Buildings that have unreinforced masonry columns are especially prone to damage in an earthquake (photo top). This fine old California bungalow had a vast porch along its front that was supported by stone pillars until the Coalinga quake of 1983 brought it to its knees. The wood-frame structure behind the porch flexed enough to make it through the jolt.

Seismic Retrofits

Anchor bolts and shear walls are the way to beef up older homes in earthquake-prone areas

by David Benaroya Helfant

Seismologists and geologists tell us that parts of the West Coast and the rest of the United States mainland are on two different, shifting tectonic plates. Geologically speaking, the communities on the western plate are seceding from the rest of the Union at a rate of approximately 2 in. per year. It doesn't take an earthquake to see the results of this movement. Even in quiet times, you can see the effects on the land in this area. It cracks and subsides, slides and creeps, occasionally winding up on the neighbor's side of the property line.

During a sizable earthquake, such as the 6.7 shock that hit Coalinga, Calif., in 1983, things happen in a hurry—especially to older homes. Foundations fail; gas lines break, causing fires; framing connections prove inadequate; and unreinforced masonry crumbles.

I work for a company in the San Francisco Bay Area that specializes in upgrading older homes to meet current standards of structural integrity. We work closely with soils engineers, structural engineers and civil engineers to develop strategies for reinforcing complicated structures. We also do work on simpler buildings, which can be strengthened following some basic guidelines. This article talks about those guidelines, and the tools and materials that we use to reinforce older wood-frame houses.

Most of the houses that we upgrade are built upon short stud walls, called cripple walls, which in turn bear on concrete foundations. In my 10 years of experience in this business, I have seen enough old buildings to draw some conclusions about what makes them fail in an earthquake, and what can be done to prevent those failures.

Whenever we do an earthquake inspection, we spend some time with our clients describing the basic components of a building, and how they are affected by an earthquake. Houses consist of four kinds of structural elements: horizontal members, such as joists, which support and transfer the weight of the building and its contents to the walls; vertical members, such as walls and columns, which transfer the weight downward; the foundation, which supports the weight of the house and transfers it to the ground; and all points of connection between the wood members, between wood and concrete, and between concrete and concrete.

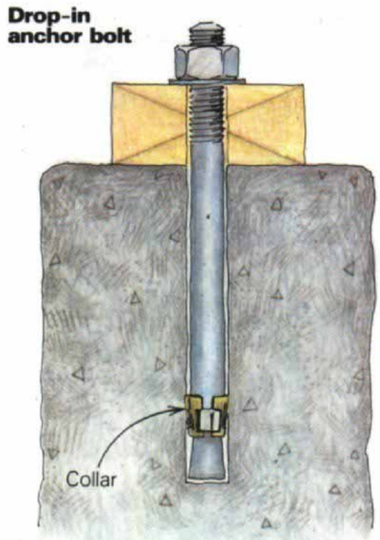
It's these points of connection that require special attention in earthquake country. We begin fixing most older homes at the foundation, by connecting the mudsill to the concrete footings with anchor bolts.

Anchor bolts—Until 1940, most California building codes did not require foundation anchor bolts. Consequently, a lack of anchor bolts is one of the most common deficiencies in older homes. But many of these homes are built on solid, steel-reinforced concrete foundations that, except for needed foundation bolts, are perfectly adequate to their tasks. Fortunately, there are bolts that can be added to the foundation with the building in place, and we spend much of our time doing just that.

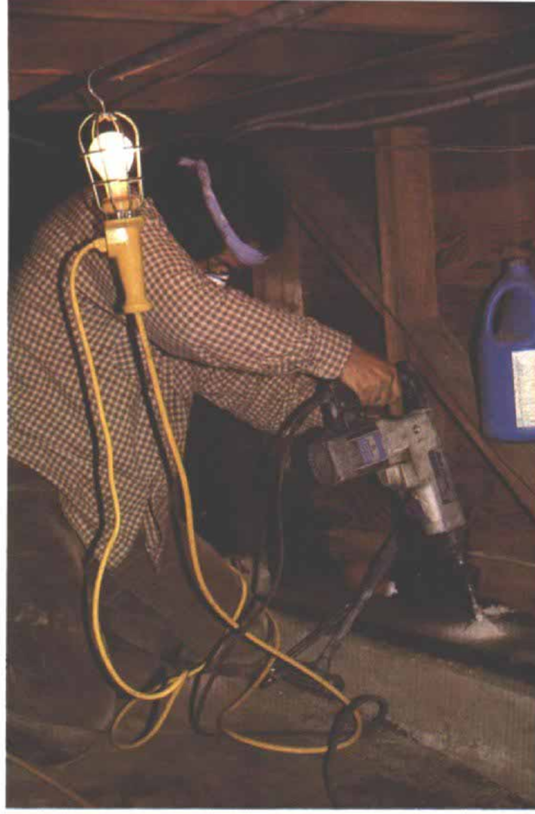
Retrofit anchor bolts go by various names and are made by several companies. They are called anchor bolts, expansion bolts or drop-in bolts. Some available brands include Quik Bolt (Hilti Co., PO Box 470400, Tulsa, Okla. 74147), the Redhead (Phillips Drill Co., P.O. Box 364, Michigan City, Ind. 46360), the Stud (Rawlplug Inc., 200 Petersville Rd., New Rochelle, N. Y. 10802) and the Para-bolt (Molly Div., Emhart Corp., 504 Mt. Laurel Ave., Temple, Pa. 19560). The bolts come with a zinc chromate finish to protect them from corrosion, or in stainless steel for anchoring in areas that are constantly wet.

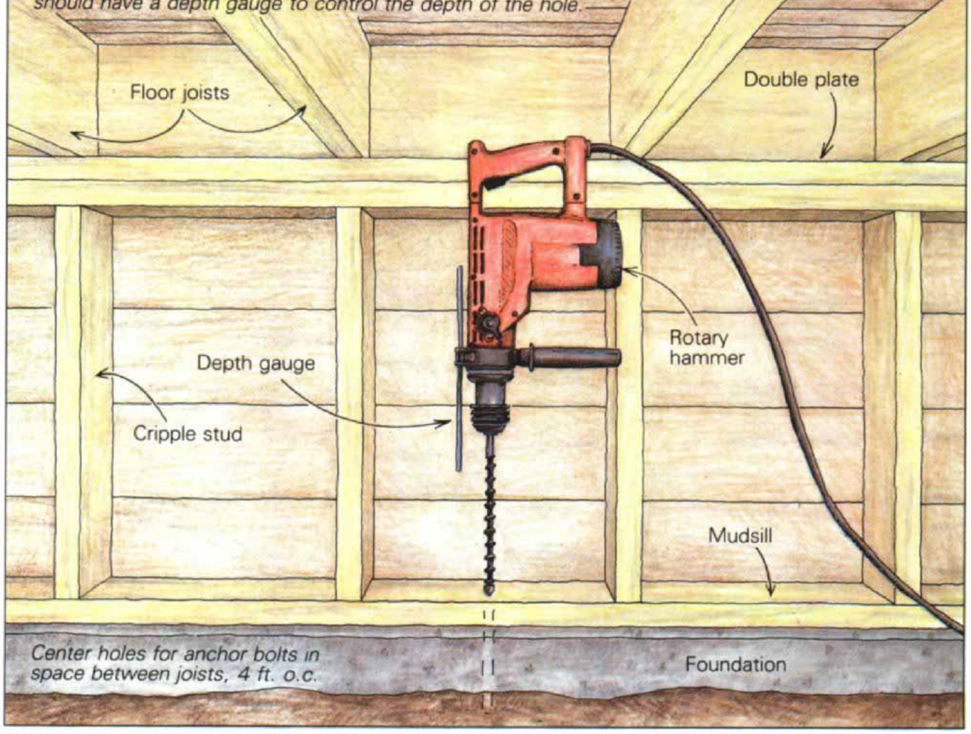
The key design feature of the anchor bolt is the metal collar near the tip of its conical end (top drawing, facing page). Once the bolt has been driven home, three turns on the nut with a crescent wrench will lift the cone end just enough so that it engages the collar and begins to expand it. This enlarges the diameter of the bottom of the bolt's shank by about ⅛ in. Once expanded, it will take several tons of withdrawal pressure on that bolt to get it out. When the collective withdrawal resistance of a given number of bolts exceeds the weight of the house multiplied by an engineered safety factor, the mudsill will stay connected to the foundation even under the most extreme geologic upheaval.

We generally use three sizes of anchor bolts in our work. For small buildings (600 sq. ft. or less), we use ½-in. bolts, 7 in. long. Larger one-story buildings and two-story structures get ⅝-in. bolts, 8½ in. long. We hold three-story buildings down with ¾-in. bolts, 10 in. long.



Homes can be secured to their foundations with drop-in anchor bolts. Once a hole has been drilled through the mudsill and into the concrete (photo right), a bolt is inserted. As its nut is tightened, the collar expands to anchor the bolt.





Under the house—*Drop-in anchor bolts rely on close tolerances, so the rotary hammer should have a depth gauge to control the depth of the hole.*

Foundation candidates—Some foundations cannot be bolted. Brick foundations, which suffer the greatest damage during earthquakes, do not take anchor bolts very well. The bricks usually crack from the drilling and pounding that occurs during installation, and the mortar doesn't have enough adhesion to keep the bricks together during a severe earthquake.

Crumbly and porous concrete cannot hold an anchor bolt because it offers little resistance to the flared end of the bolt. During an earthquake, a bolt in crumbly concrete will be pulled out of its hole and right through the mudsill. We drill a few test holes in suspect concrete and set some anchor bolts, then tighten their nuts to see if they grab. If the bolts keep right on climbing out their holes, you can bet you've got poor-quality concrete on your hands. You can usually pick at this stuff with a screwdriver and it will fall apart. In these cases, we recommend either complete or partial foundation replacement.

Bolting schedule—Full-length drop-in anchor bolts follow the same schedule as those for a normal, J-bolted foundation. We place them 4 ft. o. c., and within 12 in. of the end of any mudsill. Any single stretch of mudsill- gets at least two bolts, and we place them within 6 in. of any butt joints in the sill. Because of the vagaries of this kind of work, we always end up putting in more than one bolt every 4 ft. An average-size house usually requires between 30 to 50 bolts, with costs per bolt ranging from about $2.50 for a ½-in. by 7-in. bolt up to about $5.00 for a ¾-in. by 10-in. bolt.

Tools and installation procedure—Power and light are the first priorities on a bolting job. This work relies heavily on electric power, so we have on hand plenty of grounded 12-ga. extension cords with thick rubber sheathing. We use at least two droplights with Tuff-skin bulbs for illumination. Tuff-skin bulbs hold up better to the knocks and drops of the work process.

A rotary hammer (photo above right) is essential for drilling holes in concrete. We've used many brands, and our favorites are Hilti's T.E. models 52 and 72. They are light and powerful, and have a nicely designed swivel handle with a locking mechanism to hold it in place anywhere in a 360° circle.

The holes for expansion anchor bolts should be drilled the same diameter as the bolt, so we carry a set of masonry bits that grow by ⅛-in. increments from ¼ in. on up to ¾ in. These are the most common anchor diameters.

Our standard job equipment also includes several plastic tubes that are about 3 ft. long. We use them to blow concrete dust out of the freshly drilled holes. We use a tube that is ⅛ in. smaller than the hole, which makes it easier to insert and allows room for the dust to escape.

We used to begin setting a bolt by drilling a hole in the mudsill with a spade bit mounted in a standard electric drill. Then we would use the rotary hammer to finish the job in the concrete. But we've decided that this is a waste of time. We're not drilling holes for dowel plugs here, and not surprisingly, a rotary hammer has no problem gnawing through wood. So now we use the rotary hammer to bore into both materials.

Bolts are best installed in a bay between joists (drawing, above). This allows enough room to hold the rotary hammer so that the bit is as perpendicular as possible to the sill. The holes for expanding anchor bolts have to be drilled to fairly precise depths, so we set the depth gauge on the hammer to the depth required by the bolt. If the hammer doesn't have a depth stop, we wrap a piece of tape on the bit to show how deep the hole is.

Once the hole is bored to its finished depth, we blow out the dust with tubing and pound the bolt home with a 18-in. long, 3-lb. or 4-lb. sledgehammer. A sledge is necessary because you don't have much room to swing a hammer under these conditions. Also, larger bolts require a lot more mass in the pounding hammer to drive

Drawings: Christopher Clapp

them home, and a wimpy little hammer just won't get the job done.

If you do this work, sooner or later you'll need a good pair of 10-in. or longer vise grips. You'll need them because the rotary-hammer bit will occasionally bind during drilling. This happens when the bit gets caught on some steel or aggregate in the concrete, or because you drilled too deep and the thicker shank at the top of the bit gets wedged in the hole. A rotary hammer drills in only one direction, so there is no way to back a bit out of the hole. Once you're stuck in high-psi concrete your only recourse is to release the bit from the machine and back it out with the vise grips. As a last resort you can drill another hole along side the stuck bit and attempt to free it by breaking up the adjacent concrete. If you're persistent and lucky, you'll get it out. If not, kiss it goodbye. At $30 to $50 on up for each bit, you'd better hope you're lucky and this doesn't happen too often.

Occasionally the drill bit will bind when you're drilling a foundation at the 3-in. to 4-in. level. When this happens several times in different spots, chances are good that you're hitting a piece of rebar placed within 4 in. of the surface of the foundation. In this case, you'll have to use shorter bolts spaced closer together. Cut the spacing down to 32 in. o. c.

Once you've drilled all your holes and you've blown them out, it's a good idea to make sure the holes are deep enough for the bolt to be pounded down all the way. There is nothing more frustrating than pounding an anchor bolt into a predrilled hole that inadvertently got partially backfilled with concrete dust when you pulled out the drill bit. No matter how hard you pound the bolt, it will not be driven to its proper installation depth. And when you're lying on your side, and dust is everywhere in the dark and dank space that is typically 30 in. high at most, the last thing you want to do is to create additional, unplanned and unbillable work for yourself. A fast and easy way to avoid this is to carry a depth gauge and check the hole depth just before setting the bolt in it. If it's too shallow, redrill it, clean out the dust and remeasure.

To set the bolt, first put the washer and the nut on the bolt, then start it in its hole and drive it home. After it's set, all that should be exposed is the washer flush on the sill, the nut and about half the threads.

Sometimes it's impossible to get at the top of the mudsill to drill vertical holes for anchor bolts. In such cases, metal plates, lag-bolted to the sill and anchor-bolted to the concrete foundation, can be used to tie the sill and the foundation together.

Horizontal drilling—The standard method in retrofit anchor bolting is to drill vertically into the foundation. But sometimes this is impossible. Many older buildings are built so close to the ground that there is not enough height to operate the drill vertically. A worker needs at least 24-in. clearance for vertical drilling. In crawl spaces with less than this, we attach the mudsill to the foundation with metal plates installed along the side of the sill and the foundation (photo left). This allows us to drill horizontally. We install our bolts through predrilled holes in the ⅛-in. thick plate steel—½-in. lag bolts into the sill, and ½-in. anchor bolts into the side of the stem wall. The lag bolts are half as long as the width of the sill, and the anchor bolts half as long as the thickness of the stemwall. We make sure the anchor bolts are at least 5 in. from the top of the stemwall. If the sill is inset on the surface of the foundation, we block behind the steel plate and use longer lag bolts.

Shear walls—Some earthquakes do their damage by shaking a building for a prolonged period. This movement can weaken a structure's frame, and eventually pull it apart if it isn't properly braced. Other earthquakes wreak havoc when the ground heaves upward suddenly. This action can lift an entire building off its mudsill.

Shear walls help a building resist both types of ground movement. Simply stated, a shear wall is a stiffening panel, rigid membrane or brace designed to prevent a structure from racking under a load. Shear-walling is a logical second procedure in seismic reinforcing, and in some cases, the shear wall is the major connection between the mudsill and the rest of the framing. A structure's mudsill may be bolted right up to code, but if the framing isn't tied to the sill, the anchor bolts are useless (photo facing page).

One-by-six sheathing under exterior siding is the weakest form of cripple-wall bracing. Let-in diagonal 1x6 braces that tie mudsill, studs and plates together are stronger. A plywood shear wall that connects mudsill, cripple studs, and plates is the strongest. We use ½-in. CDX plywood for shear walls on nearly all of our jobs, except for large and unusually heavy buildings, where we use ⅝-in. CDX.

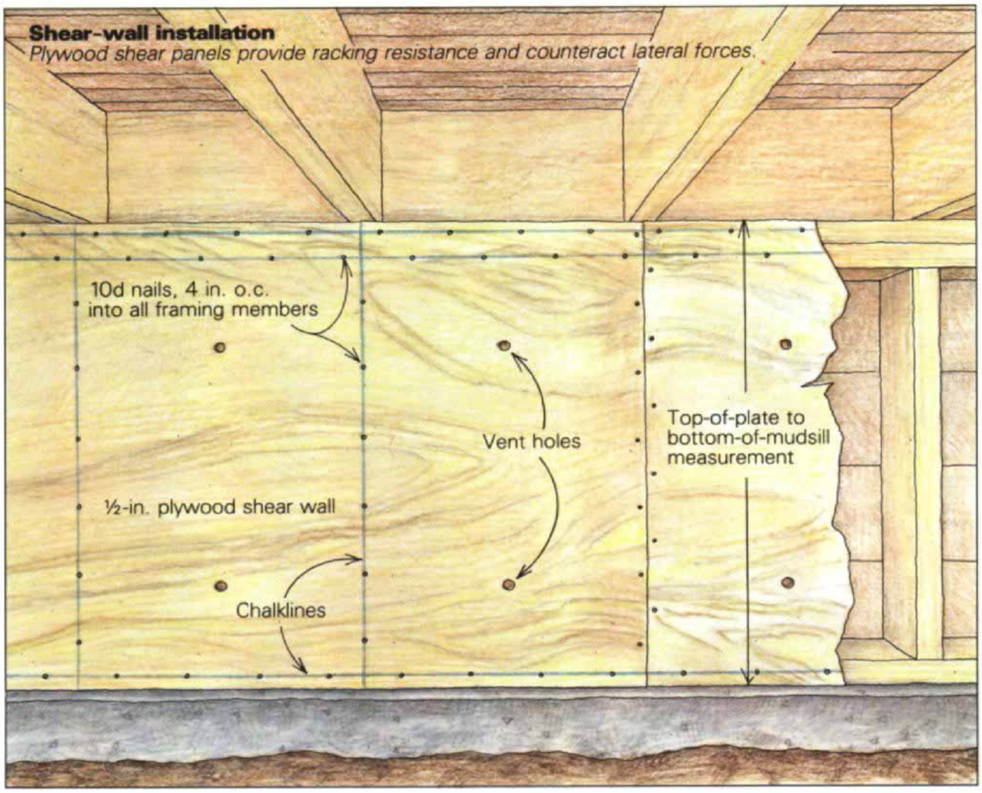
On existing buildings, we retrofit the shear walls on the cripple studs from the inside. This saves the expense of tearing out the existing exterior siding. In determining the shear-wall needs, we check the direction of the floor joists and roof rafters. If both of the framing elements run in the same direction, then the two bearing walls on which they rest are carrying and transferring the major portion of the structural, load. In this case, more shear-walling should be installed under these walls. A standard rule of thumb for determining the amount of shear-walling is to install it 4 ft. in each horizontal direction at each corner in one-story houses of 1,000 sq. ft. or less, 8 ft. in each direction in two-story houses, and on all cripple stud walls in the substructural areas of three-story homes. If we are at all in doubt about what shear bracing we need, we consult a structural engineer.

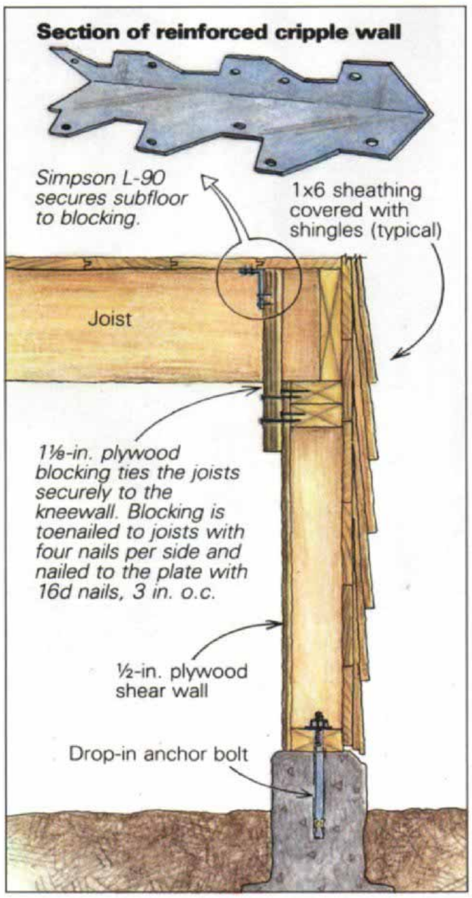
Shear-wall installation—We start by measuring from the base of the mudsill to the top of the plate (drawing, top right), and deciding what length is appropriate. We cut the plywood with a worm-drive panel saw. We then hold it in place, scribe hash marks noting the positions of the plate, studs, any diagonal bracing, and the sill. We then remove the plywood and snap chalklines to indicate all the existing framing. Before installing the plywood, it's a good idea to paint the mudsill with an anti-termite and dry rot chemical. We typically use Cuperlignum or Copper Green for this; both are readily available.

After we've snapped our lines, we put the sheet back in place and tack one corner with 10d common nails. Then we nail the plywood along all the chalklines with a nail gun loaded with 10d galvanized common nails. Starting at the upper left and working our way to the right side, we nail the plywood at 4 in. o. c. to every framing member it touches. While this may seem like overkill, the more nails you install the stronger the bracing becomes. Given the minimal extra time and expense, the greater strength that is produced seems well worth it. By nailing from one side to the other we are able to remove any of the warp in the plywood, resulting in a tight, firmly secured shear wall. You know it's been installed properly if, after you've finished, you can slap it between the studs and produce a resonating drumlike sound. Once you've got it tight as a drum, go back with a good electric drill and drill a row of ½-in. dia. vent holes within 5 in. of the top plate and the mudsill, approximately 16 in. o. c.—between all framing members. If any moisture builds up behind the plywood, air circulating through the vent holes will allow it to dissipate.

For houses built on slabs or those built without sufficient crawl space for retrofitting the shear wall, it may be necessary to strip the exterior siding away from the walls and install the plywood from the outside.

After the stud walls have been shear-walled, it's a good idea to inspect the first-floor framing diaphragm. Good floor diaphragms have blocking between the joists at all plates, and then every 8 ft. to 10 ft. If the joist span is 10 ft. or less, then at least one line of blocking at midspan will do. If the joists lack sufficient blocking, they are subject to tipping movement and could collapse during a serious earthquake. Check the subfloor-





The house at right sat atop cripple studs that were toenailed to an anchor-bolted mudsill. Unfortunately, the exterior sheathing was the only connection between the sill and the house, and the Coalinga quake sent the building about a foot north. The drawing above shows how blocking and angle ties can remedy this weakness.

ing. Most older homes have 1x material nailed to the joists either perpendicular or diagonal to the direction of the floor joists. Note also how the joists are connected to the plate. Remember that the floor connection to the plate is vital. If it is weak, it may separate from the cripple-stud construction during heavy seismic activity and could slide off that substructural base.

A good reinforcing procedure is to add blocking to the floor joists if they are insufficiently blocked. At the cripple walls, run the blocking down over the shear wall at least 4 in. At these overlaps nail through the blocking into the plywood and the plate (bottom drawing, previous page). In addition to toenailing the sides of the blocking to the joists, we install Simpson L-90 ties at 4-ft. intervals where the blocking hits the bottom of the subfloor. These angle ties are about 8 in. long, and have holes for five screws on each flange. We use #10 Phillips-head wood screws to connect the ties to the block and to the subfloor. Once this is accomplished, the first-floor diaphragm is more securely attached to the reinforced and bolted substructure. This is particularly important at the building's corners, and along the plate and cripple walls where joists bear. A lot of weight comes together and is transferred in these areas.

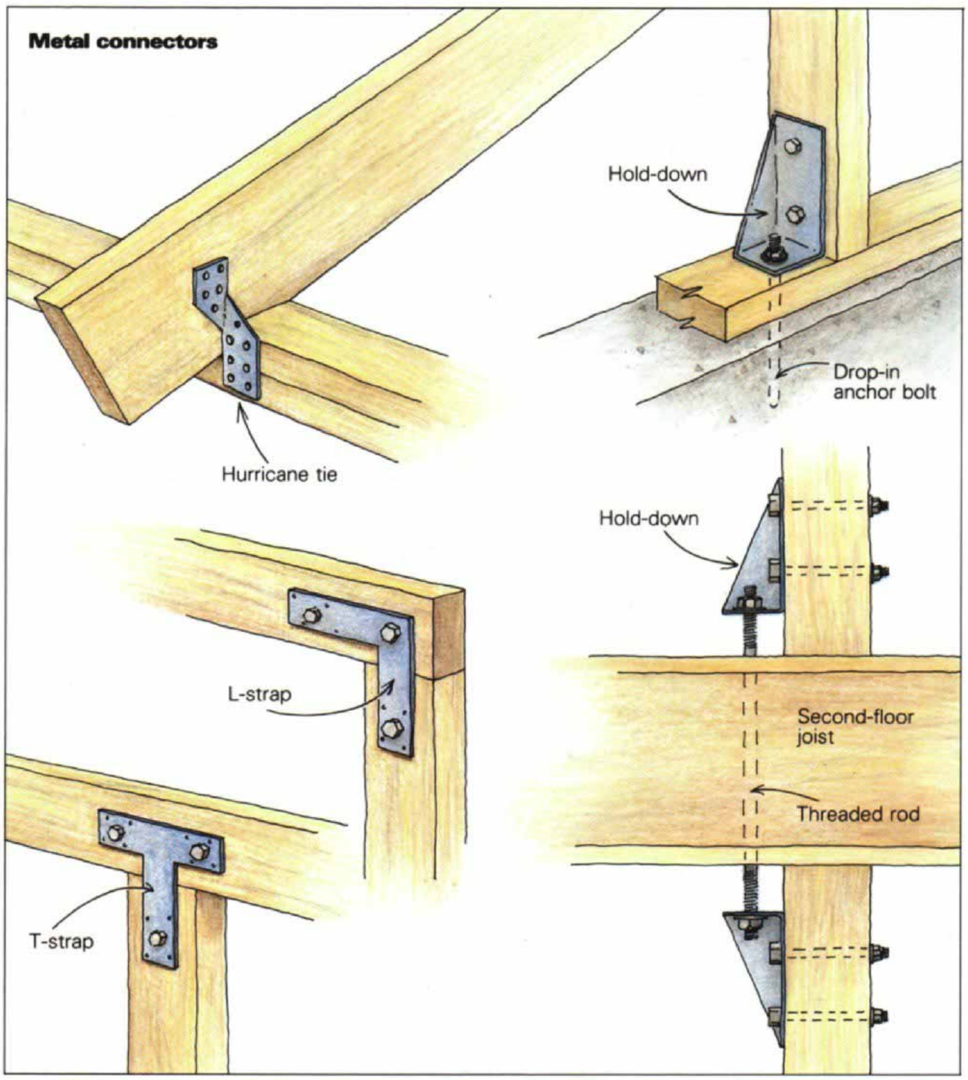
Metal connectors—Anchor bolts and plywood shear walls are the standbys of our reinforcing strategy, but many other pieces of construction hardware can come in handy when it's time to upgrade an old building. The drawing below shows some of the metal connectors that we use regularly in our work.

We use hurricane ties to reinforce the connection between the rafters and the plates on which they rest. These metal connectors are bent so that two perpendicular framing members can be joined using the fasteners' shear strength, rather than their withdrawal capabilities. Hurricane ties are also useful for anchoring floor joists to their plates when the original fasteners aren't substantial enough.

On homes with center girders, we use a lot of T-straps and L-straps to stiffen these potentially wobbly junctions.

Hold-downs can be used along with a drop-in anchor bolt to secure a post or stud to a footing. A pair of hold-downs linked with a threaded steel rod can be used to create a tension tie from one floor to another.

Although we don't use it for structural purposes, another metal connector that we commonly use is plumber's tape. We make straps out of it to secure water heaters to the adjacent framing, which cuts down on the likelihood of a gas-line break at the water heater during an earthquake. Much of the destruction caused by earthquakes is from natural-gas fires, so it's very important to anchor gas appliances that are likely to fall over in a major quake. We also encourage our customers to install automatic gas shutoff valves.



Safety under the house—Running a powerful rotary hammer while wedged between floor joists and the ground makes for deafening noise and very sore elbows and knees. The risk of injury is relatively great, and protective equipment is essential.

Concrete dust is bad for the lungs, so wear the best dust mask you can find. It should fit tightly over the nose and cheeks and around the mouth. We usually wear knee pads and elbow pads over a long-sleeve shirt. Good ear protectors are vital—without them your hearing will be damaged if you do this kind of work on a daily basis. Safety goggles are a must to protect the eyes from flying chips of concrete and wood. As an added precaution, we always keep a well-stocked first-aid kit on every job near the entrance to the crawl space.

Trials and tribulations—Retrofit bolting and most of the reinforcing work involving substructural carpentry takes place in dark, dusty and suffocatingly small crawl spaces. Quite often the work is done in crouching or reclining positions, or on your knees. Often the installer must lie on his side or stomach while doing the work, which is noisy, involves powerful, heavy, hand-held equipment (two hands), and is physically demanding and exhausting. It is not work for the weak, the meek or the claustrophobic. It's actually a lot more like coal mining than carpentry work. And that's no joke.

Reinforcing work is rarely seen by the client or by anyone else. Once in a blue moon an owner will crawl along with you for a tour of the completed work. Inevitably, the client marvels at the accomplishment and looks at you in amazement, wondering if you're superhuman, neurotic or just plain crazy for doing this kind of work. Sometimes, I wonder myself.

Nonetheless, there is a significant measure of satisfaction from knowing that in areas hit by earthquakes, seismic connections often mean the difference between ruin and relatively minor losses. Research and experience have shown that these retrofits can result in far greater safety for those who live in these homes. □

David Benaroya Helfant, Ph.D., is managing officer of Bay Area Structural, Inc., general engineering and general building contractors in Berkeley, Calif. For more on this subject, see Peace of Mind in Earthquake Country *by Peter Yanev (Chronicle Books, 1 Hallidie Plaza, Suite 806, San Francisco, Calif. 94102),* Earthquake Hazards and Wood Frame Houses *(Center for Environmental Design Research, Wurster Hall, University of California at Berkeley, Berkeley, Calif. 94720) and* Earthquake Resistant Design *by D. J. Dowrick, (John Wiley and Sons Inc., 1 Wiley Drive, Somerset, N. J. 08873).*