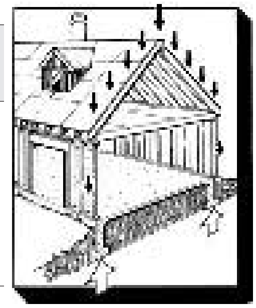
A Porch Roof Diaphragm

by Harris Hyman, P.E.



It was a beautiful spot on an island off Maine, facing the summer sunrise. The architect sited the house in a meadow next to a grove of pines, about 150 feet from the water. The client wanted a design in the local Downeast style, but with an open floor plan and a two-story-high cathedral ceiling.

Structurally, the design was a horror. The architect specced some stout posts and LVL headers to provide vertical support for the tall east-facing eaves wall, but there was no lateral strength (Figure 1). Gusts of wind from a nor'easter were sure to shake the house quite severely. From experience with a lot of wood frame coastal buildings, I know this shaking and shuddering is nothing to really worry about, but it sure makes you feel insecure during a storm. And in this case — a fairly expensive dwelling — shuddering was an intolerable design error. Personally, I think that perceptible shaking during a windstorm is an intolerable design error in *any* house, but in ordinary houses the designer and builder are not as likely to get unpleasant letters on engraved vellum.

In a conventional floor plan, the first-floor partitions stiffen the whole building. No matter which way the wind blows, some walls are lined up with the wind. The other major stiffening element in a two-story house is the second-story floor system, which runs from exterior wall to exterior wall and ties the structure together horizontally. So most conventional houses are pretty stiff. But in an open plan with two-story window walls, something else must do the stiffening.

A traditional choice is a creature called a *portal frame* — a large, stiff, steel frame buried in the walls. At the corners of the steel frame are *moment connections*, usually welds, which cannot rotate as nailed wood connections can. The steel posts and lintels of the portal frame resist deflection, and since the connections can't slip, the building is braced against lateral forces. However, a portal frame is expensive, and most wood frame contractors do not have the necessary skill at ironwork. The same job can be accomplished more easily.

Putting the porch to work. In the case of our Maine island house, local tradition and good sense for amenities dictated a wraparound porch where you can sit in warm weather with a roof to keep the rain and sun off. So I designed the porch roof as a *diaphragm* to strengthen the walls of the house against flexing.

Diaphragm Basics

A diaphragm is a sheet of material that resists loads in its own plane. There are three common uses for a diaphragm: as a vertical shear panel to keep a building from racking; as a compression strut to transfer loads between different parts of the structure; and as an extremely deep, narrow beam. The design of a diaphragm must consider not only the characteristics of the sheet material, but also the reinforcing structure that gives stability to the diaphragm, so that it stays in its plane.

The *Uniform Building Code* deals extensively with the first two kinds of diaphragms. But our porch roof was really the third type of diaphragm — a deep, narrow beam.

The porch roof was built of 2-by rafters and plywood sheathing. Plywood and OSB are of course quite flexible in deflecting to forces applied directly to the face of the sheathing, but they are extremely stiff against forces applied to the edge. The only trouble with applying a force to the edge of sheet material is that you will probably cause it to buckle.

Demonstrate this with a piece of paper on the table in front of you (Figure 2). Hold the short edges of the paper and move your hands together. The paper arches up at once. Now stiffen the paper with a number of folds and do the same thing again, applying force parallel to the folds — it takes a lot more force to make the paper buckle.

The porch roof sheathing can work as a diaphragm because the plywood is stiffened by the rafters. The sheathing is securely nailed to the rafters, to a doubly 2-by lintel at the front edge, and to a supporting ledger at the house wall. The roof actually functions as an extremely deep beam, laid flat to resist the horizontal force from the wind (Figure 3). The porch roof "beam" spans from one end of the house to the other and transfers wind loading to the end walls of the house — the "supports" for the beam. The end walls are strong enough to handle the load because they are sheathed with plywood and firmly anchored to the foundation.

Wind Loading

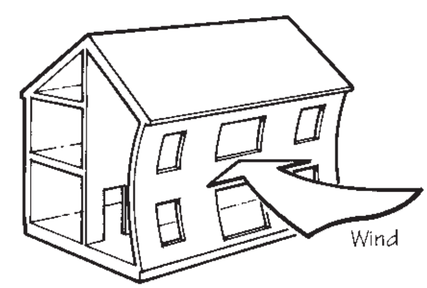


Figure 1. *A two-story exterior wall, if unbraced by interior partitions, will flex under heavy wind loads.*

Running the Numbers

I designed the porch roof in the same way I would any simple beam. Rather than show all the calculations here, I'll just give the results. (For a review of the steps involved in beam sizing, see *Practical Engineering,* 8/94 and 9/94.)

Envision this particular beam — the porch roof — as 30 feet long, 8 feet deep, and $1/2$ inch thick (Figure 4). The material is $1/2$-inch Doug fir plywood. Note that I don't credit the rafters as adding to the thickness of the beam — their purpose is to stiffen the plywood, but the plywood itself does all the work. The section of this beam is thus $1/2$ inch thick by 96 inches deep (two sheets of plywood

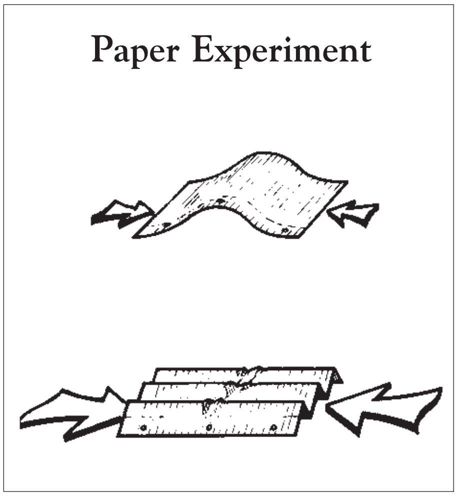


Figure 2. *A sheet of paper will buckle quickly if you apply force at each end. But stiffen the paper with folds and more force is needed to deform it.*

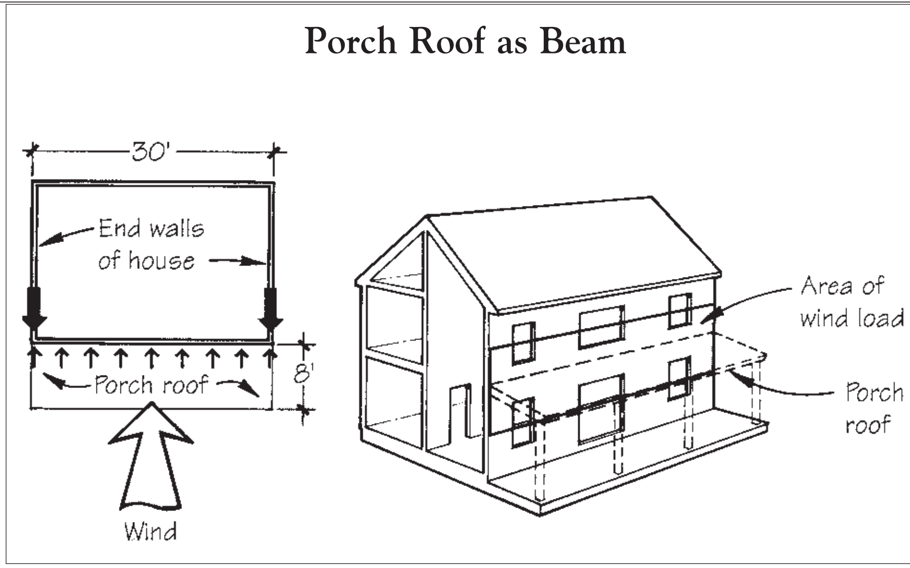


Figure 3. *The porch roof, because it's designed as a plywood beam, stiffens the middle half of the house wall against wind loading. The wall is in effect "hanging" from the porch roof, and transfers its load back into the roof sheathing. The sheathing carries the load to the gable-end walls of the house.*

laid side by side). Using the standard formula, the section modulus of an 8-foot-deep, 1/2-inch-thick beam is 768 $in.^3$.

So how does one go about designing a beam made of plywood? Fortunately, APA, The Engineered Wood Association, of Tacoma, Wash., has published the *PDS (Plywood Design Specification)*, which gives design values for all the different grades of APA-rated plywood. I used AB Doug fir plywood, which has an allowable bending stress (Fb) of 1650 lb./sq. in.

Next I figured out what forces the roof was resisting. The horizontal design force of the wind in an open coastal area is 65 pounds per square foot. The wall of the house resisting this force is 30 feet long and 16 feet tall from the eaves of the windward wall to the first-floor deck. The porch roof runs across the midpoint of this space, so as a beam it withstands the wind load on the middle 8 feet of the wall.

This works out to 43 pounds per inch, and a maximum bending moment of 696,600 inch-pounds. To check the strength of the roof beam, I calculated the section modulus *required* to withstand this bending moment, using the formula $S = M / Fb$. The required section modulus works out to 422 $in.^3$.

The designed section modulus (768 $in.^3$) exceeds the required section modulus (422 $in.^3$), so the roof diaphragm is *strong* enough. But what kind of *deflection* will there be? Using the deflection formula gives 0.17 inch of deflection over the 30-foot length of the roof, which equals l/2,100. So the roof is *plenty* stiff enough.

The final check is for shear stress. The shear force is 7,740 pounds, which gives a shear stress of 241 $lb./in.^2$. The allowable shear stress for AB plywood is 190 $lb./in.^2$, but since we are designing against sudden, short gusts of wind, we're okay. The *PDS* allows a 33% increase in design values for wind or earthquake loads. (I could also apply this to Fb, although I didn't need to — the design for strength is conservative.)

Keeping the Plywood Flat

So far, so good — the 8 feet of sheathing, designed like a beam, can handle the loads. But a sheet of plywood stressed in this way is "structurally unstable." Here, I use a very precise meaning for unstable — that a stress much lower than the applied stress will cause the plywood to take on a different shape, so that it can't handle the stress properly. Recall the experiment in Figure 2: When the paper buckled up from compression, it had nowhere near the same strength as when the folds resisted buckling.

We give the plywood stability by securely nailing it to the lintel, the rafters, and the ledger. Looking at the plywood sheathing as a flat beam, the outer edge is in compression. This compression edge will buckle — go unstable — unless it is either securely braced at proper intervals or the bending stress is greatly reduced. Without repeating the arithmetic here, I calculated that using an 8d nail every 3 1/2 inches into Doug fir framing would provide the necessary bracing. (For the technically minded, I used the Euler and Yuon formulas to arrive at these numbers.) The nailing interval applies both to the edges and the field of the plywood.

Since the cost of extra fastening is quite low, for the job in Maine I suggested an actual nailing interval of about half the calculated interval, or 2 inches.

Continuity. There's another important consideration. Plywood doesn't come in sheets 8 feet wide and 30 feet long. To work as a beam, the roof sheathing must be continuous — that is, the stress must be directly transferred from sheet to sheet as if there were no joints. I achieved this by actually adding a second layer of 1/2-inch plywood, with the joints of the two layers offset in both directions. The roof is quite rugged, but so is the wind off the North Atlantic. In hindsight, I believe the same effect could be achieved by using solid blocking at all plywood edges. Given the price of plywood these days, blocking would probably be the more cost-effective option.

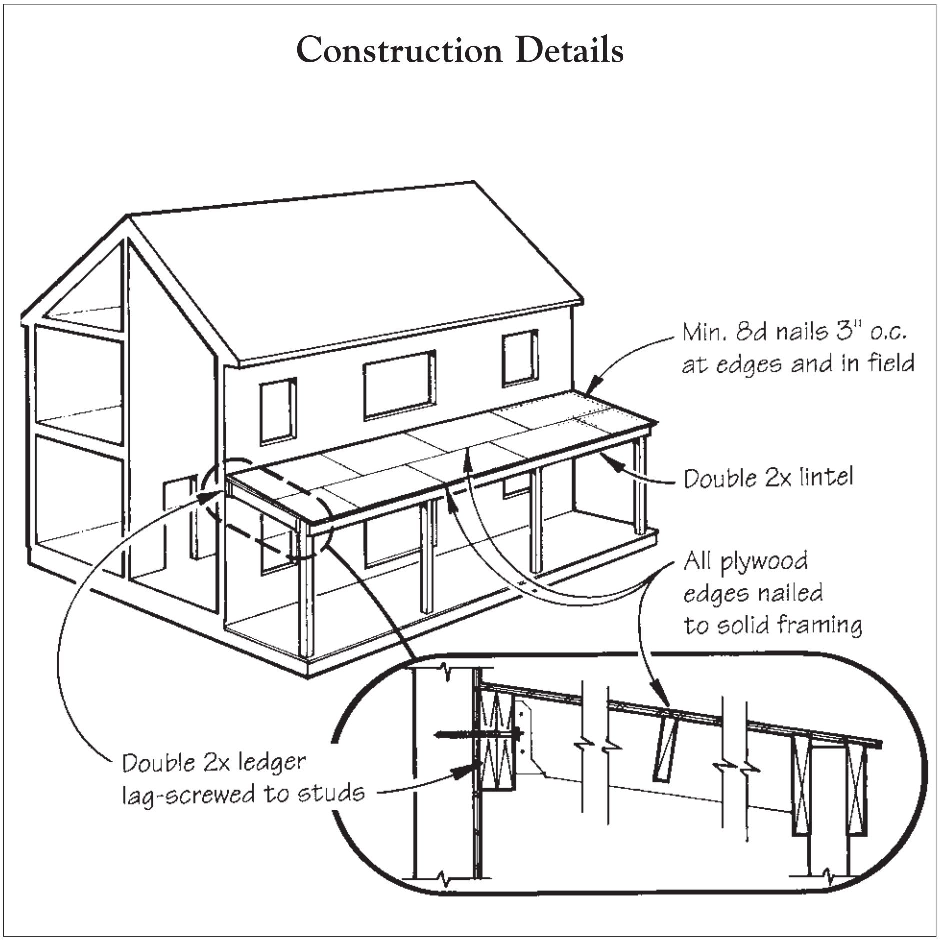


Figure 4. *For the porch roof "beam" to work, the double 2-by ledger must be securely anchored to the house wall studs with lag screws. The plywood sheathing must also be nailed to solid framing at all edges.*

Some Rules of Thumb

But can you do this in real life, without the engineering calculations? Here are some guidelines.

If you're using a 1/2-inch plywood roof to stiffen a two-story wall against high winds, you'll need a width-to-length ratio of about 5:1. This means that a 5-foot-wide roof can strengthen 25 feet of wall, or an 8-foot-wide roof can stiffen 40 feet.

The size of the outer lintel is quite important. A rule of thumb is to take the width of the roof in feet and use a double 2-by of equal or greater size in inches: So a 5-foot-wide roof calls for a double 2x6 and an 8-foot-wide roof needs a double 2x8. I'd support the lintel with posts not more than 8 feet apart. Space the rafters 16 inches on-center and use rafters appropriate for the span. Then nail off the plywood with 8d galvanized nails at 3 inches on-center everywhere.

The nailing schedule isn't a joke — follow it. You can keep the spacing with a couple of strips of black tape on your air nailer or hammerhead.

Orient the plywood as shown, with the length perpendicular to the rafters. It might sometimes be simpler to run the plywood perpendicular to the building, but that places the plywood in the weak direction.

Finally, plan the rafter layout and add blocking so that all plywood edges land on solid framing. (Or you can use a double layer of plywood instead — but the material costs will probably outweigh the labor. I would recommend this only for design conditions where you need the extra strength.) Framing clips and tongue-and-groove plywood will not work as a substitute for blocking. ■

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