Basic Design Issues in Timber Frame Engineering

WHY do we need structural engineering for design of timber frame buildings? Haven't they stood the test of time? Well, yes, some have, and if every timber frame building we were planning to construct were based on an existing structure whose performance was proven, and whose location and loads matched those of the original building, certainly there would be little need for structural engineering in our designs. However, the scale, complexity and site conditions of many contemporary timber frame projects make traditional frames unreliable for predicting the performance of these new ambitious structures. More and more designs depart from strictly traditional forms to find new ways of defining space (Fig. 1).

The challenge then is to come up with the right timbers, the right joinery and the right structural system to get satisfactory performance from a design that has never been built before. Structural engineering gives us a consistent method for achieving that goal while not relying on the mysterious wisdom sometimes ascribed to traditional heavy timber construction.

Engineering a timber-framed structure is more than just sizing individual joists, beams and rafters. We need an understanding of how the whole timber frame and cladding assembly function as an integrated system to support loads. In this article, the first of two, we will review the structural engineer's methodology for building design and look at some of the basic strategies we use for accommodating loads in timber frame buildings. We will also touch on integrating the design process into construction. We will not get into any higher mathematics here—no equations or number crunching. The emphasis will be on basic design issues.

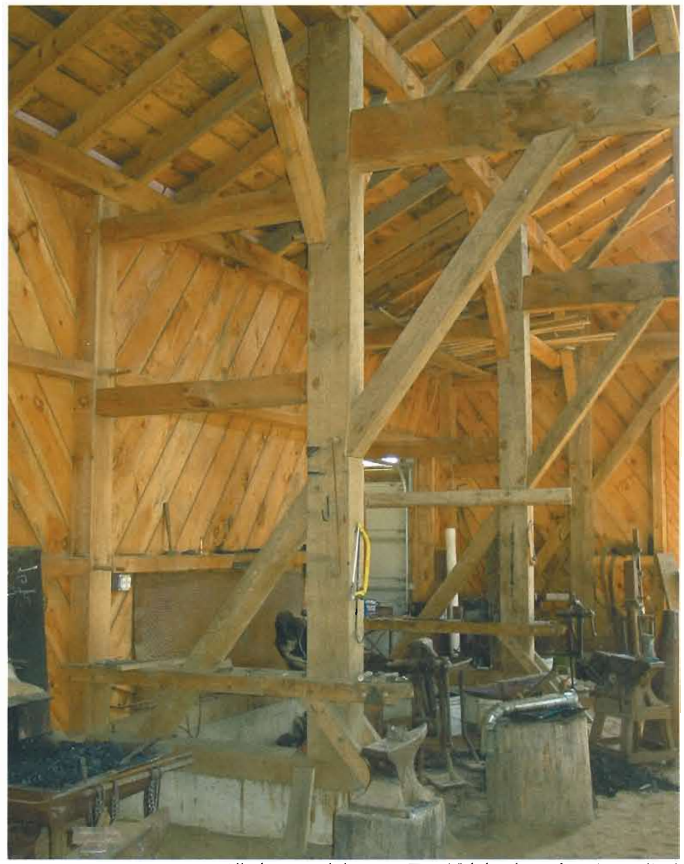

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Fig. 1. The Herb Nehring Blacksmith Shop at Tillers International, Kalamazoo, Michigan, incorporated large diagonal braces, tension joinery, diagonally sheathed shearwalls and a flexible roof diaphragm to achieve adequate racking resistance for code wind loads. Design by Dick Roosenberg, Tom Nehil, Amy Warren.

The Engineering Method. What then is the structural engineering approach to design? Once the preliminary size and shape of the building have been developed, we then proceed through the following steps:

1. Identify and quantify the loads on the structure.
2. Select the member sizes and materials for the structure.
3. Examine how the building behaves under load.
4. Refine materials and member sizes to achieve satisfactory and effective performance.

So, rather than taking our best guess on an initial sketch and then proceeding with construction, keeping our fingers crossed, we put our initial assumptions through some testing to see if they are valid and make adjustments as necessary while it's still easy—that is, before the timbers have been ordered. Let's look at each of these points briefly and see how the method works.

1. Identify and Quantify the Loads. We have two basic categories: loads that weigh down on our building as a result of gravity, such as the weight of the structure plus occupants, furnishings, fixtures, and snow and ice on the roof; and the loads that push sideways or up and down on our building, that is, wind loads or seismic loads. We have to keep in mind that wind passing over and around a structure can also cause suction on the building and create uplift on roof framing.

For most conventional uses, loads a building must be designed to support are defined by the building codes. The International Building Code (IBC) is now pretty much our national model code in the United States; Canadian building codes of course apply north of the border. The IBC prescribes that the typical living areas of a residence need to support a 40 lbs. per sq. ft. (psf) superimposed live load; sleeping areas can be designed for 30 psf, attic storage areas for 20 psf. The typical office floor loading requirement is 50 psf. Commercial spaces used for retail or restaurant use and lobby areas must be designed for 100 psf—which is like covering the entire floor wall to wall with sacks of cement stood on end, a pretty high demand! For many other applications, such as stadiums, industrial buildings, storage buildings, and the like, the code establishes the required load capacity. Special applications such as agricultural storage (hay) or workshop loads such as lumber or timber storage may require you to make your own rational assessment of the maximum likely loads. By "maximum" here we mean the maximum average loading over the floor area. Stickered hardwood stacked 3 ft. high covering half the floor would represent an average load of about 50 psf (depending how green the wood is and how thick your stickers are). Now, how often might you be stacking that wood 4 ft. high?

The building code also defines snow loads for various geographic areas of the country. We will discuss roof loads in more detail later.

Finally, the code prescribes the lateral loads that our buildings are required to resist. Wind pressures vary considerably with location and exposure—whether, for example, we are on the top of a treeless bluff facing the Atlantic Ocean in a hurricane-prone region or tucked safely in amongst trees and hills in the relatively placid northern Midwest. Seismic loads similarly vary from location to location depending on the likelihood of ground movement. Fortunately for most locations, seismic loads for our relatively lightweight wood structures do not control design. Rather, wind loads are our major challenge for lateral bracing.

The building code, by the way, not only prescribes the loads we must be able to resist but also sets limits on how far we can stress the materials we will be using to build with. A building or structural element can be expected to perform safely and satisfactorily only if under full load it is not stressed right to the edge of breaking. A safety margin is prescribed so that under full loading some reserve capacity remains. This helps prevent not only catastrophic collapse in the event we end up getting that hundred-year snowstorm but also plays a part in controlling the amount of sag and sway we will see in our construction. The code also sets limits on permissible deflections in floors and roofs and on the sway of buildings under lateral loads.

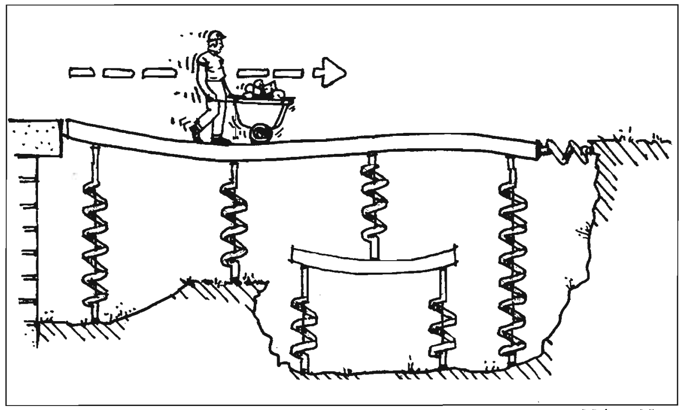
The building code is often maligned by owners, builders and designers alike, and we have done our share of complaining, but we have to appreciate its role in standardizing the rules of design and construction. By eliminating guesswork or personal opinion regarding standards of safety and performance—that is, minimum loads, maximum stresses and maximum deflections—the code helps to ensure safety and dependable performance in construction. This is important, not only if you are building for yourself, but especially if you are the consumer purchasing a home or commercial building from others. We are sure many of you have seen the unhappy results when code requirements are not considered and a combination of bad guesswork, stubborn independence and sometimes downright cheapness produces an unsatisfactory or even unsafe structure.

Following the building code, then, is the first step on the road to taking the guesswork out of the design process. It will generally result in a safe, conservative design, often seeming over-conservative. It helps to remember that the code prescribes for safe performance under fairly severe loading conditions. Following the building code also ensures a legal design, which those of us who are registered architects or engineers are obligated to provide and which you are expected to provide to obtain a building permit.

2. Select Member Sizes and Materials. The initial selections of member size and species for defining a model of a building can be based on some simple rule-of-thumb formulas, or it may be based on appearance considerations such as how massive (or not) you would like the timbers to appear in the finished frame. The selections may be based on what's readily available and affordable. For us in Michigan, white oak and red oak are readily available but, when I proposed using these non-native species to West Coast clients, they were understandably hesitant. We need to make a preliminary guess at not only species but also grade of lumber, since grade affects the allowable stresses we can use in design and also affects the code-prescribed modulus of elasticity (elastic stiffness of the material) we use in modeling the structure's behavior. Unless the timbers are to be graded, it's best to assume the most economical grade reasonable for construction purposes, No. 2, unless you have appearance requirements that will automatically dictate a higher grade. Selecting higher grades may imply needing to have the timbers graded, however, to ensure they meet No. 1 or Select Structural grading rules. Not all mills are able to provide certified grading, so the expense of hiring a grader could be yours.

3. Examine How the Building Behaves Under Load. Once we have established the loads for the building and its basic size and shape, and we have preliminary member sizes and species in place, we are ready to test our ideas. We apply the code loads to a model of the structure to make predictions how the building will behave. In other words, we undertake a structural analysis.

What exactly do we mean by "structural analysis"? Our models are usually mathematical rather than physical. We idealize the structure as essentially a big pile of springs (Fig. 2).



Nelson Nave

Fig. 2. Structural analysis can be likened to applying loads to a pile of springs—an idealized mathematical model of the structure—and then solving a series of equations to determine the load in each spring.

This type of mathematical analysis is usually referred to as stiffness analysis, since the final calculated loads depend on the relative stiffness of the various components of the model. The stiffness of each member is formulated as a series of equations, a function of the member's size, species, and grade of timber, and can be changed by changing any one of these three attributes. It's also important in our modeling to consider the stiffness of the connections (the joinery) that relate these members to one another. The structural analysis then amounts to an accounting problem to keep track of which members are pushing or pulling on which other members, how hard, and how much they have moved as a result of being pushed or pulled. The answers we get from these analyses are the forces that the individual members and the joinery need to resist. The analysis will also predict for us how much the members will sag or sway.

The complexity of the analysis depends upon the complexity of the members and the assembly. Simple elements or frames can be analyzed quickly by hand whereas complex structures may require a computer-aided analysis to crank through all the equations.

4. Refine Materials and Member Sizes. Design is an iterative process and it's certainly easier to make changes to a mathematical model than to a nearly completed frame or building. After the first analysis, we examine the loads and stresses on the members and joinery that have been predicted by the analysis, make changes as necessary to fix those members that appear to be overstressed, and rerun the analysis to examine how the loads redistribute in the model as a result of the changes. This methodology is common to design of structures regardless of the material used for framing.

Now that we've looked at the basic engineering approach to building design, let's next examine some basic strategies for handling loads in timber frame structures.

Strategies for Supporting Floor Loads. Typically, floor load is the beginning point of structural design, and the solution we arrive at will affect our overall building design. We can think of the organization and function of wood framing as being a steady accumulation and concentration of gravity loads, somewhat like rain running down through the upturned branches of an imaginary hollow tree, gradually accumulating from twigs to branches, branches to main limbs and eventually down the trunk to the roots. Similarly our floorboards deliver the floor loads to the joists, then the joists to the beams, then the beams to the posts, and finally the posts to the foundations that rest upon the earth. We can even draw an analogy between the foundations of our building and the roots of a real tree, which not only distribute the weight of the tree to the soil but also help prevent it from overturning. Our foundations must perform both these functions as well.

Basics of Floor Framing. Selection of the floorboards or roof deck usually does not take much effort. We know from experience that nominal 1-in. sheathing boards are satisfactory to span up to 2 ft. and nominal 2-in. tongue-and-groove material can handle spans between joists up to 4 ft. The numbers bear us out on this. The bending stresses in decking materials are low under uniform loads. It's the concentrated loads that put the highest demand on any individual boards. Tongue-and-groove joints help to spread those loads out (provided the tongues actually come into contact with the grooves) so that several boards can participate in resisting a concentrated load such as the leg of a pool table or grand piano.

Our joists are typically simple-span members; for load-bearing purposes, their ends simply rest on a beam at each end. There is always a temptation to space joists farther apart so that we need fewer of them, and to have them span farther, thereby minimizing the number of bents we have to build and reducing the number of posts in our floor plan. Still, we have to keep the bay sizes and spans reasonable to successfully use normally available timber sizes.

As the spacing between joists increases, the load increases proportionately. If we need to span 12 ft. between beams in a residential situation, we can use 2x8s spaced 16 in. on center or 6x8s spaced 48 in. on center. It's the same amount of joist material either way, just distributed differently. On the other hand, as the joist span increases, the bending force on the joists increases in proportion to the square of the span length. In other words, it's no longer a linear relationship and so we are going to need much stronger and stiffer joists if we want to increase the distance between supporting beams.

These same ideas apply to the design of beams. As the spacing between bents increases, the load on the beams carrying the floor joists increases proportionately. So, if an 8x10 beam is satisfactory in bents spaced 12 ft. on center, then we may need to go to a 9x10 or 10x10 beam to space the bents 14 ft. on center. But if we want to make our bents wider and thereby require the beams to span farther from post to post, the bending force in the beams will increase as the square of the span. Beams spanning 16 ft. have almost twice as much bending load as do beams spanning 12 ft.

Fortunately, the geometric section properties that affect the strength and stiffness of our joists and beams are not just proportional to the volume of wood used. The strength of a rectangular timber is directly proportional to its width but proportional to the square of its depth—and the stiffness is proportional to the cube of the depth. In other words, deeper is better than wider. In our joist example above, rather than using 6x8s at 48 in. on center, we could also use 4x10s at that spacing. Less lumber can produce the same strength, and actually better stiffness. By stiffness, here we mean the ability to resist sagging, and since limiting deflections in our floor framing usually controls our design of long-span floor joists (remember, the code sets not only minimum requirements on strength but also maximum limits on sagging), we are especially interested in the increased stiffness that comes with increased depth of the joist or beam. As another example, an 8x12 timber laid on the flat is only 50 percent stronger than an 8x8, but the same 8x12 turned vertically is more than twice as strong as the 8x8 and more than three times stiffer.

Sometimes we need to put openings through our floor framing that will interrupt the span of our joists. This commonly happens at stairways. We must remember that the headers and joists that surround our openings need to be treated like beams: they are collectors of increasing amounts of load, a fact that was often not addressed by old-time carpenters. It's all too common to see the floor around stair openings sagging, sometimes alarmingly so. We have to quantify the amount of load on the header and size it accordingly to handle that load and to span between joists on either end. Similarly, we need to account for the increased shear and bending loads in the joists on either side of an opening. This does not have to be guesswork.

The cutting of notches at the ends of joists and housings in the sides of beams to receive the joists can have significant effects on the strength and stiffness of those members. We will not go into the details here, but clearly if you cut away significant amounts of wood from critical, highly stressed areas of framing members, you are not going to end up with the same strength you started with. Specific limits on notching are imposed by the *National Design Specification for Wood Construction*. Working with, or around, those limitations is a significant part of trying to blend timber framing and all-wood joinery with engineered design and modern code requirements.

Longer Spans for Floor Framing. What solutions are there for achieving longer spans in timber frame construction? Modern solutions include the use of manufactured lumber such as LVL (laminated veneer lumber, those beams and joists that look like long sticks of plywood) or PSL (parallel strand lumber, referred to by a friend of ours not so affectionately as maggot wood) and their related variations. None of these is acceptable for exposed framing.

Glued-laminated beams offer a more visually acceptable solution to achieving greater strength and stiffness in timber construction. Very high quality material can be used at the top and bottom laminae of a beam, where stresses are highest in bending members, and cheaper, lower quality material in the middle of the beam, where stresses are lower. We have used glulam beams in timber frame structures to achieve longer spans and greater load-carrying capacity than could be achieved with solid timbers of greater depth. Not everyone likes the appearance of the glue lines in the timber. With suitable rustication of the exposed surfaces and a dark stain, however, it can be difficult to see the glue lines if the laminae are visually consistent. (You will need to order the appropriate appearance grade glulam.) If the design calls for curved timber, taking a straight timber, sawing it into flexible strips, bending the strips and gluing them back together to form large curved members that look like solid timber achieves results that could not be accomplished by cutting the curve from a single wide stick. (See TF 80, pp. 16–17.)

One traditional approach to achieving longer span capabilities with "normal" sized timbers is the use of so-called keyed beams (Fig. 3).

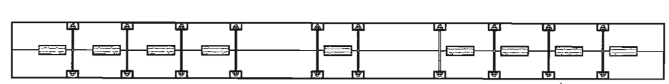


Fig. 3. Schematic drawing of a keyed beam.

If we take two timbers and stack them one on top of the other, clamp them together with bolts and insert mechanical "slip resisters" to prevent the upper and lower members from slipping past one another when loaded in bending, we can make the two timbers behave almost as if we had one solid piece of timber of the combined cross-section. There is some tendency for slip to occur along the mating surfaces and so the keyed beam is not quite as stiff as a solid piece of timber would be. There is also a great deal of work in cutting and assembling keyed beams. They have been used for hundreds of years and provide us with a means of fabricating timber much bigger than could be harvested from readily available trees. So, for example, two 8x10 beams stacked and properly keyed can be nearly as effective as an 8x20 timber, that is, about twice as strong and three times as stiff as the unkeyed 8x10s simply stacked.

Another traditional way to achieve long spans in floor framing with normal timber sizes is by trussing. Timber trusses can readily be built to span 30 to 60 ft., and longer spans are possible. Trusses used for floor framing will typically have both the top and bottom members parallel and horizontal, so the truss outline becomes a rectangle rather than a triangle such as is used for roof framing. They often incorporate some metal, for example steel rods for tension members, or straps and bolts used for reinforcement at highly stressed joinery.

In overall structural behavior, most trusses act like deep beams simply spanning from support to support. Their depth, however, commonly in the range of one-sixth to one-tenth of the span length, is one of their disadvantages. If you plan on spanning 30 ft. across a large room, you will probably need a truss about 5 ft. deep. Design and cutting of the oft-required serious tension joinery can be complicated. Trusses are expensive and labor intensive to design and build, but their appearance can be a significant aesthetic plus to a timber frame building.

If the depth of trusses at intermediate floors within a building is impractical—think of adding 5 ft. to the rise of a set of stairs from first to second floors—then we can always position the trusses up at the roof and then hang the intermediate floors from the trusses by means of hanger rods (Fig. 4).

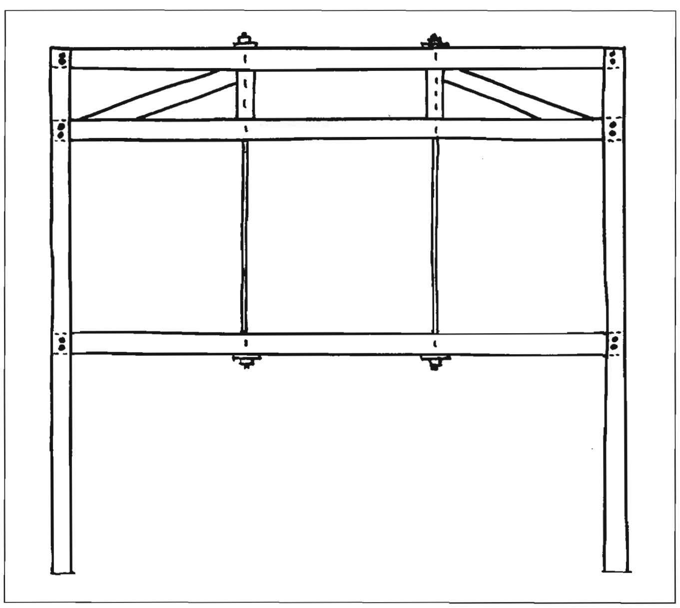


Fig. 4. Hanging the second floor from trusses in the attic or roof can leave the first floor free of posts.

This solution was commonly used during the 1800s in industrial buildings and especially in theaters, where the balconies were hung from large timber trusses in the roof framing. We can also install trusses a full story tall in the interior partition walls of upper- level floors, frame the floor joists to the trusses and leave the floor below clear of posts. This strategy likewise dates back at least to the 1800s.

Interior Supports for Floor Framing. As the width of our timber frame buildings increases, clearspan framing is often impractical. We are more likely to use intermediate supports to reduce the spans of our floor framing and thus avoid the need for excessively large timbers or the more complex solutions discussed above. If the second-floor posts in the design line up over the first-floor posts, then the posts can be continuous from top to bottom, which lets us collect the loads from the beams and direct them immediately to the foundation through the posts. Often, however, differences in layout and function between first and second floors require that interior second-floor posts be offset from those on the first floor. In these cases, we rely on the second-floor beams to collect the loads from the second-floor posts and transmit them to the first-floor posts. Since offset posts can impose large bending and shear loads in the second-floor beams, these beams need to be specifically designed for the amount of load and the spans involved if we are going to avoid excessive sagging of the second-floor beams (Fig. 5).

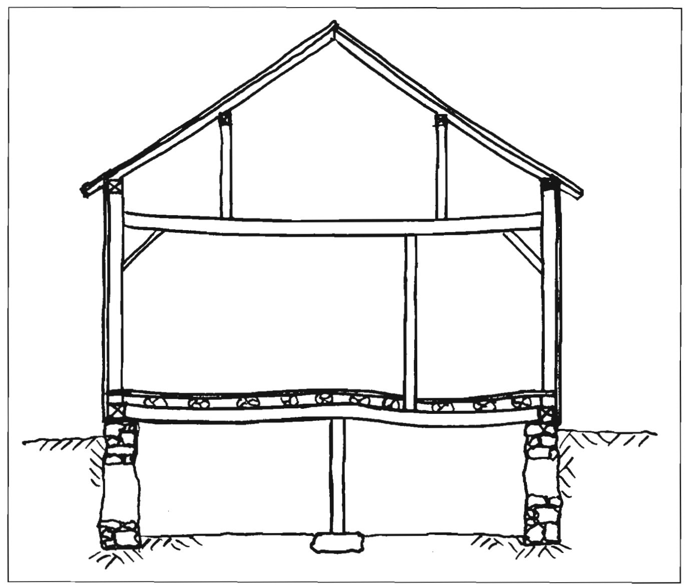


Fig. 5. Cross-section of 100-year-old oak timber frame barn in southern Michigan. Offset posts can cause sagging of supporting beams unless post loads and beam bending stresses are adequately accounted for.

Cantilevering exterior walls beyond first-floor walls as in garrison-style construction is a special example of offset posts. Here again, second-floor beams need to be specifically sized for loads imposed on their outside ends to avoid a sag outside the outer walls and a hump in the interior main span of the cantilevered beam. But cantilevers can thus be used to advantage to reduce maximum bending stress in the main span, with the cantilevered portion acting as a lever relieving main span sag.

Bolsters (capitals) can be used to increase the effective width of posts and thereby decrease the effective span of beams. The bolsters serve then to stiffen the floors and increase the shear capacity of the floor framing in the vicinity of the posts. Since they interrupt the posts at the floor, their use is restricted to buildings with level-by-level construction, such as 19th-century industrial buildings. Bolsters can be useful for support of the first-floor beams in a timber-frame structure, installed over the posts in the lower level.

Knee braces provide us with another means of effectively increasing the width of our support and reducing beam spans.

Fig. 6. Knee braces can effectively widen a support and stiffen beams, helping to transfer loads to posts.

Knee braces can reach out farther than bolsters and provide stiffer support for beams. The longer they are, the better job they can do. They also offer some design flexibility at beam-to-post joints because posts can run through vertically or beams can run through horizontally (Fig. 6).

When a knee brace is loaded by a beam, it transmits that load to the post in a direction parallel to the brace axis. The brace not only pushes downward on the post but also sideways (and with equal force in a 45-degree brace). At an interior post where there may be knee braces on both sides, there is no net sideways thrust on the post when loads are balanced on the spans above. At an exterior post, however, there is no balancing load coming in from the outside, and so the post is subjected to a combination of axial loading from the weight of framing above and bending loads from the sideways thrust of the brace. Knee braces act like wood arches, and there is always outward thrust in an arch. The knee braces are trying to push the posts outward, and that means we need to have both adequate bending strength in our posts and restraint at the top and bottom of the posts to keep them from being forced outward. Thus we need to check the tension capacity of the beam-to-post joinery above the knee brace and the shear resistance at the base of the posts (Fig. 7).

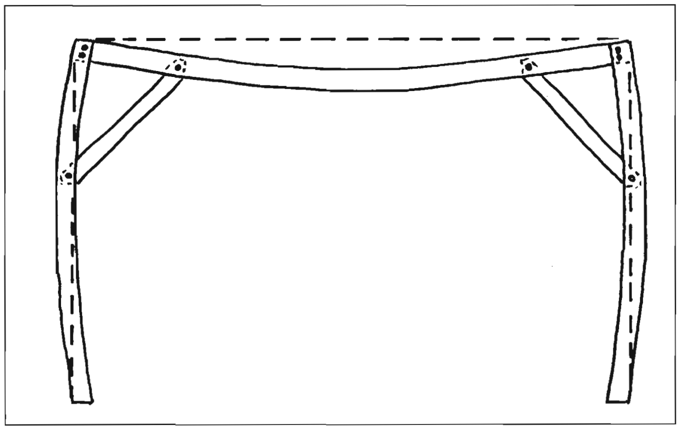


Fig. 7. Behavior of simple knee-braced frame under gravity load.

One last point: how do we make a "nonstructural" knee brace? That is, if we intend to install knee braces in a frame just for appearances, is it possible to prevent them from putting sideways loads on posts when beams above deflect under loading? We come across a lot of nonstructural knee braces in old barns where the braces are rattling around in their housings or have even fallen to the floor below. Shrinkage of the post and beam can introduce some play in a knee brace that originally fit perfectly; the beam has to sag somewhat to close the gap. That is typically an unintentional effect. If we really want knee braces to be nonstructural, we need to provide gaps at the bearing surfaces in housings and use small-diameter flexible pegs. Ignoring the possible inadvertent loading of a nonstructural knee brace on a post may not be of any consequence at short stubby posts and beams, but could produce some undesired effects in tall, more flexible frames. Remember that exterior posts in a building may already have a significant bending load on them from wind suction.

Strategies for Handling Roof Loads. Roof loads consist of the weight of the roof framing and roofing materials plus any superimposed live loads in the form of snow, ice, or maintenance personnel and equipment. Snow loads are highly variable in many regions of the country. In Michigan and upstate New York, for example, lake-effect conditions cause increased snow-load requirements for sites close to the Great Lakes. In mountainous areas, snow load requirements vary with elevation and exposure. For design purposes, it's mandatory that you contact the building official where a new project is to be constructed to obtain the local snow-load ordinance.

It's not that roof loads are different from floor loads; both are gravity loads pulling down on the frame. It's just that we usually choose to frame roofs with some significant slope. If (heaven forbid) all roofs were flat, then our strategies for supporting roof loads would be identical to those for floor loads, but sloping roofs do a much better job of shedding rainwater. If the roof is steep enough and slippery enough, it can shed snow loads as well. Pairs of opposed rafters, however, can produce a significant additional effect: they may generate outward thrust on the walls.

Shed Rafters (Fig. 8). Just because a rafter slopes does not automatically imply that it will generate thrust. A sloping rafter supported at both ends by walls or beams, as in a shed roof, generates no thrust at all. It acts the same as a perfectly flat floor joist. Why is that? Well, both ends are simply supported to prevent the rafter from moving downward, and there are no lateral loads on this rafter, just the weight of snow and gravity drawing it straight down. So, the reaction at each end of the rafter is straight up. It's when we put rafter pairs together opposing one another that interesting things can happen.

Ridge-supported Rafters (Fig. 9). It's possible to have rafter pairs that behave like shed rafters. That's what we get when we incorporate a structural ridge beam into the framing. The ridge beam (posted or otherwise supported) prevents the upper ends of rafters from moving downward under the weight of roof loads. The lower ends of the rafters are similarly supported on either beams or walls and so cannot move downward. The net effect includes no outward thrust. Structural ridge beams do pose some challenges for us. They carry half the rafter span loads on either side and so can support significant areas of roof. They span between distant supports such as trusses, interior king posts or gable end walls, and can very quickly become large heavy timbers or even trusses if the distance between supports becomes large. Structural ridges must be designed just like floor beams to resist bending and shear forces.

Purlin-supported Rafters (Fig. 10). Instead of making the ridge beam do all the work, we can split it up into a pair of supports located at some fraction of the length along the rafter span. We

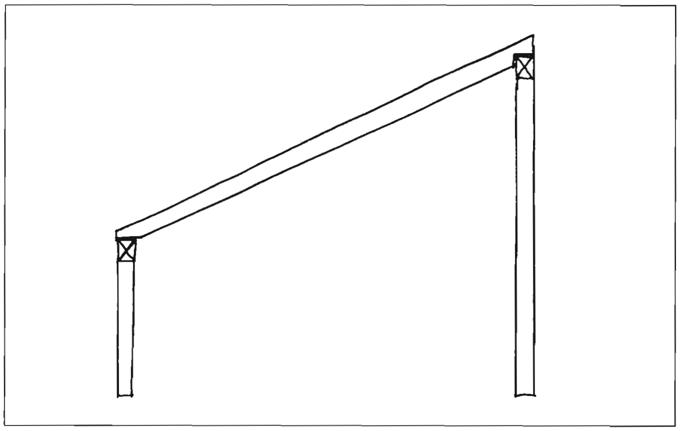


Fig. 8. Shed rafters, supported at each end, produce no thrust.

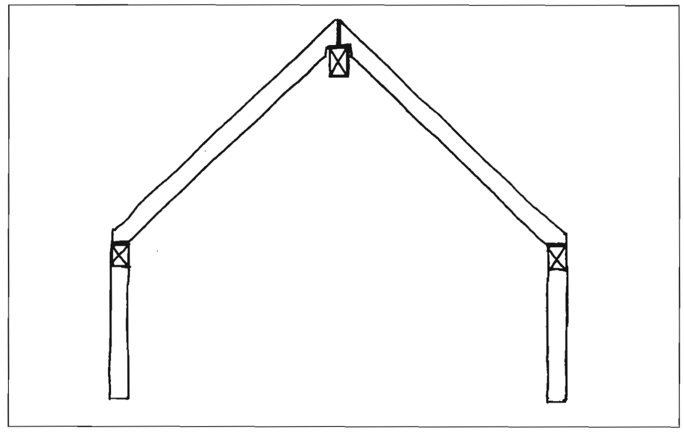


Fig. 9. Ridge-supported rafters act like individual shed rafters.

now have two beams (again, themselves supported) helping to carry the load of the roof instead of just one ridge beam, and so we may be able to span farther or use lighter beams. There is no hard rule where the purlin beams should be located along the rafter span. In practice, because of functional requirements inside the building, we find that purlins lie most often in the range of one-half to two-thirds of the distance from plate to ridge. Provided the purlins are more than halfway up the length of the rafters and the rafters are uninterrupted from plate to ridge, the purlins do a fairly good job of supporting the upper ends of the rafters and reducing thrust from the rafter pairs. In other words, the rafters in a purlin-supported roof can still behave almost like ridge-supported rafter pairs. The farther the purlins are located from the ridge and the lighter and more flexible the rafters, however, the more thrust will be generated by the upper span of the rafters under load.

Let's move on to look at what happens when we remove the ridge beam and the purlin beams completely from an opposing rafter pair. There is nothing to support the upper end of the rafters and, as the ridge line moves downward under load, the geometry of the sloping rafters causes their lower ends to move outward, thereby generating horizontal thrust. If we do not want our ridge to come down, and that is usually the goal, we need to restrain the outer ends of the rafters from moving apart. That can be most directly done by some structural element that "pushes back" to prevent the spreading of the rafter feet. The resisting element could take the form of massive masonry walls, simply too heavy or too well buttressed to be tipped over by the thrust imparted by the rafters. The external restraint does not have to be masonry. It can be provided by the intersecting walls of other portions of the building framed perpendicular to the direction of thrust.

Base-tied rafters (Fig. 11). Rather than external restraint, we often use some form of internal restraint. The most efficient approach is to tie the rafter feet together with an internal tension member. The tie can be timber, it can be a steel rod or it can be dimension lumber. Placing the tension tie right at the foot of the rafters, at the level of the plates at the top of the supporting walls, puts the restraint right at the point of application of the thrust and creates a basic truss. The rafters now act somewhat like an arch: they carry axial load from the ridge down to the plate, but they also have to resist bending between the ridge and plate caused by roof dead load and snow load. Collar struts can help brace the rafters and reduce sagging; we'll get to that in the discussion of trusses that follows shortly.

Base-tied rafters are more complicated than shed rafters or ridge-supported rafters, which sustain no axial loads. Properly designed rafters tied at the plate take into account this combination of axial loads and bending loads. On steep pitches, say 12:12 or greater, the effect is negligible. As the slope gets low, it can be significant and the rafters may need to be heavier than simple span rafters otherwise would be for the same span and roof loads. For a 6:12 slope, the axial load in the rafter is a little over twice the gravity load reaction at the support, whereas for a 4:12 slope it is over three times the reaction and at a 3:12 slope more than four times the reaction. Put in a summary way, at 12:12 the horizontal reaction is half the gravity load, at 6:12 out-thrust equals vertical load and, at lower pitches, the thrust exceeds the gravity load.

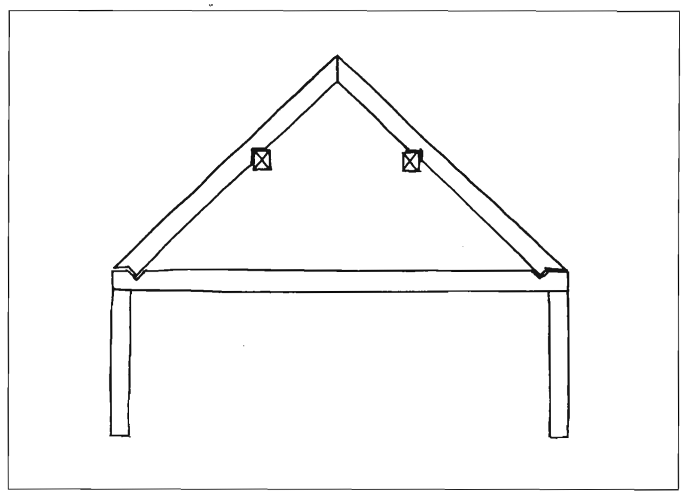


Fig. 10. Purlin-supported rafters produce little thrust at plate.

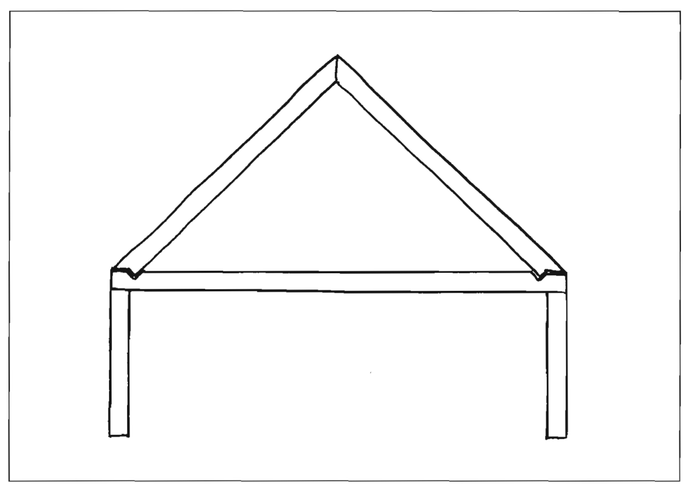


Fig. 11. Base-tied rafters directly solve thrust but sustain axial loads.

Raised Ties (Fig. 12). It's not uncommon for a designer to want to move that tension tie at the plate up "just a little bit" to gain increased headroom without having to increase the height of the building. Such a move can also allow an interesting vaulted ceiling effect. As we raise the tension tie up along the rafter span, however, some additional challenges begin to develop. This discussion is pertinent not only to simple rafter pairs such as are found in common-rafter roof assemblies, but also to principal rafter pairs or trusses when the bottom chord (tension tie) does not intersect the top chord (rafters) at the supporting beam or wall. The rafter pair still is subjected to bending loads applied between the ridge and outer support under the action of roof loads, but in this case the raised tie adds to the bending loads by pulling inward at its connection to the rafter.

Raised ties are an unsatisfactory way to resist the thrust of rafters because they put such large bending loads into the rafters and also generate large forces to be resisted at the joinery between the tie and the rafters. Furthermore, joinery from tie to rafter weakens the rafter right at its most highly stressed location. The higher the tie is above the plate, the tougher these design challenges become and the heavier the rafters need to be to avoid excessive sag in the roof and outward bulging of the walls.

Dropped Ties (Fig. 13). Instead of raising the tension tie above the level of the plate, 19th-century American framers dropped it below the plate, for example in the high-posted (story-and-a-half) capes of New England and many barns throughout the country. The dropped tie greatly simplified the joinery required by the English tying joint, which it largely displaced, by bringing the tie beam in below the point where post, plate and principal rafter would meet.

There is a trade-off in this system, though. Similar to the raised tie, the dropped tie removes the restraining element from the point of application of the thrust, the feet of the rafters. The result is that we induce bending in the posts rather than in the rafters as was the case with the raised tie. As the distance from plate to tie beam level increases, so do the tension in the tie beam and the bending loads in the posts. Here again, joinery from tie to post weakens the post at a highly stressed location. In barn framing in the Midwest, a common rule was never to drop the tie more than 2 ft. from the top of the plate. Even this guideline was not enough to prevent many tension joinery failures at the joint between tie beam and post. The problem of tension loads at a dropped tie beam-to-post joint is further exacerbated by the presence of knee braces and wind loads.

So, placing the tension tie at the level of the plate is the most efficient way of resisting rafter thrust. That does not mean the other options are not available to use, just that we need to design for the extra bending and joinery forces involved.

Trusses (Figs. 14–18). Similar to the challenges we face with increasing spans in our floor framing, we face limits on what we can do with the simple triangular truss represented by the rafter pair with the tension tie at the plate. As the span between supporting walls or beams gets large, the bending loads and thus the sag in the rafters and in the tension tie increases—particularly when the tie supports a ceiling or attic storage space. This forces us to go to ever larger timber sizes until that simply is no longer a practical or economical solution. But just as we solved this problem in our floor framing by introducing intermediate supports along the length of the span, we can do it in our roof framing as well, not by putting more posts in the buildings to support the roof framing (although that works too), but rather by installing internal supports within the roof framing assembly.

If we place a kingpost in the simple triangular truss (Fig. 14) we can greatly reduce the sag in the tension tie. The kingpost acts as a hanger and essentially pulls the gravity loads up from the tie beam

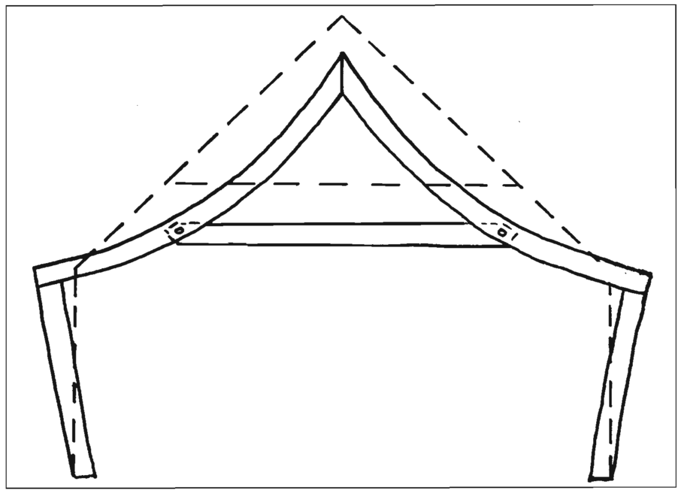


Fig. 12. Raised tie introduces additional bending loads in the rafters and increases tension in the tie.

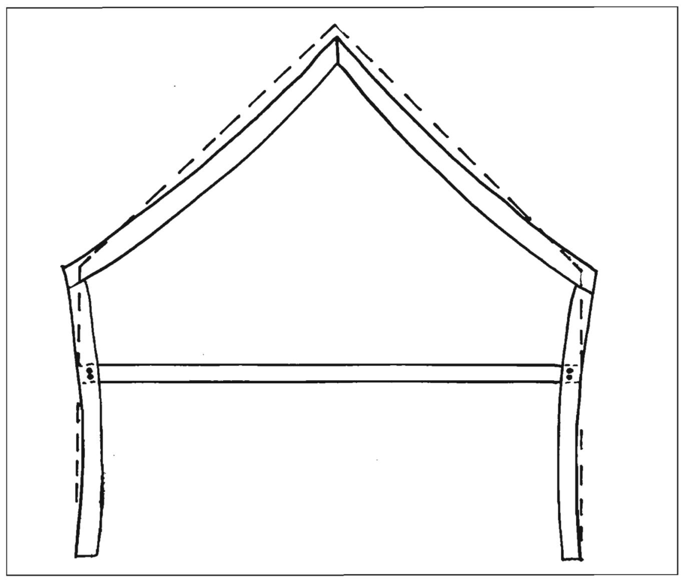


Fig. 13. Dropped tie introduces bending in the posts and increases tension in the tie.

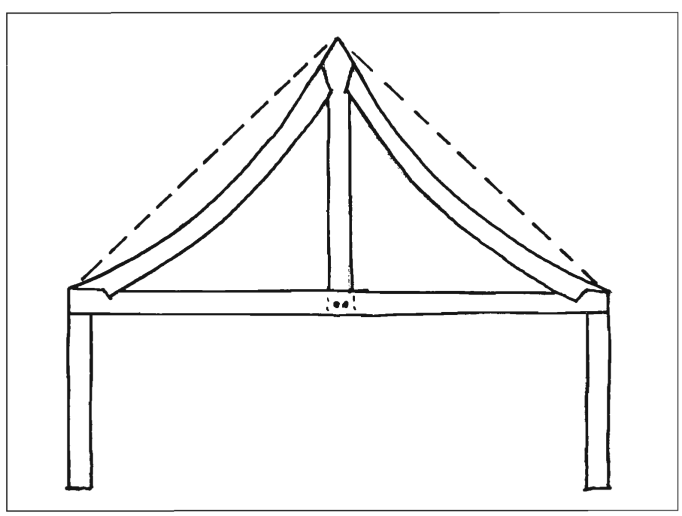


Fig. 14. Kingpost reduces sag (and thus tension) in tie beam of a base-tied truss. Rafter sag can be solved by struts from kingpost to rafters.

into the rafters, thereby increasing the thrust on the rafters and increasing the tension load at the joint between tension tie beam and rafters. That helps the tie beam, but what about the rafters? We can insert an intermediate support there as well in the form of a horizontal collar strut that prevents the rafters from sagging inward at midspan (Fig. 15).

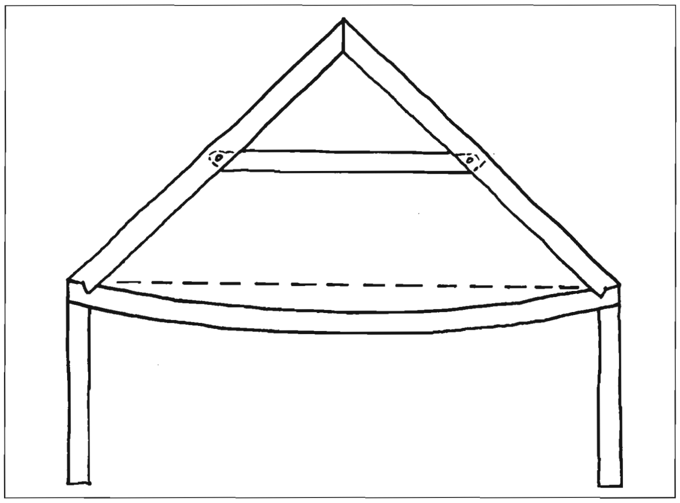


Fig. 15. Introduction of a compression collar between the rafters stiffens them against sag.

This solution also increases tension in the joinery between tie beam and rafter but greatly stiffens the rafters and allows us to reduce their heft. If we put these two ideas together, we have an early form of roof truss found in European churches of the fourth and fifth centuries (Fig. 16). A modern configuration is seen in Fig. 17.

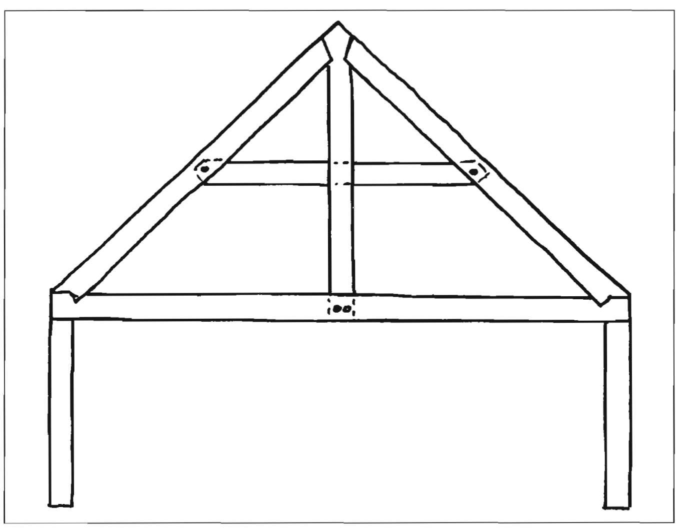


Fig. 16. Together the kingpost and the collar struts form a 4th-century Roman truss.

Hammer Beams. No discussion of roof framing in timber buildings would be complete without at least a brief look at hammer-beam roofs. People often mistakenly look at hammer-beam roof framing as a means of pulling yourself up by your bootstraps—that is, somehow achieving large clear spans without a tension tie and yet avoiding the problem of thrust from the rafters. It just ain't so. Rather, think of the entire hammer-beam assembly as forming simply a large rafter pair with no support at the ridge (Fig. 18).

Fig. 17. Typical modern kingpost truss with diagonal web members to support rafters. White oak 6x12 rafters and tie beams span 30 ft.

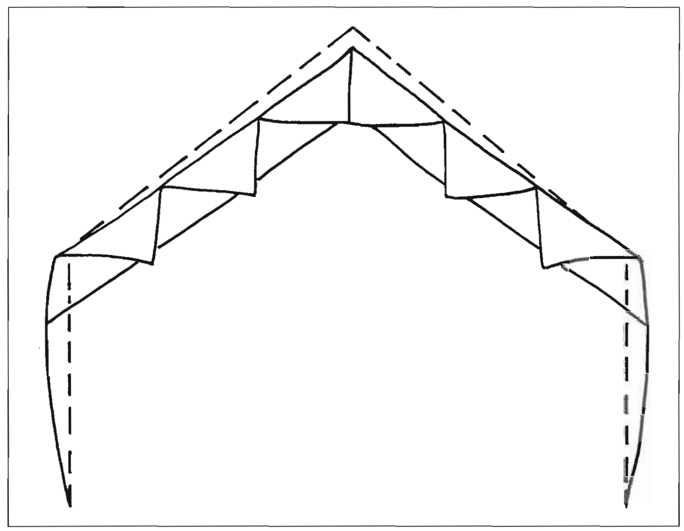


Fig. 18. Hammer-beam trussses can be understood as pairs of trussed rafters thrusting outward against their restraints.

The actual behavior is somewhat more complicated than that, and these structures are properly called hammer-beam trusses. (See TF 48.) Still, roof thrust comes down through the lowest diagonal framing member to the supporting wall or timber post, and that thrust is going to have to be resisted or the ridge will come down and the supporting walls or posts will move outward. If we do not have massive masonry walls with external buttresses or walls from other parts of the building functioning as external restraints, then we will need internal tension ties or hefty posts and some serious tension and compression joinery at the intersection of the post with the lowest diagonal brace and with the rafter. We also will likely need restraint against outward movement at the base of the posts. There is no cookbook formula for these forces and the associated joinery. These depend on the spans, the pitch and spacing of the trusses and the height of the walls, and they must be specifically engineered if satisfactory performance is to be assured.

—Tom Nehil and Amy Warren

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