to exterior walls.

Some critical considerations include the following:

- Depending on the height of the wall, the stud size may need to be increased, the spacing of the studs may need to be decreased or both.
- Walls with large windows may require specific columns, headers, and connection detailing to provide a proper continuous load path.
- The typical "switch back" stairwell wall that is 8 ft. wide can usually be platform framed because the double top plate and bottom sole plate in the wall can span across the opening to resist out-of-plane loads. Single-run stairs on exterior walls should be balloon framed.



GUIDANCE	DIFFICULTY	COST
Wall studs: Ensure that studs are continuous from support at the sole plate (foundation or floor) to support at the top plate (ceiling diaphragm or roof sheathing) to resist loads perpendicular to the wall. [1]	Easy	$
Sheathing: Fasten wall sheathing directly to the framing members. [1]	Easy	$
Alternate 1: IRC limits stud height for exterior bearing walls to 10 ft. in regions with wind speeds greater than 130 MPH. For lower wind speeds with snow loads less than or equal to 25 psf, 2x6 studs supporting a maximum of 6 ft. of roof load can be 18 ft. tall if spaced at 16 in. o.c. and 20 ft. tall if spaced at 12 in. o.c. [1]	Easy	$
Alternate 2: At tall walls with windows, provide double or triple 2x6 studs on each side of windows. Provide angle connectors from window mullion studs to top and bottom plate in addition to code minimum nailing. [1]	Easy	$
Alternate 3: Sheathing interior face with plywood will add strength. Engineered design may be required for two-story walls that are bearing walls or have larger windows openings to ensure proper window mullion and header sizes and connections.	Moderate	$$
Alternate 4: Walls more than 18 ft. may require 2x8s or engineered lumber.	Moderate	$

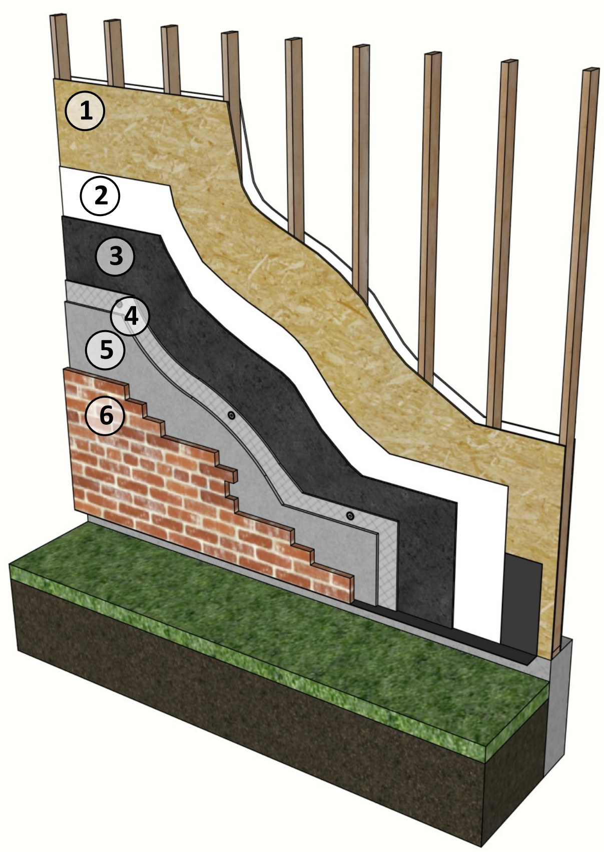
RESOURCES

1. Section R602.3 Design and construction. 2018 IRC.

Brick veneer damage.

THIN BRICK VENEER EXTERIOR CLADDING

Due to their rigidity, brick and masonry veneer represent two of the most vulnerable finishes on a wood-framed building. California Earthquake Authority Insurance does not cover brick veneer due to its high susceptibility to damage through earth movements. A tendency to break into rubble and fall creates a life-safety hazard during a seismic event. Limit installation to first story (not more than 20 ft.) over grade with veneer not exceeding 4-in.-thick. At a minimum, corrugated sheet metal ties used for connecting brick veneer to the wood backup should satisfy performance requirements, including sufficient strength and stiffness to transfer lateral loads, adequate transverse flexibility to accommodate differential movements, and resistance to corrosion and moisture.



1. Wood sheathing
2. Weather-resistive barrier
3. Drainage mat
4. Metal lath
5. 100 percent parsed backing to mesh
6. Adhered thin brick veneer

Damage Frequency

LOW

Construction Practice

Install masonry over sheathed walls; use brick and stone material substitutes, and substitute conventional brick ties with seismic anchor and straps.

Mitigation Strategy

Select suitable alternative material for exterior cladding and connect with seismic anchor and straps.

Cost & Benefit

Cost range to implement: $–$$

Benefit: Good attachment of brick veneer using a seismic anchor and straps minimizes the tendency to break into rubble and fall, creating a life-safety hazard during a seismic event.

GUIDANCE	DIFFICULTY	COST
Distance from finished exterior surface: Install adhered masonry veneer at a minimum of 4 in. above the earth, 2 in. above paved areas, or ½ in. above exterior walking surfaces that are supported by the same foundation that supports the exterior wall. [1]	Easy	$
Application: Use adhered masonry (such as thin brick or cultured stone) veneer over brown coat.	Easy	$
Installation surface: Always install masonry over sheathed walls because shear-wall sheathing with oriented strand board or plywood will provide a more rigid subsurface, less susceptible to movement and deformation (dynamic out-of-plane lateral loading). [2]	Moderate	$$
Alternate 1: Use polypropylene brick and stone substitutes.	Easy	$

RESOURCES

1. Section R703.12.1 Clearances. 2018 IRC.
2. *Brick Veneer/Wood Stud Walls*. Technical Notes on Brick Construction, The Brick Industry. November 2012.

Failure due to lack of drag struts.

Damage Frequency

LOW

Construction Practice

Ensure that interior shear walls have a load path to roof or floor diaphragms above by direct connection to the roof trusses or joists or provide blocking between the trusses or joists. Use double top plates with offset splices and proper nailing.

Mitigation Strategy

Follow good framing practices.

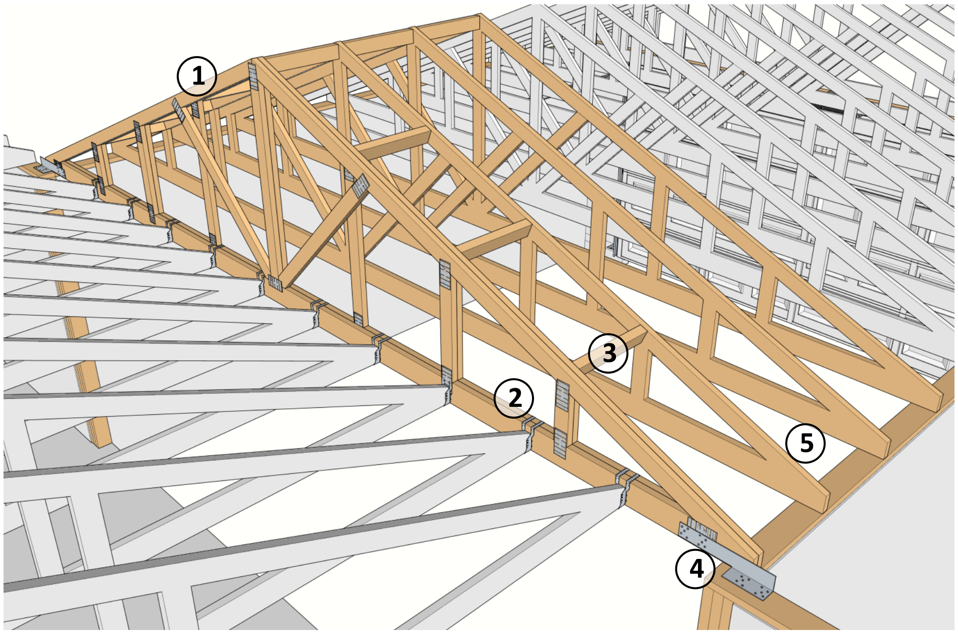
Cost & Benefit

Cost range to implement: $–$$

Benefit: Keeping building design simple without irregularities, such as re-entrant corners and large openings in the floor, could avoid the need of additional drag struts.

DRAG STRUTS AND DRAG TRUSS

Drag struts provide a path for lateral loads to be delivered to the lateral force-resisting elements. In wood-framed homes, common drag struts are “drag trusses” or collector trusses that connect the roof diaphragm to shear walls. Similarly, joists or blocking provide connections from the floor diaphragm to shear walls. The continuous header in a garage portal frame also functions as a drag strut to transfer loads across the garage door opening. Another important drag strut element is the double top plate of walls, which serves to distribute shear loads above windows and doors to adjacent shear walls. Drag struts are also used to tie together different parts of an irregularly shaped building, such as an L-shaped building with re-entrant or internal corners.



1. Girder (“drag”) truss
2. Truss hanger
3. Blocking
4. Drag strut connector
5. Truss

GUIDANCE	DIFFICULTY	COST
Interior shear wall connection: Ensure that interior shear walls have a load path to roof or floor diaphragms above by direct connection to the roof trusses or joists, or provide blocking between the trusses or joists.	Easy	$
Top plates: Use double top plates with offset splices with proper nailing. [1]	Easy	$
Critical zones: At critical zones, such as an opening in a floor diaphragm, detail the double top plates to have no splices.	Easy	$
Alternate 1: Keep homes simple and stay within parameters of IRC; avoid irregular buildings. [2]	Easy	$
Alternate 2: Follow good framing practices. Choose Seismic Design Category D when possible. [3,4,5,6]	Easy	$
Alternate 3: Provide engineered design with load path details for irregular building elements. [7]	Moderate	$$
Alternate 4: Use engineered design per IBC with the importance factor 1.5 or a fraction thereof. [8,9]	Moderate	$

RESOURCES

1. *Homebuilders' Guide to Earthquake-Resistant Design and Construction*. FEMA 232. 2006.
2. Section R301.2.2.6 Irregular buildings. 2018 IRC.
3. Table R602.3(1) Fastening Schedule. 2018 IRC.
4. Section R602.3.2 Top plate. 2018 IRC.
5. Section R602.10.8 Braced wall panel connections. 2018 IRC.
6. Figures R602.10.8(1&2). 2018 IRC.
7. *Earthquake-Resistant Design Concepts: An Introduction to the NEHRP Recommended Seismic Provisions for New Buildings and Other Structures.* FEMA P-749. 2010.
8. ASCE 7-16 *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*.
9. Table 1604.5 Risk Category of Buildings and Other Structures. 2018 IBC.

Chimney failure.
Source: FEMA P-530 courtesy of National Geophysical Data Center

Damage Frequency

LOW

Construction Practice

Construct chimneys of reinforced masonry, reinforced concrete, or wood frame.

Mitigation Strategy

Proper framing and sheathing for wood-framed chimney chase, provide sufficient ties for brick veneer in chimneys, and follow code for reinforced masonry or concrete chimney chase.

Cost & Benefit

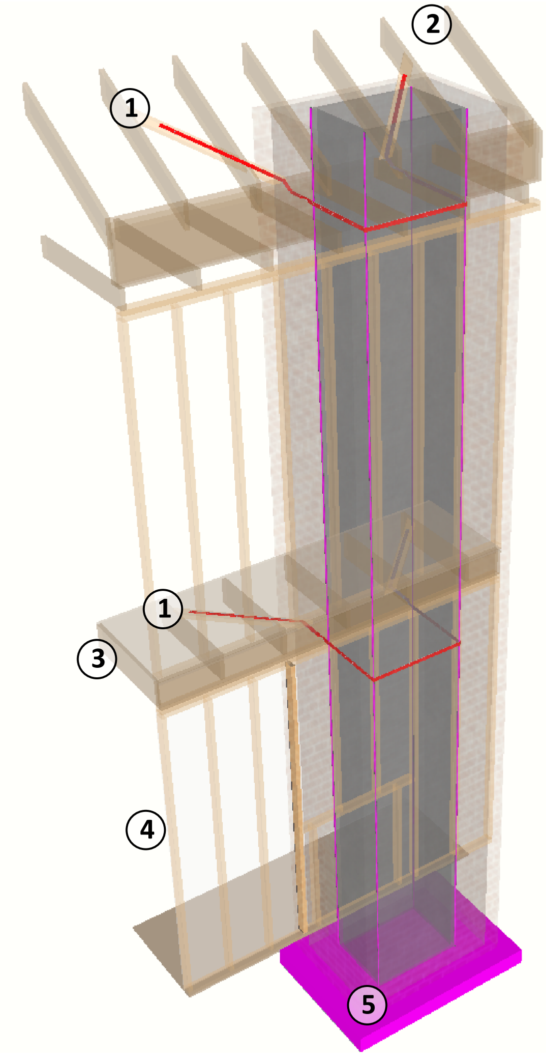
Cost range to implement: \$–\$\$

Benefit: Good connections that tie the chimney to the roof provide continuity in the load path and minimize damage of chimneys during seismic events.

CHIMNEY ANCHORING

Chimneys have a history of significant damage and collapse during earthquakes. The debris can cause personal injury, block exits, and cause additional damage to the building structure.

Use a wood-framed chimney where possible to reduce lateral loads, and anchor it properly to the framing.



1. Anchoring straps for chimney bolted to blocking
2. Roof truss framing
3. Floor framing
4. Wall framing
5. Concrete slab for supporting chimney

GUIDANCE	DIFFICULTY	COST
Anchoring chimneys: Anchor all chimneys to the floor framing and ceiling/roof framing. [1]	Moderate	$–$$
Floor and roof frames blocking: Block floor and ceiling/roof framing and double up members as needed to accommodate anchoring the chimney. [2]	Moderate	$–$$
Alternate 1: Masonry or concrete chimney: Reinforce masonry or concrete chimneys in Seismic Design Category D0, D1, or D2 and strap the chimney to the floor, ceiling, roof structures, using a continuous load path. [3,4]	Easy	$
Alternate 2: Wood frame chimney chase: Use wood-framed chimney chase to reduce lateral loads where possible. Incorporate a continuous load path.	Easy	$
Alternate 3: Chimney with brick veneer: Provide additional ties to connect the brick veneer to the building framing to help prevent or minimize the brick veneer from spalling off the chimney.	Moderate	$$

RESOURCES

1. Hurricanes and Wind Overview, Building America Solution Center (BASC). 2020.
2. *Homebuilders' Guide to Earthquake-Resistant Design and Construction.* FEMA 232. 2006.
3. Section R1001 Masonry Fireplaces. 2018 IRC.
4. Section R301.1 Application. 2018 IRC.

Sinkhole damage.
Source: U.S. Geological Survey

Damage Frequency

LOW

Construction Practice

Conduct tests for studying the probability of sinkholes, provide proper drainage, collect rainwater, and avoid excessive irrigation.

Mitigation Strategy

Test for geological condition of the soil.

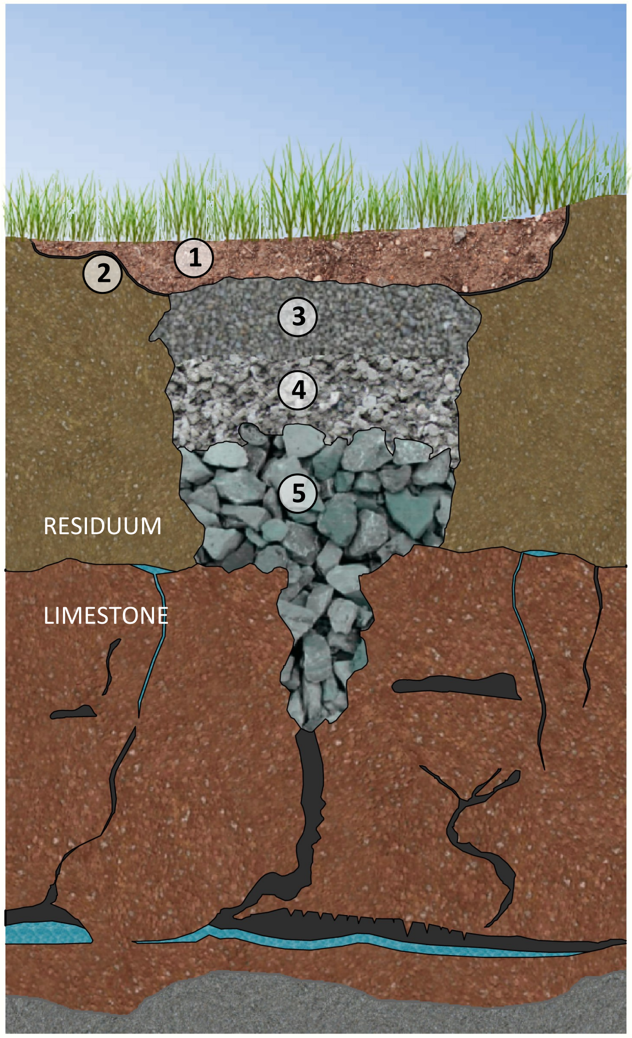
Cost & Benefit

Cost range to implement: $–$$$

Benefit: Avoids potential for major damage due to soil movement.

SINKHOLE MITIGATION

Predicting or preventing naturally occurring sinkholes is difficult. Sinkholes caused by human activity can be prevented by maintaining the integrity of irrigation systems and water lines, not over pumping groundwater for irrigation, and avoiding changes to natural drainage that carries surface water away from developed areas. Soils and geological studies can predict the potential for sinkhole events in areas with high propensity. Sinkholes can occur in almost all regions of the United States, although they are rare in most places.



1. Topsoil or fill material
2. Landscaping fabric
3. 1 in. to 4 in. gravel
4. 4 in. to 8 in. gravel
5. 8 in. to 12 in. gravel

GUIDANCE	DIFFICULTY	COST
Geotechnical study: Before developing, a geologist or geotechnical engineer can conduct a sinkhole study as part of the construction engineering to determine the probability of sinkhole development. These tests may include ground-penetrating radar or electrical resistivity surveys and soil borings. [1]	Easy	$$$
Drainage: Builders should provide proper drainage during construction and avoid collecting rainwater in detention ponds without an outlet. Water leaching down through the soil and into the bedrock can cause the erosion of bedrock, leading to the creation of sinkholes. [2]	Easy	$
Irrigation control: Control irrigation to avoid overwatering and avoid overpumping groundwater if a groundwater irrigation system exists. Maintain a vegetative cover over undeveloped land.	Easy	$
Positive drainage: Maintaining positive drainage around structures and avoiding areas where water will collect without an outlet will help new developments avoid sinkhole occurance for future homeowners.	Easy	$
Water mitigation: On susceptible soils, piles and other construction methods will support buildings to bedrock below the water table. A layer of clayey soil can help mitigate water leaching through surface soils but should only be done with supervision of a soil specialist to avoid expansive soils.	Complex	$$$
Avoid constructing over known sinkhole.	Easy	$

RESOURCES

1. FAQ: I have (or think I have) a sinkhole on my property. What should I do? www.usgs.gov.
2. *Erosion and Sediment Control Pollution Program Manual*, Pennsylvania Department of Environmental Protection. 2012.

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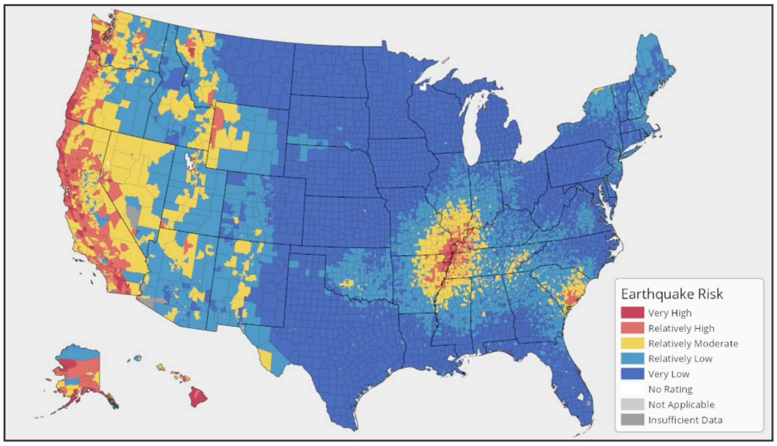

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