

HISTORIC AMERICAN ROOF TRUSSES

II. Queenpost Trusses

THIS article is second in a series to discuss and illustrate the form, function and joinery of American timber-framed roof trusses of the past, showing typical examples with variations. The series was developed from original research under a grant from the National Park Service and the National Center for Preservation Technology and Training. Its contents are solely the responsibility of the authors and do not represent the official position of the NPS or the NCPTT. Further articles to appear in TIMBER FRAMING will treat Kingpost Trusses and Composite Trusses.

... exhibits the design for a roof whose tie beam is intended to have 40 ft. bearing, but it may be extended to 45 ft. without increasing the size of the timbers. This example is provided with two queenposts instead of one kingpost. (Asher Benjamin, *Elements of Architecture*, 1843)

... a roof supported by two queenposts, instead of a kingpost, to give room for a passage or any other conveniency in the roof. (Peter Nicholson, *The Carpenter's New Guide*, 1837)

A QUEENPOST TRUSS typically comprises two posts spread apart by a straining beam joined near their heads and supporting a tie beam (bottom chord) at their feet, and substantially braced by members rising from the outer ends of the tie beam to the heads of the queen posts (Fig. 1, facing page). These main braces and the straining beam form the top chord of the truss. In service, the queenposts are in axial tension, although they are also compressed transversely between rafter and straining beam at their heads. The straining beam and main braces are in compression. The tie beam is in tension but, because of its length and any loads imposed upon it, it is also subject to bending. It's common for the queenposts to have top tenons carrying principal purlins or principal rafters in the plane of the roof, but these members are part of the load on the truss rather than essential to its operation.

A queenpost truss is to be distinguished from any of a great variety of double-posted roof frames called queen-posted, queen-strutted or post-and-purlin roofs. In a truss, the queenposts hold up the tie beam rather than bearing upon it. Among its other advantages, the queenpost truss can span the same or greater distance than a kingpost truss while using shorter members (or, in the case of the tie beam, smaller sections) since it is supported at two intermediate points. An early example, the 1755 Market Street Meetinghouse in Philadelphia, was roofed with straightforward and well-detailed queenpost trusses of 57-ft. span (Nelson 1996, 16).

Builders' guides of the 17th, 18th and 19th centuries commonly illustrated these truss types, recommending kingpost trusses for shorter spans and queenposts for longer ones. For example, Thomas Treadgold in *Elementary Principles of Carpentry* (1828) conservatively recommends the kingpost truss for spans between 20 and 30 ft. and the queenpost for spans of 30 to 45 ft.

(Treadgold, 88). Edward Shaw in his sixth edition of *Civil Architecture* (1852) stretches the simple queenpost truss to 60 ft., but using queen rods instead of posts (Shaw, 118). Actual practice was complicated by kingpost variants using struts, double or even triple rafters and secondary posts (called queens or princes) for very long spans, as much as 75 ft. in the clear at First Congregational Church in New Haven, Ct., built 1811-14. Ithiel Town designed this church, and the truss, while long, is not novel in form. As usual, it's unclear whether the truss was designed by the architect, the framer or both.

Queenpost trusses were also commonly built with smaller kingpost or kingrod trusses encased within them or above them (providing a peak to the roof), or with large kingpost trusses superimposed upon them or framed among them. The small, subsidiary posts in these trusses have also been called princesses in both English and American practice (Brunskill, 72). St. Helena's Episcopal Church (1842 roof system) in Beaufort, S.C., is a good example of a conventional queenpost truss extended to 61 ft. wide through the use of strutted princess posts. St. Michael's Church (1761) in Charleston, S.C., is an example of a queenpost truss, spanning 54 ft., where principal rafters suspend a kingpost that in turn supports the middle of the queenpost truss straining beam.

Queenpost trusses with smaller, encased kingposts appear in what is probably the earliest illustration of the form, the bridge at Cismone shown in Palladio's *Four Books of Architecture* (1570). This same truss, sometimes with rods instead of posts (even Palladio's version has metal tension connections at the bottoms of all the posts), survives today in many historic wooden bridges and church attics throughout New England, with at least one 1881 bridge example in Elmira, Ont. This category of queen-dominated composite trusses presents clear load paths to the eye and to the experienced framer's intuition and uses no more material than is necessary to do the work (Fig. 2).

The same cannot be said for the trusses where neither king or queen dominates, and the appearance given is of a redundant and sometimes confusing superimposition of forms, statically indeterminate and functioning in parallel or even interfering with each other. Examples are found in the First Moravian Church, Bethlehem, Pa., 1803 (Fig. 3), the large First Congregational Church, Hartford, Ct., 1806 (Kelly, I-203), and Piper's Opera House, Virginia City, Nevada, 1883 (Fig. 4). However, such trusses are recommended for long spans by builders' guides as early as *The British Carpenter* (1733) by Francis Price, whose understanding of truss action is primitive, and forward to William Bell's highly sophisticated (despite its title) *The Art and Science of Carpentry Made Easy* (1857).

Fortunately, the student of historic truss form does not have to depend upon quantitative or graphical analysis or fully understand the operation of a truss to decide whether it is functioning successfully. A long-standing truss can be analyzed qualitatively by directly examining its joints and members for signs of distortion, displacement or failure, and declared good or otherwise.

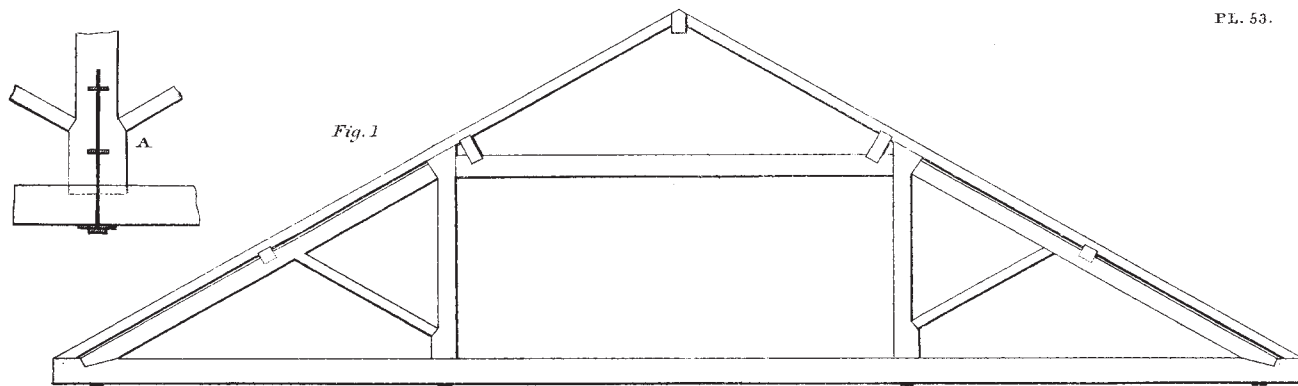


FIG. 1. QUEENPOST TRUSS BY 19TH-CENTURY AMERICAN ARCHITECT ASHER BENJAMIN. INSET SHOWS HIDDEN TENSION BOLT AT POST JOINTS.

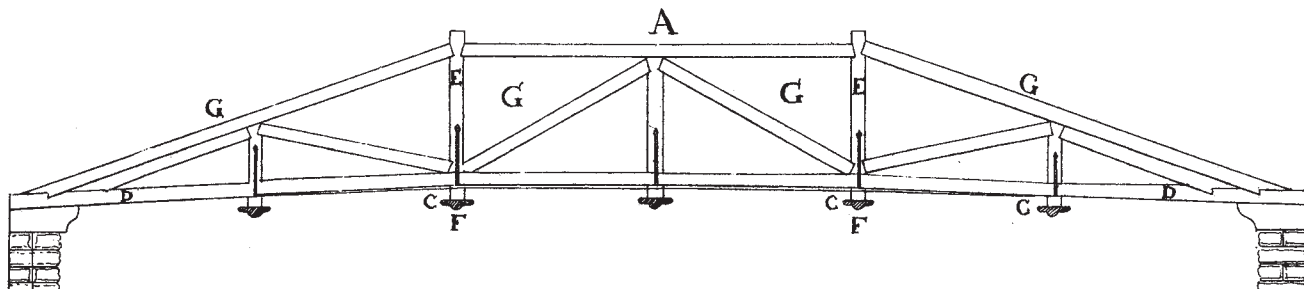


FIG. 2. QUEENPOST TRUSS OF THE BRIDGE AT CISMONE, SHOWN IN PALLADIO'S *FOUR BOOKS OF ARCHITECTURE* (1570).

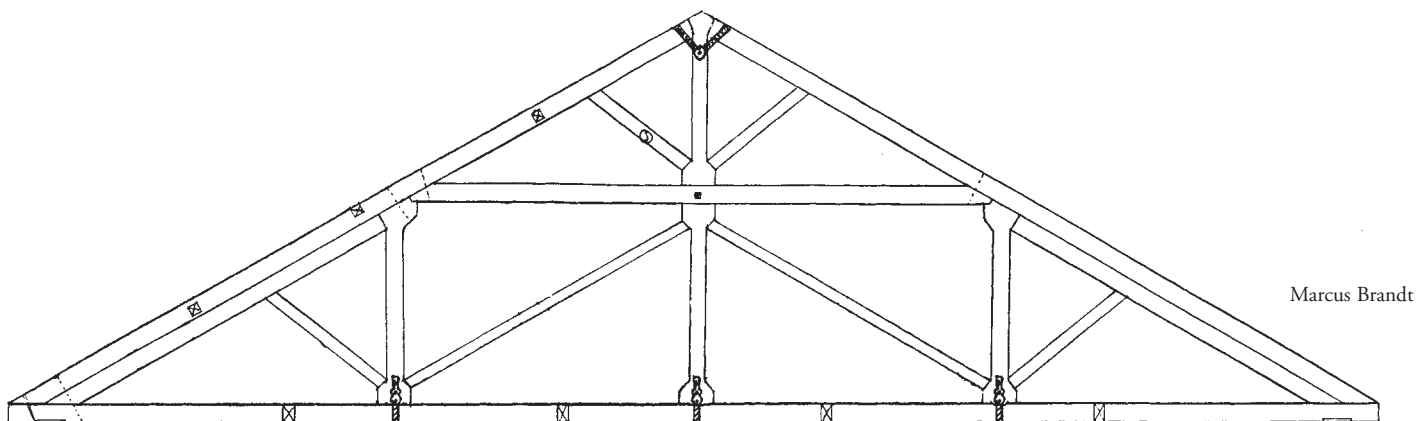


FIG. 3. PRINCIPAL TRUSS, CENTRAL MORAVIAN CHURCH, BETHLEHEM, PA., 1803, SPAN 60 FT.

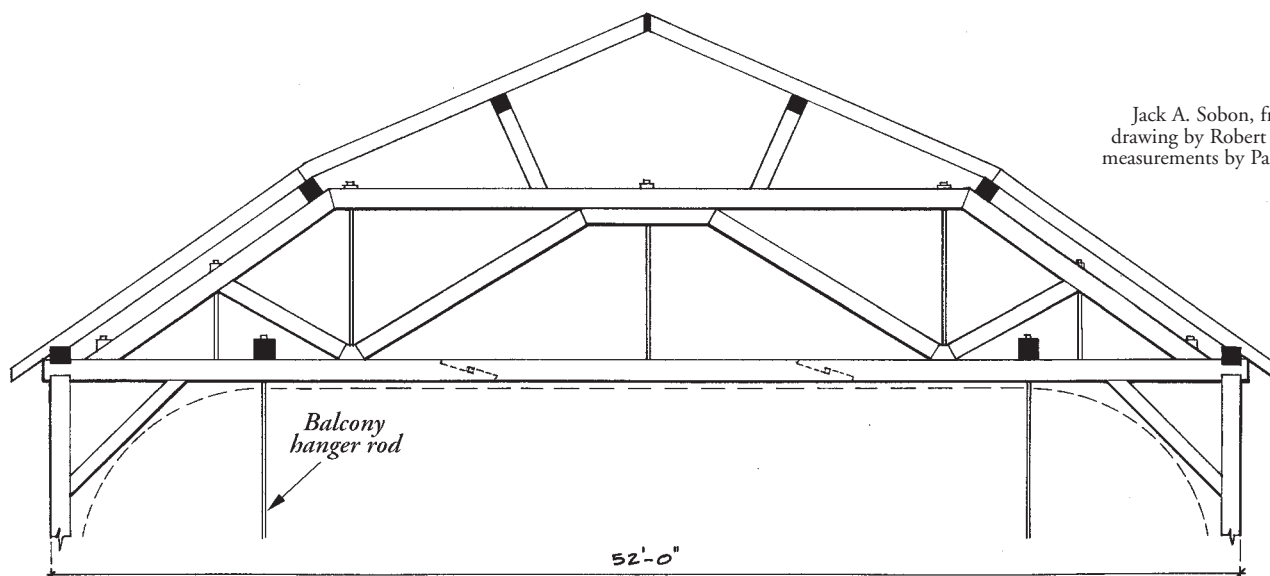


FIG. 4. COMPLEX ADAPTATION OF QUEENROD TRUSS, PIPER'S OPERA HOUSE, VIRGINIA CITY, NEVADA, 1883. NOTE SCARF JOINTS.

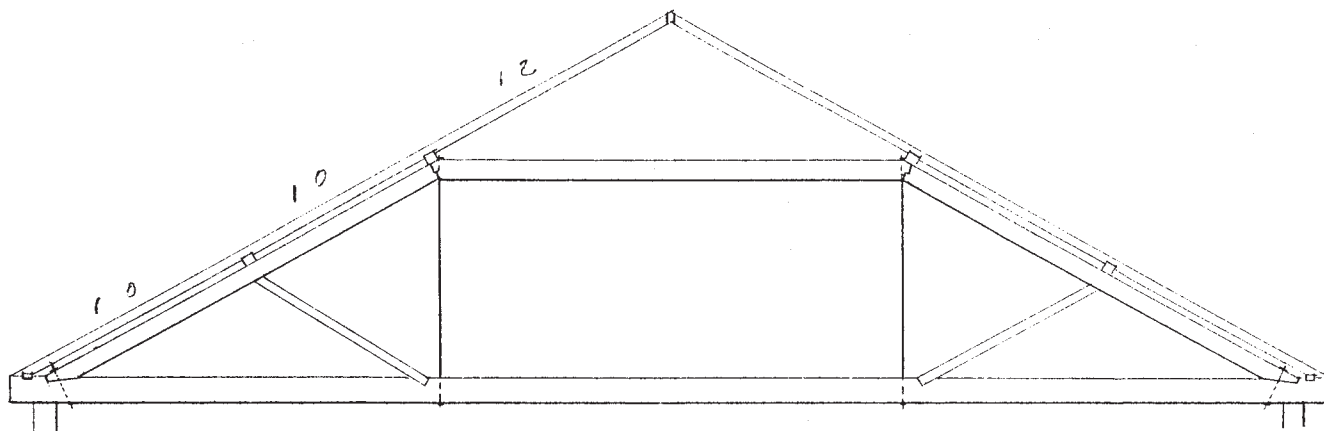


FIG. 5. QUEENROD TRUSS, 54 FT. SPAN, AT THE FIRST CHURCH OF BRIMFIELD, MASS., 1847,
DRAWN BY THE CHURCH'S DESIGNER, CAPT. EDWARD LAMB, ARCHITECT.

Quantitative analysis of the properties of wood and of timber structure is not new. It began in the 1790s in Europe and continued with the work of engineers such as Peter Barlow at the British naval yards in the early 19th century and the American bridge engineers Herman Haupt and Squire Whipple at mid-century. Quantitative analysis remains controversial today. As recently as 1900, the third edition of a widely used text, W.C. Foster's *A Treatise on Wooden Trestle Bridges*, argued at the outset, "A few engineers have advocated the use of mathematics in the designing of trestles, but as wood is an article whose strength and properties vary widely with each piece, no dependence whatsoever can be placed upon the results, and such practice is to be condemned. It is far wiser to merely follow one's judgement and the results of the experience of others as to the proper proportioning of the various parts."

We should avoid the tendency to see inevitable historic progress from the darkness of confused forms to the light of simplified, "cleaner" design over time. The bridge over the Sarine at Fribourg, Switzerland, built in 1653 and still standing, was a very uncomplicated two-span queenpost truss. The next 150 years in the same country saw the construction of fabulously complex, statically indeterminate and increasingly longer-span wooden bridges, often incorporating queenpost elements, culminating in the internationally celebrated Schaffhausen Bridge of 1756-8 (Soane, 130).

Queenpost trusses are repeatedly recommended by builders' guides such as Benjamin's *Elements of Architecture* (Benjamin, 51) for attic spaces, where lodging rooms are conveniently accommodated by the open quadrangular section formed by the truss. Queenpost trusses are widely used also at the rear wall of steeples, where the tower posts can become the queenposts. This arrangement is doubly efficient because the two verticals are already available for use and because the back of the steeple imposes a greater load than the kingpost trusses in the rest of the roof are asked to bear. Examples of the queenpost steeple truss, as in the Universalist Church, South Strafford, Vt., 1833, or the United Church, Craftsbury Common, Vt., 1816, are so common as to be considered standard practice for the period in the northeastern US. (The alternative methods of carrying steeple loads in the late 18th and 19th centuries set the tower posts to bear on large-dimension sleeper timbers crossing three trusses, or used a vestibule wall to bring steeple loads to the ground if the interior aesthetics of the church permitted.) In many other 18th- and early 19th-century churches, notably in Connecticut, apparent queenposts in the attic are actually extensions of gallery posts rising from below, producing what J.F. Kelly in *Early Connecticut Meetinghouses* (1948) calls a post-and-purlin system, not a truss in the modern sense.

By 1839, Asher Benjamin is recommending iron queen rods in place of wooden queenposts. Edward Shaw in *Civil Architecture*

(Shaw, 118) credits Benjamin with the first publication of this idea as well as first using it in trusses as early as 1828. There are at least two advantages to replacing wooden posts with iron rods. First, a major source of settlement in any truss is shrinkage across the king- or queenpost head. The post timbers are frequently 12 to 14 in. across to accommodate perpendicular (square-ended) bearings of the main braces at the head. Shrinkage and compression can easily amount to $\frac{5}{8}$ in. across this joint, accumulating well more than an inch for the two joints, which translates into sag in the truss. The change in shape produces an eccentric bearing of the main brace at the head, causing the sharp end-grain corner of the brace to indent even further into the side grain of the post until some equilibrium is reached. This process takes some time and must be anticipated by increasing the initial camber of the truss by some guessed or calculated amount.

Using rods instead of posts allows the main braces and the straining beam to meet directly, with largely axial, end-grain bearing, effectively forming a polygonal-arch top chord. On the other hand, the loss of a substantial timber volume between main brace and straining beam renders it impossible to create normal (90-degree) bearing surfaces; rather, the angle of intersection between the two members is typically mitred. A second reason to use iron rods instead of posts is the difficulty of developing a satisfactory tension joint in wood within the depth of the tie beam, i.e. without the ends of the queenposts penetrating the ceiling normally found just below the truss. The wedged half dovetail tenon, usually pinned as well, became the timber joint of choice between the queenpost and the tie, but its dependence on side-grain bearing, short double-shear distances on the pins and shrinkage make it subject to creep over time, though it rarely fails completely. Iron straps or inset bolts have been in use at these connections since the Middle Ages (Hewitt, 144, 244; Nelson, 1996, 11-23; Palladio), so the step to a completely iron member was not a large one. Queenrod trusses are found in many large structures, ranging from the First Church of Brimfield, Mass. (1847), with its 54-ft. truss span (Fig. 5) to the railroad depot freight shed in Virginia City, Nevada (1875), whose truss spans 32 ft. (Fig. 6). While it is difficult to say if Benjamin's was the first use of vertical rods as the primary tension members of a truss, it is known that rods were being used diagonally as counterbraces or suspension elements at the Schaffhausen Bridge in Switzerland by 1780 (Maggi, Haupt, Nelson 1990) and in Louis Wernwag's "Colossus of 1812" across the Schuylkill in Philadelphia (Nelson 1990).

Railroad Freight Shed, Virginia City, Nevada, 1875. The queenrod trusses in this shed span 30 ft. 8 in. in the clear and belong to a class of trusses that do not bear on a wall plate but rather tenon

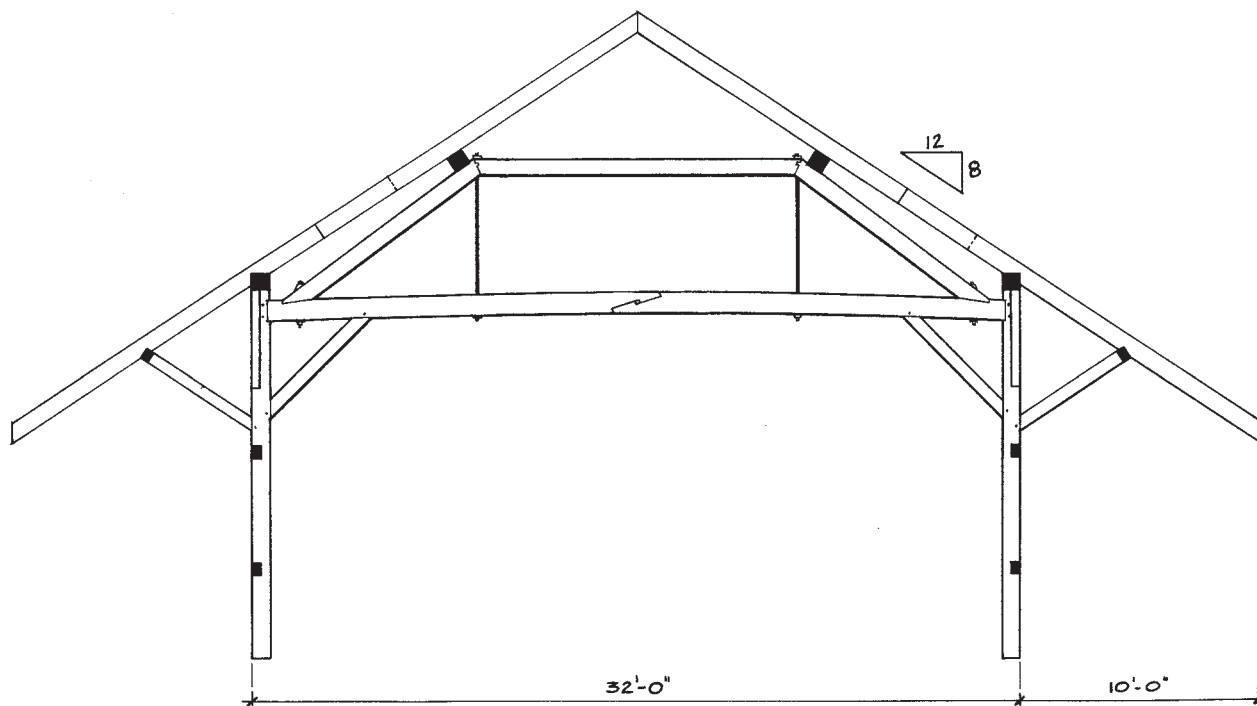


FIG. 6. QUEENROD TRUSS IN A 52X138-FT. RAILROAD FREIGHT SHED, VIRGINIA CITY, NEVADA, 1875. TRUSSES STAND ON 16-FT. CENTERS.

into the side of a wall post (Fig. 6). In this case, the 8x10 scarfed bottom chord bears on a 1-in. shoulder as well. Since neither ceiling nor floor is carried on this bottom chord, the 24-in. stop-played tabled and wedged scarf doesn't suffer significant bending. Knee braces rising from the post also add support against shear and reduce the overall span. The 1-in. iron rods nutted with ogee washers drop from the junction of the main brace and straining beam to support the bottom chord about 9 ft. out from the posts on each end. Trusses stand 16 ft. on center in this 138-ft.-long building. No timber is longer than 18 ft.

The angle between main brace and straining beam is mitred with a small integral tenon to keep the members in line. The main braces dap 3 in. into a bearing shoulder in the bottom chord where they are fastened by a 1-in. bolt. The ultimate bearing of the brace is 6 in. from the face of the post. A projected line of the main brace's slope if carried through the tie beam would end up within the post before exiting the tie beam, suggesting that little bending or shear will occur.

The 2x8 freight shed rafters, lapped and spiked to form a 31-ft. length, are all commons supported on a purlin carried at the queenrod head and at the plate. They continue outboard to form a 10-ft. overhang supported by 4x6 bracing rising from the wall posts in approximate opposition to the interior braces that rise to

the tie beam. The extensive cantilever of the rafters and their continuity reduce the loading of the truss and place more of their weight on the wall posts.

Peacham Congregational Church, Peacham, Vt., 1806 (photo p. 20). The roof of this church rests on six queenpost trusses, 9 ft. on center, tightly joined and densely framed, 46 ft. 8 in. in the clear and 50 ft. 5 in. overall. The lower chords of the trusses are cambered progressively from the ends of the church toward the middle, in the pattern 8-14-17-16-14-8 in. of transverse rise, forming curvature in both directions and thus a shallow dome in the ceiling of the audience room below (Fig. 7).

The 7x10 queenposts taper slightly in all dimensions toward the top, and the 7x8 main braces and straining beams engage the queenposts with normal bearing, tenoned but without pins. Principal rafters 7x10 by 30 ft. sit on tenons at the heads of the queenposts, each affixed by a single 1-in. pin. The principal rafters are pinned in mortises at the extremity of the 11x14 bottom chord, bearing over the wall plate and extending to the eaves. The main braces of the truss are shouldered and tenoned (but again unpinned) into the bottom chord 23 in. from the inside of the plate. The queenposts, centered 15 ft. apart, support the bottom chord by means of the through-wedged half-dovetail joint, wedged

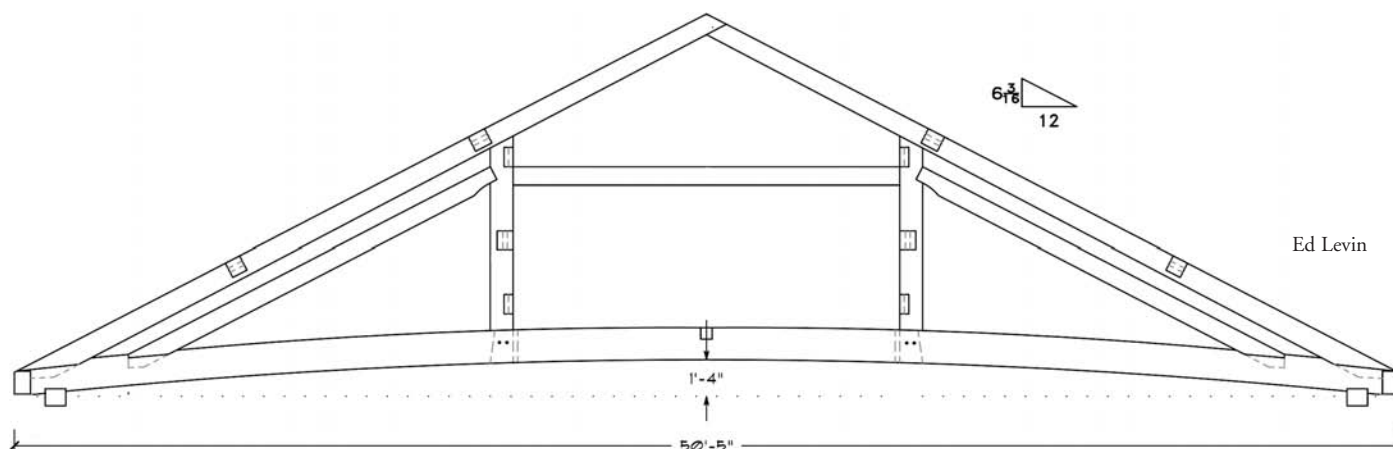


FIG. 7. QUEENPOST TRUSS AT CONGREGATIONAL CHURCH, PEACHAM, VT., 1806. TRUSSES ARE CAMBERED TO PRODUCE DOMED CEILING.

from above and with 1½ in. of taper on the dovetailed tenon. A pair of inline 1-in. pins also transfixes the dovetail 6 in. down from the top of the chord.

The trusses at Peacham are joined longitudinally by 7x8 connecting girts with rising and falling 4x5 hardwood braces at each post. The principal rafters carry 7x8 horizontal purlins mortised in at two positions, dividing the roof plane in three, and 3x4 and 4x4 common rafters soffit tenon into these purlins. There is also extensive 4x6 diagonal bracing in the plane of the ceiling and of the roof, but not arranged in the typical diamond pattern of opposing short 45-degree braces. Instead, the roof braces rise from the plates in long parallel lines crossing several trusses, and then descend again to the plates. The braces lying in the ceiling plane form a giant X seen in plan. All of these braces are not actually passing braces since they comprise mortise-and-tenoned segments between each major framing member, but their collective appearance and effect are those of long continuous braces (see cover photos).

Peacham is framed in hewn spruce and pine for the longer timbers and vertically sawn maple, birch and beech for braces. The frame is fully scribed, with Roman numerals at every joint. The level lines are obvious on the posts, but 2-ft. marks cannot be distinguished at the expected locations. Except for its rich color, the timber appears in like-new condition, densely framed but with no superfluous members. The framer, we know, was one Edward Clark of Peacham.

Rindge Meetinghouse, Rindge, N. H., 1797 (photo p. 20). The large and highly cambered queenpost trusses at Rindge belong to a recognizable subset of trusses (both queenpost and kingpost) that use naturally curved main braces, always working in concert with a straight principal rafter directly above (Fig. 8). These curved main braces occur also, for example, in kingpost trusses at the Old Ship Church (1681) in Hingham, Mass., and the 1714 Lynnfield, Mass., Meetinghouse. The British framing scholar David Yeomans comments that this form does not appear in the English truss work that he is familiar with, and he leaves the question of its origin open (Yeomans 1981). Likely the inspiration comes from late medieval kingpost and crownpost roof framing, where it was common for curved braces to rise along the span of a tie beam and tenon into a kingpost (or the shorter crownpost), aiding the post in supporting the ridge or a collar. Examples are found in the 14th-century Major Barn at Lenham in Kent, the 14th-century Frindsbury Barn, also in Kent, the even earlier Warnavillers Barn in France, and the late 16th-century Bishop's Palace in Fulham, London (Kirk, 1994, 59, 101, 115; Hewitt, 1980, 214). The form of an inner curved brace strutting to an outer and straight rafter is characteristic of cruck framing as well. In all the cases cited, the upward arching of the inner brace serves to stiffen the rafter more

effectively than a straight member with its tendency to bend. In turn, the weight of the roof stiffens the arching brace against buckling out and upward from the load imposed by the kingpost and its dependent areas. These kingpost, crownpost and cruck roofs were usually open to view and thus easily absorbed into the vernacular framer's worldview of good practice.

The roof frame at Rindge is notable for both the size of some of its timbers (Fig. 9) and the tendency of almost all members to curve or taper in some dimension, giving it an especially dramatic pre-modern appearance. The wall posts are 28-ft. oak 10x12s and the tie beams atop them are 55-ft. white pine timbers, tapered from 12x14 to 12x12 and cambered between 14 and 25 in. to produce a shallow dome, as is found later at Peacham. The camber is so great in the ties that the framer had to use a system of 3-ft. marks rather than the usual 2-ft. marks to scribe the queenpost to the tie beam marks.

Rindge is considered a single-braced queenpost truss since the main braces form the primary loadpath, but the principal rafters, while mostly in bearing, are tightly joined to the truss. The queenposts are pine, typically 11x11 at the bottom and tapering to 8x10 at the head, where they tenon into the principal rafters, long pine timbers tapering from 8x12 at the eaves to 8x8 at the peak. The queenpost main braces and straining beam engage the queenposts 15 in. below the rafter and are tenoned and pinned, the straining beam normal to the face of the post and the main brace dapped in at its top end producing a 1½-in. shoulder (Fig. 10). The main braces and the straining beam, all roughly 7x7s, are of mixed oak species and slightly upcurved. A 4x6 hardwood strut rises from a mortise low on the queenpost to support the main brace near its midpoint. Pairs of short 4x6 blocks then strut from the main brace to the principal rafter, though neither of them is directly over the queenpost strut. The stoutest timber in this assemblage is the interrupted flying plate supporting the feet of the common rafters: each segment, 13 ft. long and tenoned into the sides of the tie beam right at the eaves, measures 24x12 in section.

The joint between the queenpost and the tie beam uses a 3-in. through-wedged half-dovetail tenon with a reinforcing ¾x1½-in. U-strap with forelock bolt (Fig. 10). The iron appears original and was likely necessitated by the difficulty of pulling and holding the huge tie beams into the exact curve required by the dome, even if the ties started with some natural sweep and hewn camber. Bending to strike two points correctly (the queenposts) is much more demanding than pulling up a long tie beam to one kingpost at its center.

At the foot of the oak main braces is a 3-in. tenon, end wedged. The wedge facilitates the assembly of these huge curved forms, and driving or changing the size of the wedge allows the framer to fine-tune the camber of the truss and guarantee that the main brace is the major bearing member. The principal rafters are mortised over

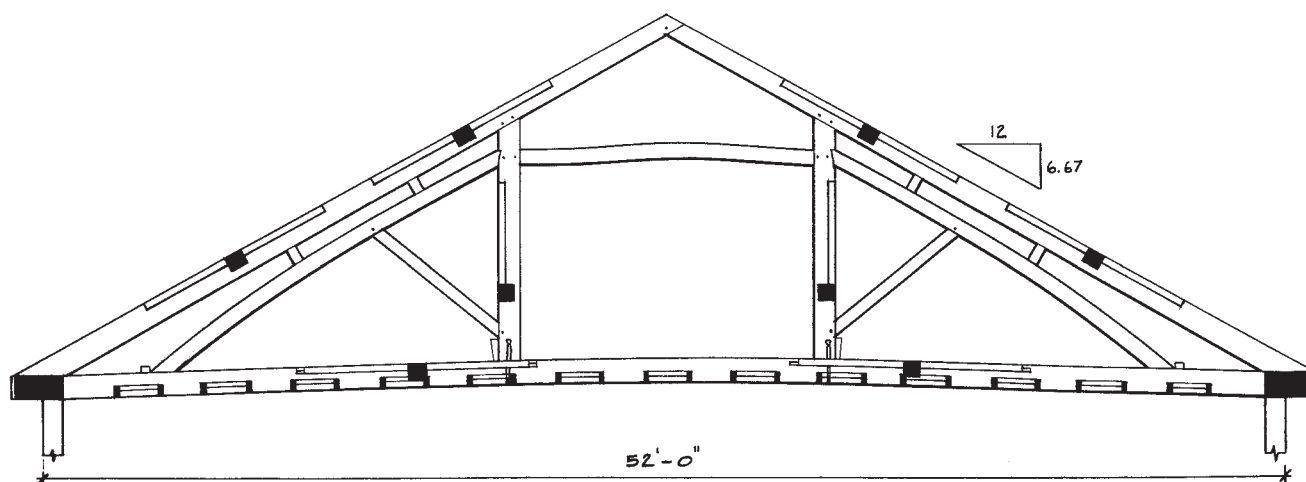


FIG. 8. EARLY-FORM QUEENPOST WITH CURVED OAK MAIN BRACES AND STRAINING BEAM AT MEETINGHOUSE, RINDGE, N.H., 1797.

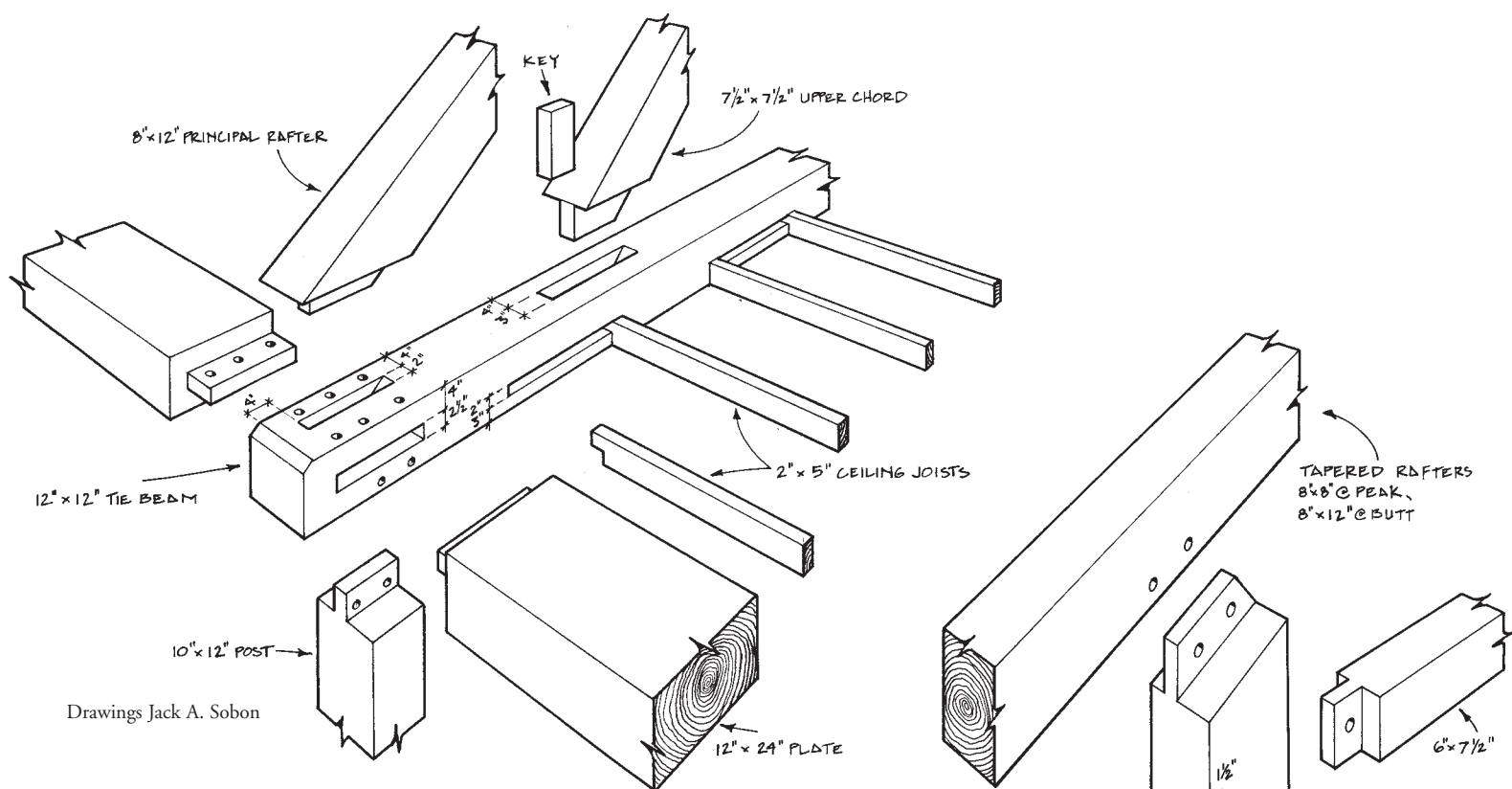


FIG. 9. AT RINDGE, PRINCIPAL RAFTERS AND END-WEDGED MAIN BRACES SEAT IN THE LOWER CHORD OF THE TRUSS.

the queenposts and tenon at their feet into the ends of the tie beam. The queenposts are all connected longitudinally with 7x8 girts, diagonally braced off each post. There are substantial connecting girts with braces joining bottom chords in the plane of the ceiling as well. The bottom chords are fitted with long horizontal chase or pulley mortises on one side, allowing the ceiling joists to be slipped in after erection of the trusses (Fig. 9). This scribe-rule mixed pine and oak frame is all handhewn or vertically sawn. Apart from minor overall sagging of the heavy roof system from shrinkage and two centuries of compression, the queenpost trusses at the Rindge Meetinghouse are performing well.

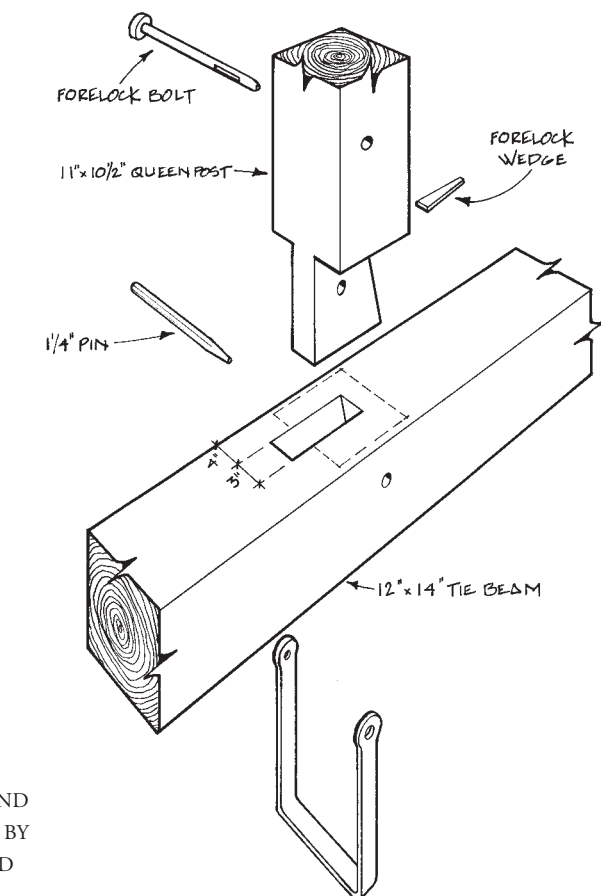
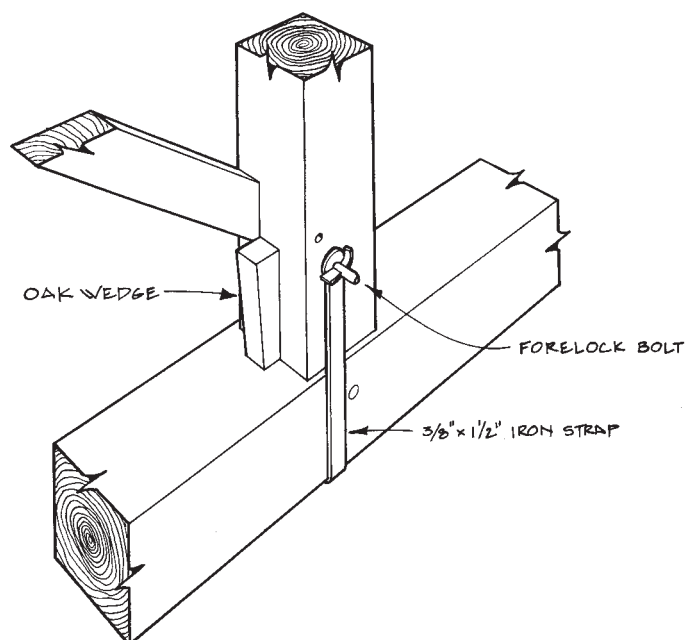


FIG. 10. ABOVE, TO RESTRAIN THE LOADED TENSION JOINTS BETWEEN QUEENPOSTS AND TIE BEAM AT RINDGE, WEDGED AND PINNED HALF-DOVETAIL TENONS ARE REINFORCED BY STOUT IRON STRAPS WITH FORELOCK BOLTS. ABOVE RIGHT AND AT RIGHT, EXPLODED VIEWS OF QUEENPOST TOP AND BOTTOM (TENON WEDGE NOT SHOWN).

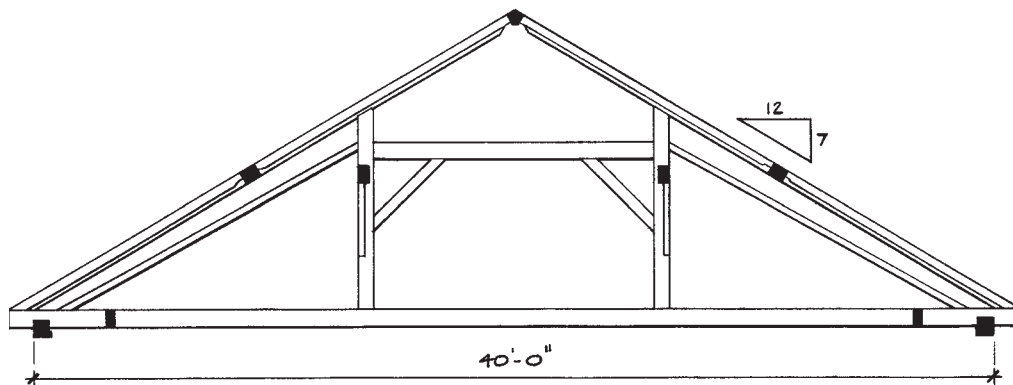


FIG. 11. COMMUNITY CHURCH, WATERBURY CENTER, VT., 1831, WITH NAÏVE KNEE BRACING AND UNDERSIZED MAIN BRACES.



FIG. 12. DETAIL OF TOWER TRUSS, UNITED CHURCH, CRAFTSBURY, VT., 1816.

The Waterbury Center Community Church, Waterbury Center, Vt., 1831. Significantly remodeled in the later 19th century, this 40-ft.-wide brick church (photo p. 20) is spanned by queenpost trusses of good material and joinery, but with disproportionately undersized main braces (Fig. 11). This potentially fatal flaw has already produced local deflections in the trusses and roof of 2 in. to 6 in.

The 9x10 bottom chord is 42 ft. long and laps and bears on an 8x8 plate. The 8x8 queenposts stand 14 ft. apart separated by an 8x9 straining beam, with 4x4 braces rising to it from the queenposts. While bracing of this sort is common in the so-called queenpost purlin systems of houses and barns, it is rare and unnecessary in trusses, where the compressive load of the roof system and the main braces of the truss itself, unsupported across a long span, are constantly forcing the heads of the queenposts inward and down, with little possibility of transverse racking. These unneeded braces may be the first clue that the framer did not understand how different the behavior of a truss was from a frame with intermediate posts. The main braces are the weak point of this truss: often waney, they are variously sized between 3, 4 and 5 in. thick by 7 in. deep. In service, they are all buckling along their 16 ft. length and compressing their inadequate end-grain sections into queenpost and bottom chord—all of this exacerbated by the low 7:12 roof pitch. Queenpost tenons enter the principal rafters above in greatly elongated mortises, removing the possibility of adding stability to the truss.

There is a pattern of patched holes in the original floor of the audience room below that may indicate the former presence of posts supporting a gallery. If gallery posts had continued upward to support the bottom chords of the trusses, even though they would have arrived at the truss several feet outboard of the queenposts, they may have mitigated the great flaws of this design. However, 1831 is late for galleries. Also, there is no evidence along the examinable sides of the bottom chords, in the form of shoulders or pegholes, or traces of old compression, to indicate such posts. Further, the church has no written or oral tradition of a galieried form. The frame is entirely spruce and hemlock, square ruled. Currently the Waterbury Center trusses are supported with cables, stiffening planks and nailed bracing while being monitored for ongoing movement.

The United Church of Craftsbury Common, Vt., 1816. Like many other church roofs framed with kingpost trusses, Craftsbury's also employs one queenpost truss at the rear wall of the steeple, incorporating the tower posts (Fig. 12). These double-duty 10x10 posts, set about 9 ft. apart, are 20 ft. tall, with 22-ft. belfry posts rising from within them in telescoping fashion. An additional 33 ft. of spire and vane sit atop the belfry. Half of this collected load is carried by this queenpost truss. Main braces (8x9)

rise from mortised bearings on the bottom chords almost 2 ft. inboard from the wall posts and tenon into the queenposts, directly opposed by an 8x8 tower girt acting as a straining beam. The 6x6 principal rafters at this truss, rising at a slightly steeper pitch than the main braces, also tenon into the sides of the tower posts and contribute some support (Fig. 12, second rafter from left). There is no straining beam in a direct line with these principal rafters, but 4x5 hardwood braces descend to the straining beam below, where they are opposed by rising braces, and so provide some additional stiffness to the tower post. Unlike Waterbury Center, where the diagonal braces to the straining beam were superfluous, those at Craftsbury expand the effectiveness of the straining beam and, more important, help brace the tall steeple against racking movement.

The truss at Craftsbury Common has hewn spruce major members and vertically sawn and riven maple and yellow birch braces. In spite of its late date of 1816, it is scribe ruled and marked with Roman numerals at every joint. Roof leakage once caused the north end of the queenpost truss to deteriorate badly; it is now assisted by posts rising through the back of the audience room to the bottom of the chord near the posts. Nonetheless, there is no evidence at any of the joints or members of past distress from overloading, such as cracked mortise cheeks or withdrawn joinery.

The Stowe Community Church, Stowe, Vt., 1867. This large, tall and prominent wooden church (photo p. 20) stands on the main street of a busy commercial village. The sophisticated, substantial framing of the stages of the 165-ft. steeple uses paired members, called partners, that eventually clasp a tall spire mast. The steeple work was carried out by a Mr. Edgerton of Charlotte, Vt., a steeple specialist, and appears different in kind from the truss work.

The queenrod trusses supporting the roof and the ceiling of the audience room span 50 ft. (Fig. 13). They are lightly framed, with little mortise-and-tenon joinery, but they stand only 8 ft. apart and are performing well today. Other examples of queenrod framing are common from this period and even earlier, as in the 1847 Brimfield, Mass., Congregational Church (Fig. 5), where queenrod trusses with minor struts rising from the tie beam to the main braces span 54 ft.

The bottom chords of the Stowe trusses do not bear on a plate or post but (like the 1875 Nevada freight shed we saw earlier) instead use shouldered tenons to engage the wall posts about 1 ft. below the plate. The 9:12-pitch main braces sit in a 1½-in.-deep housing on the bottom chord, about 6 in. in from the post (Fig. 14). Instead of a tenon, a ⅝-in. bolt secures the connection. The 8:12 pitch common rafters bear on the top surface of the plate. The 6x7 main braces meet the 6x6 straining beam in a mitred butt joint fitted with a small key to help keep the members aligned (Fig. 15). Iron rods drop through this junction and support the bottom

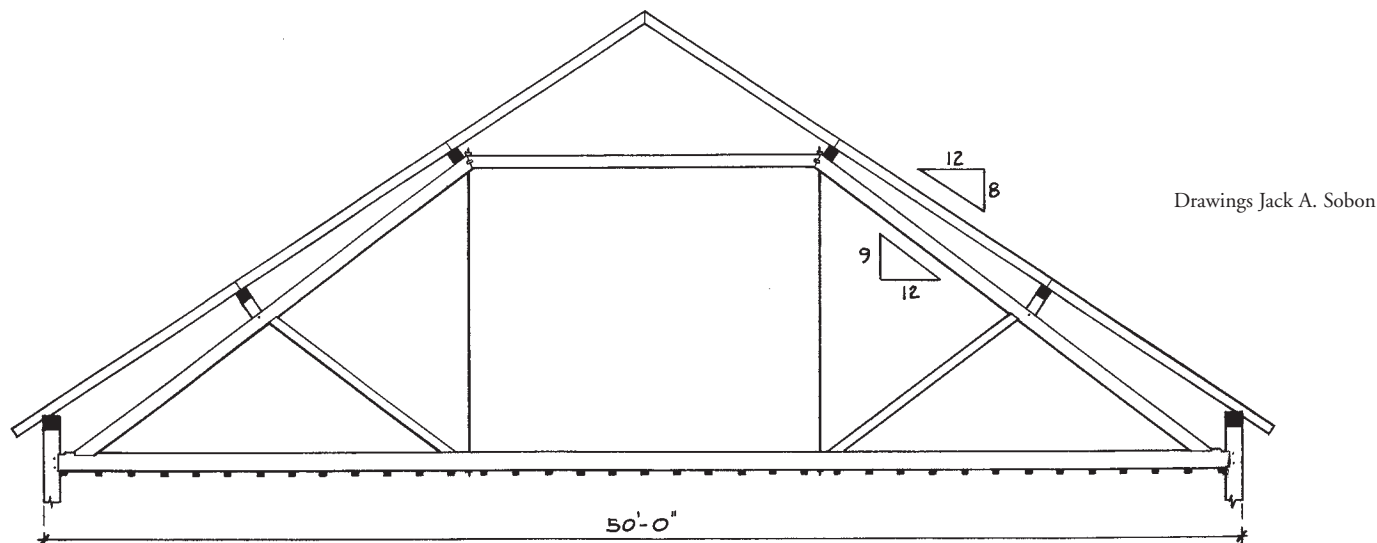


FIG. 13. LIGHT, SOPHISTICATED QUEENROD FRAMING AT THE COMMUNITY CHURCH, STOWE, VT., 1867.

chord at two points. A 4x6 strut rises from the bottom chord next to the rod and supports the midpoint of the main brace. Another short strut, nearly in line with this one, rises from the main brace to support a purlin under the common rafters of the roof plane. Another 6x6 purlin carries out the same function while sitting atop the main brace right next to the junction with the straining beam. In the monumental and architecturally elaborate Stowe Community Church we see the beginning of modern wood framing, where the roof truss is efficient, the joinery minimal, more metal is included and the appearance of the hidden structure inspires little awe.

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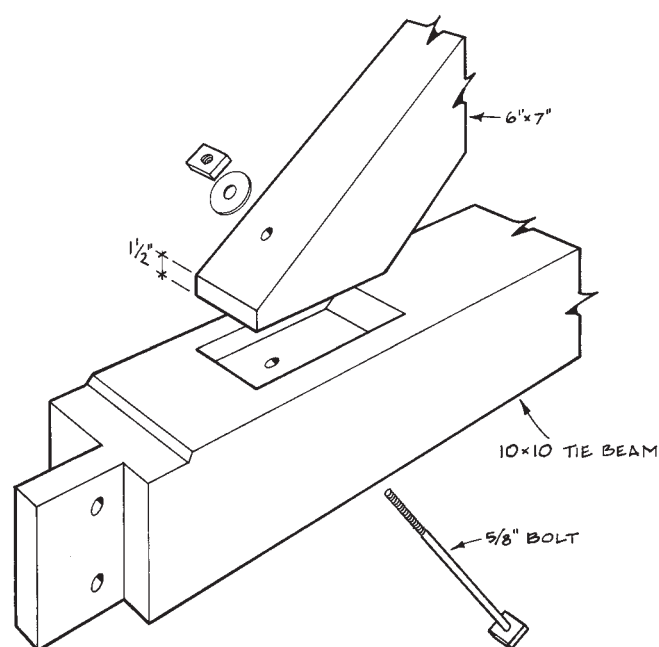


FIG. 14. MAIN BRACE FOOT IS DAPPED AND BOLTED TO THE TIE BEAM.

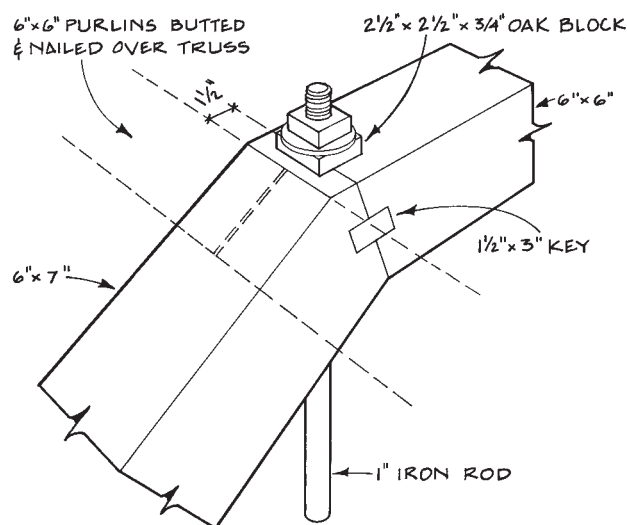


FIG. 15. MAIN BRACE IS BUTTED AND KEYED TO STRAINING BEAM.



Community Church, Waterbury Ctr., Vt., 1856.

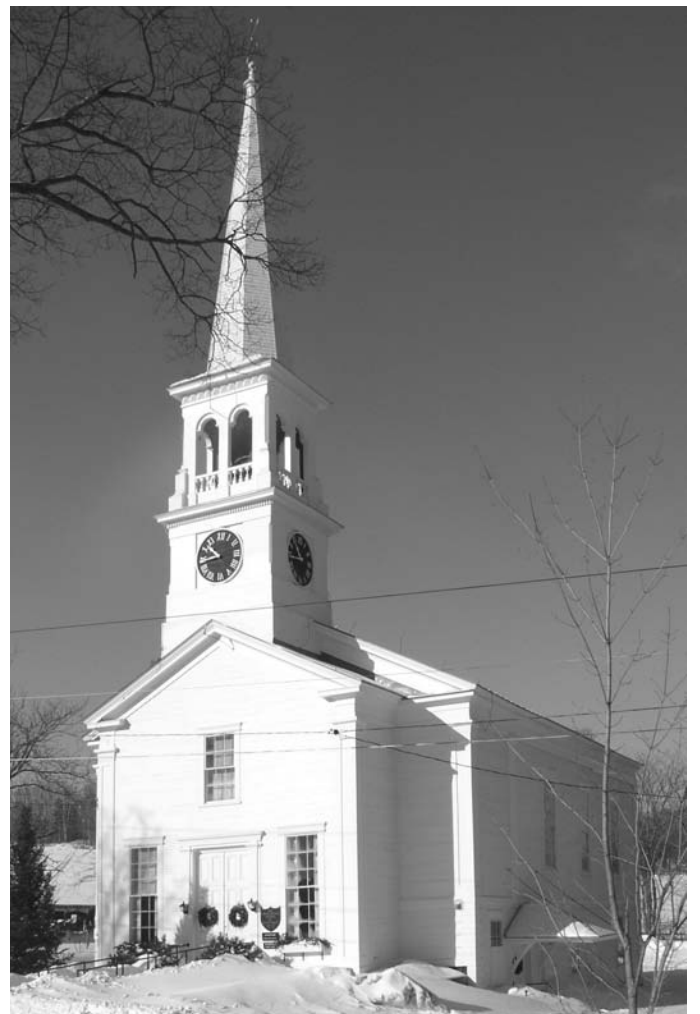


Meetinghouse, Rindge, N.H., 1797.

Photos K. Rower, J. Sobon



Community Church, Stowe, Vt., 1867.



Congregational Church, Peacham, Vt., 1806.

Historic Queenpost Truss Analysis

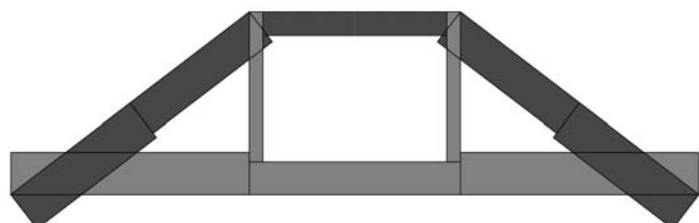
AN ATTIC census of early American public buildings would show that the vast majority of roofs are kingpost trusses and variants thereon, though early American builders were certainly familiar with queenpost trusses via the popular builders' guides of the day—indeed, queenposts were the recommended solution for long span roofs.

Over the course of the 19th century, queenpost trusses evolved considerably: the trusses of the 1797 Rindge Meetinghouse evoke English predecessors with their highly cambered tie beams and naturally curved oak main braces and straining beams, while the 1867 Stowe Community Church queenrod roof trusses use relatively little wood and make essential, efficient use of iron.

TRUSS VITAL STATISTICS						
Name	Date	Span	Truss Spacing	Pitch	Timbers	Iron Rods
Rindge Meetinghouse	1797	52'	13'-0"	6.67:12	14	0
Peacham Congregational Church	1806	48'-2"	9'-0"	6.2:12	8	0
Waterbury Center Community Church	1833	40'	10'-3"	7:12	10	0
Stowe Community Church	1867	50'	8'-0"	8:12	8	2

One post good, two posts better? To quantify the supposed advantage of queen over king, I constructed comparative Finite Element Analysis (FEA) models of kingpost and queenpost trusses, using configurations typical of the church roofs in our study: 50-ft. span, 7:12 pitch, trusses 10 ft. on center. In modeling trusses here, our governing load case was a balanced load combination based on 65 psf ground snow load plus the dead load of frame, ceiling and roof, mitigated and magnified by factors based on load duration, attic temperature, audience room capacity, wind exposure and probability of concurrent combined loading.

It was not surprising to find that axial tension in the lower chords (tie beams) and compression in the upper chords (principal rafters or main braces) was unaffected by the switch from king to queen. But maximum vertical deflection was reduced by 20 percent, and tie beam (lower chord) bending stress dropped by 40 to 50 percent. Compression force in the main braces decreased by 20 percent, probably a result of these sticks being more closely aligned with the direction of the forces they carry. Finally, tension in the posts fell by a third from 18,500 lbs. in the kingpost to 12,500 lbs. in each of the queenposts. This last decrease may be the most significant, since separation of post foot from tie beam is probably the most common joinery failure in traditional timber truss work.



Ed Levin

The essential core of the queenpost truss is a trapezoid founded on a long tie beam or bottom chord. In the force diagram above, darker shading indicates compression and lighter shading tension. Sloping inward and upward from the tie beam spring two main braces that rise to meet paired queenposts held apart by a horizontal straining beam. (In the case of queenrod trusses, the main braces meet the straining beam directly.) Load is applied by the

roof above and the floor or hung ceiling below, putting the composite upper chord (main braces and straining beam) into compression while the tie beam and queenposts are placed in tension. Earlier queenpost roof trusses, such as those at Peacham, Rindge and Waterbury (Figs. 7, 8, 11, pp. 15, 16, 18, respectively), complicate this structure by doubling the main braces with principal rafters above and, in the case of Rindge, by adding struts linking the more or less parallel inner and outer elements. The rafter-doubling strengthens the truss but also makes it more difficult to sort out the load path and quantify forces and stresses.

Taking Rindge as our example, the distribution of axial load between the main braces and principal rafters varies directly with the relative stiffness of the joints connecting rafter and brace feet with the tie beam (Fig. 8, p. 16). What do we mean by joint stiffness? Like the beams that they connect, joints are not infinitely stiff, but rather act as powerful springs linking the timbers. Pull on a beam and the joint securing it will open up a bit. Put the same beam in compression and the joint will tighten up.

Now, if there is a first law of framing, it is that load goes to stiffness. So, given a choice, axial compression in the upper chord of our queen post truss will prefer the path of greatest resistance. If we model the outer joint as significantly stiffer than the inner one, then the principal rafter carries the bulk (70 percent) of the axial force. This high compression load (around 36,000 lbs. in the Rindge model) delivers a strong inward push to the top of the queenpost where it cantilevers above the straining beam, causing a spike in post bending (up to 2000 psi). When the respective joints at the feet of the main brace and the principal rafter are equally stiff, the principal rafter still carries 64 percent of the load (about 33,400 lbs.) and queenpost bending is slightly reduced (to 1800 psi). In all cases, the predicted total load, the sum of the compression in principal rafter and main brace, is about 53,000 lbs.

As the inner joint at the foot of the main brace becomes stiffer than the outer joint at the foot of the principal, the main brace starts to pick up the lion's share of the force and bending stress at the head of the queenpost drops into the allowable range. But the bending problem has relocated rather than disappeared: now the considerable force in the main brace is delivering a jolt where it intersects the tie beam, with tie bending stress climbing rapidly. With the inner joint four times as stiff as the outer, the rafter and brace share load equally—and predicted bending stress in the tie at the unsupported brace joint exceeds 2000 psi. Double the inner joint stiffness advantage and the main brace has 62 percent of the load, treble it and brace load share rises to 72 percent, with tie bending stress climbing, respectively, above 2600 and then 3000 psi. Finally, when the outer joint at the foot of the principal loses all its capacity to retain thrust, the main brace carries the entirety of the axial load, and apparent bending stress in the tie spikes to an attention-getting 4000 psi.

Where along this theoretical load spectrum does the truth lie? The connections in question are blind mortises, those for the principal rafters located (often inaccessibly) at the extreme ends of tie beams, encumbered with secondary framing, sheathing, insulation and debris. So we have no way of knowing, but educated guesses are possible. To the degree that the builders understood the play of forces in queenpost trusses, they had to see the main brace as the preferred load vehicle, trading its secure inboard location (abundant relish opposing outthrust) against the risk of bending in the tie beam. Certainly the location of the principal rafter foot joint so

close to the end of the tie implies high risk of shear failure in the mortise and housing.

The results of our modeling exercise provide a clue regarding likely force disposition: where principal rafters shoulder the load, we would expect to see evidence of bending at the tops of the queenposts; where the main braces take the brunt, one might note a local sag in the tie beam. Our visits to historic trusses have disclosed several of the latter, none of the former. These findings combined with our modeling evidence lead us to conclude that main braces provide the primary upper chord load path for queenpost trusses.

Remember those big tie bending stress numbers in the model? What if this load is excessive? Why don't we see more substantial sag in tie beams? Might they not break altogether? The modulus of rupture of dry, clear Eastern white pine is 8600 psi, so the Rindge tie beams are probably not prone to failure even if the inner joints carry the entire load. We shouldn't expect to see main braces poking down through audience room ceilings. But why don't we find more—and more pronounced—sagging in tie beams?

One answer is that wood as a material, and timber framing as a structural system, have built-in load accommodation mechanisms. As a tie sags under brace compression, the brace in question falls away from its superimposed load, some of which then flows elsewhere in the frame, most likely down the principal rafter. This inherent load sharing maintains equilibrium by shunting force and stress between and among members in a reverse Robin Hood process, taking from the poor and giving to the rich, a classic case of load going to stiffness. A similar process equilibrates load at the joinery level, where connections can be out of alignment because of subsidence, shrinkage or poor workmanship. The resilience and relative softness of timber (compared with, say, steel) allows first elastic and later plastic deformation, bringing joint abutment surfaces back into alignment.

Another probable reason for better than expected truss performance is that our codes and computer models posit loading harsher than the real world conditions experienced by the buildings. In Rindge (Fig. 8, p. 16), we note a pair of short struts joining principal rafter and main brace opposite a single strut carrying on from brace to queenpost, elements that help support point loads delivered by the purlins to the principal rafter. At Peacham (Fig. 7, p. 15), these struts are absent, and the principal rafters must handle substantial point loads from the lower purlins (estimated at 4500 lbs.) on their own, resulting in model deflections of up to 1.8 in. and bending stress up to 2300 psi in the spruce principals. You would expect the magnitude of these results to indicate a kink in the rafter, but apparently the Peacham principals never got this memo, and deflection is undetectable with the naked eye. Could we have overdone the model loading? I don't doubt the 65 psf ground snow, but we're talking about a tall church near the top of a hilltop village in a windy place, and for some time now the church has had a metal roof. The rules mandate conservative loading, but how much snow stays on these roofs?

The unsupported purlin arrangement in Peacham is also found in Waterbury (Fig. 11, p. 18), but here the load effects predicted by the frame model are abundantly clear in the flesh. Here, truly, is the little roof that couldn't, a frame caught in the act of failure. So why does Peacham persevere while Waterbury comes to grief? In his discussion of Waterbury in the article just preceding, Jan Lewandoski pegs the villain by describing the church as "spanned by queenpost trusses of good material and joinery, but with disproportionately undersized main braces. . . a potentially fatal flaw."

Our analyses show the two structures with similar nodes of high bending stress, and accompanying deflection. But trusses are not about bending. By definition, a truss is a framework that bears its burden via axial loading, in pure tension and compression. In this capacity, timber (and indeed all framing material) is many times

stiffer than it is in bending. As a beam bridge, a 12-ft. 6x6 carries a midspan point load of 1000 lbs. with a half-inch of deflection. Stand the same stick up on end, load its top with half a ton and the newborn column will shorten a few thousands of an inch. Loaded axially the timber is a hundred times—two orders of magnitude—stiffer than it is bending.

Conversely, consider the effect of an undersized truss member: in bending (beam action) it can cause a local distortion of the frame but, in buckling under axial load, it stands fair to bring down the whole structure. As specified by the *National Design Specification for Wood Construction (NDS)*, the controlling design value used to size a column or other timber loaded in compression is compression parallel to grain (F_c) as modified by the column stability factor (C_p). F_c specifies maximum allowable axial compression stress by species and grade. To avoid the tendency of long thin members to buckle in compression, C_p lowers the working value of F_c via a complex calculation involving stiffness, slenderness ratio (effective length divided by least cross-section dimension), end conditions and other terms (Sect. 3.7.1, p. 22). Additional equations come into play if the timber in question is loaded in bending as well as compression.

Survive running the *NDS* math gantlet, and you find the 7x8 main braces in Peacham rated for a load of 25,500 lbs., which compares fairly well with the predicted load of 27,500 lbs. At Waterbury, on the other hand, the 7x3 main braces are limited by code to carry a mere 2,100 lbs. This against the 29,000-pound load estimate from the FEA model! Compared in terms of stress values, Peacham's main braces are rated to carry 455 psi (down from a tabulated F_c value of 900 psi) and Waterbury's to carry 100 psi (much reduced from the tabulated F_c of 800 psi)—while dealing with a whopping 1385 psi axial stress! So the Peacham main braces weigh in working at 108 percent of capacity, while at Waterbury they struggle to fill shoes 1385 percent too big. Put another way, the Waterbury main braces are undersized by a factor of 14.

In contrast to Waterbury, consider the later, highly evolved queenrod truss at Stowe (Fig. 13, p. 19). Here the 6x6 and 6x7 upper chord members (main braces) seem dangerously light for their job. But both our structural analysis and the excellent condition of the frame belie this judgment. So well did the builders understand their business that load effects are the lowest of any of the frames we have studied. Maximum deflection is less than half an inch. Bending stress is close to zero, except for a jolt in the tie where the main braces land. Maximum tensile stress in the tie is 180 psi against a tabulated value of $F_t = 700$ psi. Maximum compression in the main braces tops out at 499 psi (tabulated $F_c = 800$ psi, calculated allowable $F_c' = 577$ psi, and maximum straining beam compression is 320 psi vs. tabulated F_c of 800 psi and calculated F_c' of 389 psi. In sum, under the biggest load we can throw at it, the Stowe truss operates at 25 percent of capacity in tension and 82 percent to 85 percent capacity in compression, and does so using 55 percent of the volume of material employed at Peacham and 65 percent of the total used in Rindge (material percentages adjusted for truss spacing).

Two posts better, redux. Turning back to the Rindge and Peacham FEA models, it's worth pointing out that, despite the high compression heroics in the upper chord components, tension in the queenposts never exceeds 12,000 lbs. at Rindge and 7000 lbs. at Peacham. If the genius of the scissor truss is its ability to carry significant tension load in its lower members without resort to tension joinery (see TF 69), queenpost trusses approximate this tactic, with joints everywhere in compression save at the post feet. (Of course, queenrods, as at Stowe, are in tension top and bottom.) Thus we discern a primary survival strategy of the queenpost truss: eliminate all tension joints apart from post feet and minimize joint tension there by doubling the tensile element. —ED LEVIN