Basic Design Issues in Timber Frame Engineering II

IN the first part of this article (TF 86:16), we discussed the engineering method generally, common methods for supporting floor loads and specific strategies for handling simple gable roof loads. Before we leave our discussion of roof framing, we should talk briefly about hips and valleys. In a regular square hip roof, where there is no ridge (Fig. 1), it's not hard to see that the opposing pairs of hip rafters function much like simple rafter pairs. In this case the necessary tension tie is provided by the joined and restrained plates, which function as a tension ring.

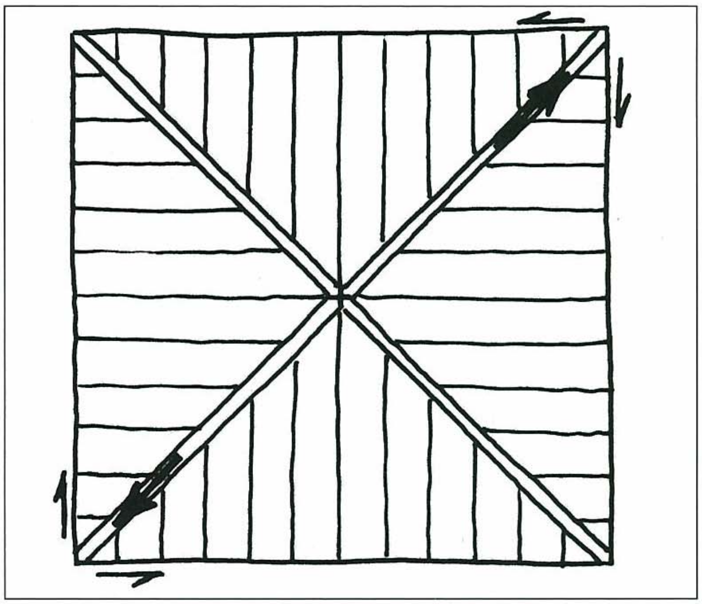
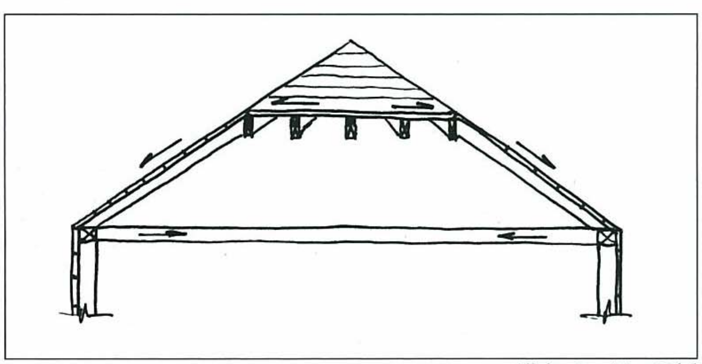


Fig. 1. Ridgeless hip roof frame, its rafter action resolved in the plates.

Hip rafters do not necessarily need to be sized to handle the full gravity load of the jack rafters they appear to support. We know that in many old houses the hip rafters are not much bigger (if at all) than the jack rafters that frame into them, despite the seemingly much larger bending and shear loads they have to support. Yet most of the time they perform pretty well. How come? The roof sheathing and jack rafters must be working together with the ceiling framing to form a kind of arch or truss (Fig. 2).



All drawings Tom Nehil

Fig. 2. Sheathing works with framing to form a kind of arch.

When the roof framing is open, as we often see in timber frame buildings where no ceiling joists tie the feet of the rafters, the jack rafters and hips in the system function more like stiffeners to brace the roof sheathing, which becomes a three-dimensional shell or folded plate.

Hip roofs work on rectangular-shaped buildings as well as on square plans; the arch action is still there. The opposing rafter pairs that frame into the ridge along the main roof of the building, however, still need to be designed using one of the strategies previously discussed for gable roof framing.

Valleys are in some respects just upside-down hips; rather than throwing the roof sheathing into compression as do hips, valley rafters pull on the sheathing as they sag under load. Nevertheless, to simplify design and to be conservative, we usually design both valley and hip rafters to support their full tributary area roof loads, especially in open timber-framed roofs.

We left the discussion of hips and valleys for last in the roof-framing section because it leads us to think about our buildings as three-dimensional assemblies, where the sheathing or skin functions as a part of the structural system. We are no longer looking at our buildings as simple two-dimensional assemblies. Such three-dimensional thinking is exactly what we need when it comes to the issue of dealing with lateral loads.

Strategies for Resisting Lateral Loads. Lateral loads are imposed on our buildings by wind or, in some cases, by seismic activity, but they can also be caused by unbalanced snow loads. Asymmetric frames also have a tendency to drift sideways under gravity loads.

Wind loads are defined by the building codes, as are the forces resulting from ground accelerations. Of all the code requirements, lateral loads are perhaps the most difficult to understand—and to believe. We have looked at many timber frame barns, relatively simple and easily-understood structures, and found they cannot be shown to be capable of resisting full code-required wind loads. Thus a considerable amount of retrofitting is necessary when a barn is to be converted to residential or commercial use. Yet such barns have stood for over 100 years without collapsing or lifting off their foundations despite a lack of anchor bolts. Some old barns will even sit stably for years with no hay stored inside to serve as ballast and with the barn doors open, a so-called "partially enclosed structure" that acts something like a parachute.

It's often difficult for us structural engineers to justify code lateral load requirements in light of such performance. Even so, code wind loads are based on meteorological records and physical measurements of pressures on buildings, and are therefore more than just extravagant guesses. We all have to remember that code requirements are intended to make our houses or commercial buildings safe shelters even in fairly extreme weather conditions. Because of code limits on the stresses we can apply to our framing members and limits on deflection or sway of the frame, the building needs to come through these extreme weather events without much swaying or damage to interior finishes. If you design and build to meet the code requirements for lateral loads, you can feel pretty safe in your building during a storm.

The lateral loads applied to buildings from wind are a function of the wind speed. Maximum design wind speeds are defined in the building codes for various areas of the United States. For design purposes, most of the interior of the country is classified for a 90-mile-per-hour, 3-second-gust maximum wind speed. (Note that we do not try to design for tornados since these are considered too unlikely an event for any individual building, and economically impractical to design for.) On the other hand, design wind speeds along the Gulf Coast are upward of 120 mph. That may not sound like a big increase from 90 until you realize that the pressure the wind exerts on an obstacle in its path, such as a timber-framed building, is proportional to the square of the wind speed. A 120-mph wind thus exerts almost twice as much lateral load on a building as does a 90-mph wind.

So how big are the code wind loads? Let's say you are building a two-story Colonial 30 ft. by 40 ft. with a 12:12 pitch roof, and your building will be in a 90-mph wind speed region in fairly open terrain. The pressure a 90-mph wind applies to your building will be on the order of 15 to 20 lbs. per square foot of vertical sail area. This can quickly add up to a lot of lateral load—you could be looking at 7 to 8 tons. Clearly you need to design to resist these racking forces.

We have two basic strategies for resisting lateral loads in timber frame buildings: frame action, where the racking loads are resisted by the frame using knee braces, full-height diagonal wind braces or even posts cantilevered up from the foundations; and shearwalls. Let's look at the specifics of these strategies.

Frame Action. In a pure timber frame structure such as the typical 19th-century American barn, we usually see numerous relatively small diagonal members connecting posts and beams, termed knee braces (even though they are not actually made from natural-grown knees) to distinguish them from long, wall-height braces typical of other framing traditions. In American timber framing, these knee braces evolved to a standard size, often 4 in. wide by 3 in. deep in the Midwest (vs. 3x4 in New England), with vertical and horizontal runs both at 36 in. Often these braces were not pegged in place but simply held in position by their housings and confinement by the timber frame around them. This configuration has been described as "compression-only" joinery.

What happens when we try to rack a knee-braced frame? The corners formed by the posts and beams change from 90-degree angles to something less on the leeward side and something greater on the windward side. As the angle tries to close on leeward side, the knee brace is put into compression and resists closing of the angle. Remember from our earlier discussion that a knee brace pushes not only down but sideways as well, thus putting the joint between the post and beam into tension; we maintain there is really no such thing as compression-only joinery. As the knee brace is very stiff in compression, the angle is maintained pretty close to its original 90 degrees. The post and beam, however, bend around the knee brace as shown in Fig. 3.

The bending of posts and beams is significant in a large frame despite their hefty cross-sections. If we increase the size of our knee braces so that we have room for decent tenons and good-sized pegs, we can start to develop tension joinery on the windward knee brace and thereby get both the windward and leeward sides of the frame working to resist the racking. On the windward side, however, we have not only the flexibility of the post and beam to consider but also the flexibility of the pegged joinery.

All these effects taken together, a simple knee-braced frame is very flexible. You have probably noticed this on small frames, where it's not hard for one person to get the frame rocking back and forth. Big frames with heavy members and large-diameter pegs such as 1½-in. are still flexible. Though not much of a concern in agricultural buildings or perhaps open pavilion structures, this flexibility is certainly not acceptable for residential or commercial buildings incorporating rigid finishes and often large window walls.

In our structural analysis, we have to take into account the flexibility of tension joinery to properly predict the magnitude of compressive forces in the knee brace on the leeward side of the frame and the resultant bending forces in the associated posts and beams. Analyzing wood tension joints as if they are similar to monolithic concrete or structural steel framing is inappropriate. (See Erikson and Schmidt 2001 for additional information on the stiffness of pegged tension joinery.) Notice in Fig. 3 how the windward post shows less bending than the leeward one: this is due to the flexibility of the pegs in the tension joinery that limit the capacity of the tension brace to "pull" on the post. The compression brace will have a larger load in it than the tension brace, but not as large as if there were no tension joinery at work. (See our companion article, TF 79:18, for further discussion of the interaction between tension and compression joinery.)

If instead of knee braces at the top of our frame, we incorporate so-called down braces at the bottom of the frame, as shown in Fig. 4, we can get better resistance to racking. That's because the foundation that the compression down brace (now on the windward side) pushes against is rigid, unlike the beam at the top of the frame. Note that as the frame pivots around this compression brace, the windward post tends to be pried up out of its joint to the sill, so the forces at that joint have to be considered. Fortunately, we have the weight of the building on the post working in our favor to resist this uplift. If we plan to use tension joinery in down-braces on the leeward side of the frame, then we need to have good anchorage of the sill to the foundation at those points as well as good tension joinery.

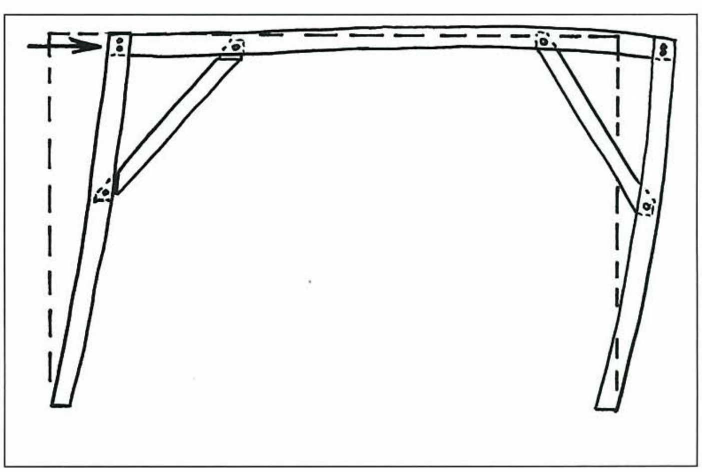


Fig. 3. Racking a simple knee-braced frame. Posts and beams bend to accommodate stresses applied by braces.

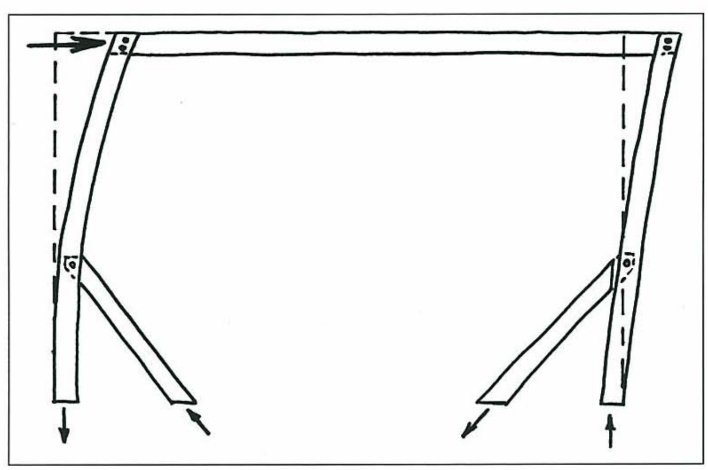


Fig. 4. Locating knee braces at sill rather than plate obtains greater racking resistance for frame since the fully supported sill cannot bend.

There is still flexibility in a down braced frame because the posts can bend. Other bracing options are more effective. Instead of using just 36-in. horizontal and vertical runs for the brace, we can take the brace from corner to corner of a frame, as in X-bracing. We will get a much stiffer building with lower joinery forces. This configuration starts to look like what we might call Old-World bracing, as seen in the half-timbered structures of Germany and England. Sill-to-plate bracing is stiffer because it turns our frame into something more closely resembling a truss. The nearer we bring the ends of the diagonal brace to the intersections of the posts and beams, the less bending there will be in those members. Because the diagonal brace is long, it has a better lever arm to resist the racking forces, and thus the forces in the brace are lower.

When we study those half-timbered structures from Europe, we notice they are not pure timber frames in the same sense as a typical 19th-century American barn. With the kind of infill typically in place in a European timber frame, we start wondering how much work the braces really have to do, which leads us to our other main strategy.

Shearwalls. What is a shearwall? It's a wall or portion of a wall that's essentially rigid in its plane. It will not rack, it will not slide and it will not tip over when design lateral loads are applied. In wood construction the resistance to racking can be provided by a number of arrangements.

¶ Horizontal or vertical sheathing. This forms a relatively soft shearwall, since all the resistance to racking is provided by the nailing of the boards to the framing members.

¶ Diagonal board sheathing. A much better and stiffer method. We still depend on the nails to fasten the boards to the framing members, but now the sheathing boards function as diagonal braces.

¶ Plywood sheathing. Even better since we get a much "smoother" flow of the forces in the panel and we can put many more fasteners through the plywood into the framing members without risk of splitting the sheathing. The more fasteners, the stronger and stiffer the shearwall action.

¶ Structural insulated panels (SIPs). Similar in behavior to plywood sheathing but particularly applicable to timber frames since the panels can span larger distances between framing members and provide an insulated skin at the same time.

Research presented in this journal (Erikson and Schmidt 2002) has shown that shearwall-braced timber frames can be much stiffer than timber frames with knee braces alone, even those incorporating tension joinery. The loads in a structure go to the stiffest elements. With any form of shearwall in place, the timber frame will likely not have much opportunity to resist racking since the shearwalls will take up the load first.

There can be some interaction of braced timber frames and shearwalls in a structure, where loads are shared between the two systems. This is the case when frames are designed with relatively rigid bracing and the diaphragms are relatively flexible (read on for the discussion of diaphragms). We find that in most residential and commercial buildings it's usually more practical to deal with lateral loads simply by the use of shearwalls. Shearwall systems have the advantage that they can be designed using code-accepted rules that define racking resistance as a function of the thickness of the sheathing and the size and spacing of the nails used to fasten it. Research sponsored by the Guild, the Business Council, the USDA and the University of Wyoming has made great strides toward developing accepted standard practice for use of tension joinery in braced timber frames (Schmidt and MacKay 1997, Schmidt and Daniels 1999, Schmidt and Scholl 2000, and Miller and Schmidt 2004), but it's still more straightforward to get a building permit, especially in seismically active regions, using shearwall systems.

For engineered design of SIPs as shearwalls, at this time we need to use manufacturer-specific shearwall resistance values. The International Code Council Evaluation Service has testing procedures in place and evaluates the suitability of a particular SIP manufacturer's products for use as shearwalls in wind and low seismic demand applications. The Structural Insulated Panel Association is working with the American Plywood Association to add evaluation procedures for SIPs used in more seismically active regions of the country. SIPs will be included in the next edition of the International Residential Code for use in prescriptive design (that is, cookbook or pre-engineered design provided in the code) for wall applications, including use as shearwalls.

Diaphragms. Whether you are using braced frames or shearwall systems, keep in mind the function of the floors and roofs as part of the lateral load-resistance system. The sheathing on floors and roofs essentially creates horizontal shearwalls that we call diaphragms. The diaphragms act as horizontal beams that provide lateral support to the walls of our building and transfer the wind loads on the walls to the braced frames or shearwalls, elements of the building that resist racking.

Figs. 5 and 6 show the flow of wind forces through a simple building. Wind causes pressure against the windward face of the building and suction on the leeward face. The wall sheathing and framing direct the wind load to the floor and roof diaphragms, which in turn direct it to the shearwalls or braced frames. These are anchored to the foundation. Diaphragms can be constructed of board sheathing laid perpendicular to the joists but, just as with shearwalls, a stronger and stiffer structure results when the boards are laid diagonally to the joists. Plywood-sheathed diaphragms are even better. Design of diaphragms follows code-accepted rules that define strength as a function of the size and spacing of nails and the thickness of the sheathing.

Diaphragm action allows us to position shearwalls and braced frames in a building in asymmetric arrangements, and it opens the door to creativity in building configuration. We are not confined to a rectangular box with solid walls on four sides. The diaphragms

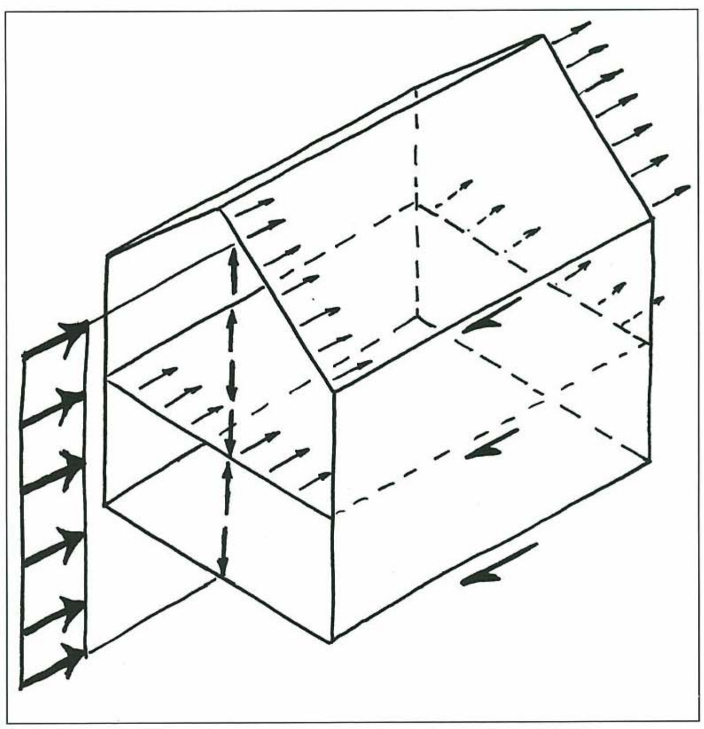


Fig. 5. Diaphragms and shearwalls at work. As windward and leeward walls try to push and pull roof and floor with the wind, side walls hold back roof and floor to stabilize building.

have to be specifically engineered for the forces they must resist, and understanding the three-dimensional behavior and flow of loads through a building is required.

As a system for resisting lateral loads, shearwalls and diaphragms reduce the strength and stiffness required of the timber framing. Posts can be sized to accommodate the joinery at beam intersections without having to worry about the effects of racking that would be at work in an unsheathed braced frame. It was a combination of engineering and trial and error that led barn designers and builders in the early part of the 20th century to appreciate and take advantage of sheathing working as diaphragms and shearwalls to greatly reduce the amount of framing in barn construction. The classic 19th-century gable-roofed timber frame barn of the eastern states evolved into the laminated curved-rafter clear-span dairy barn of the 1920s.

Project Development and Management. When should you get a structural engineer involved in the design of your timber frame project? We encourage you to get architectural and engineering advice as soon as you have developed those first freehand sketches showing rough plans and elevations for the building. Don't try to take your design too far and make it pretty before you discuss the basic issues with an architect and a structural engineer. Definitely do not wait until you have already signed contracts and ordered timbers before contacting an engineer, hoping to get your drawings approved and stamped for a building permit. At that point your options for modifying the building are all going to be expensive and could lead to some very soured relations with the client, or with your bank if the project is for yourself.

Remember that design of a building starts from the top and works down as you figure out the loads and framing for the roof and the gradual accumulation of roof loads and floor loads down to the foundation. If you keep that in mind you will see why it makes no sense to build the foundation until you have a clear plan for resisting both gravity and lateral loads applied to the building.

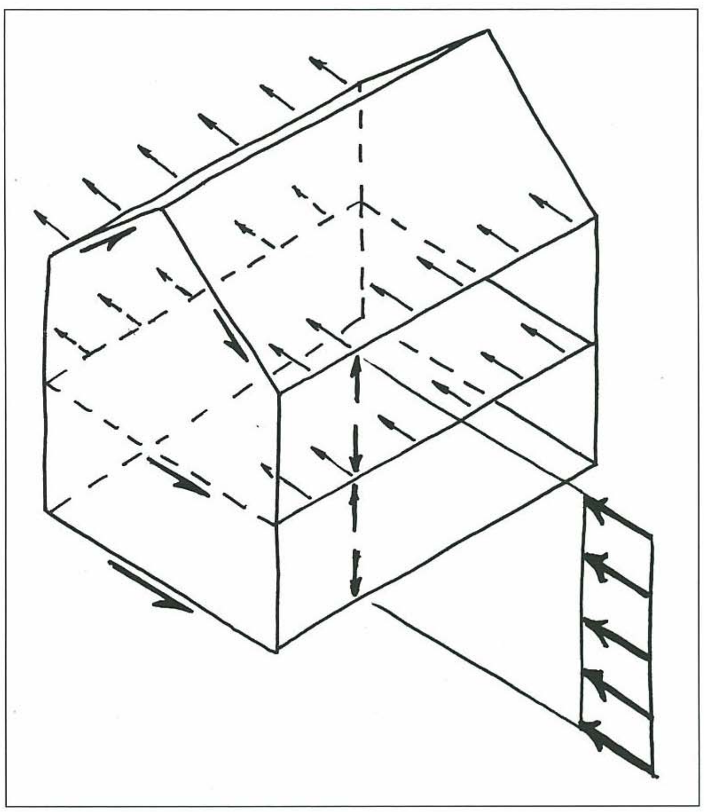


Fig. 6. Wind against eaves side of gable roof building puts diaphragms and shearwalls to work but produces more complicated forces because of roof slope. For roofs steeper than 6:12, wind produces positive pressures on windward side but suction on leeward side, while for roofs shallower than 6:12 both sides experience suction (not shown).

There are often misunderstandings by architect, owner, builder, and even sometimes the structural engineer, of the role of the timber frame components in the completed structure. The team sometimes assumes that the timber frame structure will perform something like the Rock of Gibraltar, capable of resisting all gravity and lateral loads. Because of such misunderstandings, often not enough attention is paid to designing the structure specifically for resistance to lateral loads. The timber framer needs to verify with the architect or engineer how the building is to be braced for wind or seismic loads and whether the design for lateral loads has been provided in the drawings. If SIPs are to act as shearwalls, make sure the SIP suppliers are aware of this fact. Before prices are established and contracts written, clarify whether the suppliers are responsible for design for lateral stability or whether it will be provided by others. To repeat, design for lateral loads needs to be addressed before the foundation is designed because the foundation and the attachment of the lateral-load-resisting system to it are critical components of the lateral stability system for the building. The foundation must have adequate mass and appropriate reinforcing at critical locations.

For architects, engineers and timber frame shop owners, we believe it is negligent not to clearly spell out responsibilities for gravity load and lateral load design on any contract documents and on shop drawings. It is unacceptable and unethical to stamp shop drawings without a thorough review of all critical joinery and a clear statement on the drawings whether or not the timber frame has been designed to resist lateral loads.

Engineering for timber frames is a craft like the craft of timber framing itself. To be proficient requires both training and practice. The basics of structural engineering are well within the grasp of most timber framers, and you can learn to do some of the preliminary design for yourself. The more complex aspects of structural design take specialized training and time to master, so we urge you to get structural engineering review. There is no one right answer to the design of any timber frame structure. Structural engineering can help you achieve creative ends while still having confidence that the building will perform as expected under loads.

—Tom Nehil and Amy Warren

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