

**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.

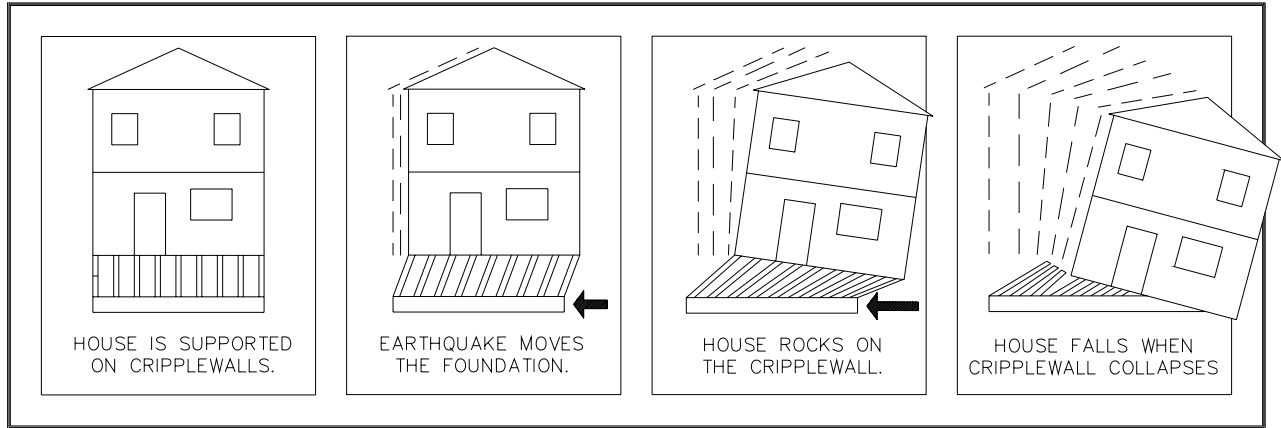
Many homes on the West Coast were built at a time when the floor of the house was elevated off of the foundation with something called cripple walls. Most of these homes were also built before the building code was either established or had provisions for making newly constructed homes earthquake resistant. Older homes with these cripple walls need to be retrofitted to avoid collapse in a major earthquake.<sup>1</sup> 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.

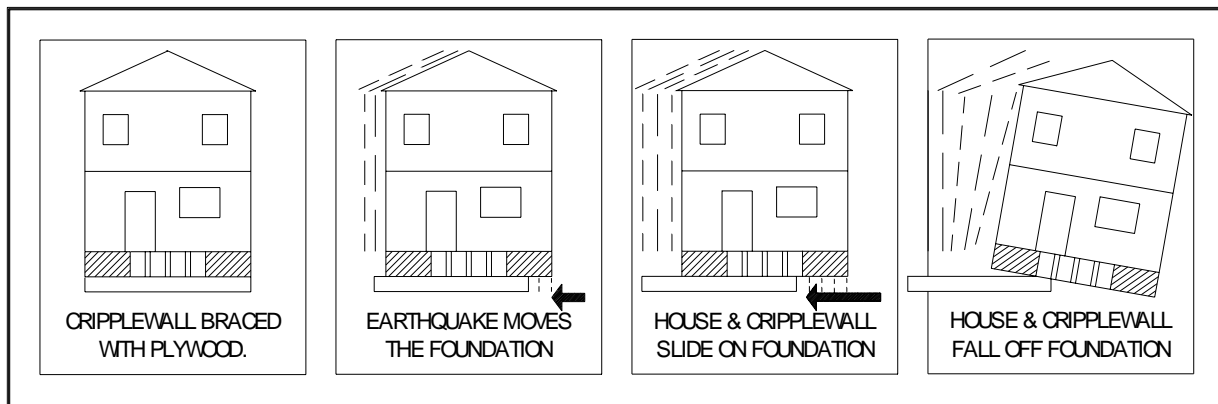
## 1. Bracing the Cripple Walls with Plywood



**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.

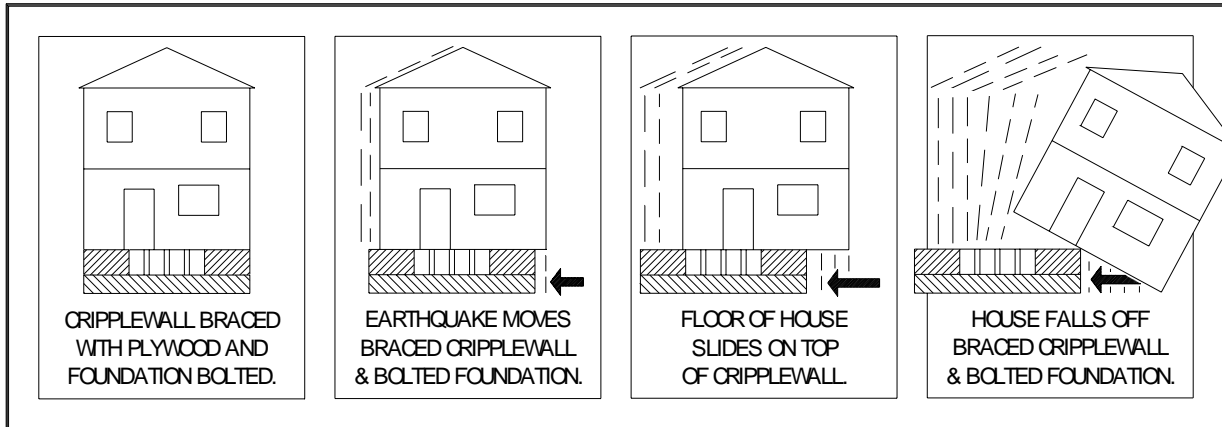
## 2. Bolting the Braced Cripple Walls to the Foundation



**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.<sup>2</sup> 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.

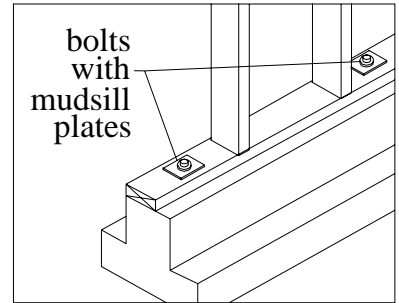
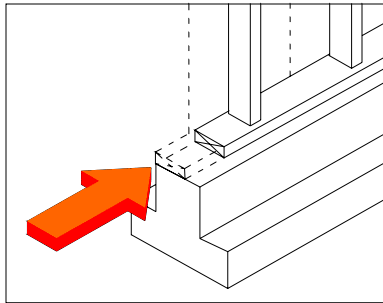
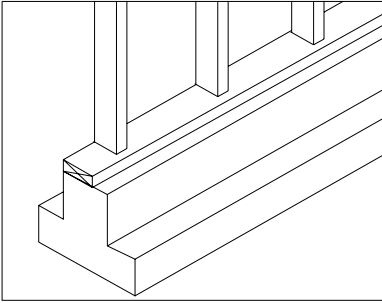
### 3. Attaching the Floor of the House to the Braced Cripple Walls



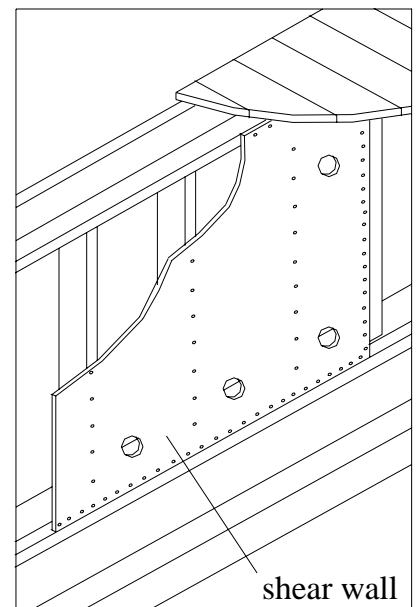
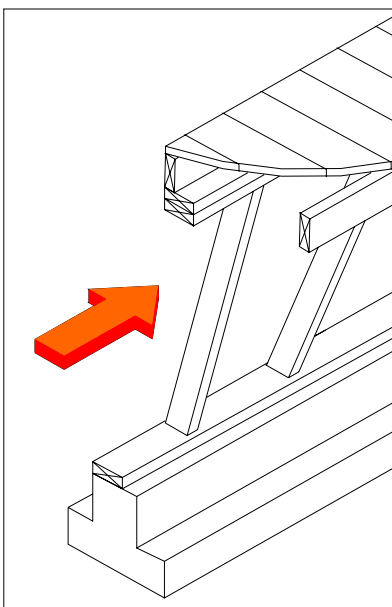
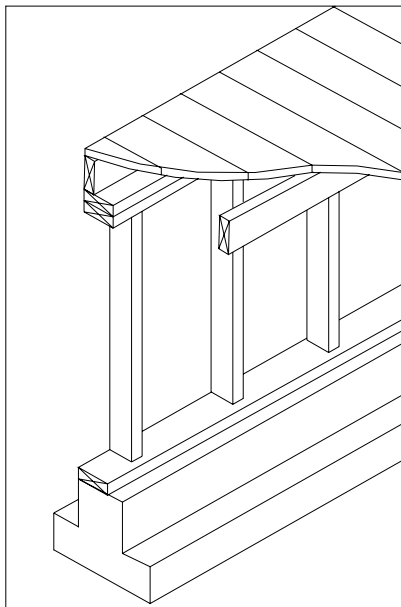
**Figure 3:** Failure due to no connection of floor to cripple wall

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*.

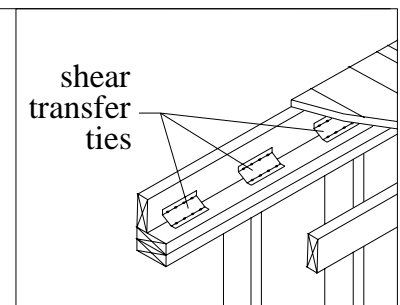
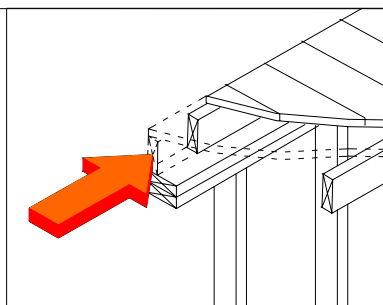
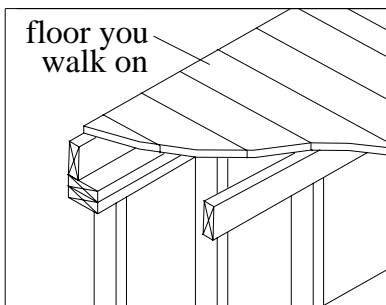
The following cross-sectionals give you another view of how the house can move in the three areas during an earthquake and where the bracing will be applied to curb the movement.



Movement prevented by bolts.



Movement prevented by plywood shear panels.

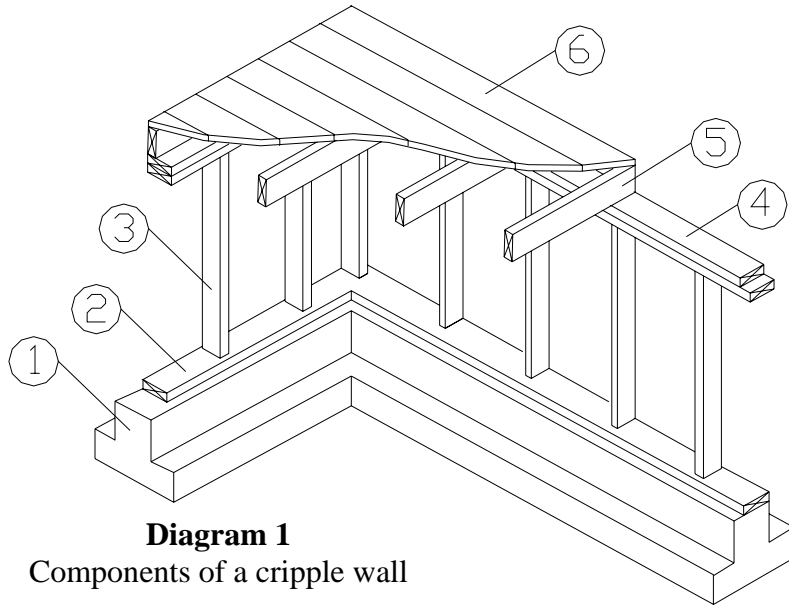


Movement prevented by shear transfer ties.

# Under your House

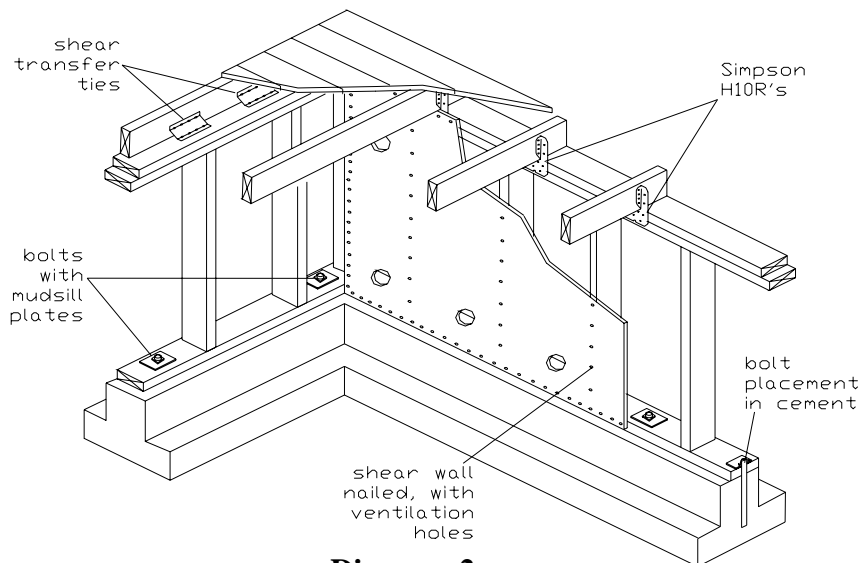
Diagram 1 shows what a cripple wall would look like if you cut the floor away. As a homeowner in the Bay Area, you should be able to look under your house and identify the components shown in Diagram 1.

- 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.

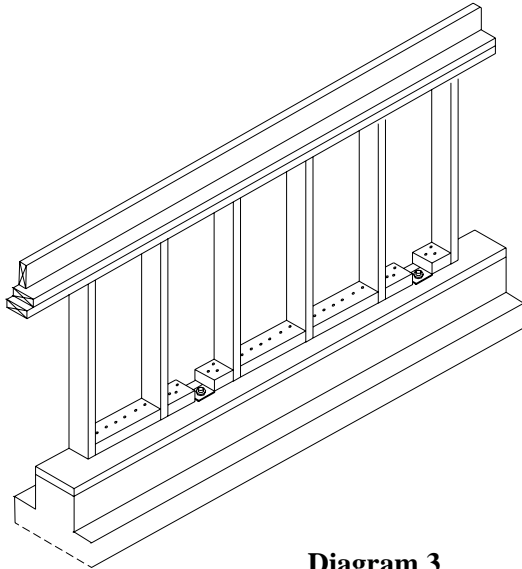


Diagram 3

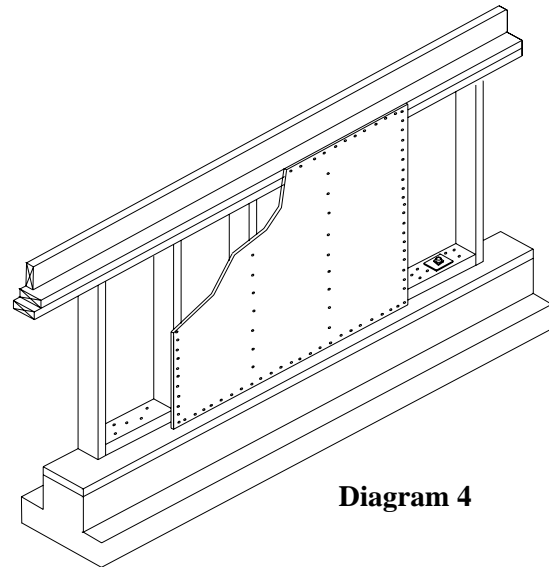


Diagram 4

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.

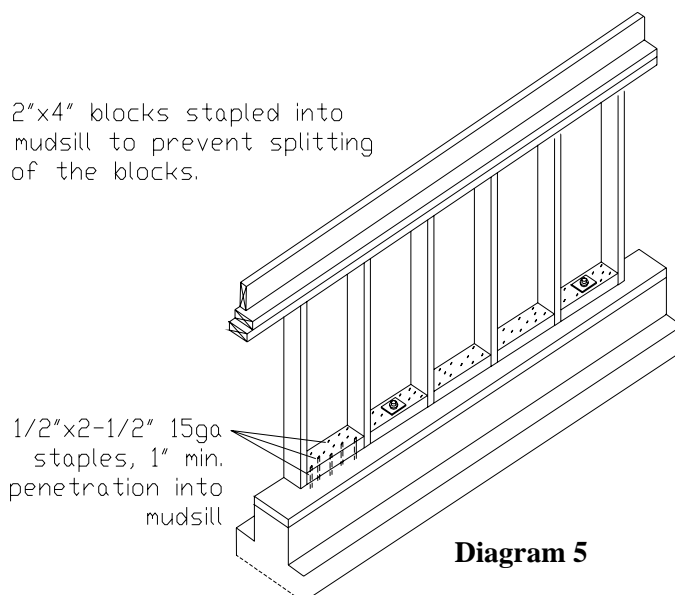


Diagram 5

### 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



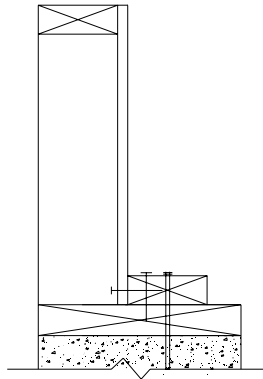
The photo above shows a block behind a shear wall that split with only four nails installed.



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

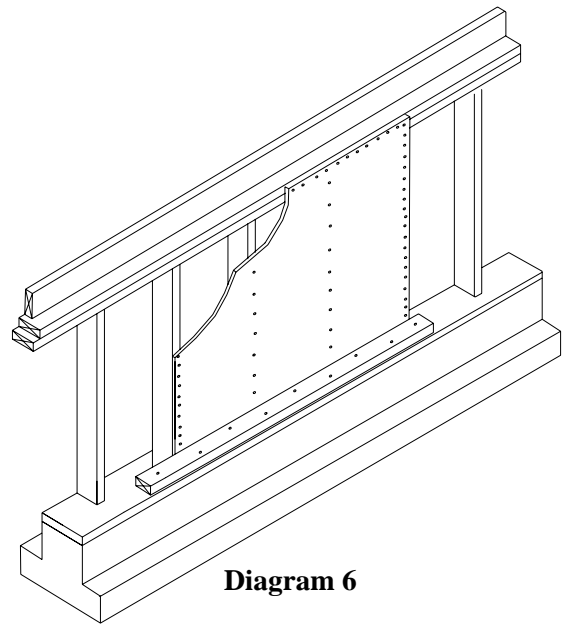


Diagram 6

### 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.

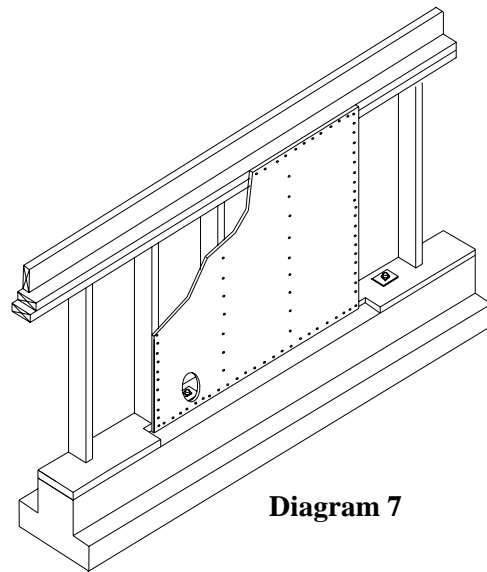
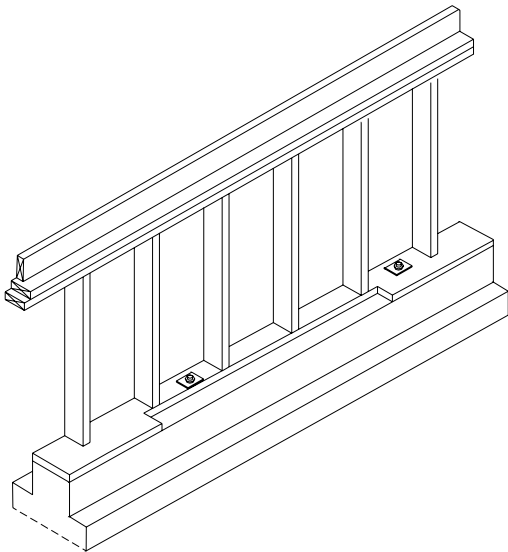


Diagram 7

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.



A P A

*The Engineered Wood Association*

To: The International Code Council

Dear Council Members,

Based on my professional opinion, I would judge the retrofit strategies in the following order, from most preferred to least preferred.

- 1.) Flush-cut mudsill method
- 2.) Reverse block method
- 3.) Stapled blocking method
- 4.) Nailed blocking method

I have chosen to order the retrofit strategies based on several reasons. In the past 8 years, there has been an unprecedented amount of cyclic testing on shear walls by APA and other organizations. The results from these various programs would be more similar to either the flush-cut mudsill or the reverse block method; hence I have a great deal of confidence in either of these methods. I believe the flush cut method would be more practical for most retrofits, but the reverse block method would be an acceptable alternative.

In my experience of personally working with small blocks of wood in the laboratory as well as small building projects of my own, I believe that multiple nails through the face of the small blocks greatly increase the splitting potential of the small wood blocks. Obviously if the blocks split for either the nailed or stapled blocking method, the structural integrity of the retrofit will be compromised. Nails tend to split wood worse than staples. Therefore, I believe the stapled block method is preferred over the nailed blocking method.

In summary, on paper, all of the retrofit strategies are acceptable. Since APA has not, and has no plans to conduct testing of these retrofit strategies, engineering judgment based on experience can be used to rank the different methods. I am of the opinion that my itemized list above is a reasonable ranking of the four methods.

I hope you find this information useful and if you have any questions, or would like to discuss this further, please don't hesitate to contact me.

Sincerely,

THOMAS D. SKAGGS, Ph.D., P.E. Senior  
Engineer Technical Services Division

## The Base Shear Formula

You will have to do a bit of arithmetic and use a very simple formula known as the base shear formula to determine exactly how many bolts, how much plywood, and how many shear transfer ties your house will need.

Geologists are able to calculate an “anticipated” amount of force that will be generated by a major earthquake in a specific geographical region. Knowing that “anticipated” force, retrofitting uses what is called the *base shear formula* to calculate the amount of shear force (earthquake force) that will hit the base of a specific house. If the three potential areas of failure are made strong enough to resist the forces determined by the base shear formula, the house is considered retrofitted and should survive a major earthquake. Elementary multiplication is all you need to know to understand this formula.

The base shear formula is:

$$V = 0.2 (W)$$

$V$  represents the shear force that will be generated at the base of a building.

0.2 represents anticipated force of ground acceleration from a major earthquake. This number varies from region to region and is based upon proximity to known earthquake faults.

$W$  represents the weight of the building. Single story homes weigh approximately 50 pounds per square foot. Two story homes weigh 80 pounds per square foot of the first floor area.

**Example:** We have a two-story house with a first story that is 25 feet by 40 feet. The first story is thus 1,000 square feet ( $25 \times 40 = 1,000$ ). If we multiply this times 80 pounds, we determine that the building weighs 80,000 pounds. Using this information and the base shear formula we can determine the amount of earthquake force expected to strike this building. We will want to design a retrofit that will resist this amount of force.

So, the base shear formula tells us the anticipated earthquake force equals 0.2 times the weight of the house being retrofitted.

For our example we would use the base shear formula as follows:

$$V = 0.2 \times \text{weight of house}$$

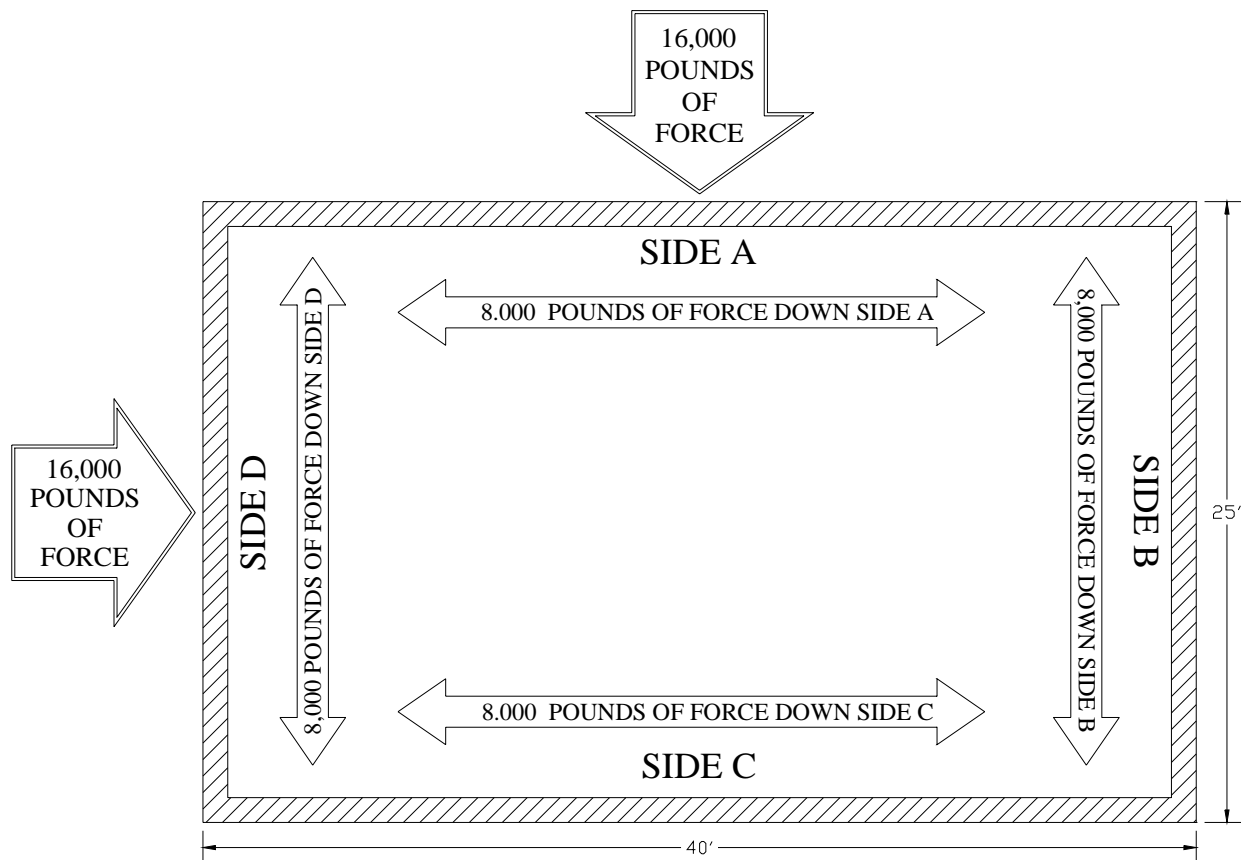
$$V = 0.2 \times (\text{area in square feet of the first floor} \times \text{weight per square foot})$$

$$V = 0.2 \times 1,000 \text{ sq. ft.} \times 80 \text{ pounds per sq. ft.}$$

$$V = 0.2 \times 80,000 \text{ pounds}$$

$$V = 16,000 \text{ pounds}$$

Therefore the earthquake force that is anticipated to strike this home at its base (foundation area) during a major earthquake is 16,000 pounds.

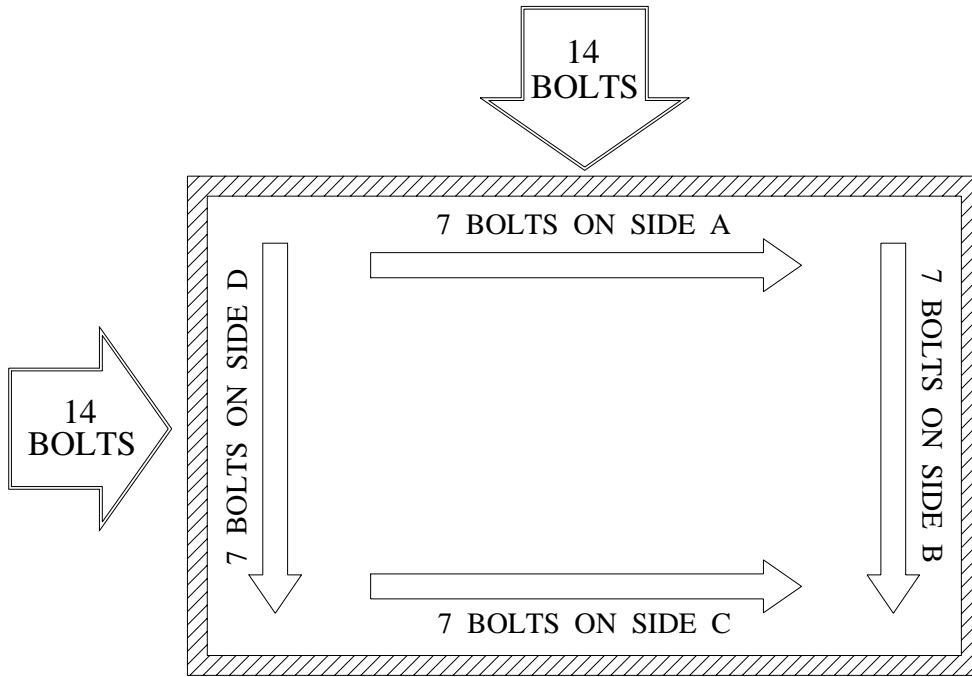


**Diagram 8:** Earthquake force against base of house

This means a properly designed retrofit for this house must have enough bolts to resist a minimum of 16,000 pounds of force where the mudsill sits on the foundation, AND enough plywood on the cripple walls to resist a minimum of 16,000 pounds force and keep the cripple walls from collapsing, AND enough shear transfer ties to resist a minimum of 16,000 pounds of force where the floor framing sits on top of the cripple wall.

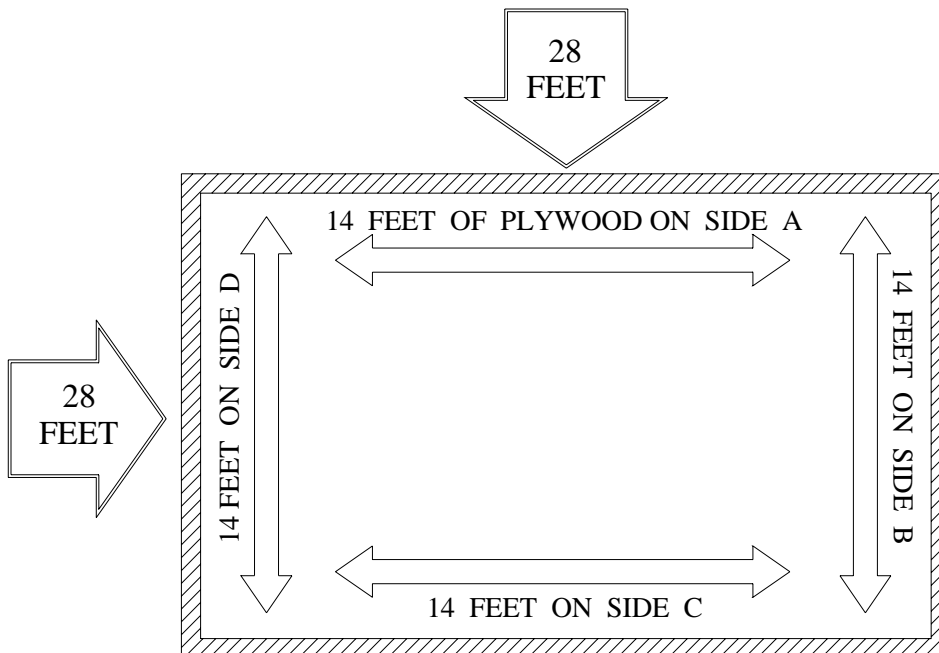
This information allows us to determine how much hardware and plywood is needed to protect these three weak areas. All bolts, nails, plywood, shear transfer ties, etc., are rated in terms of the amount of earthquake force they can resist. For example, a 1/2-inch bolt with a mudsill plate and plate washer can resist 1,200 pounds of force. Each linear foot plywood bracing using the flush cut method can resist 600 pounds of force. Good shear transfer ties can also resist around 600 pounds of force.

The house in our example could be attacked by 16,000 pounds of earthquake force in any direction. We know that a 1/2-inch bolt with a plate washer and mudsill plate provides 1,200 pounds of earthquake resistance. To determine the number of 1/2-inch bolts we will need, we divide 16,000 by 1,200. The answer is 13.3 bolts. We round this up to 14 bolts. This means we need a total of 14 bolts to protect the house in the north-south direction and 14 bolts to protect it in the east-west direction. To protect this house we will need to install 7 bolts along each foundation wall. Bolts only need to be installed at plywood shear wall locations because practically all of the earthquake forces is absorbed by the plywood and transferred to the bolts located at the base of the shear wall.

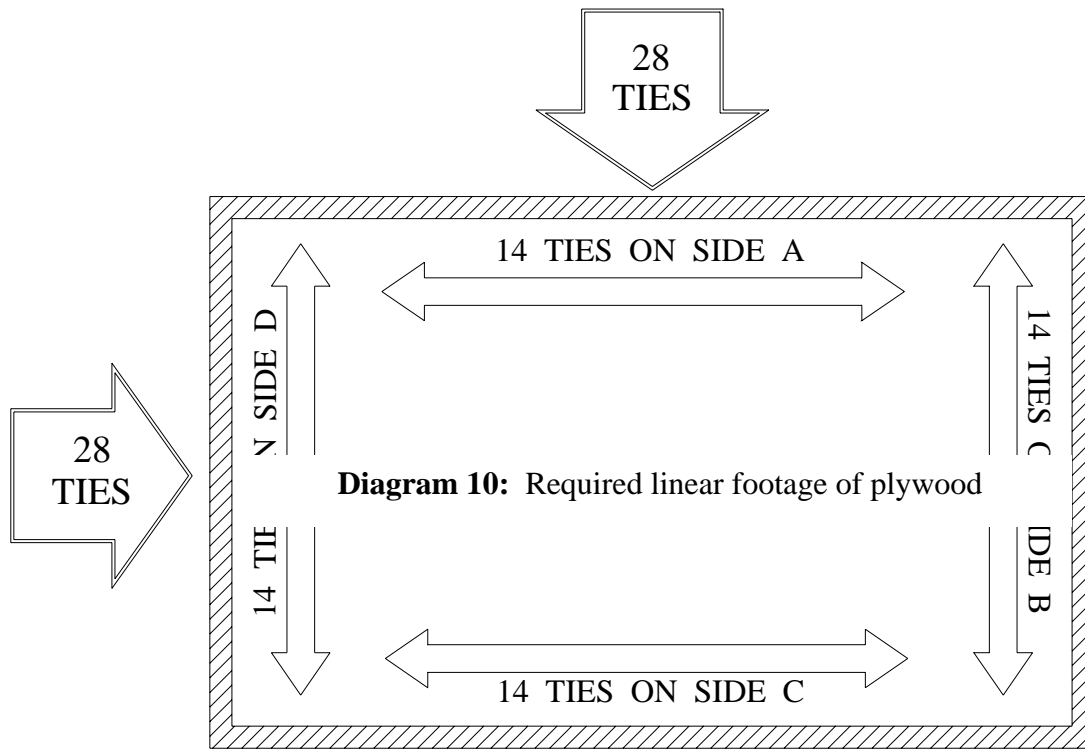


**Diagram 9:** Required number of bolts

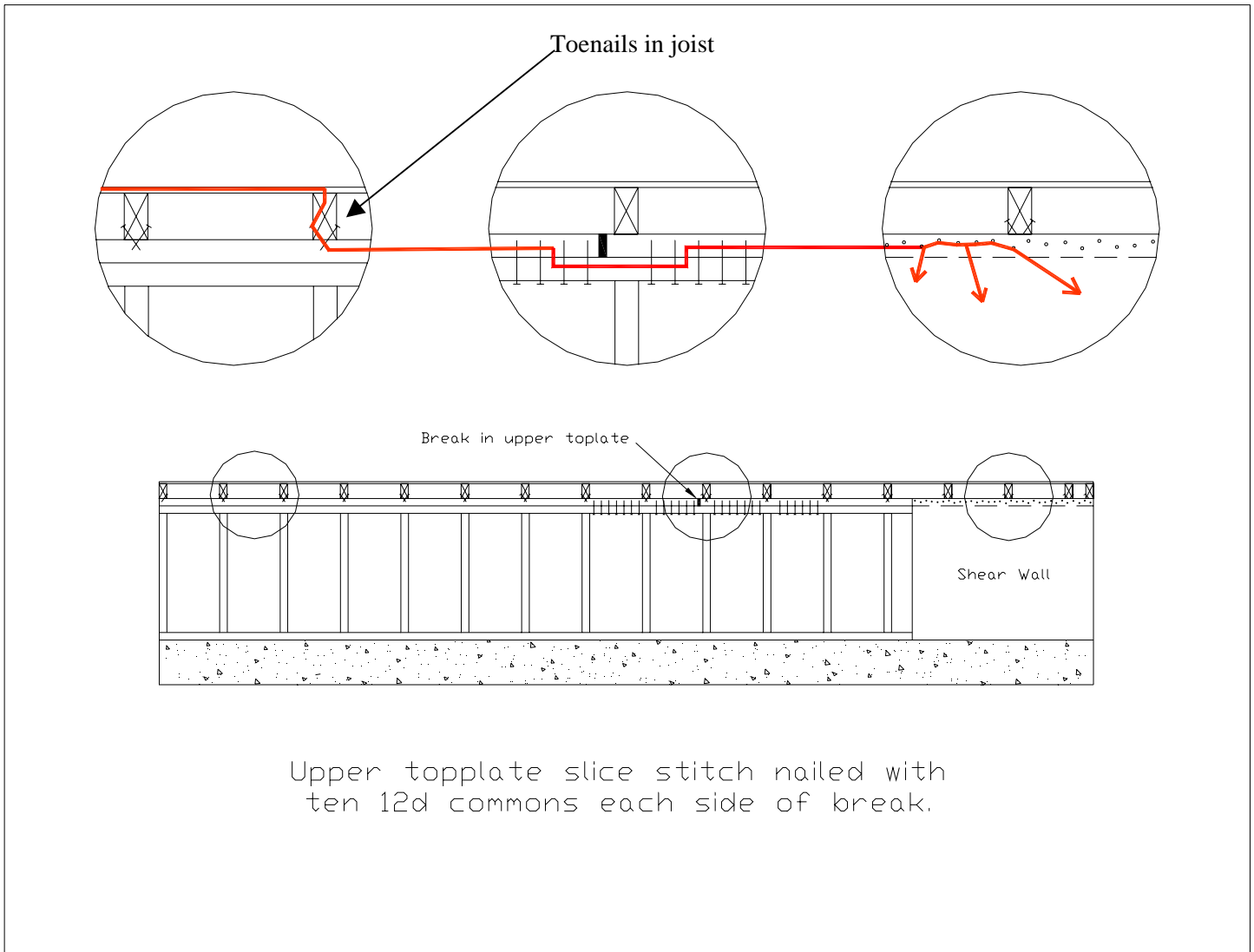
Next we need to address the bracing of the cripple walls. Each linear foot of good plywood cripple wall bracing using 15/32" structural 1 plywood can resist 600 pounds of earthquake force for each linear foot of plywood. If we divide 16,000 by 600 we get 26.6. We may round this up to 28 because plywood comes in 2-foot length increments. This means we need 28 linear feet of 15/32" structural 1 plywood in the east-west direction and 28 linear feet of plywood in the north-south direction, or 14 feet of plywood on the cripple wall on each side of the house.



The same method is used to determine the number of shear transfer ties needed to attach the floor framing to top of the cripple wall. Good shear transfer ties can resist 600 pounds of earthquake force. 16,000 divided by 600 equals 26.6. We round this up to 28 so that we can have an equal number of shear transfer ties on each side of the house. This means we need 28 shear transfer ties in the east-west direction and 28 in the north-south direction; or 14 shear transfer ties along each side of the house.



**Diagram 11:** Required number of shear transfer ties

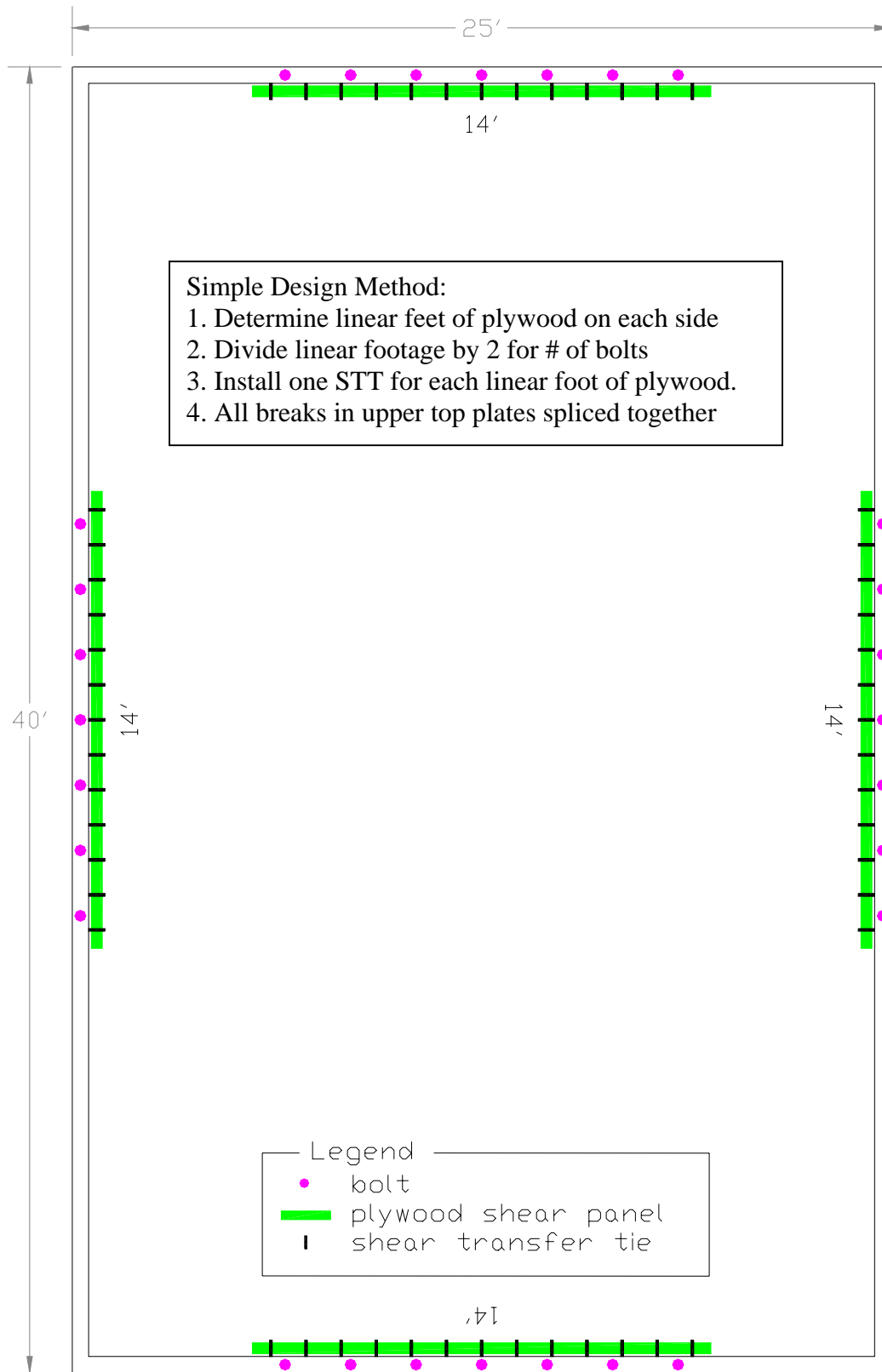


**Diagram 12: Upper top plate splice**

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.

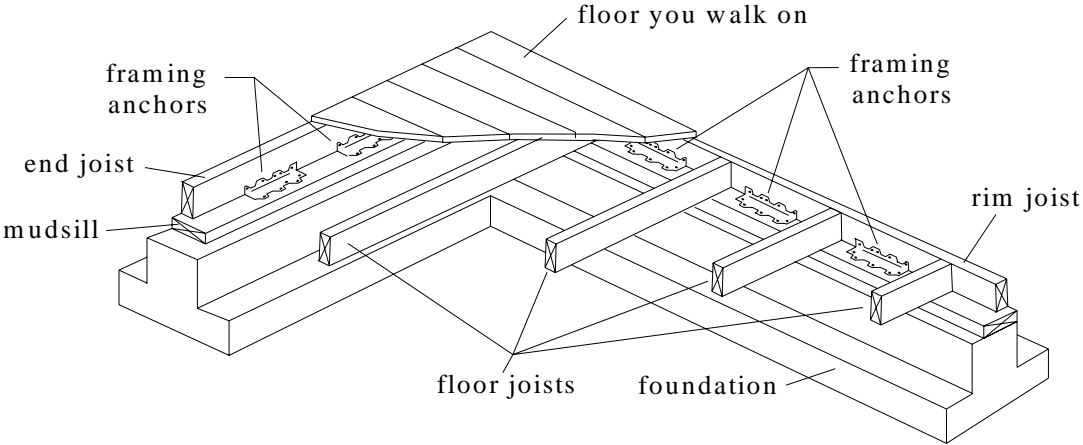
The circled portions and red line of the diagrams above illustrate what happens. As the floor moves to the left the movement of the floor is transferred to the toenails. The toenails in turn push on the upper top plate. This force is transferred all along the upper top plate until it reaches a break 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 what our final retrofit would look like.**



**Diagram 13: Complete retrofit**

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.

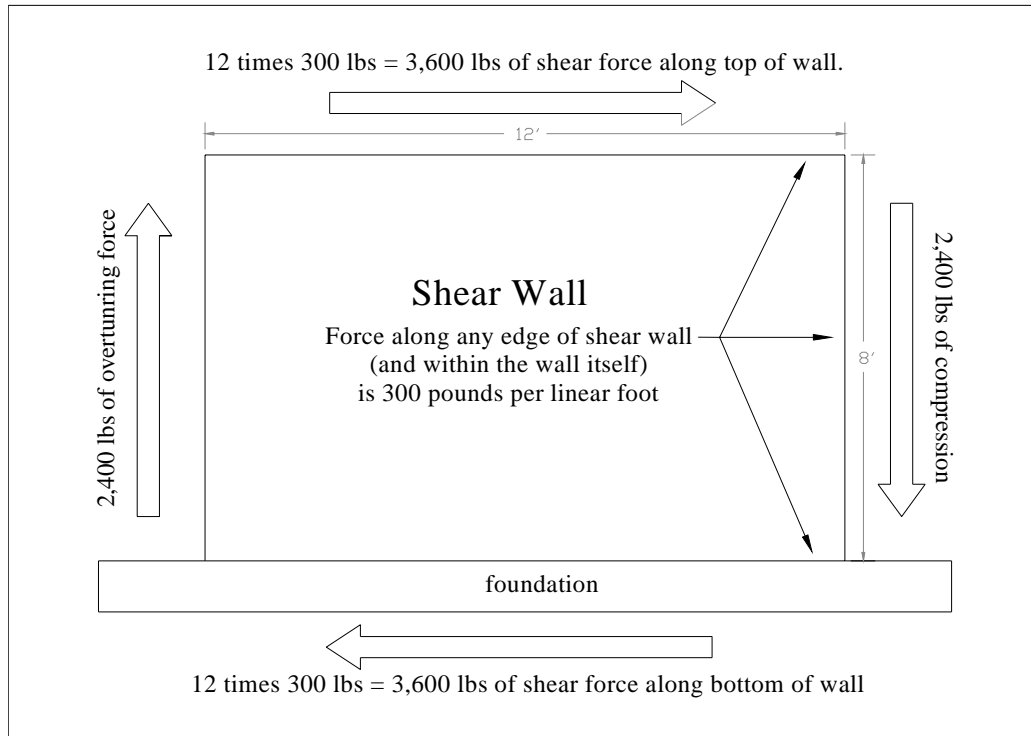
In a sense, 214 Elm Street was the "control element" in this amazing experiment. "The building came apart in four sections," O'Hearn said: "The one we had retrofitted (210 Elm St.) cost us \$5,000 to repair. The other one (214 Elm St.) cost us \$260,000 to repair. The whole building had to be jacked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

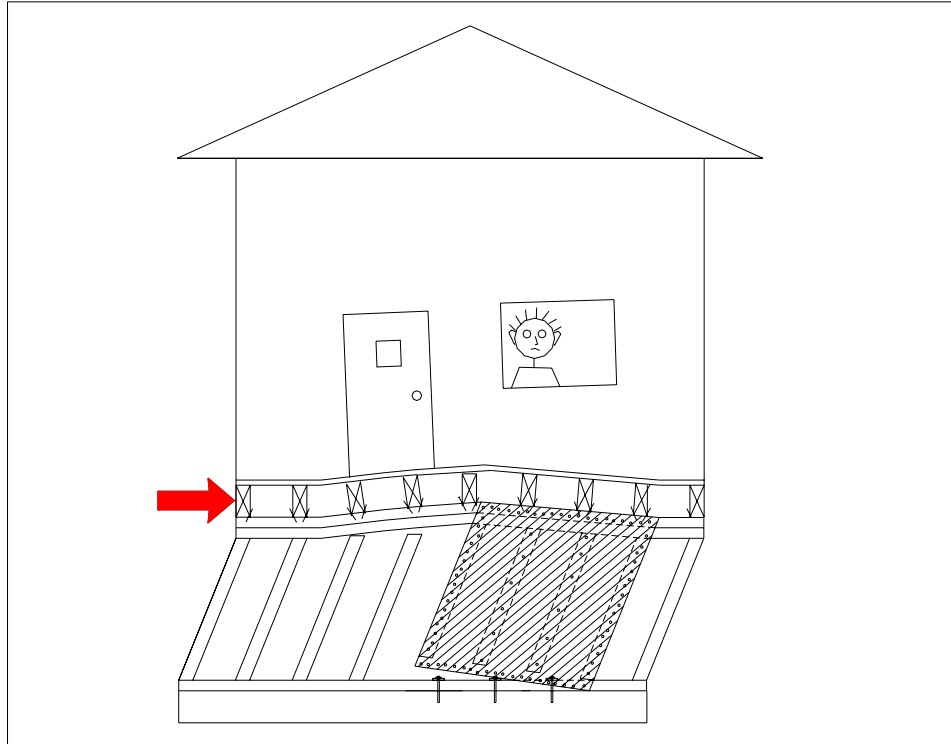


### Lateral and Overturning Forces acting of a Shear Wall

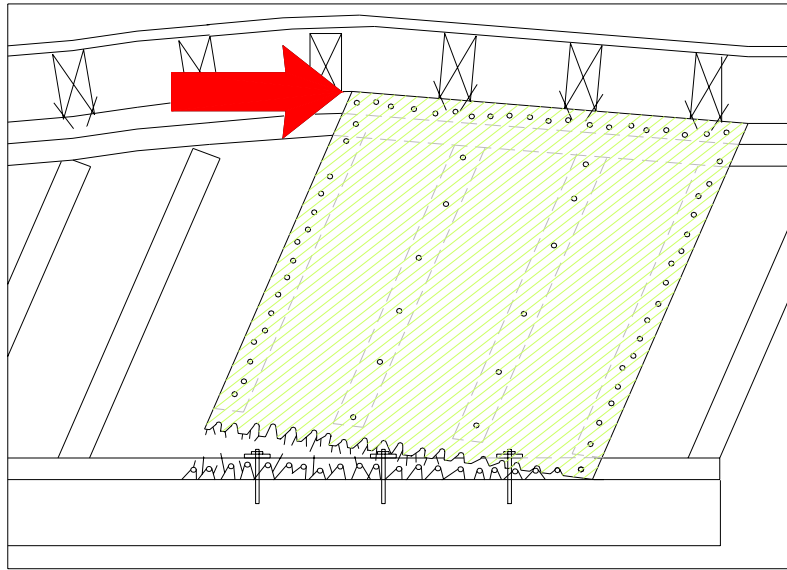
When the floor of the house pushes along the top of the shear wall, it not only tries to slide the wall along its length but also tries to roll it over. The lateral forces of an earthquake (called shear forces) acting along the top of a shear wall create overturning forces much as a tall chest of drawers 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.



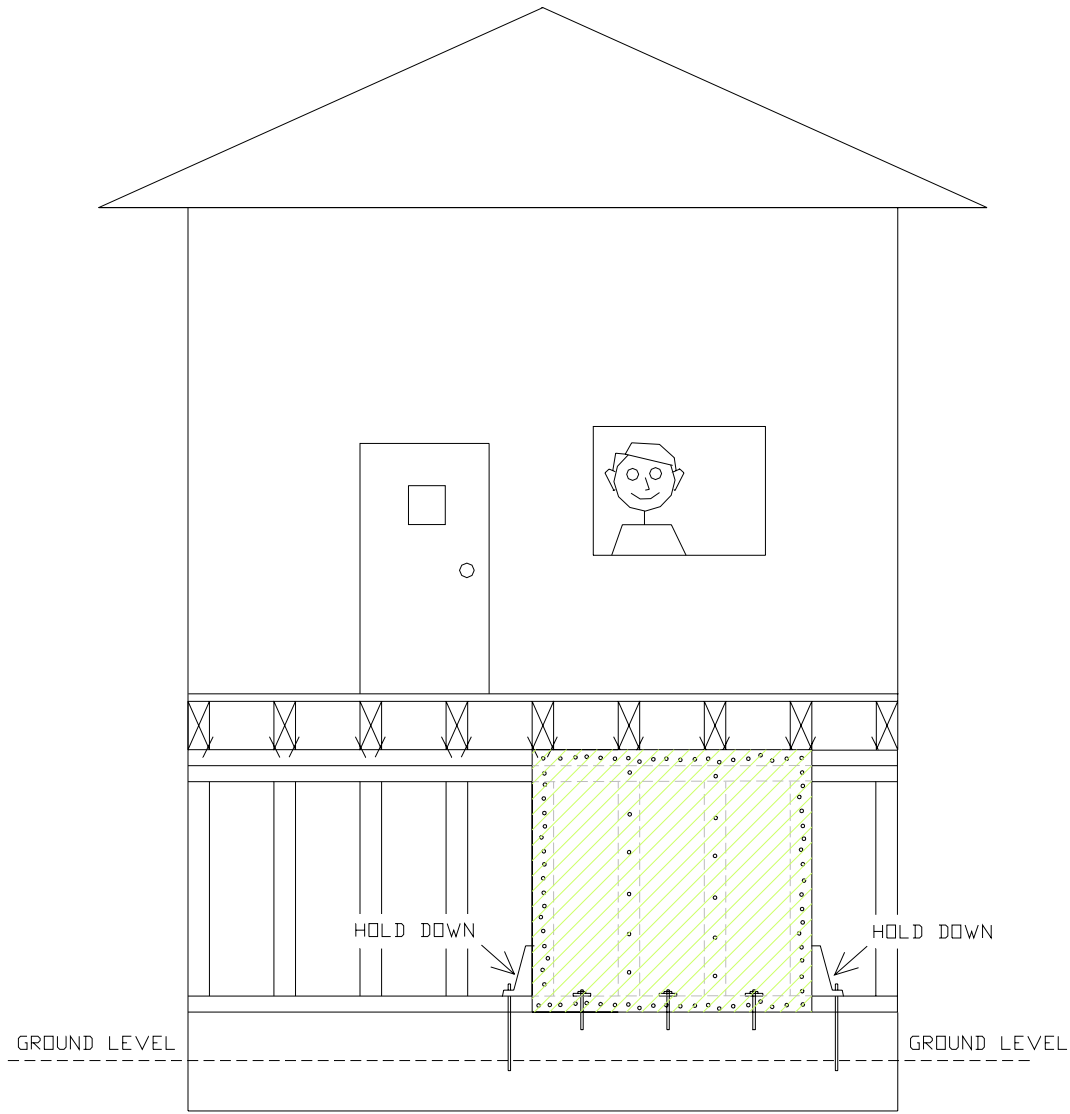
Here is an example of a shear wall overturning. This drawing is exaggerated in order to illustrate what happens. Most of the damage to the shear wall occurs where the plywood lifts up and away from the mudsill. The house will also sustain a significant amount of damage. Below is a close up illustrating tearing of the plywood at the mudsill. Once this happens the shear wall can not longer transfer shear forces into the bolts.



Overturning damage caused to shear walls at front of garage.

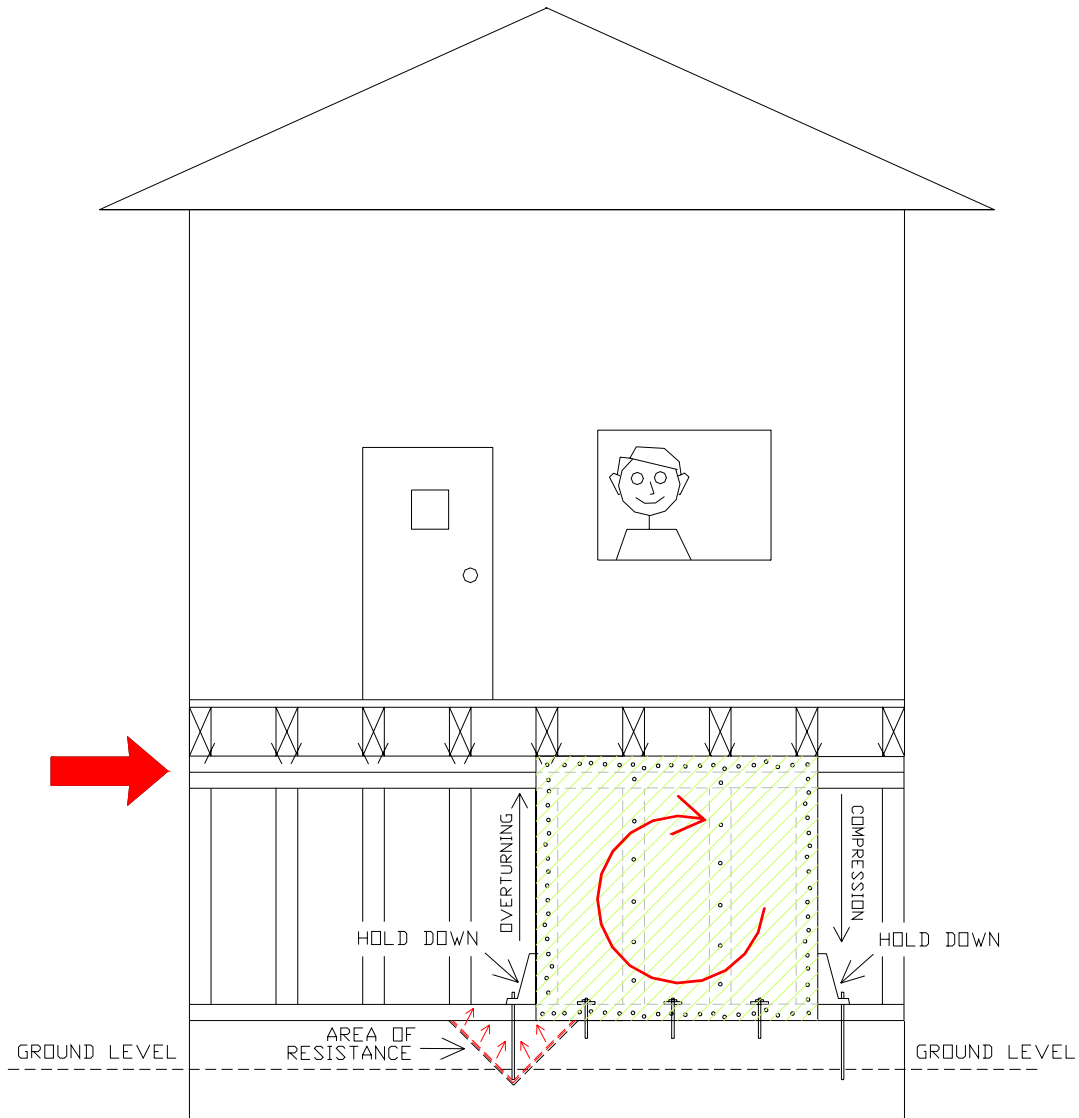


The building on the left used to be two stories. This collapse was caused by overturning of tall narrow shear walls that could not resist the earthquake forces generated by the heavy living area above a garage

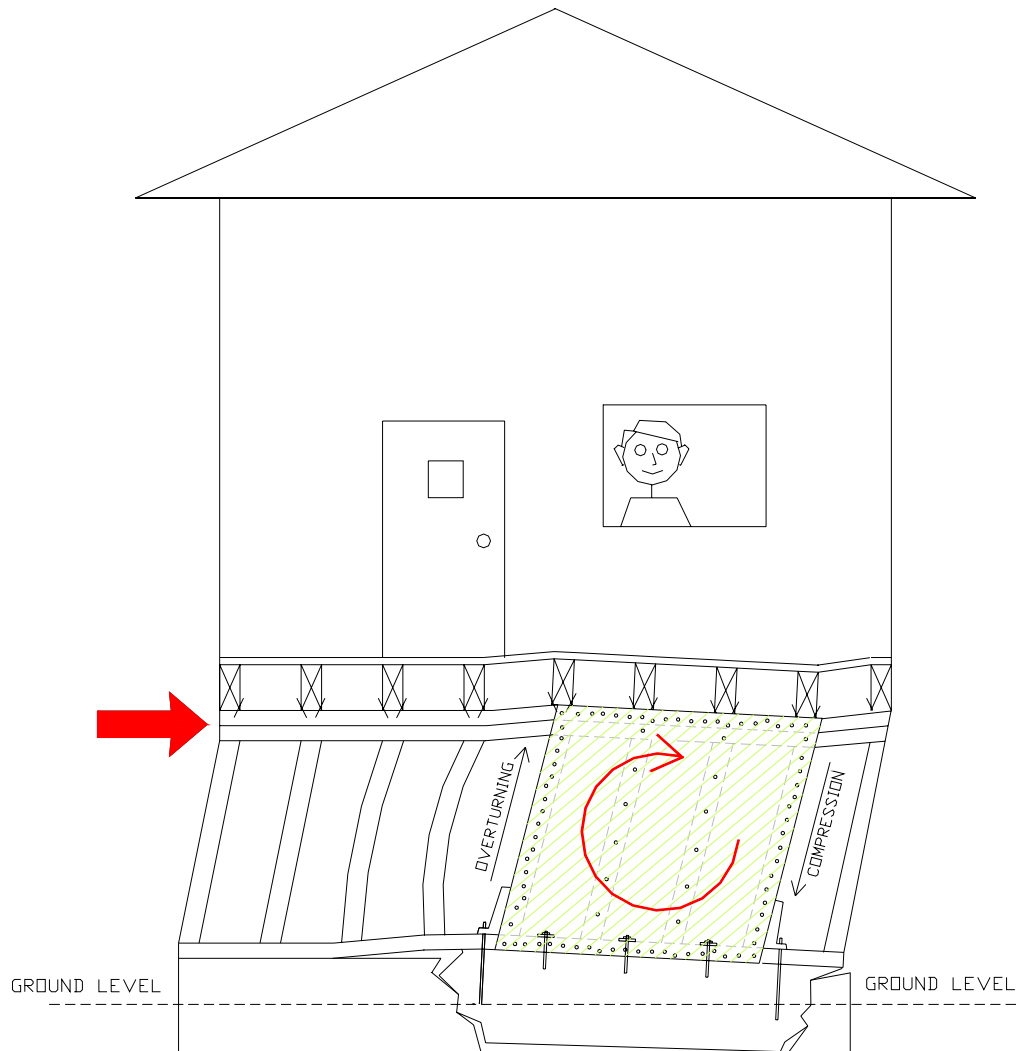


### **Shear Wall with Hold-downs to resist overturning**

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



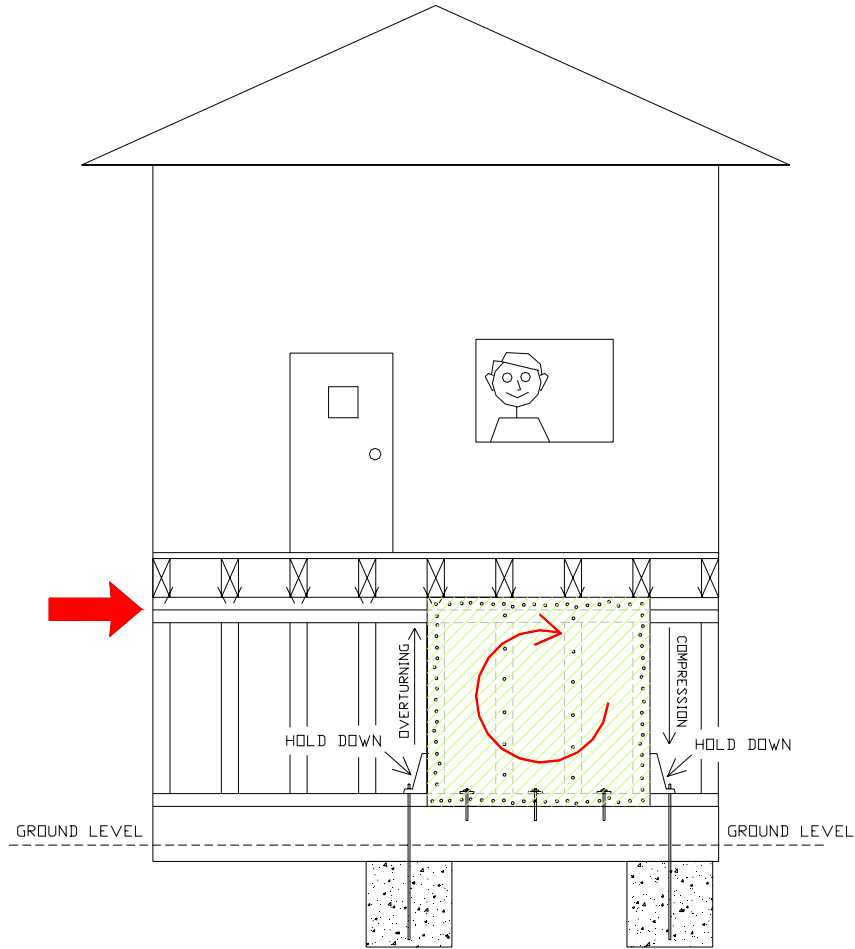
weight to anchor the hold-downs. This can be done by pouring heavy blocks of concrete beneath the hold-downs. One cubic yard of concrete weighs 4000 pounds; on tall narrow walls you often need a full cubic yard of concrete under each hold-down.

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.

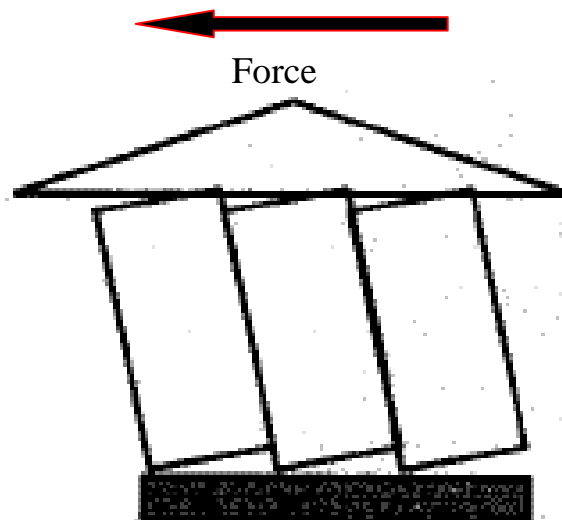
Lastly, if you have used the base shear formula and information provided here to calculate how much uplift you will have and what size hold-down to use, it's a very simple step to determine how much concrete it will take to resist that uplift. Its not so simple if you want to count soil adhesion and/or 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**

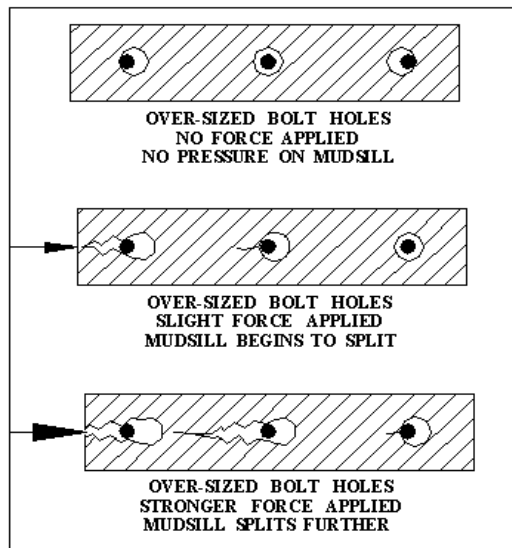
The figure above shows a shear wall made of 3 pieces of plywood. Each piece must resist overturning forces and this force can cause the shear walls to tear apart at the seams. This type of failure occurs because the individual sheets of plywood are not connected well enough where they are butted together.

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.

## Additional Concerns

- The concrete needs to be checked to make sure it can resist both shear and overturning forces.
- Mudsills need to have enough bolts with plate washers to prevent cross-grain bending. The configuration used in tests performed by the American Plywood Association were done with bolts installed in a 2 by 4 mudsill every 18 to 24 inches with 3 inch plate washers installed on each bolt. In their tests this effectively resisted cross grain bending.
- The bolt holes in the mudsill should be no more than 1/16" oversized as per the National Design Specification, or oversized holes filled with epoxy or non-shrink grout.
- The nail heads need to be flush with the skin of the plywood (not overdriven) so that all the plies of the plywood are engaged in an earthquake.
- Great care must be taken to insure the framing behind the plywood does not split. A chalk line must be snapped to mark the center of each stud where nails will be placed. Nails that are spaced close together should be staggered.
- At all plywood joints use either a full 4 by 4 or doubled 2 by 4's so that the shear walls do not tear apart at panel joints where two pieces of plywood meet.
- When using doubled 2 x 4's, nail them together with 12d commons at the same spacing used for the edge nailing of the plywood attached to them.

## Conclusion

The base shear formula and the other information in this guide will help you evaluate if your home has been properly retrofitted or not. Retrofits cost thousands of dollars and to make sure that your retrofit is a good one, the best thing you is to research the topic. For additional information about seismic retrofitting, go to [www.bayarearetrofit.com](http://www.bayarearetrofit.com). If you have any questions you can post them on the message board found at this website.

This explanation of seismic retrofit principles would not have been possible without the help of two wood frame structural engineers: Nels Roselund in Los Angeles and Thor Matteson in Central California. Nels Roselund is a historic building preservation engineer and evaluated much of the damage after the Northridge earthquake. Thor Matteson wrote the very best book on shear walls available and is published by the International Code Council. To get a really good understanding of shear walls I suggest you read his book available at [www.shearwalls.com](http://www.shearwalls.com) or from the International Code Council.

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## **Retrofitting a Home with this Information**

**Step 1:** Make a drawing that shows where the perimeter foundations are located and the outside dimensions of your house measure in feet. Just pace it off and get a rough estimate of the dimensions. Determine if the walls are made of plaster or sheetrock and what type of roof it has. Older homes almost always have walls made of plaster.

**Step 2:** Determine the square footage of the house by multiplying the length times the width.

**Step 3:** Multiply this number by the appropriate weight per square foot as determined below:

### **Types of Roofs**

Light roof is composition shingles or wood shingles.

Heavy roof is clay tile or cement tile.

#### **One Story Building Weights**

Wood siding, light roof, sheetrock walls    39 pounds per square foot.

Wood siding, light roof, plaster walls:    49 pounds per square foot.

Wood siding, heavy roof, plaster walls :    58 pounds per square foot.

Stucco siding, light roof, plaster walls:    50 pounds per square foot.

Stucco siding, heavy roof, plaster walls:    65 pounds per square foot.

#### **Two Story Building Weights**

Wood siding, light roof, sheetrock walls:    66 pounds per square foot.

Wood siding, light roof, plaster walls:    84 pounds per square foot.

Wood siding, heavy roof, plaster walls:    92 pounds per square foot.

Stucco siding, light roof, plaster walls:    72 pounds per square foot.

Stucco siding, heavy roof, plaster walls:    98 pounds per square foot.

**Step 4:** Multiply this number by 0.2 and divide by 2.

**Step 5:** As defined in the Homeowner's Guide, and all other available information you may have determine the number of bolts, linear footage of plywood cripple wall bracing and shear transfer ties needed to match the number arrived at in Step 4. If you find that you do not have enough available foundation on any side to meet the required linear footage of plywood tell the homeowner to install as much bracing as possible on the deficient wall and at least an equal amount of bracing on all the other walls.

**Step 6:** Tell the homeowner to research this subject for himself with the documents you provide him.

Determination of house weights based on calculations found in ICC Plan Set A's

**SUBSTANTIATING DATA FOR CRIPPLE WALL and SILL BOLTING**

**SEISMIC RETROFIT of ONE & TWO FAMILY DWELLINGS**

4/21/04

These weights are the engineering basis of Plan Set A. The building weights in the original calculations were for 4 cases of buildings. A fifth case, **Case D) Heavy roofing with wood sheathing or board finish**, has been added to the original calculations because this configuration is common in the Bay Area. All page citations are from the document mentioned above. .

The cases are as follows:

**Case A) Lightweight roofing (5 psf) of wood shake, wood shingle, or composition shingle, exterior wood sheathing and 1/2" gypsum wallboard interior finish. :**

**Case B) Lightweight roofing, (5 psf) of wood shake, wood shingle, or composition shingle, exterior wood sheathing, and gypsum lath and plaster interior finish.**

**Case C) Lightweight roofing (5 psf) of wood shake, wood shingle, or composition shingle, cement plaster (stucco) exterior finish, and gypsum lath and plaster interior finish.**

**Case D) Heavy roofing (11 psf) of concrete or clay tile, exterior wood sheathing or board finish, and gypsum lath and plaster interior finish.**

**Case E) Heavy roofing (11 psf) of concrete or clay tile, cement plaster (stucco) exterior finish, and gypsum lath and plaster interior finish.**



**Case A Weight for 30' x 40' One Story House (1,200 Sq. Ft.)**      **Page 10**

Dead loads (W) tributary to cripple wall level:

Roof/Ceiling:  $11 \text{ psf} (34' \times 44') = 16.456 \text{ kips}$

First floor:  $7 \text{ psf} (30 \times 40') = 8.4 \text{ kips}$

Exterior Walls:

1 <sup>st</sup> Story wall:	$8 \text{ psf} (8') (30' \times 2 + 40' \times 2) =$	$8.96 \text{ kips}$
Gable end walls:	$5 \text{ psf} (5' \times 30') 2 / 2 =$	$0.75 \text{ kips}$
Cripple walls	$6 \text{ psf} (2') (30' \times 2 + 40' \times 2) =$	$\underline{1.68 \text{ kips}}$
		$11.39 \text{ kips}$

Interior walls:  $8 \text{ psf} (8') (30' \times 3 + 40' \times 2) = 10.88 \text{ kips}$

Sum W =  $16.456 + 8.4 + 11.39 + 10.88 = 47.126 \text{ kips}$

***47.126kips/1200sf=39.27psf for a 1200sf one story Case A house.***

**Weight per square foot=-39 pounds**

**Case A- Weight for 30 ft x 30 ft Two Story House (1,800 Sq. Ft.)**      **P 42,**

Dead loads (W) tributary to cripple wall level for 1,800 square feet:

Roof/Ceiling:  $11 \text{ psf} (34' \times 34') = 12.716 \text{ kips}$

Second Floor:  $9 \text{ psf} (30' \times 30') = 8.10 \text{ kips}$

First floor:  $7 \text{ psf} (30' \times 30') = 6.30 \text{ kips}$

Exterior Walls:

1 <sup>st</sup> & 2 <sup>nd</sup> Story walls:	$8 \text{ psf} (16') (30' \times 2 + 30' \times 2) =$	$15.36 \text{ kips}$
Gable end walls:	$5 \text{ psf} (5' \times 30') 2 / 2 =$	$0.75 \text{ kips}$
Cripple walls:	$6 \text{ psf} (2') (30' \times 2 + 30' \times 2) =$	$\underline{1.44 \text{ kips}}$
		$17.55 \text{ kips}$

Interior wall:  $8 \text{ psf} (8') (29' \times 5 + 29' \times 3) = 14.848 \text{ kips}$

Sum W =  $12.72 + 8.10 + 6.30 + 17.55 + 14.85 = 59.51 \text{ kips}$

***59.51kips/1800sf=33.06psf for an 1800sf two story Case A house.***

**Weight per square foot=-33 pounds**

**Case B-Weight for 30' x 40' One Story House (1,200 Sq. Ft.) P19**

Dead loads (W) tributary to cripple wall level:

Roof/Ceiling:  $14 \text{ psf} (34' \times 44') = 20.944 \text{ kips}$

First floor:  $7 \text{ psf} (30 \times 40') = 8.4 \text{ kips}$

Exterior Walls:

1 <sup>st</sup> Story wall:	$10 \text{ psf} (8') (30' \times 2 + 40' \times 2) =$	$11.20 \text{ kips}$
Gable end walls:	$5 \text{ psf} (5' \times 30') 2 / 2 =$	$0.75 \text{ kips}$
Cripple walls	$6 \text{ psf} (2') (30' \times 2 + 40' \times 2) =$	$\underline{1.68 \text{ kips}}$
		$13.63 \text{ kips}$

Interior walls:  $12 \text{ psf} (8') (30' \times 3 + 40' \times 2) = 16.32 \text{ kips}$

Sum  $W = 20.944 + 8.4 + 13.63 + 16.32 = 59.294 \text{ kips}$

*59.294kips/1200sf=49.41psf for a one story Case B house.*

**Weight per square foot=-49 pounds**

**Case B-Weight for 30 ft x 30 ft Two Story House (1,800 Sq. Ft.) P48,**

Dead loads (W) tributary to cripple wall level for 1,800 square feet:

Roof/Ceiling:  $14\text{psf} (34' \times 34') = 16.184 \text{ kips}$

Second Floor:  $11 \text{ psf} (30' \times 30') = 9.90 \text{ kips}$       First floor:  $7 \text{ psf} (30' \times 30') = 6.30 \text{ kips}$

Exterior Walls:

1 <sup>st</sup> & 2 <sup>nd</sup> Story walls:	$10 \text{ psf} (16') (30' \times 2 + 30' \times 2) =$	$19.20 \text{ kips}$
Gable end walls:	$5 \text{ psf} (5' \times 30') 2 / 2 =$	$0.75 \text{ kips}$
Cripple walls:	$6 \text{ psf} (2') (30' \times 2 + 30' \times 2) =$	$\underline{1.44 \text{ kips}}$
		$21.39 \text{ kips}$

Interior wall:  $12 \text{ psf} (8') (29' \times 5 + 29' \times 3) = 22.272 \text{ kips}$

Sum  $W = 16.18 + 9.90 + 6.30 + 21.39 + 22.27 = 76.05 \text{ kips}$

*76.05kips/1800=42.25psf for a Case B Two Story House*

**Weight per square foot=-42 pounds**

**Case C Weight for 30' x 40' One Story House (1,200 Sq. Ft.) P27**

Dead loads (W) tributary to cripple wall level:

Roof/Ceiling: 14 psf (34' x 44') = 20.944 kips

First floor: 7 psf (30 x 40') = 8.4 kips

Exterior Walls:

1 <sup>st</sup> Story wall:	17 psf (8') (30' x 2 + 40' x 2) =	19.040 kips
Deduct for Windows:	-7 psf (130 sq. ft.)	<-0.91 kips>
Gable end walls:	12 psf (5' x 30') 2 / 2 =	1.80 kips
Cripple walls	13.5 psf (2') (30' x 2 + 40' x 2) =	<u>3.78 kips</u>
		23.71 kips

Interior walls: 12 psf (8') (30' x 3 + 40' x 2) = 16.32 kips

Sum W = 20.944 + 8.4 + 23.71 + 16.32 = 69.374 kips

*69.374kips/1200=57.81psf or a Case C One Story House*

**Weight per square foot=-58 pounds**

**Case C- Weight for 30 ft x 40 ft Two Story House (2,400 Sq. Ft.) P52**

Assume SD soil with Ca = 0.44; Na = 1.3; I = 1.00; and R = 5.5; Conversion to ASD force level: 1 / 1.4  
Seismic V = 0.186 W

Dead loads (W) tributary to cripple wall level for 30 x 40 two story = 2,400 square feet:

Roof/Ceiling: 14 psf (34' x 44') = 20.944 kips

Second Floor: 11 psf (30' x 40') = 13.20 kips      First floor: 7 psf (30' x 40') = 8.40 kips

Exterior Walls:

1 <sup>st</sup> & 2 <sup>nd</sup> Story walls:	17 psf (16') (30' x 2 + 40' x 2) =	38.08 kips
Deduct for windows:	-7 psf (240 sq. ft.) =	<-1.68> kips
Gable end walls:	12 psf (5' x 30') 2 / 2 =	1.80 kips
Cripple walls:	13.5 psf (2') (30' x 2 + 40' x 2) =	<u>3.78 kips</u>
		41.98 kips

Interior wall: 12 psf (8') (29' x 5 + 39' x 3) = 25.152 kips

Sum W = 20.94 + 13.2 + 8.4 + 41.98 + 25.15 = 109.68 kips

*109.68 kips/2400=45.7psf for a Case C Two Story House*

**Weight per square foot=-46 pounds**

### **Case D Weight for 30' x 40' One Story House (1,200 Sq. Ft.)**

Dead loads (W) tributary to cripple wall level:

Roof/Ceiling: 20 psf (34' x 44') = 29.92 kips

First floor: 7 psf (30 x 40') = 8.4 kips

Exterior Walls:

1 <sup>st</sup> Story wall:	8 psf (8') (30' x 2 + 40' x 2) =	8.96 kips
Gable end walls:	5 psf (5' x 30') 2 / 2 =	0.75 kips
Cripple walls	6 psf (2') (30' x 2 + 40' x 2) =	<u>1.68 kips</u>
		11.39 kips

Interior walls: 8 psf (8') (30' x 3 + 40' x 2) = 10.88 kips

Sum W = 16.456 + 8.4 + 11.39 + 10.88 = 60.59 kips

***60.59kips/1200=50.49 psf for a CaseD One Story House***

**Weight per square foot=-50 pounds**

### **Case D Weight for 30 ft x 40 ft Two Story House (2,400 Sq. Ft.)**

Assume SD soil with Ca = 0.44; Na = 1.3; I = 1.00; and R = 5.5; Conversion to ASD force level: 1 / 1.4  
Seismic V = 0.186 W

Dead loads (W) tributary to cripple wall level for 30 x 40 two story = 2,400 square feet:

Roof/Ceiling: 20 psf (34' x 44') = 29.92 kips

Second Floor: 9 psf (30' x 40') = 10.80 kips      First floor: 7 psf (30' x 40') = 8.40 kips

Exterior Walls:

1 <sup>st</sup> & 2 <sup>nd</sup> Story walls:	8 psf (16') (30' x 2 + 40' x 2) =	17.92 kips
Gable end walls:	5 psf (5' x 30') 2 / 2 =	0.75 kips
Cripple walls:	6 psf (2') (30' x 2 + 40' x 2) =	<u>1.68 kips</u>
		20.35 kips

Interior wall: 8 psf (8') (29' x 5 + 39' x 3) = 16.768 kips

Sum W = 16.46 + 10.8 + 8.4 + 20.35 + 16.77 = 86.234 kips

***86.234kips/2400=35.93psf for a Case E Two Story House***

**Weight per square foot=-36 pounds**

**Case E Weight for 30' x 40' One Story House (1,200 Sq. Ft.) P 58**

Dead loads (W) tributary to cripple wall level:

Roof/Ceiling: 20 psf (34' x 44') = 29.92 kips

First floor: 7 psf (30 x 40') = 8.4 kips

Exterior Walls:

1 <sup>st</sup> Story wall:	17 psf (8') (30' x 2 + 40' x 2) =	19.040 kips
Deduct for Windows:	-7 psf (130 sq. ft.)	<-0.91 kips>
Gable end walls:	12 psf (5' x 30') 2 / 2 =	1.80 kips
Cripple walls	13.5 psf (2') (30' x 2 + 40' x 2) =	<u>3.78 kips</u>
		23.71 kips

Interior walls: 12 psf (8') (30' x 3 + 40' x 2) = 16.32 kips

Sum W = 29.92 + 8.4 + 23.71 + 16.32 = 78.35 kips

*78.35 kips/1200=65.29psf for a Case D One Story House*

**Weight per square foot=-65 pounds**

**Case E-Weight for Two Story House 30 ft x 40 ft (2,400 Sq. Ft.) P61**

Assume SD soil with Ca = 0.44; Na = 1.3; I = 1.00; and R = 5.5; Conversion to ASD force level: 1 / 1.4  
Seismic V = 0.186 W

Dead loads (W) tributary to cripple wall level for 30 x 40 two story = 2,400 square feet:

Roof/Ceiling: 20 psf (34' x 44') = 29.92 kips

Second Floor: 11 psf (30' x 40') = 13.20 kips      First floor: 7 psf (30' x 40') = 8.40 kips

Exterior Walls:

1 <sup>st</sup> & 2 <sup>nd</sup> Story walls:	17 psf (16') (30' x 2 + 40' x 2) =	38.08 kips
Deduct for windows:	-7 psf (240 sq. ft.) =	<-1.68> kips
Gable end walls:	12 psf (5' x 30') 2 / 2 =	1.80 kips
Cripple walls:	13.5 psf (2') (30' x 2 + 40' x 2) =	<u>3.78 kips</u>
		41.98 kips

Interior wall: 12 psf (8') (29' x 5 + 39' x 3) = 25.152 kips

Sum W = 29.92 + 13.2 + 8.4 + 41.98 + 25.15 = 118.65 kips

*118.65kips/2400=49.43psf for a Case D Two Story House*

**Weight per square foot=-49 pounds**