

This guide is intended to help you evaluate a home to determine if it needs retrofitting or has been retrofitted properly. Every house is different and no house matches exactly what you will see here, though the engineering principles discussed are always the same.

The Home Owner's Guide to Seismic Retrofitting

The retrofitting principles discussed here only deal with the area under the floor. This is because most commonly observed earthquake damage is caused by inadequate lateral bracing under the floor. Under the house, there are generally almost no effective earthquake resisting elements such as bolts and plywood. Above the floor, interior finishes on the walls and partitions, though not designed to resist earthquakes, do in fact provide a lot of earthquake resistance and typically brace the house against serious damage. After a quake, wall and partition finishes may be cracked, doors and windows may be racked, and costly repairs may be required to restore livability to common standards, but damage above the floor is much less likely to result in a hazardous condition than would be found in a house damaged due to inadequate underfloor bracing. Effective underfloor bracing should keep your house from falling from its foundation. You should not expect that an underfloor retrofit will protect your house from earthquake damage above the floor.

Many homes on the West Coast were built at a time when the floor of the house was elevated off of the foundation with something called cripple walls. Most of these homes were also built before the building code was either established or had provisions for making newly constructed homes earthquake resistant. Older homes with these cripple walls need to be retrofitted to avoid collapse in a major earthquake.¹ Yet surprisingly, even now, even in California, we do NOT have building codes and special contractor licensing for seismic retrofit work. Although your city may issue permits for retrofit work, the city has no code by which to evaluate the work. This puts the onus on the homeowner to evaluate their retrofit. If you take the time to understand the basic principles of seismic retrofitting you can make sure your retrofit is done properly.

Most homes need to be strengthened in three areas:

1. The cripple walls need to be braced with plywood.
2. The braced cripple walls need to be bolted to the foundation.
3. The floor of the house needs to be attached to the braced cripple walls.

The following illustrations explain what these areas are and why they are important. If any one of these three areas is not earthquake resistant, your house can fall off of its foundation.

1. Bracing the Cripple Walls with Plywood

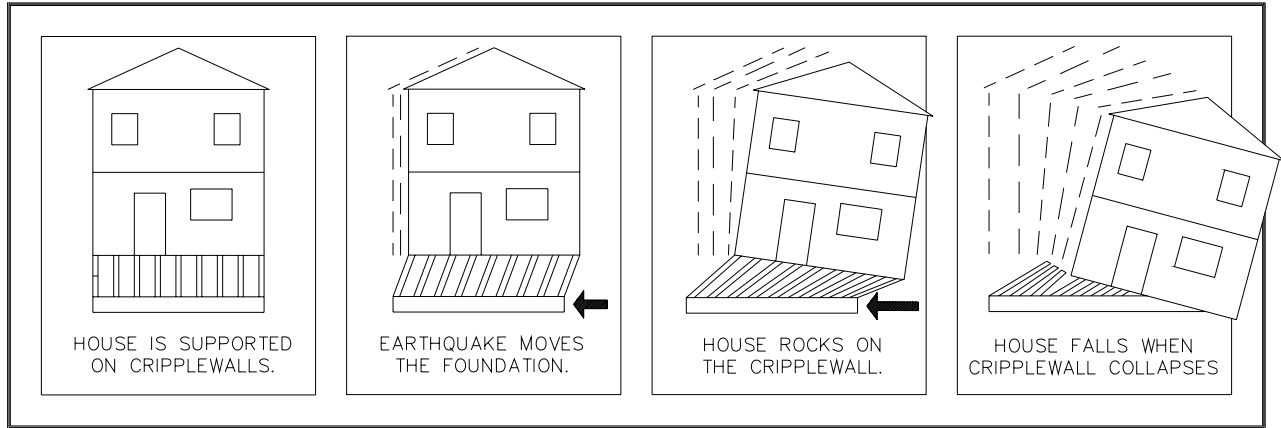


Figure 1: Failure of house due to lack of cripple-wall bracing

Figure 1 shows what can happen to a house if it is not properly retrofitted with plywood on the cripple walls. History has shown that unbraced cripple walls are the first thing to fail in an earthquake and their failure usually makes the home uninhabitable.

2. Bolting the Braced Cripple Walls to the Foundation

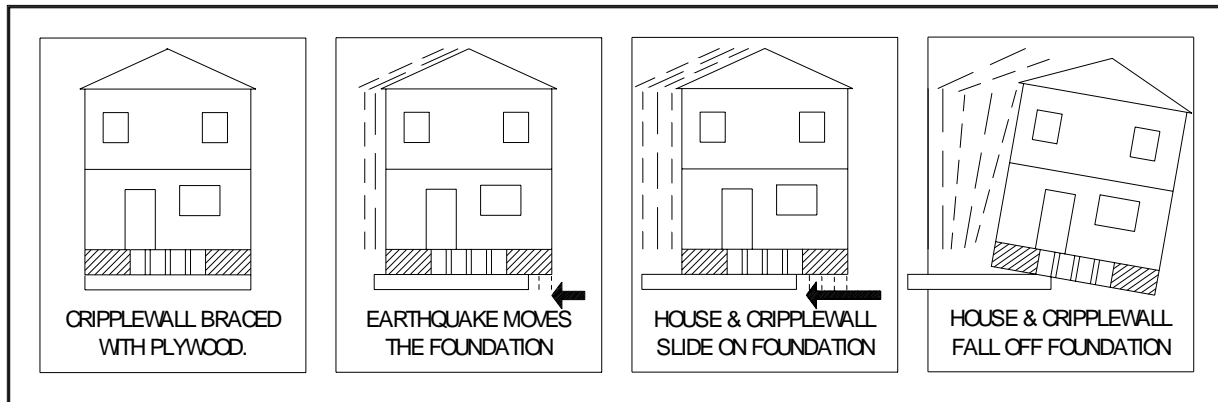


Figure 2: Failure of house due to lack of foundation bolts

The plywood-braced cripple walls should be bolted to the foundation to keep them from sliding off of the foundation.² Notice in Figure 2 that plywood is only on part of the cripple wall. It is not necessary to put plywood on the entire cripple wall (and its not necessary to place plywood only in the corners.) Knowing how much plywood to install involves the use of an engineering formula known as the *base shear formula*. This formula is explained later in this paper.

3. Attaching the Floor of the House to the Braced Cripple Walls

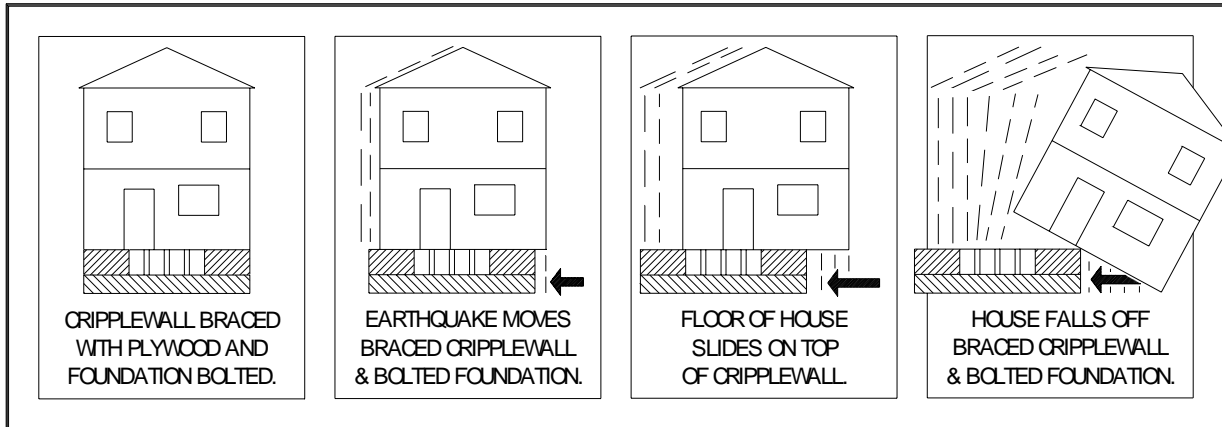
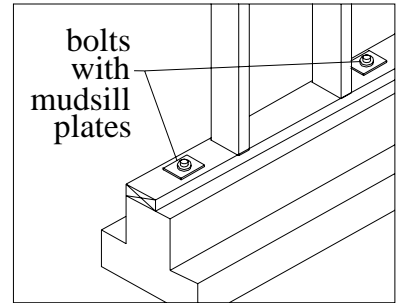
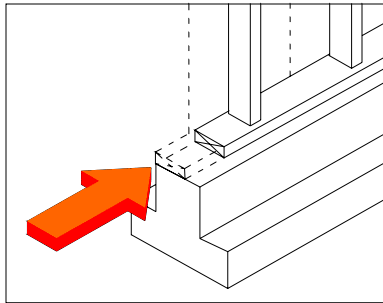
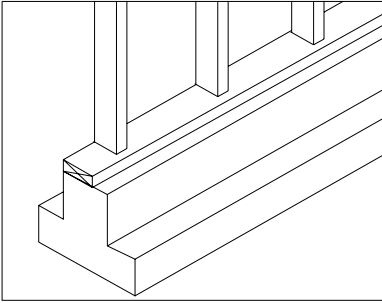


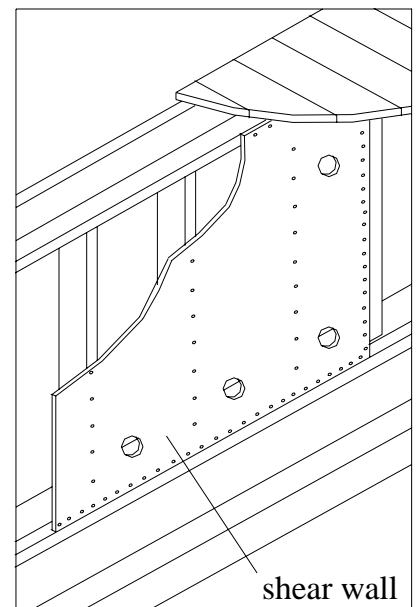
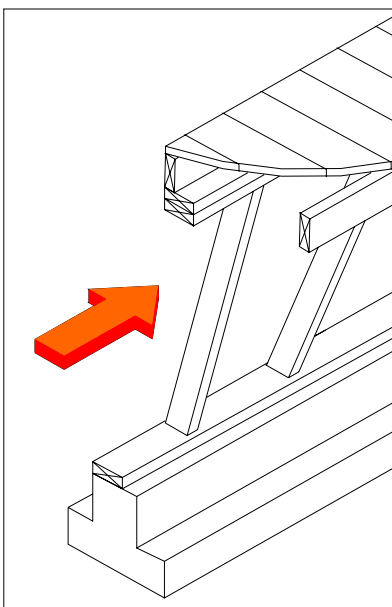
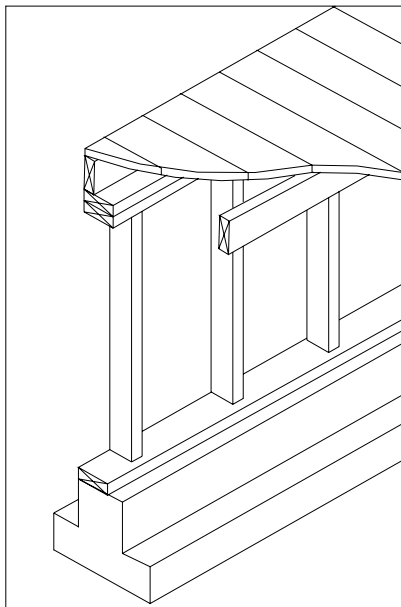
Figure 3: Failure due to no connection of floor to cripple wall

Attaching the floor of the house to the braced cripple walls is the third component in any effective retrofit. In Figure 3 the cripple wall is braced with plywood to prevent collapse and it is bolted to the foundation, but the floor is not attached to the braced cripple wall. This connection is strengthened with hardware called *shear transfer ties*.

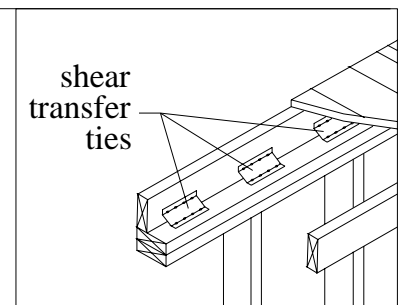
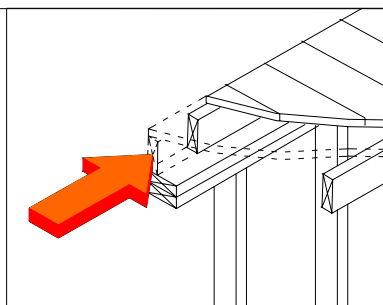
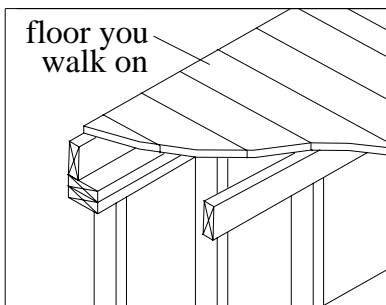
The following cross-sectionals give you another view of how the house can move in the three areas during an earthquake and where the bracing will be applied to curb the movement.



Movement prevented by bolts.



Movement prevented by plywood shear panels.



Movement prevented by shear transfer ties.

Under your House

Diagram 1 shows what a cripple wall would look like if you cut the floor away. As a homeowner in the Bay Area, you should be able to look under your house and identify the components shown in Diagram 1.

- 1 –foundation
- 2 – mudsill
- 3 –cripple wall stud
- 4 –top plates
- 5 –floor joist
- 6 –flooring you walk on

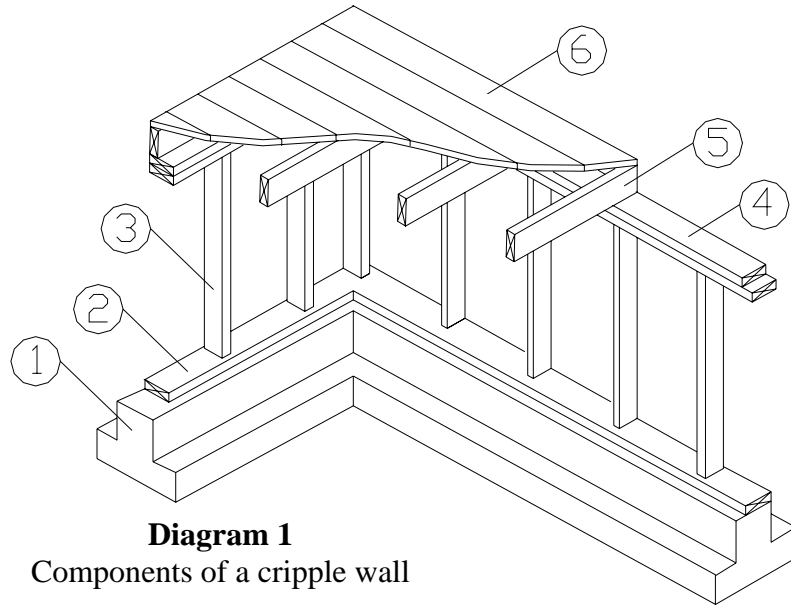


Diagram 1
Components of a cripple wall

Diagram 2 below shows the same cripple wall after it has been retrofitted. The plywood shear wall keeps the 2x4 studs of the cripple wall from falling over in an earthquake, the bolts keep the mudsill from sliding off the foundation, and the shear transfer ties keep the floor joists from sliding off the top of the cripple wall. When you crawl under your house you should see something that looks similar to Diagram 2. Unfortunately, Most retrofitted homes are missing at least one of these components.

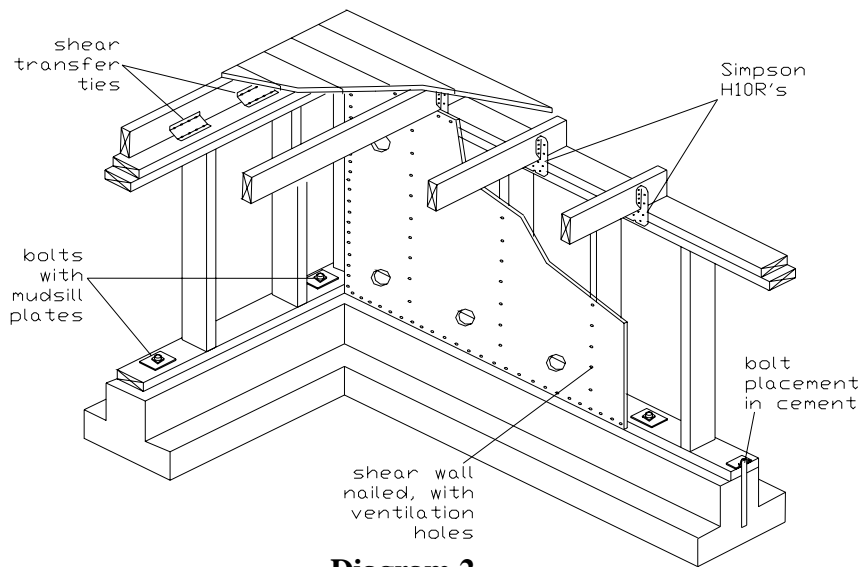


Diagram 2
Retrofitted cripple wall

Different Ways to Build Retrofit Shear Walls

Retrofit plywood shear walls can be built in four different ways. The following shows those four ways starting with the least effective, and progressing to the most effective.

1. Nailed Blocking Method

This method nails 2x4 blocks between the studs into the mudsill. The plywood is then nailed to these blocks. This is the most common method used to attach the plywood to the mudsill. The 2x4 blocks are placed between the upright 2x4 studs and nailed onto the mudsill.

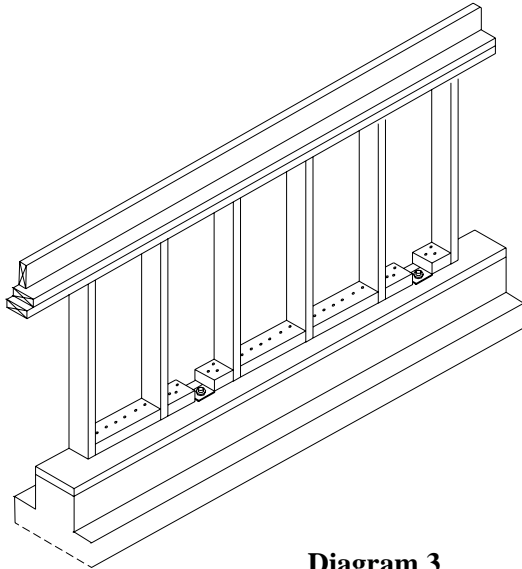


Diagram 3

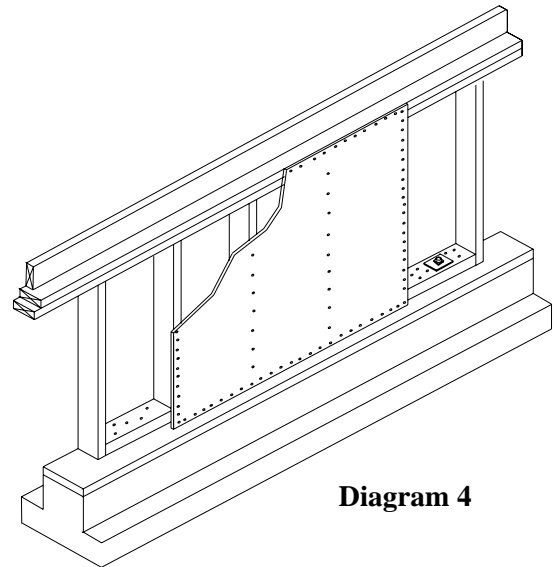


Diagram 4

The plywood is then nailed into the 2x4 blocks at the bottom of the panel. The point of concern when using the nailed blocking method is that the blocks can split.

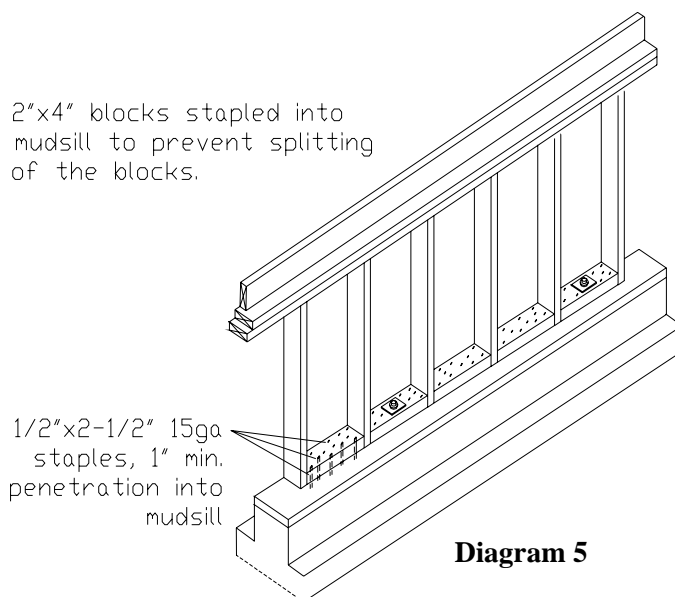


Diagram 5

2. Stapled Blocking Method

This method is identical to the nailed blocking method except staples are used as shown in Diagram 5. The American Plywood Association recommends the use of staples. A report published by the American Plywood Association states: "Staples provide a method for developing high design shear values while still using 2 inch nominal framing. The small diameter of the staple legs is not as apt to cause splitting- of the framing as are large diameter nails



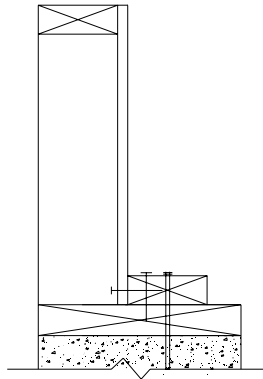
The photo above shows a block behind a shear wall that split with only four nails installed.



This photo shows a 14-inch block with **114** 2-1/2 inch staples. Notice no splitting of the block.

3. Reverse Blocking Method

Diagram 6 shows a shear wall made with reverse blocking. The reverse blocking method is quite effective in homes that have wide mudsills. The 2x4 reverse block is nailed to the plywood before the plywood and 2x4 are installed on the cripple wall. Please note that the bolts and the shear transfer ties are not shown in the drawings below.



from the side

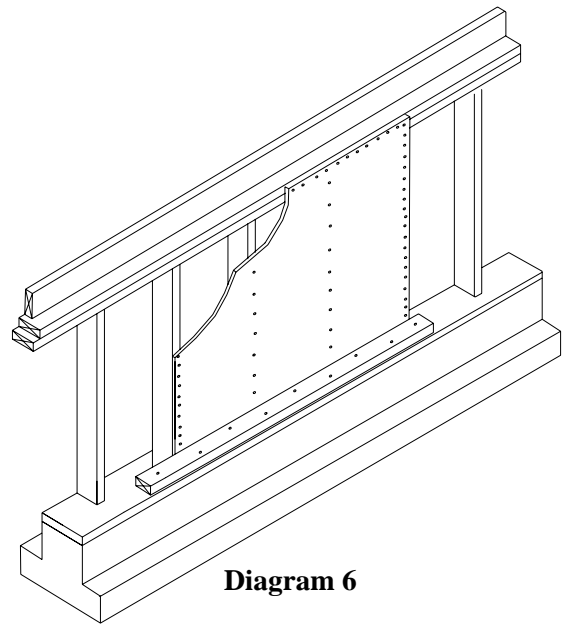


Diagram 6

4. Flush Cut Method

With this method the mudsill is cut flush with the 2x4 upright studs with a special saw. The lower edge of the plywood is then nailed directly into the redwood mudsill as shown in Diagram 7. This method of building a retrofit shear wall is the method that most resembles the shear walls that have been tested in laboratories by the American Plywood Association.

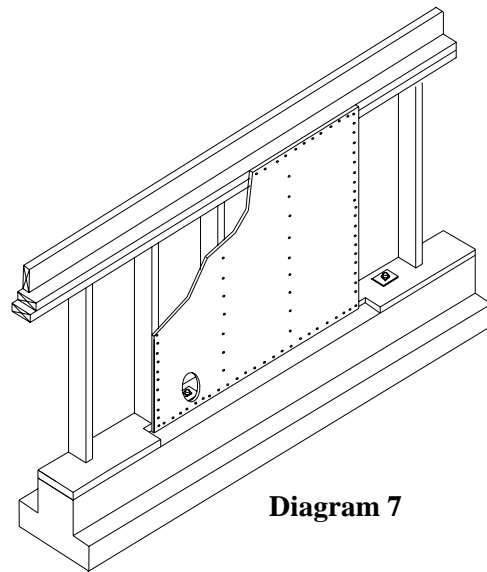
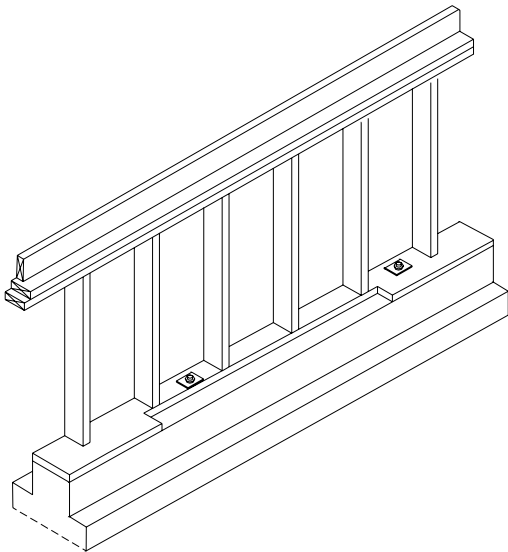


Diagram 7

The International Code Council asked the American Plywood Association, the world authority on plywood construction and testing, to evaluate these four methods for creating shear walls. The following letter is the American Plywood Association's response.

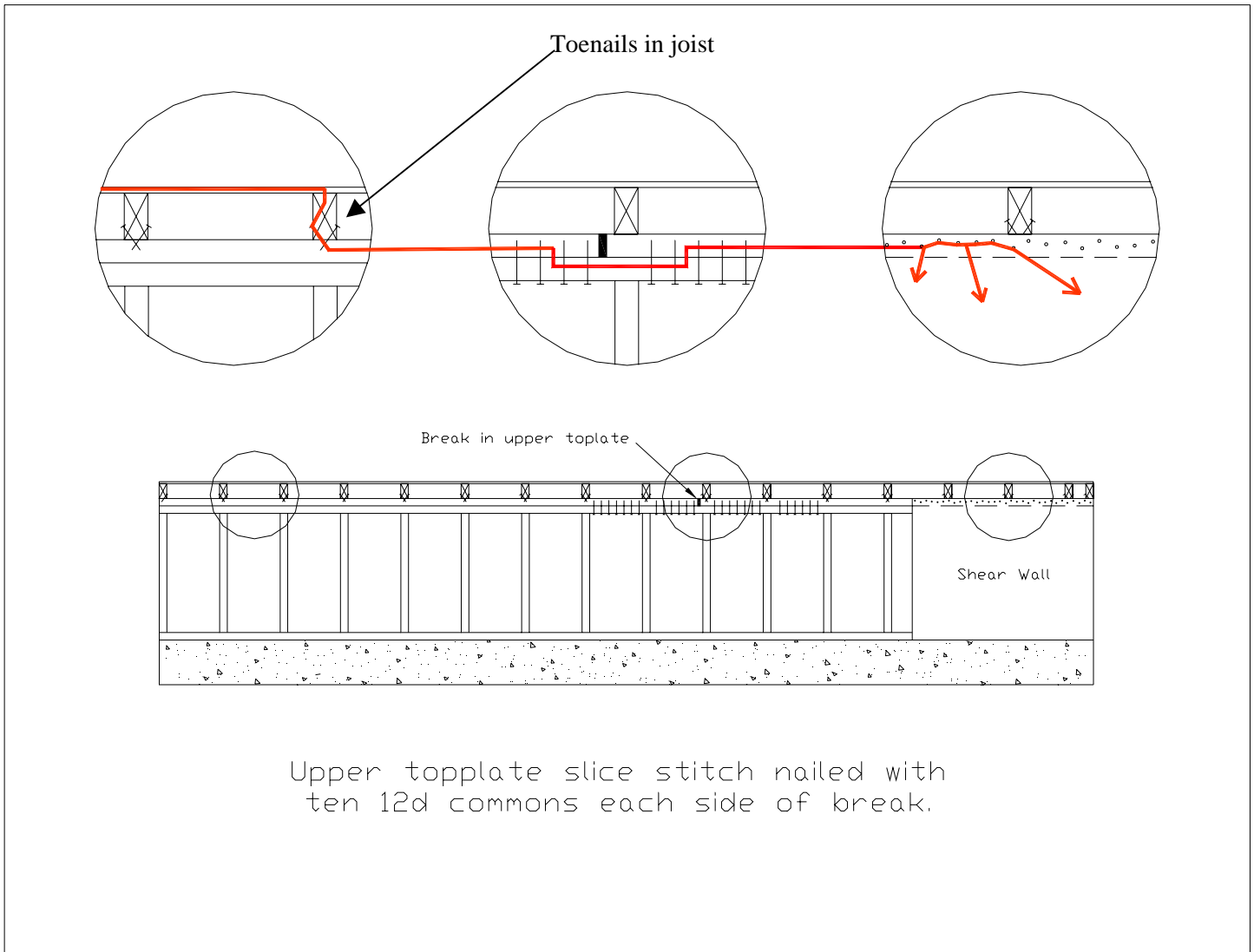


Diagram 12: Upper top plate splice

It is very important to connect make sure any breaks in the upper top plate are spliced together. This is because the movement of the floor is transferred through the toenails into the floor joists and the toe nails push and pull on the upper top plate. You want to make sure this movement is transferred to the shear wall.

The circled portions and red line of the diagrams above illustrate what happens. As the floor moves to the left the movement of the floor is transferred to the toenails. The toenails in turn push on the upper top plate. This force is transferred all along the upper top plate until it reaches a break in the upper top plate at which point it stops, unless the two pieces on either side of the break are spliced together with nails or a steel strap. 12d common nails installed with a nail gun by shooting the nails up though the lower top plate into the upper top plate on each side of the break is the easiest and cheapest way to make this connection. Install a lot of nails, probably 20 on each side of the break in the upper top plate. Spread them out over 2 or 3 stud bays, they are cheap and easy to install.

Below is a drawing of what it probably looks like under your house if you do not have a cripple wall. The mudsill needs to be attached to the foundation and the end and rim joists attached to the mudsill.

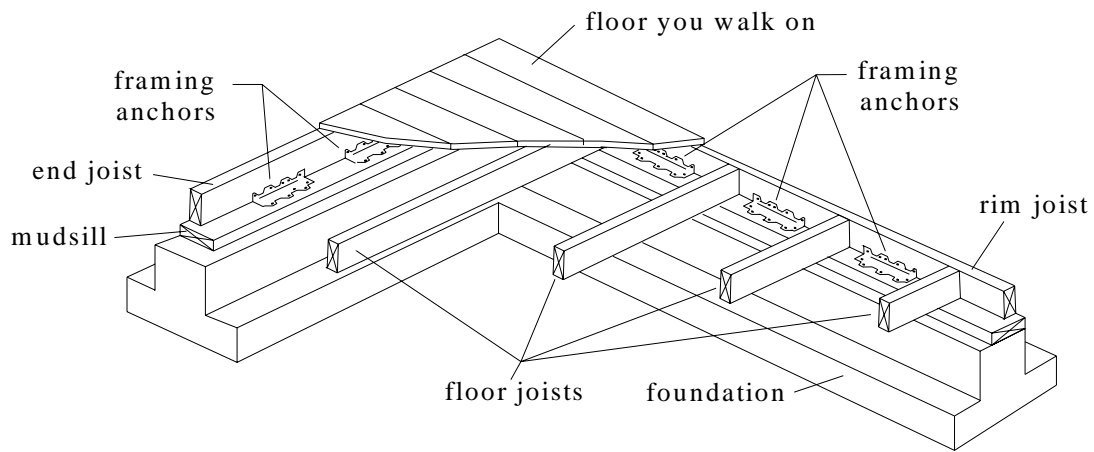


Diagram 14: No cripple walls

Here is an example of what can happen when the floor framing is not attached to the mudsill. The unbolted mudsill can also slide off if not bolted to the foundation. The mudsill on this house happened to be bolted. This house slid off its foundation because it did not have shear transfer ties.



Does retrofitting work?



210 Elm Street in Santa Cruz saved by retrofitting

In 1989, at the corner of Center and Elm streets in downtown Santa Cruz, architect Michael O'Hearn unwittingly created a laboratory for the study of seismic retrofit design.

On that corner, at 214 and 210 Elm Street, were two identical Victorian style homes. The same builder, with identical materials and using the same construction techniques, built them 100 years ago.

O'Hearn started by retrofitting #210 by installing plywood shear panels on the cripple walls and bolting the mudsill to the foundation. Unfortunately, there was no time to retrofit #214 before the 7.1 Loma Prieta earthquake hit on Oct. 17, 1989.

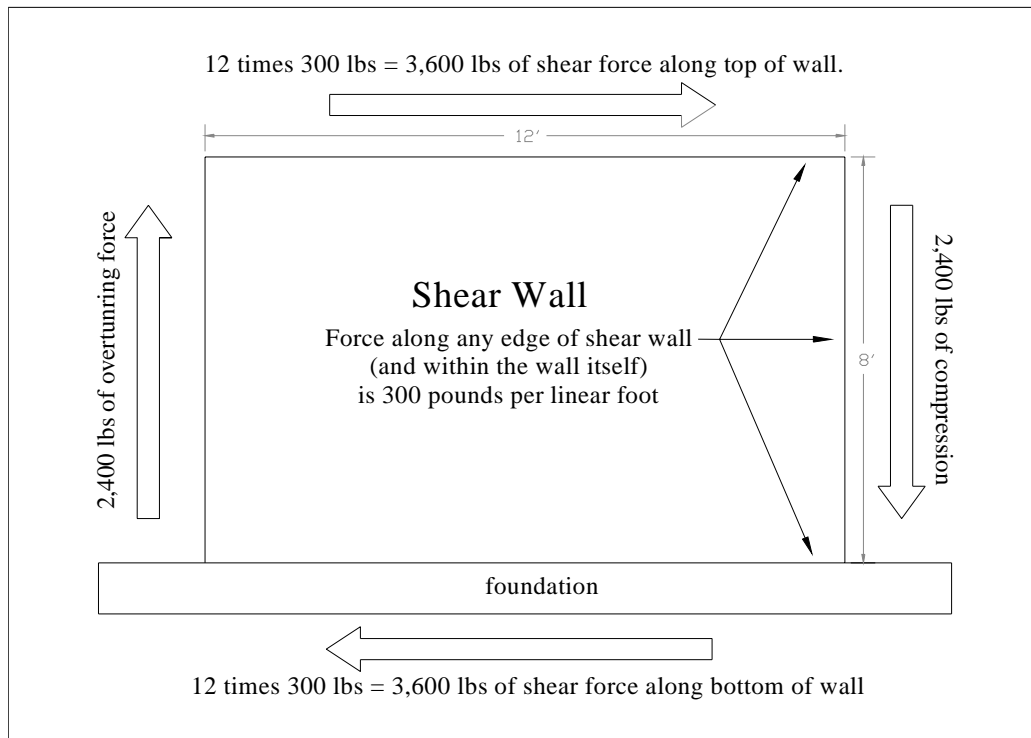
In a sense, 214 Elm Street was the "control element" in this amazing experiment. "The building came apart in four sections," O'Hearn said: "The one we had retrofitted (210 Elm St.) cost us \$5,000 to repair. The other one (214 Elm St.) cost us \$260,000 to repair. The whole building had to be jacked up, repaired, and slid back on a new foundation."

O'Hearn offers this advice, "For homes more than 20 years old located in areas of seismic activity, I strongly urge owners to consider seismic retrofit. It's a lot cheaper to retrofit a house now than to repair it after an earthquake."

Courtesy: American Plywood Association

Overturning Forces

Overturning forces act on all shear walls. However, sometimes a shear wall will be subjected to very strong overturning forces that can damage the shear wall. These forces must be resisted to prevent this damage. In the following pages we will discuss overturning forces and how to resist them.

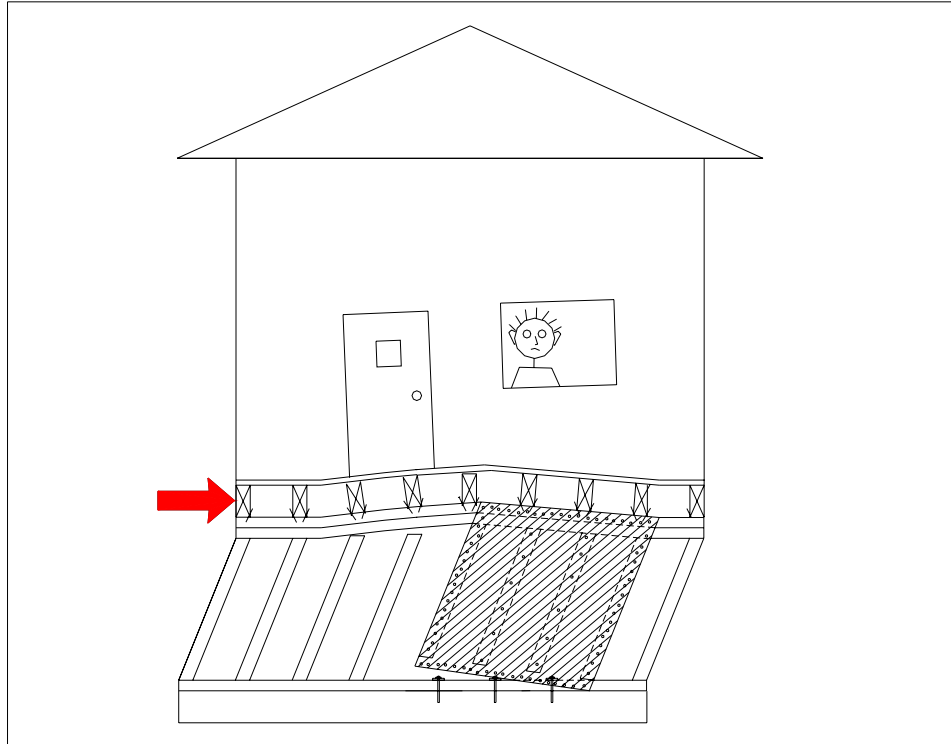


Lateral and Overturning Forces acting of a Shear Wall

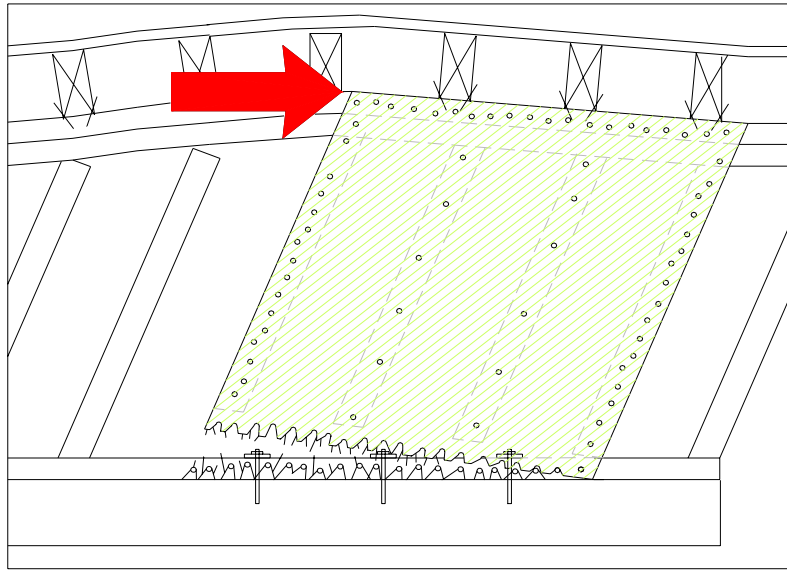
When the floor of the house pushes along the top of the shear wall, it not only tries to slide the wall along its length but also tries to roll it over. The lateral forces of an earthquake (called shear forces) acting along the top of a shear wall create overturning forces much as a tall chest of drawers will tilt up and overturn if you try to slide it across the floor by pushing it from the top.

If the floor is pushing along the top of the shear wall with a certain amount of force, that force will be distributed evenly over the length of the shear wall. In the above example, 3600 pounds of force is acting along the top of a 12-foot-long shear wall. This force is distributed along the top of the wall so that the shear wall must resist 300 pounds of force per linear foot of wall (300plf.) The bottom and both sides of the shear wall must also resist 300plf. The arrow at the left end of the shear wall indicates 2400 pounds of overturning force that must be countered by a downward force of 2400 pounds (300plf x 8ft.) to prevent the wall from overturning or rocking up off the foundation. This 2400 pound force can be provided by a 'hold-down' device; in some cases the weight of the building is enough to keep the wall from overturning. At the right end of the wall 2400 pounds of compression pushes down on the mudsill and foundation. The bolts anchoring the mudsill of the shear wall must resist the 3600 pounds of force acting on the top of the shear wall that is transferred through it to the mudsill. This force is trying to push the shear wall along the top

of the foundation. In an actual earthquake this force alternates back and forth rapidly against the shear wall as the earth shakes back and forth, and the forces represented by the arrows alternate directions back and forth just as rapidly. Therefore both ends of the wall must be able to resist both compression and overturning forces alternately.



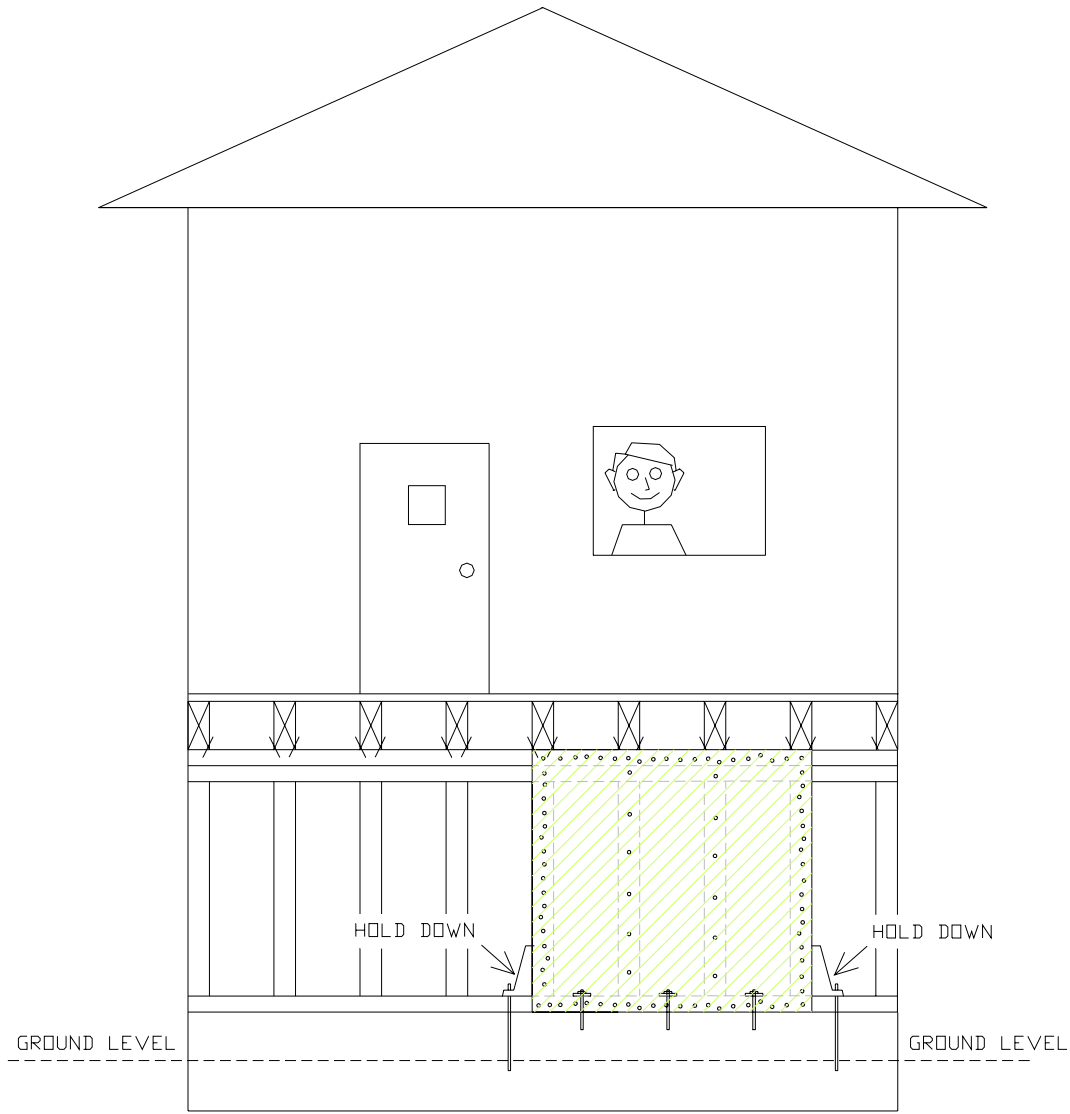
Here is an example of a shear wall overturning. This drawing is exaggerated in order to illustrate what happens. Most of the damage to the shear wall occurs where the plywood lifts up and away from the mudsill. The house will also sustain a significant amount of damage. Below is a close up illustrating tearing of the plywood at the mudsill. Once this happens the shear wall can no longer transfer shear forces into the bolts.



Overturning damage caused to shear walls at front of garage.

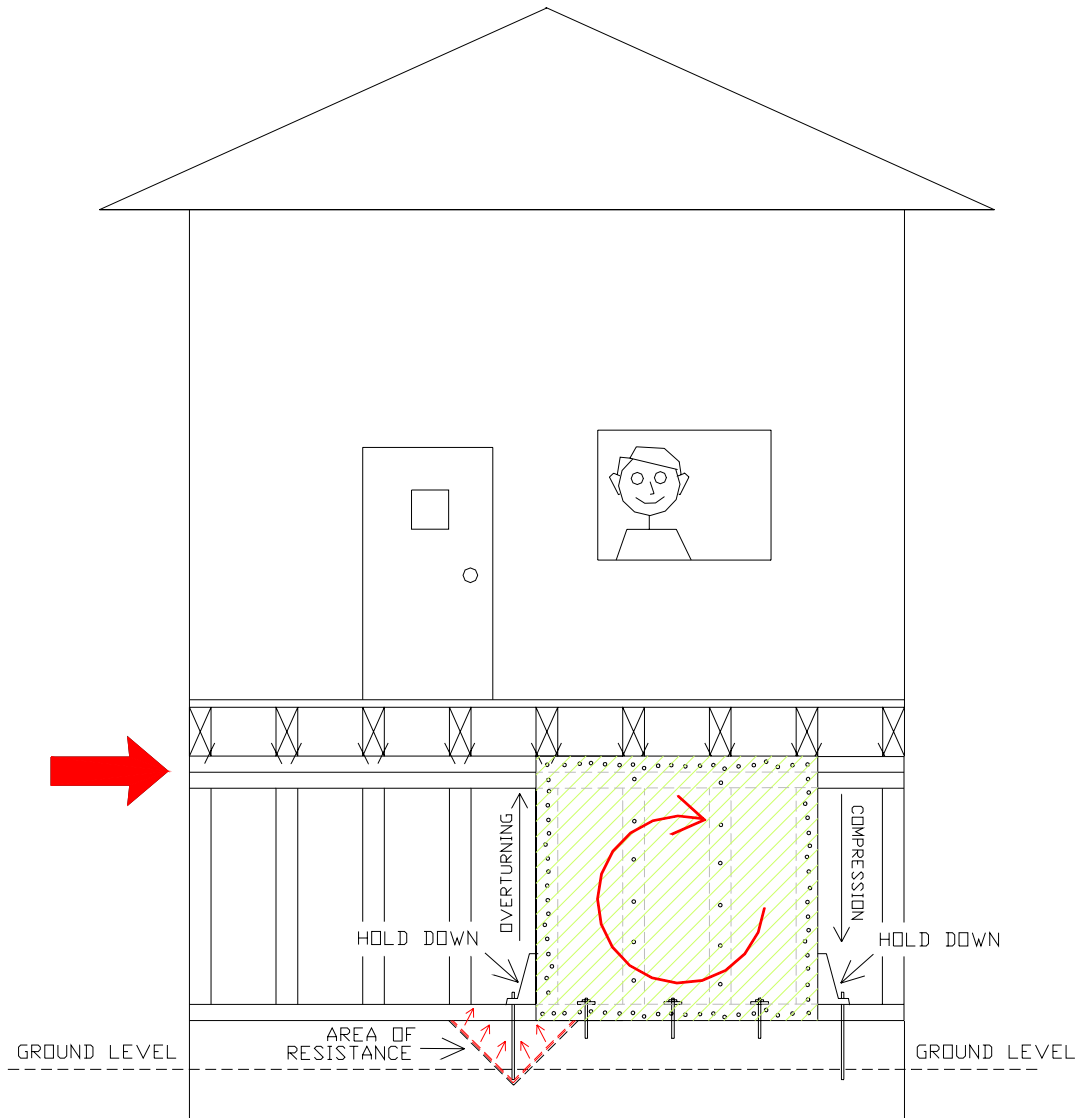


The building on the left used to be two stories. This collapse was caused by overturning of tall narrow shear walls that could not resist the earthquake forces generated by the heavy living area above a garage

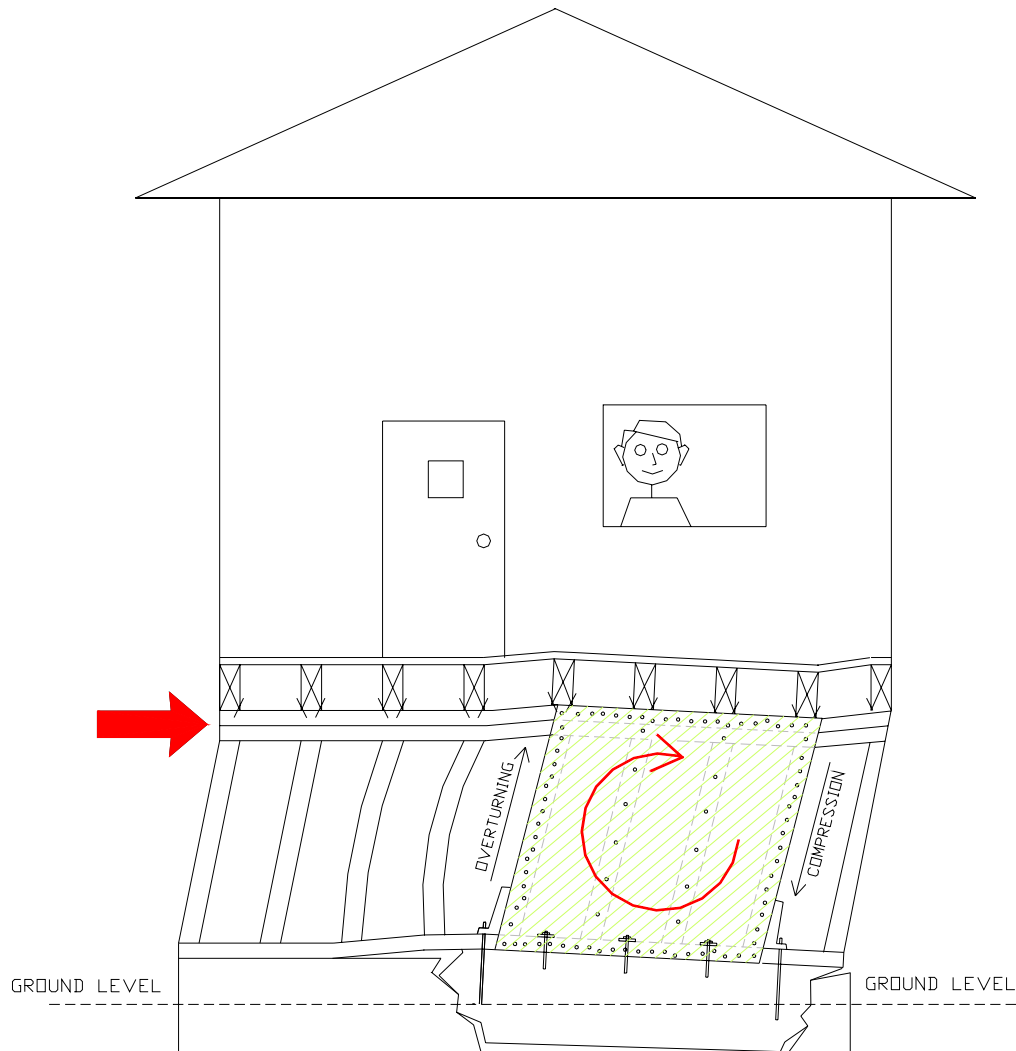


Shear Wall with Hold-downs to resist overturning

The hold-down hardware shown at the ends of the shear wall in the figure above is designed to resist overturning forces. The holddown hardware is attached to the posts at each end of the shear wall and as the ends of the shear wall try to lift up and overturn, the holddowns keep them held firmly to the foundation. Each hold-down is connected to the foundation with a foundation anchor rod set deep in the concrete, secured with epoxy.



As it tries to overturn, the left end of this shear wall pulls up on the hold-down, which in turn pulls up on the foundation anchor rod. The concrete must be strong enough so that the foundation anchor rod does not break out of the foundation. In addition, the foundation must have enough strength and weight so that it does not lift up or deform. Large hold-downs can resist upwards of 15,000 pounds of force, but can only be effective if attached to a foundation that also weighs 15,000 pounds (or can mobilize 15,000 pounds of building weight). Note that only *one* hold-down acts at any given moment as the shear wall rocks back and forth.



Sometimes the overturning forces are so great that an un-reinforced concrete foundation breaks, or an improperly reinforced foundation deforms. This can lead to a lot of movement of the floor that results in significant damage to the structure.

Concrete poured under holdowns and foundation to prevent overturning

Long anchor rods for holdowns need full embedment in concrete

Foundations under retrofit shear walls often need extra attention in order for them to resist large overturning forces. Many old foundations are shallow and narrow and most do not have reinforcing steel. Many of them are also cracked. Without reinforcing steel these foundations can snap at the hold-down locations. Ideally we want to make sure that the uplift force on the hold-down is resisted by the same amount of downward force provided by the foundation weight. The best solution to prevent overturning in shear walls with un-reinforced concrete foundations is to provide additional

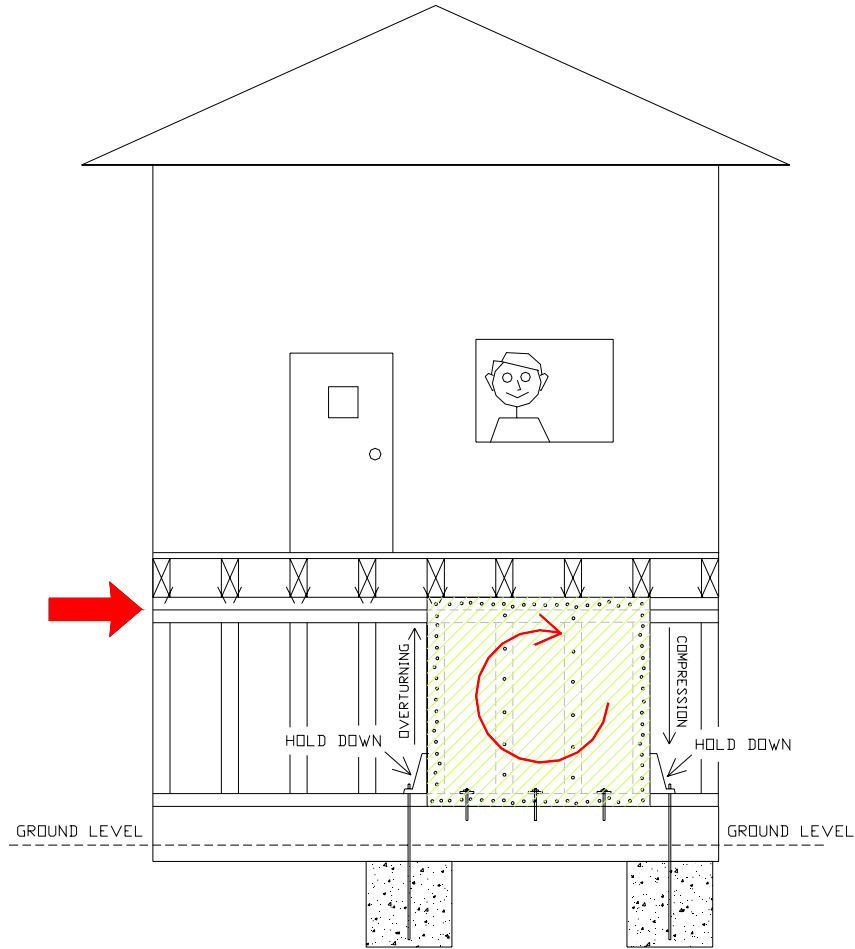
weight to anchor the hold-downs. This can be done by pouring heavy blocks of concrete beneath the hold-downs. One cubic yard of concrete weighs 4000 pounds; on tall narrow walls you often need a full cubic yard of concrete under each hold-down.

After calculating the required weight, dig a hole centered under the hold-down location that is large enough to hold the amount of concrete you will need. Once you dig the hole under the old foundation, drill through the existing concrete at the hold-down location next to the end studs so that you can extend the hold-down anchor rod through the hole to be embedded in new concrete. Install the all-thread anchor rod through the old foundation until it extends to 4 inches above ground level at the bottom of the hole. Put a nut on the end of the anchor rod then fill the hole with concrete. If your shear wall is 8 feet tall and carries a force of 500 pounds per foot then you will have 4000 pounds of uplift and since concrete weighs 4,000 pounds a cubic yard, you have effectively resisted the overturning force.

The existing un-reinforced concrete foundation shown here is only 8 inches deep and 12 inches wide. This is clearly insufficient to resist the overturning forces that a new 8 foot tall by 8 foot long shear wall will exert on the foundation. A one-cubic yard hole has been dug out under both ends of the shear wall so that these holes can hold 4000 pounds of concrete.



Here is the same view after the concrete has been poured and the plywood installed. An all-thread anchor rod with a nut at its lower end has been cast into each block of concrete to anchor the hold-downs to the new concrete.



Some engineers have concerns that the added concrete weight will cause settlement of the ground beneath. Concrete weighs about 145 pounds per cubic foot while soil weighs about 115 to 120 pcf. Digging out soil and replacing it with concrete results in a net increase of about 30 pounds per cubic foot, or about an 800 pound increase for a cubic yard. But when you dig down three feet (assuming a cube) you get a significant increase in the allowable bearing capacity of the soil. So in almost all cases, you're better off with respect to settlement by adding the concrete. It is extremely rare for the additional concrete to cause settling problems unless the house was built on uncompacted fill, in which case it would already be settling.

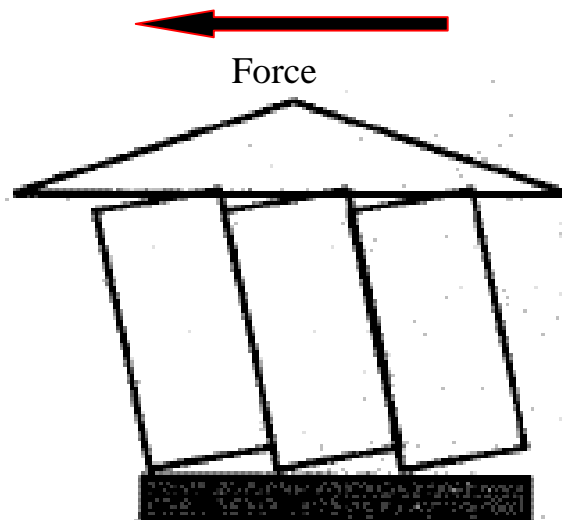
Lastly, if you have used the base shear formula and information provided here to calculate how much uplift you will have and what size hold-down to use, it's a very simple step to determine how much concrete it will take to resist that uplift. Its not so simple if you want to count soil adhesion and/or weight of adjacent building components, which can lessen by a substantial amount the quantity of required concrete and related excavation--but in the end it will probably be a toss-up between engineering costs vs. concrete/excavating costs. If you're curious, you might ask for a half hour of a structural engineer's time and get his opinion on these matters. Digging a hole for more concrete than you actually need is an unpleasant task, especially if it is not necessary.

Foundations with steel reinforcing are much stronger than plain concrete foundations but surprisingly, the building code used in California only began requiring reinforcement (“rebar”) in residential foundations in 1997, and then only in Seismic Zones 3 and 4. The Bay Area is in seismic zone 4. All concrete cracks as it cures so rebar is placed in foundations to hold the concrete together after it cracks. Unfortunately, in an older foundation there is no way to know for sure if it has rebar without using a special metal detecting device.

Cracks leave un-reinforced foundations very prone to breaking near the hold-downs due to the large uplift and compression forces that shear walls can exert at those locations. Cracks may be microscopic and are not always obvious to the naked eye. Fortunately, after about 1960 it was a common construction practice to install rebar in foundations, but it is still possible that a retrofit shear wall can exert sufficient forces on a reinforced foundation to damage it.

In reinforced foundations, because the concrete is connected together with steel, the hold-downs will try to pick up longer segments of foundation. Foundations reinforced with steel are much less likely to break, even though the foundation may not have sufficient weight to resist the overturning forces.

Homeowners often cannot afford the work involved in pouring additional concrete to anchor hold-downs, but still insist that something done. Here it is very important to inform the owner of the limitations his retrofit will have without this concrete work. Simply nailing up plywood on the walls should keep the studs from collapsing onto each other, but once overturning forces tear the plywood out of the sill the wall will no longer be able to resist shear forces. If the concrete is good and the footing deep the shear wall assembly should remain intact and keep the house from collapsing.. Best of all is to install concrete under the hold-downs to resist any significant overturning. These options should be explained to the homeowner. If the homeowner still chooses not to do this foundation work it is important to install the hold-down anchor rods as deep into the existing foundation as possible. This way the hold-downs will try to pick up as much of the foundation as possible; the deeper the hold-down anchor rod embedment, the more concrete the hold-down anchor rod will try to pick up.



Three segments of a shear wall tearing at vertical joints

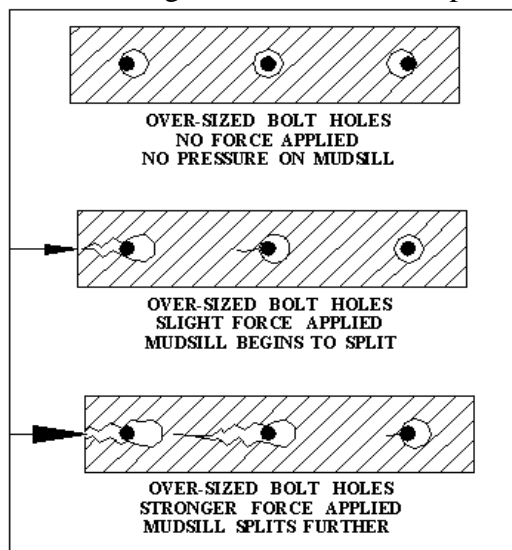
The figure above shows a shear wall made of 3 pieces of plywood. Each piece must resist overturning forces and this force can cause the shear walls to tear apart at the seams. This type of failure occurs because the individual sheets of plywood are not connected well enough where they are butted together.

It is very important that plywood shear walls be well stitched together at adjoining edges so that they perform as one piece of plywood. The American Plywood Association recommends framing at panel joints be a single 3x4 or double 2x4s nailed together with 12d common nails 3 inches on center staggered.

Shear, Compression, and Overturning Forces

The shear, compression, and overturning forces can cause a shear wall to fail in the following ways:

- Earthquake forces are ultimately resisted by the bolts in the mudsill. If there are not enough bolts, or the bolts are installed in oversized holes, the mudsill can split. Inadequate bolting allows the whole wall to slide along the foundation and split the sill.



Split Mudsill

- When the nails in the plywood lift up on one edge of the mudsill while the bolts anchor the mudsill to the foundation, the mudsill is put into “cross-grain bending.” A primary function of plate washers on anchor bolts is to reduce cross grain bending damage.



•
Cross-grain bending

- The nails tear out of the edge of the plywood where it connects to the mudsill. This is more likely if the nails are driven too close to the edge of the plywood. In these cases you will see the nails remaining in the mudsill.
- The nails bend over due to the plywood pushing against the nails. This tears holes in the plywood at the nail head locations.
- Finally, the end studs can crush the mudsill. This is usually found in tall, narrow shear walls where a lot of compression force pushes downward on the end studs.

All of the above problems can occur individually or in combination. Any shear wall is only as strong as its weakest link. Because shear walls can fail in so many ways, it is very important that they be built very carefully and as strongly as possible.