

# HISTORIC AMERICAN ROOF TRUSSES

## *III. Kingpost Trusses*

*THIS article is third 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. Previous articles in the series have treated Scissor Trusses (TF 69) and Queenpost Trusses (TF 71). The final article to appear in TIMBER FRAMING will treat Composite Trusses.*

THE kingpost is likely the earliest truss form. Its evolution has been sketched by numerous authors, who cite ancient examples thought to predate other truss types and who speculate knowledgeably how a builder might first try to span a great chamber. As in any other study of a particular object of material culture, we are limited to examining as many as we can of the surviving examples, which represent only a tiny fraction of the roof frames built in the past. In addition, we can look at old drawings and read ancient commentary, sometimes written by architects but rarely if ever by actual framers. Within these limits it is still possible to discover something.

As soon as we exceed about 40 ft. of clear span, even the largest timber, of the highest quality, of the best species, will sag under its own weight if used as a tie beam, and the even-longer rafters above it will both sag and put great outward pressure on the exterior walls. The outward pressure on the walls can be mitigated by supporting the rafters at their peaks by a ridge or purlin supported on posts bearing on the tie beams (Fig. 1a). Such roof frames were common in Europe during the Middle Ages, examples of which survive, and possibly during Antiquity, where examples don't. But, unless the span is short and the tie beam stout, this configuration will just depress the tie and allow the rafters to deform anyway.

Outward pressure on the walls can be eliminated entirely by affixing the feet of each rafter couple to their own tie beam. The problem of sag can then be addressed by hanging a joggled vertical member, or kingpost, from these rafters and using it in tension to support the midspan of the tie beam. (Fig. 1b). By a less obvious intuitive leap, it might be realized that the midspan of the long rafters can be kept from bending by struts rising from lower joggles on the suspended kingpost (Fig. 1c).

Looking back, we hypothesize that successive highly experienced framers with good structural intuition developed a frame where loading was axial, forces were balanced or balanceable by a none-too-thick wall below and triangulation with fixed joints was achieved. This was the truss and, at first, probably a kingpost truss. It evolved in Europe or in the Mediterranean region and apparently did not develop independently elsewhere, even in the highly sophisticated timber framing traditions of China or Japan.

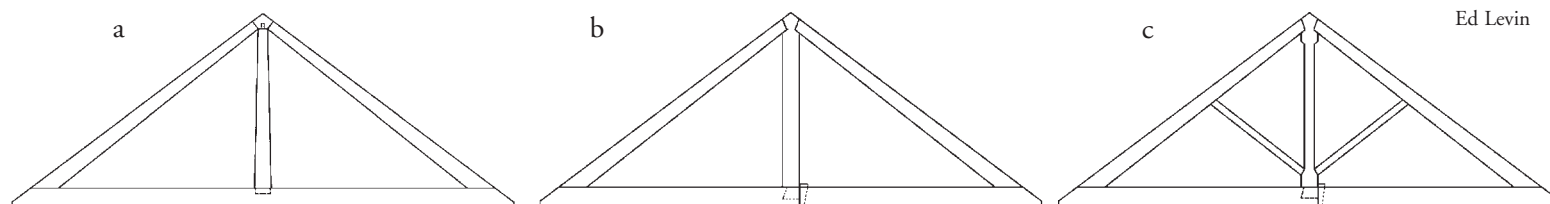
Early examples from the Roman Empire exist as written accounts of public buildings with clear spans as great as 90 ft. (necessitating a truss), or suggestive early illustrations of framing with abundant triangulation, such as those found on Trajan's column shown below.



C. Chicorius, 1904

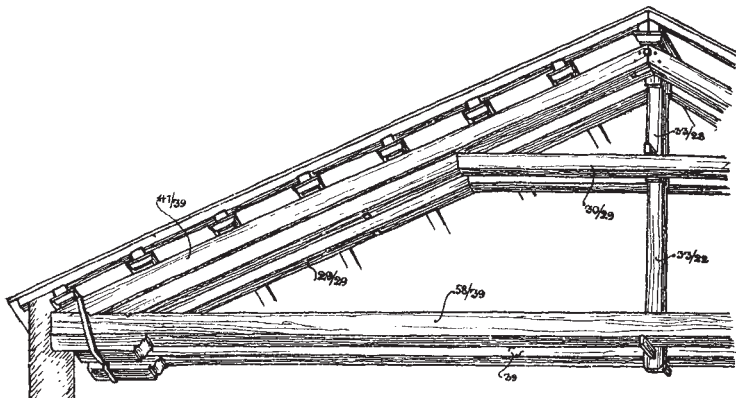
*Panel from Trajan's column depicting Apollodorus's bridge (ca. 105) across the Danube. Trussed segmental arches spring from triangulated supports to carry the bridge deck. Triangulated railings may help.*

Ancient roof systems that survived into the 19th century, such as the 78-ft.-span kingpost trusses at St. Paul's Outside the Walls, in Rome, represented three different periods of construction between the 4th and 15th centuries, and extensive repairs (Fig. 2 facing page). However, at least two observers (Gwilt 1867 and Rondelet 1881), while dating the trusses differently, agree that the kingpost was suspended and had tension joinery at its intersection with the tie beam.



Ed Levin

FIG. 1. HYPOTHETICAL DEVELOPMENT OF KINGPOST TRUSS: (A) CROWNPOST SUPPORTING RIDGE, (B) HUNG KINGPOST, (C) STRUTTED RAFTERS.

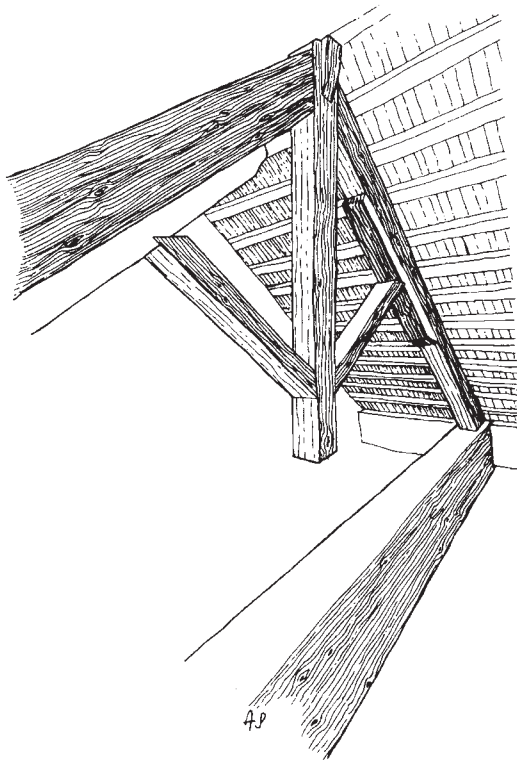


Ostendorf, 1908

FIG. 2. OSTENDORF'S DRAWING AFTER RONDELET'S OF THE KINGPOST TRUSS OF ST. PAUL'S OUTSIDE THE WALLS, BEGUN CA. 384-86, REPAIRED IN THE 9TH CENTURY AND DESTROYED BY FIRE IN 1823.

The mid-6th-century roof truss at the Monastery of St. Catherine at Mount Sinai, Egypt, is our oldest securely dated extant example. It is a kingpost variation known in England as kingpendant, i.e., the pendant kingpost doesn't reach or suspend the tie beam, in this case because the roughly 20-ft. span doesn't require midspan support (Fig. 3).

The great Gothic cathedral of Notre Dame in Paris (roof system ca. 1200) contains complex frames with kingpost-like elements supported by pairs of principal rafters, but their functioning as a truss is complicated by the existence of what Gwilt calls queen stirrups, that is, wooden suspension members to either side of the kingpost that are hung from both upper and lower collar beams that span between the upper principal rafters (see Fig. 2, page 8).



Amy Stein

FIG. 3. KINGPOST TRUSS INSIDE THE NAVE OF THE 6TH-CENTURY MONASTERY ST. CATHERINE'S AT MOUNT SINAI IN EGYPT.

These queen members are described by Gwilt as having somewhat more substantial tension connections at the tie beam than does the kingpost; they are understood by Courtenay to have been installed to support work platforms for the masons and their materials in building the vaults below (Fig. 2, page 8 and Courtenay 1997).

This complex and indeterminate framing is often successful, not because clear load paths exist as in the case of a truss, but because experienced framers knowing the properties of their wood species and executing appropriate joinery at a multitude of locations were confident that they could design a rigid and enduring roof frame. This old complex framing was common even in the prestigious buildings of the 18th century and continued to be used by vernacular builders in rural America during the early 19th century, long after builders' guides and patented plans describing the details of truss construction were readily available. Some of these complex roof frames and truss variants will be described in the fourth part of this series.

By the 16th century, illustrations of trusses and more-or-less modern discussions of their behavior were available in numerous Italian publications and, by the early 17th century, such trusses were being built and written about in England as well. In Italy, the truss was called *trabo reticulari* or "beam in the form of a net," not unlike some modern engineers' descriptions of trusses as having chords and a web (Yeomans 1992). In 1678, Moxon's *Mechanick Exercises* illustrates a fully developed kingpost truss with a flared head and struts rising from joggles on the kingpost to the midpoint of the rafters—but, inexplicably, over a fully studded gable wall in an otherwise common rafter roof (Fig. 4).

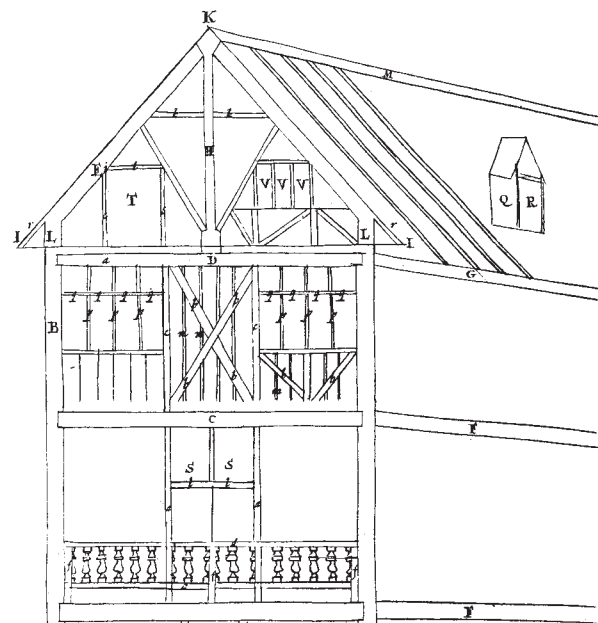
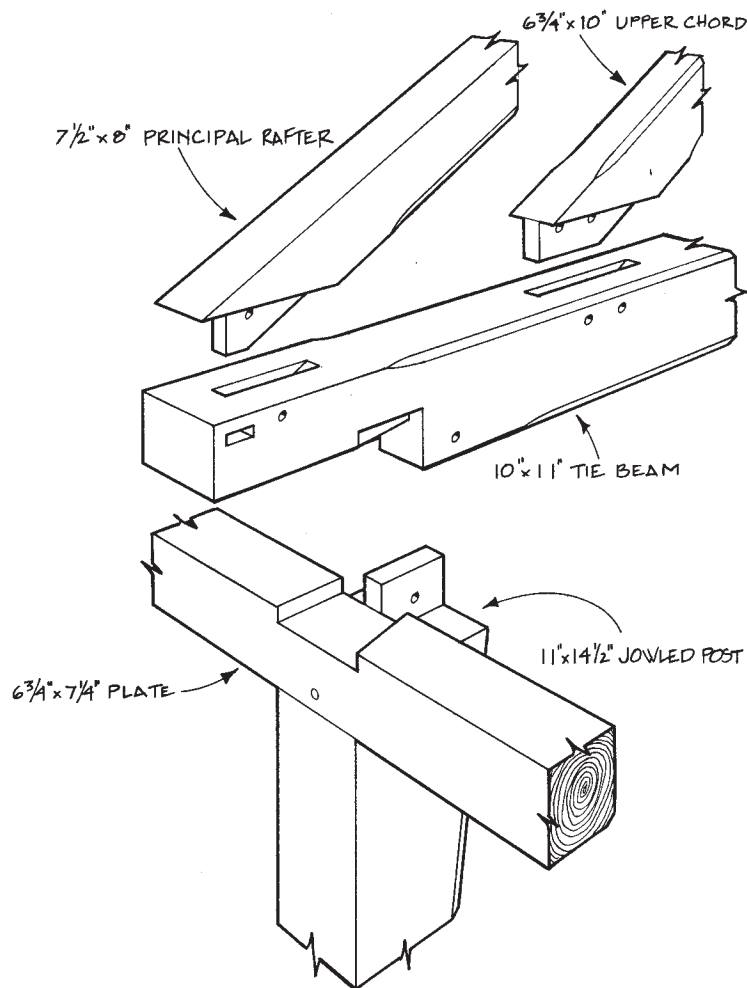


FIG. 4. MOXON'S DRAWING OF A KINGPOST TRUSS, 1687, DETAIL. POSITION OF TRUSS OVER FULLY STUDDED GABLE WALL MAY ALLOW PRESENTING NORMALLY DISPARATE ELEMENTS IN ONE DRAWING.

Moxon does use the word truss and refers the reader to sections on kingpiece or joggle piece for explication. (For the English etymology of the word *truss*, see the first article in this series in TF 69.) The 1681 Old Ship Meetinghouse in Hingham, Massachusetts, employs the oldest extant American example of a kingpost truss, although in a roof system of unusual form. Kingpost truss roof systems (and other truss form systems in lesser numbers) were built sporadically during the first half of the 18th century, but then by the tens of thousands during the later 18th and throughout the 19th centuries, by vernacular carpenters framing meetinghouses, churches, public buildings and bridges all over eastern North America.





All drawings Jack A. Sobon  
unless otherwise credited

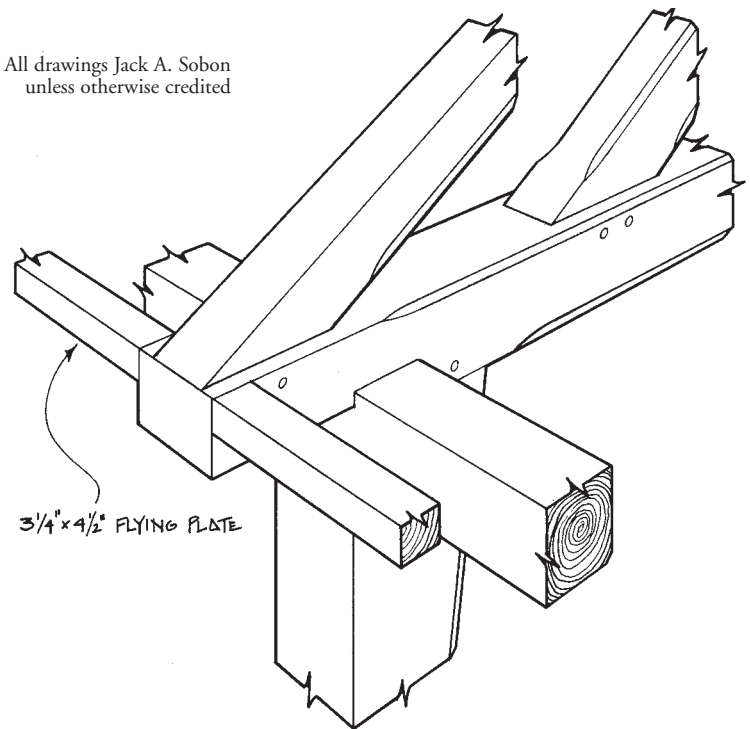


FIG. 6. RAFTER, TIE AND PLATE JOINTS, LYNNFIELD MEETINGHOUSE, AN ENGLISH TYING JOINT WITH OUTSHOT PLATE.

At least three reasons account for this explosion of truss construction in the New World. One was the increased availability of builders guides that explicated and advocated timber truss work (Nicholson 1837 and Benjamin 1839). A second was the availability of large and long timber that lent itself to truss construction, particularly with kingposts. (The old complex framing could be accomplished with a multitude of smaller members, accommodating what timber was ordinarily available in medieval Europe.) A third reason was the increased popularity of a sort of neoclassical architectural design, even in rural areas, that used white painted timber to represent masonry construction and took pains to eliminate any exposed framing. This style also emphasized wide, open audience rooms under relatively low roof pitches and, in consequence, increasingly eschewed the aisled and galleried constructions, associated with outmoded political and social systems, that lent structural support to the nontrussed roof systems.

Lynnfield Meetinghouse, Lynnfield Center, Mass., 1714. The frame at Lynnfield originally measured 32 ft. 4 in. wide and 38 ft. long. Jowled wall posts, exposed to the interior, supported two kingpost trusses, framed entirely of oak. These trusses used naturally curved inner principal rafters to trap and support a gently tapering kingpost with a wedged, blind half-dovetail joint at its foot supporting the midspan of the tie. Outer principal rafters rising from the cantilevered ends of the 35-ft. tie beams tenoned into the slightly flared head of the kingpost and were supported at their midspan by short struts rising from the arching inner rafters. Large curved braces rose from elongated mortises on the flared posts to long, three-pin mortises on the ties, to help support the inner rafters where they bore on the tie beam inboard of the post (Figs. 5, 6).

In 1782, using a typical method of the time for enlarging buildings, the structure was sawn in half and spread apart. Sections of sidewall, roof and two new trusses, similar but not identical to the old ones, were installed in the middle, bringing the building to its current length of 57 ft. The two new trusses were different in several details, representing both changes in architectural taste and availability of materials. The kingposts remained oak but the tie beam and rafters became pine. The inner rafters were still slightly

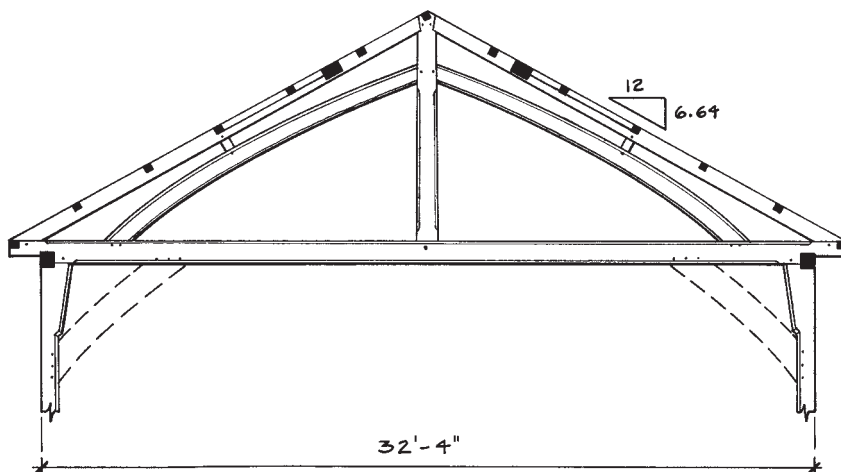


FIG. 5. LYNNFIELD (MASS.) MEETINGHOUSE ORIGINAL TRUSS, 1714.



*Lynnfield exterior is austere and without tower.*

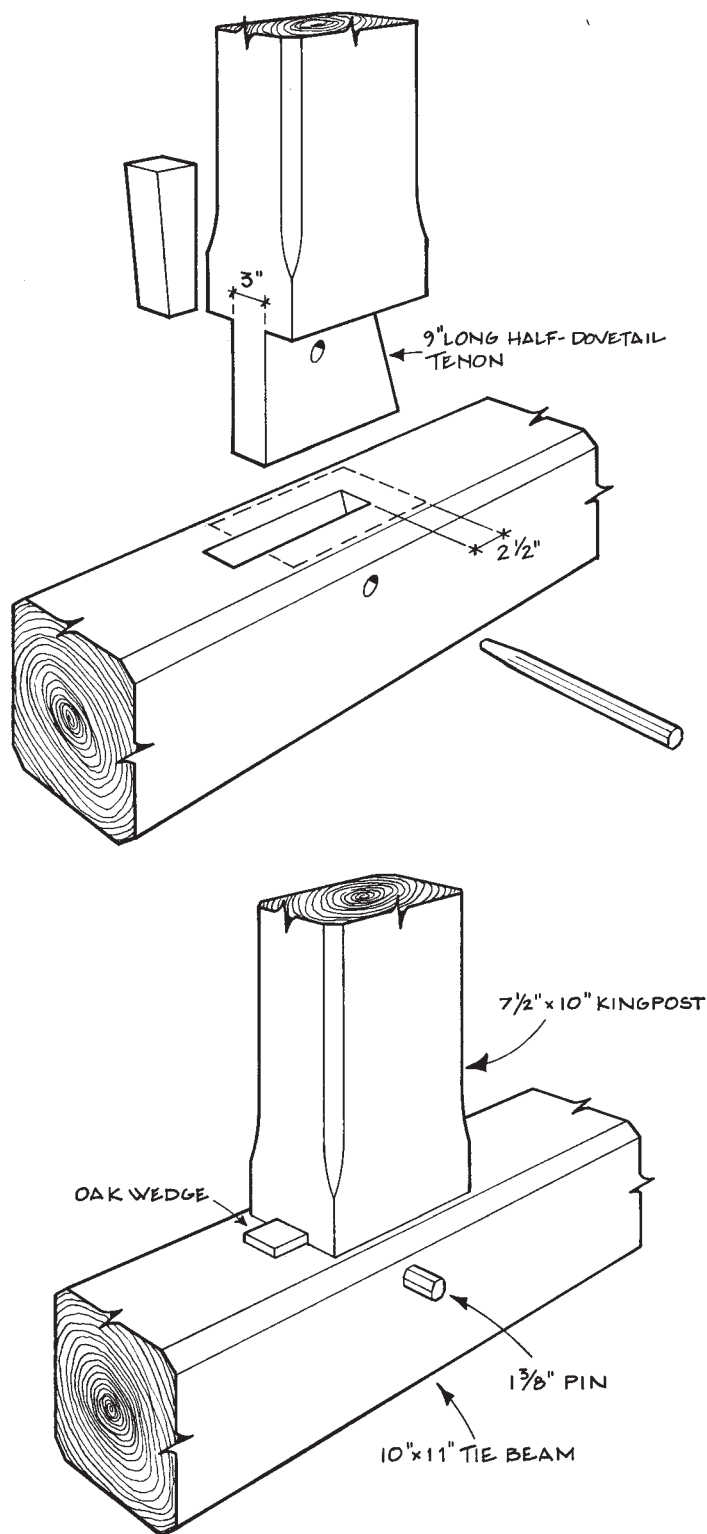
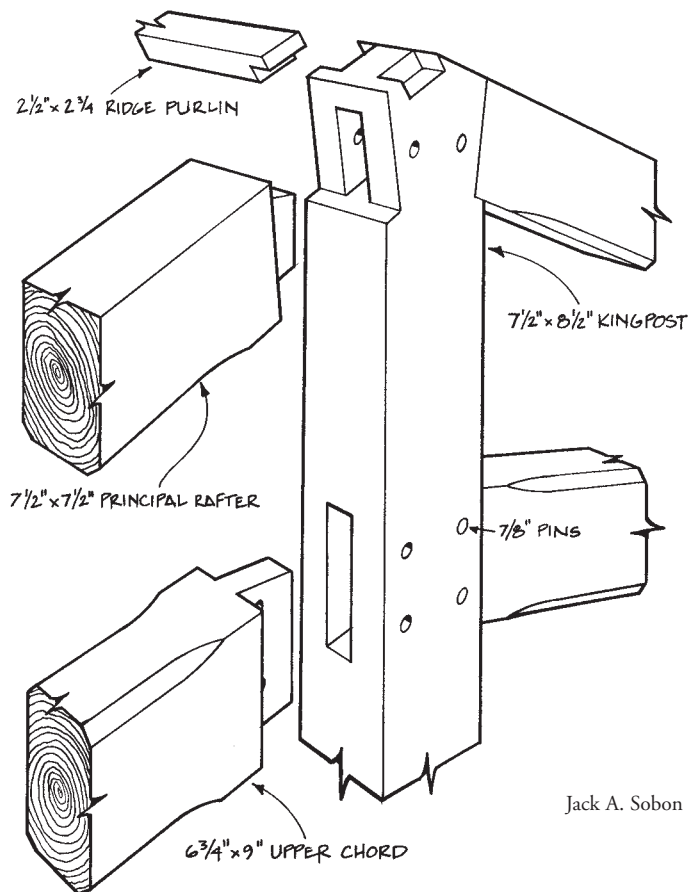


FIG. 7. KINGPOST-TO-TIE JOINT, ASSEMBLED AND EXPLODED VIEWS, LYNNFIELD MEETINGHOUSE. ORIGINAL TRUSSES ARE ENTIRELY OAK; LATER ONES USE PINE RAFTERS AND TIE BEAM.

curved, but there was no provision for large curved bracing rising from the wall posts to support them. On the old trusses the wedged half-dovetail at the kingpost-to-tie joint is not in a through mortise, the dovetail has 2 1/2 inches of slope, and it is transfixed by a single 1 3/8-in. pin (Fig. 7). On the new trusses the kingpost is not as wide, 8 1/2 in. as opposed to the 10 in. of 1714; the mortise passes through the 10x11 tie beam, the slope of the dovetail is only 1 1/2 inches and it is transfixed by a single 7/8-in. pin. The old trusses are performing better at this joint than the new ones; the explanation may be the crushing of end grain in the mortise in the pine tie, the reduced slope on the dovetail tenon or the relatively small pin—solely or in combination.



Jack A. Sobon

FIG. 8. EXPLODED VIEW OF PEAK JOINT, LYNNFIELD MEETINGHOUSE. UPPER TRUSS CHORDS ARE INDEPENDENT OF ROOF RAFTERS.

The old trusses had stopped chamfers cut on the arrises of all major members, absent on the new, perhaps because in 1782 (or in a later remodeling) a plaster and lath ceiling was installed and the wall posts likewise covered. Today the roof system is again exposed.

The new trusses, unlike the old, also have no flared abutments or joggles at the kingpost head (Fig. 8); but if there is anything surprising that our examination of a great many historic trusses has shown, it is that normal bearing or the lack of it at chord-to-kingpost connections results in no truss deformation. The 1801 Windham Congregational Church in Windham, Vermont, with its very heavily built kingpost trusses of 45-ft. span, is just one more example of many whose rafters, both inner and outer, engage the kingpost with no cut joggle of any sort, instead using a 2- or 3-in. tenon with shoulders cut at the roof angle (Fig. 10 below). It may be that the kingpost-to-tie joint is always weaker and that failure will occur there rather than at the head. It may be also that the weight and nailed-together matrix of roof boarding and shingles keep the joint together at the very head of the post.

Another possibility is that when a truss initially bears its load, the end grain at the upper end of principal rafters or braces compresses itself into the side grain of the post, developing enough friction that a smallish tenon with a pin is enough supplemental restraint to provide a rigid joint with no slippage.

The Lynnfield Meetinghouse has all the appealing characteristics of late medieval framing: everything is hewn or hand surfaced, all members either curve or taper slightly and the timber edges are decorated with a nonmechanical sort of easement that widens and narrows with irregularities of the hewn surface. Meant to be exposed, and well protected over time, the trusses have a beautiful patinated color. This roof system is in very good condition, particularly the older trusses.



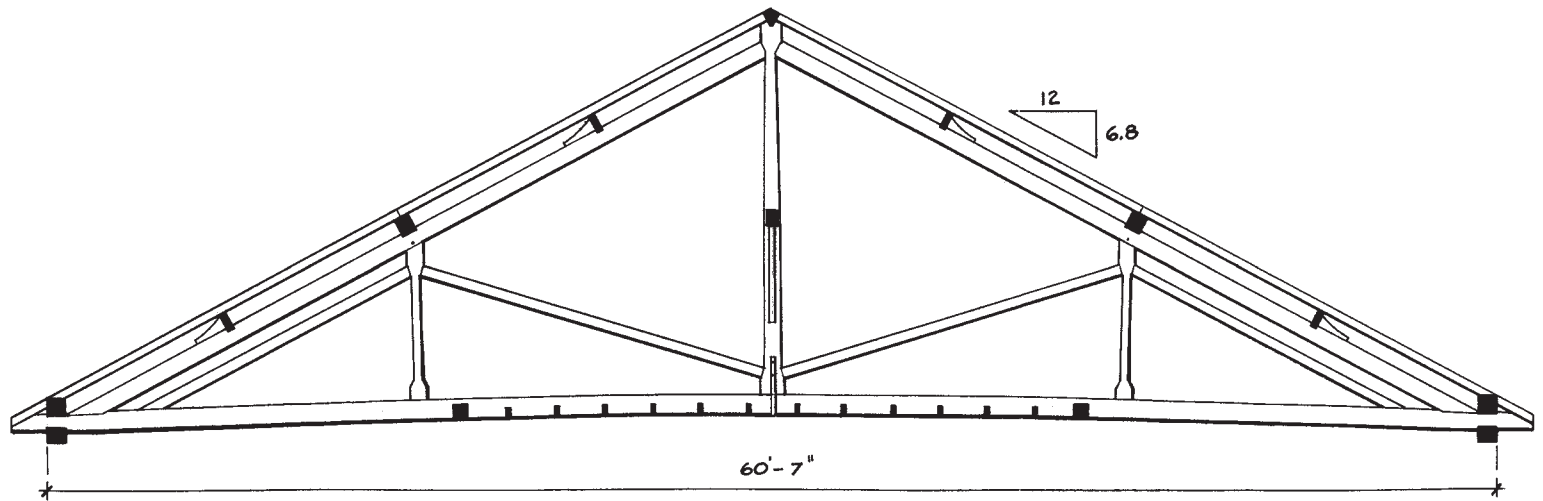


FIG. 9. CASTLETON FEDERATED CHURCH, 1833. LONG-SPAN KINGPOST TRUSSES ARE CONSIDERABLY STRENGTHENED BY PRINCEPOSTS IN TENSION.

**Castleton Federated Church, Castleton, Vermont, 1833.** Castleton Federated is a large brick church with a timber roof system and a storied steeple that terminates 132 ft. above the ground. The roof is composed of kingpost trusses spaced 10 ft. apart, spanning 59 ft. 1 in. in the clear, with a single-stick 11x11 bottom chord length of 63 ft. 7 in. overall. The trusses are fitted with princeposts (sometimes called queenposts) that flank the kingpost and further divide the span. The chords are not the only long members in the building. The  $8\frac{1}{2} \times 9\frac{1}{2}$  purlins notched over the truss rafters directly above the princeposts are single timbers nearly 70 ft. long (Fig. 9). The pendant mast of the spire, originally a 51-ft. 9x9 chestnut timber, was replaced with an equal-sized stick of pignut hickory in 1989 by the author.

The builder of the church was Thomas Dake, a well-known house joiner of Castleton who designed, framed and notably finished a number of houses still widely admired in that village. Dake's aesthetic sense is revealed in the church roof frame as well, where 6 in. of camber in the tie beam, sizing and shaping of members proportional to load and function, and the dramatic entasis of the kingposts, produced a graceful and eye-pleasing truss. The hemlock kingposts measure  $11\frac{1}{2} \times 10$  at the bottom and taper, at an increasing rate as they ascend, to measure only  $5 \times 10$  below the normal joggles for the  $8 \times 8$  principal rafters. The kingposts extend for another 12 in. above the rafters, providing adequate shear distance for the shoulders and ultimately carrying a notched-in ridge-pole for the common rafters.

The truss at Castleton has single principal rafters with three lines of purlins lodged atop the rafters, carrying a deck of  $4 \times 4$  common rafters. One purlin is the aforementioned large timber above the princeposts, but the other two are lines of  $3 \times 9$  interrupted timbers sitting against cleats at the approximate quarter points along the principal rafters. The princeposts, which have joggles top and bottom, are correctly supported by low-angled struts, one rising from the lower joggles on the kingpost and the other from a mortise in the bottom chord about 3 ft. inboard of the bearing walls, so that the princeposts suspend the bottom chord as well, rather than bearing upon it. The kingpost suspends the center of the bottom chord with a 2-in. through tenon assisted by an iron strap with 1-in. iron pins, while the princeposts use a mortise and tenon joint with two wooden pins and no ironwork.

This treatment of secondary posts as suspension members, with their own truss work within the larger truss, was not universal in the roof frames of the 18th and 19th centuries. In a typical example, at the Windham Congregational Church (1800),  $4 \times 5$  struts rise from an unshouldered mortise high on the kingpost to support the inner principal at approximately its upper third point, while



Ken Rower

*Castleton Federated, 1833, in Greek Revival style (though with Gothic arched windows), including colonnaded porch; tower is supported by front wall and sleepers over first three trusses.*

additional  $4 \times 5$  raking struts rise from bearings on the bottom chord midway between the kingpost and the wall posts to support the same rafter lower down. Five short struts then rise from this inner rafter, none of them directly over the lower struts, to support the outer principal rafter that carries the purlins for the common rafters and roof deck (Fig. 10 facing page). In a second instance, at the 1826 Newbury, Vermont, Methodist Church, square  $8 \times 8$  timbers rise from truss chord to principal rafter in a kingpost truss as if awaiting the support of galleries below that were never built.

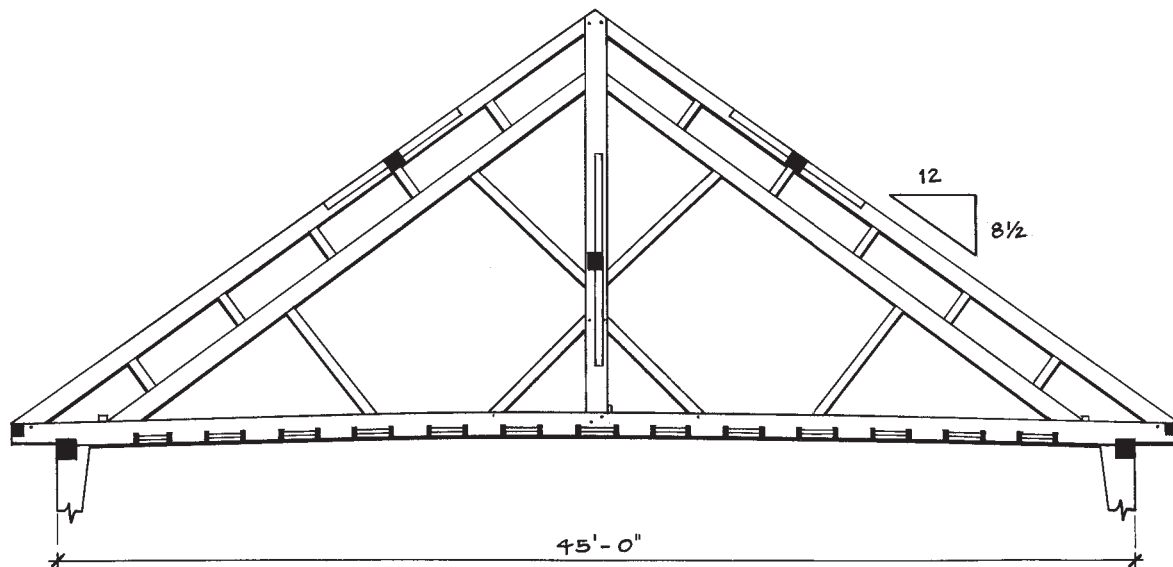


FIG. 10. WINDHAM, VERMONT, CONGREGATIONAL CHURCH, 1800. STRUTS AND UPPER CHORDS BEAR ON UNJOGGLED MORTISES.

The Castleton roof system is framed almost entirely in hemlock. The pins are ash, 1½-in. diameter in the larger members and ⅞-in. in the smaller. Of interest are the white oak poles woven in between the common and principal rafters toward the front of the church, reaching into the steeple perimeter. These were likely some of the rigging used to build the tall steeple once the roof trusses and roofing were already in place. Also located at the rear of the steeple are braced and now cut off 10x10 posts that probably served as the bottom of the derrick for erecting the steeple or perhaps the trusses themselves. The trusses are functioning well, even carrying some of the steeple load on a pair of sleepers crossing the forward three trusses. Other than small openings at the kingpost-to-tie joints, they show no signs of stress.

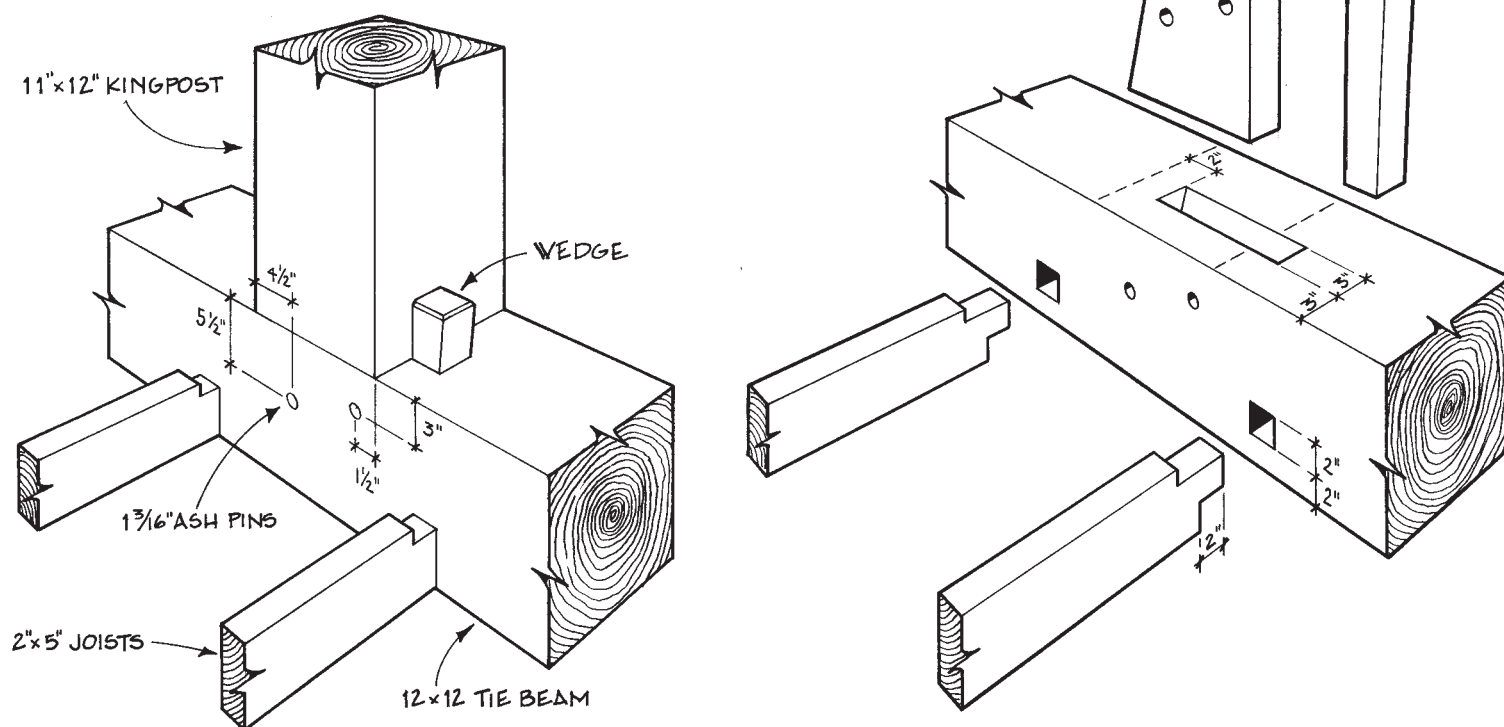


FIG. 11. KINGPOST-TO-TIE JOINT ASSEMBLED AND EXPLODED, WINDHAM CONGREGATIONAL CHURCH, 1800. JOISTS ARE INSERTED AT ONE END AND SWUNG INTO PLACE AT OPPOSITE END VIA PULLEY MORTISES, SEEN IN TRUSS ELEVATION ABOVE.



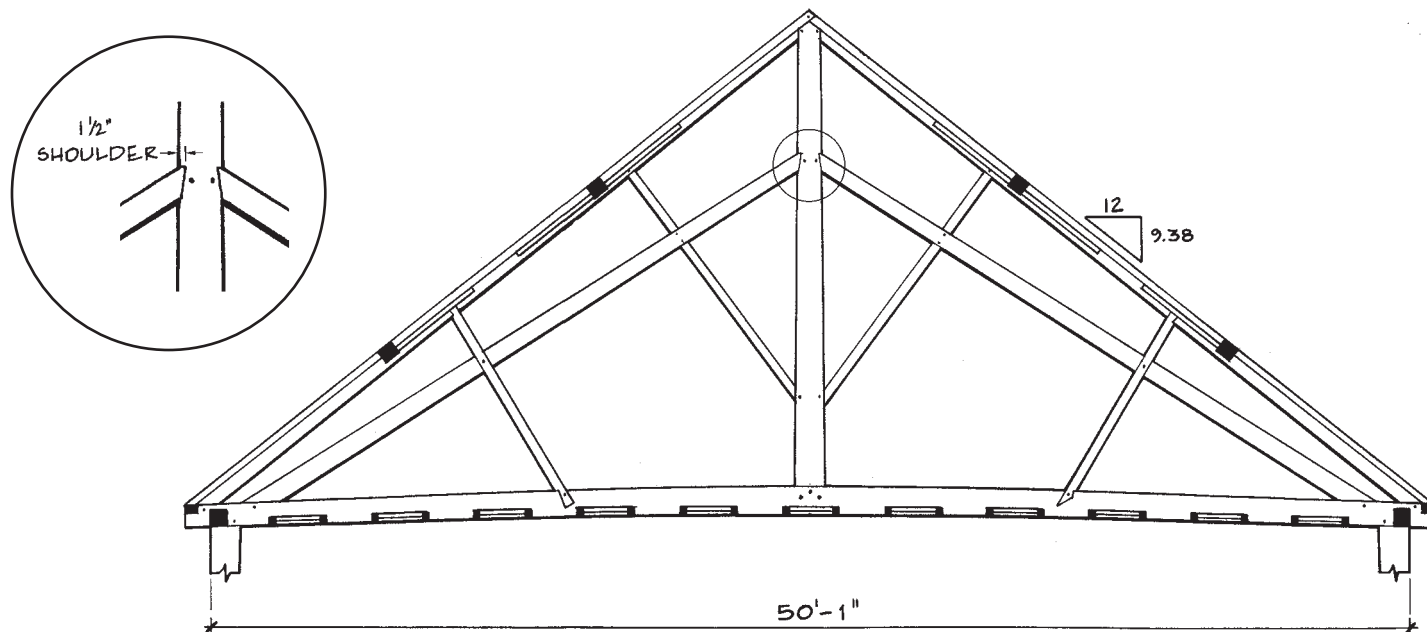


FIG. 12. STRAFFORD, VERMONT, MEETINGHOUSE, 1799, WITH DETAIL OF UPPER CHORD ABUTMENTS.

**Strafford Meetinghouse, Strafford, Vermont, 1799.** Strafford is a late example of an older style of New England meetinghouse, with a plain exterior little influenced by classicism and a steeple rising from the ground at one gable wall rather than engaged with the body of the building atop a portico, as was already stylish at the time. The roof is steep, pitched  $9\frac{1}{2}$  over 12, and its trusses, framed by the scribe rule, are monumental and complex: the span is 50 ft. 1 in. and the height of the kingposts themselves 22 ft. Bay spacing is slightly irregular within several inches at around 12 ft., with no two (of five) bays identical. The hewn bottom chords, principal rafters, kingposts and plates are spruce, while the vertically sawn braces, struts, joists, common rafters, purlins and flying plates are hardwood: a mixture of beech, yellow birch and maple (Fig. 12).

The 12x14 bottom chords show, variously, 5 to 7 inches of camber. An 11x14 kingpost rises from a three-pinned through tenon at the bottom chord to measure 10x11 at the peak. The inner rafters taper from  $7\frac{1}{2}$ x10 at the bottom to 7x7 at the top, and tenon into the kingpost with  $1\frac{1}{2}$ -in. bearing shoulders, indicating that these members were intended to be the top chords of the truss (Fig. 12 detail). The outer rafters measure 9x10 at the bottom and again taper toward the top where they are tenoned and pinned, without flared shoulders and with very little relish, into the top of the kingpost. These outer rafters carry the two lines of 8x9 purlins, and consequently the 3x5 common rafters and the roof deck, the weight of which helps keep them in place. The inner rafters, providing main support for the kingpost, bear on the bottom chord right over the inner edge of the wall posts. The outer rafters bear at the very ends of the bottom chord with very little relish (Fig. 13). In four cases this short relish has failed in double shear, a result of the innate vulnerability of the joint and the unfortunate addition of slate roofing on a frame designed for wood shingles; these four joints are now restrained with steel bolts.

The inner and outer rafters are not parallel. The inner ones have a lower pitch and are thus shorter and potentially more resistant to buckling. However, this choice of inner rafters as the important top chord of the truss, unattached to horizontal purlins or the weight and diaphragm of the roof, leaves them vulnerable to buckling under load. The framers at Strafford tried to deal with this problem by adding supplemental struts and a raking strut to each side of the truss, but with only partial success. The supplemental struts are more or less typical, 4x4s rising from anunjoggled mortise in the post at a steep angle and tenoning into the inner rafters at



Ken Rower

*Strafford Meetinghouse, 1799, modest and chaste except for its proud octagonal steeple over a square clock tower.*

about their upper quarter points. Further short supplemental struts, tenoned and pinned, rise on the opposite faces of the inner rafters to support the outer rafters near, but not under, the 8x9 purlin joints.

The intellectual genesis and the function of the raking strut are harder to understand. A hardwood 4x4 springing from about the quarter point of the bottom chord to a point nearly two-fifths up the outer rafter, it has half-dovetail laps at both ends, suggesting an attempt to suspend the bottom chord from above, or perhaps

restrain the outer rafter from upward buckling or outward slippage (photo below). Crucial to understanding the framer's thought is the halving and tight trenching of the 4x4 where it crosses the inner rafter and is fastened as well by a 1½-in. pin. The joinery suggests the raking strut is to help the inner rafter resist buckling, adequate in an upward direction but a marginal construct against horizontal buckling. On the Strafford trusses, several inner rafters have buckled outward, away from their joints with this raking strut, or have bent or even broken the member when a rafter elected to buckle toward one already weakened by excessive slope of grain. The half-dovetails on the raking struts also have bearing shoulders that can work in compression to help the outer rafters bear the lower 8x9 purlins. That is what the raking struts seem to be doing at this point in the life of the trusses even though the purlin bearings are 2½ ft. away.

In an unusual arrangement, the Strafford roof framing includes floor-level 4x7 horizontal braces that tenon into the sides of the tie beams, notch over the plates and tenon into the sides of the 4x6 flying plates to help support them near their midspan (photo below).

The Strafford trusses are generally performing well at more than 200 years of age, sagging a bit due to the weight of slate but profiting from not having to bear any steeple loading thanks to the appended rather than dependent steeple.



Jack A. Sobon

*At top, pinned dovetail lap at lower end of raking strut connecting tie beam with upper rafter at Strafford. Above, brace that helps support the interrupted flying plate spanning from tie beam to tie beam.*

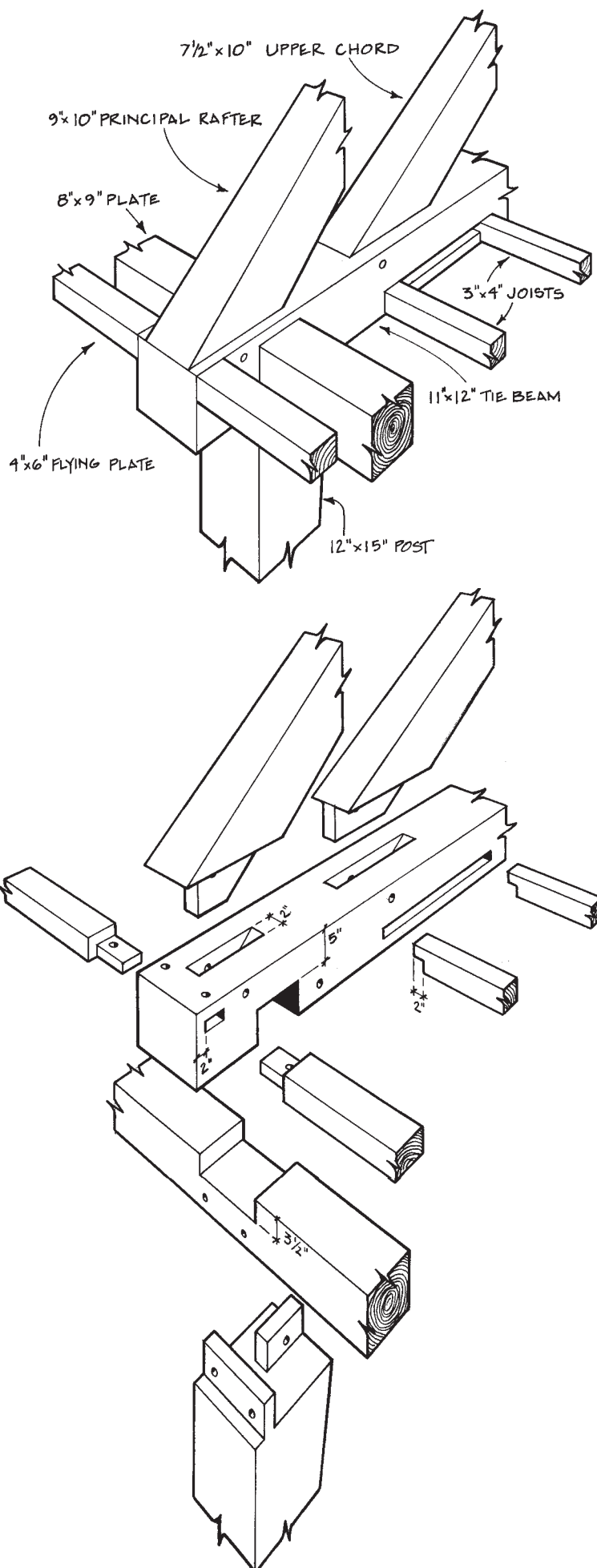


FIG. 13. STRAFFORD MEETINGHOUSE, ASSEMBLED AND EXPLODED VIEWS OF TYING JOINT WITH UPPER CHORD SEATS.



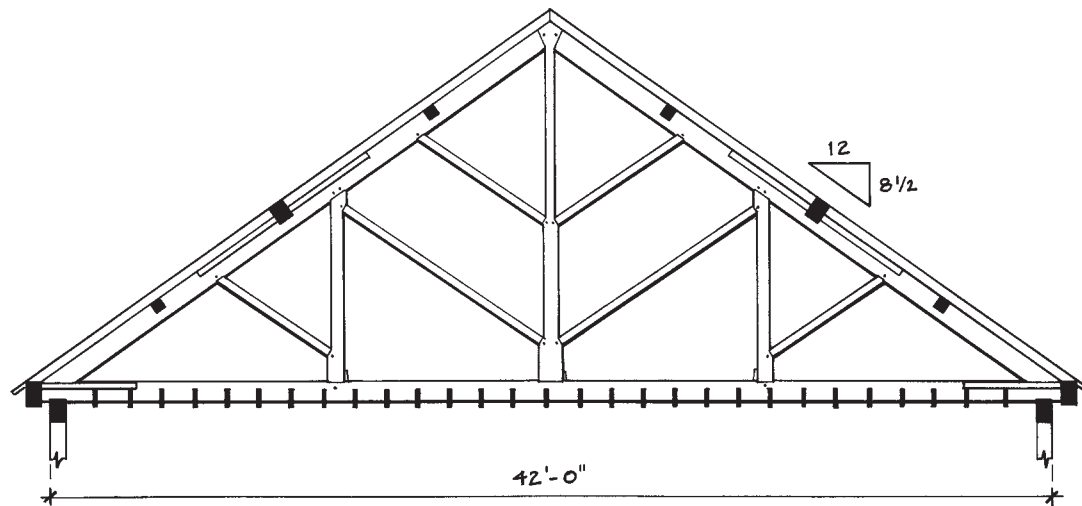


FIG. 14. UNION MEETINGHOUSE, 1870, APPARENTLY CLOSELY PATTERNED AFTER THE BUILDER'S GUIDE DRAWING BELOW.

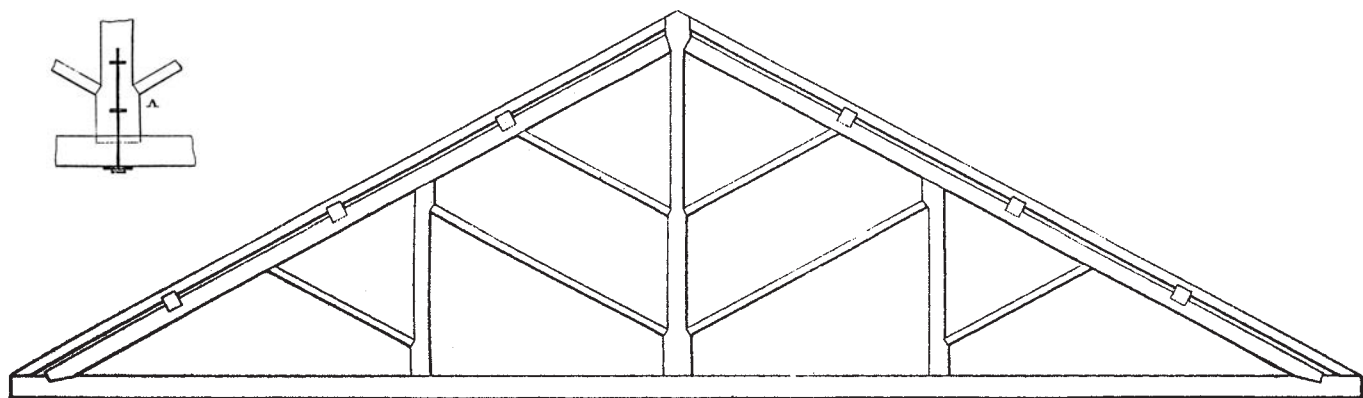


FIG. 15. ASHER BENJAMIN'S DRAWING OF A KINGPOST TRUSS WITH "QUEENPOSTS," PUBLISHED IN HIS *PRACTICAL HOUSE CARPENTER*, 1839. DETAIL SHOWS METHOD OF FASTENING POSTS WITH VERTICAL BOLTS THROUGH TIE BEAM TO CAPTIVE NUTS SUNKEN IN THE POSTS.

**Union Meetinghouse, Huntington, Vermont, 1870.** The kingpost truss with princeposts at the Union Meetinghouse spans 41 ft. 8 in. in the clear with the bottom chord 44 ft. long overall (Fig. 14). This truss is an example of the persistence of good design; it is nearly identical to one shown on Plate 54 of Asher Benjamin's *Practical House Carpenter* (Benjamin 1839), which he describes (p. 78) as "very ancient, strong and simple . . . and the best constructed plan of any now in use" (Fig. 15). Union's unusual feature, which suggests direct copying from the pattern book, is the double-strutted kingpost, from which one pair of struts rises to the approximate upper quarter point of the rafter while a lower pair rises to brace the head of the princeposts (or queenposts in Benjamin's terminology). Each pair of struts rises from its own set of joggles on the kingpost, diminishing the kingpost twice until it is only 4½x8 before flaring to near-perpendicular bearing at the heads of the rafters.

In spite of Benjamin's assertion that this truss is of ancient lineage, the double strutting from double joggles is rare in practice or in the literature surveyed. There are minor departures in joinery between Benjamin and the Huntington truss. Benjamin, in 1839, recommends using the then-modern center drilled bolt to join the kingpost with the bottom chord. In this system, a long hole is drilled up through the end grain of the post, arriving at a square chisel-cut hole where a nut will await the bolt that also passes through the bottom chord (Fig. 15 detail). The possibility of turning or restraining the upper nut is provided by grooves filed in the sides of the square nut that can be hit with a cold chisel. Further, at Huntington, both the king and princes have wedged half-dove-

tails at their bottom chord joints and, in the case of the trusses helping to support the steeple, the princes are closely paralleled by 1-in. iron rods dropping from the rafters and passing through the bottom chord. The rods may be contemporary with the truss but could also have been installed during the next 50 years with no identifiable difference in their form or manufacture. In addition to the bolt, Benjamin's drawing also provides for a larger wooden shoulder at the principal rafter-to-tie point of bearing than that found in the Union Meetinghouse.

While the Union Meetinghouse truss appears similar to the Castleton Federated truss, Castleton's support of the princeposts is more fully realized: the latter are trussed themselves by struts, serving as small main braces, rising from kingpost and bottom chord on opposing sides (Fig. 9). The difference may be attributed to Castleton's greater span. At Huntington, the princes are strutted from the kingpost but depend on a shoulder and pins at their junction with the principal rafter to resist movement toward the eaves as the princes are pushed and pulled downward. Meanwhile, a strut rises from a joggle at the foot of the princeposts at Huntington to support the rafter at its lower quarter point, while the head of the prince supports the rafter near its middle. As is often the case in traditional framing, the purlin loads are not supported by posts or struts directly under them, so as to avoid weakening the principal rafters by excessive joinery at any one point.

A steeple rises from the front end of the Union Meetinghouse, the corner posts of its lower stage resting on sleeper beams that cross the front eaves plate and two successive truss bottom chords (ties). At the nearer truss, the load at the rear of the steeple has

forced the shoulders to open a small amount at the post-to-tie joints. Any dovetail joint, particularly if fixed with but one pin, will be subject to deformation under load since its main source of resistance is the relatively weak side grain compression on the edge of the tail. The increasing density of the compressing material on the edges of the tail eventually brings this to a halt. In addition, the iron rods paralleling the princeposts at Huntington can carry all the tension at the joint, even though they stretch a bit and their washers indent the side grain of the rafters and chords where they bear.

The concerns of modern engineers contemplating the reuse of the building led to the introduction of a supplementary steel truss at the rear of the Huntington steeple. Fortunately, concerned preservationists involved in the project kept the new truss independent and nondestructive of the historic truss. This process of underpinning or overlaying the historic with the modern is not new. Patrick Hoffsummer illustrates a nave roof at Liege in Belgium composed of 12th-century collared rafter frames largely deprived of function when sistered by late 17th-century kingpost trusses little different from those we have been discussing (Hoffsummer 2002, 103).

—JAN LEWANDOSKI

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Photos Ken Rower

*Union Meetinghouse, Huntington, Vermont, 1870, finished in late neoclassical style, now converted to a public library.*



*Huntington, upper part of truss with struted princepost. Wind-braced principal purlins overlap the upper chords and connect the trusses.*

*Lower part of truss. Toe-nailed 2x8 joists pass under the tie beams to set lath 2 in. below ties. Long-serving tension joints have been reinforced.*



# Kingpost Truss Engineering, An Addendum

*The following commentary accompanies the article "Kingpost Trusses," published in the last issue of this journal as part of our continuing historic truss series. The author and the editor regret the delay in coming to publication. The thumbnail truss elevations at the top of the facing page can be seen in their proper size in TF 72.—The Editor.*

AS with the scissor and queenpost trusses described respectively in TF 69 and 71, the four kingpost roofs described at length in TF 72 were tested virtually via Finite Element Analysis (FEA), subjected to a standard roof live load based on 65 psf ground snow load, plus dead load of ceiling, floor, frame and roof as indicated. The results of these analyses are presented below. In the axial force diagrams printed on the facing page, compression is indicated by blue, tension by red.

The Lynnfield (Mass.) Meetinghouse (1714) stands out in age, material and morphology. Lynnfield is 83 years older than the next frame in sequence and, on average, well over a century older than its fellows. In its original form, it was framed entirely in oak, unlike any later structure we visited. The pattern of the Lynnfield truss, with its curved and tapered members, harkens back to the late Middle Ages, antecedents it shares with its closest chronological neighbor, the 1797 Rindge (N.H.) Meetinghouse (see TF 71).

The Lynnfield truss model performed well under load. Given mitigating factors like the modest span (32 ft., 4 in.), the stout material (oak) and the lack of a ceiling load, this does not come as a surprise. Predicted deflections remain within allowable ranges. Likewise bending stress, with the exception of the main braces at midspan where they share roof load with the rafters via connecting struts (which carry 6900 lbs. in compression). Here the deeper, stiffer braces take the lion's share of the load, supporting—and minimizing bending in—the rafter above at the cost of a 1650 psi spike in bending stress in the braces. Axial load distribution is ideal, with the major elements handling the bulk of the force (16,600 lbs. tension in the tie beam, 18,000 lbs. compression in the main braces). Tension at the kingpost foot is a mere 4100 lbs. Given the minimal force in the rafters near the peak, above the main brace junction the kingpost goes into compression, signifying the absence of uplift at the peak.

The Stafford (Vt.) Meetinghouse (1799) also evokes older carpentry traditions, with its distinctive strut layout and doubled, divergent upper chords, evocative of scissor trusses. Here long and large section timbers are spruce, the smaller, shorter pieces mixed beech, birch and maple. FEA output for the Stafford truss again shows deflection, shear and bending stress remaining in the fold save for local maximums in the tie beam where it cantilevers beyond the wall to support the flying plate and principal rafter foot. Given ample real world proportions (as opposed to the slender single line geometry of the model), this can be mostly written off as a computer artifact. Resultant axial forces break down as follows: 24,700 lbs. tension in the tie beam and kingpost, 13,400 and 18,200 lbs. compression in the main braces and principal rafters, 6400 and 7200 lbs. compression in outer and inner struts. Contrary to the builder's expectation as indicated by strut lap dovetail ends, the Stafford outer struts are loaded in compression rather than tension.

The major loads at Stafford—in main brace, rafter and tie—are equivalent to or smaller than those for the comparable span, double-rafter queenpost roof at Rindge (TF 71). Perhaps Stafford has an advantage because of its steeper pitch (about 9:12 vs. about 7:12). Offering dual vertical load paths to Stafford's one, the Rindge queenpost retains the advantage in post load. Outboard of the main brace feet at Stafford, tie tension drops from 24,700 to 14,200 lbs. And in the Stafford kingpost, tension falls off above the main braces and below the inner struts, to 10,500 lbs. at the peak and 11,600 lbs. at the kingpost foot joint.

In load sharing between doubled upper chords, the key issue is the relative stiffness of the end joints of the principal rafter versus those of the main brace (see TF 71, 21). The inboard locations of the braces allow them ample relish beyond their mortises into the tie and kingpost, a potential advantage over the principals, which land right at the tie and post ends. Foot joints are often difficult to examine *in situ*. Those we can inspect seem more prone to failure and impairment than most other connections in the truss, for a combination of reasons: the lack of relish beyond the mortise and the large forces involved, coupled with the low angle of attack of rafter to tie, all exacerbated by a high incidence of leaky eaves. The significance of the roof slope is that the geometry of low-pitch roofs channels more horizontal force against potential long-grain shear failure in the tie at the foot joint than it does comparable vertical breakout load on the kingpost at the peak (see TF 72, 19). The point: on both empirical and theoretical grounds, the principal rafter-to-tie beam joint is the likely weak sister in the mix.

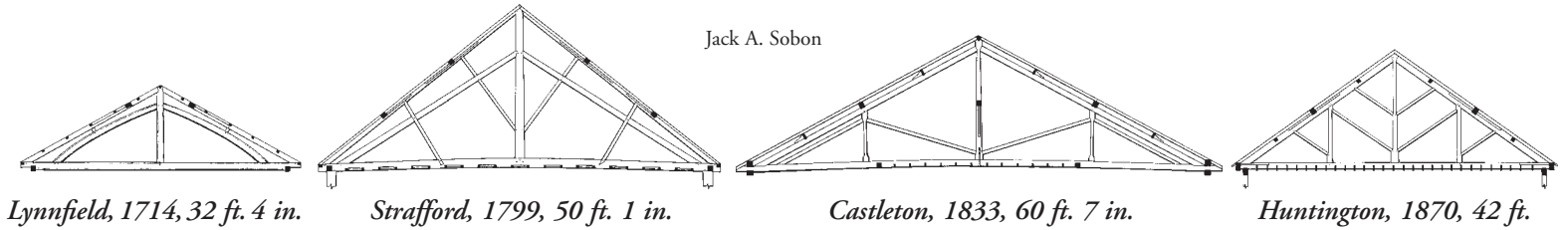
All in all, it's a fair assumption that the load-carrying capacity of the Stafford main braces is greater than that of the principal rafters, a conjecture reinforced by the absence of housing or joggle at the head of the kingposts. The Stafford truss was modeled first with the foot joint as a pinned connection, with results detailed above, then as a roller bearing (vertical support but no horizontal restraint), and finally with full vertical and partial horizontal restraint.

Under the roller bearing scenario, tie tension rises to 30,400 lbs., kingpost tension to 27,900 lbs. Main brace compression climbs to 36,300 lbs., while principal rafter foot load falls to a paltry 980 lbs. Strut compression grows to 8900 and 5500 lbs. in and out. The kingpost foot joint carries 13,300 lbs. in tension, while the post peak goes into compression to the tune of 10,700 lbs. (thereby putting the rafter peaks in tension).

The third, and perhaps most realistic, loadcase shows tension of 20,700 and 25,900 lbs. in tie and kingpost, 24,800 and 9300 lbs. compression in main brace and rafter, 8400 and 6000 lbs. in inner and outer struts. Some 12,100 lbs. hang from the kingpost foot, while the kingpost peak is almost a no-load situation, with 530 lbs. compression in the post. Tension load at the tying joint (rafter foot to tie) is a modest 6900 lbs..

The Castleton (Vt.) Federated Church (1833) moves us firmly into the classical kingpost idiom, with a truss spanning an ambitious 60 ft., 7 in. Nesting inside the major triangle are two minor trusses built around princeposts which, fractal-like, echo the parent truss. The central struts rising from the kingpost foot double as struts descending from the princepost peaks, each opposed by an outer strut paralleling the main upper chord (principal rafter).

The Castleton computer model predicts tension loads of 37,900 and 15,500 lbs. in tie and kingpost, 31,000, 17,800, 12,800 and 2700 lbs. compression in rafter, inner strut, outer strut and princeposts. The kingpost pulls tension throughout, carrying 4900 lbs. at the foot joint and 15,500 lbs. at the peak. The princeposts lift 2600 lbs. at their feet and carry a compression load of 8500 lbs. at their heads. Tying joint tension at the eaves is 26,500 lbs. Nothing alarming about these numbers, but there are multiple instances of bending stress up in the 1600 psi range, pretty high for Eastern hemlock, and a 1½-in.-plus sag in the rafters.



Trying the partial or total foot thrust release (as at Strafford, above) is no help. Deflections increase to over 2 in. and then over 4 in., and bending stresses inflate, first slightly, then off the scale. So Castleton's load-carrying capacity doesn't seem to measure up to expectations engendered by its elegant design and neat construction, although I can't say that we found visible signs of structural inadequacy during our inspection. It may be that the truss was never fully loaded in service (indeed Vermont snow load tables specify a design load of 40 psf in Castleton compared to 50 psf in Strafford, 60 psf in Huntington and 70 psf in ski-country Stowe). Or perhaps, as we have also suggested before, the old-growth hemlock used in Castleton outperforms modern design values.

Maybe it would have helped to adopt a truss pattern more like that of the 1870 Union Meetinghouse in Huntington, Vt., an almost exact copy of a pattern from Asher Benjamin's *Practical House Carpenter* (1830). The FEA model of the Union truss does not disappoint. Predicted deflections are minimal. Bending is modest save at the ends of the princeposts where impacted by strut loads, and even there, stress does not exceed allowable values. Axial loads are among the lowest we have seen: 22,200 and 14,100 lbs. tension in tie and kingpost, 27,800 lbs. rafter compression. Strut compression ranges from 4300 to 5800 lbs. Princeposts feel scant axial force at midspan, 2400-2500 lb. compression at their end joints. Adjacent princerods pull 2500 lbs. Tension at the kingpost foot joint is a mere 2000 lbs.

—ED LEVIN

