HISTORIC AMERICAN ROOF TRUSSES

I. Scissor Trusses

THIS article is first 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 Queenpost Trusses.

She. . . devoured a Trusse of Sallet. (Thomas Tickell, 1712)

The Wooden Trusses, or rather Arches under its Roof . . . .
(C. Labelye in a description of Westminster Bridge, 1751)

A truss is a framed structure with a system of members so arranged and secured to one another that the stresses transmitted from one member to another are either axial tension or compression. (H. Parker, *Simplified Design of Structural Wood,* 1988)

IN THE English language, the word *truss* has been used since at least the 14th century to refer to a group of objects, usually agricultural products, bound firmly together. By the mid-18th century, the word is in use to describe both built-up beams and roof frames that would, by virtue of ingenious joinery and arrangement of members, span greater distances and support heavier loads than would traditional English late-medieval roof systems. These improved roof frame designs, based largely upon Italian examples found in books by Palladio and others, had been sporadically used in England since the 16th century. By the mid-19th century, the modern principles of truss behavior were articulated and, following the work of Squire Whipple, Herman Haupt and others (see Bibliography), subject to quantitative analysis.

Most vernacular wooden roof trusses constructed during the several hundred years when these principles were evolving were designed and built by framers using their experience, structural intuition and familiarity with the materials, on occasion with the assistance of a drawing in one of the many contemporary builders' guides, which often illustrated trusses for different spans. Some of the trusses, even comparatively early ones, conform tightly to strict notions of axial loading and equilibrium of forces. Others, from all periods, depart from what a modern engineer would call true truss form and reflect either the need to position members eccentrically to make room for their timber joinery or an idiosyncratic understanding of the form. The historical availability of very large dimension timber, and certain properties of timber such as its great resistance in shear perpendicular to the grain, have allowed many departures from true truss form to function successfully for hundreds of years.

Anywhere in the eastern US, the best framing in town is likely to be concealed in the attics of churches and public buildings, in the form of timber trusses commonly spanning 36 to 72 ft. in the clear. Before 1850, the great majority of American roof trusses fit into four categories—kingpost, queenpost, scissor and raised bottom chord—and regional variations on them such as the Germanic *Liegenderstuhl* (see TF 52) in eastern Pennsylvania. The trusses were undoubtedly built by the more ambitious professional framers in a locality, whose names in most cases have been forgotten. Their material was local timber—the preferred and the available species—and it's evident from the checking and movement in the truss members as well as commentary from the period that the timber was used green. "Observe that it is best to truss girders when they are fresh sawn out," wrote Peter Nicholson in the 1837 edition (the 12th) of *The Carpenter's New Guide*. Earlier, in *The New Practical Builder* (1825), Nicholson had written:

> The usual EXTERNAL FORM of a roof has two surfaces, which generally rise from opposite walls, with the same inclination. . . . To FRAME TIMBERS, so that their external surfaces shall keep this position, is the business of *trussing*; and the ingenuity of the carpenter is displayed in making the strongest roof with a given quantity of timbers. . . . No direct rule can be given for the disposition and position of supporting timbers: the best way to judge of this is, such a disposition as will make the connecting timbers as short as possible, and the angles as direct as possible. Oblique or acute angles occasion very great strains at the joints, and should therefore be avoided. One grand principle to be obtained, in every frame or roof, is, to resolve the whole frame into the least number of triangles, which must be considered as the elements of framing. Quadrilateral figures must be avoided, if possible; and this may be done by introducing a diagonal, which will resolve it into two triangles; for, without this, a four-sided figure will be moveable round its angles. Sometimes it may be necessary to resolve a quadrangular piece of framing into *four* triangles, by means of two diagonal pieces, particularly when this figure occurs in the middle of a roof.

While constructed of large wooden members, many historic trusses use original iron straps or bolts at joints where substantial tension occurs. Trussed roof systems are common; perhaps as many as 10,000 still exist in the US from before 1850. After 1850, many trusses are found fitted with more iron in the form of king or queen rods and iron shoes at the feet of principal rafters. If we extend our survey period to 1925, after which roof trusses become replaced by all-steel trusses or factory-made wood trusses with steel connectors, their number may be 20,000.

Whatever their number, historic roof trusses are little studied. Church and meetinghouse attics are dark, filled with bat droppings and noxious thermal insulation materials; they normally lack floors and they are difficult of access. But searchers who persevere are amply rewarded by the magnificence of the structure they find. Notable work was done by J. Frederick Kelly in his two-volume

Early Connecticut Meetinghouses (1948), which contains drawings of the truss forms found in 84 pre-1830 meetinghouses. David Yeomans' book *The Trussed Roof* (1992) deals primarily with English sources for American trusses but also includes New World examples, as do his articles "A Preliminary Study of 'English' Roofs in Colonial America" and "British and American Solutions to a Roofing Problem." The late Lee Nelson also devoted valuable attention to roof truss joinery in the Delaware Valley and elsewhere.

It is common today to refer to the upper and lower major elements of trusses as *top* and *bottom chords*, and to be understood. But the published builders' authorities in 18th- and 19th-century America used a more familiar terminology. Generally, in the works of Benjamin, Nicholson, Treadgold and Bell, roof frames are said to have *principal rafters* and *tie beams* rather than top and bottom chords. In the extensive papers of John Johnson, a framer of both bridges and churches in Burlington, Vermont, from the 1790s to 1840, and later the Surveyor General of the state, church trusses have beams below and rafters above. In our discussion of scissor trusses, reference to the tie beam or lower chord is complicated by the two-part nature of what in other trusses is a single member. The terms *scissor chord* and *scissor tie* will be used interchangeably to refer to one part of this distinctive assembly and, in the plural form, to refer to the complete assembly.

THE SCISSOR TRUSS. Distinct from other major truss types, the scissor has a two-member tie beam, or bottom chord, with each member bearing on a wall and restraining the principal rafter (or upper chord), then rising at an angle to cross the other rising tie and terminate near the midpoint of the opposite principal rafter. Frequently a kingpost and sometimes struts are incorporated into the truss as well. Occasionally the tie beams cross but do not reach the opposing rafters, terminating in space or in the side of a vertical strut instead. Scissor trusses were commonly used in roof framing to accommodate interior vaulting, domes and coves, or whenever the center of the ceiling beneath was designed to rise higher than the wall plates of the building. The lack of any horizontal tie beam separates the scissor truss formally from various raised bottom chord trusses that may have scissors braces or ascending bottom chord-like members. It is also distinctive because the rising members are positively joined at their crossing.

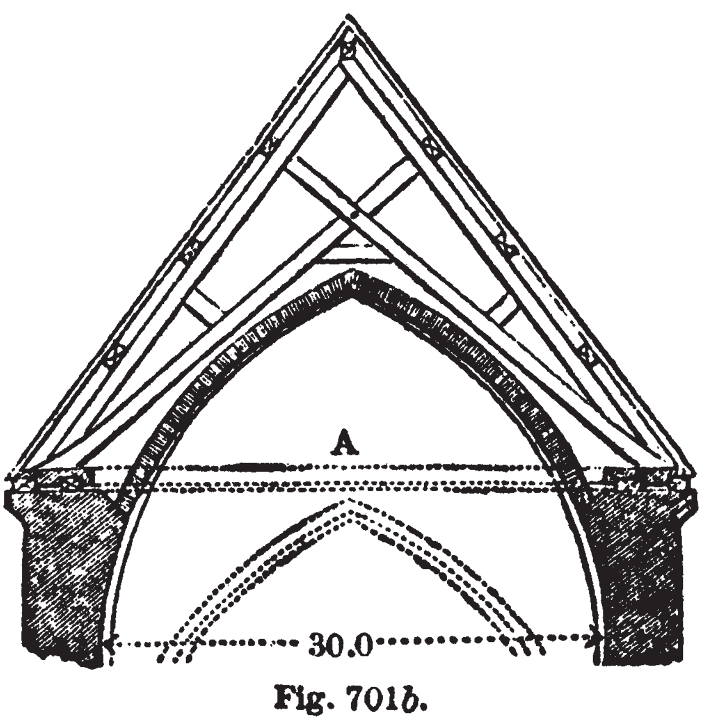
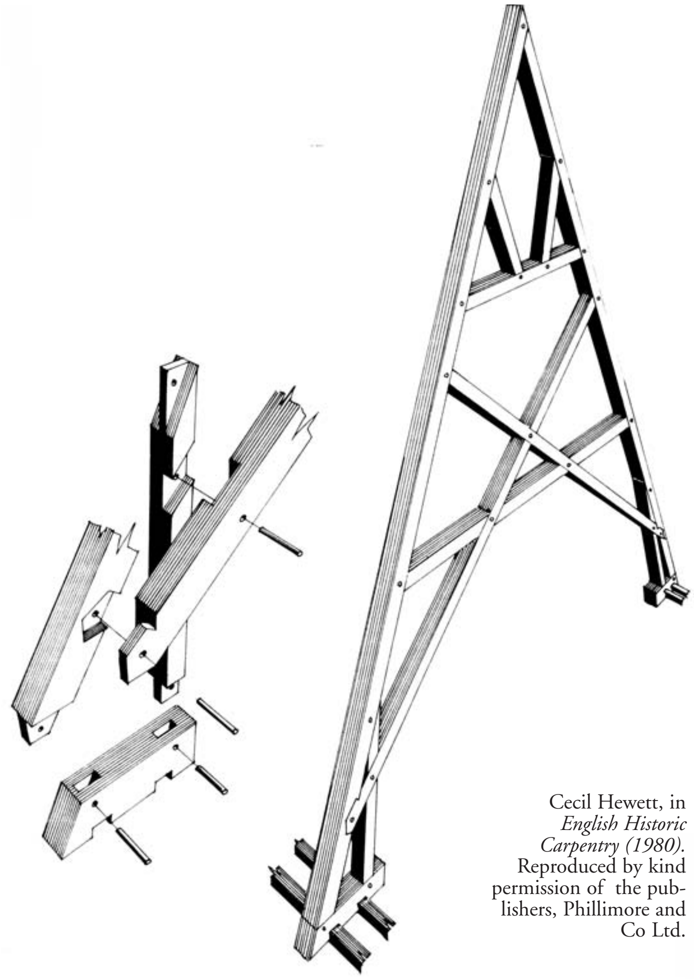


FIG 1. GWILT'S ILLUSTRATION OF AN EARLY FORM OF SCISSOR TRUSS.

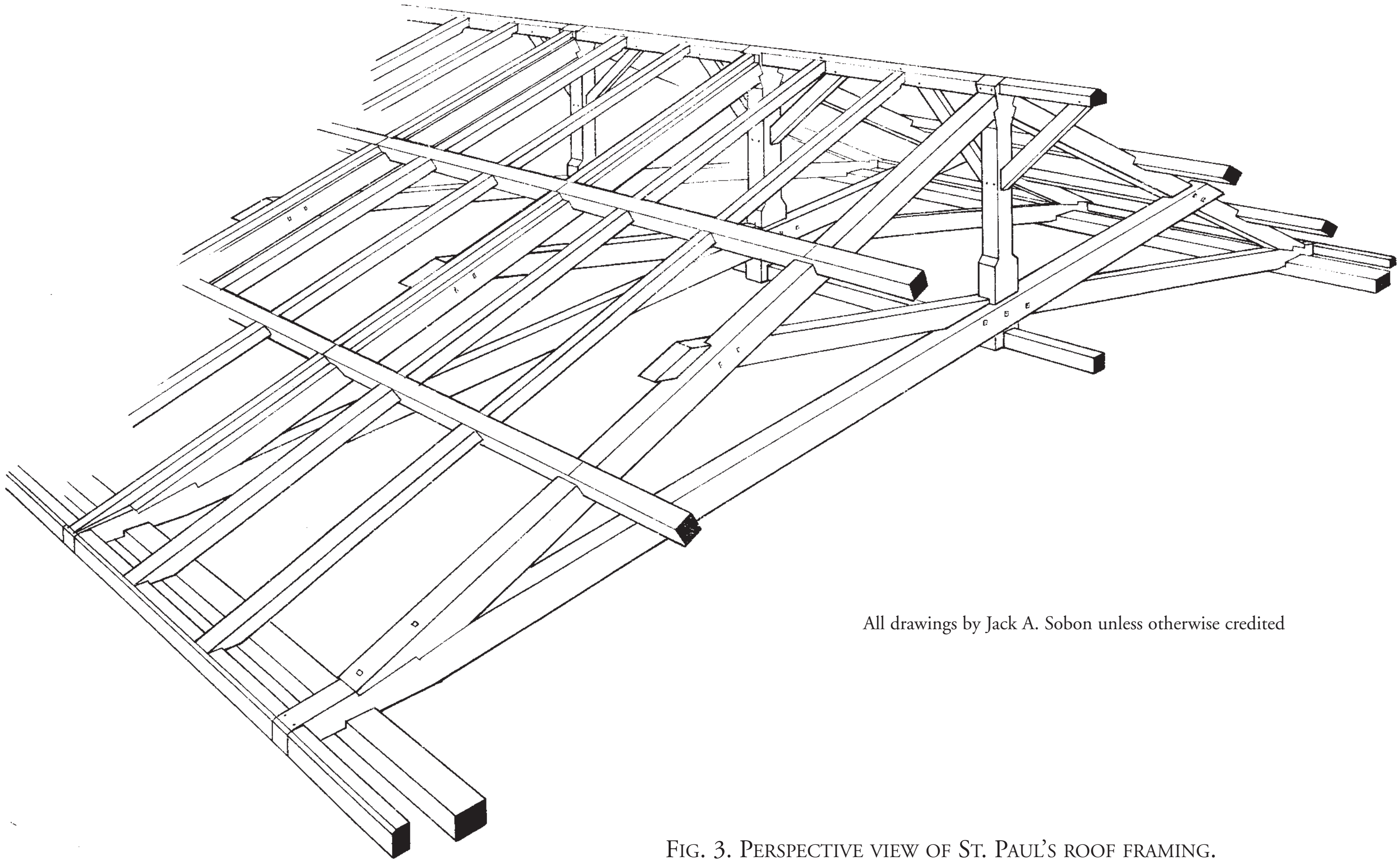


Cecil Hewett, in *English Historic Carpentry (1980).* Reproduced by kind permission of the publishers, Phillimore and Co Ltd.

FIG. 2. SCISSOR-BRACED ROOF CROSS-FRAME, NORTHEAST TRANSEPT, LINCOLN CATHEDRAL, CA. 1200.

A great many medieval roofs were of scissor truss form. If the scissor members did not provide bearing to the principal rafters, or if they were not continuous, such roofs were, properly termed, *scissor braced*. Joseph Gwilt's 1867 *Encyclopedia of Architecture* provides a drawing of a roof frame identifiable to us as a scissor truss without kingpost, and calls it a northern French method of roofing over vaulting (Fig.1). Hewett illustrates a number of scissor-braced roofs (Fig. 2). In both sources the indicated timber sections (or scantlings) are small, typically 5x5. Scissor trusses of similar form, though with larger timber, show up again during the Gothic revival in America during the mid-19th century. A good example is in the 1876 Congregational church in Barton, Vermont, discussed below. The steep pitches and relatively narrow spans of medieval Gothic roofs avoided many of the problems of bending and pushing walls apart that heavy timber trusses are designed to solve in relatively low-pitched, wide-span structures.

Throughout most of the 18th and 19th centuries, Neoclassical designs dominated church construction in the eastern US, encouraging flatter roof pitches, commonly as low as 6:12, over wider spans of 32 to 70 ft., unsupported by aisle posts. Sometimes trusses were asked to support steeple loads and suspended galleries as well. Shallow vaults, domes and coved ceilings were in style, and scissor trusses were built to accommodate them. These trusses sustained higher bending and tensile forces than the steeply pitched Gothic forms. Consequently, strengthening members were added, different joinery incorporated and scantling sizes increased. In Kelly's 1948 study of pre-1830 Connecticut churches, some ten out of 84 roof systems were varieties of scissor trusses, and all included kingposts as well as subsidiary posts variously called queenposts, princeposts or struts.



All drawings by Jack A. Sobon unless otherwise credited

FIG. 3. PERSPECTIVE VIEW OF ST. PAUL'S ROOF FRAMING.

ST. PAUL'S EPISCOPAL CHURCH (1822), Windsor, Vermont. With a span of 50 ft. and a roof pitch of 6:12, St. Paul's is a successful example of an American-style scissor truss used in a Neoclassical rather than a Gothic design. The scissor chords foot their principal rafters and join opposing principal rafters near the latter's midpoints, the whole assisted only by a single kingpost. The scantling sizes are large: the scissor ties are 7x13, the principal rafters 9x11 and the kingposts 9x12. The joinery is sophisticated and exacting, in that a great many bearing shoulders are produced and then well fastened with T-headed wrought bolts recessed into the faces of the timber. The timber is all high-quality old-growth white pine except for the braces of mixed oak. The layout, like that of virtually all historic trusses, is scribed, but with no evidence of the use of the 24-in. mark system of fitting (see TF 24:9).

The role of the kingpost in this scissor truss is fourfold:

1. With the flat pitch of the roof and low rise of the vault, the scissor beams are long and subject to sagging because of ceiling- and self-weight, and possibly subject to compressive buckling. The kingpost, trapped and supported at the top by the principal rafters,

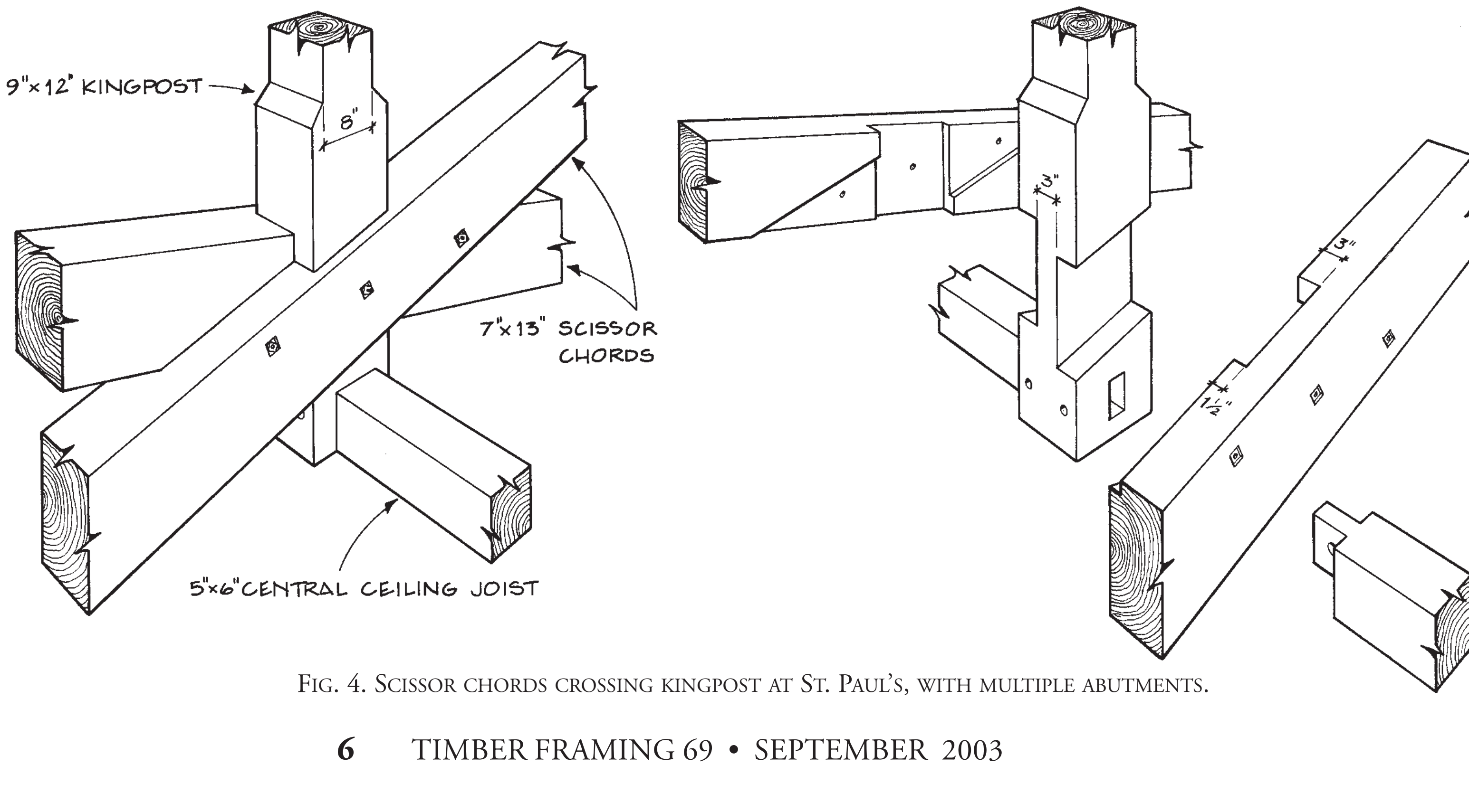


FIG. 4. SCISSOR CHORDS CROSSING KINGPOST AT ST. PAUL'S, WITH MULTIPLE ABUTMENTS.

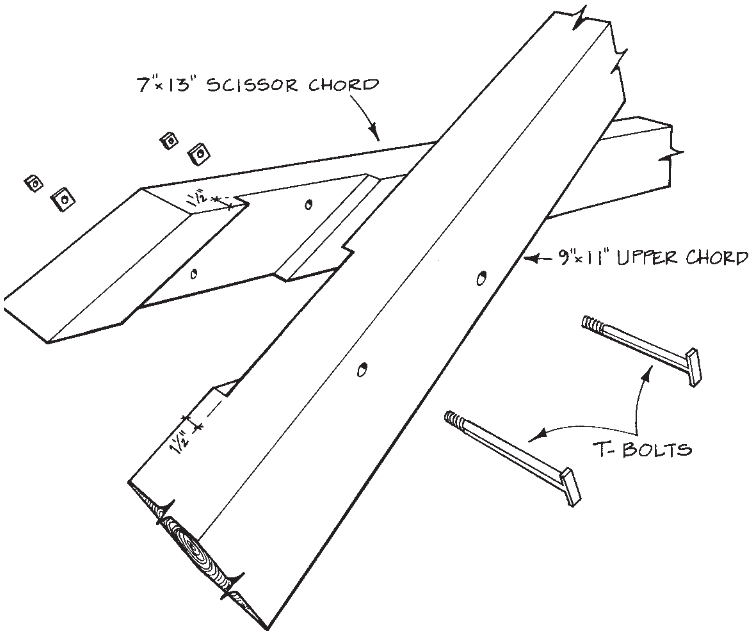


FIG. 5. CONNECTION AT UPPER END OF SCISSOR CHORD, ST. PAUL'S.

is in tension, holding up both scissor chords where it intersects them near their midpoint.

2. Since the combined scissor chords can be seen as a divided, angled tie beam or bottom chord, the joint where they cross each other is responsible for bearing the tensile loads in that tie. The addition of the kingpost at that joint provides both additional room for joinery and more bearing shoulders. At St. Paul's, the kingpost allows 12 sets of bearing shoulders to be developed around it (Fig. 4), as opposed to only four if the bottom chord members merely clasped each other in passing. It also contributes its own triangulated stiffness. In fact, the framers of St. Paul's were so eager to use the extra material the kingpost made available for joinery that they fabricated a non-planar truss—it will not lie flat on a deck—by bending the scissor beams outward slightly (or perhaps by using a natural bend) where the three members meet, in order to clasp and shoulder adequately but still leave plenty of wood in each member.

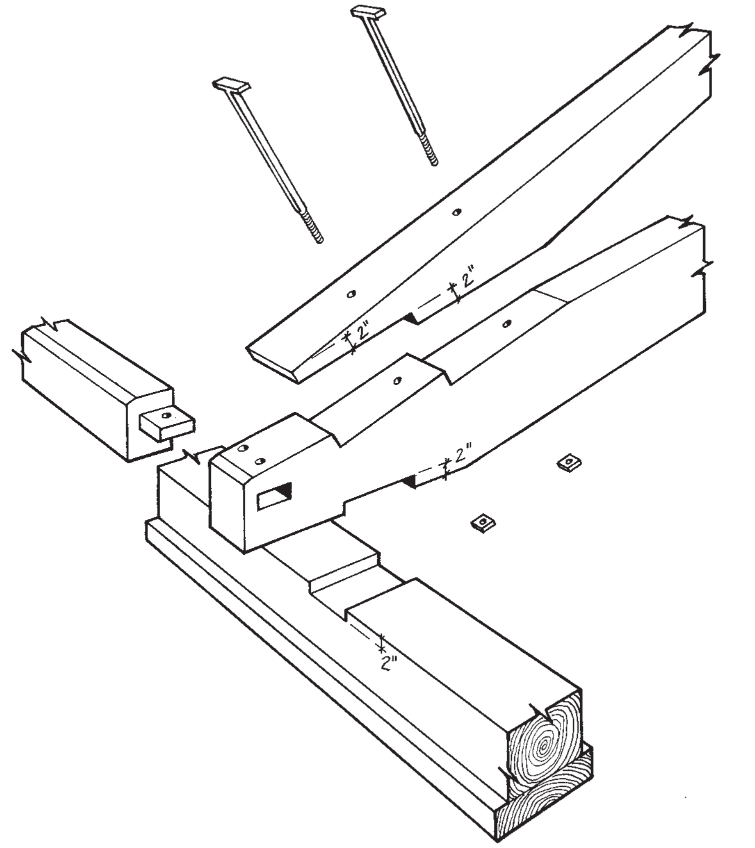


FIG. 7. EXPLODED VIEW OF PRINCIPAL RAFTER BEARING ON SCISSOR CHORD AND SCISSOR CHORD BEARING ON PLATE AT ST. PAUL'S.

The joint at the opposing rafter also may contribute to resisting tension in a lower scissor chord, but in most observed cases the joint is shallow, providing short relish on the pins (if they are there at all), and suggesting that the framer only expected compression at this joint. Asher Benjamin in *The Elements of Architecture* (1843) is specific on this point, describing the portion of a scissor beam between the rafter foot and the kingpost as being in tension, and the segment from kingpost to rafter as being in compression. The behavior of the members may well be more complex and depend upon loading conditions such as wind, snow, steeple loads and suspended galleries. Stress reversals may occur. At St. Paul's, between the upper end of the scissor beam and the principal rafter (or upper chord), the framers fabricated a semi-engaged, double-bolted and shouldered lap joint with a small amount of end relish (Fig. 5). Their intention may have been to gain additional resistance to tension in the scissor chord, or this joint may have been necessitated by the notable displacement from the truss plane of the scissor members at the kingpost, and the subsequent difficulty of bending the scissor members back into the plane of the rafters over a short distance.

3. The kingpost provides the basis for longitudinal bracing of the roof system, achieved by braces rising from the kingposts to a five-sided ridge.

4. Finally, the kingpost in St. Paul's carries a longitudinal wooden member tenoned into its bottom end that supports the center of the lath system for the plaster ceiling below. (In stone vaulting this element is called a ridge rib.)

The bearing of the principal rafter on the scissor chord is a double-shouldered notch normal to the rafter, affixed with two T-bolts (Figs. 6 and 7). The outermost shoulder has bearing right at the outer edge of the wall plate. Beyond this outermost shoulder, 13 in.

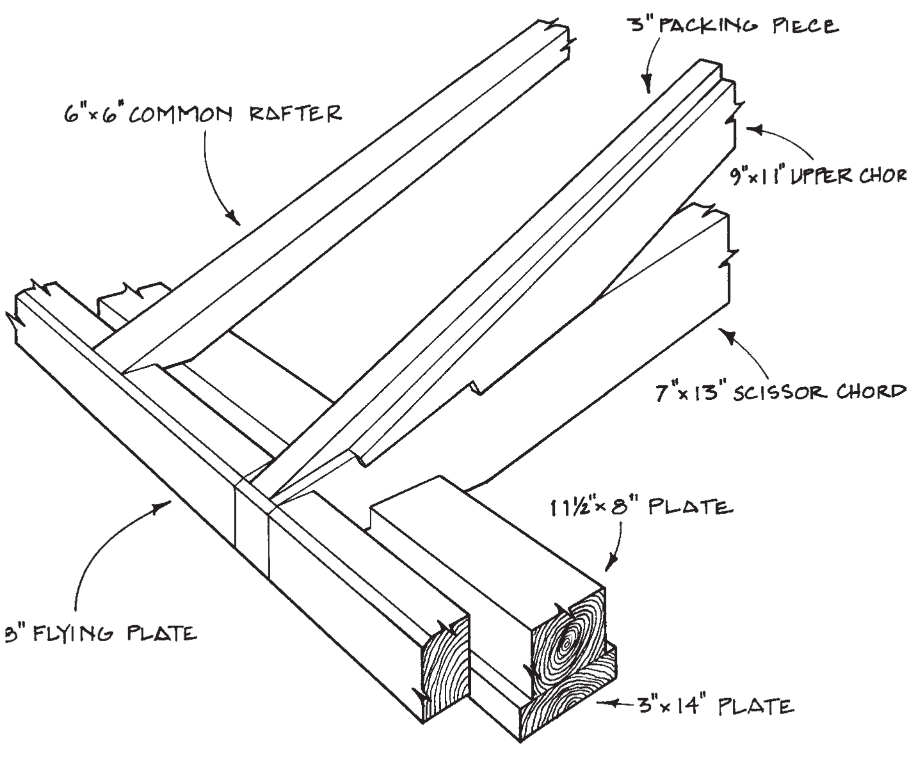


FIG. 6. ST. PAUL'S TRUSS FRAMING VIEWED AT WALL PLATE.

Ken Rower

St. Paul's Episcopal Church, Windsor, Vermont, 1822.

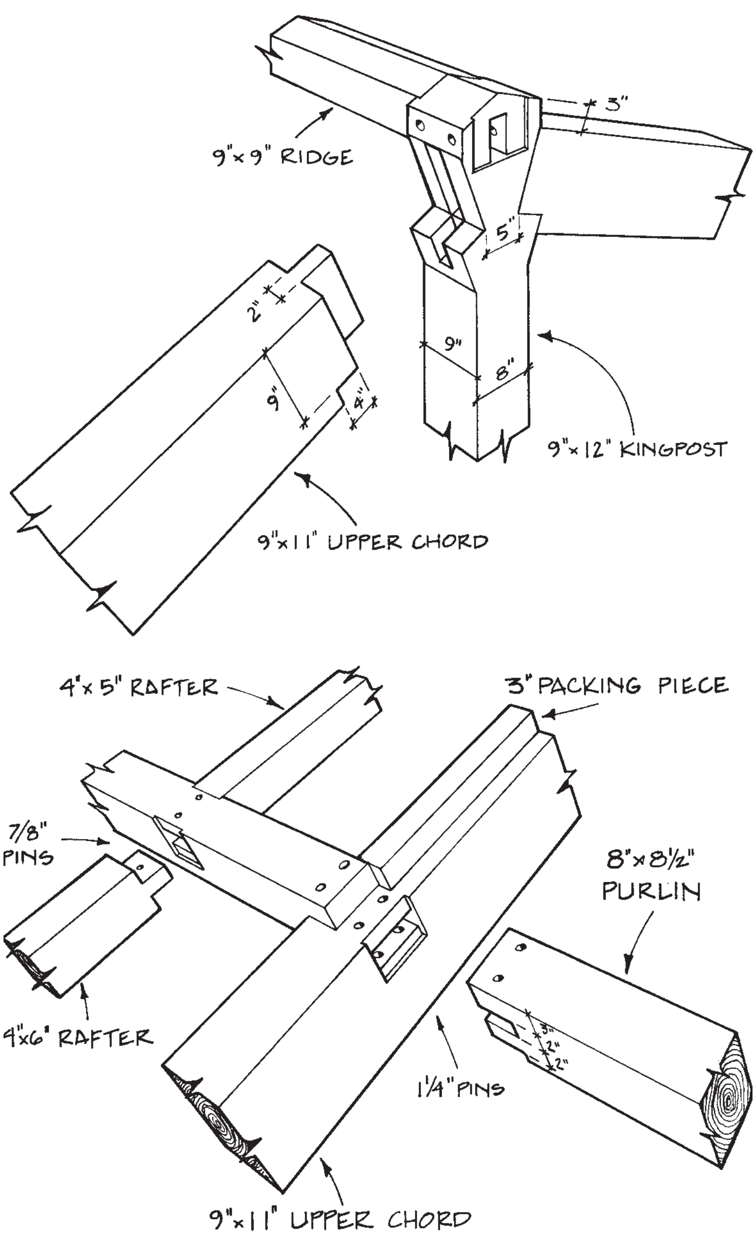


FIG. 8. KINGPOST AND PURLIN CONNECTION DETAILS, ST. PAUL'S.

of relish form an eave overhang, including a flying plate tenoned and pinned. Substantial relish beyond the bearing shoulder serves two purposes: one is the provision of adequate end distance for the joint, and the second, particularly important in cold and snowy parts of the country, is the location of joinery well inward from the eaves, which are very subject to leakage and deterioration from ice damming. Lowering the top of the principal rafter 3 in. below the top of the common rafter and purlin plane accomplishes this inward movement, and also favorably allows the purlins to bear partly on top of the principal rafter (Fig. 8).

Each scissor chord is notched over the 11½ x 8 wall plate, itself notched 2 in. deep to receive the chord. This plate sits upon a 3x14 plank covering most of the top of the brick wall. It is impossible to determine in its assembled condition how well this lower plate is affixed to the brickwork, but it is clear that the upper plate is meant to float atop the lower, attached with only a few nails. This is probably designed to accommodate the tendency of a scissor, or any truss with a raised or discontinuous bottom chord, to spread apart some distance when first erected.

The first interior scissor truss at St. Paul's stands under the rear of the telescoping framing that carries a two-stage belfry and cupola. The designer or framer was aware of the deflection these loads were likely to cause in any truss so located, particularly a scissor truss. Intermediate posts were thus erected off the top of the vestibule wall that crosses under the middle of the belfry frame, and braced girts and steeply angled braces were framed from these vestibule posts into the rear belfry posts over the truss, so as to transfer most of this rear steeple load forward and to the ground through the vestibule wall, with apparent success.

The St. Paul trusses stand 9 ft. 6 in. on center, linked longitudinally by a 9x9 five-sided ridge and its oak braces mortised into each kingpost head, the ridge rib mortised into each kingpost extension at the center of the vault and, finally, by the 8x8½ purlins (Figs. 3 and 8). There are three rows of purlins including the eaves purlin (or flying plate), and three sets of common rafters. Reflecting their load, the upper common rafters are 4x5 in section, the middle commons are 4x6 in section and the lower are 6x6, while their lengths are nearly identical. Such refined reflection of load in timber sizing is more typically a trait of older scribe rule framing (before 1800)—which, often following the natural lines of the material, used non-uniform sections, tapered rafters, flared posts, and the like—than of 19th-century industrialized framing, which tended toward repetitive member sections, modularity, uniformity of section along a length and a very simplified lumber list, in spite of an increasing ability by builders to analyze frame loads quantitatively.

St. Paul's of Windsor, seen in the photo above at left, was designed by Alexander Parris, and the roof was possibly framed by Solomon Willard, with whom Parris is known to have worked in Boston. Parris is associated with Asher Benjamin and Ammi Young as the best-known designer-builders of the transitional period from the Federal style to the Greek Revival style in New England. Elements of both styles appear in the photograph. It is not known whether the roof truss was designed by Parris or Willard or by a skilled local framer, but Parris did apprentice from 1799-1801 with a housewright, and it was common at the time for architects (or at least those who owned books) to design the framed truss if one was called for by the nature of the building.

THE FIRST PARISH FEDERATED CHURCH (1826) in South Berwick, Maine, shown in the photo on the facing page, is 47 ft. wide by 68 ft. long; its scissor trusses (Fig. 9) span 45 ft. in the clear over the audience room. (This last term, found in Kelly, will be more inclusive for our purposes than the modern "sanctuary" or the Gothic "nave.") The trusses include

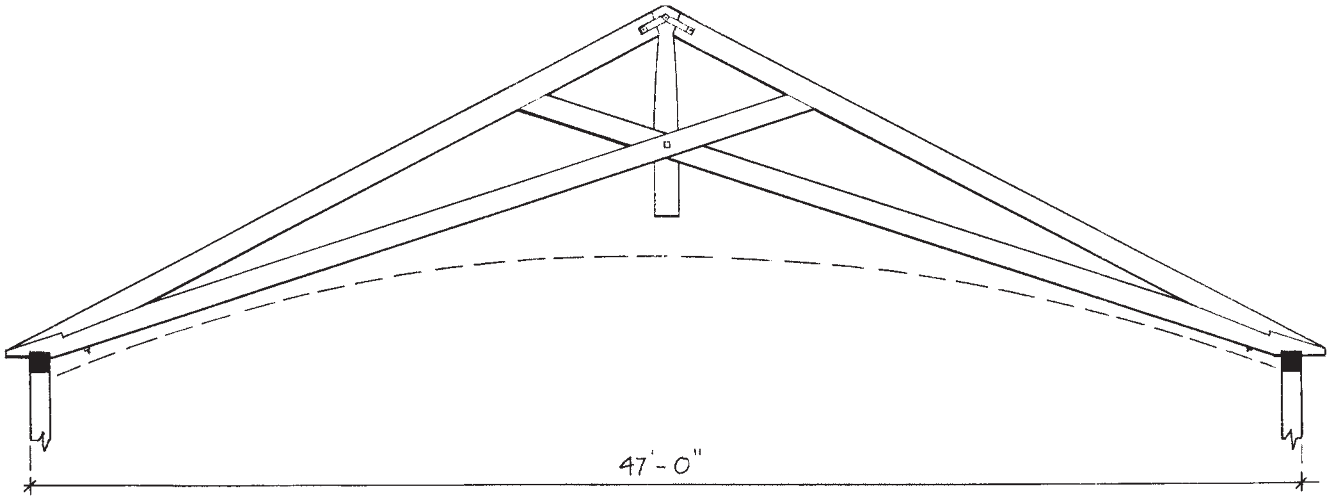


FIGURE 9. ELEVATION OF SCISSOR TRUSS AT FIRST PARISH FEDERATED.

Ken Rower

First Parish Federated Church, South Berwick, Maine, 1826.

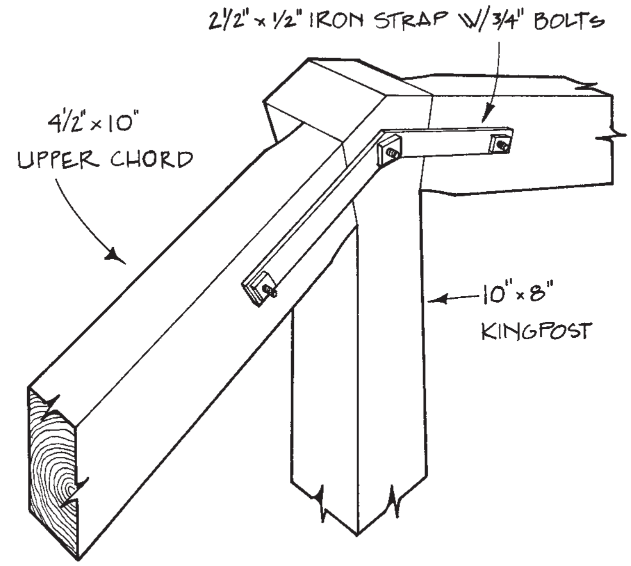


FIGURE 10. STRAPPED KINGPOST JOINT, FIRST PARISH FEDERATED.

kingposts and are closely spaced, 2 ft. 11 in. on center, producing a remarkable count of 19 trusses. Close spacing reduces scantling sizes and eliminates the need for purlins or common rafters (see "The Close Spacing of Trusses" in TF 67). The timber is all softwood, a mixture of Eastern white pine and Eastern hemlock; the roof pitch is 6.3:12. The 4½ x10 rafter and scissor chord material is hewn three sides and sawn one side, indicating that baulks were hewn approximately 10x10 and then sawn down the middle to make two timbers. An iron strap with three bolts spans the face of the mortise and tenon joints between the kingpost and the principal rafters (Fig. 10), probably an attempt to compensate for the less-than-right-angle bearing of the rafters at the kingpost head.

Many historic trusses in this country depart farther yet from normality to the rafter axis at the kingpost joint, without any resulting displacement at the joint. (A good example is the kingpost truss at the 1760 Christ Church in Shrewsbury, N.J.) This stability may be due to the rafter's hard end grain compressing into the kingpost's softer side grain at the joint and so developing adequate friction, along with a little help from the stub tenon—although relish between the end of the rafter mortise and the top of the kingpost is generally so short that it alone could bear little load.

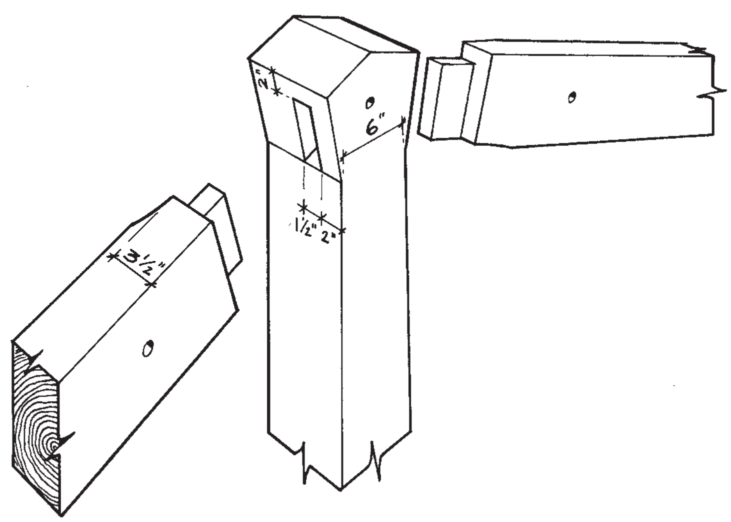


FIGURE 11. AT FIRST PARISH, PRINCIPAL RAFTERS ARE HELD TO FRONT FACE OF KINGPOST RATHER THAN CENTERED, AND INNER TENON SHOULDERS ARE HEWN AWAY.

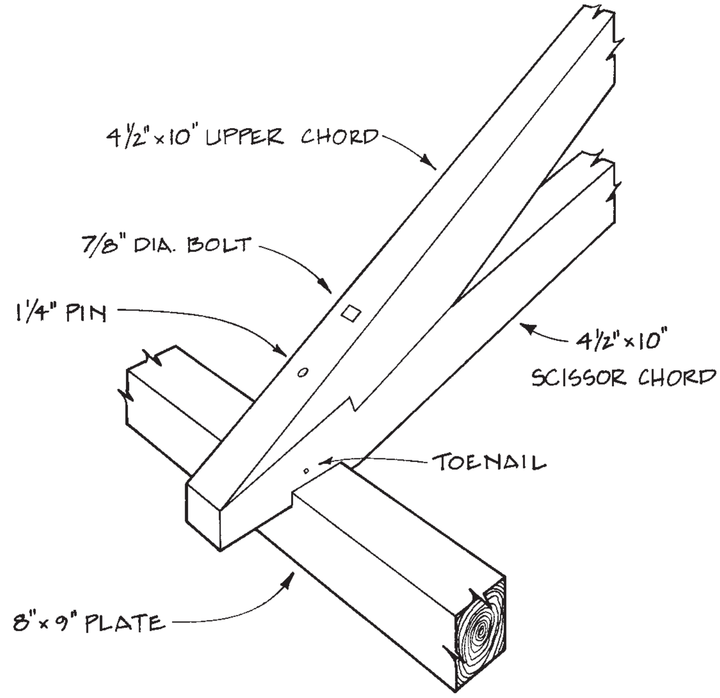


FIGURE 12. RAFTER FOOT AND SCISSOR CHORD TERMINATION AT PLATE, FIRST PARISH FEDERATED.

At First Parish Federated, 4½ x 9½ scissor tie beams sit upon the wall plate and 4½ x 9½ principal rafters bear upon them with a single shoulder, normal to the rafter, assisted by a 1¼-in. pin and a ⅞-in. bolt (Fig. 12). The scissor ties cross and clasp each other at the kingpost and then continue on to join via barefaced tenons the bottom surfaces of the opposing principal rafters, above the latter's midpoint (Fig. 15). The mortise and tenon joint at the rafter is unpinned, designed only to work in compression, but, when examined, it was slightly withdrawn on most trusses, indicating that, if compression occurs, it is sporadic.

The 8-in.-thick kingposts are shaped with a form of entasis: at 10 in. wide for the lower two-fifths of their length, they curve in gracefully to 6 in. at the neck below the rafters, then return to 10 in. wide across the flared head. The scissor ties half-lap into each

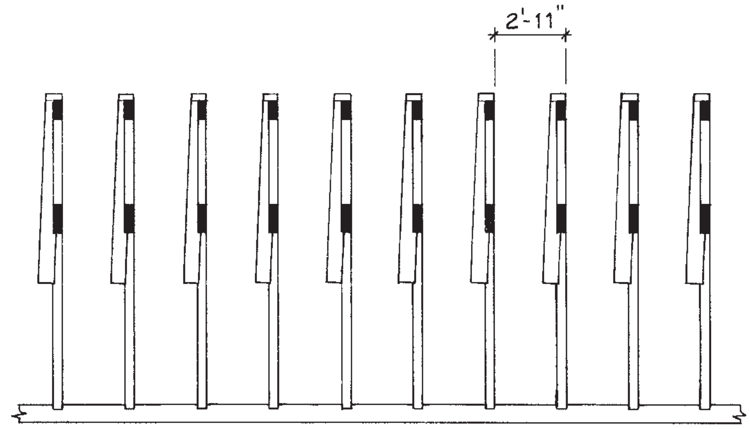


FIGURE 14. KINGPOSTS AT FIRST PARISH ARE FORCED OUT OF PLUMB BY CROSSING OF SCISSOR CHORDS.

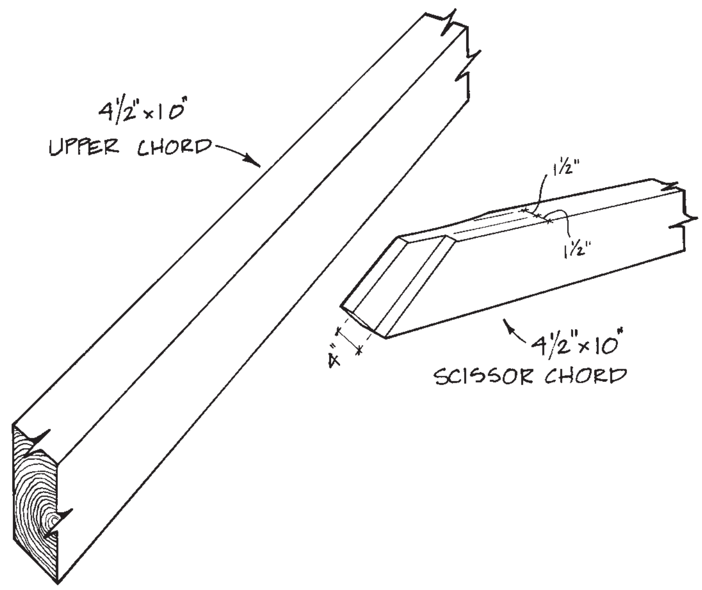


FIGURE 15. EXPLODED VIEW OF SCISSOR CHORD TO UPPER CHORD (PRINCIPAL RAFTER) CONNECTION, FIRST PARISH FEDERATED.

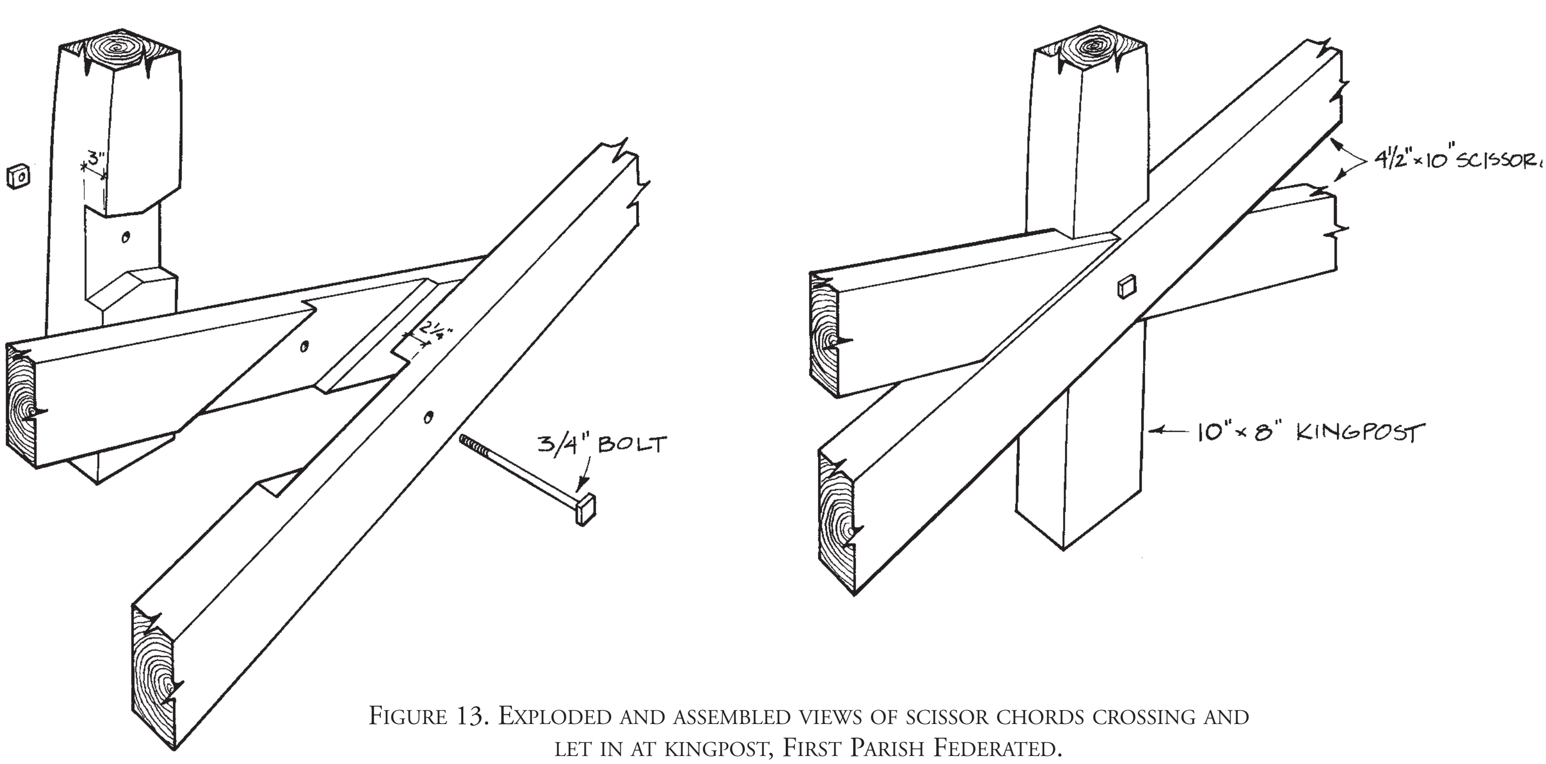


FIGURE 13. EXPLODED AND ASSEMBLED VIEWS OF SCISSOR CHORDS CROSSING AND LET IN AT KINGPOST, FIRST PARISH FEDERATED.

other at their crossing and bear on a kingpost shoulder there, but (unlike the truss at St. Paul's) do not clasp the kingpost, although the three members are all transfixed by a ¾-in. bolt (Fig. 13). The geometry of this arrangement is such that the kingposts do not hang plumb but slope a few degrees to the rear of the rafter-tie beam vertical plane (Fig. 14). Again we have a non-planar truss (but at St. Paul's the rafters depart from plumb rather than the kingposts). Additional eccentricities at the South Berwick church are the greater thickness of the kingpost compared to the principal rafters, the setting of the principal rafters to the front face of the kingposts (presumably to minimize the distortion in the truss) rather than to the customary center (Fig. 11), and the adzed reduction of the rear shoulder of the principal rafter at this joint. The resulting barefaced tenon has substantially less compressive bearing than a two-shouldered tenon.

The trusses are seated in a trench on the 8x9 wall plate. The scissor chord does not notch over the plate, but is affixed to it by a 1¼-in. hardwood pin and two small toenails (Figs. 12 and 16). This arrangement suggests that the trusses were erected and allowed to find an equilibrium within themselves while spreading a bit, unrestrained by any notch. Once the trusses settled, the toenails likely stabilized them while the 1¼-in. hole for the pin was bored. St. Paul's of Windsor also has provision for some spreading of the scissor truss—always preferable, of course, to the trusses pushing the walls out of plumb.

The only visible signs of a layout system at Berwick are Roman numerals on each kingpost, slightly above the scissor crossing, suggestive of the scribe method that persisted in bridge and roof truss framing long after it had been abandoned for other sorts of frames.

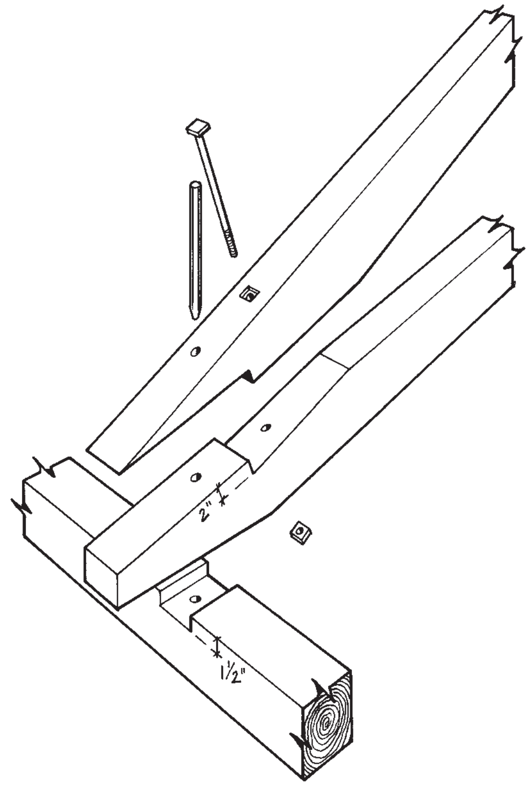
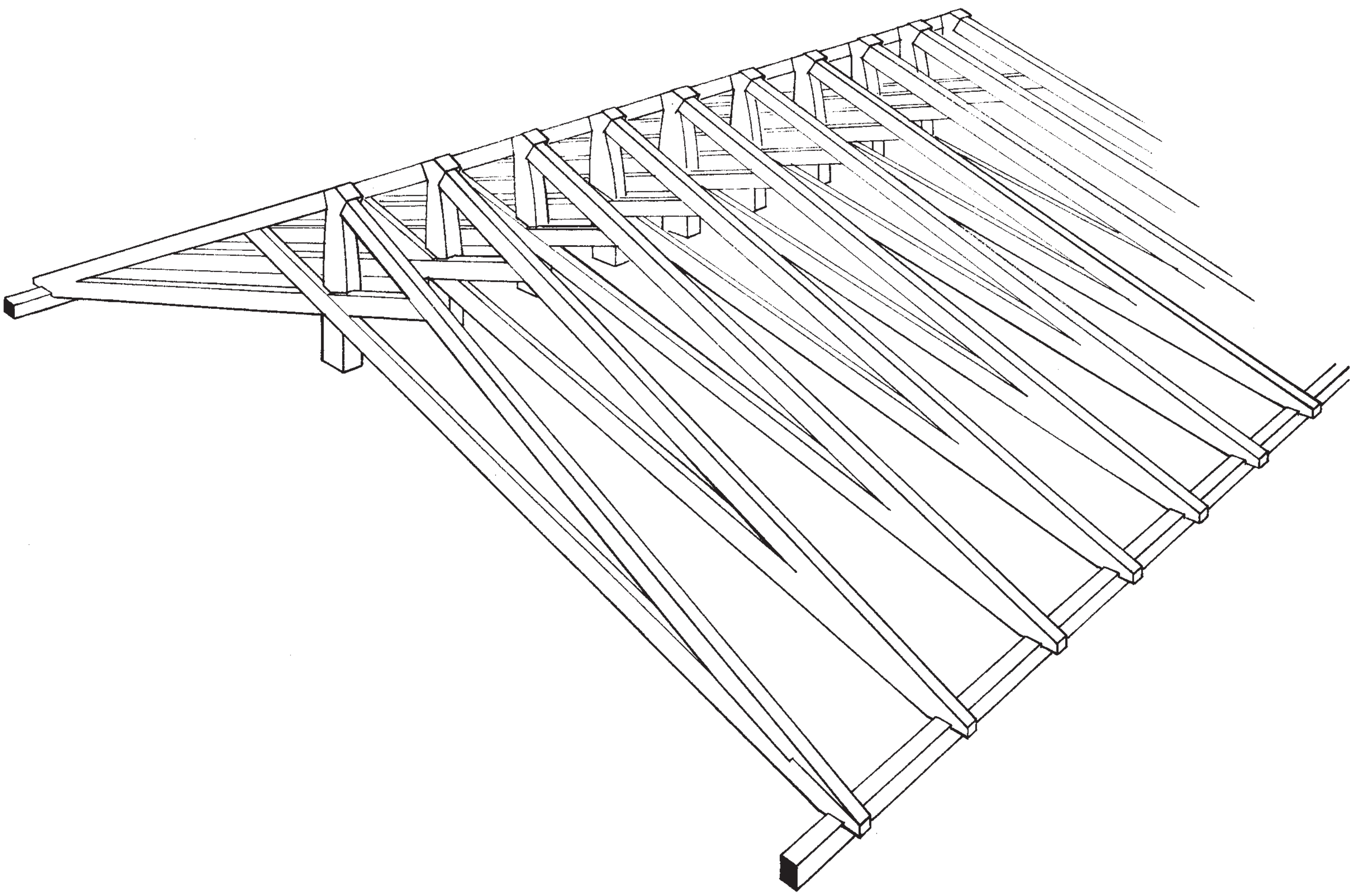


Figure 16. Exploded view of rafter and scissor tie at plate, First Parish Federated. Truss was free to settle and spread before being pinned to plate.



Perspective view of closely spaced trusses at First Parish Federated.

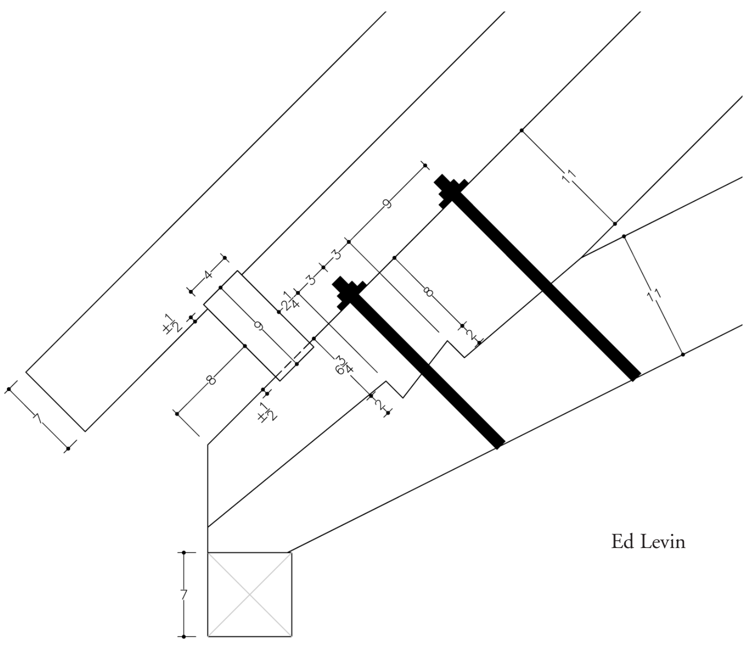
THE BARTON CONGREGATIONAL CHURCH (1876), Barton, Vermont. The scissor trusses in this northern Vermont church more closely approximate medieval Gothic scissor roof frames than do the earlier, Neoclassical-designed examples in Windsor and South Berwick. The Barton church, shown at right, has Gothic features such as asymmetrical front towers, a Gothic pinnacle at the apex of the front gable and, most important, a 12:12 roof pitch. (However, most of the door, window and exterior finish detailing is Italianate.) The main body of the church measures 42 ft. 8 in. wide by 68 ft. long, and the interior of the audience room is ceiled with a three-sided vault spanned by four decoratively cased trusses. These polychrome ceiling trusses have a raised bottom chord, queenposts of a sort and straight arch-bracing members rising from brackets attached to the wall posts. The apparent principal rafters of these visible decorative trusses, rising at a 6:12 pitch, are actually the bottom chords of the scissor trusses that support the high roof of the church, and they emerge in the attic uncased, to cross each other and rise to join the principal roof rafters. The cased arch braces may also conceal a structural wall brace rising to these ties, but the remainder of the truss visible from below is non-structural.

There are four trusses in the attic, on 14-ft. centers, with principal rafters 7x11 rising at a 12:12 pitch. These bear upon the 7x11 scissor chords with a double-shouldered joint transfixed by two $\frac{15}{16}$-in. bolts (Fig. 18). The outer 2-in. vertical shoulder is developed over a very short horizontal distance, 6 in., and is thus vulnerable to horizontal shear failure. However, examination of the joints shows only massive compression from this large and heavy roof. The junction of the principal rafters and tie beams begins inboard of the wall plate, but the outer bearing shoulder ends up right over it. The joined truss members continue beyond the plate into the cornice where they dead-end in space, not forming the basis of any cornice framing. All the timber is very high quality Eastern spruce.

The principal rafters are simply mitered at their apex and support a $1\frac{1}{4}$-in.-dia. king rod that drops between them to support the scissor ties at their crossing several feet below. The scissor ties are tenoned into the principal rafters and affixed with two $\frac{7}{8}$-in.-dia. turned white ash pins. Because of the high vaulting inside, the scissor ties intersect the principal rafters far above their midpoint,

Ken Rower

Barton Congregational Church, Barton, Vermont, 1876. Italianate finish and trim enclose a decorated Gothic interior, below. The cased rafters at the ceiling enclose the scissor chords of the roof truss.

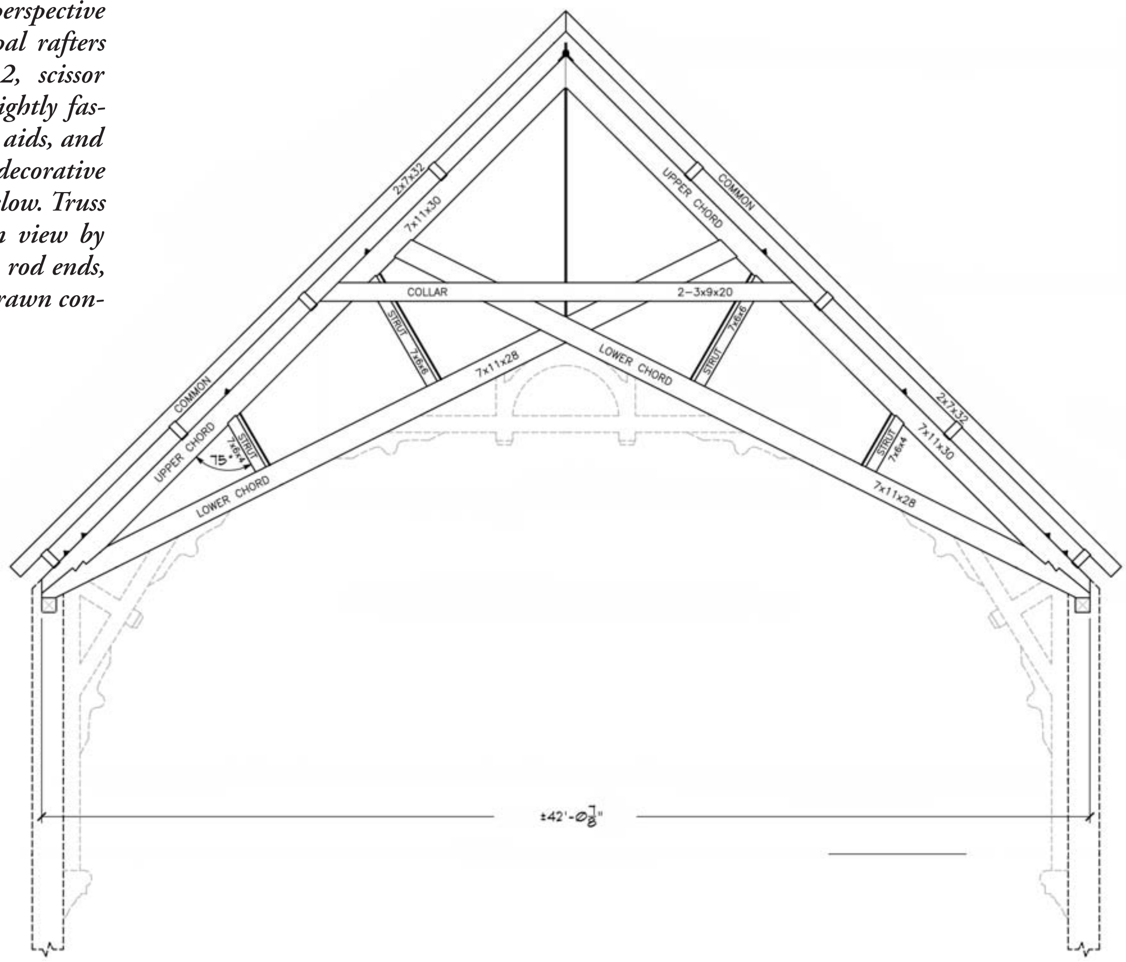


Ed Levin

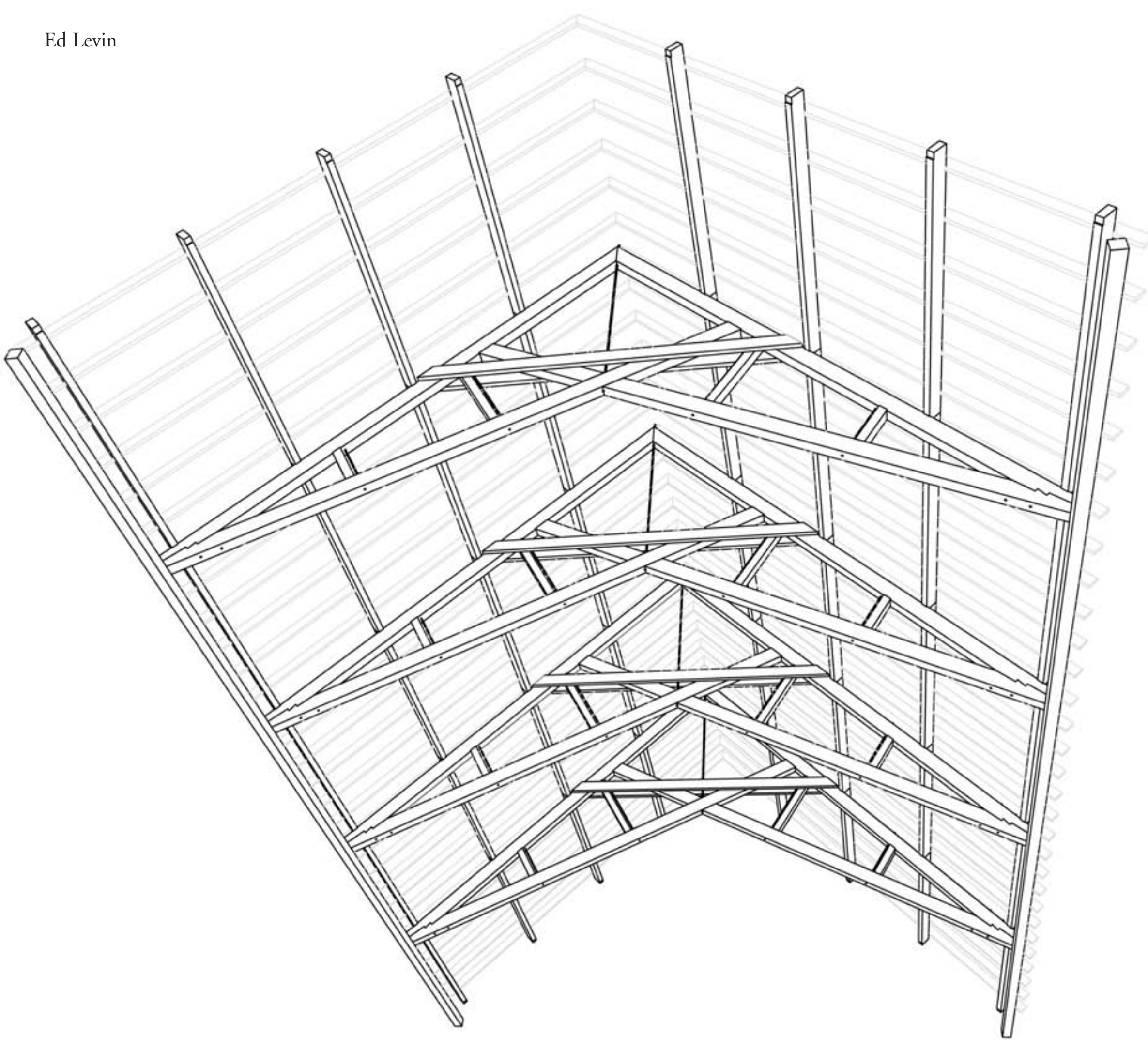
FIGURE 18. DOUBLE-SHOULDERED, DOUBLE-BOLTED JOINT BETWEEN PRINCIPAL RAFTER AND SCISSOR CHORD, BARTON CONGREGATIONAL. TERMINATION SHOWN AT PLATE IS CONJECTURAL.

Jan Lewandoski

Scissor truss elevation and interior perspective view, Barton Congregational. Principal rafters (upper chords) are pitched at 12:12, scissor (lower) chords at 6:12. The collars, lightly fastened, appear to have served as raising aids, and were left in place. Light lines indicate decorative framing visible from audience room below. Truss terminations at plate, concealed from view by purlins in the attic, and lower tension rod ends, concealed by interior finish, are here drawn conjecturally.



Ed Levin



Jan Lewandoski

Researchers E. Levin and K. Rower (as Diogenes) in the attic of the Barton Congregational Church. Spruce scissor chord rises to meet principal rafter just above Levin's left hand. Untenoned strut combined with iron rod visible at lower left. Pair of 3x9 planks flanking strut and scissor chord appear to have been raising aids.

leaving long lengths of unsupported rafter below this point. To help reduce bending in these long spans, struts paralleled by 1-in.-dia. iron rods rise from the top surface of the scissor ties to the bottom surface of the principal rafters at two other points. These struts are let into gains but are not tenoned into the truss members. While the upper ends of the scissor ties are compressed heavily into their mortise shoulders in the principal rafters, the top ends of the struts show greater or lesser openings (one being quite detached), suggesting that tension outward, or sagging of the scissor ties, has produced greater displacement in the truss than any compressive weight of the roof. (It would be instructive, however, to examine this truss under heavy wind loading to see if the rafters compress on the lower struts. Snow loading may not be a problem because of the steep pitch.)

At their crossing, the scissor tie beams half-lap and clasp one another in the plane of the truss. The kingrod, which allows a truly planar truss, helps the bottom chords resist bending, especially where the chords are reduced by joinery; but, unlike Windsor's kingpost, it cannot increase stiffness by adding shoulders or triangulations. Examination of the crossing joint shows that the ties are uniformly compressing one another's top shoulders, leaving a ⅜-in. opening at the bottom, which reflects either compression above or shrinkage, or both. This condition of the joint is consistent with some spreading in tension under load.

The four trusses and the untrussed gables at Barton carry four lines of bolted 4x9 purlins, with 2x7 rafters on 30-in. centers set above them. Shallow trenches in the lower edges of both rafters and purlins locate them on their supports. Viewed from the outside, the roof plane is flat and regular, without telltale bumps or openings of the cornice at truss locations, indicating a uniform, successful functioning of the roof system in spite of the long span between trusses. There is exterior evidence of slight outward buckling of the wall posts, suggesting that the cased arch bracing that rises to the scissor ties in the audience room of the church is structural and is transmitting roof loads to the wall posts, which might be too small to easily resist them.

The tendency of timber framers to imitate medieval roof systems originally designed to be restrained by massive masonry constructions, and to build them instead over relatively light timber-walled structures, began at least with the Gothic revival and continues today. In recognition of the resulting problems, 19th-century English Gothic style wooden churches sometimes included brick-founded wooden buttresses added to the exterior of every wall post. At St. Andrew's (1869) in St. Johnsbury, Vermont, which has such an arrangement, a large floor beam continues from within the church out onto the buttress base to receive a mortised timber brace at its outer end that rises at a steep angle to help the wall post support horizontal loads. The connection is made at two-thirds of wall height. St. Luke's (1870) in Chester, Vermont, has wooden buttresses, but they are empty inside. The aisled, untrussed roof system needed restraint by tie rods in the late 20th century.

—Jan Lewandoski

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Historic Scissor Truss Analysis

Some writers have given designs for . . . having the tie-beam omitted for the accommodation of an arch in the ceiling. This and all similar designs are seriously objectionable and should always be avoided; as the small height gained by the omission of the tie-beam can never compensate for the powerful lateral strains, which are exerted by the oblique position of the supports, tending to separate the walls. (R. G. Hatfield, *The American House-Carpenter,* New York, 1857.)

[The figure] exhibits an example of a roof with tie-beams so framed as to admit of finishing a curved ceiling. This practice of thus dispensing with a horizontal or single tie-beam should be used with great caution, as the work is always liable to settle. (Thomas W. Silloway, *Text-Book of Modern Carpentry,* Boston, 1858.)

AUTHORS of mid-19th-century builder's guides were not alone in holding the scissor truss in low esteem, helping to account for the relative scarcity of the truss type, and the dim regard for scissor trusses that persists to the present day. However, a close look at four proven examples of the truss type, described in summary form in the table below, may go a long way to belie the general opinion.

Truss Vital Statistics

Name	Date	Span	Truss Spacing	Pitch	Timbers	Iron Rods
St. Paul's Episcopal	1822	50'	9'-6"	6:12	5	0
First Parish Federated	1826	47'	3'	6.3:12	5	0
Trinity United Methodist	1858	62'	16'	9:12	12	12
Barton Congregational	1876	42'	14'	12:12	8	5

We inspected St. Paul's Episcopal in Windsor, Vermont; First Parish Federated in South Berwick, Maine; and Barton Congregational in Barton, Vermont. Information on Trinity United Methodist, in New Bedford, Massachusetts, was provided by David Fischetti of DCF Engineering in Cary, North Carolina.

The four roofs divide naturally by age, style and form. The churches in Windsor and South Berwick both date from the 1820s, and both are in Neoclassical style, featuring low-pitched roofs supported by elegantly simple trusses almost identical in form. The trusses comprise five timbers each: two upper chords (principal rafters), two lower chords (scissors) plus kingpost. In both buildings the framing is essentially medieval in character, with heavy timber members connected with traditional timber joinery, augmented by through bolts (plus an iron strap across the peak joint in South Berwick). Truss layout is based on traditional geometry rather than any evolved sense of statics. This geometric genesis is particularly apparent at St. Paul's, where scissors join rafters at midspan (6:12 rafter pitch, 2:12 scissor pitch), and purlins and ridge split the span into six even divisions.

In contrast to these classical antecedents, the frames in New Bedford and Barton are mid- and late-century Gothic Revival structures with steeper roofs, and a proliferation and elaboration of truss parts. Pure geometry has clearly ceded its driving role to analytical logic in the determination of truss layout. The number of elements in the truss has doubled and trebled, with the majority of pieces segregated by function (compression-only, tension-only), and iron rods substituting for timbers as tension members. There is also a change in timber species. In the earlier trusses, Eastern white pine and hemlock serve as major members (with oak braces at Windsor), but at Barton structurally superior Eastern spruce is used throughout, and at New Bedford even stronger long-leaf Southern yellow pine (presumably imported by sea).

The Barton trusses have double 3x9 collars sandwiching the upper ends of the scissors and upper struts, but the 3x9s are only lightly nailed and seem to have served principally to stiffen the truss in plane and to restrain lodged struts during raising. The Barton struts are not tenoned or pinned but sit in simple shallow housings in the chords. Each strut is paired with a 1-in.-dia. steel rod just upslope, thus the struts act as compression-only members, the rods in tension only. In the Finite Element Analysis model described below, the coupled rods and struts are represented by single elements, and the collars are omitted.

TO sort out the workings of scissor trusses, and compare and contrast performance of the structures under review here, I built Finite Element Analysis (FEA) models of the individual trusses and examined their behavior under load as predicted by the computer models. *Minimum Design Loads for Buildings and Other Structures* (ASCE Standard 7-98) and the *National Design Specification for Wood Construction* (NDS-1997) provided load conditions and design values.

Each truss was freighted with appropriate dead load plus live load, based on 65 psf ground snow load and 90 mph wind. While this may have been a bit heavy on the snow and light on the wind for New Bedford (and vice versa for Barton), the numbers are not too far out of line with official specs, and served to level the field for meaningful comparison among the four structures.

Each truss was then subjected to 15 separate load cases. *Balanced gravity load* was the sum of timber self-weight, roof dead load, suspended ceiling dead load plus uniform snow load. *Unbalanced load* factored in the three dead load cases, plus upwind wind pressure, downwind suction, 0.3 times windward side snow load and 1.5 times leeward side snow load. To account for the transitory nature of wind and snow loads and for the probability of multiple loads combining at full strength, load combination and duration factors were applied to the balanced and unbalanced load cases. To test for possible stress reversals in parts of the truss, I also looked at dead load plus wind at up to twice normal strength, and at dead load plus wind uplift.

I drew conclusions from the frame models principally on qualitative output. Were given members in tension or compression? Was there significant bending? Deflection? Could certain load combinations be associated across the board with particular patterns of resultant behavior? Quantitative output can be used to compare behavior truss to truss, or as an indicator of order of magnitude of resultant loads and stresses. But there is no guarantee of close correlation between FEA resultants and real-world forces and stresses.

The principal advantage of the scissor truss is the inclined profile of its lower chords, which easily accommodates vaulted ceilings. The tradeoff is the acknowledged tendency for the eaves of scissor trusses to spread outward and the roof to settle (as cautioned in the epigraphs from Mssrs. Hatfield and Silloway). But how much spread and settlement can one expect?

Compare St. Paul's to a standard kingpost truss with continuous tie beam and equivalent span, pitch and load. Under dead or uniform live load, horizontal deflections at the eave are four times greater in the scissor truss, while vertical displacements are two and a half times higher. In quantitative terms, the 50-ft. span, 6:12 pitch kingpost truss can be expected to spread 1⁄16 in. under dead load, 3⁄16 in. under uniform dead plus live load, with attendant vertical deflections of 3⁄16 in. and ½ in. respectively. Under the same loads, the St. Paul's scissor truss spreads 9⁄16 in. and 1 5⁄16 in. and sags ¾ in. and 2 1⁄16 in.

These numbers reflect elastic behavior of standing trusses under load, modeled using tabulated NDS elastic moduli for timbers and assigned joint stiffnesses based on available research literature. The point of the latter is that timber frame joints do not behave like pinned connections—they have give above and beyond the elasticity of the members being joined, and some accounting must be made for the joint flexibility to obtain realistic results.

And what about the initial settlement that occurs when a truss is first raised and the joints come home under load? Even the most carefully cut joinery is not perfectly snug. And, since long-span church roof trusses operate at the upper end of allowable stresses and loads for heavy timber, one might expect significant initial settlement. (For example, it's not unusual for timber bridge trusses to lose several inches of camber upon initial erection.) The only reliable indicator of initial settlement is prior experience, but we can put together an educated guess. By assigning a certain amount of slippage to each joint in the truss and then stretching and squeezing the frame in accordance with the expected tension and compression loading, we arrive at a theoretical deflected elevation representing the net effect of the expected settlement.

Once again using St. Paul's as our guinea pig, and assuming ⅛ in. travel per joint, we find 1⅛ in. spread at the eaves and (depending where you measure) 1¾ in. to 2 in. subsidence at midspan. Increase individual joint travel to ¼ in. and (not surprising) you double this accumulated X and Y movement. In comparison, given ⅛-in. quantum slippage in the equivalent kingpost truss (see above), we can expect a gain of half an inch horizontally and a corresponding drop in height of about 1 to 1⅜ in.

With both initial settlement and ongoing deflection under load, truss behavior is governed by connections rather than members, as you might expect in a truss, by definition a structure in which axial loads predominate over bending. In addition to initial settlement and deflection under load, shrinkage of green timber also causes trusses to sag. For instance, as the width of a kingpost diminishes, the abutting rafters squeeze in and down at the peak. Similar effects are felt at other major intersections. The resulting subsidence was well known to 19th-century carpenters, and it was standard practice to compensate by pre-cambering the truss. Indeed, established formulas were used to calculate incremental increases in member length to overcome shrinkage for given spans, truss types and timber dimensions.

Idiosyncrasies. One peculiarity of our two Neoclassical scissor trusses is that they were not built in plane. In Windsor, the scissor chords bend around the kingposts, deflecting out of plane around 1½-in. a third of the way along their 39-ft. length. Evidence indicates that the scissors did not have to be forced to assume this curve. Examining the stock used, it seems clear that paired scissors for a given truss were converted from a single tree. Accumulated tension towards the bark side caused the cloven halves to bow away from the heart, and the builders took advantage of the resulting curves. Under load, the predominating tension in the lower chords wants to straighten them out, but since they oppose one another on either side of the kingpost, any distorting tendency is damped out.

The asymmetry in South Berwick takes a different form. Here the chords all run true to plane (subject to minor variations in timber section) while the kingpost is tilted out of plumb, lying flush with the rafters at the peak, but skewing out of plane 1½-in. at the scissor crossing 5 ft. below. No forced curves here (hardly possible in a short 8x10). In the FEA model, this apparent eccentricity imparts a twist to the truss under load, pulling the crossing and kingpost foot side-ways, resulting in significant horizontal deflection and bending stress in scissors and rafters. But the problem vanishes under closer inspection: absent the kingpost, all parts of the truss lie symmetrically along the centerline, and there is no inherent tendency to torque out of plane under load. Reinserting the central column does nothing to alter this action, the only eccentricity being that the lines of force in the kingpost do not run parallel to the grain of the piece. It seems that, at least when analyzing traditional timber framing, there is some danger in leveling a charge of eccentricity simply because centroids of intersecting members are disjunct. And, in any case, at First Parish the close spacing of the trusses and their frequent attachment to the roof and ceiling diaphragms above and below would arrest any sideways distortion.

At Barton, the decorative casework framed into the lower chords below the ceiling plane (photo page 20) may play a role. Making conjectural allowance for this in the Barton frame model, we find it seems to offer a considerable assist to the roof above, reducing force, stress and deflection in the truss. However, this contribution comes at a cost, since the load is channeled down the interior bracket at the eave, pushing out against the sidewall. Indeed, when sighting up the exterior walls at the truss locations, a modest bulge appears at the appropriate distance below the eave.

Comparison of the FEA results reveal more similarities than differences among the trusses, notwithstanding the noted characteristic variances that distinguish Windsor and Berwick from New Bedford and Barton. In all four structures, the balanced gravity load case governs (i.e., produces the most stringent test of truss members and connections). The resultant axial load pattern is similar in all four trusses: principal rafters (upper chords) in compression, kingposts in tension and scissors (lower chords) in tension below their crossing and in compression above it. This distribution of force and stress persists in almost all loadings. The only condition that provokes any stress reversal is dead plus wind load in the absence of snow. In that situation, the upper end of the downwind scissor goes into tension, but it takes wind in excess of 100 mph to do the job, and even then the stress reversal is fairly mild (tension loads ≤ 1,000 pounds). Crank the wind speed up to 130 mph and the leeward scissor-to-rafter joint is still only looking at a ton or two of tension load.

This analysis also puts to rest concerns about uplift, since maximum wind uplift force is in every case less than opposing dead load. Lateral load due to wind poses a more difficult problem. Because of the inherent tendency of scissor trusses to push outward on supporting sidewalls, their builders often provided minimal lateral connection between truss and wall. To complicate matters for the researcher, this joinery often remains a mystery sandwiched inaccessibly in the eaves between ceiling and roof. So the best evidence of the adequacy of the arrangement may simply be the persistence of the union between roof and walls.

Given the minimalist layout of the Windsor and Berwick trusses, one feels tempted to simplify them even further by eliminating the kingposts. Don't submit to this urge! Remove the kingpost from any of the scissor truss models under consideration here and disaster ensues: the scissor crossing plummets downward, and bending stresses and deflections go off the charts. To cite a favorite example, absent the kingpost in Windsor and maximum bending stress jumps from 858 psi to 5335 psi, eave spread widens from 1 11⁄32 in. to 6 in. and midspan deflection grows from 2 in. to an astonishing 16 in.! Kingpost excision results in similar radical inflation in bending and deflection in the other three trusses (although the effects are somewhat less severe in New Bedford and Barton with their optimized truss layouts). Meanwhile, truant kingposts actually provoke slight reductions in axial forces in truss members since more load is taken up in bending. But the lesson remains brutally clear: no scissor trusses without kingposts (or kingrods).

Predicted values of axial, shear and bending stress remain within allowable ranges in all four structures (I did not check combined bending and axial loading). Since loads are often applied eccentrically and members are continuous across joints, bending stress is not negligible, as one might expect in an ideal truss. As suggested earlier, connections rather than members are the controlling factor, so it's surprising that it isn't tension stress that governs, but rather bearing and shear.

In fact, a key to the viability of scissor trusses lies in their ingenious avoidance of tension joinery at timber ends. From early examples like Windsor and Berwick, it's clear that each scissor truss must pass four crucial joinery tests: at the roof peak and foot, and at the scissor crossing and scissor-to-rafter intersection. The kingrods in Barton develop 40,000 lbs. in tension, mandating total washer area of 130 sq. in. bearing against the upper rafter surfaces. (Similar conditions obtain in New Bedford.) Actual washer area in Barton is in the 40-60 sq. in. range, implying cross-grain pressure on the spruce rafters two to three times greater than the tabulated 400 psi. So either actual kingrod tension is significantly less than the FEA prediction or the timber can bear side-grain pressure well in excess of the allowable, or both. It's worth noting in passing that the builders in Barton and New Bedford asked and got a lot from their materials throughout—the kingrods in both cases undergo tension stress in excess of tabulated values for mild steel.

SINCE our four scissor truss peak joints are no different from those in an ordinary kingpost truss, we will ignore them here and examine the three remaining connections peculiar to scissor construction, focusing on Windsor and Barton as exemplars, respectively, of early and late scissor truss construction. In the exposition below, the following design values were used to assess stress levels: 1000 psi for bearing parallel to the grain (F_g), 400 psi for compression perpendicular to the grain ($F_{c\perp}$) and a maximum of 130 psi for shear parallel to the grain (F_v).

Scissor-to-Rafter Joint. As indicated earlier, the scissor chords shift from tension to compression above their crossing. Along with the sign reversal, the magnitude of the axial load also drops, with compressive forces in the upper scissors from a fifth to a third the values of the lower tensile loads. Predicted compression ranges from a low of 4000 pounds in Berwick up to 15,000 pounds in Windsor, and in each case ample size of the members and abundant joint area offers sufficient bearing surface to resolve these forces within allowable stress limits.

The Crossing. Three force vectors are resolved at this connection: compression loads from the opposing scissors pushing in and down, and tension load from the kingpost pulling up. Forces in the scissors at the crossing are essentially unchanged from those at their upper ends where they join the rafters and, as above, the scissor-to-kingpost-to-scissor crossing provides plenty of joinery surface. The big hit is the contribution of the kingposts and kingrods, with forces of 40,000 pounds in kingrods at Barton and New Bedford (see discussion above) and 14,500 and 21,000 pounds respectively in the 8x10 and 9x12 kingposts in Berwick and Windsor. Kingpost tension imparts bearing stress to the scissor side-grain. At First Parish, this works out to 10 percent above the allowable value, at St. Paul's, a comfortable 29 percent below the limit. The other limiting factor is shear in the kingpost abutments that support the scissor chords. At Berwick, there is an abundance of relish, over 200 sq. in. In Windsor, we seem to have close to the absolute minimum required, around 165 sq. in.

The Foot Joint. By framing the rafter over and into the scissor chord, what would otherwise be an impossible tension connection is ingeniously transformed into a compression joint. Since all accumulated force in the scissor truss must flow through this joint, load magnitudes here are the highest in the system, and it's not surprising that this is the locus of greatest divergence between the expectations of the historic builders and modern engineering standards.

Again the issues are bearing and shear. Looking first at the former, for the three churches where we have data, the joinery is similar: the rafter is footed on the scissor, secured by one (Berwick) or two 2-in.-deep abutments (Barton and Windsor) abetted by two bolts (Berwick, one bolt and one 1¼-in. pin). Typically, available side grain bearing area is ample, at minimum 500 percent above what's needed. Not so end grain bearing. Allotting 3000 pounds per bolt or pin (a generous allowance by NDS specs) the timber joinery is left to carry considerable load: 14,200 pounds in Berwick, 37,500 at Barton and a daunting 42,300 pounds for St. Paul's. This works out to respective bearing stresses of 1580 psi, 1340 psi and 1510 psi on the abutments. Taking into account bearing at angles to the grain of the members (the angle between the incoming rafter and scissor), allowable bearing stress values range from a low of 870 psi in Barton to 885 psi in Windsor and a high of 959 psi in Berwick, putting bearing in Barton at 154 percent of capacity, Berwick at 165 percent and Windsor topping the list at 171 percent.

Let's look next at long-grain shear stress in the material backing up the abutments in the scissors. Given its lower shear load, First Parish squeaks by under the allowable at 124 psi (95 percent of capacity). In Windsor we're looking at 195 psi (150 percent) and in Barton at 211 psi (162 percent).

Have we found the Achilles heel of historic scissor trusses? I think a few words in mitigation are in order. First, a reminder that, on almost all prior counts, the trusses have stood up to scrutiny. In vetting the preceding analysis, several questions come to mind. Let's start with bolt capacity: NDS specs notwithstanding, it seems possible, even likely, that the bolts and pins securing scissor foot joints carry significantly more load than tabulated values allot to them. Second, there is the issue of the loads themselves. Given timber weight plus conservative mandates for snow and roof and ceiling dead load, our trusses are modeled as carrying 80 lbs. of load per sq. ft. of tributary area. If we could weigh the roofs, I suspect that we'd find them tipping the scales somewhere in the 40-50 psf range, perhaps 60-70 psf in the heaviest snow years. ASCE 7-98 provisions call for the trusses to bear an additional 10 percent of snow and 15 percent of wind load due to audience room capacities in excess of 300 people, plus a 20 percent snow surcharge given their unheated attics (Importance Factor, I=1.1 for snow, I=1.15 for wind; Thermal Factor, Ct = 1.2). And, despite the height and exposed position of the church roofs, no concomitant provision is made for lessening snow load via exposure factor (Ce).

A one-third reduction in load would bring even the beleaguered foot joints into compliance with code. Taking into account the ameliorating factors, the reader must decide whether this is a reasonable proposition. Some modest load discount does not seem out of line. One must also consider the possibility that the clear, fine-grained, old-growth timber in the trusses can cope with stress well in excess of modern limitations. I came to the subject a skeptic of historic scissor trusses, but my sceptical inquiries have revealed only their ingenuity and the wisdom of their builders. The most persuasive argument remains the trusses themselves. They stand unbowed, largely unchanged from their natal state, ready to face future centuries of heat, cold, snow and wind.

—Ed Levin

Research and advice for this article were contributed by Jan Lewandoski, Ken Rower and Jack Sobon. Axial and bending diagrams for the four trusses are available from the author (elevin@valley.net).