Riding Out the Big One

A structural engineer explains what happens to a wood-frame building in an earthquake and how it can resist collapse

by Ralph Gareth Gray

The area affected by the Loma Prieta earthquake, which shook up much of the San Francisco Bay Area in October of 1989, included 1,544 California public schools. Only five of them suffered severe damage. No lives were lost, and there were no injuries in these buildings. Most of them were wood-frame construction very similar to that of a typical custom house, and they were either built from scratch or upgraded following the five sacred principles of earthquake-resistive construction.

There's nothing mysterious about these principles, and I'll discuss them all in this article. To understand them, you must first visualize clearly how a structure carries the loads imposed on it by an earthquake. To put the principles to use in the real world of construction, you might have to make a few simple but critical modifications to standard building practice. Also, you must pay close attention to details, and to get them done right, you'll probably have to be steadfastly persistent. This is a big topic, so in this article I'm going to talk mostly about new construction. In a subsequent piece we'll look at retrofitting existing houses to withstand earthquakes.

Some of what follows is subject to continuing debate among structural engineers, and I'll probably rub some of my colleagues the wrong way. But shall I tell you what I really think, or dose you with bland, safe consensus? I choose the former.

Sudden shock—In an earthquake, the ground moves violently and chaotically, up and down, side to side, twisting and rocking, with all these motions changing very quickly. Anything on the ground, such as a house, will tend to slide and overturn. Various parts will rattle around on their own and maybe come adrift. Things stacked one on another, like bricks on deteriorating mortar, will tend to slide and overturn independently, and framing members, like beams, may come right off their posts, or the posts off their footings. The connecting links—particularly tension and shear-carrying components—are put to the supreme test in an earthquake. If they are incorrectly designed or constructed, they will cause serious trouble. Thus the first principle: *Tie it together.*

Overlaps and straps—The platform frame holds together better in earthquakes than the balloon frame, in part because a platform frame is tied together by the overlap of the double top plates on the walls at every level. But they must be spliced correctly, with minimum 4-ft. overlaps (top drawing, facing page). While the code requires at least two 16d common nails on each end of the splice, I think four 16d nails is a better minimum. If more are needed, the drawings should show them. As you add more nails, follow a nailing pattern like the one shown in the drawing to avoid splitting the wood.

Post-to-beam connections are also important, and any measure of reinforcement is better than the following common condition: a couple of toenails through the bottom edge of the beam into the post's end grain. Instead, use steel connectors, such as commercially available post caps. You can make an effective site-built post-to-beam connector using a 2x bolster and a couple of 2x yokes on either side of the post to cradle the beam (bottom drawing, facing page).

Steel column bases are the best way to tie posts to their piers (drawing below, facing page). But even minimal connections, such as short steel Ls secured with drilled-in anchor bolts, or even plumber's tape affixed with concrete nails are better than a couple of toenails.

Parts other than framing members should also be tied together. Use metal straps to secure mechanical equipment, such as the water heater, to the walls. Concrete or clay roofing tiles (and roofing slates) should all be anchored to the roof sheathing with corrosion-resistant fasteners. Unfortunately, there are roof-tile systems, with ICBO approvals, that do not require mechanical fasteners above the first few courses. I shudder to think what might happen to people who are running out the door during a serious shake when the tiles depart the roof.

Stucco can be a fine finish, and it's excellent fire protection, but it has to be tied to the wall. This means that the mesh must stand off the sheathing far enough to key and support the scratch coat, and the nails mustn't pull out of the sheathing because it's decayed or because the nails are too short, rusted or both. In San Francisco's Marina District I saw great sheets of stucco that had peeled right off the walls. If the Marina fire had spread, that stucco wouldn't have protected anything but the paving it was lying on.

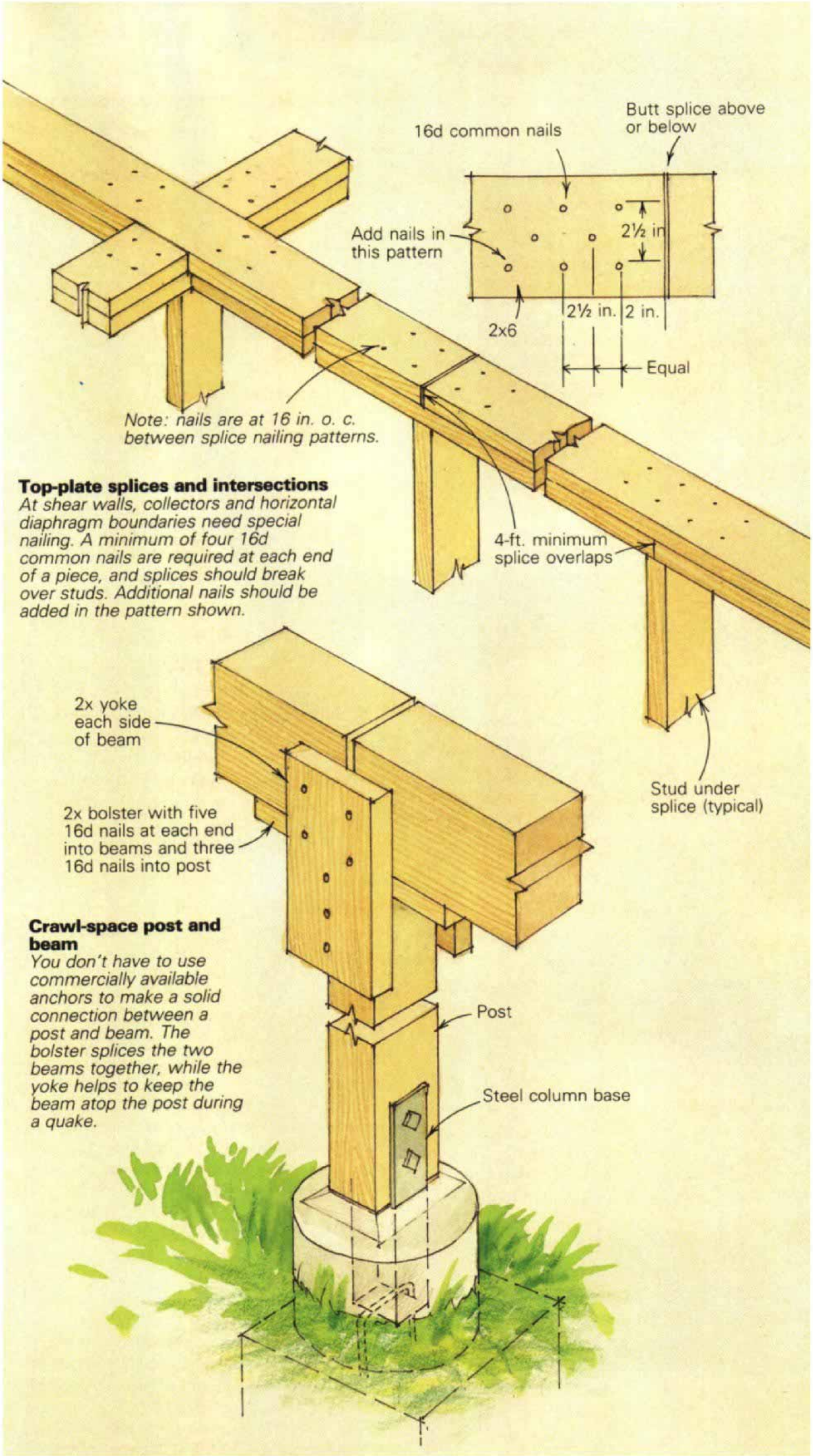
Inertia—The sudden movement of the ground under the building and the rapidity of change in the ground's motion set earthquakes apart from other dynamic actions on buildings, such as wind. The sliding, overturning and so on are primarily due to inertia, a physical object's reluctance to be moved, and once moving, its reluctance to change direction or velocity.

The heavier the object, the greater its inertia. The heavier the building, the harder it is to control the forces applied by an earthquake. Thus the second principle: *Keep it light.*

If you're dead set on having a handsome veneer of brick on the sides of your house, remember that the inertial force due to its weight in sudden motion must be channeled successfully through the structure to the ground. That's because our first principle says that we have to tie it together. If you don't tie it, the force will be smaller, but only because the brick will have been thrown off the building, like great lumps of shrapnel. I have clients with expensive earthquake damage to their house that occurred because the brick veneer added to the effective weight of the building, and the structure couldn't handle the increased inertial forces.

Brick chimneys act about the same way as brick veneers, but more so. They are tall and narrow, so the whiplash tension across the mortarbed joints is significant. They are seldom tied to anything, they typically break off in an earthquake and their weight makes them deadly. I try to get people to take down the brick chimney and put in a metal prefab fireplace and double-wall metal flue. If the whole thing can't be removed for some reason, then take it down to the smokeshelf and go up from there with a metal flue. Prefab metal transition pieces are made for precisely this application. Be sure to grout it in so hot gas can't escape.

Tracking the loads—Another key to a building's survival in an earthquake is a strong, stable path for the transmission of inertial forces to the ground. Engineers size the fasteners, shear panels and boundary members (framing elements that take tension and compression loads) that transmit these forces based on a portion (typically around 15%) of the building's weight.



Note: nails are at 16 in. o. c. between splice nailing patterns.

Top-plate splices and intersections
At shear walls, collectors and horizontal diaphragm boundaries need special nailing. A minimum of four 16d common nails are required at each end of a piece, and splices should break over studs. Additional nails should be added in the pattern shown.

Crawl-space post and beam
You don't have to use commercially available anchors to make a solid connection between a post and beam. The bolster splices the two beams together, while the yoke helps to keep the beam atop the post during a quake.

Understanding the forces at work during an earthquake can take some mental gymnastics (see load-path sidebar, next page). But when it comes to designing, building, repairing and retrofitting buildings to resist earthquakes, being able to track the inertial forces through their load paths is an essential skill. Therefore our third principle: *Know the load paths.*

If you can see a plausible path for loads to travel when you study the potential shaking of a house in each of the principal directions, you are a long way toward an effective earthquake-resisting system, and with this knowledge, you're also in a position to understand some of the more subtle but still important aspects of anti-earthquake construction.

As you can see from the drawings of our little house (see drawings in sidebar), the shapes of its various parts change during the violent shaking of an earthquake. If there's anything in the way, like a tree, the house next door, or even parts within the same structure, it gets hit with a lot of energy—sometimes repeatedly. While this battering dissipates energy, it can cause big chunks to fall off a house and even cause an otherwise sound building to collapse. This leads to our fourth principle: *If you can't tie it together, separate it.*

Obviously we can't separate elements that depend on each other for load transmission, such as a beam from its post. But what about separate portions of a house that might tangle during an earthquake? Consider, for example, a split-level house that steps down a hillside. Assume that the lower part of the house has a big roof abutting a stud wall that carries the weight of another roof (the one over the uphill portion of the house). During an earthquake, the lower roof will try to shake at a different frequency. Thus, the studs might have to be huge—maybe 3x8s at 12 in. o. c.—because in an earthquake, the roof would push and pull against them with great force. In a case like this, it could make sense to separate the lower roof and the walls from the upper wall by 2 in. or so (by about ¼ in. per foot of wall height), which means building a separate studwall to support the lower roof rather than nailing it into the studwall supporting the upper roof. Between the upper wall and the lower roof, you should provide flashings with slip joints so the elements can shake around in all directions without tearing.

A sewer, gas or water pipe passing through a wall and then turning down into the ground is locked into the wall if there isn't space around it at the wall. Leave a ½-in. gap around all sides of such lines, and fill around them with flexible caulk.

Myth of the fantastic optimum—Building structures are analogous to chains, with each element serving as an appropriately sized link to carry out its function. In a perfect world you could design and build a house using the very minimum number of fasteners, the smallest allowable foundation and the lightest structural members. Unfortunately, that's an unsafe and unrealistic approach, because the loads from a strong earthquake are just plain unpredictable. This leads to our fifth (and most important) principle: *Buildings should fail gently.*

Notice that our model building has a shear wall on each side of the floor diaphragms, for a total of four. It's possible to get by with three, provided they are laid out correctly (they should never align to a point, like spokes in a wheel). But even with three, if you lay them out correctly, there's no reserve for construction or design errors, dry rot or future remodeling by klutzes. If one of those three walls fails, for whatever reason, the whole house will fail. This is a plea for redundancy in the structure—the provision of more than just the minimum load path. Put some plywood on other walls (not shown on our drawing), all the way up to the roof, so that if one element fails, the loads flowing through the structure

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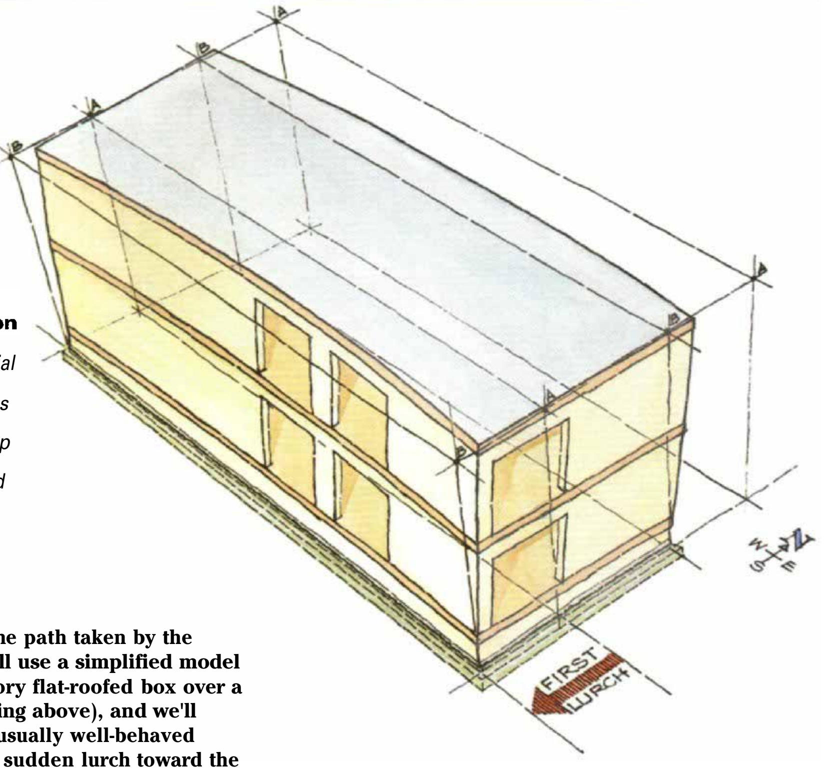
Load path



Earthquake-induced distortion
In our hypothetical earthquake, the initial lurch moves the foundation south. As the structure attempts to catch up with its foundation, the walls, floors and roof diaphragm are distorted.

To help visualize the path taken by the inertial forces, we'll use a simplified model building—a two-story flat-roofed box over a crawl space (drawing above), and we'll subject it to an unusually well-behaved earthquake: first a sudden lurch toward the south, followed by a sudden lurch back to the north. Period. We'll start at the bottom of the building and go up, concentrating on primary effects.

***The first lurch*—You can see where the house starts from by the ghost outlines defined by the A labels on the corners of the roof. During the first lurch, the building would immediately follow the ground motion exactly to the ghost outlines labeled B on the roof corners if it weren't for inertia. The building's inertia causes it to lag behind the ground, as shown by the rendering.**

A good foundation is embedded in the ground, so during the first lurch it is carried south along with the ground, taking the jack walls around the crawl space with it because their mudsills are anchor-bolted to the footings. The tops of the walls lag behind a bit, and the east and west walls are changing shape from a rectangle to a parallelogram—a kind of distortion called shear distortion—hence the name shear wall. If they were weak, the east and west walls would just mash over to the north. But they are sheathed with plywood (or diagonal sheathing) and are thus stiff and strong. Unsheathed jack walls are a common weak link in older wood-framed buildings.

The jack walls on the north and south are also sheathed, but can't resist north-south motions at all, for their stiffness and strength work only in an east-west direction. They follow along because their tops are nailed to the first floor, rotating as if on a piano hinge along the sill.

I've shown jack walls here because they're often used on the West Coast to elevate first-floor joists above grade and to level floors on hillsides. The same hinge principle described here, however, also applies to floor assemblies that bear directly on mudsills and stem walls.

The inertial force of the bottom half of the north and south jack walls goes to their footings and the force from the top half goes to the edge of the floor. So for this south lurch, the north and south walls are part of the load, not part of the resistance.

The east and west jack walls drag the first floor (and everything above it) toward the south, but reluctantly. That's because the first floor has its own inertia, plus some contributed by the north and south walls, and any attached partitions or mechanical equipment.

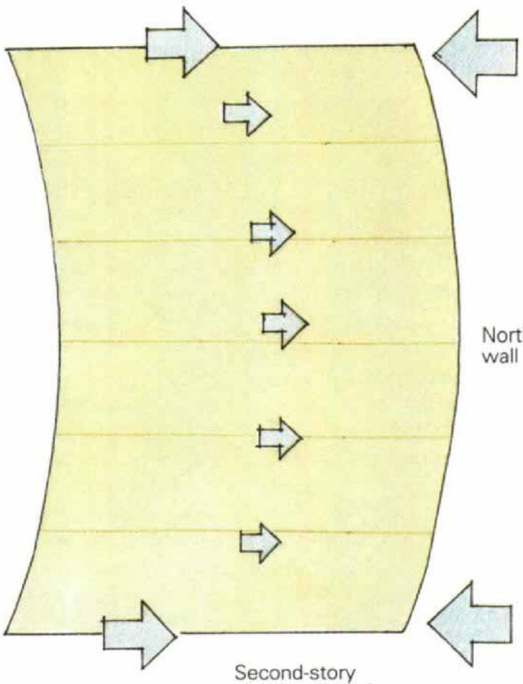
The middle of the floor lags behind its ends, the north and south edges changing from straight to curved. The south edge gets a little shorter and the north edge gets a little longer—a typical sign of bending distortion. Beams and girders act in bending (as well as shear), and that's what the floor is: a big, flat beam that resists lateral forces in a horizontal plane. It's usually called a horizontal or floor diaphragm.

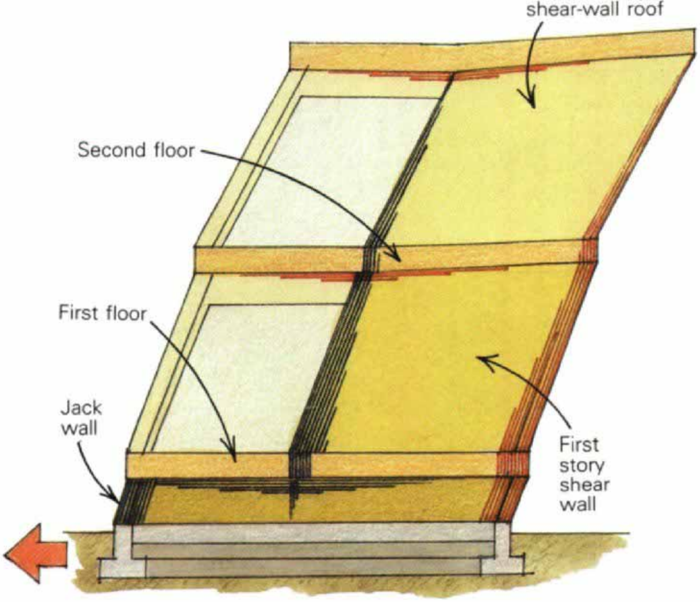
The next layer of the cake, first-story walls plus second-story floor, acts much the same way. So does the top layer—the second-story walls plus the roof.

To summarize from the top down, the roof diaphragm carries its inertial load to the east and west second-story shear walls. The drawing labeled "Distorted horizontal diaphragm" (drawing right) shows a plan view of how the floor might look in mid-lurch. The little arrows represent the inertial loads from the floor itself, and those delivered to the floor from the north and south walls. Bigger arrows at the east and west ends represent the accumulated inertial loads delivered by the east and west shear walls from above. The largest arrows represent the resistance of the shear walls below, and ultimately, the foundation. They are equal to the sum of

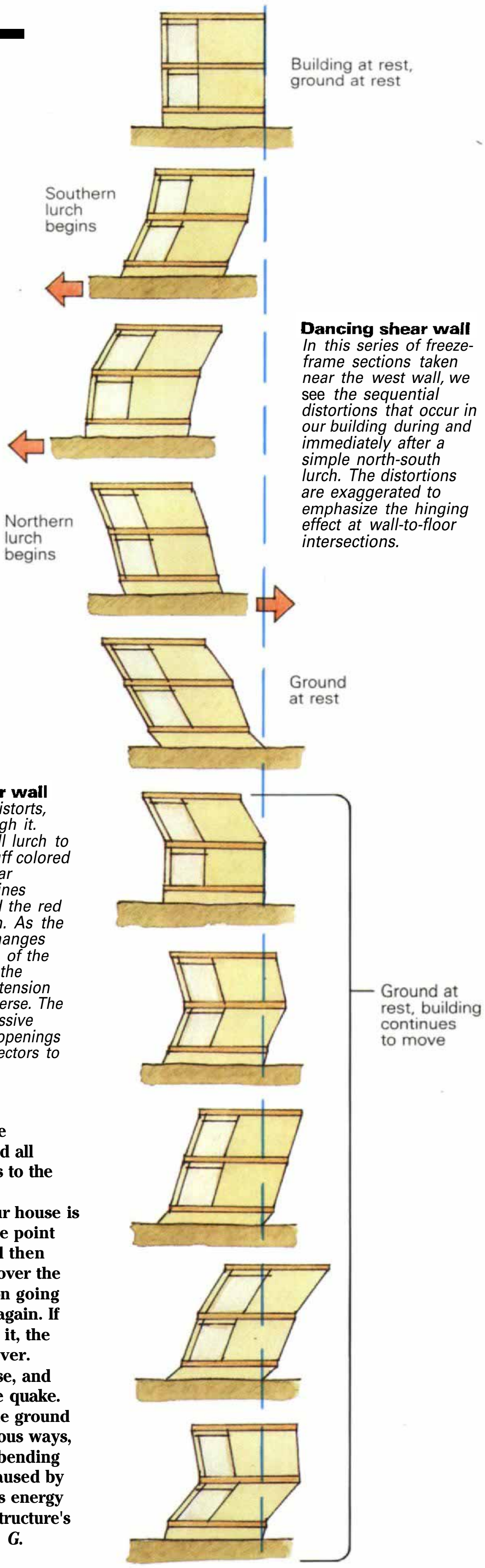
Drawing this page: Ralph Gareth Gray

Distorted horizontal diaphragm
At mid-lurch, the second floor resists the menial forces represented by the small arrows. The inertial force of the floor, while shown by a row of arrows, is actually distributed evenly over the diaphragm. The inertial forces of the north and south walls are distributed along the north and south edges. The big arrows adjacent to the east and west walls represent the effect of the movement of the ground as transmitted by the shear walls.





Distorted shear wall
As the building distorts, forces pass through it. Shown here at full lurch to the south, the buff colored areas denote shear forces, the blue lines show tension and the red lines compression. As the ground motion changes and the distortion of the building reverses, the compression and tension paths will also reverse. The horizontal compressive forces above the openings are carried by collectors to the shear walls.



Dancing shear wall
In this series of freeze-frame sections taken near the west wall, we see the sequential distortions that occur in our building during and immediately after a simple north-south lurch. The distortions are exaggerated to emphasize the hinging effect at wall-to-floor intersections.

the forces represented by the opposing arrows (if not, the building is collapsing). The drawing above shows how the east-west walls are distorted as the loads from the horizontal diaphragms are passed by way of the shear walls to the foundation. As the plywood shear walls tug at the south corners of the building, the boundary members stretch (blue for tension). Simultaneously, the shear walls compress the north boundary members (red for compression).

The second lurch—Well, here we are at the end of the first lurch. We've got our simple house traveling south with a sizeable amount of energy. At this point the earthquake reverses direction, lurching north. But what happens to our house? Except for the foundation, everything else continues stubbornly southbound. Pretty soon the southbound superstructure passes the northbound foundation, and the distortions and forces we've studied all reverse directions. The ground gets to the end of its north motion and stops. Earthquake's over? Not as far as our house is concerned. It's still moving. At some point the superstructure slows down and then starts moving north. So it passes over the now pacified ground, and keeps on going until it slows down and reverses again. If something doesn't happen to stop it, the house could go on oscillating forever.

Something does happen, of course, and has been happening throughout the quake. Energy imparted to the house by the ground motion has been dissipated in various ways, mostly from phenomena like nails bending back and forth, and from friction caused by various parts rubbing together. This energy dissipation is very important to a structure's survival in an earthquake. —*R. G. G.*

All other drawings: Malcolm Wells

will have an alternate path. The house might sag or show cracks but won't collapse, killing someone. Such precautions will cost a few extra dollars, but that's cheap insurance.

The horizontal diaphragm—During an earthquake, the floor and roof diaphragms undergo shear and bending. The subfloor sheathing carries the shear, like the web of an I-beam, while the boundary members (rim joists and top plates) carry the tension and compression due to bending like I-beam flanges.

To withstand and transfer the shear loads, plywood sheets have to be spliced together to prevent adjacent edges from sliding past or over each other. Plywood sheet edges should be butted and nailed to joists in one direction, and to solid blocking or rim joists in the other. Butted on the centerline of a 2x joist, you've got only ¾-in. bearing for each piece, so the nail has to be ⅜ in. from the edge. The edge-nailing called for by code can be as close as 3 in. o. c. This layout works, but there is no margin for error. Layouts must be accurate, and the nailing has to be done with care to avoid shiners and split joists or blocking.

Plywood or diagonal board sheathing is edge-nailed to the rim joists or blocking on all four sides of the diaphragm. They in turn must be connected to the top plates below, which serve as chords (like I-beam flanges), carrying tension or compression.

The edge joists and top plates compose the boundary members. Walls are often longer than the lumber available, so top plates or edge joists must be spliced for the tension'and compression. If they've been severed, boundary members must be spliced (plumbers are especially good at finding and disabling the most critical diaphragm chords, usually because designers have given them no alternative). If for instance, a vent stack has been let into the side of a top plate, the load in the top plate becomes eccentric, magnifying the stress on it during an earthquake. This may snap it. Custom-made splints of ¼-in. steel angle, for example, may be required to fix this.

Large openings, like stairwells, need boundaries around them. Put blocking and strapping perpendicular to the joists across several joist spaces to compensate for the local increase in shear and bending due to the hole (drawing right). The same kind of detailing is needed at inside comers of L-shaped or more complicated diaphragms.

Shear walls and collectors—Just as the horizontal diaphragm is a big, flat beam that resists lateral forces in its horizontal plane, the shear wall is a big, flat vertical cantilever beam that resists lateral forces in its vertical plane. Again, the plywood or diagonal sheathing carries the shear, and the boundary members—stud corners or end posts—carry the bending tension and compression. Shear walls tend to be harder to engineer than floor and roof diaphragms, in part because they're smaller (one does need doors and windows). Also, loads accumulate from the top down, so the loads tend to be just plain bigger. All plywood edges, horizontal and vertical, should bear on, and be nailed to, studs, plates or blocking.

The connection between a shear wall and its foundation typically serves two functions: the transfer of shear forces delivered by the wall to the ground by way of the foundation; and the transfer of overturning forces (called uplift) to the foundation. Anchor bolts take care of the shear at the foundation level—the larger the shear force, the larger or more closely spaced the bolts. Tiedown anchors, bolts, straps or other devices resist uplift.

The shear forces from the roof boundary members are transferred to the top of the shear wall in several ways. They pass by way of nails that slant from the edge joist or blocking into the top plate, or by flat blocking between the joists nailed in turn to the top plate (the flat blocks can also be used for drywall backing). Another method is to run the wall plywood an inch or so up onto the blocking or edge joist (drawing facing page). Here, the heavy edge-nailing schedule for the wall will be used, and another line of nails will be embedded into the center of the top plate. This detail has many forms. Note that the plywood does not run all the way to the top of the joists and blocks. That's because they will shrink, while the plywood does not, causing humps in the walls and sometimes splitting the boundary members. At the joists between floors, the bottom edge of the plywood should not get too close to the top edge of the wall plywood below, because the cross-grain shrinkage of the floor or contact during the quake will strip the plywood off, split the floor members, or both. Leave about a 1-in. gap between them—enough to account for shrinkage.

At the base of each wall, shear is transferred from the plywood to the sole plate by nails, and then from the sole plate to the floor plywood. Special nailing schedules sometimes apply to this connection.

Shear walls in the lower stories resist accumulated shear, uplift and compression from the walls stacked above. Think of it all as one wall, continuous from foundation to roof, spliced at intersecting floors.

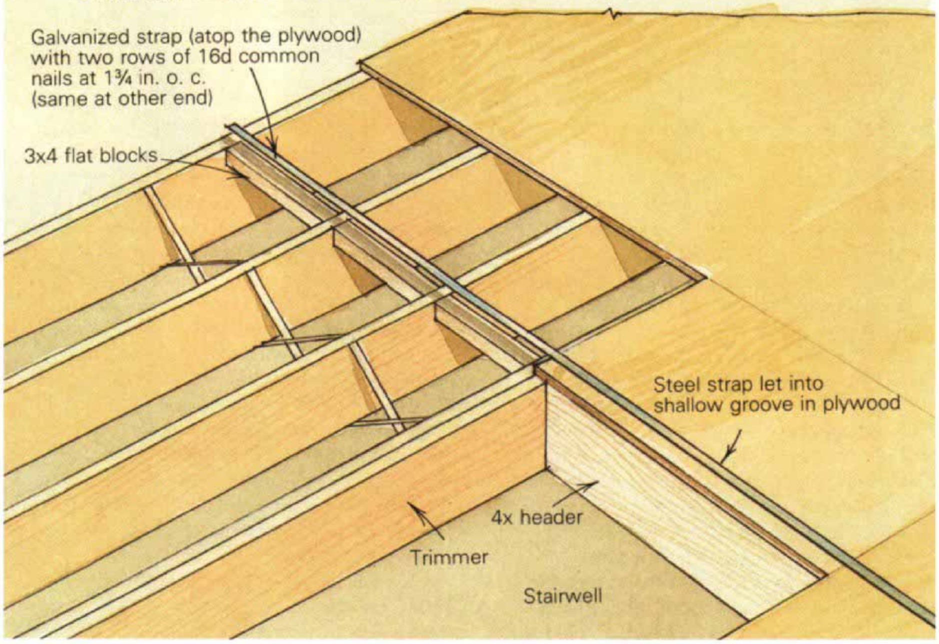
As shear forces move through walls, they have to take a path around openings for windows and doors. The forces are concentrated in the boundary members over the openings before they can be dumped into the shear wall. The framing members that handle this task are called collectors, or drag struts. Often the top plates above the headers serve this function—another reason why the top-plate splices are important. Sometimes beams are used as collectors. This is a tricky little item that is very important and often overlooked, so be aware when there are long openings in the plane of a shear wall, particularly if the roof or floor above is flush-framed. Like top plates, collectors are targets cherished by plumbers.

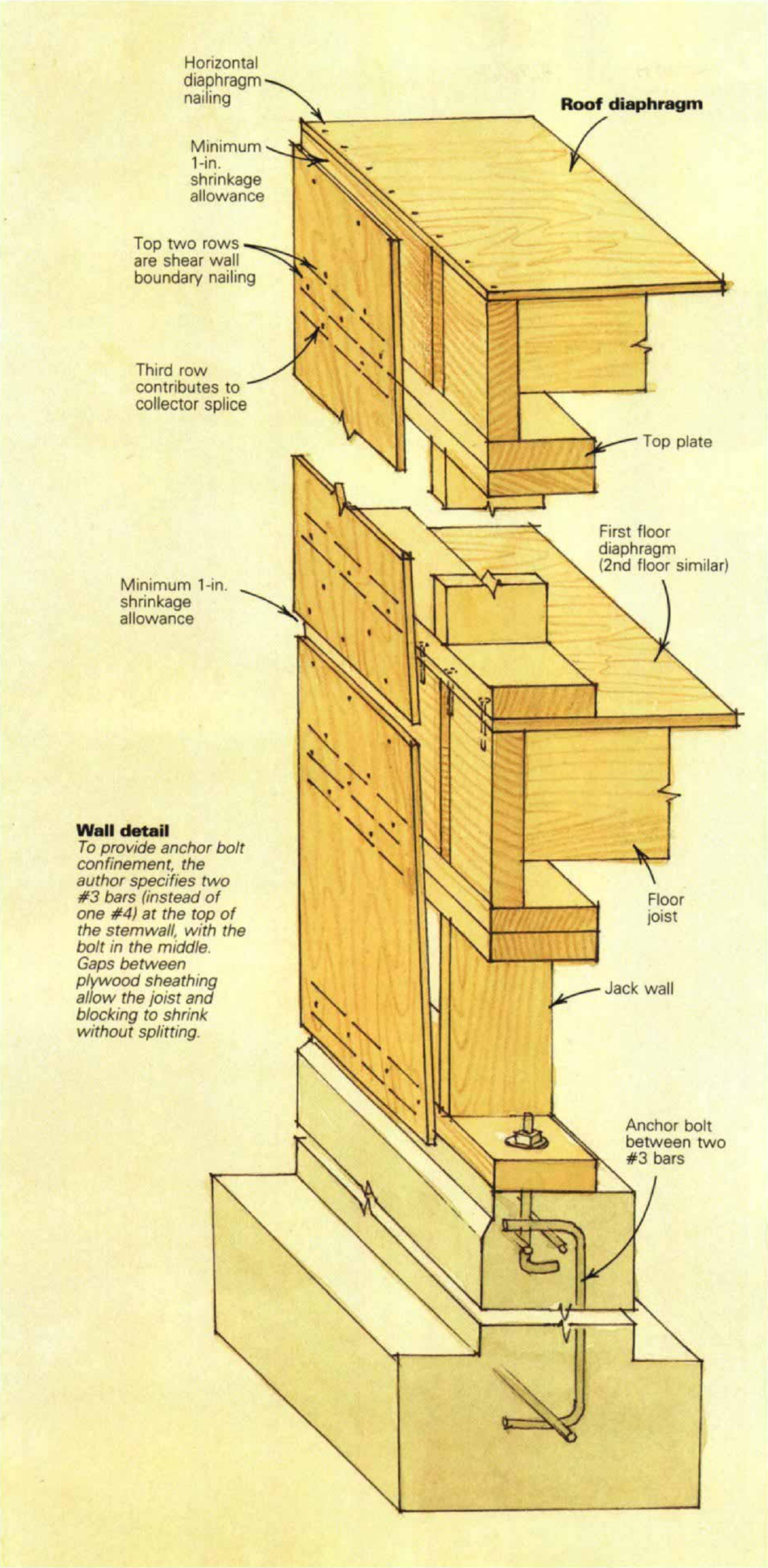
Fasteners—No structural element is better than its connections, and no connection is better than the fasteners. The common nail is a magnificent device for resisting earthquakes. Tests I helped conduct at the University of California's structural research facility showed that properly nailed plywood shear walls have an amazing capacity to resist earthquakes and dissipate energy owing to the ability of the nails to flex back and forth repeatedly without breaking.

But, the plywood walls secured by *overdriven* nails (nails that penetrated the plywood beyond the first veneer) failed suddenly in our tests, and at loads far below those carried by

Opening in diaphragm

Shear forces in a diaphragm are concentrated near openings such as stairwells. Their corners should be reinforced with flat blocking and steel straps to carry tension and compression forces better.





Wall detail
To provide anchor bolt confinement, the author specifies two #3 bars (instead of one #4) at the top of the stemwall, with the bolt in the middle. Gaps between plywood sheathing allow the joist and blocking to shrink without splitting.

correctly nailed plywood panels. Overdriven nails are typically installed by careless nailgun operators. If the gun sets the nails erratically, back off on the pressure, let them stand a little proud and drive them flush by hand.

In our tests, stapled plywood shear walls performed pretty well, but they weren't as strong as the nailed walls. Staples, being cold-worked, may be susceptible to brittle-failure, and being thin, subject to corrosion. This is an unhappy combination. So waterproofing the wall is more important when using staples than when using nails. Overdriven staples reduced strength, but not so badly as overdriven nails. Drywall, great for fireproofing and finish, should not be used for resisting earthquakes. As the walls flex, the nails just excavate little slots in the drywall. Bugle-head drywall screws, annular-shank or threaded nails, or regular screws are cold-worked, so they can't stand the repeated reversal and extreme deformation that common nails can. Don't use them for shear walls, unless you're certain they are annealed to the performance level of a common nail.

Lag bolts are fine for connections where loads are concentrated. But to work properly, the hole has to be drilled twice—once for shank and once for the threads—then lubricated with paraffin wax and the bolt turned in. No hammering allowed.

Another fastener that's subject to improper installation is the anchor bolt. It carries shear loads from the mudsill into the footing, or would if it weren't too close to the edge of the footing or outside the line of any rebar that might prevent the concrete from spalling during a quake. An equally useless method for installing anchor bolts is to stab them into the concrete after the pour has initially set—a disgusting practice that guarantees the bolt shank will be "anchored" in a cone of laitance (weak and crumbly concrete). Prior to the pour, anchor bolts should be wired inside a double run of rebar at the top of the stemwall (drawing left). The bolts' threads should extend far enough above the finished level of the concrete to accommodate the mudsill, the washer and the nut.

Moisture and shrinkage—Don't expect anything to work structurally when you really need it if it's decayed or being digested by termites. Make sure you've protected your work. Decay is the more insidious of the two. At the point when a specialist can only marginally detect decay under a powerful microscope, *80%* of the wood's shock resistance has vanished.

Strap ties used as tiedowns between floors will buckle as the joists dry, unless they're installed after the joists have shrunk. For the same reason, bolted tiedowns need to have their nuts tightened just before the walls are closed in. ☐

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