TIMBER FRAMING

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Choosing Wood Species

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On the front cover, moving Alaskan yellow cedar logs and timbers at a millyard in British Columbia. On the back cover, cleaning old-growth Western hemlock timbers preparatory to planing. Photos by Bruce Lindsay. Story, page 3.

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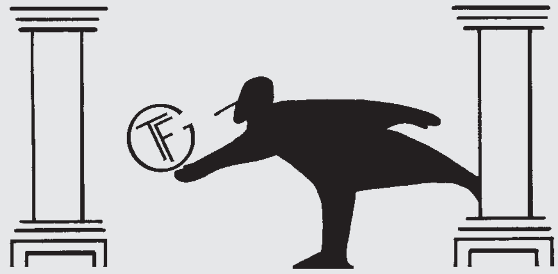
TFG 1985



GUILD NOTES & COMMENT

TRAVELING home to Oregon from the Coeur d'Alene conference in April, I found myself thinking about a conversation I'd had with a young guy attending his first Guild event. After several minutes of friendly talk, I had asked him what he thought of the Guild. He replied that it seemed like a bit of a "good old boy club"—that he found it hard to fit in when so many experienced members seemed to know each other. For him it was like attending a high school reunion only to discover it was not his class.

His perceptions resonated with me. Eight years ago, I had driven all the way from Corvallis, Oregon, to Banff, Alberta, braving a frigid snowstorm that closed the Trans-Canada Highway, to attend my first Guild conference. I was filled with unbridled eagerness and enthusiasm for everything related to timber framing. I had completed my first timber frame course, a one-week square-rule class, the previous summer. My first conference was somewhat of a disappointment. I, too, found it cliquish. Between sessions, I listened from the fringe as many of the pillars of the Guild reconnected with old friends and exchanged stories. My polite attempts at conversation were met largely by indifference or distraction.

As I prepared to leave Banff, one person stood out, literally, from the crowd, the owner of a successful timber frame company whom I had met earlier. As I headed toward the door, he left the others and made a point to come over to me. I was surprised that he remembered my name and wanted to wish me a safe trip home. He said a few words of encouragement before I departed. For me, that was a turning point. Here was a successful member of the timber framing community who seemed to be saying, "You matter—don't give up."

At Coeur d'Alene this year, I met several people who I felt could become close friends. One of them went out of his way to invite me to dinner when he noticed I had been left behind. I felt deeply moved when he later confided in me that he was suffering from a serious illness. Here was a guy who obviously had a lot to deal with, yet he still went out of his way to help me feel included. At the other end of the spectrum, my interactions with several more experienced members left me wondering. My polite inquiries were met, as at Banff, by an indifferent response and a lack of eye contact.

I wonder with some concern about the future of the Guild. I ask myself how we will ever become a more diverse group if a middle-aged, white guy like me often struggles to fit in. I have now transitioned out of the role of new member: this was my fifth Guild conference in nearly twice as many years. I am no longer looking for acceptance as much as feeling part of a larger whole. Though I have yet to cut my first full frame, I have had enough years of serious woodworking, log salvage, and milling to give me a level of confidence. My perspective has shifted. I find myself pondering what I can do to make the world, and the Guild in particular, a better place.

As you reconnect with old friends and make new ones at a conference, look for the people sitting alone or who have that eager, tentative look in their eyes. Show some interest in them and what they do—and let them know that they matter. The future of the Guild depends on how well we help them feel connected.

—DOUG POLLOCK

Choosing Wood Species

Will Beemer

1 Student-built demonstration frame at author's building school, with white pine posts and rafters, cherry and ash tiebeams and joists of all three species, partly reflecting timber available in Berkshire Hills of Western Massachusetts.

BUILDING some years ago in Patagonia, in the southern part of Argentina, for someone who *really* wanted a timber frame, taught me a lesson in appropriate building. There was a tradition of timber framing in that part of the Andean foothills, using a wonderful local cypress, but cypress was now unavailable, locked up in national parks. The client had another piece of land 900 miles away with a stand of southern beech (*Nothofagus alpina*) from which he produced the necessary timbers and shipped them down to the site. When we arrived, the milled hardwood timber had been sitting in the arid Patagonian climate for a few months and had checked and twisted almost to the point of being unusable. The only local timber available for a second project there was Lombardy poplar (*Populus nigra*), a usually fast-growing tree used for windbreaks. Luckily, the particular timber we obtained then had grown in the right conditions to produce relatively dense growth rings. In both projects we had no prior idea what the strength of the timber was; we didn't have reference books to look it up and couldn't even be sure of the species. We had to take a few representative pieces and test them with weight attached to calculate backward through the deflection formulae to come up with design values. In the end the frames are up and serving well, but we haven't gone back to build more. The short supply of suitable material made us realize that timber framing is just not an appropriate technology there, and we had to look no further than the adobes of the gauchos to see what made more sense. The client remains unconvinced.

Choosing the species of wood for your timber frame or a client's will be governed by a number of factors, some under your control and some to be decided by others. While you usually don't have a choice at the local building supply for the brand of common nail or sheet of drywall, timber is not so standardized. There are many species, and grades within them, to pick for a frame (Fig. 1).

As a natural material, wood differs from homogenous (and predictable) building materials like concrete, plastic or steel. Wood is anisotropic, which means that its physical properties are different when measured along different axes, and that its behavior is different depending on its orientation. These properties arise from the structure of the tree the wood comes from. Wood cells are generally long and narrow, though they vary in length and shape both within and across species; strength, shrinkage, workability and other factors depend on which direction they run in a workpiece. Entire books have been written about wood science and structure; we'll concern ourselves here with general considerations.

The major difference we see across species is between so-called *hardwoods* and *softwoods*. Depending on where you live, the forest may be dominated by one or the other, or it may be mixed. "Hard" and "soft" are often misnomers, because some softwoods are very hard (Southern yellow pine) and some hardwoods are soft (balsa). All trees are seed-bearing, and the proper botanical distinction is between the angiosperms (covered seeds), which produce hardwoods, and the gymnosperms (naked seeds) that produce softwoods, the latter often called *conifers* after their seed form. Softwoods and hardwoods differ in cell structure and even the shape of the tree. Most hardwoods (but not all) are deciduous, which means they lose their leaves in autumn, while most softwoods (but not all) keep theirs. In general, hardwoods are broad-leaved and softwoods are needle-bearing. (Needles are also considered leaves.)

The most accurate way of identifying wood is to look at its cell structure with a microscope or handheld lens, and then use a key, or process of elimination, to narrow down your choices. A different key can also be used to identify trees in the forest, but variables in growth can throw you off and you can't really be sure what you've got in some cases until you look at the cells. It's not necessary for the timber framer to have a vast knowledge of cell structure, but understanding the broad differences between softwoods and hardwoods, and being able to identify trees in the forest before harvesting, are obviously important.

Terminology and classification. To accurately identify a species in discussion requires the use of its scientific name in Latin, a combination of *Genus* (with a capital) and *species* (lowercase). Common names such as "poplar" or "ironwood" are inconsistent and vary across locales. The forums on the Guild website illustrate how people from different parts of the country and overseas refer to different species by the same name, or to the same species by different names, until someone offers the botanical name to really pin it down. Tulip poplar, for example, is a great timber framing tree, but it's *Liriodendron tulipfera*—not even in the *Populus* genus with the true poplars and cottonwoods, which are not preferred for timber framing. And all may be called *popple* by local loggers or sawyers. But timber framers usually work with a few species, and it won't be long before you recognize the differences among *Pinus* (pines), *Quercus* (oaks), *Picea* (spruces), *Acer* (maples) and others.

Distinctions are made in milling and grading among boards, lumber and timber. In general, boards refer to anything 1 in. or less in its smallest dimension, lumber ranges from 2 in. to 4 in. and timber is anything 5 in. or above. Understanding this not only makes you look smarter at the sawmill but also helps you pick out the right table from the grading manual since design values change somewhat with the cross-section.

Sapwood and heartwood. A major distinction within a tree is between sapwood and heartwood. Sapwood is made up of the living cells nearer the bark that carry nutrients. Cells that die form heartwood, while the tree expands outward by layering on more sapwood. Sapwood is often visible on the end of the log as the outermost band of a paler color, and it varies considerably in width, mostly according to the species and somewhat according to growing conditions. A mature oak log, for example, might have only six or seven annual rings of sapwood whereas a beech log of the same age might have 25. There is little difference in strength between sapwood and heartwood.

Fungi and rot are more likely to attack sapwood, even in species with rot-resistant heartwood, so its presence should be minimized or whenever possible avoided in exterior applications. Blue stain is a common problem in white pine that has been harvested when the sap is running and the fungi go for the sugars. It does not affect the strength of the timber but it can be a big appearance issue for some clients. A knowledgeable timber framer working with pine will recognize the risk and harvest timber before the sap flows.

Annual rings, earlywood and latewood. When you examine growth rings on the endgrain of a North American forest tree, you can see a distinction in each complete ring between *earlywood* produced by the growth spurt in spring and early summer, and denser *latewood* produced during the rest of the growing season. In softwoods, the demarcation is between light (earlywood) and dark (latewood) bands, and it can be abrupt or gradual. In some hardwood species like oak and ash, ring-porous woods, the distinction is quite pronounced between obviously porous (earlywood) and obviously dense (latewood) bands. In other species like maple, a diffuse porous wood (and in tropical woods that grow evenly all year), there may be little visible distinction. The density difference between earlywood and latewood can be a practical concern for woodworkers. Douglas fir, for example, has quite dense latewood that has been known to chip chisels (so you might opt for a machine to cut joinery rather than hand tools, or wet down a surface before cutting). The earlywood of all softwoods has a tendency to chip out when the framer chops across the grain, such as when trimming the end of a mortise.

Excluding the atypical juvenile wood put on around the pith when a tree is very young, the proportion of latewood to earlywood is the key to density in all species, hardwoods and softwoods alike. A relatively greater measure of latewood in the rings of any example indicates a greater density, and thus usually stength, for that example compared with others of the species. Popular notions that in any species fast-grown or coarse-grained timber is relatively weaker, and that slow-grown or fine-grained timber is relatively stronger, are misleading, as is the belief that an old tree will necessarily yield denser wood than a young tree of the same species and diameter.

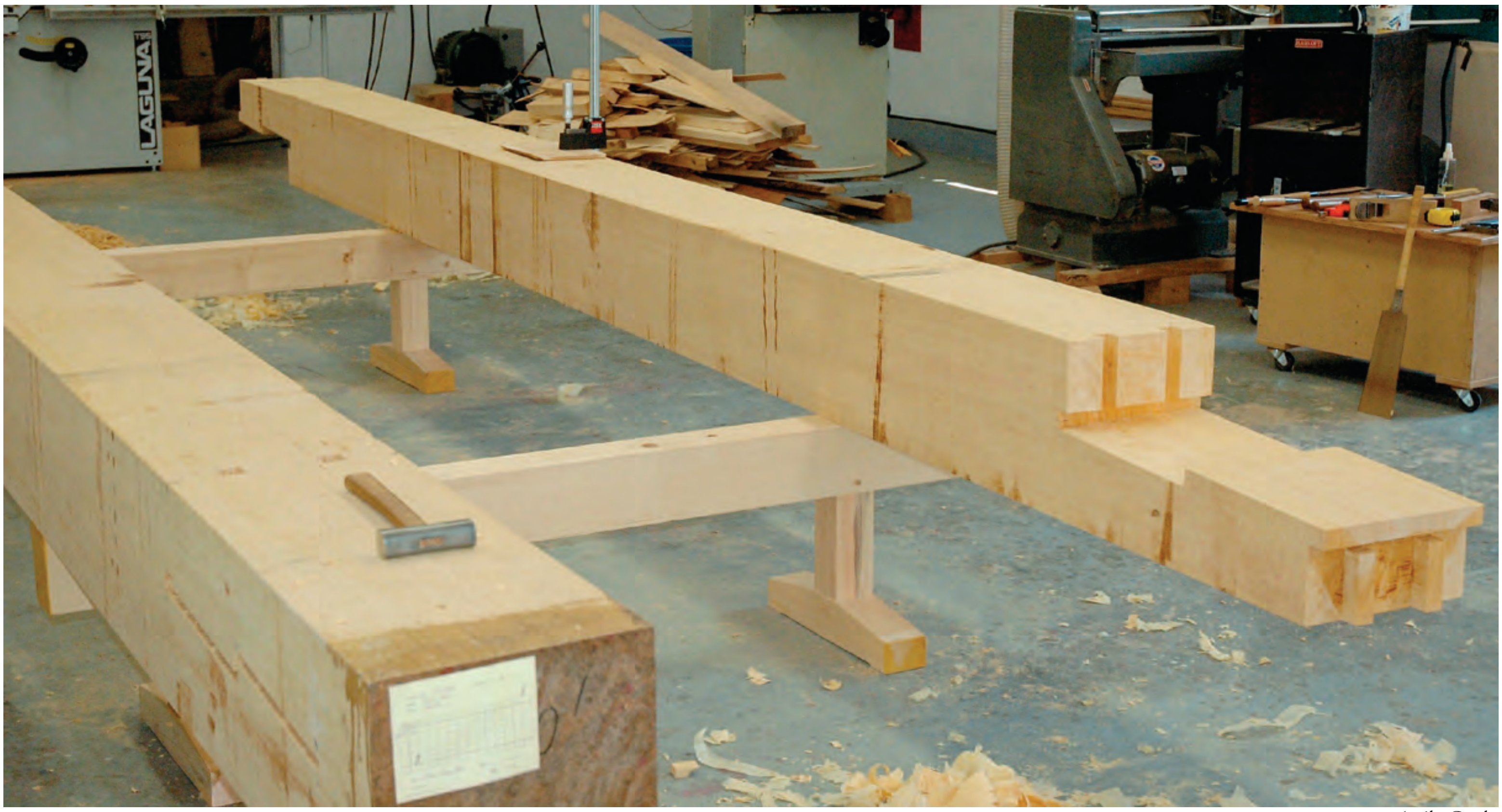
It's not simply the number of annual rings per inch as measured on the endgrain of a sample that tells you how dense a timber or log may be, of its species. It's the collective amount of latewood in the rings, whatever their number. This can vary significantly even within softwood species (such as Douglas fir) with a reputation for consistent latewood production. And in hardwoods such as oak and ash, relatively faster grown timber typically has a higher proportion of latewood and is thus *denser* than slow-grown, fine-grained material.

CRITERIA FOR SELECTING WOOD SPECIES. Most timber framers in North America frame with one of four tree genera: *Pinus* (pine), *Quercus* (oak), *Tsuga* (hemlock) or *Pseudotsuga* (Douglas fir). More specifically, dominant timbers are Eastern white pine, Eastern hemlock, red and white oak in the East, Southern yellow pine in the South and Douglas fir and a variety of pines out West. Reclaimed timber is usually Douglas fir, and specialty woods such as the Alaskan yellow cedar (*Callitropsis nootkatensis,* formerly *Chamaecyparis nootkatensis*) in Fig. 2 or Port Orford cedar (*Chamaecyparis lawsoniana*) are specified for high-end outdoor projects everywhere. But just about any wood can be used for timber framing if the choice is made appropriately. There are numerous considerations.

Historical precedent. When doing conservation or repair work on historic buildings, replace damaged pieces with like material, especially when scarfing into a longer piece. It's possible that the same species may no longer be available, but the attempt should be made to find it. In the case of some important old-world buildings, trees were planted when the frame was built to grow replacement parts.

Availability. For new work, availability is probably the primary consideration when you measure the embodied energy in the final product. Compared with timber shipped from a long distance, timber harvested and milled locally not only supports the local economy, but also allows you to get additional or replacement pieces easily while keeping your trucking costs down. The ultimate economy in transport would be to use trees right from the building site. If local timber is not available, you will have to ship it in from one of the suppliers you see advertising in these pages, or perhaps you should consider other building systems that may be more appropriate.

My shop in the Berkshire Hills of Western Massachusetts is located in a mixed northern hardwood forest with not a lot of harvestable timber (but good firewood). A few dozen miles away, another 500 ft. in elevation produces my favorite wood for timber framing, Eastern white pine, and a good choice of sawmills to convert it. Delivery usually costs me less than $200 for a frame load. I feel lucky to have a reasonably local good supply, but also prefer white pine for other reasons: it shrinks the least of almost all woods, it's easy to work with hand tools and it's light in weight. Its disadvantages include a propensity for blue sap stain and relatively



Attila Gardo

2 Scarf joints underway in Alaskan yellow cedar 12x12s at Torii Woodworking in Trenton, Maine. Note waxed end of left-hand timber.

low strength. The bottom line is that your selection of timber, whatever it may be, will be a compromise to some degree.

Mixing species within a frame. After accounting for the effects of differential shrinkage, this is ultimately an aesthetic question. Some people like the variety of appearance and finish that mixing species provides, while others find the uniformity of a single species preferable. One species may perform better structurally than another, for a given purpose. For example, Douglas fir is much stronger and stiffer than Eastern white pine, and you might choose the fir for major spans that would need a much larger timber if in white pine. Joists, rafters and other spanning members need to be of stronger species than minor members such as girts or studs. If your woodlot has mixed species, it is appropriate to use them all, but judiciously.

Of course, just having lots of trees to choose from doesn't automatically get them onto your sawhorses as timbers. You need access to tools to fell the trees and a tractor or draft animals to get the logs out to a sawmill. Most forested areas open to harvesting have these resources but, if you're in a remote area like the wilds of Alaska or on an island, it may be most cost-effective to get a portable sawmill to the site. If you plan to fell trees yourself, take a good chainsaw training course such as "The Game of Logging" (www.gameoflogging.com) and learn tree identification.

Appearance. Different species vary markedly in appearance, especially when planed and finished. Heartwood colors can range from reddish-brown through tans and pinks to creamy white. Get samples from your timber supplier (best) or consult books that show woods or timber frames in various species. Often a frame is asked to complement the rest of the prospective home's woodwork, such as stairs, trim, cabinets and doors, which might be chosen in advance. Timber changes in appearance after it is planed—different woods reflect light differently—and a liquid finish can greatly affect the color, usually making it darker. Unfinished wood will also darken over time, with pine going from a light cream to almost orange.

The blue stain that can infect the sapwood of pine harvested after the sap starts running can propagate into an alarming black mold if the timber is not stored with proper air circulation. Woods high in tannins—oak, cedar, redwood, cypress—and with high moisture content will react with iron in fasteners and tools to cause inky blue-black stains.

Moisture content. The use of green (unseasoned) timber for framing is widespread because wet wood is much easier to work than dry and because large timbers air-dry at an impractically slow rate for most framing operations. Nevertheless, dry timber is certainly more stable and has reached its final dimensions, and some suppliers can provide kiln-dried, standing dead or salvaged dead timber. Kiln drying most timber without significant cracking requires a radio frequency vacuum (RFV) kiln, of which there are only a few in North America, and not all species can be dried successfully this way. Standing dead timber usually comes from beetle-killed stands out West and ideally has dried for at least two years before being felled. Timber salvaged from old buildings is often of very high quality, but it may have hidden metal fasteners or be structurally compromised by decay or even previous joinery. Salvaged timber from a reputable supplier is typically resawn to expose or remove these hazards.

If you use green timber, here is a checklist of good practices:

- Consider species with low shrinkage rates.
- Design the frame to minimize the effects of shrinkage.
- If spring-cut or summer-cut logs must sit for more than a few weeks before milling, remove the bark to deter insects.
- Use end sealer on the logs as soon as possible after felling to minimize drying through the ends and consequent end-checking.
- Once the timbers are cut from the log, do your joinery and erect the frame as soon as possible so the timbers can shrink and settle while in place. If it's going to be longer than, say, a year between milling the timbers and erection, you should leave the timber in log form until ready to begin cutting.
- Provide good air circulation for timbers while they are stored, keeping each separated from its neighbors by at least 1 in., with a cover over the stack but sides and ends open.

The amount of shrinkage from green to dry for various species can be calculated and thus predicted for frame design (see in particular Hoadley 1980 and Chappell 1995).

Weight. This is related to moisture content, of course, but also to the specific gravity of the species when dry. In general, hardwoods weigh more than softwoods for a given volume, and green wood may weigh 30 or 40 percent more than dry wood of the same species. Weight is most useful to know for shipping and raising calculations. I assume a green weight of 3 lbs. per board foot for Eastern white pine and 5 lbs. for red oak. A board foot is a volume measuring 1x12x12 in.

Durability. Timbers placed indoors and protected from the elements will last indefinitely regardless of species. Sills, however, are the most likely to rot over time, as the lowest placed members of the frame, vulnerable to splash from roof runoff and where any water getting into the building will settle. Most building codes require a rot-resistant species or treated wood if the sill is within a certain distance of the ground. Any timber showing signs of active insect infestation while being felled or stored should not be used in any part of the frame, although many bugs will die off after a time once the timber and surrounding environment have dried out. (Powderpost beetles will survive.) Insects prefer sapwood, so removing it during milling will go a long way to deterring future infestations. Termites are especially pernicious the further south you go toward the equator, and certain tropical woods have evolved to be very resistant. If you use some other species that's not so resistant, then you must install a barrier to keep termites out of the house, or chemically treat the timbers.

You'll require a decay-resistant species for outside elements such as porches or pergolas (see the *Wood Handbook* for appropriate species). Some species such as black locust and Osage orange are extremely rot resistant but may not be available in sizes that make timbers. Remember that untreated sapwood is not at all resistant to decay and may form a large portion of the tree in second-growth stands of certain species, such as maples, hickories, ashes, some southern pines and ponderosa pine.

Sapwood should be removed during milling, though the sectional dimensions required for the job may prevent complete removal. Species chosen for the rot resistance of their heartwood include baldcypress (old growth), black cherry, white oak, black locust, redwood, cedar and black walnut.

Size and shape. Some species don't grow big enough or straight enough to produce major timbers (or they may die or start decaying once they reach a certain size), but you may have plenty of smaller members in the frame for which these species can serve. Black cherry around here usually grows with sweeps that make them attractive as curved braces, whereas if I need a 20-ft. 10x12, I'm going to be limited to white pine or hemlock.

The methods of the timber frame depend on the species, size (section) and length of available timber. Short or relatively crooked timber might call for different layout, assembly and joinery methods from long straight pieces. An obvious example would be the scarf joints required by shorter timbers to make up any long members. Short posts lend themselves better than long posts to hand raisings, with their less top-heavy assemblies. A big carrying beam might tolerate the weakening effect of drop-in joist notches, whereas a smaller one put to the same use might require soffit-tenoned joists in centered mortises. And irregular timber may be more efficient to lay out by a scribing method than by any orthogonal system.

You must also consider the layout system and level of finish required. Timbers coming off a sawmill are roughsawn and most (not all) homeowners will want them planed to a smooth finish. If your sawyer is good, you may not need to compensate very much for roughsawn irregularities during layout. But if a planed finish is contemplated, you may want to ship your roughsawn timber to a timber sizing facility with a "four-sider" planer. There your rough timber can be planed square and to a consistent dimension. It makes sense, of course, to get the timber planed square and sized right at the sawmill, and many timber suppliers can provide this service. Timbers for barns or rustic cabins may not need to be planed at all. Our sawyers here in the Berkshires are very good (almost everything within 1⁄16 in. of square and dimension), so we can lay out and cut joinery on roughsawn stock with little preparation. If the timbers are for a house frame, we can then plane for appearance with hand planes or portable power planers before shipping.

Workability. Dry timber is easier for the framer to work with machines. Hand tools prefer green wood. The ease of working wood is directly proportional to its moisture content and inversely proportional to its density: the wetter the wood, the easier it is to cut with a sharp hand tool, and the denser the wood, the harder it is to cut.

Depending on the tooling in your shop, you may prefer one species or another. Some species split more readily than others, or are more likely to tear at the edges of machined mortises. Some timber framers prefer hollow chisel mortisers to chain mortisers for Douglas fir, a popular species very weak in tension perpendicular to the grain and thus prone to chipping out.

Strength. This is perhaps the major determinant of which species ultimately ends up in your frame. The size of timber required for a given load and span is calculated using engineering formulae that depend on design values for the species and grade of timber. Frame drawings usually specify the design values used to size the timbers, and any species meeting the design values may be used. Design values for most woods we use for structural purposes in North America are given by the *National Design Specification* (*NDS*); the *Wood Handbook* has similar information for imported and exotic woods. Because wood is anisotropic, its strength in a structure varies according to its use or position (as a post, joist, rafter, etc.) and the direction the stresses are applied (parallel or perpendicular to the grain). Design values change accordingly within a species. Design values also change within a given species according to the grade of the timber.

GRADING. We are concerned here with structural grading, so be aware that another set of rules for appearance grading is used for finish materials. Structurally, the ideal timber would be clear, straight-grained and free of all defects. Since some defects will always be present, various grades describe their permitted size and quantity. The three main grades for timber are Select Structural, No. 1 and No. 2, in descending order of strength, though not necessarily in all measures. Douglas fir and Southern yellow pine have intermediate grades as well, such as Dense No. 1 and Dense No. 2. The general species lists in the *NDS* or the grading rulebooks have a number of subspecies or related species, so if you can't find your particular species you may have to hunt to find which category it falls under. This task can be further complicated by local variations in common names. (The *NDS* uses common, not scientific, names.)

Since it would be impractical to test each piece of wood mechanically, we rely on visual grading rules to determine the grade of a particular timber (and laboratory tests of small defect-free clear wood specimens to determine species strength). Some mills and suppliers have trained and licensed graders on staff. Graders also will come in from a grading agency (for a fee) to grade your timbers if need be. The agency that sets the rules for a particular species is listed in the *NDS*, and you can purchase a grading rulebook from each agency that illustrates how defects are measured and grades determined.

The grade, species and design values of the timber to be used may be specified on your plans by the designer or engineer and thus obligate you to have your timber graded. But many projects and jurisdictions don't require it, especially in rural areas. Even if licensed grading is not required, it's strongly recommended for safety and legal reasons, and a timber framer should know the grading rules for the species used. Following are some of the factors that determine grade.

Knots are measured by both their frequency along the length of the timber and their cumulative diameter across the timber's width. Knots weaken the timber, so as size and number increase, the grade goes down. The structure of the knots (loose, tight, clustered) and their location on a face or edge also affect grade. Select Structural grade for a certain species, for example, may require the combined diameter of knots on the widest face be 25 percent or less of the face width, while No. 2 could have 50 percent or more, measured in any 6 in. section of length.

Slope of grain is a measure of the angular deviation of grain from parallel to the longitudinal axis of the sawn timber, expressed as travel over a "drop" of 1 in. A slope of 1:12, the limit for Select Structural in some species, means that the grain drops 1 in. over a length of 12 in., whereas 1:6 might be the maximum allowable slope of grain for No. 2. Note that "grain" here is not usually the growth rings but rather the splitting planes of the timber. As slope of grain steepens, the lower the ultimate strength of the timber, since the splitting planes at any point on the timber soon run out to an edge. Timbers with excessive slope of grain should only be used in short lengths and in low-stress locations. The splitting planes are indicated in numerous hardwood species (such as oak) by the visible rays on flatsawn surfaces, but often the indications are too subtle for an inexperienced eye. Resin canals can be a clue in softwoods. And, of course, in pieces that have begun to dry, checking follows the grain.

Checking is the separation of wood along the ray planes of the wood (perpendicular to the growth rings) and occurs during drying as the outer surface or the ends of a timber attempt to shrink over incompressible adjacent fibers. End checking can be reduced by sealing the end grain of the original log and any newly crosscut surface of the timber, and all checking can be reduced by not heating the completed structure for an extended period of time (years). It's not uncommon to hear loud noises like gunshots during the first heating season for a frame in a northern climate, as the timbers release stresses caused by surface fibers drying out sooner than inner ones. The considerable difference in shrinkage rates radially and tangentially to the growth rings in most species contributes as well to the development of stresses that checking relieves. In grading, checks are only measured at the end of a timber, and, according to grade, may penetrate a specified depth as measured perpendicular to the wide face and may extend a restricted distance from the end. Surface checking usually occurs most on the timber face closest to the pith (center) of the original tree, and thus you can orient the timber to hide it. Softwoods check less than hardwoods, in general, and proper kiln drying can minimize or virtually eliminate it. Surface checking does not significantly affect the strength of timber (the same amount of wood is still there) unless it happens to occur right where there's a notch.

Shake is the lengthwise separation between the annual growth rings and occurs mostly in hemlock in the East. It has significant structural effects regardless of species, and its permitted length is limited by grade to a certain proportion of the dimensions of the timber. Unfortunately, there is no way to predict shake until the tree is felled (some believe felling itself can cause shake to occur), and it may not show up until the tree is bucked to lengths.

Wane is original log surface remaining on a corner or face of a timber converted from a log too small to yield the full desired rectangular section. It may be limited to one-eighth the width of any face for Select Structural to one-third the width for No. 2, depending on the grading rules that govern that species.

Other grading criteria, most with negligible effects on structural performance, include staining, pitch pockets, pinholes and milling imperfections in planed timber such as skips or torn grain.

Boxed heart. One grading criterion does not normally influence structural calculations but should be part of your specifications for milling timbers. Boxed heart (Fig. 3a) is a milling specification that means the pith of the log is included in the timber and completely enclosed by all four faces, usually by at least three growth rings. (Hewn timber is automatically boxed heart.) This method keeps the heart hidden, tends to equalize the effects of shrinkage on all surfaces and produces some checking on all faces. In the frequent case of an off-center pith, checks will likely concentrate on the face closest to the pith. Some workers stress-relieve boxed-heart timbers when green by saw-kerfing that surface, expecting to hide it as an upper or outside face, and to expose relatively check-free surfaces to the inside and to below.

The specification *free of heart center* (FOHC), by contrast, means that the timber has been cut to exclude the pith (Fig. 3b). This method minimizes checking and produces predictable sectional distortion, but it requires large trees and is generally limited to western species. Where such trees aren't frequently available, such as in the East, we expect to use boxed-heart timber for all major members.

Fraserwood Industries, photos by Mike Crane Photography

3a, 3b Boxed heart (left) and FOHC timbers of Douglas fir.

Reaction wood. One last consideration to be aware of when visually grading timber is reaction wood. This problematic material, usually associated with leaning trees and crooked limbs, is caused by the tree compensating for uneven stresses during growth. In softwoods, this abnormality is called *compression wood* and occurs on the underside of the leaning tree; in hardwood it's *tension wood* and occurs on the upper side. It can be indicated on the end of the log by a markedly offset pith and asymmetrical growth rings, much denser on one side than the other, and darker patches on the end grain. When the log is on the sawmill, it or timbers removed from it may warp significantly when stresses are relieved by cutting, and because of its increased density the affected surface of the timber may not work or plane normally.

The proper use of grading relies on experience and knowledge of woodworking, timber framing and design. For example, a lower grade timber may be used in a part of the frame where the stresses are low, even though the same component may need a higher grade in a different location. To complicate things a bit further, one supplier's Select Structural grade may be different from another's, although this usually affects appearance more than structural capabilities.

NOW that we've looked at general considerations for selecting woods, let's identify the significant general characteristics of species used for timber framing in the US. The table shows comparative densities at 20 percent moisture content (about the state of air-dried timber), total volumetric shrinkage and decay resistance (Fig. 4).

Common name	Shrinkage rate[1]	Density (lbs./cu.ft.) @ 20% moisture content	Heartwood decay resistance
SOFTWOODS			
Eastern white pine	8.2	25	Medium
Eastern hemlock	9.7	28	Low
Douglas fir	11.8	33	Medium
Cedars			
Western red	6.8	23	High
Northern white	7.2	22	High
Atlantic white	8.8	23	High
Port Orford	10.1	31	High
Alaskan yellow	9.2	31	High
Southern pines			
Slash	12.1	43	Medium
Longleaf	12.2	40	Medium
Shortleaf	12.3	35	Low
Loblolly	12.3	35	Low
Ponderosa pine	9.7	28	Low
Sugar pine	7.9	25	Low
Lodgepole pine	11.1	29	Low
Western white pine	11.8	26	Low
Red pine	11.3	31	Low
Spruces			
Red	11.8	28	Low
White	13.7	28	Low
Black	11.3	28	Low
Englemann	11	23	Low
Norway	12.1	24	Low
Sitka	11.5	28	Low
Tamarack	13.6	37	Medium
Western Larch	14	37	Medium
Cypress	10.5	32	High
HARDWOODS			
Northern Red Oak	13.7	42	Low
White Oak	16.3	47	High
Black Locust	10.2	48	High
Tulip (Yellow poplar)	12.7	28	Low
Quaking aspen	11.5	26	Low
Bigtooth aspen	11.8	27	Low
American Beech	17.2	45	Low
Yellow Birch	16.8	41	Low
White Ash	13.3	41	Low
Hickory (shagbark)	16.7	48	Low
Sugar maple	14.7	42	Low
Red Maple	12.6	38	Low
Black Cherry	11.5	35	High
Black Walnut	12.8	38	High

1. Shrinkage rate is expressed as a percent of volume from green to oven-dry moisture content.

Will Beemer

4 **Comparative table of shrinkage, density and decay resistance.**

SOFTWOODS

Eastern white pine (*Pinus strobus*). Northeastern US. Very stable, lightweight, abundant, very easy to work and available in large sizes and lengths. Moderately low in strength. Pitch can ooze from sapwood if cut during growing season and blue-stained sapwood a problem in certain conditions. Widely used for historic and modern timber framing.

Eastern hemlock (*Tsuga canadensis*). Eastern US. Moderately strong, lightweight when dry, works easily, available in large sizes and lengths. Prone to ring shake, sheds splinters, heavy when green, very low rot resistance. Western hemlock (*Tsuga heterophylla*) fine-grained, moderately dense, runs clear (back cover).

Douglas fir (*Pseudotsuga menziesii and var. glauca*). Western US. Very strong and stiff in bending and compression, though weak in tension perpendicular to the grain. Moderately lightweight, rich in color, readily available in large sizes and lengths, also as salvaged timber. Brash to work with hand tools, splintery when dry, tends to bleed pitch. Widely used for modern timber framing.

Cedars. Western red (*Thuja plicata*), Northern white (*T. accidentalis*), Atlantic white (*Chamaecyparis thyodes*). Available in many related species throughout the US. Highly rot resistant, low in shrinkage, low in strength, lightweight. Wide variation in availability of large sizes or lengths of clear wood. Two specialty cedars, Port Orford (*C. lawsoniana*) and Alaskan yellow (*C.* [now *Callitropsis*] *nootkatensis*), botanically cypresses, are denser, higher in strength, much finer textured, straight grained and highly valued (cover photos and Fig. 2).

Southern pines. Longleaf (*Pinus palustris*), shortleaf (*P. echinata*), loblolly *(P. taeda*), slash (*P. Elliottii*). Southeast US. Strong and stiff. High shrinkage, heavy. Old-growth from salvage much prized.

Ponderosa pine (*Pinus Ponderosa*) and sugar pine (*P. lambertiana*). Western US. Lightweight, low shrinkage, straight-grained, grows to be the largest of all the pines. Moderately low in strength.

Lodgepole pine (*Pinus contorta*), Western white pine (*P. monticola*). Western US. Lightweight, easy to work. Moderately high shrinkage, low strength.

Red pine (*Pinus resinosa*). Northeast US. Moderately strong, straight grained. Moderately high shrinkage, low rot resistance.

Spruces. Red (*Picea rubens*), white (*P. glauca*), black (*P. mariana*), Engelmann (*P. engelmanii*), Norway (*P. abies*), Sitka (*P. sitchensis*). Many related species throughout the US. Generally lightweight, moderately strong (Sitka the strongest) and easy to work. Moderate shrinkage, low rot resistance. Knots small but famously hard.

Larches. Tamarack (*Larix laricina*) in the eastern US, Western larch (*L. accidentalis*) in the West. Moderately strong, moderate rot resistance, straight grained, easy to work. Moderately high shrinkage rate. Lose their foliage in the fall.

Cypress (*Taxodium distichum*). Southeast US. As baldcypress, not readily available green but common as a salvaged wood from docks, vats and heavy construction. Heartwood of old-growth highly rot-resistant. Like the larches, loses its foliage in the fall.

HARDWOODS

Red oak. Northern (*Quercus rubra*), Southern (*Q. falcata*) and many related species. Eastern US. Strong, rich red color, good workability. High shrinkage, low rot resistance, heavy. Widely used for timber framing and peg stock (Fig. 5).

White oak (*Quercus alba*). Many related species. Eastern US. High rot resistance, strong. High shrinkage, heavy.

Black locust (*Robinia pseudoacacia*). Eastern US. Strong, high rot resistance, moderately low shrinkage. Difficult to work when dry. Not usually available in long straight pieces. Good peg stock.

Tuliptree (*Liriodendron tulipfera*). Eastern US. Easy to work, straight grained, moderately low strength, moderately high shrinkage. Also known as tulip poplar and yellow poplar.

Quaking aspen (*Populus tremuloides*) and bigtooth aspen (*P. grandidentata*). From Rocky Mountains eastward in US. Lightweight and easy to work. Moderately low strength, moderately high shrinkage, no rot resistance. Often called popple.

American beech (*Fagus grandifolia*). Eastern US. Heavy, dense, strong, rich color. Very high shrinkage, susceptible to powderpost beetle and carpenter ants in damp locations.

Hull Forest Products, photo by Sarah Hull

5 Northern red oak bent assemblies built by South County Post & Beam, Kingston, Rhode Island, await erection.

Yellow birch (*Betula alleghaniensis*), and sweet birch (*B. lenta*). Eastern US. Heavy, hard, strong, works well. Moderate shrinkage, low rot resistance.
White ash (*Fraxinus Americana*). Eastern US. Heavy, strong, stiff and grown long and straight with few knots. Moderate shrinkage and prone to large checks, moderately difficult to work, low rot resistance.
Shagbark Hickory (*Carya ovata*). Many related species throughout Eastern US. Exceptionally heavy, hard and strong. Very high shrinkage, low rot resistance. Ideal wood for tool handles.
Sugar Maple (*Acer saccharum*) and red maple (*A. rubrum*). Many related species, throughout eastern US. Strong, stiff, hard. High shrinkage, moderately difficult to work with hand tools, and prone to spiral grain and twisting. Low rot resistance.
Black Cherry (*Prunus serotina*). Eastern US. High rot resistance, even grain, rich color, fine texture, aromatic, works well. Though highly valued for furniture, it can be inexpensive where abundant in the Northeast. Moderately high shrinkage.
Black Walnut (*Juglans nigra*). Midwestern US. High rot resistance. Moderately heavy and strong, prized for fine woodworking and where abundant found sometimes in historic house or barn frames.

This brief rundown of US species suitable for timber framing omits hundreds of other species available throughout the world, some with unique properties. Though framers in North America use mostly pine, hemlock, oak, Douglas fir and cedar, many other species can be used in some form in frames. Some are very difficult to work with tools or are very unstable, however. There can be significant variations in qualities among related species in one genus; refer to the *Wood Handbook* and the other resources for specifics. Particular US woods to avoid are willow, box elder, elm and cottonwood.

No discussion of woodworking species would be complete without mentioning American chestnut (*Castanea dentata*), once dominant from New England to Georgia and now found only in standing dead pockets in the Appalachians and as isolated specimens or short-lived volunteers elsewhere. Many considered chestnut to be the ideal wood: large, abundant, lightweight, easy to work, highly rot resistant, low in shrinkage and moderately strong. Groups such as the American Chestnut Foundation are trying to bring it back, and perhaps in a hundred years it will again return as a timber framing wood. —Will Beemer

Books (by importance)

Understanding Wood, by R. Bruce Hoadley, 1980. The authoritative volume on wood behavior and anatomy.
Wood Handbook: Wood as an Engineering Material, U.S. Department of Agriculture, Forest Products Laboratory, 1999. Can be downloaded for free at the Guild website at *www.tfguild.org.*
Timber Frame Construction, by Jack Sobon and Roger Schroeder, 1984, and *Build a Classic Timber Frame House*, by Jack A. Sobon, 1994. Both books offer analyses of eastern species for timber framing.
A Timber Framer's Workshop, by Steve Chappell, 1995. Good coverage of working with green timbers and calculating amount of shrinkage in frame components.
Standard Grading Rules for Northeastern Lumber, Northeastern Lumber Manufacturers Association, 2006. Grading rules and design values for most species. Similar manuals are available from ruling agencies elsewhere.
National Design Specification for Wood Construction, American Forest and Paper Association and the American Wood Council, 2005. Supplement gives design values for all commonly used species and addresses of grading agencies by species.

Websites

www.fpl.fs.fed.us. USDA Forest Products Laboratory. The *Wood Handbook* can be downloaded here (as well as through the Guild website). Includes many additional resources on wood science.
www.globalwood.org. Click on the "Technology" link for useful tools, calculators, glossaries, photos and woodworking tips for woods from around the world.
www.woodweb.com. Good forums and knowledge base.
www.forestryimages.org. Forest health, natural resource and silviculture images.
www.arborday.org. Arbor Day Foundation. Tree identification tools and resources for US species.
www.forestryforum.com. Good on timber framing, logging, tree identification.

Photos and drawings Glenn Dodge

1 Layup of plate level for small structure. Scribing tool kit includes purpose-made timber-leveling devices, plumb sticks, trammel points.

Plumb Line Scribe 1

OVER the years I've found it's easier to get a timber framer to switch political parties or religions than layout systems. We all eventually find a system that complements our tooling, our shop space or just our general attitude toward building things, and we stick with it. In 1993, after about five years of timber framing, I was just realizing I needed a new one. A recent college graduate armed with a type A personality and way too many math courses, I found it excruciating on raising days, having fussed so diligently during layout and joinery on sized timbers, to see what I thought was flawless joinery being beaten together with commanders and comealongs. Despite the effort, some joints would still be sporting ⅛-in. gaps or worse, which were, fiendishly, always located in the most conspicuous of places. How could this be?

The reasons were many. At the time we were working primarily with hardwood, sawn and sized locally here in southern New Hampshire, and with as much length as possible. It only made sense to me that a single long timber would be inherently stronger and less work than two or more shorter timbers joined together. We also had never taken the time to learn any other layout system. The timbers were perfect, so what would have been the point? We just drew mortises and tenons where they should go. It was just numbers and naïveté. It was also a really bad combination.

Long timbers, especially hardwood, are naturally at much greater risk to bow or twist during conversion and drying, and these lengthwise defects are largely preserved during sizing. Though hardwoods are plentiful in our area, tall straight ones are less common. Typically a tree is selected that has enough girth to accommodate its bow for the desired length. When the log is "straightened" by the sawmill, inevitably more material is removed from one side of the log than the other, and differently at the ends and the middle, which tends to cause the straightened timber to bow again. With timbers of slight dimension, it's expected that with gravity and good joinery, a slight bow or twist will be corrected by connecting timbers when forced into place during erection. Obviously, cross-section, stiffness and span of the timber play roles here but, for any magnitude of bow or twist, it's not difficult to find a combination of the three that would fail to be corrected by the strength of a peg or the dead load of timbers that bear upon it.

Compounding the problem is that some sawyers just don't care enough to saw out a good timber. Usually they are far more interested in the grade of the boards coming off the log than they are of the grade of the remaining timber. Sometimes they are just at the mercy of the junk that's been loaded onto their mill. Curved logs sawn straight, or heavily tapered logs not properly centered on the sawmill carriage, yield timbers that move around throughout the drying process, which starts as soon as they come off the sawmill and ends some time after the structure is roofed over and heated. If really tight joinery is important to you, any severely bowed or twisted timber poses a dilemma. Do you take the chance that it won't cause any gaps in the finished frame, do you correct this one piece with mapping or housings—or do you reject it entirely?

Aside from bow and twist, any layout system needs to deal with deviations in dimension and sectional squareness, most of which can be remedied by a timber sizer (if you can easily get your material to it). I have great respect for timber sizers. I have always secretly wanted one, but they are not perfect, because of operator indifference, dull knives or the general impossibility of straightening each and every timber. I also cringe at the thought of every sized timber losing a significant percentage of its volume to a shavings bin—nearly 20 percent if a 6x6 is sawn full and sized a half inch under nominal.

In 1993, the Timber Framers Guild conference was held in nearby Rindge, New Hampshire. Lecturing that year was Paul Russell, an Englishman educated in the art of French scribe by a retired Compagnon. Regardless of Paul's intent, what I came away with was the notion of giving up on the perfect timber and dealing with the problem of perfect joinery in a totally different and, in my mind, liberating way. Where once I had been blind to the idiosyncrasies of timbers, I had now become hyperfocused on them, and dealing with them in a haphazard way frustrated me. Paul Russell's lecture started the wheels turning in my mind.

About this time, the articles about the Cabildo roof reconstruction project in Louisiana were also published (see TF 23 and 24), which described a math-free process of laying out timbers in any configuration. Between those articles and further writings by Paul Russell forwarded to me by Will Truax, I gained what I thought was enough information to try it on my own. I built a 16x16-ft. shed and then a larger Cape-style house frame. The results were respectable but clearly something was missing. I felt I had mastered the scribing technique itself, but not the methodology of relating the positions of individual timbers to one another during the process, nor the ability to make it repeatable and reliable.

Ironically, it all came together for me 18 months later when trying to master scribing's rival system, square rule. I had contracted to design and build a large fort for the local Cub Scout camp, with a 48-ft.-square footprint ringed by an 8-ft.-wide, two-story hallway or gallery and sporting guard towers in two corners that I, in a masochistic moment, decided to cantilever and raise a half-story above the rest. There was also an integral 20x18-ft. sheriff's office. Including the 16 hip and valley rafters and the 70 principal posts, all told 721 timbers (one kingpost) had to be cut and sawn from standing timber on the site and joined in the rough, amidst an endless multitude of energetic, screaming children. I'm not really sure what I was thinking. In the end, it became the single most enlightening experience of my timber framing career.

In building this daunting square of timber around ourselves nearly 200 ft. in perimeter, with over 40 post-to-girt intersections along the way, we wanted the last post, girt and braces to connect to the first without adjustment, at least in part because there were a whole lot of people watching us. In the square-rule system we were using (and learning as we went), we were picking the most nearly square corners of the timbers as our *arris*, a line along which two planes meet. In the structure, one of the intersecting faces of the timber that form an arris is usually aligned with a building reference plane such as an outside wall, a floor or the roof surface.

The problem was that defining the arris sometimes left the worst-looking faces in the most visible locations. Sometimes there wasn't an acceptable square corner and, if there was, it might not last for the length of the timber. Sometimes a timber was bowed or had a slight hump along an edge such that the blade of a framing square set against it would not truly lie parallel to the long axis of the timber. Squaring a line around all four sides inevitably produced a discrepancy when the last tried to meet the first. Twisted and bowed timbers were of course still issues, especially with 48-ft. plates. The myriad of discrepancies would be exacerbated by our long journey around the building, and every time I tried to find something on the timber I could rely on, I couldn't. I began to feel like Adrian Monk in the eponymous TV series.

We finally decided to take the maxim of square rule, "a perfect timber within an imperfect one," to an obsessive-compulsive level. We gave up completely on the faces and corners of the timber and instead relied only on datum lines that we snapped on every face in a manner some would reserve for rough-hewn timber. This departure from traditional square rule required us to put housings everywhere rather than just on the nonreference sides. It worked perfectly, and over the course of the project we developed a complete understanding of and faith in a system that freed us from every imperfection or ill except the monotonous task of laying out and cutting what must have been a million housings. We have since combined that regimented system of planes and datum lines, which we called *snap line square rule*, with the free-spirited world of scribing, to create a reliable and orderly way to lay out and join timbers of any shape or form into structures of any shape and form, quickly and efficiently.

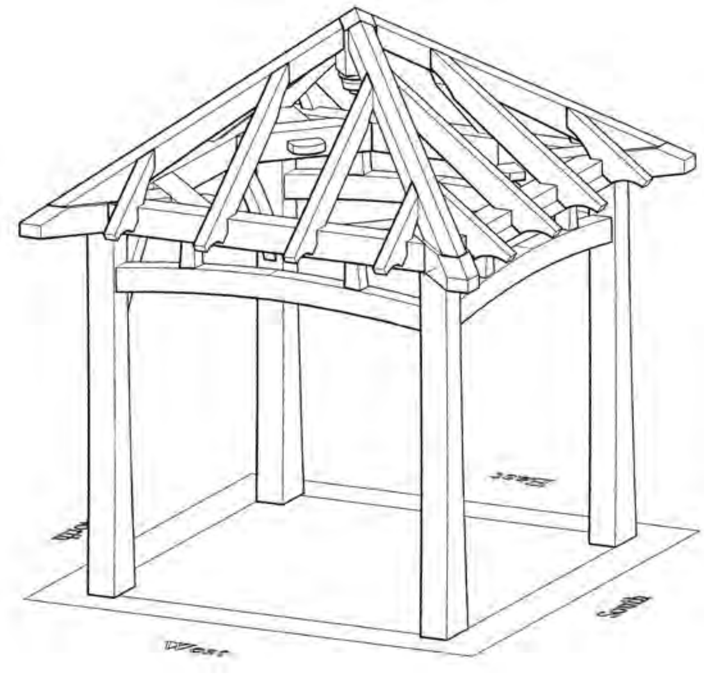
WHAT follows is an exercise in using a system we've come to call *plumb line scribe*. Though it has French scribe at its core, inspired by my brief exposure in 1993, I have never trained under the guidance of Compagnons or even had a conversation with one, and I am respectfully reluctant to claim any conformity with their system. Through trial and error I filled in gaps in my knowledge and ultimately developed this system unaware of whether it parallels French scribe.

In our shop, we use plumb line scribe exclusively, in part because it avoids the tedium of housings and reductions and frees us of the need of perfect timbers, but mostly because I believe it allows for the most creativity. Curved or tapered timbers are the norm. For some frames we shape every timber, following the fibers of the grain rather than cutting across them. It also allows us to use timbers that others would be forced to reject. One of its advantages for compound roof work is a reduction in drawings and data needed, though that comes with an increase in layout time. (Spending as much time parked in front of the computer as I do these days, it's a trade I gladly make.) For those without drafting software or design staff, it's a way of avoiding some of the expense of acquiring it.

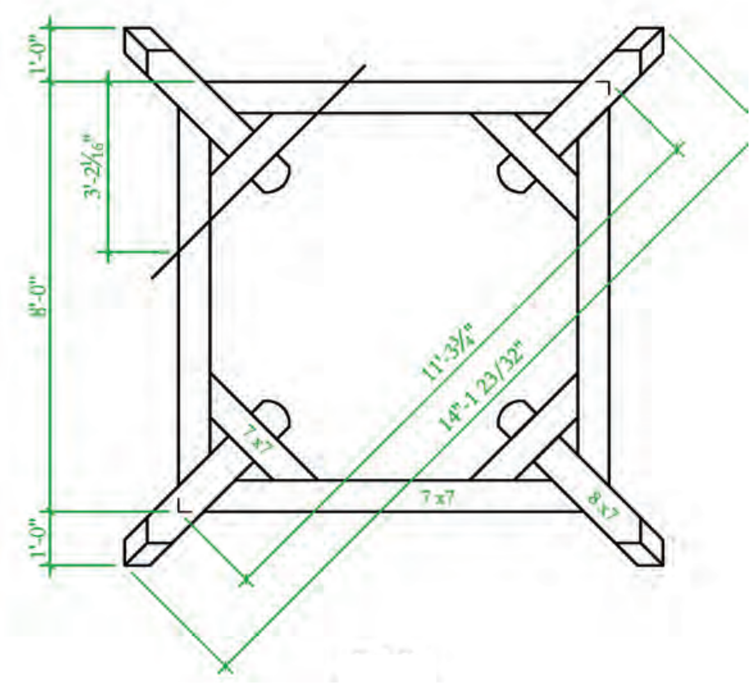
Scribe rule layout in general is a radical departure from the norm for most workers. Rather than simply sending timbers through a sizer to remove most or all of its imperfections before it hits the sawhorses, most scribing systems accept timbers as they are, electing to merely project the characteristics of the imperfect timbers onto each other. Plumb line scribe, like any other scribe rule, is a series of steps and techniques to produce perfect joinery and a dimensionally correct structure with timbers that are not. Though this system as it applies to compound work is equally useful with planed and sized timber, I think most will find it helpful to envision the concepts here as though working with hewn or other irregularly surfaced timbers.

The intersection of any two timbers can be scribed together using plumb line scribe, but the method is best suited for sawn or hewn timber as opposed to round. Plumb line scribe is the perfect method for scribing timbers that bow or curve over their length but to scribe and retain the curved face of a round pole, the intersection needs to be drawn as a series of points rather than a true arc, a task better suited to bubble scribers (dividers fitted with cross levels). In most of our work, even with shaped, twisted or curved timber, we are usually only interested in four points of intersection marked on both of the timbers forming a joint.

Plumb line scribe achieves its goal by first snapping lines on a floor representing the limits of a particular section of a structure such as a bent, a wall or, in this case, a roof. Then the timbers to construct that section are carefully placed and leveled in their appropriate positions above these lines (Fig. 1). This usually requires several timber layers. For example, in a wall section we'll typically start by laying down the posts on support blocks to keep them off the floor. Plates and girts are then placed above as a second layer,



2 Perspective view of demonstration structure with hip roof.



3 Plan view of tie/plate layup.

and then the braces go in the third. Where the layers of timber overlap one another, a plumb bob and line are used to assist in projecting the characteristics of one timber onto another. This arrangement of timbers, called a layup, is then taken apart, each timber is individually moved to a sawhorse and the lines for the joinery are drawn using the lines of intersection that have been scribed on the timber. Typically this process is repeated for every section of the structure before any joinery is cut.

We begin discussion of the system with some definitions. *Building plane* is a generic term for any of the imaginary, infinitely thin and perfectly flat surfaces that define the borders or limits of a structure or a section of it. Usually timbers are centered on or aligned to such a surface, such as the tops of floor joists aligned to the floor plane, or all the posts in a south wall being aligned to a south wall plane. A plane can also run through the center of a section as sometimes occurs with a bent. Though they may define a border of something else, planes have no borders or endpoints.

Rise, run and diagonal. The three dimensions of any triangle that includes a right (90-degree) angle. They are used to describe any roof pitch or deviation between building planes. The *run* is typically the length of the horizontal line (or leg), the *rise* is the dimension of the vertical leg and the *diagonal* is the dimension of the pitched or angled leg opposite the right angle.

Layout floor. A level floor (often concrete) on which reference lines for a particular section of a frame are laid out full scale, and timbers are placed and scribed.

Level mark. A cross-flattened area on a single face of a timber, usually near midspan lengthwise, to establish its reference planes.

X,Y and Z axes of a timber. To define the position or orientation of a timber, it's convenient at times to describe it in relation to these imaginary lines. In general, viewed from the side of a timber, the *x-axis* runs through the geometric center of the timber for its entire length. The *y-axis* runs vertically, and the *z-axis* runs horizontally directly at the viewer. In a 6x10x12 timber in normal orientation, the x-axis is 12 ft. long, the y-axis 10 in. long and the z-axis 6 in. long.

To demonstrate the system, I've chosen a simple 8x8-ft. hip-roofed structure with a 12 in. overhang all around. Including the overhangs, the roof then covers an area 10 ft. square (Fig. 2). Take note of the dragon ties directly below the hip rafters and the dragon beams that run diagonally between adjacent plates and support the inner ends of the dragon ties. The first section we are concerned with aligns to the plane of the plates, dragon ties and dragon beams (Figs. 1 and 3). We call this the tie/plate layup.

The Layout Floor. To begin work, we set up the reference lines on the layout floor (Fig. 4). Construct two perpendicular lines, (labeled 1 and 2 in the figure) using a 9-12-15 triangle (or any other method) and then snap two lines (labeled 3 and 4) 10 ft. from and parallel to the first two. Together these four lines represent the eaves planes of the roof. Double-check the diagonal measurements between the opposite corners to prove the integrity of the line construction, then snap lines between them to represent the centers of the dragon ties. Snap lines 12 in. from the eaves planes to represent the outer edges of the plates or wall planes.

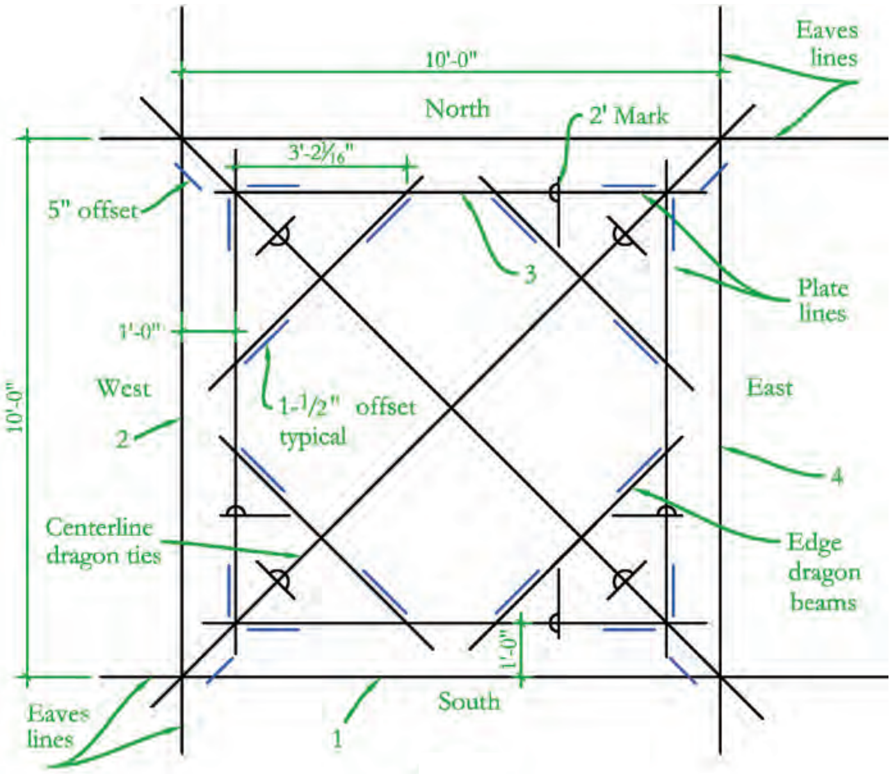
Snap the lines representing the inner faces of the dragon beams using the dimension given. You have now established the location of all major reference planes for this layup.

Draw lines offset 1½ in. from the lines representing the outside of the plate in the locations shown and do the same for the dragon beams. For the dragon ties, establish offsets 5 in. from the centerline.

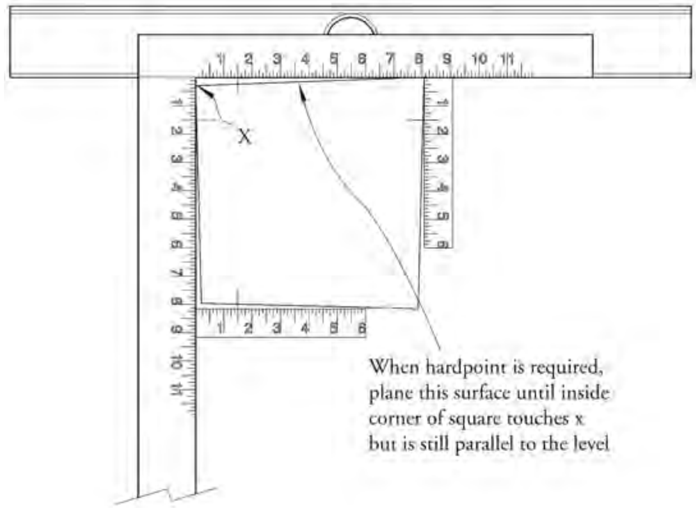
From the intersection of the plate lines, measure 2 ft. along one of them and make a 2-ft. mark (so labeled in Fig. 4). Establish a short line perpendicular to the plate line, then using a compass draw a 2-in.-dia. semicircle with the 2-ft. mark as its center, and the open side of the arc toward the point the 2 ft. mark was measured from. From the intersection of the eaves lines measure along the diagonal 2 ft. 6 in. and make a similar perpendicular, but this time with a 2½-in.-dia. semicircle. I'll explain the necessity of these lines later on.

We could now set the timbers on blocks and align their edges to the lines on the floor representing their edges, but there are a few things to consider first. When we set the timbers into the layup, each needs to be leveled along its length and across its width. Because we don't want to have to rely on any particular edge or surface to do this, we snap an offset reference line called a *datum line* (or just a *datum*) on each surface of the timber, representing a certain distance from their theoretical edges.

We could do this rather randomly on each face without any interrelationship, but the datums will be more useful if they are



4 **Reference lines struck on floor for tie/plate layup.**



5 **Lining of timbers and marking hardpoints.**

constructed so that the lines on opposite faces of the timber are parallel and thus between them form a plane. This plane needs also to be perpendicular to the plane defined by the datums on the other two opposite faces.

Lining a Timber. To establish these lines on one of the plates, first locate or create a flat spot on one of the wider faces of the timber near the midpoint of its length, verifying with the edge of a small builders' level or some equivalent straight length of wood. If the spot is flat (or slightly hollow), the level will not be able to rock. Trace the edges of the level and mark with an X. This is called a *level mark* and, from now on, it's the only reliable surface on the timber. For this exercise, let's call the face of the timber it's on the *reference face*. When choosing which face to mark, if practical choose a face that will be aligned to one of the building planes, preferably one that will not be seen, such as the top of a floor member or the outside of a wall member. (I prefer, however, to see the level mark on one of the larger sides of a rectangular timber and hesitate to put it on any side more than an inch smaller than adjacent sides.)

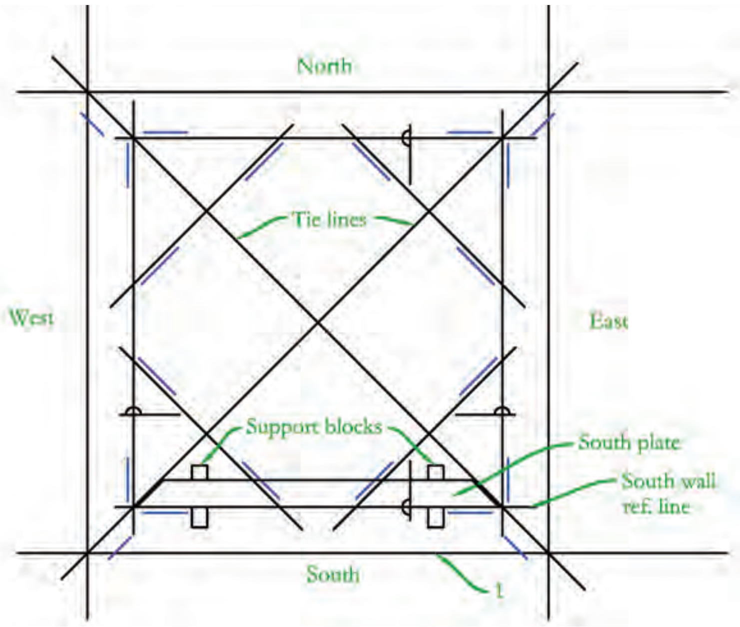
Next, on the layout floor measure the line that represents the length of the plate between its intersections on each end. On the plate itself roughly mark off where on the timber you would like this interval to fall. Take this opportunity to avoid knots where the joinery will be cut, or perhaps slide the points closer to the better end. Now, with the level mark facing up, place the level back on the level mark and the tongue (the narrower, shorter leg) of a framing square on the timber at one of the indicator marks you just made. Sight down the length of the timber and shim the tongue of the framing square until it is parallel to the level on the level mark, then slide the hanging blade of the square to the timber until any part of it is touching the side. In this position, the inside corner of the framing square defines a point on the arris of the theoretically perfect timber which lies outside of the actual timber, unlike square rule where the perfect timber is within.

Note whether the inside corner of the square is touching the corner of the timber. When lining most timbers, it does not need to touch, because we don't normally rely on the edges or corners anyway. The plate, however, will be going into the roof layup rotated about its x-axis, as will be seen, which will require reference marks we call *hardpoints*. I'll expand upon the role of hardpoints later on, but for now imagine them as a pair of reference points, near either end of a timber, where the theoretical corner is necessarily made to be on the physical corner. If the inside corner of the square is not touching the plate, adjust one of the surfaces with a handplane until it does so, while keeping the tongue always parallel to the level on the level mark. Mark a caret with a crayon on both faces that form the corner at the hardpoint (Fig. 5).

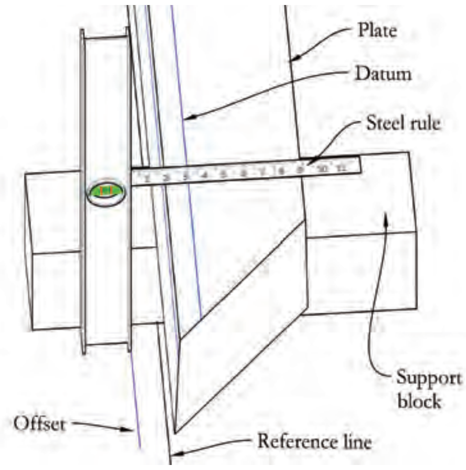
Without moving the square, mark a point along the tongue a convenient distance inward from the edge, typically 1½ in. On the bottom of the timber, measure the same 1½ in. by abutting a small steel rule to the blade of the square. Remember that whatever measurement you use on the top must be used on the bottom. Similarly, measure down the blade of the square and mark 1½ in. (or any convenient distance) on one side of the timber. Measure down the other side an equal amount by abutting the steel rule to the tongue of the square. The convenient distance for top and bottom need not match the convenient distance for the sides.

Go through the same procedure on the other end of the timber, then snap a line between the points on the top with an awl and a fine chalkline. Rotate the timber so that you are always snapping on a top surface, not a side. Be careful always to pull the chalkline so that you snap as nearly as possible in the plane that the line represents. This is extremely important with curved timbers. In other scribe systems, plumb and level lines are drawn on the ends of the timber, with lines then snapped between. We rarely do so because we want to make sure our timber is aligned with the reference planes *at the joints*, not at the waste ends. This way we have the best chance of keeping the faces of adjacent timbers flush with each other. Deviations caused by lining the ends of timbers can be eliminated to some degree by cutting off most excess first. But we like to keep our timbers as long as possible during layout. When placing them in a layup, it's often to our advantage to extend a timber well past its intersection with another to a support block beyond.

Line out the other plates in the same way. None of the remaining timbers in this layup will need hardpoints, so the square can just be shimmed as necessary and made parallel to the level mark without regard to touching the corner of the timber. The dragon beams will have 1½-in. datums on all sides and the ties will have a centered datum top and bottom with 1½-in. datums on the sides.



6 **Placement of south plate.**



7 **Aligning timber with reference line.**

Though scribing in general is a very hands-on, visual exercise, with this system it also helps to think in the abstract. A plane is an imaginary, infinitely thin and extensible and perfectly true surface established by any three points in space. We all use planes in building without giving it much thought. In a typical frame, we want all the wall posts on a particular wall to align with an imaginary plane running down that side of the building, and likewise for every side. All the rafters or purlins in a roof we generally try to align with the roof plane, and all the floor joists with the floor plane. Planes, being purely imaginary, can be established anywhere we find convenient. We can imagine and refer to planes that transect the center of a building directly below the ridgeline. We can assign planes to the reference edges or the centers of every framing bent, and we can set a plane to be a fixed distance from another.

The pairs of datum lines we establish on timbers represent more than just planes within a timber. They also represent planes within the whole frame. If we have a timber with one surface that needs to align with a particular building plane, a datum snapped 1½ in. from the theoretical edge of the timber is also 1½ in. from that same building plane. It's this concept that we need to keep in mind when laying in timbers.

Laying In. Refer to the photo on page 10 as you mentally follow these steps. Start by placing some blocks on the layout floor to support the plate that will be aligned with the reference line for the south plate. The blocks should be fairly uniform in thickness and have a smooth or slightly concave top and bottom surface so a timber doesn't tend to rock on them. Though we want the blocks as far apart as possible for stability, they cannot be too close to the intersections with other members as they will interfere with scribing. In this small frame, it gets pretty busy near the ends of the plates. If the blocks are placed about 18 in. from the plate intersections, there should still be enough room without interfering with the dragon beam intersection.

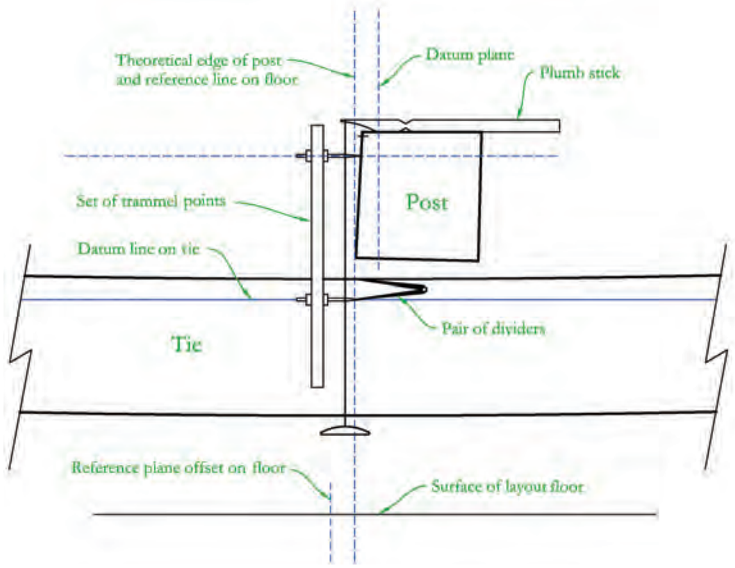
Before placing the first plate on the support blocks, it's worth taking the time to miter-cut the plates just short enough to avoid interfering with each other when laid in. We normally avoid shortening any timbers before scribing. Here, the plates do not join to each other and therefore do not need to cross in the layup. By trimming the plates, we are able to keep all of them in the same layer.

Set the south plate on the blocks with the outer edge roughly above its reference line on the floor (Fig. 6) and with its level mark on top. On one side of the timber hold a long level (4 ft. or more) horizontally with its top edge aligned to the datum snapped on the side of the timber. If necessary, add thin shims on top of one of the support blocks until level. We call this checking the *run*. Place a short builders level on the level mark of the plate and if necessary shim between the support block and the timber until level. We call this checking the *roll*. Press on the timber to see that it's stable. If not, adjust or add shims and recheck.

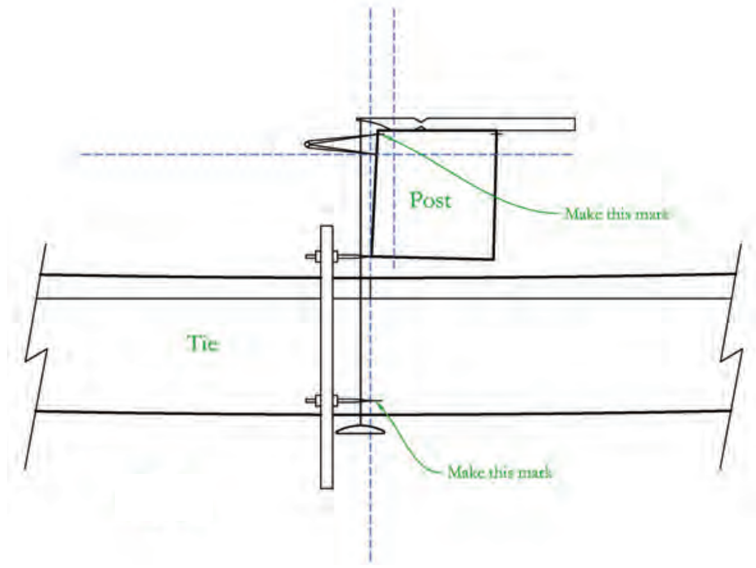
It's time to align the timber precisely with its reference line. When we first started developing this system, we put a short level with its end on the reference line on the floor, stood it up plumb and aligned the edge of the timber to it. As often as not, the timber would not flush up to the level cleanly for a variety of reasons. The timber might be out of square or twisted, or have an irregular surface. If a timber is bowed sideways or twisted, what point along its length should you align with the reference line on the floor? All such problems are solved by snapping the datum lines on the timber and adding offsets to the layout floor to clear irregularities. In theory, we want to align the edge of the perfect timber with the reference line on the floor. In practice, we take the distance from the theoretical edge of timber to the datum line and add it to the distance from the reference line on the floor to its offset. We then set the short level on end with one edge aligned to the offset, plumb it and adjust the position of the timber until the datum is the combined distance away from the level (Fig. 7).

Typically this procedure is done close to what will be the finished ends of the plate. As you adjust one end, the other will likely come out of alignment, so each end will have to be adjusted a couple of times. When finished, recheck and, if necessary, re-shim the roll and then recheck and adjust the alignment. Leveling and positioning timbers with shims and blocks, frustrating at first, becomes easier with experience. If you do it a lot, you may wish to develop pairs of leveling and positioning devices (seen in Fig. 1) to speed the work, as we did over a period of time.

Lay in the remaining plates similarly, and place the dragon ties next. We have the option of supporting one end of the tie either on the plates with a ¾-in. shim or on a separate stack of blocks. When placing successive layers, for stability we tend to set shorter, lighter timbers so they are supported by lower layers. If timbers are heavy or long, we tend to use towers of support blocks built off the shop floor. Another important consideration is whether shims and blocking on the lower layer, or a separate tower of blocks, will better allow access to the intersection being scribed. In either case, the leveling and alignment procedure is the same. Place the dragon ties in their approximate postions, level the run, level the roll, align the timbers with their reference lines and recheck. While the plates



8 Elevation view of simple right-angle intersection.



9 Transfer interval fixed on trammel bar.

were aligned by edge, the dragon ties have a centered datum on top and bottom that needs to be placed directly over the center reference on the floor. Use the 5-in. offset to position precisely.

The third layer should be the dragon beams, which can be supported by blocks placed on the plates. Remember that every time one timber is placed upon another, the roll of the supporting timber should be rechecked. If care hasn't been taken to firmly stabilize each timber during shimming and leveling, the weight of an upper one will tend to roll a supporting one.

Once scribing begins, all timbers in the layup become unique and their positions within the whole frame are fixed. For any timber that will be going back into another layup, there needs to be some way to return that timber to its proper position relative to all other timbers within the frame. The two pairs of datums snapped on the timber establish two out of the three coordinates needed to positively locate a timber. In other words, the datums decide which planes the timbers will be aligned to, but not where along those planes they are. This is the purpose of the 2-ft. marks that we placed on the layout floor along the plate lines. In general, these marks are located a certain distance from a known position, usually the intersection of two reference lines. Use the level to bring this line up the side of the plates and, where it crosses the datum, make the same semi-circle to label this as the 2-ft. mark.

Though the 2-ft. mark is the standard locator, if there is another member that interferes with this location, we might instead make a 1-ft., 3-ft. or, in the case of the dragon ties, a 2-ft. 6-in. mark, indicated respectively by circles of 1 in., 2 in. and 2½ in. Bring up all these marks before scribing to ensure that they are not forgotten. Last, measure between the datums on the top of the plates opposite each other to ensure that the positioning procedure was accurately done.

BEFORE taking up the scribing of our demonstration roof, we will look at scribing a straightforward 90-degree connection, such as between a post and a tie (Fig. 8).

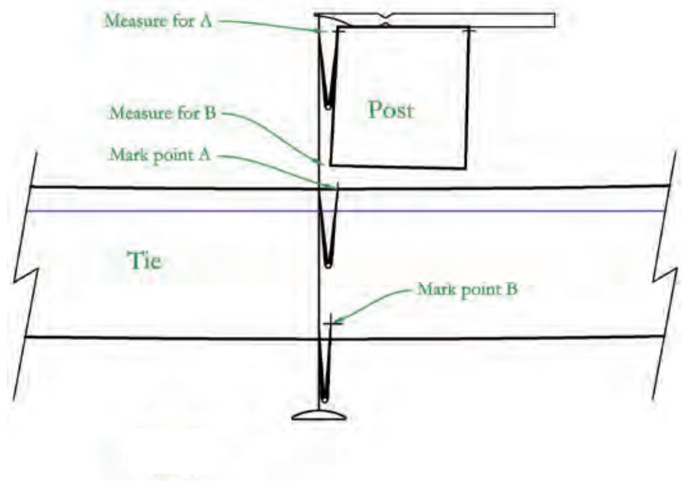
The first step is to establish the vertical limits of the timbers at the points of intersection using one of two methods, by trammel points or by dividers. For either method, set the plumb stick on the post and bring the line in so that it hangs ⅛ in. away (or a bit less) from both timbers.

Using trammel points, set the upper head of the trammel on the horizontal datum of the post next to the plumb line and adjust the lower head until it's even with the datum on the tie, again as near as practical to the plumb line. Tighten the adjustable head to fix the distance. Lower the trammel as a unit until one of the trammel heads reaches the lower edge of one of the timbers (Fig. 9).

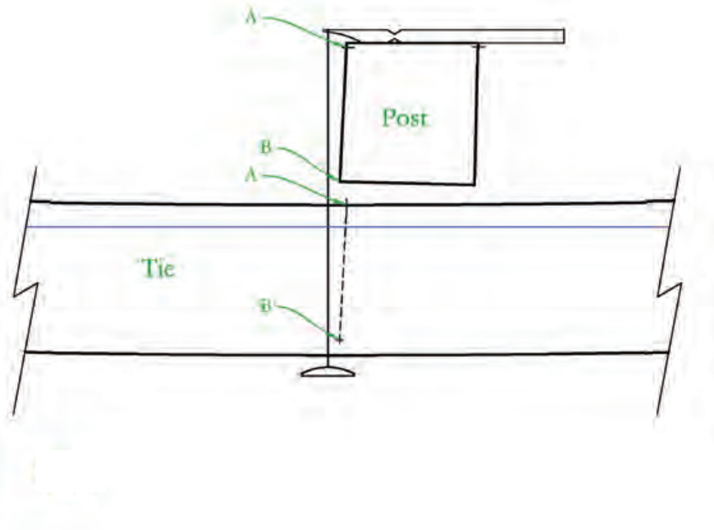
Make a mark on the other timber at the point of the other trammel head. (If both heads arrive at the lower edge of both timbers simultaneously, no marks need to be made.) Keeping the distance between the trammel heads fixed, locate the upper edge in the same fashion. Remember that trammels must be used for an entire joint without adjustment, but they will need to be adjusted for every new joint (Fig. 10).

If using dividers, open them to match the plumb distance between the horizontal datum of one timber and its upper edge. Check the opening against the distance from the horizontal datum to the upper edge of the second timber. If the opening is smaller, mark the second timber. If the opening is larger, reset the dividers to the datum-to-edge measurement of the second timber and mark the first. Fig. 9 shows where to mark the appropriate distances obtained in Fig. 8.

10 Using trammel points to match upper limits.



11 Locating points of intersection.



12 Connecting points to show line of intersection.

At this stage, all we know is that the points of intersection are on these lines. In Figs. 11 and 12, we have brought the plumb line away about an inch from the post while keeping it within ⅛ in. of the tie. Using the dividers, take measurements at the upper limits and the lower limits and transfer them to the tie.

Fig. 13 shows the side view of the same joint. The vertical limits have been established, so now move the plumb line close to the post but about 1 in. away from the tie, and use the dividers to establish *E* and *F*. (As an alternative to the use of dividers, we can bring the plumb line in as close as possible without touching either timber and, while sighting down the tie as in Fig. 14, judge the distance from *A* to the plumb line. Without changing your line of sight, make a mark at *E* the same distance from the plumb line. Repeat with *B* to find *F*.)

Now that you have these four points, it's time to check them. If they are truly the points of intersection then points *A* and *E* will become one point when the timbers are joined together. In the layup, *E* should lie on a plumb line with *A*. Check the integrity of the points by moving the plumb line away from the joint a couple of inches and positioning your eye so that both *A* and *E* are eclipsed by the plumb line simultaneously. If they are not, *E* is incorrectly located. Further, to account for the possibility of an alignment in only one plane, the points are only truly proved if the effect can be reproduced when the plumb line is moved to a second location and the points resighted. Repeat the process for *B* and *F*.

Once the points have been checked, draw a line from *F* through *E* and continue past to the upper edge of the post. This will be the line of intersection. Even after drawing the lines between points, make sure all scribe points are clearly visible as they will be used all the way through joinery and are even helpful during fitup.

To draw the joinery, locate the tenon relative to the datum, not the edge of timber. In this case, draw a line on the side of the timber 2 in. from the datum and parallel to it and then another 1½ in. from the first (Fig. 15). These lines represent the tenon cheeks. Take care not to move the timber as you draw. (I buy cheap framing squares and cut them into two pieces so I have both 1½-in. and 2-in. steel templates to use when marking out mortises and tenons.)

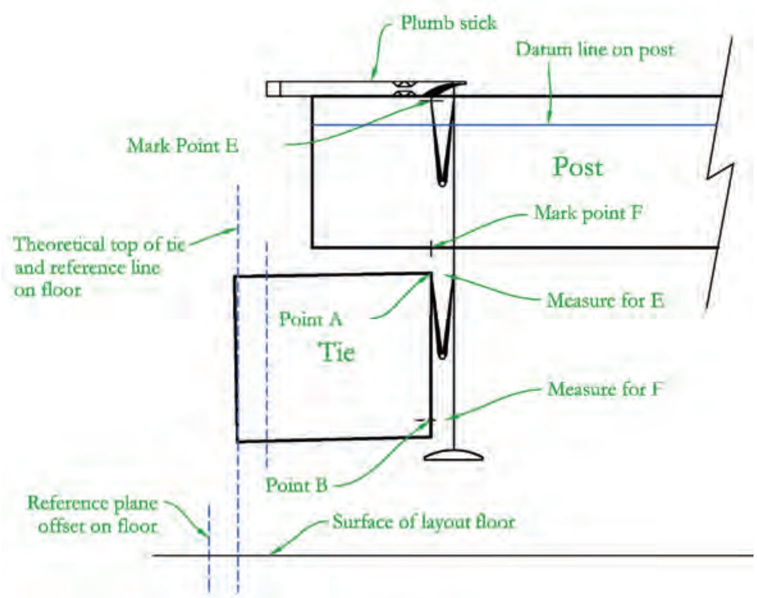
Repeat this scribing process on the other side of the post to establish *C* and *D* (Fig. 16) and two points *G* and *H* that mimic *E* and *F*. Connect the points on the tie as shown in Fig. 16 and establish the mortise location in the same manner as with the tenon. Draw the line between *G* and *H* on the post in the same manner as line *EF* and then connect these lines to complete the outlining of the shoulders flanking the post tenon.

In the preceding example, the timbers being scribed together are perpendicular to each other, unlike most of those in our compound example. I've described the procedure this way for ease, but also to illustrate an important point. Fig. 11 includes a section view of the post. All that can be seen of the three-dimensional post in this view is a two-dimensional outline. Because of the eye's position, the entire lower left edge of the post has become a single point. When we measured off this lower left edge to get the distance to mark *B* on the tie, a three-dimensional question arose: Where along that lower edge to measure? The right answer was really *F*, but at that moment we didn't know where *F* was.

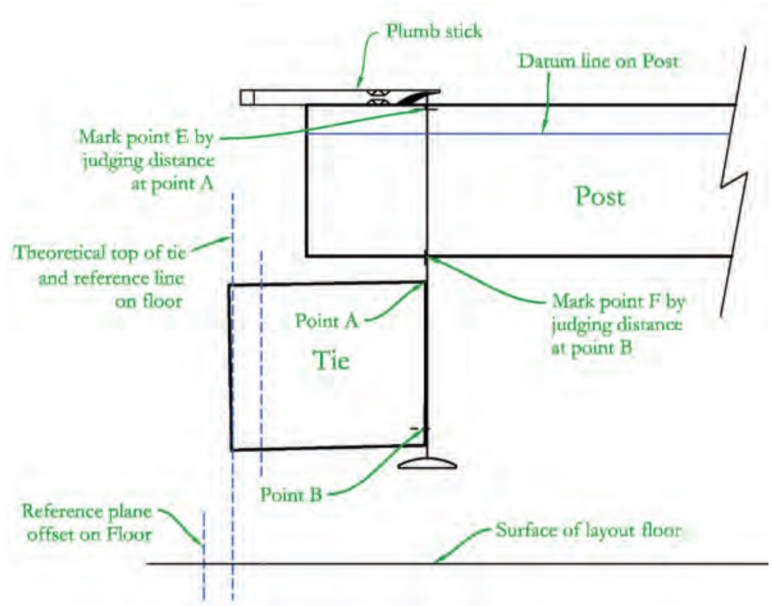
Looking at Fig. 15, one could reasonably say that *F* lies within the noted target zone. The answer to the three-dimensional question is really a two-dimensional one. Position your eye or line of sight so that every part of the lower edge in the target area is reduced to a single point. Now when you need to judge the distance from the lower edge to the plumb line, every point in that zone is the same distance from the plumb line. The trick is, you need to be in a position simultaneously to judge the distance and mark *B* without moving.

In practice, I position my eye under the post just less than an arm's length away, and look along the lower edge toward the tie. I position my left thumb horizontally with the tip of the thumbnail in the target zone on the lower edge of the post, preferably just behind the plumb line (Fig. 17). From this position it's easy to perceive the length of my nail between the plumb line and the post and then mark this distance from the plumb line on the tie using the other hand. When I need to find *F*, eye position is a little less critical (Fig. 14). I want to look at the post by sighting along the tie but I no longer need to get a variety of points to appear as one. I simply put my right thumbnail on *B* to judge the distance and, without moving, mark *F* with my left hand.

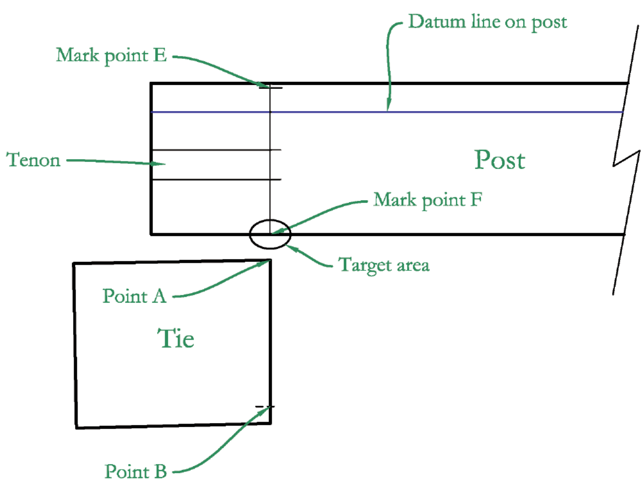
Understanding the underlying concepts of scribing a perpendicular intersection readies one for the inevitable angled intersection, and then finally a compound intersection where one of the timbers is rotated about its x-axis. If we look again at Fig. 11, when viewed from this vantage point, there is no way of telling whether the relationship between the two timbers is perpendicular or angled. In reality we may be looking at a tie whose one end is considerably closer to the viewer than the other end and therefore forms an angled intersection with the post. The scribing procedure is the same. Establish a point within a range of points, and then position your line of sight so that the range of possible points is reduced to a single point that you can reliably measure.



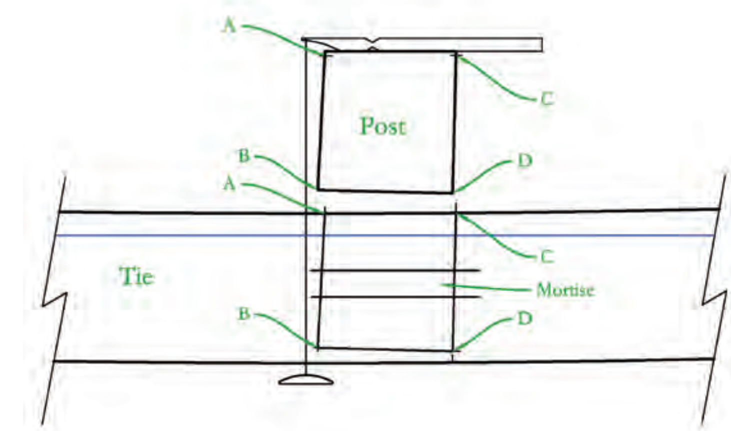
13 Measuring with dividers.



14 Measuring by sight alone.



15 Connecting scribe points and locating the tenon.

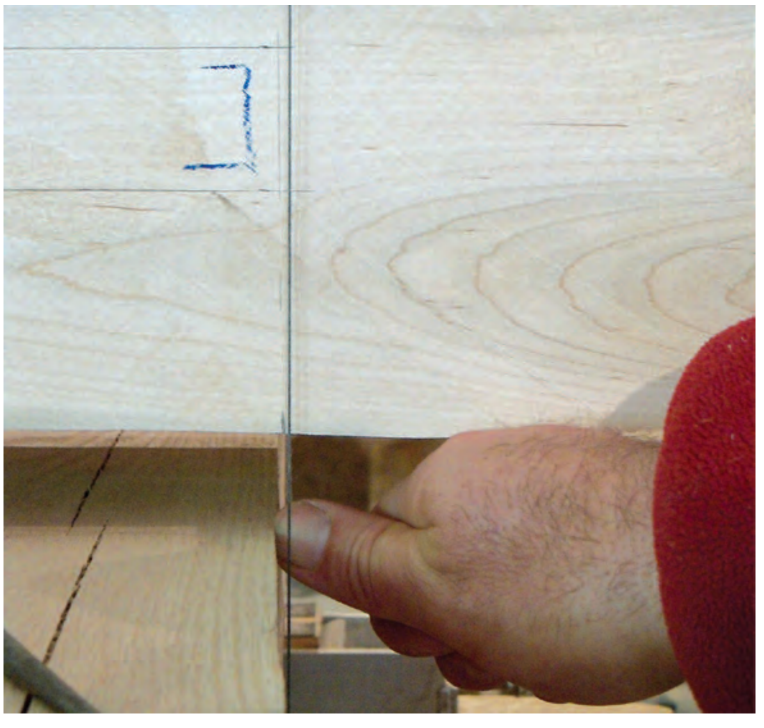


16 Connecting scribe points and locating the mortise.

Once I heard scribing likened to working "by guess and by gosh." Regardless of how it was intended, I took the remark to mean that scribing was a little crude and required a little luck. My position is the contrary, that it's the most accurate system available because it accounts for even the slightest imperfections, but certainly requires a full understanding and good procedure. Even when we use a tape measure, we still have to physically make a mark with a pencil or a knife and decide if that mark is close enough to the center of the line on the tape to be within our personal tolerance. The same goes for scribing. With good technique, the tolerance is up to the individual. Points can be checked and repositioned with amazing fineness. We often find ourselves initially dissatisfied with a point but find upon checking that it was off only by the width of a thin pencil line.

In the second half of this article, we will move on to the compound connections of this small hip roof, explaining techniques to accurately line, level and position the members rotated within the layup, such as the hips and plates. —Glenn Dodge

Glenn Dodge (gdodge@dodgco.com) owns Dodgco, New Boston, N.H., and has been designing and building with locally harvested timber since 1987. Will Truax, of Center Barnstead, N.H., collaborated on the development of plumb line scribe rule as well as its antecedent layout method, snap line square rule. Tim Whitehouse, now of Fort Collins, Colorado, collaborated in the development of leveling fixtures.



17 Gauging distance with thumbnail.

Some Umbrian Framing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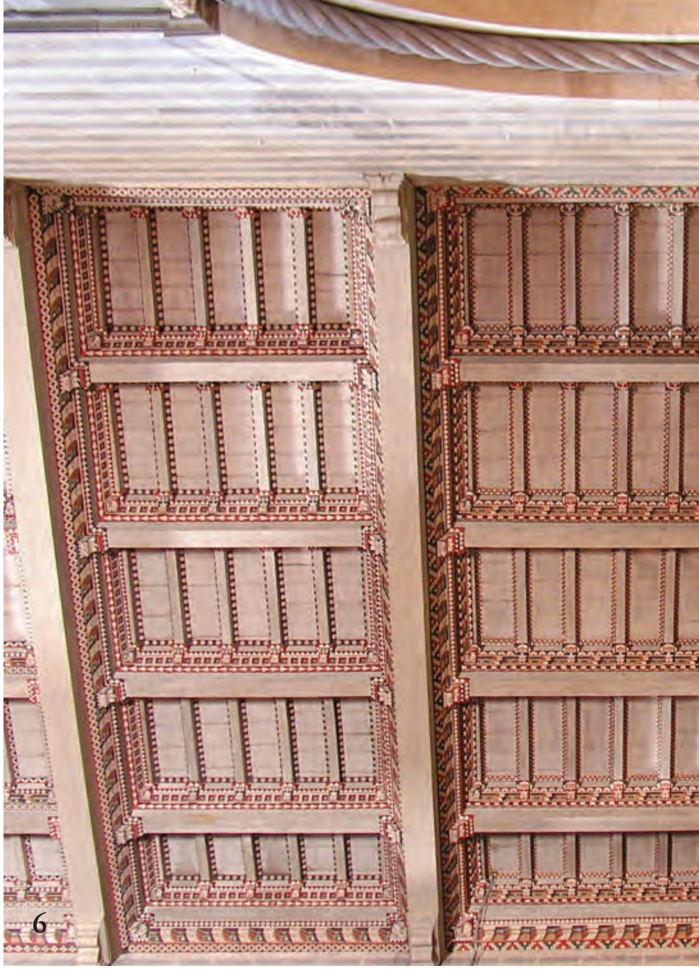

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Photos Ken Rower

Timber framing in Umbria, Italy's central province, is to be seen almost exclusively in ceilings and roofs. Traditional framing species appears to be oak (*rovere*) but in some cases may be chestnut (*castagno*).

1, 2 Passage and *sala*, Ducal Palace, Gubbio, ca. 1474. Framed ceilings are typically tiled over as seen in passage photo and in photos 8 and 9 below.
3, 4 Oak logs await conversion to planks and boards at mill near Città di Castello. Field oak (probably *Quercus petrea*) growing near Umbertide.
5, 6 Kingpost-truss decorated open roof and side-aisle coffered ceiling at the cathedral in Orvieto. Trusswork over nave dated to 1320, restored in 1890s.
7 Early form kingpost truss (*capriata*) without connection at tie beam, unnecessary if latter is unburdened. Sala delle Capriate, Palazzo Albizzini, Città di Castello, after 1450.
8, 9 Engineered softwood timberwork, ca. 1985, at La Rocca, Umbertide, built before 1400 as a fortress and today in part an art museum.

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Good Vibrations 1: A Practitioners' Guide

This article represents the first concise summary in more than a decade of the state of the art in floor vibrations. It can serve as a first source for many analysts and designers. Some of the material appears in accessible form in English for the first time; some of the conclusions are indeed the authors'. The loads that drive vibrations are difficult to characterize. How best to measure the resulting "shaky floor" is a vibrantly debated topic, and the analysis that lies between the tricky loads and the misty results can look very complex. Part 1 of the article includes a general discussion, rules of thumb, an explanation of terms and some design solutions. Part 2, to appear in the next issue of Timber Framing, will cover design methods, with example calculations for illustration. Source references below are bracketed. —B.B.

HOW many framers have walked across a timber-framed second floor to the untimely chiming of a grandfather clock? At least one timber frame engineer who lives in a home he designed, and with an antique clock he inherited, does this every day. Vibrating floors happen to lots of good buildings, and otherwise sound building techniques can be alarmingly susceptible to floor vibrations.

Generally speaking, timber-framed floors are relatively simple, remain largely unconcealed and unadorned and use lower aspect-ratio joists than their typical light-framed counterparts. Each of these factors can exacerbate the tendency of floors to vibrate annoyingly when we walk on them. One criterion in particular tends to be a good indicator of vibration predictability: deflection. While more than a few of us have observed that sagged floors can vibrate badly, long-term sag is not the type of deflection we have in mind. Rather, we want to talk about the small and quick deflections that even well-built floors sustain, the harbingers of annoying vibrations.

The new engineering school building in Biel, Switzerland, where one of the authors studied timber engineering, had a spectacularly sophisticated premanufactured floor deck with a free span of about 26 ft. (Fig. 1).

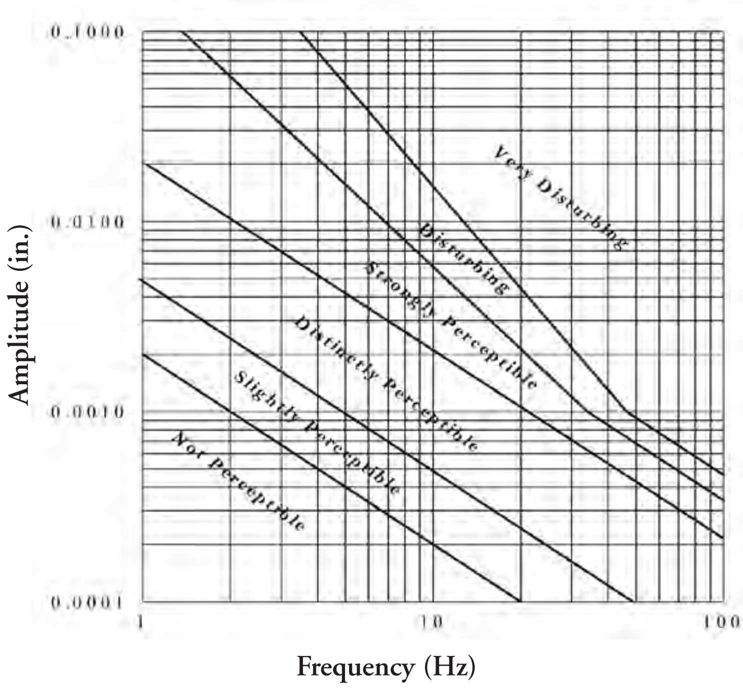
Multiple layers of gypsum board and sand had been added for mass, to improve acoustics and to take what was also considered a good measure against vibrations. No expense was spared. It was state of the art. Nonetheless, during classes when the professor walked up and down the classroom during a lecture, the floor vibrated noticeably.

The question is, if under such ideal circumstances it remained so difficult to make a timber floor that doesn't vibrate, how is it possible at all? To give the university in Biel its due, only a short time after the building was completed, research was published that predicted the effect all that extra mass would have on the deck. Had the designers known of the research beforehand, one of us was told, the floor would have been built differently. Let us take a look, then, at what they didn't know.

BFH-Biel

Lignatur AG

1 University of Applied Sciences, Biel, Switzerland (upper left), a well-designed timber building using a Lignatur® prefab floor deck system (alternate forms above). Deck shows finished ceiling to below, as seen in cafeteria view, upper right. A strongly perceptible case of floor vibration in classrooms stemmed from overly optimistic understanding of underlying physics.



2 Reiher-Meister Scale (1931) of human response to steady-state vibrations (machine vibrations) based on frequency and amplitude [1].

General Discussion. When it comes to floor vibrations there are two fundamental reasons to be interested: one is to look for an alibi, the other to search for a solution. As to both alibi and solution, the unfortunate truth is that there is no simple answer. The complications in this topic begin with establishing whether a floor is too shaky or not. Human perception of vibrations is extremely subjective. There is some disagreement where exactly the comfort threshold lies, although much research has been conducted on this topic going back to the 1930s (Fig. 2).

It has been established that what's considered an annoyance by some can go unnoticed by others, and that the presence of another person or persons can radically alter one's own perceptions. The general opinion in the literature suggests that reactions to vibrations can even vary with age, nationality and a standing or seated position.

The forces that cause vibrations in floors also vary widely in intensity, type and frequency. Because floor serviceability is subject to such variable opinions, developing a simple set of performance criteria to address them is problematic. Still, even if there is disagreement on what exactly constitutes an uncomfortable floor, there can be a general consensus on what constitutes a comfortable one. And we have a large portfolio available of practical experience and useful analytical methods that address floor vibrations. Although the basic issues of vibration design are known, there is disagreement worldwide on exactly what constitutes the best predictive model of floor performance. While some methods and theories are new, others have been around for decades. We have focused on the ones that have garnered widespread acceptability for timber floors. We will offer criteria aimed at reducing floor-design uncertainty and helping builders achieve a desired level of performance, ultimately aiding us in building timber frame floors that inhabitants will find acceptable.

Is Calculating Deflection Alone Sufficient? Considering deflection criteria is part of wood floor system design. It is common practice in the building industry to analyze dynamic behavior using equations based on far simpler static models. Based primarily on acceptable experience, a rule-of-thumb deflection limit of one part in 360 ($\Delta\ \delta = L/360$) under a live-load equivalent of about 40 lb/ft^2 (1.9 kN/m^2) is used for residential floors almost worldwide. This assumed load is somewhat unrealistic, as most floors are not loaded uniformly but rather at concentrated, scattered points, and nearly never to their design-load capacity. Using this admittedly flawed criterion, however, is a proven means to prevent excessive deflection, sagging from creep and unseemly plaster cracks in a ceiling below. As long as relatively short spans are involved, such a floor is generally thought acceptable and vibrations are rarely considered.

The introduction of new engineered wood products has ushered in a general proliferation of floors with longer spans and larger supporting beams. New floor types presenting composite behavior and heavier materials offer to meet new expectations and designs. Timber floors subjected to large loads can now be considered where timber was previously not used. This has given rise to situations where the traditional deflection criteria alone do not suffice for the accurate determination of a comfortable floor, and vibration can become an annoyance.

Some designers and builders have adapted to these trends by applying intuitive methods such as cutting back permissible spans by several feet, using larger joists than the minimum size permitted or using *L/480* and *L/600* criteria for longer-span floors. While all of these tactics represent improvements, the question remains how much quantifiable protection against vibrations each one brings. And generally the longer the span and the more demanding the intended use, the more pointed this question becomes.

Safe but Uncomfortable. The word *serviceability* is commonly used in discussions of building performance to describe the measure of human dissatisfaction with such problems as sag, creep and vibrations in otherwise safe construction [2]. Where code requirements have been implemented, they represent minimum criteria, which generally allow some tolerance of vibrations. Adhering to these code minimums does not completely eliminate noticeable disturbances. In other words, the requirements of design codes are intended to provide a safe structure, but they do not necessarily fulfill a high level of serviceability [3].

For example, if everyone is fleeing down a hallway because a building is burning, approaching the maximum load for which that floor was designed, very few people are going to stop to notice if the floor is vibrating. But if someone is simply sitting in that hallway trying to read and the floor vibrates when another person walks by, then there is definitely a problem.

The load on the floor is, of course, much lower in the second example than in the first. Code requirements were originally meant to define a point of structural failure. They represent much higher loading than expected during normal, "everyday" use. So it doesn't make sense to use the maximum load to determine a level of "normal" comfort. That is why the concept of a service load, as opposed to a rupture load, has been introduced into various national codes where vibration design is required.

In this article, p_{ser} designates the service load. Service loads commonly considered in vibration analysis include full dead load *D* and anywhere from 10–30 percent of total design live load *L* acting on the floor [3–6, 8].

Proposed Quick Criteria for Evaluating Floors. In the past several decades many methods have been proposed for predicting unacceptable levels of vibration. Mostly these involve setting limits on criteria associated with vibrations: deflections, accelerations, velocities and frequencies. Listing even a couple of very simple methods is difficult, since there is no silver bullet that addresses all vibration issues. After careful examination of the relevant sources (see References), however, we can venture to make the following generalizations for timber frame floors:

1. Short-span floors (span < 15 ft.) are best judged using point-load deflection criteria.
2. Long-span floors (span > 20 ft.) are best judged using distributed-load deflection criteria.
3. Mid-span floors (15 ft. < span < 20 ft.) represent a gray area where both point-load and distributed-load deflection criteria need to be checked.

For a quick but conservative estimate of the required beam size (certainly not a proper vibration analysis), one can apply the static deflection limits in Table 1 to an individual joist.

Span	Calculate deflection using	Applied load	Deflection δ_{max}
<15ft (4.6m)	Point load	P = 225lb (1kN)	0.04in (1mm)[6]
15–20ft (4.6–6m)	Try both deflection calculations and apply the more conservative result		
>20ft (6m)	Distributed load	p_{ser} = D only	0.55in (14mm)[3]

Table 1. Quick pre-dimensioning criteria for estimating floor joist serviceability against vibrations, based on authors' observations.

One method deserving mention was in use in the United States during the 1960s and early 1970s. The Housing and Urban Development (HUD) codes specified a maximum allowable deflection limit of 0.5 in. (12.7mm) under full loading for floor spans greater than 15 ft. (~4.5m) [7]. The eventual dropping of this requirement had more to do with market pressures and industry innovations than with serviceability issues, and some engineers still use it today in the absence of any code requirement. We will later show that it stands up well under modern analysis.

Some contemporary sources using similar deflection limits are listed in Table 2.

Source	Maximum deflection δ_{max}	Applied service load p_{ser}	Equivalent frequency $f = \sqrt{\frac{0.032g}{\delta}}$
HUD	0.5 in.(12.7mm)	D + L	5.0 Hz
DIN-1052 [8]	6mm (.24in)	D + 0.3L	7.2 Hz
Kreuzinger [9]	5mm (.20in)	D + 0.3L	7.9 Hz

Table 2. Recommended deflection criteria to avoid resonance and equivalent resonant frequencies under load. DIN-1052 is the German timber construction code. Kreuzinger is a German researcher who contributed to Eurocode 5.

In a similar fashion to the old HUD code, the DIN just lists a maximum deflection of 6mm for all spans under a service load of D + 0.3L. This happens to correspond to a resonant frequency of about 7.2 Hz. Kreuzinger points out that the recommended 8 Hz minimum resonant frequency under the Eurocode always corresponds roughly to a 5mm deflection when using a service load of D + 0.3L, regardless of span. It's important to note that the frequency of a beam will change depending upon the load. So the HUD criteria, although appearing to be at a much lower frequency than the other two, actually represent a beam of comparable stiffness. (See the physics of frequency section, facing page, for more on this singular relationship between frequency, deflection and load.)

When Is Vibration Analysis Necessary? Strangely, though there has been plenty of research on vibrations in floor decks in the last several decades, no prescriptions or guidelines have yet been adopted in the American code. In Canada, vibration design criteria have been in use since 1990. Australia and the UK have also developed code criteria. In the European Union, the adoption of vibration criteria included in the model Eurocode 5 is left up to individual member nations, but the use of the criteria is widespread. Even without formal prescriptions in the US, a certain amount of serviceability against vibrations is implicit when limiting deflections to *L/360*. So we will want to investigate when this equation no longer suffices, when one has received complaints or noticed problems. Increased client expectations can merit more conservative approaches (picky clients get big joists). It follows that primary members supporting large floor areas deserve correspondingly more attention. Larger spans, heavier loads and more heavily used floors are going to be of greater concern.

HOW then might we avoid unwanted vibration? To do so, we must consider a range of physical concepts: bending stiffness; frequency and resonance; and velocity, amplitude and damping. We'll start with bending stiffness, a composite notion.

Bending Stiffness. *Modulus of Elasticity* (also denoted as *MoE* or just *E*) quantifies the capacity of a material to deform elastically (i.e., nonpermanently) under an applied force. *E* is a material property. Each material has its own value for *E*, rubber having less than that of timber and timber having less than that of steel, for example. In the United States, values for *E* for timber species and grade are listed in the *National Design Standard* (*NDS*).

Moment of Inertia (also called the *Second Moment of Area* or *I* for short) is a geometric cross-sectional property used to help predict resistance to bending and deflection. Each section size and shape has a different value for *I*. In timber construction, the most commonly seen equation for determining moment of inertia is for a rectangular section: $I = bh^3/12$.

When you multiply *E* by *I*, you get something known as *bending stiffness*. After the length of the span itself, bending stiffness is the main determinant of a beam's resistance to deflection. The handy thing about *EI* is that it's material- and shape-neutral. For example, if you determine that a beam requires a certain value *EI* to resist deflection, this value will remain constant regardless of whether we are talking about a beam made of rubber, wood or steel. It also remains constant whether we talk about using a square section, a T-section or some other shape.

Frequency. When we walk or run, each step we take can be considered a cycle. The pace of these cycles changes according to the activity. Hertz (Hz) is the basic unit of measurement of *frequency*, defined as the number of complete cycles per second.

When talking about vibrations in buildings, we need to consider the range of frequencies generated by "normal" human activity on a floor. This is known in technical jargon as the driving frequency. Both singly and walking in groups, people tend to generate impulses that "spike" at about 1.5–2 Hz followed by a series of decaying harmonic "mini-spikes" that come in multiples of 2 Hz (i.e., 4 Hz, 6 Hz, etc). This wave train decays dramatically in the frequency range around 8–10 Hz [13]. Thus it's generally accepted in the literature that normal human activity in office or residential spaces generates *driving frequencies* that fall within the 2–8 Hz range.

People seem to be most sensitive to vibrations in the 4–8 Hz range [4]. But the heel impact of a footstep also generates higher frequency components in the 8–40 Hz range that can also contribute to human discomfort through the development of so-called *beat frequencies* [4, 10]. Above 40 Hz, the effects produced by a footfall are considered insignificant. For our purposes, we will define any frequency below resonance as *low frequency*, while any frequency higher than resonance up to a 40 Hz limit shall be considered *high frequency*.

Resonance. Resonance is the susceptibility of a system to oscillate at certain frequencies, known as the system's *resonant frequencies* (also called *natural frequencies* or *harmonic frequencies*). Resonance can be dangerous, as even small impulses will gradually build up to produce large-amplitude oscillations if those small impulses happen to occur at frequencies near to, or in multiples of, the structure's resonant frequencies. If unchecked, the resonating system is subject to oscillations of ever-mounting magnitude that can eventually result in its destruction.

Most people are familiar with Puget Sound's Tacoma Narrows Bridge, which collapsed in 1940 (Fig. 3). Ironically, it was a steady wind that created eddies that formed at the downwind edge of the bridge deck. Peeling off at just the right frequency, the eddies caused the deck to resonate. This resulted in extreme, steadily growing oscillations that eventually caused the bridge's destruction. Ironically, the bridge had, in fact, weathered much stronger winds. But those winds had never generated steady eddies that matched the bridge's resonant frequency.

In similar fashion, someone walking across a floor causes what is known as a transient impulse. If the resonant frequency of the beams supporting that floor lies close to the frequencies generated by the human footfall, each successive footfall will increase the vibration amplitude of the beam, and the floor will noticeably vibrate. There is an important distinction between a floor that merely vibrates from a single impact and one that might match the frequency of an ongoing transient impulse. We want to avoid the latter. Thus the best floors are built of beams that resonate at fre-

Tacoma Public Library

3 Tacoma Narrows Bridge, destroyed in 1940 by harmonic resonance caused by wind. Shallow deck turned out to be inappropriate design for location.

quencies that do not correspond to normal human activity. Since such activity generally falls in a range of 2–8 Hz, to avoid building timber trampolines residential floors should be designed to resonate at frequencies of 8 Hz or more under the "everyday use" service loads p_{ser}.

Velocity, Amplitude and Damping. There are types of floor vibrations that don't involve resonance at all. For these, we need to look at the other physical aspects of vibration. When dealing with high-frequency vibrations, for example, velocity and acceleration of the deck become relevant in terms of floor vibrations. *Velocity* refers to the rate of change of deflection of the floor deck, expressed in inches per second (in/s) or millimeters per second (mm/s). *Acceleration* refers to the rate of change in velocity expressed as inches or milimeters per second per second (in/s^2 or mm/s^2).

To our knowledge, Eurocode 5 is the most widely received current code recommendation that incorporates velocity or acceleration in the vibration analysis. They are also used in individual methods proposed by researchers, in one case for the design of dancing or exercise facilities [17]. British Standard 6472-1 also uses a method that involves acceleration [10].

Notably in short-span floors where resonance is not an issue, the force of a single shock to the floor can nonetheless cause noticeable vibration. Under some circumstances, even the impact energy from a single footfall can be enough. Amplitude and damping are the predominant factors in these events. *Amplitude* describes the magnitude in the oscillations we perceive as vibrations. Generally speaking, high-amplitude vibrations are more annoying than low-amplitude vibrations [16]. *Damping* refers to any constructive means that tends to reduce the amplitude of vibration, including intentional means as well as inherent properties of the deck. All floors possess some degree of damping. We speak of a damping ratio as describing how rapidly the oscillations decay in amplitude toward zero. This provides us a means of expressing the effectiveness of a damped system. The higher the damping ratio, the better.

Since early research found damping to be a critical factor in controlling vibrations for steel-concrete decks [11], much attention has been paid to damping and its effect on amplitude. They are both used in conjunction with a Reiher-Meister Scale (Fig. 2) for the analysis of steel or steel-concrete decks [12]. But this method has been found to be inadequate for predicting the behavior of light-framed floor systems [2]. Currently there is some disagreement whether damping plays an important role in lightweight timber floors or not [13]. The Eurocode, however, does take damping into consideration and identifies damping ratios (expressed as a percentage) with the types of construction listed in Table 3.

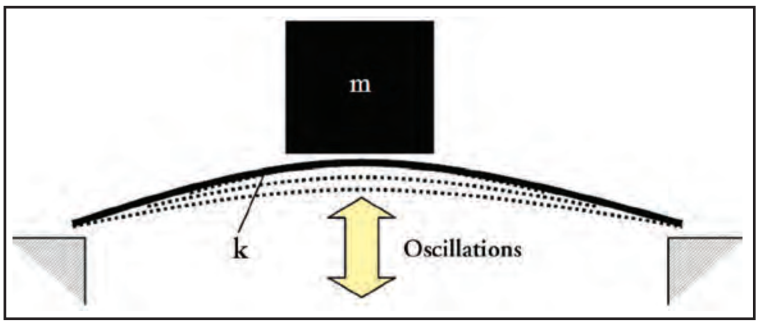
Damping Ratio ζ	Floor System
0.03	Mechanically laminated beams and wooden beams with floating floor
0.02	Glue-laminated composite floor system with floating floor
0.01	All floor types without floating floor

Table 3. Damping ratios defined according to type of construction used (Eurocode 5 recommendations).

Damping incorporates manifold considerations: detailing, partition wall location, choice of materials, efforts at careful craftsmanship and use of quality materials all contribute to increasing performance but are very difficult to quantify. This results in the damping ratio being difficult to predict with certainty during design but easy to verify in a finished building [2]. *In situ* testing has found that the average damping ratios for simple timber floors can be significantly higher than what is prescribed by the Eurocode [13]. There have been efforts to develop design guidelines that assign damping values based upon construction detailing [10]. The use of such guidelines should involve some prudence in view of the limited accuracy of predicting damping values, in any case.

The Physics of Frequency. One point we need to get across very clearly is that *the resonant frequency of a beam varies with the load carried*. There is no single resonant frequency inherent in any given beam (other than perhaps for an unloaded one). Rather, the point at which a beam will resonate depends on the amount of weight being carried. Logically, this means that when we talk about resonance, we need to be very specific about what service load is involved.

As the deflection of a beam also varies according to the load, one surmises some correlation between frequency and deflection as well. We can argue that a vibrating floor beam acts like a spring in a similar fashion to the leaf-spring suspension of a car [14]. Thus we want to imagine a system where *m* represents the mass acting on our floor, and *k* represents the floor as an oscillating "spring" (Fig. 4).



M. D. Schroeder

4 A simple harmonic oscillator.

We now have something called a *harmonic oscillator* [15], whose behavior we might be able to investigate mathematically. Let's take a look at developing a simple model, merely accurate enough for our purposes, that will nonetheless be useful in giving us a quick estimate of the resonant frequency of a floor beam. (Readers who wish to skip over the math can pick up the discussion overleaf in the right-hand column.)

Developing a Mathematical Model for Vibration

The general solution for the frequency of the oscillations is

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad \text{(Equation 1)}$$

with k (lbf/ft) the *spring-constant* and m (lb) the *mass*. The spring-constant k describes the relationship of the spring's deflection to the mass, and can be expressed as

$$k = \frac{F}{\delta}$$

with F (lbf) the *force* exerted by the mass, and δ (ft) the *deflection*. We will consider the distributed load acting on our beam as a resultant single force. Substituting for k in Equation 1, we now have

$$f = \frac{1}{2\pi}\sqrt{\frac{F}{\delta m}}$$

From Newtonian physics, we know that $F = m \times g$, with m (lb) as *mass* and g (ft/s^2) as *gravitational acceleration*. Furthermore, the acceleration induced by Earth's gravity is $g = 32\ ft/s^2$. Substituting for the known variables and solving the equation gives the following result:

$$f = \frac{1}{2\pi}\sqrt{\frac{mg}{\delta m}} = \frac{1}{2\pi}\sqrt{\frac{g}{\delta}} = \frac{1}{2\pi}\sqrt{\frac{32}{\delta}} \approx \frac{0.9}{\sqrt{\delta}} \qquad \text{(Equation 2)}$$

with the deflection δ (ft) and the resulting frequency f in cycles per second, or Hz. In SI units, using $g = 9.8\ m/s^2$ and deflection δ expressed in meters results in the following equation:

$$f \approx \frac{0.5}{\sqrt{\delta}}$$

Eureka! We now see that under *any* given load and for *any* span, if the deflection is known we can easily determine the resonant frequency. One needs to remember, though, that here we are looking at an undamped system where the oscillations never decay. Thus our mathematical model needs to be refined further to improve its accuracy before it can be of use for vibration analysis. (We will do this in Part 2 of the article.) Strictly, the damped solution is

$$f \approx \frac{1.01}{\sqrt{\delta}} \text{ (US units) or } f \approx \frac{0.56}{\sqrt{\delta}} \text{ (SI units)} \qquad \text{(Equation 3)}$$

For now this simple demonstration allows us to establish and confirm the inherent connection between *frequency* and *deflection*.

Example. Let's revisit the old HUD code again. Using the full load called for in the code for rupture, the static calculation of a beam results in the following deflection δ_p: $D = 10psf$, $L = 40psf$; $p = D + L = 50psf$; $\delta_p = 0.5\text{in} = 0.042\text{ft}$.

We now want to know the resonant frequency of this beam using a reduced *service load* p_{ser} that would more typically represent "normal," everyday use: $p_{ser} = D + 0.3\,L = 10 + 0.3(40) = 22psf$.

The resulting deflection using the reduced vibration-inducing load is easily calculated by hand:

$$\delta_{ser} = \delta_p \frac{p_{ser}}{p} = 0.042\,ft\,\frac{22\,psf}{50\,psf} = 0.0185\,ft$$

Calculation of resonant frequency of the beam:

$$f = \frac{1.01}{\sqrt{\delta_{ser}}} = \frac{1.01}{\sqrt{0.0185}} \approx 7.43\,Hz$$

Compare our result with the values shown in Table 2. We notice that the resonant frequency of the beam is much lower under the full rupture load D + L (5.0 Hz) than under a service load involving D + 30%L (7.43 Hz). We also can see that for residential use, the HUD code from the 1960s will essentially generate beams of comparable frequency (and thus also equivalent stiffness) to the current DIN-1052 and Eurocode 5.

Constructive Measures. As with so many other aspects of timber framing, quality of craftsmanship and quality of materials can be decisive in affecting the perception of a floor's acceptability. It might be said that the more expensive the building, the greater the expectations. To some people, any noticeable vibration at all is unacceptable. To be sure, it is possible to build floors that can achieve this, at a cost. From that extreme, varying degrees of protection are attainable within a reasonable budget. In all cases, doing it right is very much cheaper than fixing something done wrong. The trick, of course, is in knowing what "right" is.

In wood construction, vibration performance has traditionally been controlled by increasing bending stiffness. When one looks at the building system as a whole, however, the actual issues affecting vibrations are numerous.

And for timber framers? First of all, one might do well to apply more stringent criteria than the *L/360* demanded by code. Numerous other measures can be taken.

Reduce the effective span. First, limit the span where possible through the use of columns and supports. This is, by far, the most effective way of reducing vibrations. Using knee braces is also a good means to effectively reduce spans. Third, just as continuous beam action reduces deflection, it is also an effective measure against vibrations, but it brings the possible side effect of allowing transmission of the vibrations into adjoining rooms if joists running continuously between those rooms are not properly compensated for.

Increase beam stiffness. In most early and traditional timber framing, the height-to-width or aspect ratio of individual girders and joists is close to 1:1 (square timbers) and can be even less than 1:1. In modern Douglas fir framing the ratio is 2:1 (typical 4x8 material). This beam proportion, while retaining certain advantages in stability, joinery and good looks, is still particularly susceptible to serviceability issues. As a general rule, changing from 2:1 height-to-width to 3:1 for joists and to 4:1 for girders will give better rigidity for the same volume of wood.

Create composite T-beam-action by gluing the flooring to the joists. Dealing with glues can be a mess, and the effective bending stiffness *EI* of the composite beam is tricky to calculate. But it is well worth the trouble for the extra rigidity it brings.

Use a wood species with a high Modulus of Elasticity. For example, use Douglas fir instead of Eastern white pine.

Increase load sharing. Anything that engages more joists in resisting the point loads induced by walking can decrease the vibrations. Heavier decking is one way to do this. Another way is to include sleeper joists running above and perpendicularly to the timber joists, which helps in running plumbing and HVAC but also spreads the floor's point loads, as does the floor component in Bensonwood Homes' Open-Built® construction system (Fig. 5). This configuration includes a rubber motor mount in its steel struts to further reduce vibration (Fig. 6d). Canadian research indicates that installing bridging at the third points between joists combined with a bottom strap across the joists increases transverse deck stiffness [7], although this device is not a suitable option for exposed framing.

Increase damping. Quality of craftsmanship and quality of materials can have a significant impact on damping. Use resilient layered subflooring, also known as floating floors (Figs. 6a and 6b). Suitable materials include Regupol™ rubber elastomeric mats (distributed by Regupol America), Pavafloor™, a soft wood-fiber board (Pavatex AG) and the mineral fiberboard Flumroc™ (Flumroc AG), the latter two Swiss products.

Mechanically laminated beams offer nice damping characteristics, which offset (or rather enhance) their loss of 100 percent rigidity. Examples include key-laminated beams and lamination systems using shear fasteners or special threaded fasteners.

Chris Carbone

5 Open floor system developed with others by one of the authors in 1997, now part of Bensonwood's Open-Built® system. Sleeper joists increase load sharing across primary joists. Short steel posts create space within floor deck itself for running plumbing and HVAC.

Add mass. Adding mass is considered to be an effective means of reducing the acceleration of high-frequency vibrations in floor decks [16]. Two common ways to do this are to add a wet concrete topping or to build up layers of gypsum-board subfloor. But increasing mass is a two-sided coin. While adding more mass reduces vibration amplitudes in a floor (that's good), it also reduces the resonant frequency of the system (could be bad). Thus increasing mass by too much may create a resonance problem. If adding mass causes the resonant frequency to drop into the 2–8 Hz range, it might actually be detrimental to the acceptability of the floor. In large-span floors, adding mass significantly compounds the problem of reaching the required frequency to avoid resonance.

To come full circle, this is what happened at the engineering school in Switzerland mentioned near the beginning of the article. The mass was increased according to the then-prevalent thoughts on the beneficial effects of damping found in massive floor decks (based mostly upon the well-accepted behavior of concrete decks). It ended up generating a resonance problem instead.

—Dave Schroeder with Ben Brungraber

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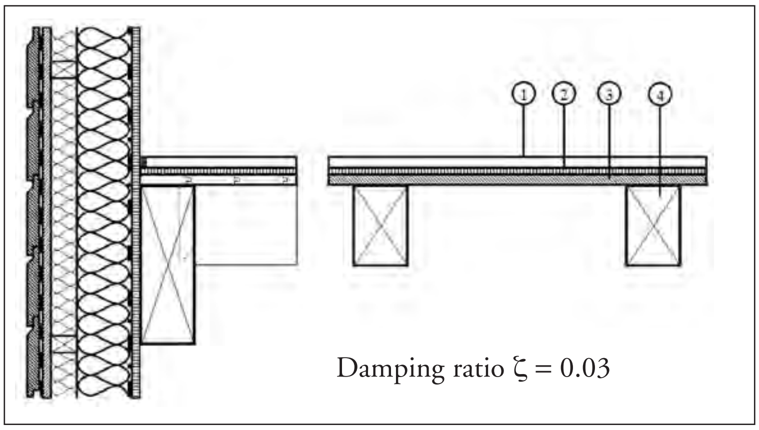
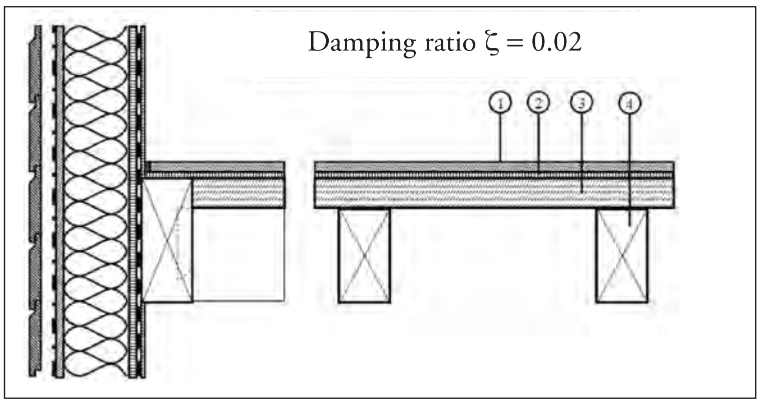
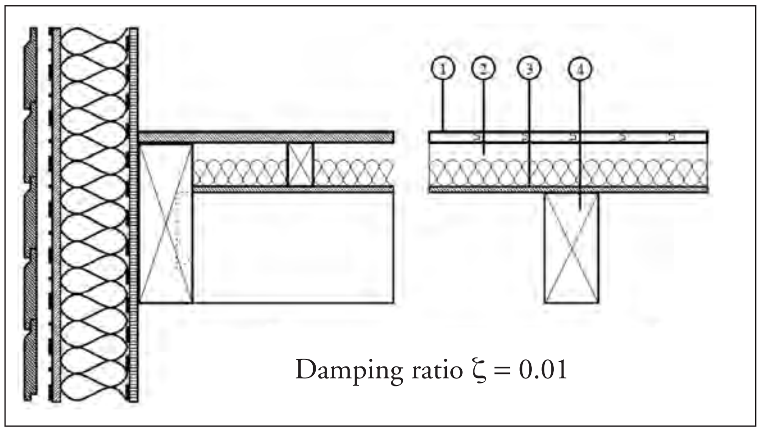


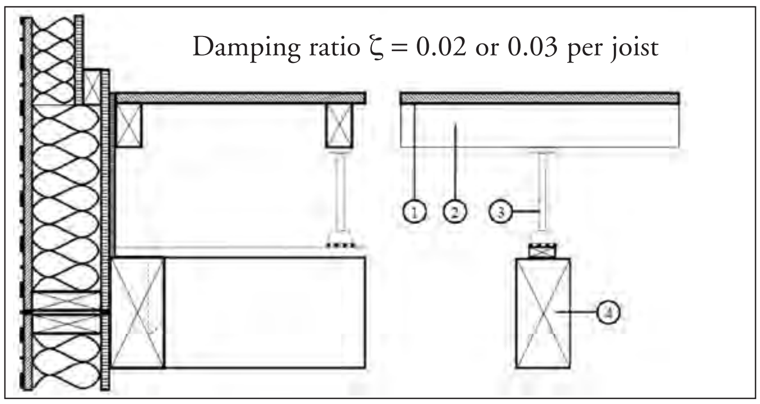
6a Wooden beams with floating floor.
1. *Wood fiberboard composite 23mm (top side hard fiber, bottom side soft fiber)*
2. *Resilient polymer layer 7mm or soft wood-fiberboard 15mm*
3. *Pine board T+G decking, 27mm, nailed to joists*
4. *Floor joist*



6b Glued-laminated composite floor system with floating floor.
1. *Particleboard T+G, 25mm*
2. *Mineral fiberboard, 15mm*
3. *Solid wood-composite deck panel, 72mm, glued to joists as T-beam flange*
4. *Floor joists acting as web of T-beam*



6c Any floor type without floating floor (system using cross-joists is shown).
1. *Pine board T+G decking, 25mm*
2. *Cross-joists with acoustic batt insulation filling*
3. *Finishing panel, 19mm*
4. *Floor joist*



6d Bensonwood Homes floating floor system.
1. *Deck panel, 25mm*
2. *Cross-joists supported by mechanical mounts.*
3. *Mechanical mounts, supported by rubber gaskets at base of each strut*
4. *Floor joist*

6 Nonexclusive examples of four possible timber frame floor configurations, each floor type assigned a damping ratio as determined by its description in Table 3. Although adapted here for timber framing, "floating floor" detailing shown in first two examples follows published Central European standard construction guidelines for timber floor decks.

15 years of professional experience working as an architect and engineer in Europe and the United States, including a stint with the extraordinary structural engineer and timber genius Julius Natterer. Robert L. "Ben" Brungraber, Ph.D., P.E. (ben@ftet.biz), is a principal at Fire Tower Engineered Timber in Providence, R.I. Other contributors to the article included Joe Miller, Ph.D., P.E., and Chris Carbone, P.E. The second part of the article will take a detailed look at existing engineering analysis methods through sample calculations and propose a short-list design guide for their application.

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