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.

2,400 lbs of overturning force

12 times 300 lbs = 3,600 lbs of shear force along top of wall.

Shear Wall

Force along any edge of shear wall (and within the wall itself) is 300 pounds per linear foot

2,400 lbs of compression

foundation

12 times 300 lbs = 3,600 lbs of shear force along bottom of wall

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 holdown 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 holdowns 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 holdown, 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 holdown 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 holdowns. 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 holdown 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 holdowns 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 holdowns 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 holdown 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 holdown anchor rod embedment, the more concrete the holdown anchor rod will try to pick up.

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 seems. 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.