

Seismic Retrofit Guidelines for Detached, Single-Family, Wood-Frame Dwellings

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FEMA

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Chapter 2

Basics of Seismicity, Wood-Frame House Construction, and Seismic Resistance

This chapter provides a basic overview of seismicity in the United Sates, and of the typical types of wood-frame houses and how they resist earthquake forces. It is intended primarily for homeowners and contractors who have little experience with seismic retrofit work. Additional information is available in the documents referenced in Chapter 1 and in the list of References.

2.1 Seismic Hazards in the United States

The map in Figure 2-1shows the earthquake shaking hazard levels in the United States. More detailed maps are provided in the companion FEMA P-50

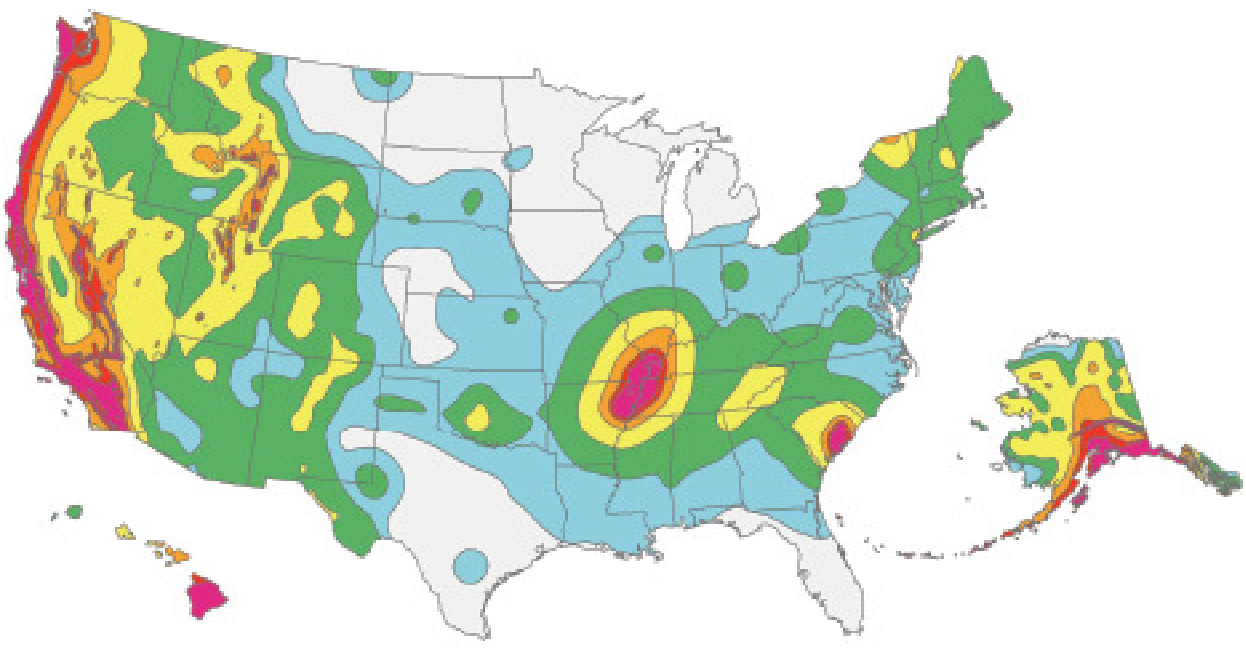


Figure 2-1 Seismic hazard map of the United States. Colors represent ranges of horizontal ground shaking, with grey representing the lowest hazard and pinkish-red representing the highest hazard. More detailed maps of acceleration response, S_{cs}, the parameter referred to in Table 1 of the Simplified Seismic Assessment Form, are provided in the companion FEMA P-50 report. (Source: U. S. Geological Survey.)

report, *Simplified Seismic Assessment of Detached, Single-Family, Wood-Frame Dwellings* (FEMA, 2012) and in the ASCE/SEI 7 and IRC documents. The latter two documents provide the basis for the seismic provisions of most state or local building codes. The shaking hazard for your home location can be obtained from the U.S. Geological Survey (USGS) Seismic Design Maps website: (https://geohazards.usgs.gov/secure/designmaps/us/). This procedure is described in detail in Table 1 in the Simplified Seismic Assessment Form (Figure 1-3).

The shaking experienced by a building is also affected by the soil under the foundation. Buildings founded directly on bedrock will shake with an acceleration similar to that of the bedrock beneath. However, buildings founded on deep soft sedimentary soils over the bedrock will experience horizontal shaking acceleration amplified by as much as five times, potentially causing more damage. An analogy is to consider a bowl of gelatin dessert being shaken; the gelatin dessert moves more than the bowl. Your building jurisdiction (local building department) may have information on soil types within the jurisdiction. An engineer designing a new building or a building seismic retrofit in accordance with the locally adopted version of the IBC will use this soil information and the bedrock shaking level to calculate the design seismic force.

2.2 Wood-Frame House Foundation Configurations

As explained more fully in Section 2.3, earthquake inertial forces accumulate in the upper parts of the building and are resisted at the foundation. The forces are larger near the foundation, and thus most earthquake damage occurs in the wood-framing adjacent to the foundation. The configuration of this framing at the foundation is critical to the seismic resistance of the dwelling.

There are four predominant configurations for supporting a wood-frame house on its foundation:

- cripple-wall crawl space,
- basement (crawl space with no cripple-wall),
- slab-on-grade, and
- post-and-pier.

A fifth common house configuration, the split-level house, is usually a combination of a slab-on-grade and a cripple-wall house configuration. Houses may have other combinations of elements of the different configurations as a result of remodeling or other considerations.

2.2.1 Cripple-Wall Crawl Space Houses

In a cripple-wall house, there is a perimeter foundation of unreinforced or reinforced concrete, brick or stone masonry, or concrete block. This perimeter foundation typically comprises a stem wall supported by a wider footing. The stem wall supports the bottom sill plate, or 'mudsill', of a short wood stud wall called the cripple, or pony, wall. The cripple wall encloses the crawl space, and supports the perimeter of the first floor. The construction of wood stud walls and floors then continues up to the roof. The minimum height of the crawl space is usually 18 inches. On a sloping site, the maximum crawl space height depends on the slope. Typically, the crawl space remains an unfinished utility space. Figure 2-2 is a section drawing through a typical cripple-wall crawl-space house. Note that, away from the perimeter cripple wall, the floor joists are supported by beams resting on posts set into concrete pier footings. Figures 2-3 and 2-4 are photographs of typical cripple-wall houses.

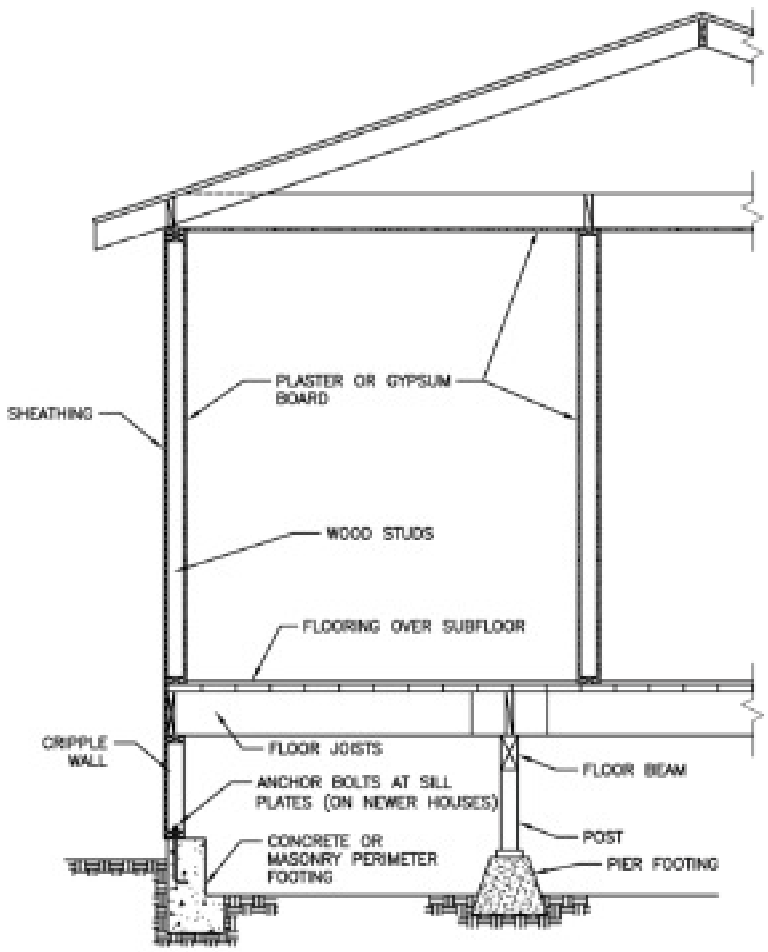


Figure 2-2 Section through typical cripple-wall crawl-space house (from ATC, 2002).

Figure 2-3 Typical one-story cripple-wall crawl-space house (from ATC, 2002).

Figure 2-4 Typical older one and one-half-story cripple-wall crawlspace house (from ATC, 2002).

Two common seismic vulnerabilities in cripple-wall houses are the insufficient strength of the cripple wall exterior sheathing and the lack of anchor bolts between the cripple wall sill and the foundation. The exterior sides of cripple walls are usually sheathed with stucco (with or without structural sheathing underneath), sawn wood siding, exterior finish structural panel sheathing, or other material. Figure 2-5 shows typical earthquake damage to a cripple wall, due to insufficient strength of the cripple wall

Figure 2-5 Typical earthquake damage to a cripple-wall house (from ATC, 2002).

stucco-only sheathing. It is also common for the posts to shake out, leaving the beams and joists with no support.

2.2.2 *Slab-on-Grade Houses*

A slab-on-grade house has a foundation formed by a cast-in-place concrete slab that lies directly on the leveled and compacted soil. Most of this foundation is a ground floor concrete slab of about four-inch thickness. At the perimeter, and often at the location of selected interior load-bearing walls, this slab is thickened to 12″ to 18″ to form a deeper footing. The slab and thickened footing are usually reinforced with steel reinforcing bars or two-way steel wire fabric. Sometimes, the slab is reinforced with sleeved pre-stressing steel tendons that are post-tensioned and anchored after the concrete has cured. Anchor bolts cast into the slabs and footings or shot-in nails connect the interior and exterior wood-frame stud walls to the slab and foundation. Interior stud walls are usually sheathed with gypsum board or plaster. Exterior walls are usually sheathed with gypsum board or plaster on the interior faces, and with stucco (with or without structural sheathing underneath), sawn wood siding, exterior finish structural panel sheathing, or other material on the exterior faces. Similar wood-frame construction proceeds upwards for the desired number of stories, with wood joists supporting the elevated floors. Figure 2-6 is a transverse section through a typical one-story slab-on-grade house. Figures 2-7 and 2-8 are typical photos of one and three-story slab-on-grade houses.

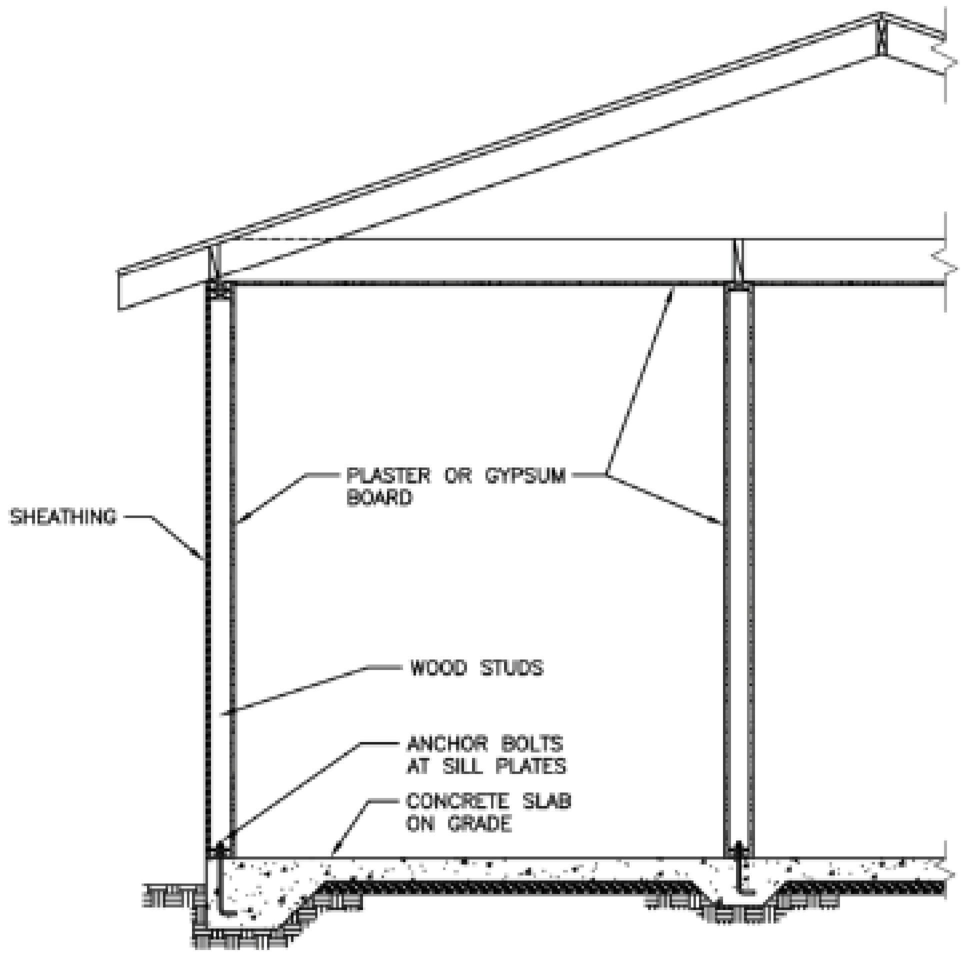


Figure 2-6 Section through typical one-story slab-on-grade house (from ATC, 2002).

Figure 2-7 Typical one-story slab-on-grade house (from ATC, 2002).

Figure 2-8 Typical three-story slab-on-grade house (from ATC, 2002).

A common seismic vulnerability in some two-story and many three-story slab-on-grade houses is the insufficient lateral-force-resisting strength of the first floor exterior and interior walls due to the large number of door and window openings in these walls and the limited strength of the sheathing materials. Figures 2-9 and 2-10 show typical earthquake damage to the first-story walls.

Figure 2-9 Cracking damage at the window to stucco first-floor walls of a two-story slab-on-grade house (from ATC, 2002).

Figure 2-10 Damage and racking displacement to the right in the first floor walls of a two-story slab-on-grade house (from ATC, 2002).

2.2.3 Basement Houses (Perimeter Foundation with no Cripple Wall)

The vertical-load-bearing elements of basement houses begin with full-height perimeter concrete or masonry basement walls founded on a concrete perimeter footing. A concrete slab is usually placed between these walls to form the basement floor. A wood sill plate supporting the first floor joists is placed on the top of the perimeter basement wall, and the wood-frame construction then proceeds upwards for the desired number of stories. Figure 2-11 is a section through a typical one-story basement house.

Figure 2-12 is a section through a crawl space house that is similar to a basement house. The perimeter walls are shorter, as they enclose a crawl space rather than a full-height basement. This configuration differs from a cripple-wall house in that the perimeter foundation walls enclosing the crawl space are of concrete or masonry rather than wood framing.

A common seismic vulnerability in basement houses is the lack of anchor bolts between the sill plate and the basement wall. Figure 2-13 shows a house of this type that was damaged in the 1992 Cape Mendocino earthquake in California as the sill plate slid along the top of the foundation wall.

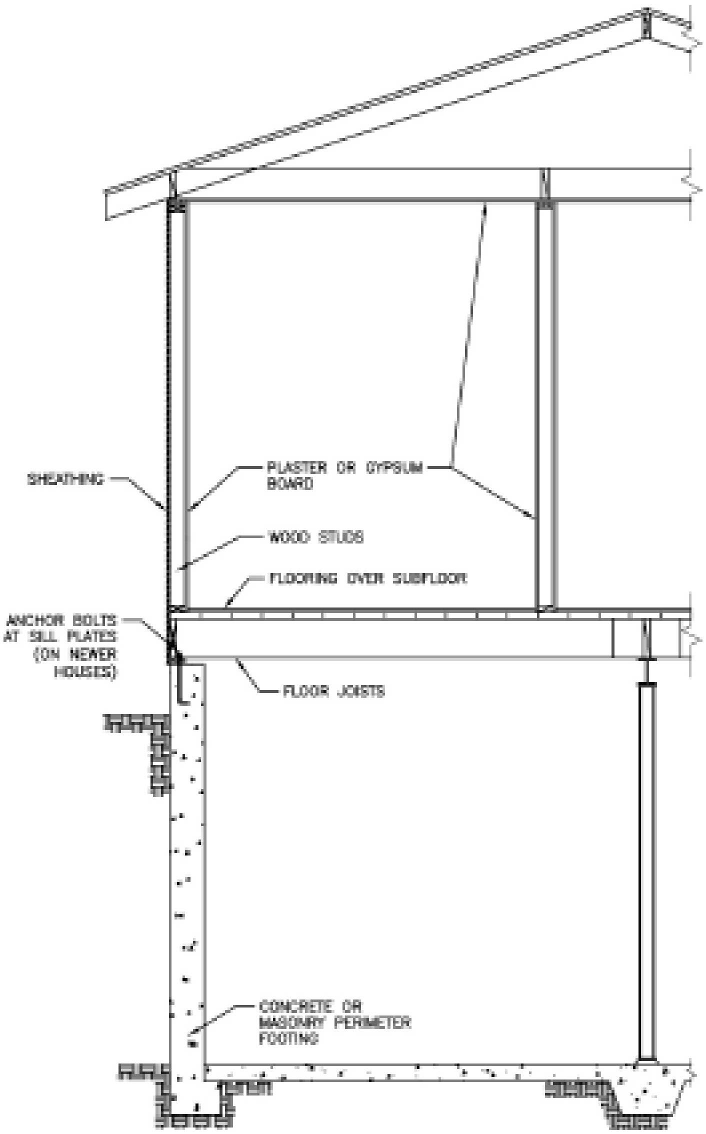


Figure 2-11 Section through a typical one-story basement house (from ATC, 2002).

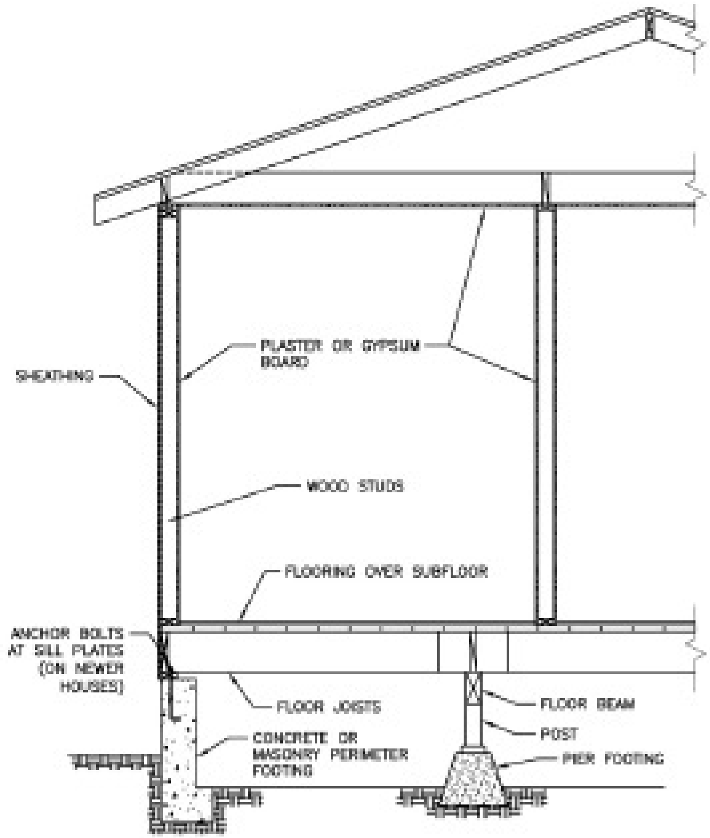


Figure 2-12 Section through a variation of the basement house where the perimeter foundation walls enclose a crawl space (from ATC, 2002).

Figure 2-13 Damage to a basement-type house where the sill plate slid on the top of the foundation wall (from ATC, 2002).

2.2.4 Perimeter Post-and-Pier Foundation Houses

In post-and-pier foundation houses, individual footings are spaced along the house perimeter and along interior lines. These footings may be shallow foundations or deep drilled piers, and may or may not be tied together by grade beams at ground level. The footings support wood or steel posts, or masonry or concrete piers. Posts are provided with lateral-force resistance by diagonal bracing, or the width/height ratio of masonry or concrete piers providing overturning capacity. The first-floor joists and the house superstructure are supported by girders supported by the posts or piers. Figures 2-14, 2-15 and 2-16 illustrate this house configuration on sloping and flat sites, respectively.

Figure 2-14 Steel post-and-pier foundation house on sloping site (from ATC, 2002).

Figure 2-15 Wood post-and-pier house on flat site (from ATC, 2002).

Figure 2-16 Masonry pier house on flat site (from ATC, 2002).

A common seismic vulnerability in post-and-pier houses is the lack of seismic-resisting strength in the post-and-pier foundation system or in the diagonal bracing system. Figure 2-17 shows earthquake damage to a post-and-pier foundation.

Figure 2-17 Earthquake-damaged perimeter post-and-pier foundation. The diagonally-braced post has overturned the shallow-founded concrete pier footing (from ATC, 2002).

2.2.5 *Split-Level Houses, Multi-Level Hillside Houses*

Houses where adjacent floor levels are separated by less than a full story height are usually designated split-level houses. One typical configuration is shown in Figure 2-18. The right part of the house is of two-story slab-on-grade wood-frame construction, with the garage space occupying the lower floor. The attached portion on the left side is of one-story cripple-wall construction.

Figure 2-18 Split-level house, where the section of flooring above the garage is at a lower level than the main second-floor level (from ATC, 2002).

Other split level houses may have all slab-on-grade ground floors at different elevations, and may not have living spaces over the garage. These houses may be on either flat or sloped sites. On flat sites, the two lower levels may be at nearly the same elevation.

A common seismic vulnerability in split-level houses with living spaces over the garage is inadequate strength of the walls at each side of the garage door to resist seismic forces from the house portion above. Damage that was in part initiated by this vulnerability is shown in Figure 2-19. Another common vulnerability is insufficient strength of the cripple wall under the single-story portion of the house, when present, causing damage similar to that of Figure 2-5.

2.3 Elements of the Primary Seismic Load Path

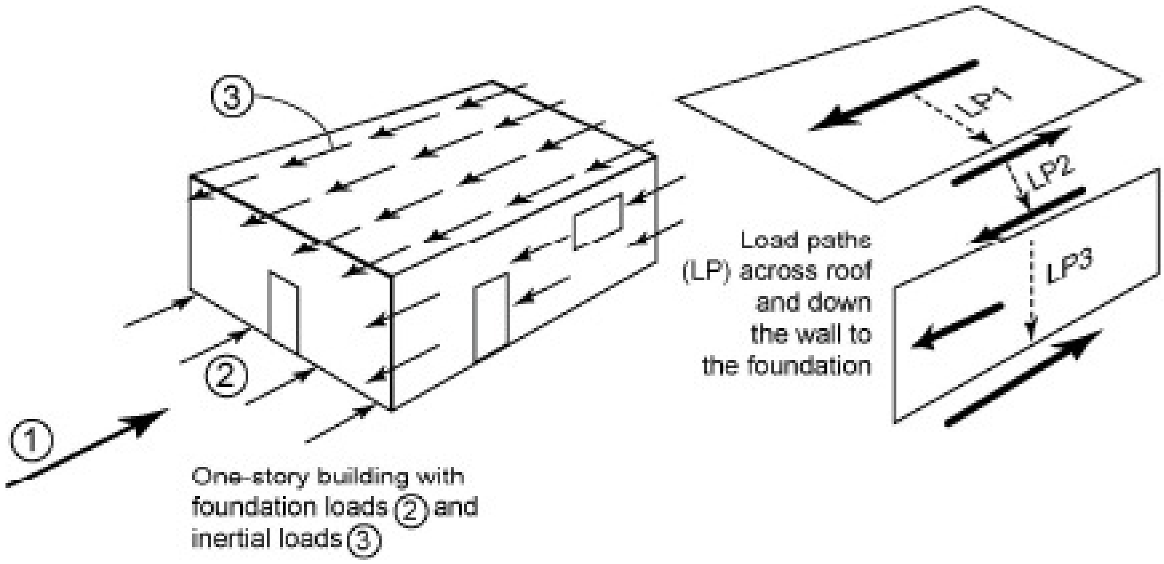
An understanding of how the various building elements work together along the primary seismic load path to resist earthquake forces will make the retrofit process more clear. A more in-depth explanation can be found in FEMA 232.

Figure 2-19 Split-level house with damage and collapse at the garage-level walls at two-story portion (from ATC, 2002).

Horizontal earthquake ground motion causes house foundations to accelerate back and forth. Because of the inertia of the heavier elements of a house structure, these heavier elements resist the tendency to follow the foundation motion. In so doing, these heavier elements supply "inertial" seismic forces to the attached structural elements. The seismic forces must be transferred along the 'seismic load path' from each element to the supporting ground. As discussed in more detail in Chapter 8, along this seismic load path may be, for example, horizontal diaphragms, nailed connections, shear walls, nailed and anchor-bolted connections, and the foundation.

2.3.1 Horizontal Diaphragms

Floors and roofs with continuous sheathing that is horizontal (or sloped, in the case of most roofs) are considered horizontal diaphragms. In the primary seismic load path, horizontal diaphragms serve to transfer the lateral inertial seismic forces from all attached elements into the shear walls or other vertical wall elements below the diaphragm level. Most often in houses, the horizontal diaphragm collects these forces from attached walls having planes perpendicular to the earthquake motion, and transfers these forces to lower shear walls whose plane is parallel to the earthquake motion. The forces are carried down through the walls to the foundation where they are resisted by friction or bearing ground reactions. Figure 2-20 illustrates this load path, with horizontal diaphragms transferring seismic horizontal forces to the tops of the shear walls, then down through the shear walls to the foundation.



Notes:

1 Peak ground acceleration, presumed constant, in direction left-right.

2 Entire foundation is moved left-right.

3 Building inertia causes bulding to lag to the left, as though every item of weight *W*, was acted on by a seismic inertial force *Wa* to the left.

LP1 Inertial forces in the roof diaphragm are transferred along LP1 to the edge of the roof by shear in the diaphragm.

LP2 Forces at the edge of the roof diaphragm are collected and transferred along LP2 to the top of the wall through connectors.

LP3 Forces at the top of the wall and inertial forces in the wall are transferred along LP3 to the foundation by shear in the wall diaphragm, nailed connections and bracing to the mudsill, and through bolt shear to the foundation.

Figure 2-20 Horizontal and vertical diaphragms (shear walls) transferring horizontal earthquake forces (from ATC, 2002).

2.3.2 Shear Walls

Shear walls have a capacity to resist earthquake forces in the direction of the plane of the wall. The sheathing of the wall must have sufficient strength to resist the shear force. The connections at the top and bottom of the wall must be strong enough to transmit the forces without breaking. The wall can only resist in-plane forces; other walls must be provided to resist forces in the perpendicular plan direction. The wall must support enough dead weight, or be connected adequately at the bottom, to resist being overturned by the horizontal shear force being applied at the top. Figure 2-21 illustrates a shear wall with applied lateral forces at the top and with dead weight and bottom restraints resisting overturning

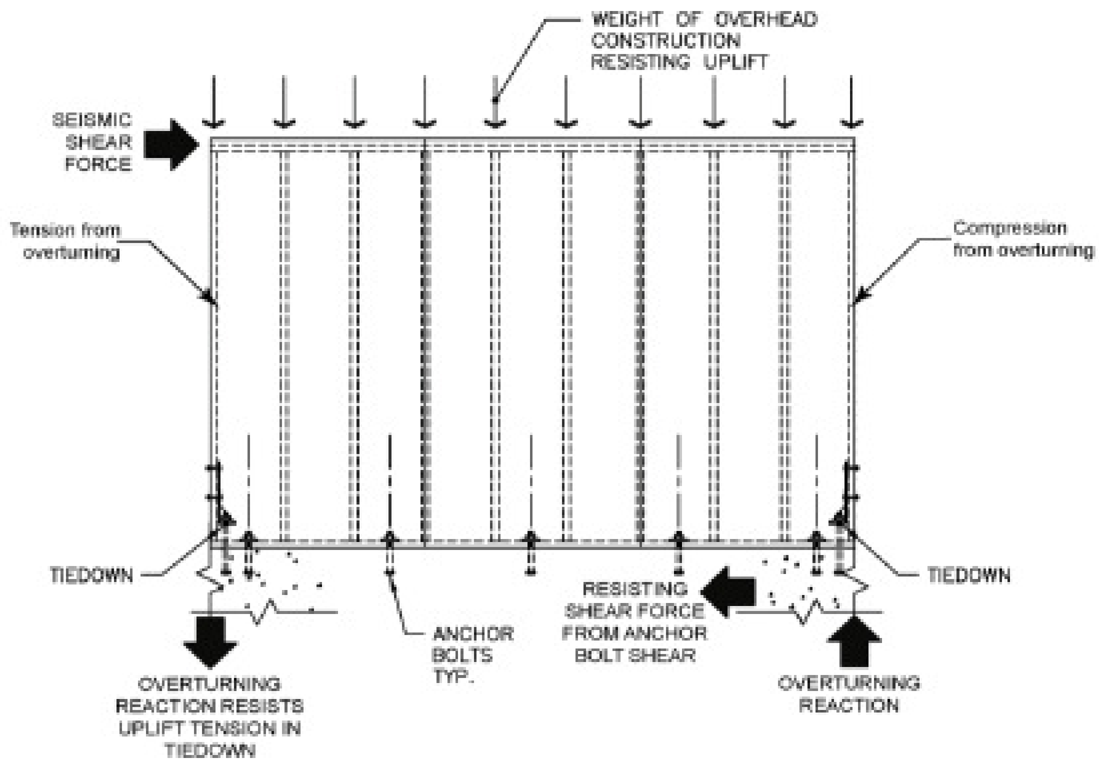


Figure 2-21 Shear wall with a seismic shear force applied at the top, and the resulting shear and overturning reactions at the base (from ATC, 2002).

Intended Shear Walls

In modern earthquake-resistant design, certain walls are designed and built to have the strength to resist a designated amount of earthquake force. The total capacity of these intended shear walls above a specific floor level must be greater than the design earthquake force at that level of the building.

Unintended Shear Walls

In many older buildings, no particular interior or exterior walls were intended to be shear walls. However, if the top edges of these walls are connected to a horizontal roof, ceiling, or floor diaphragm, and the bottom to a horizontal floor diaphragm or foundation, they will resist some amount of force as the building is shaken. The force will be resisted by the existing sheathing on the wall. These unintended shear walls may be evaluated for their capacity to contribute to the earthquake-resisting capacity of the building.

As part of an overall building retrofit, the strength of an existing wall can be increased. Existing interior walls usually already have interior sheathing on both sides, and exterior walls have interior and exterior sheathing. The wall strengthening is usually done by removing the interior sheathing for the full width of a room, improving top and bottom connections as needed, placing new structural sheathing, and placing new interior sheathing over the new structural sheathing. In an attached garage and certain other locations, the new interior gypsum board sheathing placed over new wood structural panel sheathing may need to meet fire-resistance rating requirements.

Tiedowns

Modern wood-frame houses often have steel tiedown hardware between the foundation and the shear walls or cripple walls above the foundation. The tiedowns connect the foundation to vertical boundary posts at the ends of the shear walls. They prevent the shear wall from overturning when a seismic force is applied in-plane to the top of the wall. Figure 2-21 shows the vertical force applied to a tiedown from a horizontal force at the top of the wall. Figure 2-22 illustrates typical commercially available tiedowns. The tiedown connects to the foundation with an embedded threaded rod or strap and to the post with bolts, nails, or screws. Tiedowns are required when the dead weight at the top of the wall is not sufficient to prevent overturning. This condition is more likely to occur in short walls with small length/height ratios.

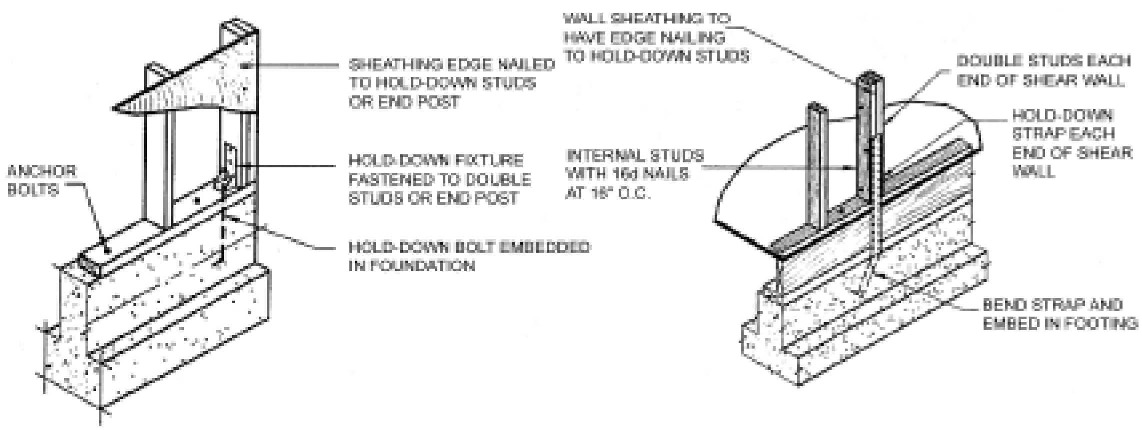


Figure 2-22 Typical commercially available tiedowns (from ATC, 2002).

2.3.3 Connections Between Walls and Horizontal Diaphragms

The connection of a roof or floor horizontal diaphragm to the walls above and below it must be adequate for the transfer of seismic forces. A typical sectional view of this connection is shown in Figure 2-23. The nailing of the wall sheathing, sills, subfloor, framing hardware and top plates forms a complete load path for the transfer of shear forces from the upper wall and the subfloor down into the lower wall.

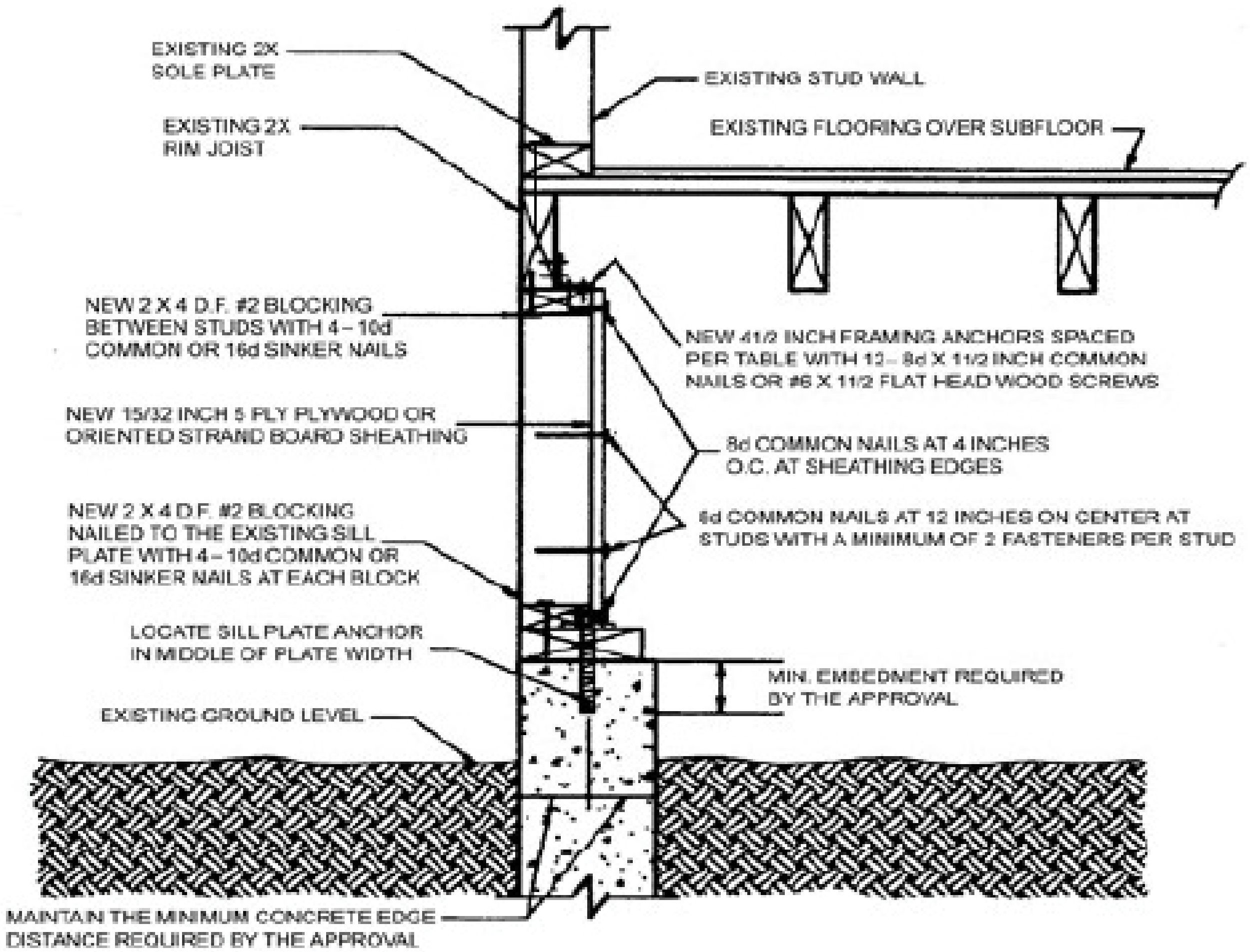


Figure 2-23 Detail from the Los Angeles Standard Retrofit Plan (See Chapter 6) of a connection between a wall and a horizontal floor diaphragm, with strengthening of the connection between the top of the cripple wall and the floor joist blocking above the wall (from ATC, 2002).

The IEBC Cripple Wall Provisions require that the connection between the top of the cripple wall and the floor joist blocking above it be strengthened. Various connection details, such as the one illustrated in Figure 2-23, are provided in the IEBC Cripple Wall Provisions.

2.3.4 Cripple Walls

The cripple walls are the lowest wood-frame walls in a cripple-wall building. All of the seismic forces collected in the horizontal diaphragms and the walls above the cripple walls are delivered to the cripple walls. As cripple walls typically are only on the building perimeter and have sheathing only on the exterior face, they have often failed when in-plane seismic forces delivered to them exceeded their capacity.

It is a very common seismic retrofit to increase the strength of the sheathing on a cripple wall. This is usually done by adding structural sheathing to the unsheathed inside face of the cripple-wall framing. By the prescriptive cripple wall retrofit provisions (to be introduced in Chapter 4), the length of an added wood structural-sheathing panel is to be at least twice the height of the cripple wall. Tiedowns are then not required because it is assumed that significant uplift forces do not occur with this length/height ratio.

2.3.5 Anchor Bolts

Anchor bolts serve to connect the bottom sill plate of the lowest-level shear walls to the foundation. All of the seismic shear forces from the wood-framed part of the house pass through the anchor bolts to the foundation. Many older houses do not have anchor bolts; once the friction and adhesion resistance of the sill plate on the foundation is overcome by earthquake forces, the sill plate can slide off the foundation.

Retrofit anchor bolts are often added to connect the sill plate to the foundation. Holes for the anchor bolts are drilled through the existing bottom sill plate and into the foundation. The new anchor bolts can be chemically bonded into the foundation with epoxy or other adhesive, or they can have a mechanical expansion wedge to grip the sides of the hole. When limited clearance in the crawl space prevents the installation of anchor bolts, hardware is available to substitute for new anchor bolts by connecting the side of the foundation to the side or top of the sill plate.

2.3.6 Foundations

The foundation receives the horizontal and overturning seismic forces from the wood-framed part of the house and transfers it into the ground. The foundation walls must have sufficient in-plane shear strength to resist the horizontal force, and they must have sufficient thickness/height stability to not collapse during the earthquake shaking. If shearwall tiedowns are used, the foundation must also have sufficient weight and bending strength to resist any vertical overturning forces they impose.

All or part of unstable, weak, or discontinuous existing perimeter foundations are sometimes replaced with new continuous reinforced concrete foundations as a part of a seismic retrofit. This is a major construction effort. Replacement of any significant length of foundation is usually done in alternating segments along the length of the foundation to avoid having to raise and support the entire house.

Post and pier foundations are usually of concrete, with a foundation pier at each post. Newer houses on hillsides, and newer houses on poorer soils are more likely to have deep pier foundations and to have grade beams connecting the piers together.

2.4 Platform Framing and Balloon Framing

Platform framing and balloon framing are the two predominant ways of using nominal two-inch thick wood framing lumber to frame a multistory house. Platform framing is much more common than balloon framing in newer houses.

In platform framing, the stud-framed walls are discontinuous at each floor level. A first floor platform is built of joists, rim joists or blocks, and subflooring. Stud walls made of bottom sill plates, studs, and double top plates, are then placed on the top of this floor platform. A second floor platform, again of joists, rim joists or blocks, is then constructed on top of these stud walls. This pattern is repeated for the required number of floors. The stud walls have exterior sheathing that is continued across the platform floors. Figure 2-21 illustrates one story level of a platform framed stud wall.

In balloon framing, the studs extend more than one story in height, usually the crawl space height and two more stories. The floor joists are supported on the studs by a ledger or a let-in "rimband".

2.5 House Elements not on the Primary Seismic Load Path

Some house elements are considered nonstructural and do not serve to resist the earthquake force caused by the inertia of the full weight of the building. These elements resist the force from some smaller part of the building. The vulnerability of these elements is considered in Section D of the Simplified Seismic Assessment Form, and their retrofit is covered in Chapter 7.

2.5.1 Roofs and Floors of Porches and Decks

Porch and deck roofs and floors are often supported vertically by the house framing on one side and by posts on the outboard side. Earthquake forces can cause them to pull or pry away from the house framing, which allows the posts to hinge, collapsing the porch or deck. Porch and deck roofs and floors can be prevented from prying away from the house by tying their framing back into the house framing.

Posts supporting porch and deck roofs and floors often cannot resist earthquake shaking. Sometimes the upper part of the post is a wood member supported by a separate wood or brick lower post. As described in detail in

Section 7.6.2, this 'hinged' assembly can become unstable and allow the roof to collapse. These posts and post footings can be stabilized so that they continue to provide vertical support during earthquake shaking.

2.5.2 Interior Pier Foundations and Posts

In a crawl-space house, the interior beams supporting the first-floor floor joists are in turn supported by wood posts, as seen in Figure 2-2. The wood posts usually rest on concrete pier footings, although in some older homes they rest on the bare earth.

Even when the cripple walls are adequate, earthquake motion can shake these posts loose from the floor beams or the pier footings so that they no longer support the beams. The posts should be well-fastened top and bottom so that they continue to provide vertical support. Where the posts rest on bare earth, pier foundations should be added. Chapter 6 provides guidance for this retrofit work.

2.5.3 Chimneys, Veneer and Roof Tile

Unreinforced brick masonry chimneys are heavy and brittle. When subjected to earthquake forces, they often crack, break apart, and become falling hazards. Many building jurisdictions in high seismic hazard areas encourage the use of less vulnerable non-masonry chimneys. Steel-reinforced brick masonry chimneys are also likely to crack, but are less likely to become a falling hazard (see Chapter 7 for additional information).

Stone or brick veneer is often used as an exterior finish on wood-frame walls. The veneer is often not well fastened to the wall framing, making it vulnerable to being shaken off the wall surface by earthquake movement perpendicular to the wall. If the sheathing on the wall, behind the veneer or on the interior face, does not have adequate strength or stiffness to resist in-plane earthquake deformation, in-plane forces can also cause the veneer to come loose. To lessen the vulnerability of the veneer, the connection of the veneer to the wall framing can be improved. Full-thickness brick veneer can be removed and replaced with a lightweight facing that has the same appearance.

Roof tiles on houses built to older codes are often not well secured to the roof sheathing. Seismic shaking can dislodge the tiles, creating a falling hazard and roof leakage. It is possible, but difficult, to retrofit the roof tile connections to minimize this condition.

Brick veneer and roof tile significantly increase the weight of the house and thus increase the seismic forces on the house shear walls and horizontal diaphragms.

Chapter 7 provides guidance for the retrofit of chimneys, brick veneer, and roof tile.