TIMBER FRAMING

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Number 95, March 2010

The Riddle of Tremblay

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On the front cover, array of timber pendants in a Philadelphia warehouse, part of a 15th-century refectory ceiling taken down near Paris in the 1920s and conveyed to the Pennsylvania (later the Philadelphia) Museum of Art. Each pendant, though aimed at the same form, appears to have been carved by a different hand. On the back cover, shield grasped by a carved angel on underside of hammerbeam in the dismantled frame. Story page 18.

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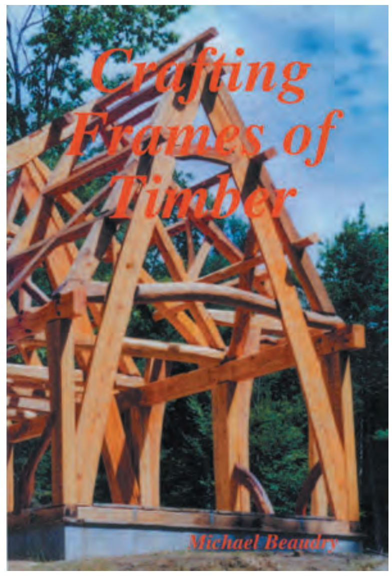
TIMBER FRAMING, Journal of the Timber Framers Guild, appears in March, June, September and December. The journal is written by its readers and pays for interesting articles by experienced and novice writers alike.

TFG 1985

BOOKS
Crafting Frames

Crafting Frames of Timber, by Michael Beaudry. Self-published, 2009, 6x9, 277 pp., heavily illustrated, list for further reading. Paper, $24.12 plus $3.99 shipping from mudpond.net/books.



THIS is a book about one man's 30 years of personal experience timber framing, cruck framing and hewing, as well as log building with half-lap and locking Norwegian saddle joints and the *pièce-sur-pièce en coulisse* style of framing. Honest, open and unpretentious, Michael Beaudry is a back-to-the-lander giving us part story, part textbook. The book is particularly well suited to people dreaming of building a handcrafted wooden building, who will get the insights of a builder who uses basic tools and works close to the land.

The author learned how to handcraft buildings on his own farmstead and by helping friends, then became a professional hewer and framer who feels that "philosophy plays a major role in handcrafting shelter," affecting the aesthetics and economics of building. Working mostly in Maine, in his framing Mike has used common purlin and common rafter roof systems, English tying joints, dropped tie beams and interrupted plates. He discusses how to make your own shingles, pegs and *domlingers* (vertical pins inside horizontal log walls) on a shaving horse or by using a Native American-style crooked knife.

Mike published an earlier book on hewing and using axes in general (*The Axe Wielder's Handbook*, 2002), so he can give detailed insight into converting logs to timbers, including log-handling tips for those who work alone and how to hew without using log dogs. He emphasizes the importance of selecting logs of straight grain with few knots and of the right size for hewn timbers. Too large a log is wasteful, more work to hew and harder to move around, while a small log may have too much wane. He also gives tips on how to hew bowed logs.

Mike confesses to being no technical purist, such as when he uses a chainsaw to score before hewing or occasionally employs timber screws or lag bolts, and sometimes sealant tape between horizontal logs—but at the same time he prefers a proper heavy timber deck to the almost universally found dimension-lumber joists in new American timber frames.

Though many photographs are blurred, drawings are hand sketched and a few typographical errors mar the text, they are perhaps in keeping with the down-to-earth nature of the new book. I have no doubt that if you called Mike up with questions, he would do his best to answer them and maybe sign you up for a workshop he teaches so you can create your own Walden Pond. —Jim Derby

Jim Derby (jim.derby@hotmail.com) is a preservation carpenter in Maine and a TTRAG member.

Drawing a Frame in SketchUp

IN Part 1 of this article (TF 94), we learned how to draw posts, beams and braces in Google SketchUp. If you followed the tutorial, you have a drawing of the four bents of the Arunah Hill Pavilion—but it needs plates, purlins, wall braces, rafters and sills to become a complete frame. This article will show you how to add those elements. Note that accompanying videos to this article can be found on www.youtube.com by searching on "Drawing a Timber Frame in SketchUp."

This tutorial does not cover joinery; all timbers are simply butted together. But once you master the techniques, adding joinery will be within your grasp. This tutorial was written for PC users but will work fine for Mac users too—simply use the **Option** key whenever the **Ctrl** key is mentioned. And make sure you have a two-button wheel mouse for zooming, panning and orbiting.

The frame we're drawing was designed by Jack Sobon and appears in the Guild's *Fourteen Small Timber Frames*. If you didn't save the frame from the last issue, or wish to see the completed frame, go to sketchup.google.com/3dwarehouse and search for "Drawing a Timber Frame in SketchUp." Download the Part 1 model and you'll be ready to work on this tutorial.

Plates and Purlins. We're starting where we left off in Part 1 of this tutorial, so your frame should match Fig. 1. Two plates and two purlins, all identical, are needed to tie the bents together and support the rafters. We'll create a plate component and reproduce it three times. The plates and purlins are 8x8x36, with each end protruding 3 ft. beyond the end bents. But we'll start by making 30-ft. members and resize them after the rafters are complete.

Create a 30-ft. 8x8 plate:

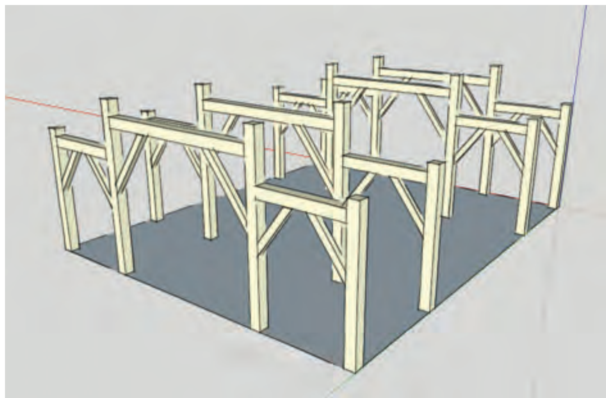
1. Select the *Rectangle* tool.
2. Move to the right post of the first bent and click on the top right corner.
3. Move down diagonally, making a rectangle on the front surface of the post.
4. Type **8,8** (this will appear in the *Dimensions* box) and press **Enter**.
5. With the *Select* tool, double-click inside the rectangle.
6. Select the *Move* tool and click on a lower corner of the rectangle.
7. Move the rectangle up until it snaps in place at the top of the corner post and click (Fig. 2).
8. Orbit around to the back side of the rectangle.
9. With the *Push/Pull* tool, click on the back side of the rectangle.
10. Begin pulling the rectangle toward the next bent, type **30′** and press **Enter** (Fig. 3).

Note: SketchUp defaults to inches in the Dimensions *box unless you specify otherwise, but you can change dimensions until you choose another tool. So if you forgot the foot symbol and made a 30-in. beam (a common mistake), simply type* **30′** *and press* **Enter***.*

As we learned in Part 1, you always want to convert new timbers into a group or component. Since all four members will be identical and they need to be resized later on, a component is the right choice.

Make a plate into a component:

1. With the *Select* tool, triple-click on the plate to select the entire timber.
2. Right-click on the plate and select *Make Component* from the context menu (Fig. 4).
3. In the *Create Component* dialog box, enter a meaningful name such as **Plate**, and click on the *Create* button.



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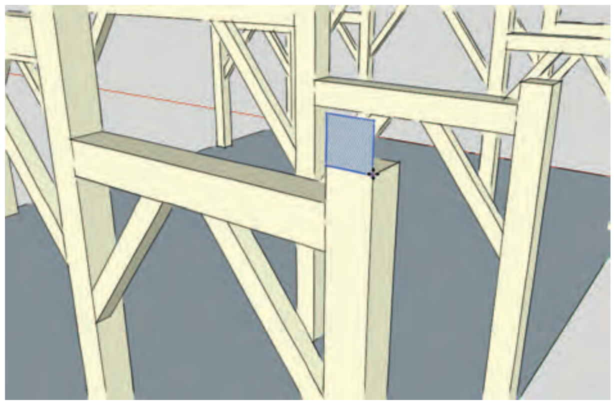
All drawings Ben Weiss



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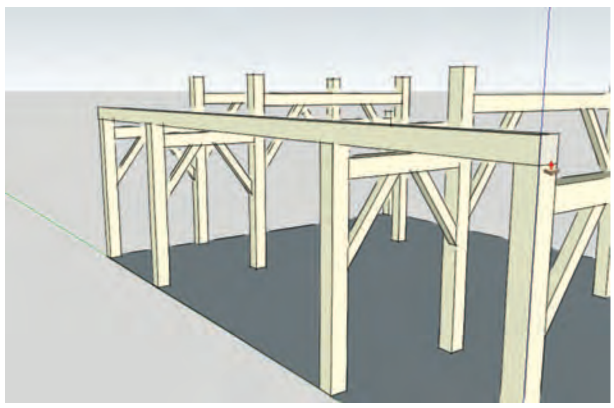

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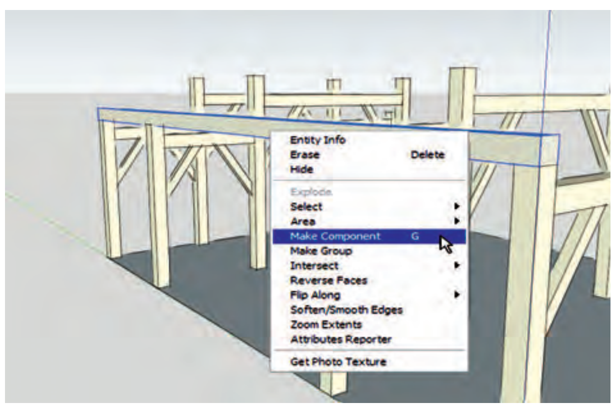

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Next to navigation, moving and copying are the most important skills to master in SketchUp. In Part 1, both skills were used, but some review is warranted.

When moving (or copying) an object, it's important to select the proper move-from and move-to points to get the object in the desired location. Fig. 5 shows a set of move-from and move-to points that would work well in this case. Notice that if the move-from point were chosen instead on a top corner or on the center of the plate, it would be impossible to get a copy of the plate to its desired position.

Copy the plates:
1. Orbit back to the front of the frame.
2. With the *Select* tool, click on the plate.
3. Select the *Move/Copy* tool and press **Ctrl** to enter copy mode.
4. Click in the lower right corner of the front face of the plate.
5. Move a copy of the plate to the top of the next post and click when it snaps to the right corner of the post (Fig. 6).
6. Repeat this process two more times to generate the two remaining members.

Note: A common mistake (one I make frequently) is to forget to press ***Ctrl*** *and start moving an object rather than copying it. You can press* ***Esc*** *to exit and start over, but instead just press* ***Ctrl****. SketchUp will return the object to its original position and keep a copy at your cursor position.*

Rafters. Rafters can be the most complicated timbers to design. With SketchUp, all we need to know is the roof pitch (5:12), the overall length of the rafter (16 ft.) and the section. We'll create a rafter pair while working on the front side of the first bent, move it into position and make copies to complete the roof.

Let's start by creating a top guideline to verify that an angled line between plate and purlin matches the 5:12 roof pitch.

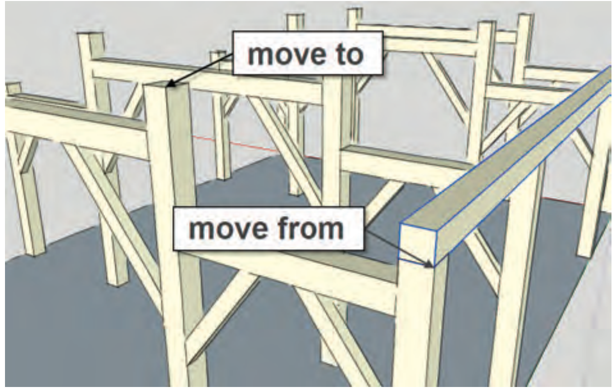
Make a guideline at the roof pitch:
1. Select the *Protractor* tool.
2. Hover over the front face of the left corner post in the first bent.
3. When the protractor turns green, hold down the **Shift** key (to lock the green axis).
4. Click on the top left corner of the plate.
5. Move horizontally until a red line appears, then click (Fig. 7).
6. Move in an upward direction, type **5:12** and press **Enter**.

The guideline that appears should intersect the top left corners of the plate and purlin (Fig. 8). This technique verifies that the angle between them matches the roof pitch. Next, we'll create a guideline to the peak of the roof.

Make a guideline to the rafter peak:
1. With the *Tape Measure* tool, click on the left edge of the left corner post.
2. Move to the right and, when a red axis line appears, hold down **Shift** (moving over the front face of a post or brace will help).
3. While holding down **Shift**, move your cursor to the center of the middle tie beam, along its bottom edge.
4. Click when a purple dot appears (this dot shows the center of the tie beam, Fig. 9).

This guideline should be vertical and located in the center of the bent, 12 ft. from the left side. The intersection of the two guidelines defines the peak of the rafter. We'll make two more guidelines to define the front face of the rafter.

Make the remaining rafter guidelines:
1. With the *Tape Measure* tool, click anywhere on the first guideline.
2. Move downward until you're hovering over the front face of a post or brace, type **5** and press **Enter**.



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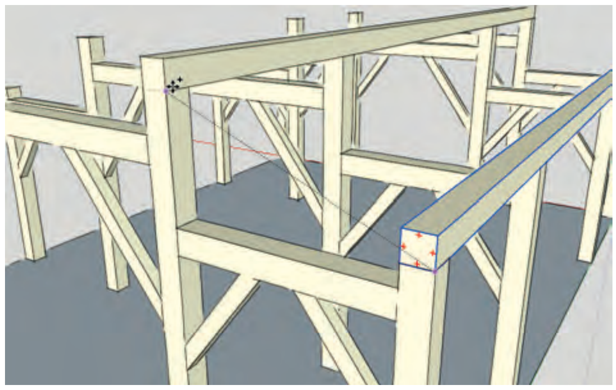
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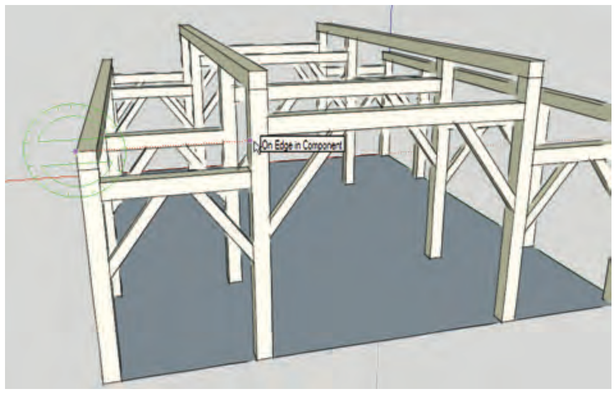

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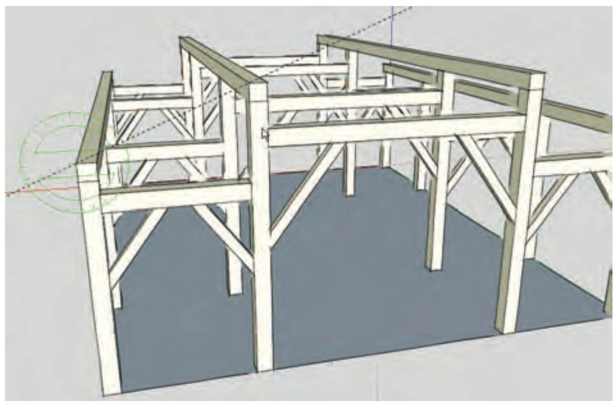
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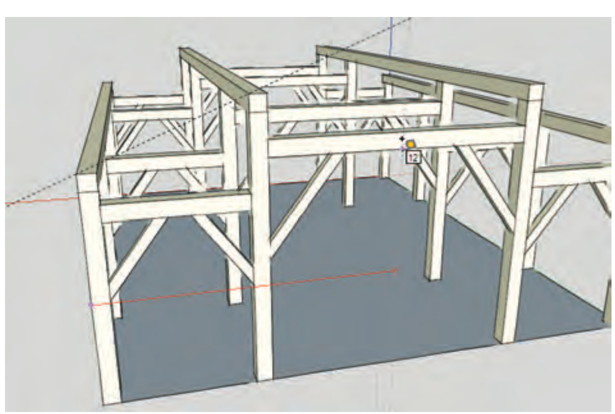
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3. Staying in the *Tape Measure* tool, move to the left edge of the left corner post and click twice slowly (a guideline should appear along the edge).

Now it's just a matter of drawing lines between the guideline intersections, pulling out the rafter and making it into a component.

Create a 4x5 rafter:

1. Select the *Line* tool.
2. Move to the first guideline intersection and click.
3. Move to the next guideline intersection and click.
4. Repeat two more times to fill in the front face of the rafter (Fig. 10).
5. Orbit to the back side of the rafter.
6. With the *Push/Pull* tool, click inside the back face of the rafter.
7. Pull back on the rafter, then type **4** and press **Enter** (Fig. 11).
8. Delete the guidelines by selecting *Delete Guides* from the *Edit* menu.
9. With the *Select* tool, triple-click on the rafter, and in the *Component* dialog box enter **Rafter** and click on *Create*.

Next, we'll add the tail on the rafter by editing the component. According to the plan, the rafter measures 16 ft. from the peak to the tip of the rafter tail and the height of the tail is 2½ in.

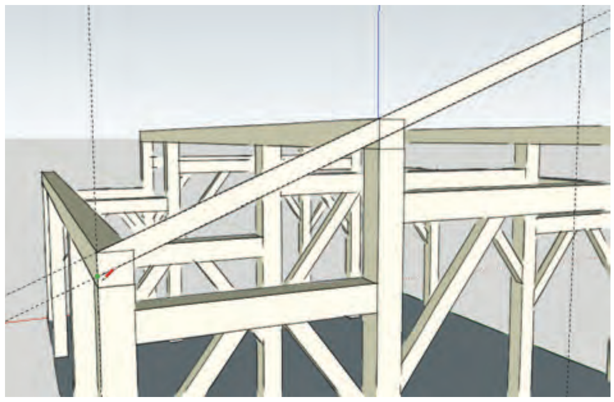
Add a rafter tail:

1. Edit the rafter component (double-click on it with the *Select* tool).
2. With the *Tape Measure* tool, click twice slowly on the rafter's top edge (a guideline should appear along the edge, Fig. 12).
3. Click on the rafter peak, then move along the rafter's top edge, type **16′** and press **Enter** (a tick mark should appear along the guideline 16 ft. from the peak).
4. With the *Line* tool, click on the tick mark and draw a line back to the rafter (along the guideline) and click.
5. Click again on the tick mark, and move down (along the blue axis), type **2.5** and press **Enter** (Fig. 13).
6. Draw a third line from the bottom of the last line, back to the bottom edge of the rafter (a two-dimensional rafter tail should appear).
7. Orbit to the back of the rafter.
8. Click in the back side of the rafter tail, pull back, type **4** and press **Enter** (Fig. 14).
9. Select the *Eraser* tool and click on the lines on the top, front and back of the rafter that separate the tail from the rafter (clicking on these lines will erase them).
10. Close the component (right-click outside of the component and select *Close Component*).
11. Delete the guidelines (*Edit* > *Delete Guides*).

The plan calls for 3 in. of the 4x5 to remain intact after cutting the birdsmouths, so we can use that figure to properly position the rafter.

Move the rafter into position:

1. With the *Select* tool, double-click on the rafter (to edit the component).
2. Select the *Tape Measure* tool.
3. Click on the top edge of the rafter.
4. Pull down until you reach the bottom edge (a tool tip of 5″ should appear), assuring that the guideline is parallel with the top edge.
5. Type **3** and press **Enter**.
6. Close the component (right-click outside of the rafter and select *Close Component*).
7. With the *Select* tool, click on the rafter.
8. Using the *Move/Copy* tool, click on the intersection of the guideline and the left edge of either plate.



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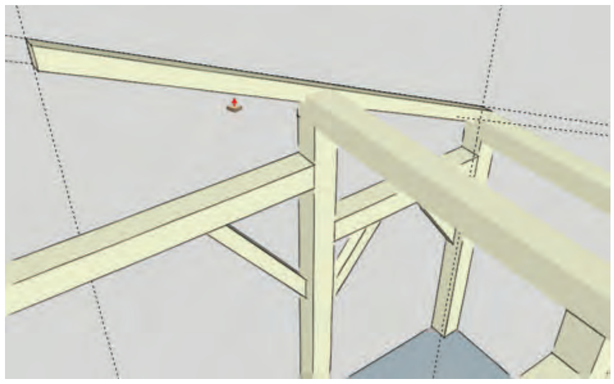

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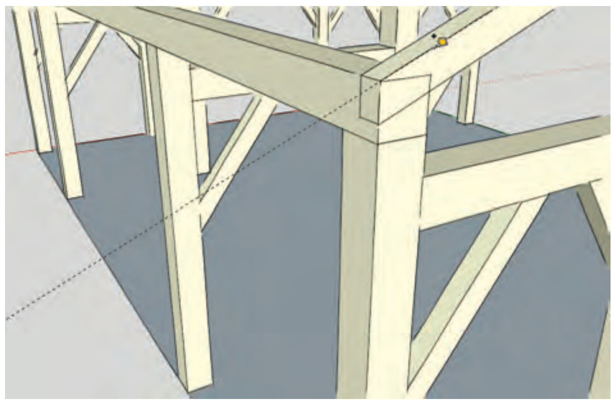

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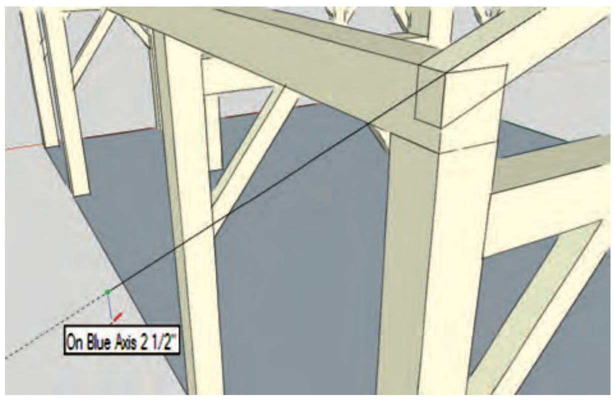

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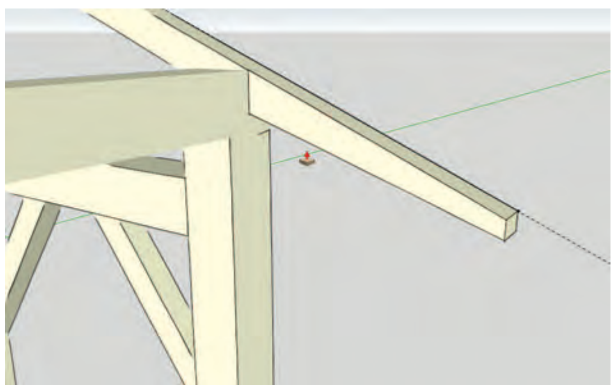

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9. Move the rafter up until the move-from point is intersecting the top left corner of the purlin, then click (Fig. 15).
10. Delete the guideline (*Edit* > *Delete Guides*).

With the rafter in its proper position, the outlines of the purlin will act as guidelines to cut the birdsmouths—without measuring!

Cut the rafter birdsmouths:
1. With the *Select* tool, double-click on the rafter (to edit the component).
2. With the *Line* tool, draw a line along the vertical intersection of rafter and purlin (click on the bottom intersection point, then the top point).
3. Draw a line along the horizontal intersection of rafter and purlin (click on the left intersection point, then the right point, Fig. 16).
4. With the *Push/Pull* tool, hover over the triangle you just created in the rafter and then click.
5. Move your cursor to the back edge of the rafter (a tool tip should display "offset limit to – 4″), then click (Fig. 17).
6. Repeat this process to cut a second birdsmouth at the other purlin location.

It's always a good idea to verify measurements, especially while you are learning SketchUp. According to Sobon's plan, the birdsmouths should measure $5\frac{3}{16}$ in. horizontally and $2\frac{3}{16}$ in. vertically.

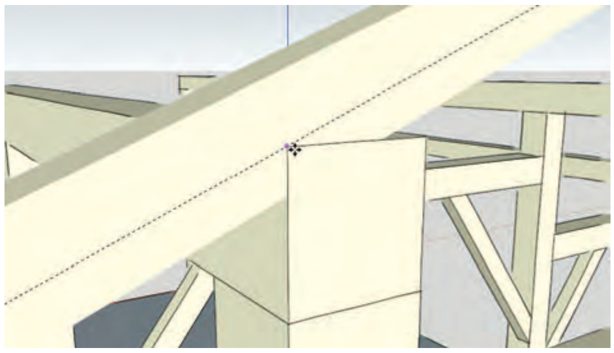
Verify the rafter birdsmouths:
1. With the *Tape Measure* tool, click on top left corner of a purlin.
2. Hover over the horizontal end of the birdsmouth—a tool tip showing a measurement of $5\frac{3}{16}$″ should appear.
3. Hover over the vertical end of the birdsmouth—the tool tip should indicate $2\frac{3}{16}$″.
4. To create the other rafter in the pair, all we need do is to make a copy, flip it and move it into position.

Create the other rafter in the pair:
1. With the *Select* tool, click on the rafter.
2. Select the *Move/Copy* tool and press **Ctrl** (to enter copy mode).
3. Click on the peak of the rafter.
4. Drag a copy along the red axis and click (Fig. 18).
5. Right-click on the copy and select *Flip Along* > *Component's Red* from the context menu.
6. With the *Move/Copy* tool, click on the peak of the new rafter.
7. Move the rafter until it intersects with the peak of the first rafter, then click (Fig. 19).
8. With the *Select* tool, hold down **Shift** and click on the other rafter (both rafters should be selected).
9. Right-click on either rafter and select *Make Group*.

Now let's return to the plates and purlins, pulling them out from the building 3 ft. on each end. Since all four are instances of the same component, all we need to do is edit one of them.

Resize the plates and purlins to 36 ft.:
1. With the *Select* tool, double-click on one of the purlins.
2. Using the *Push/Pull* tool, pull it out from the building, type **3′** and press **Enter** (Fig. 20).
3. Orbit around to the other end of the purlin.
4. With the *Push/Pull* tool, double-click on the end (double-clicking the *Push/Pull* tool repeats the previous operation).
5. Close the component (right-click outside the purlin and select *Close Component*).

The plan calls for 18 rafter pairs, spaced 2 ft. on center. With a 4-in.-thick rafter, that gives us a distance of 34 ft. 4 in. from the outside of the first rafter to the outside of the last. So, if the first rafter is positioned 10 in. from the end of the plate, the rafters will be centered on the roof.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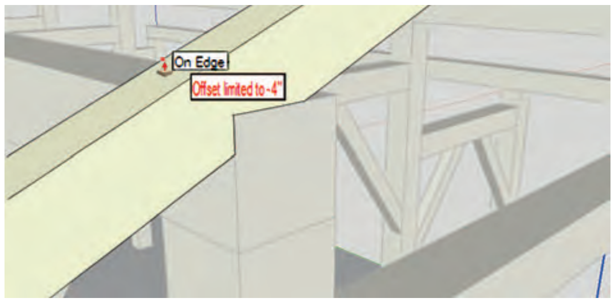

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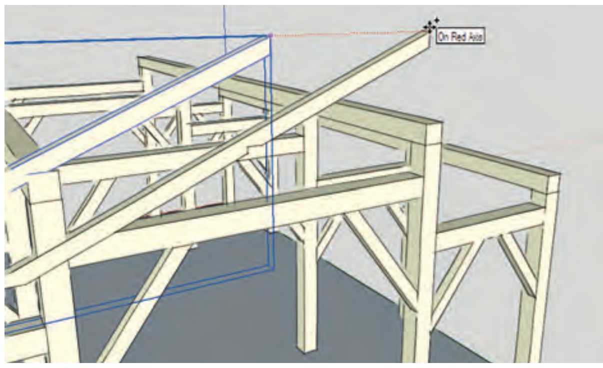
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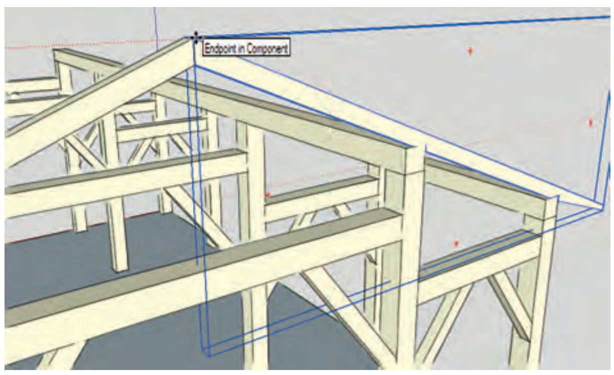

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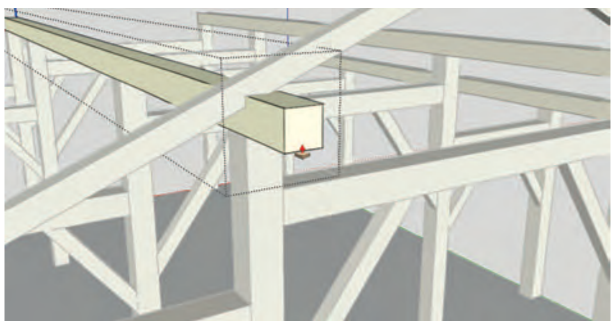
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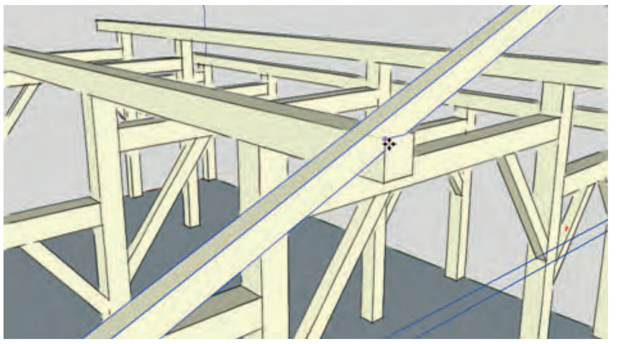
Position and copy the rafter pairs:

1. With the *Select* tool, click the rafter pair.
2. With the *Move/Copy* tool, click on the notch of the birdsmouth.
3. Move the rafter pair to the end of the purlin and click (Fig. 21).
4. Click on the same spot in the rafter pair.
5. Start moving the rafters along the purlins (green axis), type **10** and press **Enter**.
6. Press **Ctrl** and click again on the notch of the birdsmouth.
7. Start moving the copy along the green axis, type **2′** and press **Enter** (Fig. 22).
8. Type ***17** and press **Enter** (16 more copies will be created, spaced 2 ft. apart).



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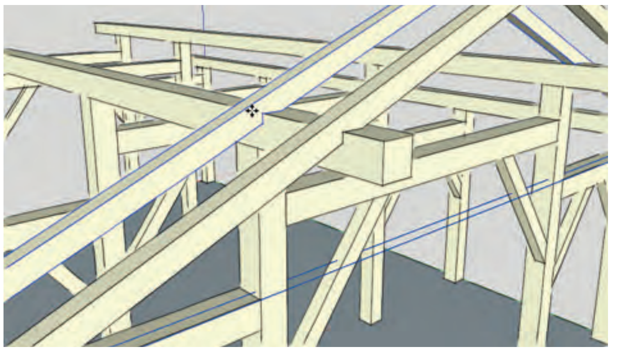

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Wall Braces. We've already created two brace sizes for the bents, but the plan calls for three new brace sizes for the walls. Like the transverse bent braces, all wall braces form a 3-4-5 triangle with the posts and beams that they connect.

But with 36 rafters in the way, it will be difficult to draw the braces. Fortunately, SketchUp allows us to hide objects and unhide them later.

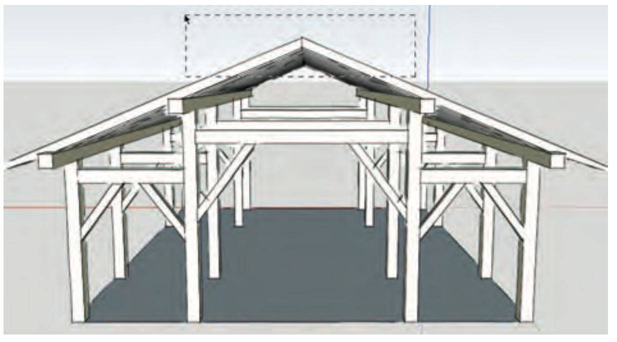
Hide the rafters:

1. Orbit the front of the frame so that the peaks of all rafters are displayed above all other timbers.
2. With the *Select* tool, draw a rectangle around the peaks, from lower right to upper left (Fig. 23).
3. Orbit to make sure all rafter pairs (and only the rafter pairs) are selected.
4. Right-click on any rafter and select *Hide* from the context menu.

We'll start by making the braces that brace the posts to the plates. These braces measure 2 ft. 8 in. vertically and will be created from a copy of one of the existing braces.

Create a 2 ft. 8 in. brace:

1. With the *Select* tool, double-click on a bent (to open the group).
2. Click on the outer brace and select *Copy* from the *Edit* menu.
3. Right-click outside the bent and select *Close Group*.
4. Orbit to an outside wall.
5. Select *Paste* from the *Edit* menu, move the brace copy away from the frame and click (Fig. 24).
6. Select the *Rotate* tool, move the cursor to a top corner brace and click when the protractor turns blue.
7. Move along the red axis and click (Fig. 25).
8. Start rotating counterclockwise, then type **90** and press **Enter**.
9. With the *Tape Measure* tool, click on the lower edge of the plate.
10. Move down along a post (blue axis), then type **2′8** and press **Enter**.
11. With the *Move/Copy* tool, click on the lower outside corner of the brace.
12. Move the brace to the intersection of the guideline and the outside of the corner post, then click (Fig. 26).
13. With the *Select* tool, right-click on the brace and select *Make Unique* (to make the brace component unique).
14. Double-click on the brace to edit it.



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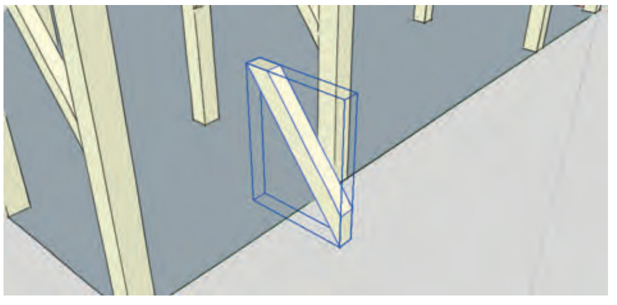

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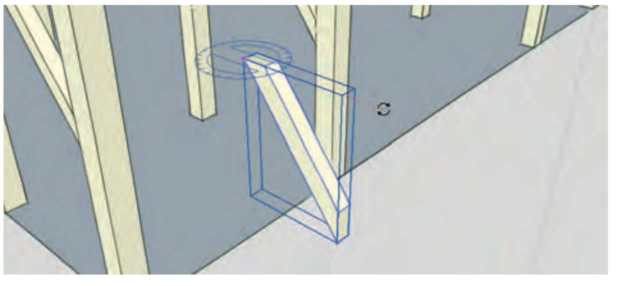

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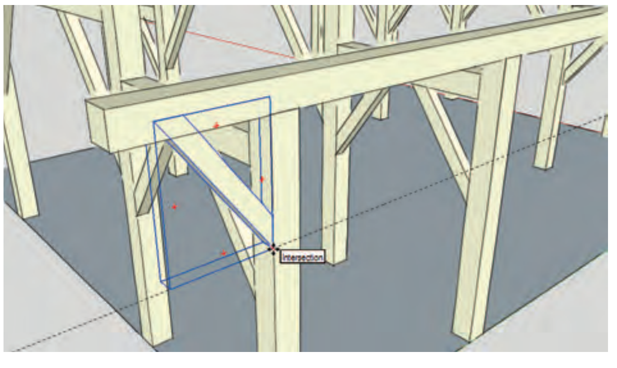

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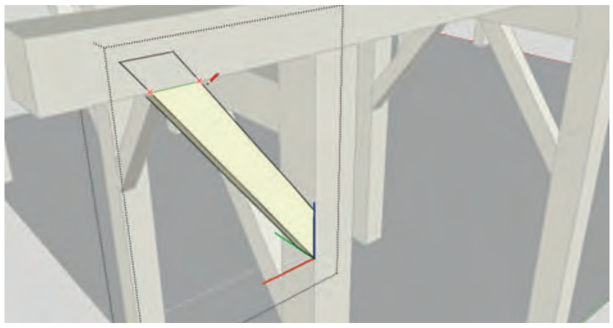
15. With the *Line* tool, make a horizontal line where the brace intersects the plate (Fig. 27).
16. With the Push/Pull tool, push inward until a limit of – 4″, then click.
17. Right-click outside the brace to close it.

With a short brace created, we can copy it to the opposite end of the plate and then copy both short braces to the adjacent purlin.

Copy the 2 ft. 8 in. brace:

1. With the *Select* tool, click on the brace.
2. Using the *Move/Copy* tool, press **Ctrl** and move a copy of the brace toward the opposite end of the plate.
3. Right-click on the brace and select *Flip Along* > *Component's Red*.
4. Click on the bottom outside corner of the brace, move it to the intersection of the guideline and the corner post, then click (Fig. 28).
5. With the *Select* tool, hold down **Shift** and click on the original 2 ft. 8 in. brace (both braces should be selected).
6. With the *Tape Measure* tool, click on the lower edge of the adjacent purlin.
7. Move down along a post (along the blue axis), then type **2′8** and press **Enter**.
8. With the *Move/Copy* tool, press **Ctrl** and click on the lower outside corner of the left brace.
9. Move copies of the braces toward the inner wall and, when the left brace snaps to the intersection of the left post and the guideline, click (Fig. 29).
10. Delete the guidelines (*Edit* > *Delete Guidelines*).



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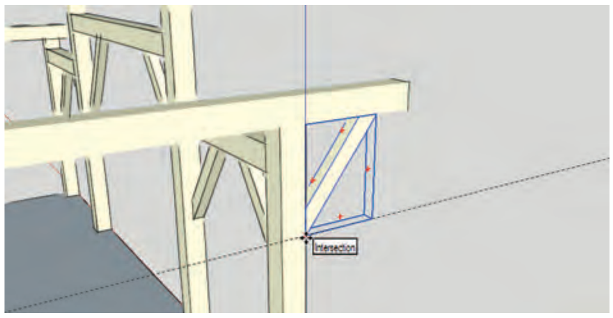

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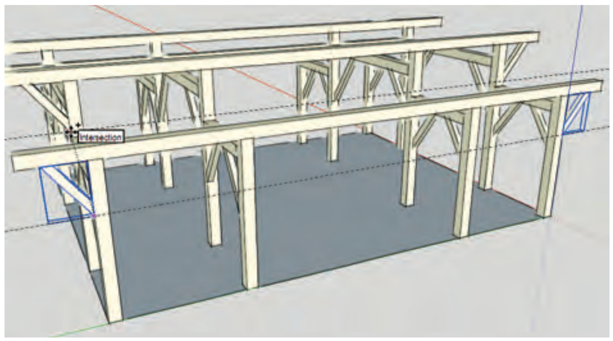

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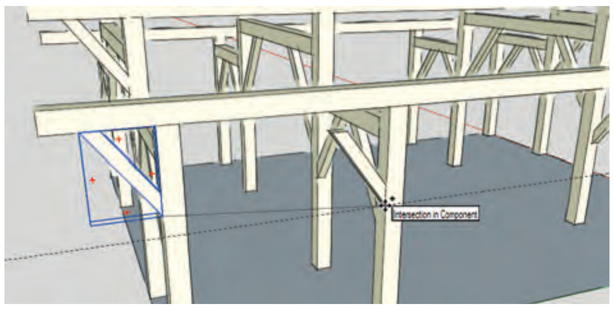
Next, we'll create the additional braces for the outside walls. Three pairs of braces will be created on one outside wall and then will be copied to the opposite wall. These braces measure 3 ft. 4 in. vertically and will be created from a copy of one of the short braces.

Create a 3 ft. 4 in. brace:

1. With the *Tape Measure* tool, click on the lower edge of a plate.
2. Move down along a post (along the blue axis), then type **3′4** and press **Enter**.
3. With the *Select* tool, click on the left side brace on the wall.
4. With the *Move/Copy* tool, press **Ctrl** and click on the lower right corner of the brace.
5. Move a copy of the brace to the intersection of the guideline and the next wall post, then click (Fig. 30).
6. Right-click on the brace and select *Make Unique* (to make the brace component unique).
7. With the *Select* tool, double-click on the brace to edit it.
8. With the *Tape Measure* tool, click twice slowly on each of the brace's diagonal lines on its outside face.
9. With the *Line* tool, draw lines from each top corner of the brace, along the guidelines, until the lines intersect the bottom of the plate.
10. Draw a third line horizontally between the two guidelines at the bottom edge of the plate (Fig. 31).
11. Orbit to the back side of the brace.
12. With the *Push/Pull* tool, click on the newly formed face.
13. Pull back on the brace, then type **4** and press **Enter** (Fig. 32).
14. With the *Eraser* tool, click on the 4 horizontal lines in the brace to erase them.
15. Click on the diagonal guidelines to erase them.
16. Right-click outside the brace to close it.



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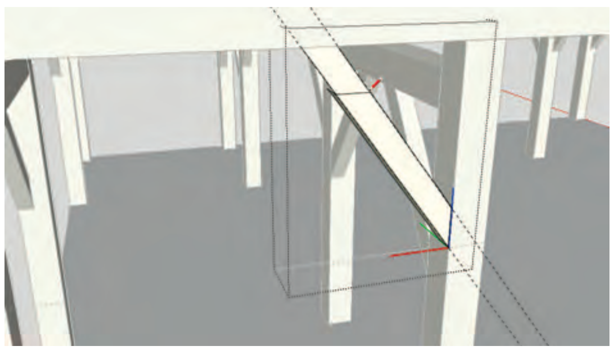

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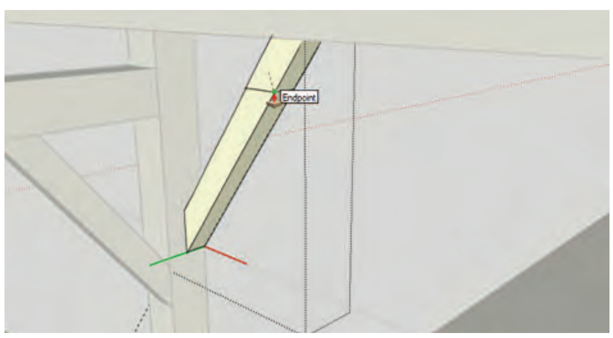
With a 3 ft. 4 in. brace created, we can copy it to various positions along the wall to complete the braces in one outside wall.



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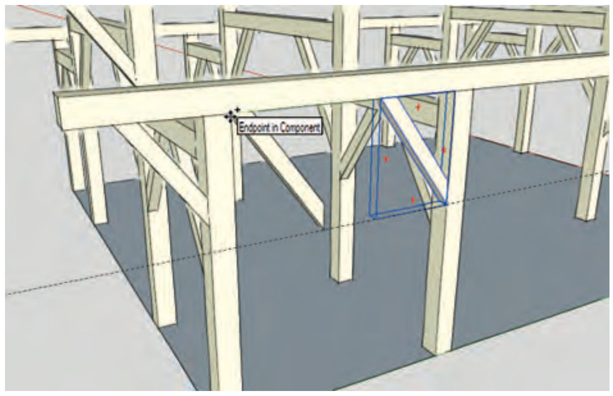
Copy the 3 ft. 4 in. braces:

1. With the *Select* tool, click on the 3 ft. 4 in. brace.
2. Using the *Move/Copy* tool, press **Ctrl** and click on the upper left corner of the brace.
3. Move a copy of the brace left (along the green axis) until it intersects the next wall post, then click (Fig. 33).
4. Right-click on the brace and select *Flip Along* > *Component's Red.*
5. With the *Select* tool, hold down **Shift** and click on the original brace (both braces should be selected).
6. With the *Move/Copy* tool, press **Ctrl** and click on the lower outside corner of the right brace.
7. Move copies of the braces toward the opposite end of the wall (along the green axis).
8. Click when the right brace snaps to the intersection of the righthand corner post and the guideline (Fig. 34).
9. Press **Ctrl** and click on the bottom left edge of the selected brace pair.
10. Move another brace pair copy toward the center of the wall (along the green axis).
11. Click when the left brace snaps to the intersection of the median wall post and the guideline (Fig. 35).
12. With the *Select* tool, click on the right-hand selected brace.
13. With the *Move/Copy* tool, click on the bottom right corner of the selected brace.
14. Move the brace toward the adjacent median wall post.
15. Click when the left brace snaps to the intersection of the post and the guideline.
16. Delete the guidelines (*Edit* > *Delete Guidelines*).



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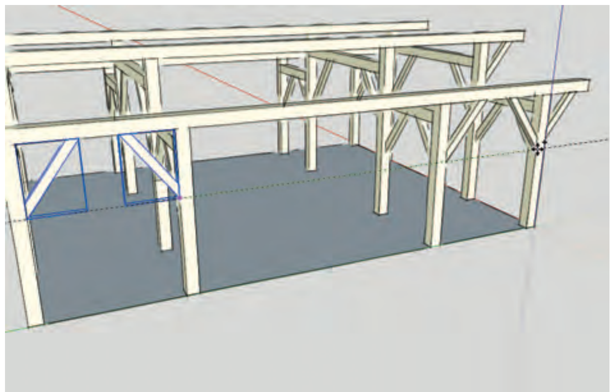
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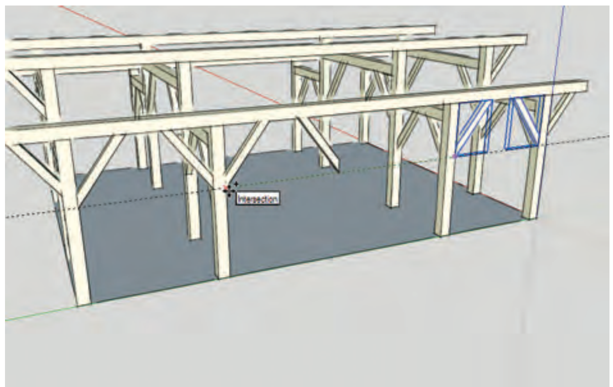

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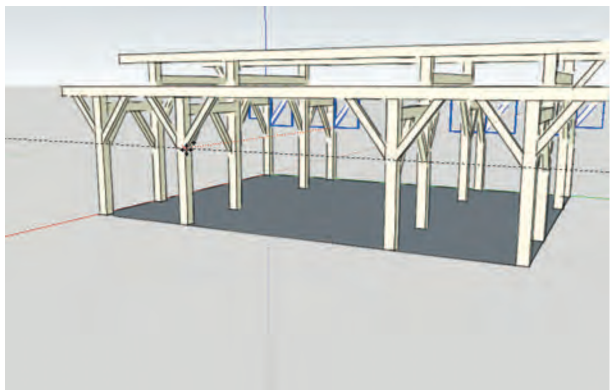
Now that all braces are created for one outside wall, we can select all of them and copy them to the opposite outside wall.

Copy braces to the opposite outside wall:

1. With the *Select* tool, hold down **Shift** and click on all eight braces in the wall.
2. Orbit to the opposite wall.
3. With the *Tape Measure* tool, click on the lower edge of the plate.
4. Move down along a post (blue axis) then type **3′4** and press **Enter**.
5. Using the *Move/Copy* tool, press **Ctrl** and click on a lower inside corner of one of the median braces.
6. Move copies of the braces to the opposite wall (along the red axis) until the move-from point snaps to the intersection of the guideline and post, then click (Fig. 36).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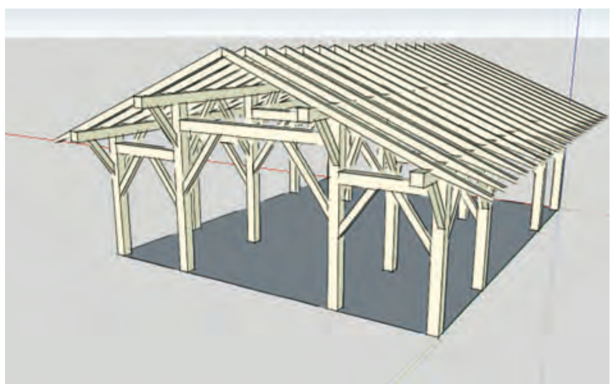
Finally, we need to create the braces for the inside walls. The process is identical to creating and copying the braces for the outer walls, except these braces measure 4 ft. 4 in. along their vertical axis. Follow the procedures outlined above, except make the guidelines 4 ft. 4 in. from the purlins.

Once you're done creating all the wall braces, you can unhide the rafters.

Unhide the rafters:

1. In the *Edit* menu, select *Unhide* > *All* (the rafters should reappear, Fig. 37).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Sills. Obviously, sills would be the first timbers to assemble in a real frame, not the last. Since we skipped over this detail in Part 1 of the tutorial, we'll need to resize our posts and insert the sills under them.

All posts in the frame are copies of two post components, so we'll only have to edit two posts to change all of them. Since the sills are 8x4, we'll have to raise the bottom of the posts by 4 in.

Shorten the posts:
1. Orbit underneath the slab.
2. With the *Select* tool, double-click on the first bent (this opens the group).
3. Double-click on a median post (in the selected bent).
4. With the *Push/Pull* tool, start pushing the post up, type **4** and press **Enter** (Fig. 38).
5. With the *Select* tool, double-click on a corner post.
6. With the *Push/Pull* tool, start pushing the post up, type **4** and press **Enter**.
7. Click outside the post and close the component.
8. Click outside the bent and close the group.

Since we'll be working adjacent to our "slab," we should make it into a group before adding the sills.

Make the slab into a group:
1. With the *Select* tool, double-click inside the slab (Fig. 39).
2. Right-click on the slab and select *Make Group*.

First we'll make sills for the end bents. Since these four timbers are identical, we'll make one component and reproduce it.

Make an end sill:
1. With the *Rectangle* tool, click on the bottom left corner of the right-hand median post.
2. Drag a rectangle to the corner of the slab and click (Fig. 40).
3. Orbit to the back side of the rectangle.
4. With the *Push/Pull* tool, click on the back side of the rectangle.
5. Pull the rectangle back, type **8** and press **Enter**.
6. With the *Select* tool, double-click on the sill.
7. Right-click on the sill and make it into a component.

Copy the end sill:
1. With the *Move/Copy* tool, press **Ctrl** and click on the upper left corner of the sill.
2. Drag a copy of the sill to the other side of the bent, along the red axis.
3. Click when the sill aligns with the corner post.
4. With the *Select* tool, hold down **Shift** and click on the original sill (both sills should be selected).
5. With the *Move/Copy* tool, press **Ctrl** and click on the top back corner of the sill.
6. Move a copy of the sills to the opposite end bent, along the green axis.
7. Click when the sills align with the outside of the bent (Fig. 41).

Next we'll make the sills for the outside walls. As with the first set, these four sill timbers are identical and will be copied from one component.

Make a wall sill:
1. Orbit to the outside of a wall.
2. With the *Rectangle* tool, click on the bottom-right corner of the first median post.
3. Drag a rectangle to the bottom corner of the bent sill (4″, 7″, 4″ should appear in the *Dimensions* box).
4. Orbit to the far side of the rectangle.
5. With the *Push/Pull* tool, click on the far side of the rectangle (Fig. 42).
6. Pull the rectangle back, type **8** and press **Enter**.

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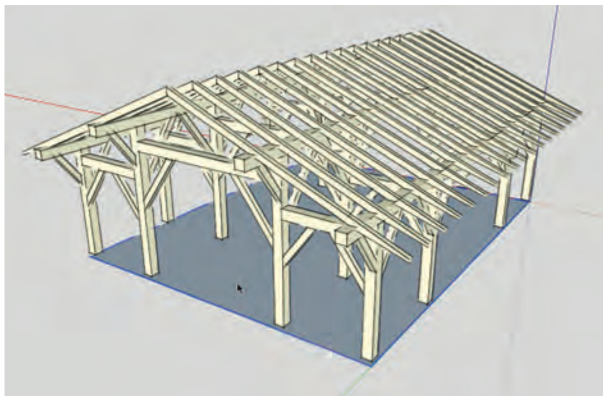

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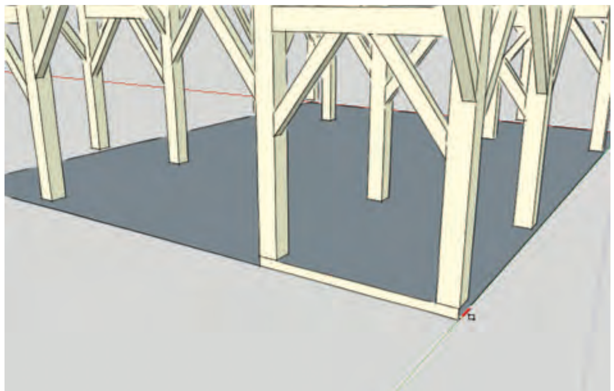

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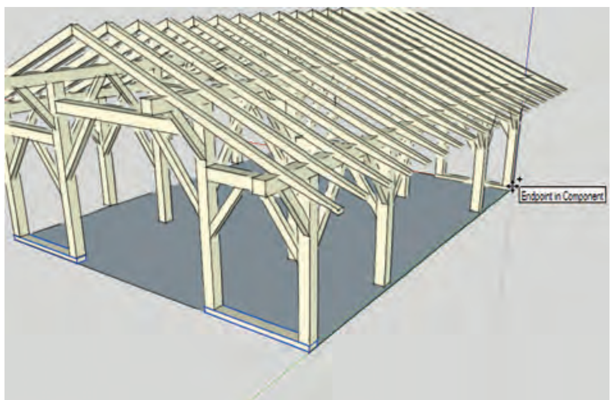

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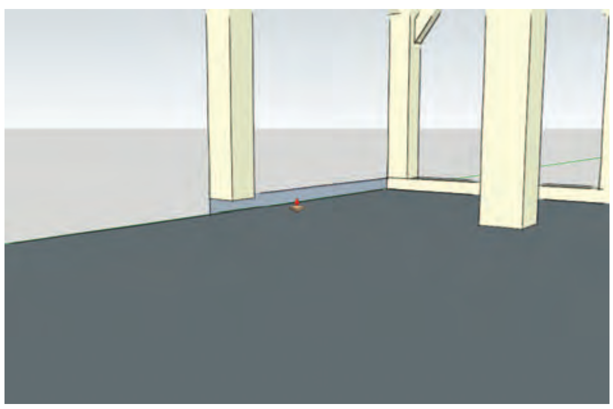

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7. With the *Select* tool, double-click on the sill.
8. Right-click on the sill and make it into a component.

Copy the wall sill:
1. With the *Move/Copy* tool, press **Ctrl** and click on the upper right corner of the sill.
2. Drag a copy of the sill to the other side of the wall, along the green axis.
3. Click when the new sill butts up to the end sill (Fig. 43).
4. With the *Select* tool, hold down **Shift** and click on the original wall sill (both sills should be selected).
5. With the *Move/Copy* tool, press **Ctrl** and click on the top back corner of the left sill.
6. Move a copy of the sills to the opposite outside wall, along the red axis.
7. Click when the new sills align with the outside of the wall.

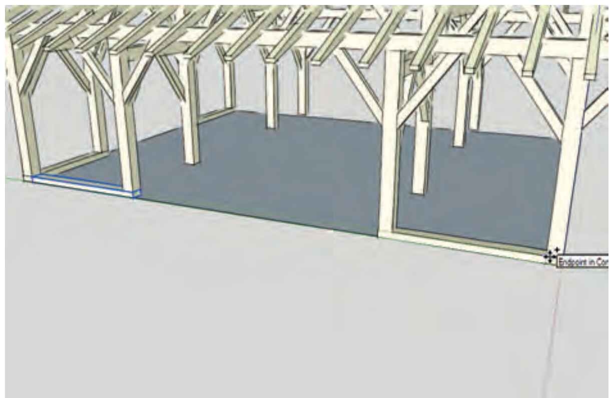
The last step is to make 8x8x4 sill blocks to fit under the inner posts. We'll create one block and copy the rest.

Make a sill block:
1. With the *Rectangle* tool, click on an open edge of the slab.
2. Start drawing a rectangle on the slab, type **8,8** and press **Enter**.
3. With the *Push/Pull* tool, click on the rectangle (Fig. 44).
4. Pull up, type **4** and press **Enter**.
5. With the *Select* tool, triple-click on the block.
6. Right-click on the block and make it into a component.
7. Right-click outside of the block and close the component.

Copy and position the sill blocks:
1. With the *Select* tool, click on the sill block .
2. With the *Move/Copy* tool, click on the top left corner.
3. Move the sill block until it intersects with the bottom left corner of an inner wall post, then click.
4. Press **Ctrl** and click on the top right corner of the sill block.
5. Drag a copy to the opposite inner wall post, along the red axis.
6. Click when the sill block intersects the bottom right corner of the post (Fig. 45).
7. With the *Select* tool, hold down **Shift** and click on the original sill block (both blocks should be selected).
8. With the *Move/Copy* tool, press **Ctrl** and click on an upper corner of one of the blocks.
9. Drag a copy of the two blocks toward the other inner wall posts, along the green axis.
10. Click when the new blocks intersect the posts.
11. Frame complete and leveled (Fig. 46).

IF you've followed these tutorials, you should now have the skills to draw just about any frame. The next step is to start working on joinery. Having mastered the *Push/Pull* and *Tape Measure* tools, adding joinery will be within your grasp. You are also ready for the Guild's publication *Timber Frame Design Using Google SketchUp,* by Clark Bremer, which offers SketchUp scripts that automate the creation of mortises. —Ben Weiss

Ben Weiss (zoomtext@gmail.com) is an owner-builder in Dorset, Vermont. This is the second part of a two-part article.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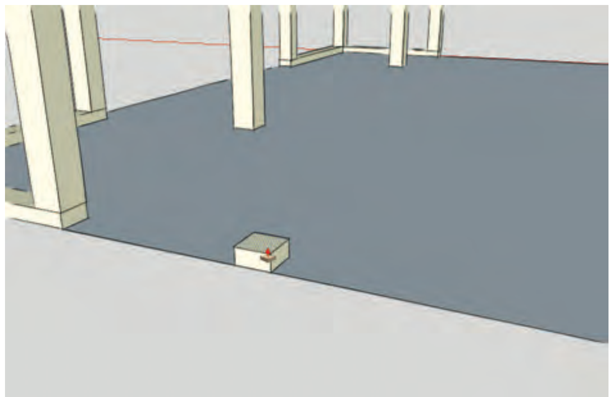
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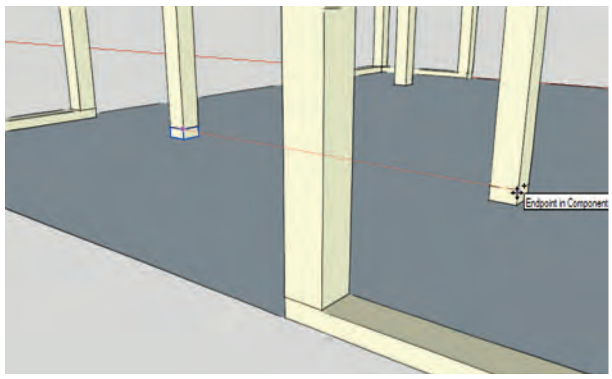

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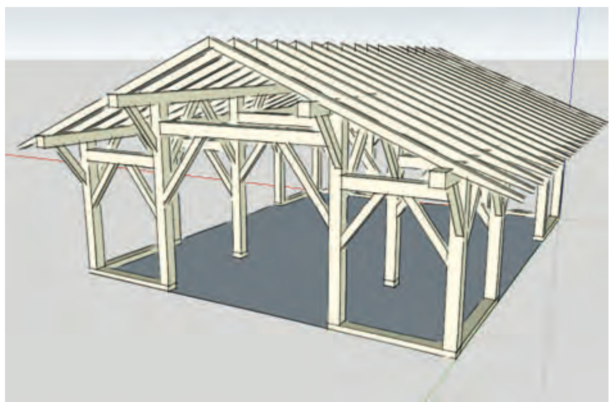
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Useful Geometries for Carpenters

DURING the Geometry and Hand Tools course that Jack Sobon and I ran at Bucksteep Manor in the Berkshire Hills of Massachusetts in late October and early November 2009, the days grew dark early and temperatures fell to freezing as winter began to close in. We were fortunate to be working in the shelter of Bucksteep's large marquee (normally used for wedding receptions), which offered a boarded dance floor extensive enough for work stations and full-scale trial layouts. As dusk fell each day, it was illuminated by vertical columns of lights that spiraled up around the marquee's three major poles. My workplace was in a corner of the marquee, where I used a large blackboard set flat on trestles for geometrical constructions and explanations. Jack moved among the work stations, explaining, discussing and demonstrating the use of hand tools for each successive stage of the carpentry.

Most evenings, after we had eaten, Jack, Rob Hadden (visiting from Australia and a student at the workshop) and I gave presentations. Jack talked of his practical experience with hand tools and gave us fascinating insights into the framing techniques of the early Dutch, German and English settlers in that part of Massachusetts. Rob inspired us all with his extraordinary single-handed estate-building program in Castlemaine, Victoria (see TF 58, 64, 74 and 87), and I showed historic timber-framed buildings from the border area between England and Wales. In support of the course, I also demonstrated some useful geometries for carpenters.

The geometries start with the simplest and, where relevant, evolve from one other. Some commence from compass construction and can be categorized as circle geometry while others are developments from the square and can be thought of as square geometry. The simplest, fastest and most accurate way to construct a square, however, is by compass geometry and straightedge—and this reveals a fundamental fact of geometrical design, that circle and square geometries are often interdependent. It should also be recognized that just as constructing a building requires scaffolding, certain geometrical developmental stages function as scaffolding and are removed after serving their purpose. Twenty-four drawings follow.

Point, line and plane. Geometry begins with point, line and plane. A point is best described as a location without dimension, the best practical example being the pinprick of a compass point into the surface of a sheet of paper. A line can be thought of as the connection between two points and, though it has length, like the point it has no dimension. The edge of a sheet of paper, for example, is a line without dimension, a division between the tangible paper and the space around it. A plane exists within linear two-dimensional boundaries such as a circle (single curved line), a *vesica piscis* (two curved lines), triangle (three straight lines), square, rectangle or parallelogram (four straight lines), etc. It is clear from these examples that a line can be either straight or curved, so that a circle passing through all four corners of a square is simultaneously a square that meets a circle at four points, an example of two different geometrical routes between the four equidistant points. A circle's continuous single line curvature has a straight line as its diameter and a point at its axis (its center), so that the circle is the simplest and most perfect embodiment of point, line and plane. —Laurie Smith

Laurie Smith (lauriesmith@uku.co.uk), an artist and graphic designer, lives in Wales and has made a speciality of geometric building analysis. An earlier article (TF 70) analyzed three historic buildings in the Welsh countryside. The 2009 workshop described will be repeated in 2010.

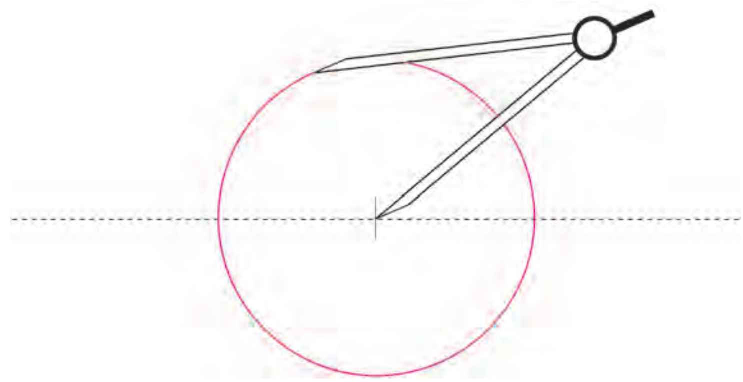

Fig. 1. Drawing a circle.

The most useful circle is best drawn from a point on a straight line because the resulting circle automatically has a diameter and in consequence three precision points: the circle's axis and the two points on the circumference at opposite ends of the diameter. The three points are useful in constructions that require more than one circle. Also, the diameter passes exactly through the circle's center and is, therefore, a centerline for any further geometrical construction.

All drawings Laurie Smith

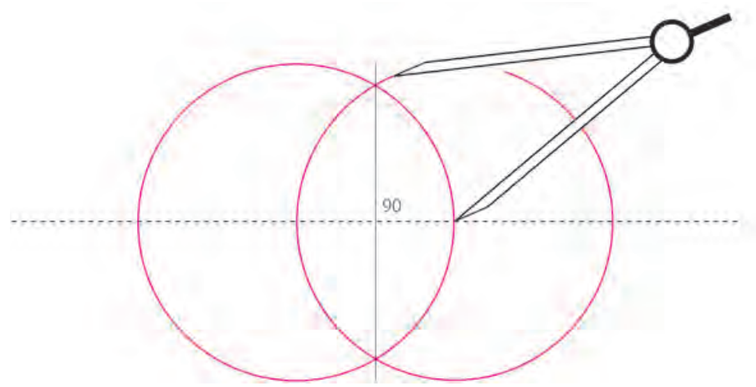

Fig. 2. Drawing a perpendicular.

A perpendicular is a line drawn precisely at 90 degrees to another. If a circle is drawn from a point on a line, then one of the two lines is already in place. If a second circle (of identical radius to the first) is drawn from where the diameter (or centerline) cuts the first circle, the two circles form a vesica piscis or mandorla. A vertical line drawn through the poles of the vesica is automatically perpendicular to the centerline and generates 90 degrees at the point where the lines intersect.

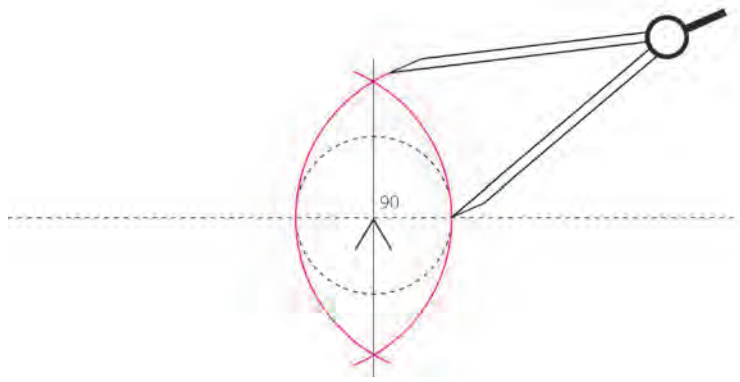

Fig. 3. Drawing a precision perpendicular.

A precision perpendicular is a line drawn at 90 degrees to another at a precisely predetermined point. Step 1 is to determine the position of the point by drawing a straight line and marking the point on it. Step 2 is to draw a circle from the point so that it cuts the centerline in two further points (the length of the radius is a matter of choice). Step 3 is to draw a vesica from where the circle cuts the centerline. In the final step, bisection of the vesica gives the perpendicular. Below, the shortcut method.

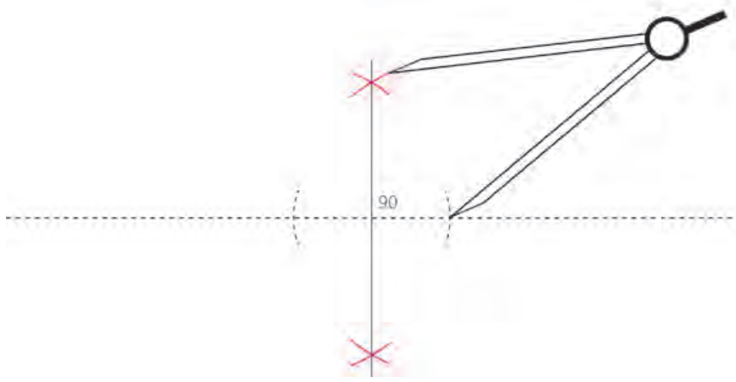

Fig. 4. Drawing a shortcut precision perpendicular.

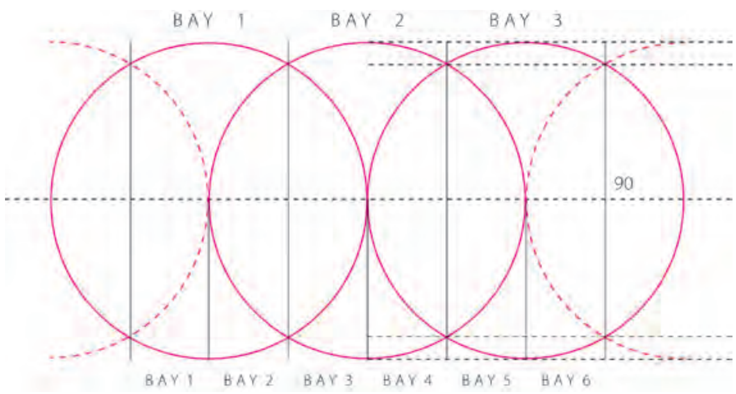

Fig. 5. Three-circle sequence.

Any number of identical radius circles can be drawn along a centerline, but a three-circle sequence is shown here. It follows that if two identical circles on a centerline generate a perpendicular then every pair of circles will, and this means that a circle sequence can generate a bay rhythm for a linear building. In the drawing above, the three-bay rhythm results from the vesica intersections, but this rhythm can be doubled to six bays if parallels are also drawn where the circle circumferences kiss along the centerline. Parallels to the centerline can be drawn either as tangents to the circle circumferences or through their points of intersection to give long wall alignments as shown on the right of the drawing.

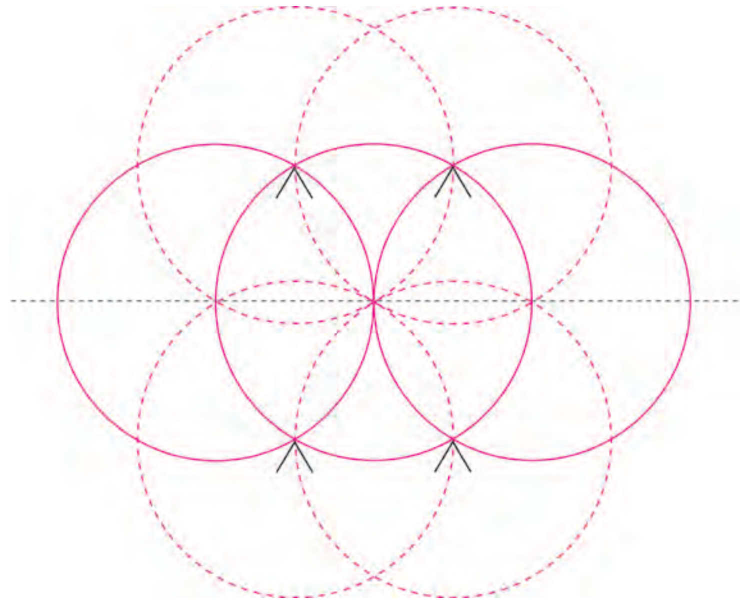

Fig. 6. Drawing the daisy wheel.

Although the daisy wheel is commonly drawn as six circles around the circumference of a central circle, it is more accurately drawn as a development of the three-circle sequence. This is because the relationship of the three circles in the sequence is governed by the centerline and they intersect each other at the four centers needed to complete the construction of the wheel.

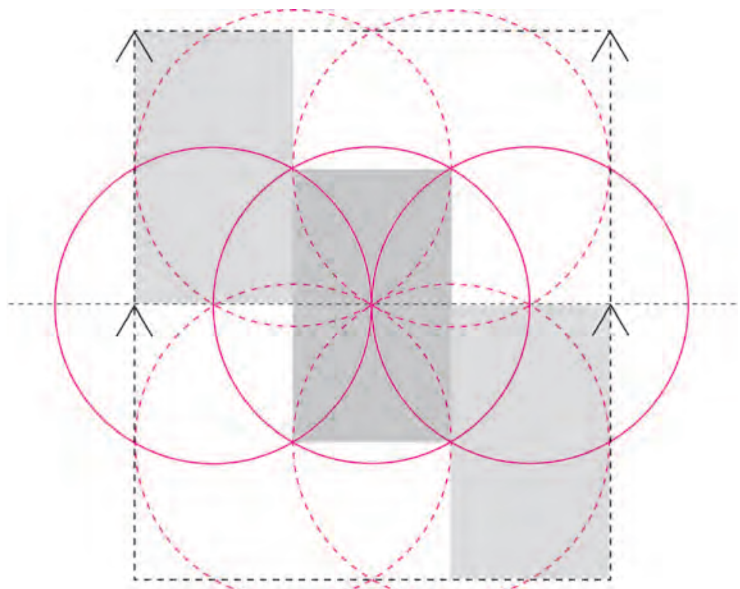

Fig. 7. The daisy wheel as a source of root 3 rectangles.

The daisy wheel is a source of root 3 rectangular proportions. A rectangle drawn through all six outer points of intersection generates two large *horizontal* root 3 rectangles (the upper rectangle is indicated by arrows). A small rectangle drawn between four of the daisy wheel's petal tips generates a small *vertical* root 3 rectangle (shaded darker). It can be seen that the large and small rectangles share a harmonic relationship where each large rectangle is equal to three small ones. Slide the small rectangles up or down mentally to fit the large rectangles.

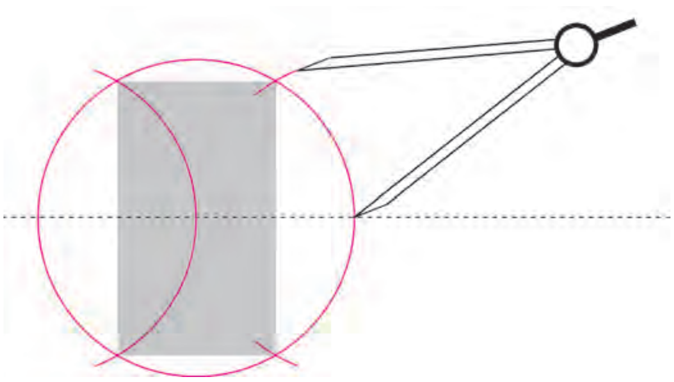

Fig. 8. Shortcut construction of the root 3 rectangle.

The circle must be drawn on a centerline so that it is cut at either end of its diameter. With the compass set to the same radius, draw arcs from the ends of the diameter so that each cuts the circle at two points. Connection of the four points gives the root 3 rectangle. The short side of the rectangle is identical to the circle's radius. This is the fastest and most accurate way to draw a root 3 rectangle: the radius is the only dimension needed and the rectangle's right-angled corners arise automatically from the compass drawing.

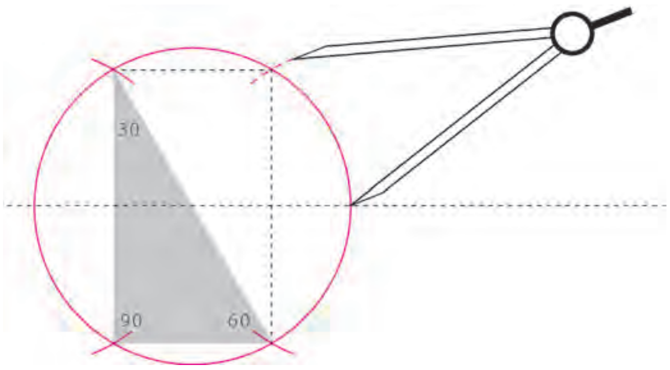

Fig. 9. Construction of a right triangle.

The root 3 rectangle can be bisected on its diagonal to give a right triangle with angles of 30, 60 and 90 degrees.

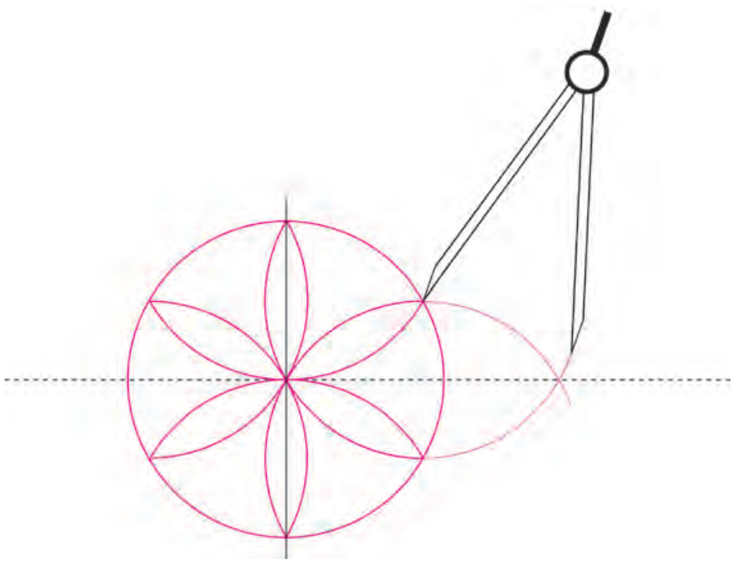

Fig. 10. Drawing a perpendicular from the daisy wheel.

The daisy wheel can be used to generate a perpendicular. In this drawing, the wheel is constructed on the vertical line. Extensions of two of its arcs intersect at a point level with the axis, and a line drawn through these points gives a horizontal perpendicular. The extended arcs can be drawn at any time, either during the wheel's initial construction or later, from an existing wheel.

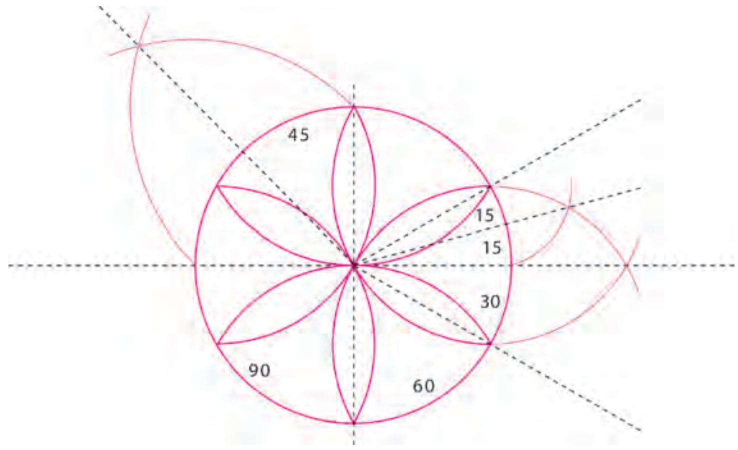

Fig. 11. Using the daisy wheel as a protractor.

The daisy wheel can be used to generate many angles. The wheel's natural division is into six 60-degree angles, constructed either by drawing diameters across the wheel between the opposite petal tips or connecting each tip to the wheel's axis. If 60 degrees is bisected, it gives 30, and this in turn bisected gives 15. The angle between the perpendiculars is 90 degrees, which bisected gives 45. Further bisections can be made to give smaller angles so that 45 degrees bisected gives 22½, or 15 degrees bisected gives 7½. Larger angles can be attained by addition, for instance 90 + 45 = 135. Many protractors are manufactured for school use and are thus too small to project angles accurately to larger scales. The daisy wheel, which can be drawn at any size, is a useful tool for laying out and cutting templates for either regularly used or unusual angles.

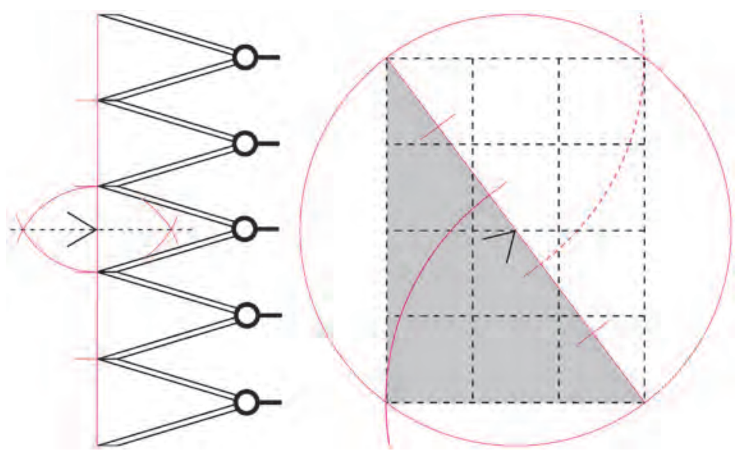

Fig. 12. Constructing the 3-4-5 triangle by compass.

Start with Side 5 of the triangle. Any chosen unit length can be stepped off five times along a line to give the length of Side 5. The center point of the line (at 2½ units) is found by drawing a small vesica, and this is the circle's axis. A circle with a radius of 2½ units is drawn from the axis; the length of Side 5 is thus automatically the circle's diameter. With the compass set to 3 units, an arc is drawn from one end of the diameter to cut the circumference. When the point is connected to the adjacent ends of the diameter, it forms the 3-4-5 triangle (shown shaded). The same construction can be repeated from the opposite end of the diameter to give the full 3x4 rectangle (shown in dashed line). The beauty of this construction is that there is no need to use a square to establish the triangle's right angle as the geometry generates it automatically.

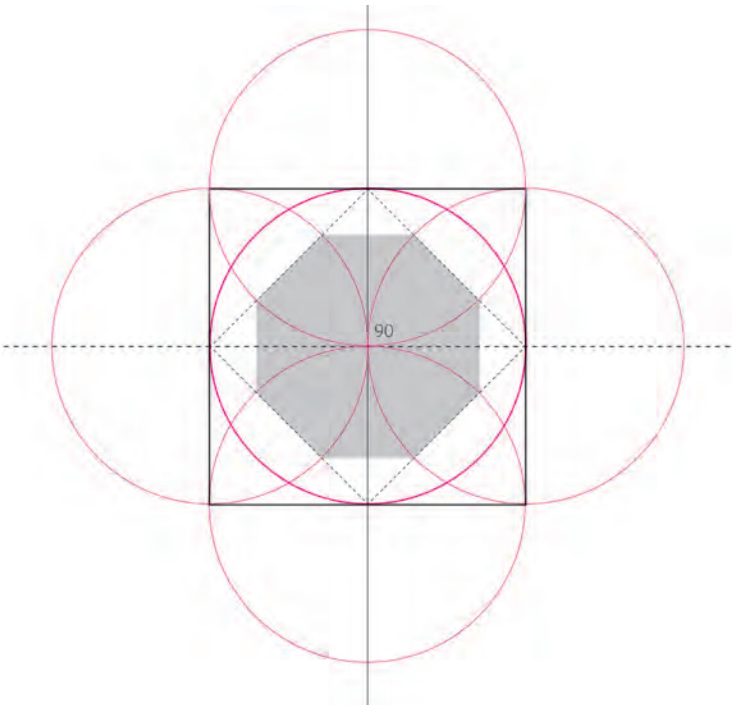

Fig. 13. Constructing the perfect square by compass.

The first circle is drawn from the intersection of two perpendicular lines so that the lines cut its circumference at four equidistant poles. With the same radius, draw four further circles from the poles. The four outer circles intersect each other at four points and these points are the corners of the square. The drawing method is completely free from the need to construct right angles at the corners of the square. Other polygons can be made from the construction. Connecting the central circle's four poles forms a diamond and, where this cuts the arcs of the other four circles, a perfect octagon (the shaded area) is produced .

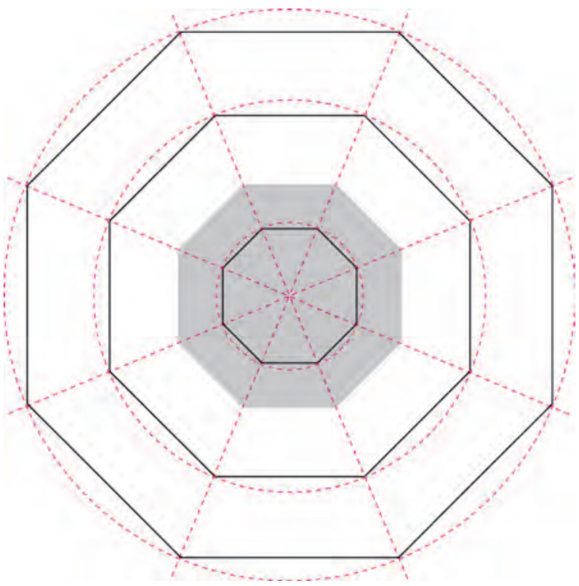

Fig. 14. Constructing larger and smaller polygons.

To increase or decrease any even-sided polygon in scale, draw lines connecting the figure's opposite angles so that they intersect at its axis. In the case of the shaded octagon the lines will form eight radials that can be extended outside the octagon's boundary to any desired length. Any circle drawn from the axis will cut the eight radials at equal distances from the axis; connecting these points gives another octagon. To increase or decrease *odd-sided* polygons such as a pentagon, draw lines from the figure's angles to the *centers of the opposite sides*, extend these lines outward from the angles, draw circles from the axis and construct the required form.

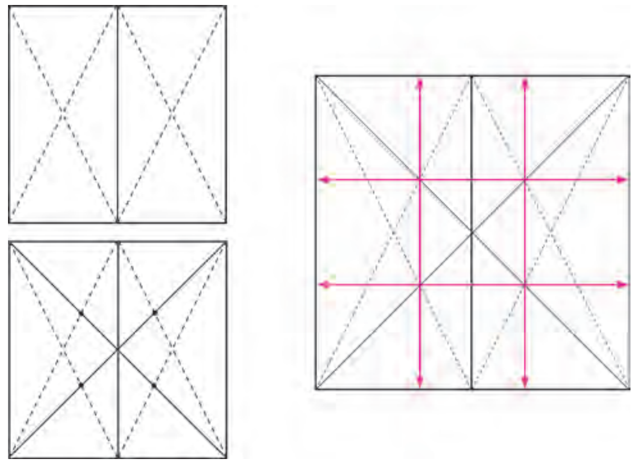

Fig. 15. Dividing a square into three sectors using diagonals.

To divide a square into three sectors, it must first be divided in half (two sectors). The diagonals of the half squares are drawn first, then the full diagonals of the square. The full diagonals cut the half diagonals in four places. Vertical and horizontal lines drawn through the four points of intersection divide the square into vertical and horizontal thirds. The vertical and horizontal lines also subdivide the full square into nine equal small squares. This principle can also be applied to rectangles.

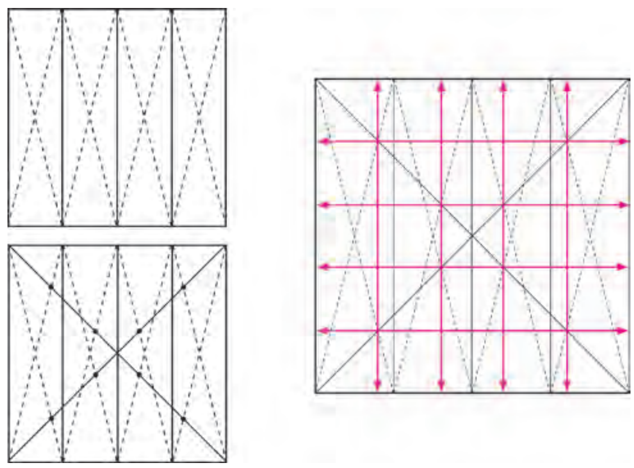

Fig. 16. Dividing a square into five sectors using diagonals.

To divide a square into five sectors, it must first be divided into quarters (four sectors). The diagonals of the quarters are drawn first, then the full diagonals of the square. The full diagonals cut the quarter diagonals in eight places. Vertical and horizontal lines drawn through the eight points of intersection divide the square into vertical and horizontal fifths. The vertical and horizontal lines also subdivide the full square into 25 equal small squares. This principle can also be applied to rectangles. Notice that this system of division will increase any number of even divisions by one, so that halves are converted to thirds, quarters to fifths, sixths to sevenths, etc. To arrive at a division of thirteen the procedure would be to halve to get thirds, halve the thirds to get sixths, halve the sixths to get twelfths, draw diagonals in each twelfth and then the full diagonals. Lines through the points of intersection will give thirteen vertical and horizontal divisions.

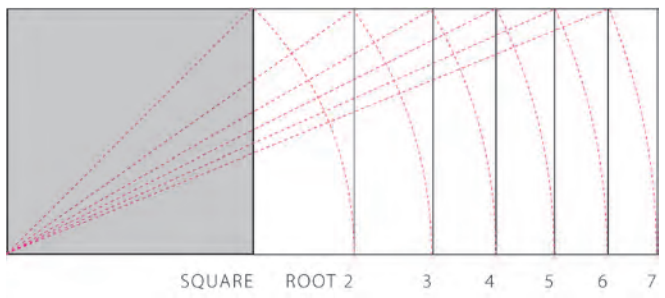

Fig. 17. Constructing root 2, 3, 4, 5, 6 and root 7 rectangles.

The rectangles are a harmonically related sequence where each consecutive rectangle's diagonal is transmitted by compass arc down to the base line to define the next rectangle's boundary. The sequence usually begins with the square so that the square's diagonal projected to the base line establishes the root 2 rectangle, the root 2's diagonal establishes the root 3 and so on. The sequence can theoretically evolve to eternity but comes to a halt when drawing the diminishing sectors becomes impossible. The related rectangles are useful in establishing floor, wall, window and door proportions that have harmonic resonance. The root 2 rectangle owes its name to the fact that a square with sides of 1 unit in length will have a diagonal of 1.4142 (the square root of 2), which becomes the rectangle's long side. Most of the root numbers, like root 2, are difficult to measure or calculate but can be drawn easily by a child with a straightedge and compass. The root 3 rectangle can be drawn more easily by compass (Fig. 8).

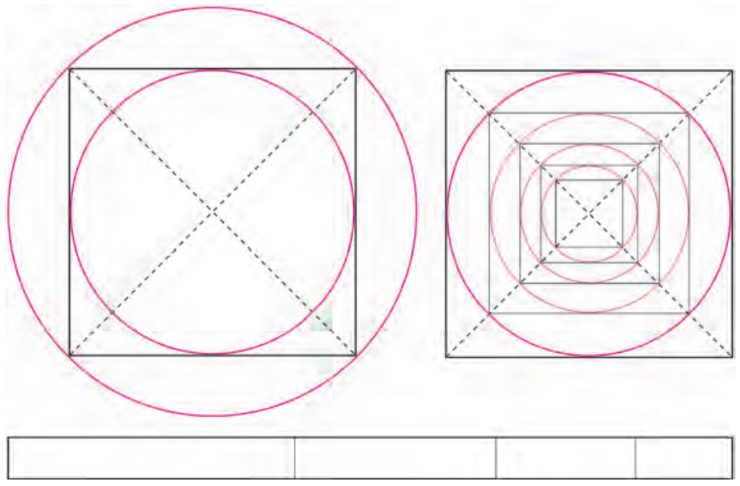

Fig. 19. Constructing harmonically related squares.

The square has an intimate geometrical relationship with two circles, the larger external circle passing through the square's corners and the smaller internal circle kissing the square at the center of each side. This relationship can be extended indefinitely by the construction of ever larger or smaller squares. The proportional relationship is always constant however many squares are developed, but on an expanding and diminishing scale. The ratios of the scale are incommensurable, which is why they work as a visual geometrical construction and not as specific dimensions. Working from an initial square (of any size, dimensioned or otherwise), one can construct a proportional rule to relate the scale of different elements of the work harmonically. The scale at the bottom of the drawing shows the proportional relationship of the first four squares' sides. The scale can be used, for example, to establish harmonically related widths or heights for different-sized windows.

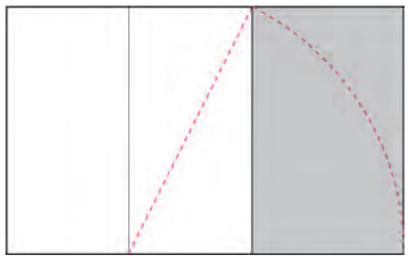

Fig. 18. Constructing the Golden Rectangle.

The Golden Rectangle is developed from the square, which is first divided into two halves. The diagonal of half the square is transmitted by compass arc down to the base line and the square is extended to this point to form the Golden Rectangle. The extension alone (shown shaded) is also a Golden Rectangle and, with its long side equal to the large rectangle's short side, the two rectangles share a harmonic proportional relationship. The Golden Rectangle was used in Classical and Renaissance times as a source of proportion for building plans, façades, doors and windows.

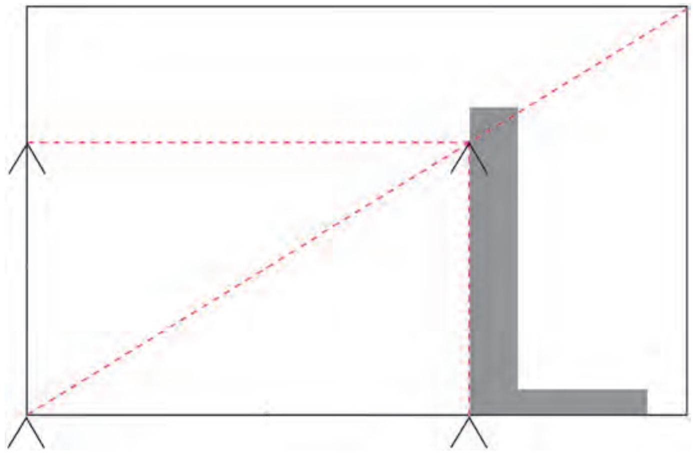

Fig. 20. Constructing a proportionally related rectangle.

Draw or snap a diagonal line across the existing rectangle and then place a carpenter's square against its base line a distance from the diagonal's origin equal to the desired rectangle's length. Scribe a vertical along the square. Mark the length of this line on the left edge of the rectangle and connect the marks to construct a parallel to the base, thus completing the new rectangle. The process can be repeated wherever the square is placed against the diagonal and the rectangle itself can be of any proportion, either horizontal or vertical (the rectangle shown is a Golden Rectangle). It is a useful technique for maintaining proportional relationships between (for instance) windows of different sizes within a single building.

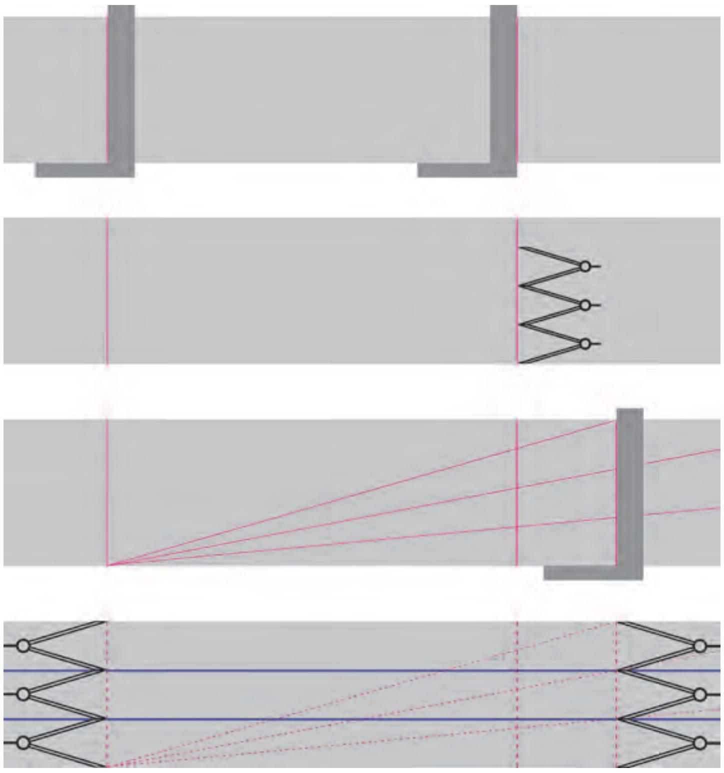

Fig. 21. Dividing timbers into odd-numbered equal widths.

Scribe two right angles across the timber (there are no exact positions). For division into three widths, set the dividers (by rule of thumb) so that three steps on the right-hand scribed line are less than the full timber width. Mark the three points on the line. Snap chalk lines between the left scribed line (where it meets the timber's lower edge) and the three points on the right scribed line so that they continue towards the timber's end. Scribe a new right angle where the highest chalk line crosses the timber's upper edge. Where this right angle cuts the chalk lines, take a new divider reading and step it out on a right angle at either end of the timber. Snap new chalk lines through the steps parallel to the timber.

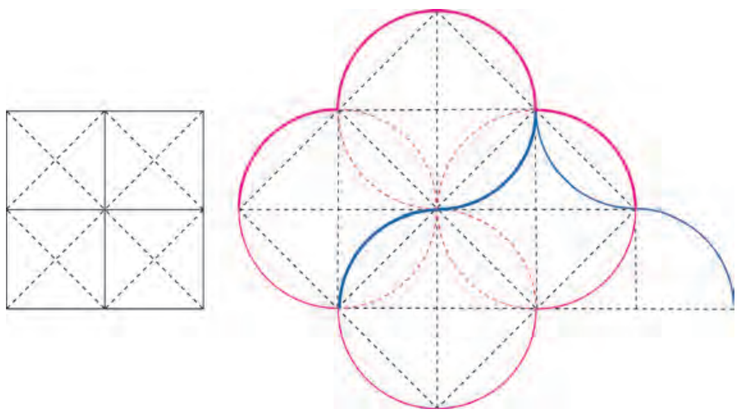

Fig. 22. Constructing a quatrefoil and ogival arch.

The construction starts from a large square subdivided into four quarters or small squares. Diagonals are drawn in each quarter and circles are drawn from where they intersect, so that the circles pass through the small squares' corners. The drawing is revolved 45 degrees so that the quatrefoil is in its correct position with vertical and horizontal center lines. If the quatrefoil is cut along its horizontal centerline, it gives a tripartite arch with a half-circle head and quarter-circle shoulders. The ogival curve (a curve with equal convex and concave sectors) follows the quarter-arcs of two adjacent circles. The curve is duplicated in mirror image to form the ogival arch. This can be constructed by drawing more squares, diagonals and circles or, more simply, by tracing the first curve.

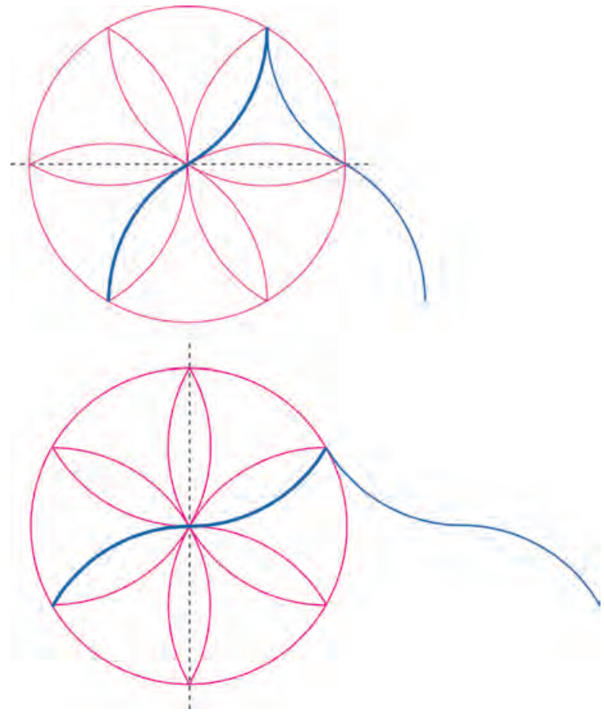

Fig. 23. Constructing daisy wheel ogival arches.

The arcs of circle that form the daisy wheel automatically generate an ogival curve (with equal convex and concave elements) across the wheel's diameter. The orientation of the wheel determines the character of the arch, the upper and lower drawings having horizontal and vertical emphasis resulting in tall narrow and wide shallow arches respectively. The wheel can be revolved on its axis to give further arch configurations.

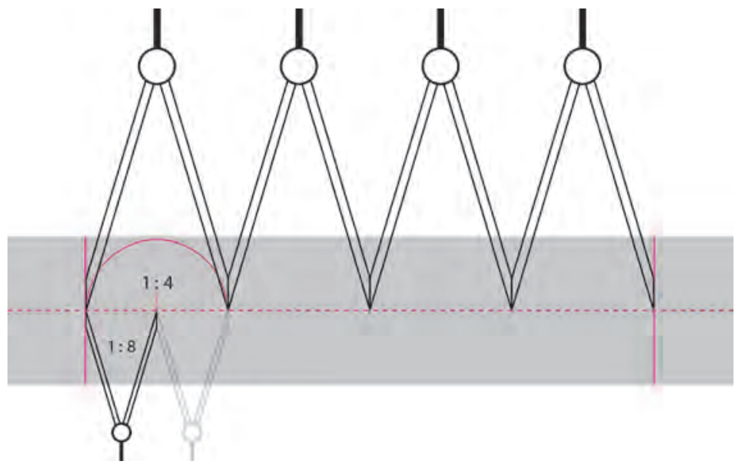

Fig. 24. Stepping off.

Stepping off with dividers along a chalk line is probably the most accurate way to translate dimensions from drawings onto timbers. Dividers can be set to any dimension irrespective of its numerical value, which eliminates the headache of numbers, and they record the dimension between two needle-fine points that, unlike steel tapes, do not twist or flex. The only opportunity for error is in remembering the number of steps to be taken. This risk can be halved by doubling the initial divider dimension to give half the number of steps. For example, if a drawing is at 1:24 scale, doubling the initial divider dimension reduces the steps to 12. The drawing shows an initial divider dimension taken from a 1:8 scale drawing and doubled to give just four steps along the chalk line. The simplest way to double the initial divider dimension is to scribe a half-circle on the chalk line, which doubles a radius into a diameter. ❖

The Riddle of Tremblay

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Photos New Jersey Barn Co.

IN 2002, the Philadelphia Museum of Art was about to relocate the contents of a storage facility, including a 6-ft. timber stack 5 ft. wide and 60 ft. long with associated crates of small pieces (photo 1), all supposedly representing a late medieval French refectory ceiling from Tremblay-lès-Gonesse, on the northeastern outskirts of Paris, and acquired by the museum in 1941. With the exception of a few accompanying contemporary letters, records were absent. Dean Walker, Curator of European Art at the museum, asked us to decipher the timbers.

In 1928, George Grey Barnard, who had discovered and disassembled the relic in France, sought the interest of the legendary architectural historian Fiske Kimball, then the museum's director. Barnard's descriptions were frustratingly elastic. His letter to Kimball of 5 October 1928 said, "the room is 160 feet long and about 45 feet in width." Eight days later he repeated the length at about 160 ft. but now reported the width "at some 25 feet." In 1991, the museum commissioned an investigation of the ruinous foundations of a likely structure at Tremblay (by then called Tremblay-en-France), which found a width of 9m, about 29 ft. Clearly none of these dimensions could be trusted as definitive.

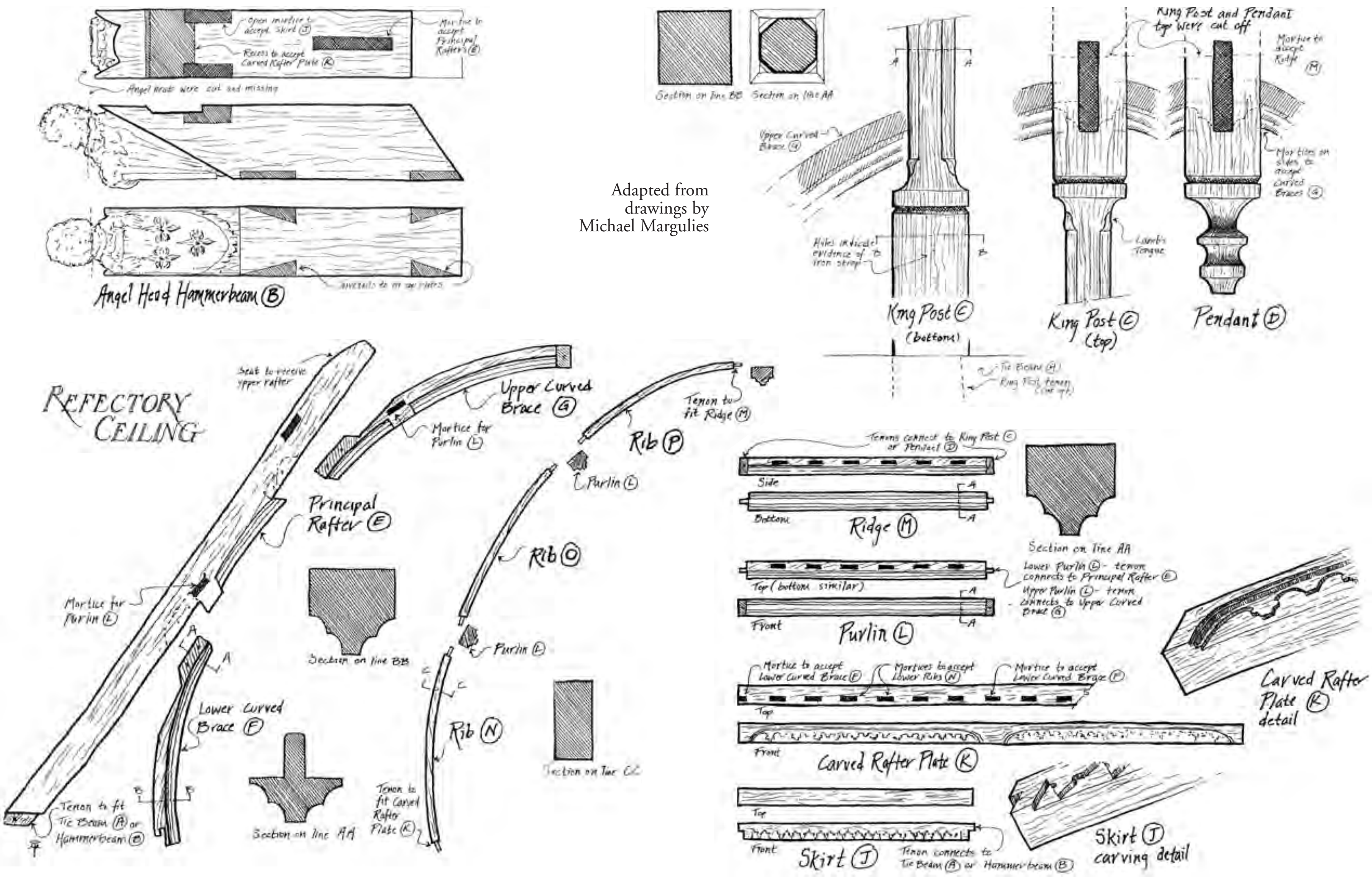
No photographs or drawings survived. Some of the hundreds of individual members bore framer's marriage marks dating to the 15th century (photo 2); others bore stenciled identifications for shipment across the Atlantic five centuries later. But there were no coded plans. A scale model apparently accompanied the frame when it was acquired but it, too, had been lost.

Descriptive accounts offered a few clues. Barnard had written Kimball, "I purchased an old Abbey in order to obtain a superb Gothic roof of oak arched and carved. . . . [An] oak beam support runs along the walls of the Ancient dining room and support[s] the arches of oak. They are not the cross beams, these cross beams are separate. . . . Many large carved heads support the upright beams in the center of these arches." A 1941 museum catalogue of the acquisition described the disassembled structure as "consisting of 64 arches, 80 cross beams, 9 columns and 9 corbels. The latter show the carved angels holding shields with alternating designs: three roses and three bishop's mitres."

So we began with more questions than answers. If the true character of the structure was to be revealed, the timbers themselves would have to tell the tale. Our approach was to seek out one or two examples of each member to understand how they might be assembled.

The timbers fell into several distinct categories. The most conspicuously decorated were the short, carved pieces the museum called corbels and we came to call hammerbeams (shown as *B,* upper left in Fig. 1), after similar unbraced members at Outwell Church, Norfolk, UK, called hammerbeams by Raphael and Arthur Brandon in their 1849 work *Open Timber Roofs of the Middle Ages.*

About 4 ft. 6 in. long and 11 in. square, the hammerbeams were embellished at one end with winged angels, all but one of whose faces (photo 3) had been hacked off, possibly during the French Revolution. The angels clutched shields adorned not just with mitres and roses but also a number of different heraldic emblems (photo 4 and back cover). At the opposite end, the hammerbeams were angled back by 7½ in., suggesting a roof pitch of 7½:11. The bottom surface was fashioned with shallow lap dovetails at each end. The upper surface near the angel carving was relieved to receive a passing timber, while an 11½-in.-long mortise was chiseled at the other end to accept a major rising timber, likely a principal rafter (Fig. 1).



Adapted from drawings by Michael Margulies

Fig. 1. Pieces of Tremblay ceiling eventually identified by their position in the frame.

A separate group comprised two sorts of probably related timbers. One, apparently kingposts (*C*, upper right Fig. 1), measured 12 ft. 9 in. long, with central chamfered sections of 9 ft. 6 in. (photo 5). The other sort, apparently pendants (*D*), were about 2 ft. long and terminated in remarkably various carved square turnings (cover photo). Both sorts of timbers were about 10 in. square in section and, with one exception, displayed 7-in. open mortises on all four sides. All of these members, short and long alike, appeared to have been cut at or just inside these mortises.

A third set of timbers seemed likely to be horizontal elements. There were four distinct, related types (*J*, *K*, *L* and *M*, lower right Fig. 1), of which *J*, *L* and *M* were approximately 7 ft. 5 in. long.

Timbers type *K* were 15 ft. 10½ in. long, with major mortises at the center and on each side a series of six evenly spaced mortises on the upper surface. The same evenly spaced mortises occurred on both the upper and lower surfaces of the *L* and *M* timbers. The tenons at the ends of the *L* timbers were oriented vertically; on the *M* timbers the tenons were horizontal. The remaining horizontal type *J* was more highly decorated, had no mortises and terminated in half-laps at both ends in place of tenons.

A final series of structural members were arched over all or part of their length. The majority of these took the form of slender ribs in three slightly different lengths (*N*, *O* and *P*, lower middle in Fig. 1). Of the remaining members (*E*, *F* and *G*), it became evident that together these formed arched bents, the principal support for the ceiling. Although different in length, *F* and *G* were fashioned with the same molded profile as on the horizontal members *L* and *M* and were acutely angled at one end with long bladelike tenons.

In sorting through the entire stack of timbers, we discovered only two examples of a particular beam into which these timbers would fit. That single pair of principal rafters (*E*) displayed the same molded profile as the curved braces (*F* and *G*) but over only 3 ft. of their much greater length. Still, when joined together with the other arched and molded timbers, they formed the two sides of a Gothic arch.

Fitting together these arched timbers was just the beginning of the assembly. The next step was to find a member to receive the tenons at the top of each of these half-arches. Eventually we recognized that the tenons could be fitted into either *C* or *D* (upper right in Fig. 1), the former a boss or pendant, the latter a kingpost.

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With the pendant in place as the central uppermost member and an angel-head hammerbeam neatly fitted at the bottom on each side, we were finally able to make a full assembly (photo 6).

The alternative composition, using the kingpost in place of the pendant, was more challenging. The base of each kingpost originally terminated in a central tenon, on the remaining evidence a wedged half-dovetail cut off during disassembly (photo 7), but we had no tie beams to span the distance between the rafter feet and to join the kingpost at midspan, despite the mysterious mention of "80 cross beams" in the museum inventory of 1941.

Judging by the lap dovetails cut into the bottom surface of the hammerbeams, they (along with the absent tie beams) were originally located longitudinally by a double set of 8-in.-wide horizontal members aligned respectively with the inside and outside of the masonry sidewalls. The distance between the outer extremities of the lap dovetails (underside of *B* in Fig. 1) established the thickness of the walls at approximately 2 ft. 8 in.

To ensure the structural integrity of the roof, the pendant and kingpost assemblies almost certainly alternated. The cadence of these roof frames can be surmised from the horizontal timbers that connected them, indicating the interval as 8 ft. on center. The ridge pieces (*M* in Fig. 2; see also Fig. 1), with vertical tenons, connected kingposts and pendants. The purlins (*L*), with horizontal tenons, connected the arched rafters and, spaced about 5 ft. apart, essentially divided each side of the arch into thirds.

The 16-ft. decoratively carved members were plates (*K*) running over the tie beams and hammerbeams and in turn supporting the lower arched braces (*F*) and the lowest rank of ribs (*N*). Pleasingly incised with a sawtooth design, the final horizontal element (*J*) formed a decorative band let into the upper sides of the alternating hammerbeams and ties.

Very little came to us of the structural roof framing originally hidden above the vaulted ceiling (shown conjecturally in Figs. 2-4). Of the two principal rafters that we did have, one terminated in a half-scarf joint with a peg hole. Among the odd unembellished timbers not previously assigned, we discovered several straight members (*H* in Fig. 3) measuring 3x4 in. and about 8 ft. long. The lower joint in each case matched the scarf, and the upper had an angled tenon that would align with the uppermost extremity of the kingposts and pendants had they not been cut short. Angled mortises in these same timbers implied diagonal struts (*I*), presumably also tied to hidden upper kingposts and the posts that terminated in pendants.

The hidden outer roof system probably demanded longitudinal components for which no evidence survives. There were 11½-in. mortises near the original midpoint of the total rafter length in the

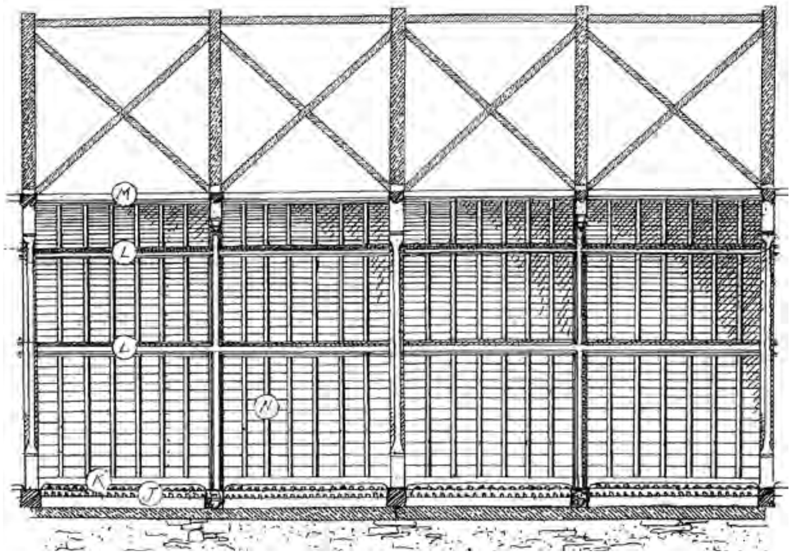

Fig. 2. Conjectural partial longitudinal section, Tremblay roof frame.

roof plane (*Q* in Fig. 3), which established where wide purlins once connected the roof frames. A lower rank of hidden common rafters might have spanned the distance from the plates to these purlins, while a corresponding upper rank would have risen from the purlins to the ridge.

Why did so little of the outer frame come down to us? Among the timbers we examined were no plates or purlins from the outer roof. Given the length of the building, there would have been many principal rafters and many more common rafters in the outer roof framing. Only the few 3x4x8 members, apparently principal rafter extensions, were included in the stack. This absence was partly explained by a late discovery in our investigations. A previously overlooked crate contained dozens of 3-ft. remnants, each slightly curved and molded like the *E*, *F* and *G* sections of the vault. The opposite surface of each of these pieces had obviously been roughsawn from larger original timbers. It was one of the great moments in our investigation when we established that these were the surviving decorative faces of 29 absent principal rafters. (In theory, there would have been 42 in the original frame.)

The rest of the explanation for both missing and mutilated timbers may have been offered by Barnard himself in his first letter: "It was necessary to buy the whole building to obtain the roof and yet we must replace it with a new roof, as a fine Chateau of the Sixteenth Century has been built entirely around the Monastic dining room." But instead of replacing the roof, Barnard appears to have had the ceiling severed and extracted, leaving all but two of

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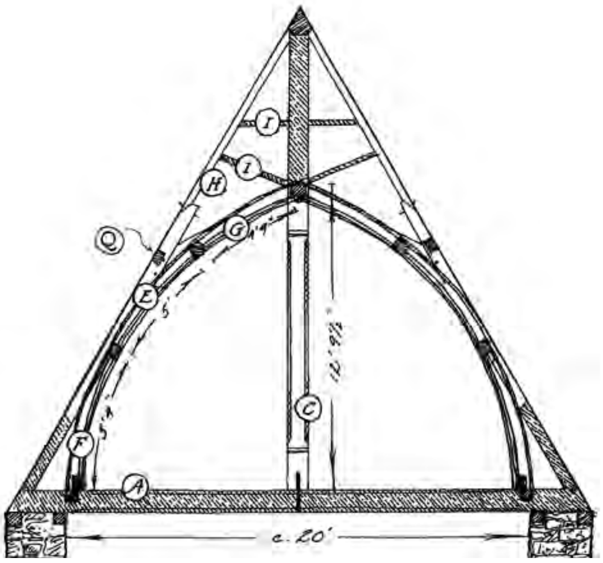


Fig. 3. Conjectural transverse section at kingpost truss, Tremblay.

Drawings Elric Endersby

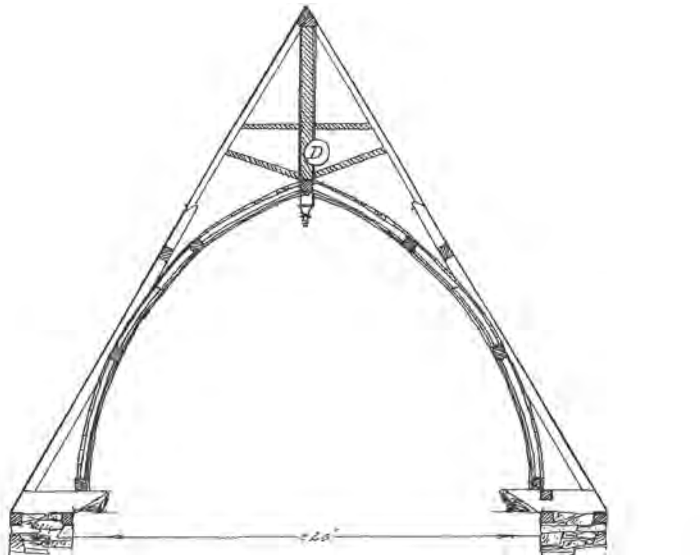


Fig. 4. Conjectural transverse section at pendant assembly, Tremblay.

the 42 principal rafters in place at Tremblay, although their decorative faces, or most of them, were cut away and came to us. Likewise, the tie beams must have been left in situ as essential elements holding together the refectory side walls. All of this material disappeared from Tremblay some time after Barnard removed the ceiling.

In his second letter to Kimball, dated 18 October 1928, Barnard wrote: "This Gothic Roof . . . I discovered in September by the merest chance. . . . When I saw this old chateau was built around an old monastery I investigated naturally in the garret and there came upon this extraordinary Gothic roof which I bought." The term "garret" suggests that in converting the monastery to domestic use, the entire vaulted space had been closed off by the introduction of a new floor at the level of the tie beams. The thrill of his discovery, particularly of the hammerbeams, which would have lain face down below the floor level in this space, can be surmised from Barnard's earlier letter: "No one knew of the interest or beauty of this roof until I personally dug out plaster and brick that had enclosed the sculpted portions and realized its value."

Barnard's extraction method (or more likely that of his contractor) was ingenious. By selectively severing some of the tenons and probably bracing the remaining timbers, the workers were able to leave the exterior roof structure above the château's garret floor below. How then were the old timbers actually taken out of the building? Included in the stack we found a group of timbers not integral to the ceiling but sharing its character. Once reassembled, these timbers constituted an arched, louvered window frame measuring 9 ft. across and just over 5 ft. high at its peak (photo 6). The removal of this frame from a gable end of the building would have afforded the requisite means of egress.

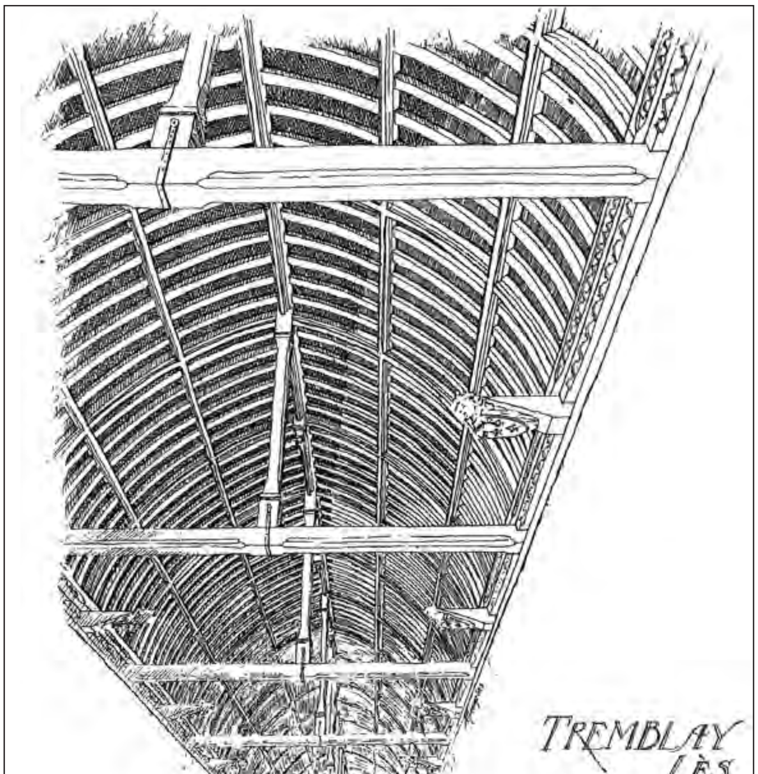
Assembly of the single principal rafter set with its curved braces allowed us to determine that the interior width of the building was just 20 ft.—remarkably narrow for such a long building, but not uncommon in timber frame truss construction of the period, as we learned by consulting the exceptional work by Patrick Hoffsummer et al., *Les Charpentes du XIe au XIXe siècle* (Monum, Paris, 2002), which helped us substantially in proposing a likely configuration for the outer roof frame, as shown in the sections above. Though its wall height could not be known, with its wall thickness determined at 2 ft. 8 in. the structure would have been just over 25 ft. wide, concurring with Barnard's second measurement, and the height of the roof structure from the bottom of the tie beams to the peak of the outer roof would work out just short of 20 ft.

Barnard twice averred the length of the ceiling to be 160 ft. As this dimension coincided with a cadence of 8-ft. bays, we felt relatively confident in embracing this measure. At that length, the refectory would have required ten pendant assemblies subdividing the bays formed by nine kingpost trusses. If this was the case, all the kingposts survive, none of the tie beams and just nine of ten pendants and seven of twenty hammerbeams. For the entire vaulted ceiling, then, about two-thirds of the timbers survived extraction, shipping abroad and a recent dormancy of some sixty years.

We took great pleasure in attempting to unravel the riddle of the timbers that once formed the Tremblay-lès-Gonesse ceiling, shown in Fig. 5 as we suppose it might have appeared in the 15th century. We hope that one day we will have the chance to stand under the recreated ceiling and experience the awe that struck Barnard in that garret long ago.

—Elric J. Endersby and Alexander T. Greenwood

Elric Endersby and Alexander Greenwood operate The New Jersey Barn Company (njbarncompany@aol.com) in Ringoes, New Jersey.



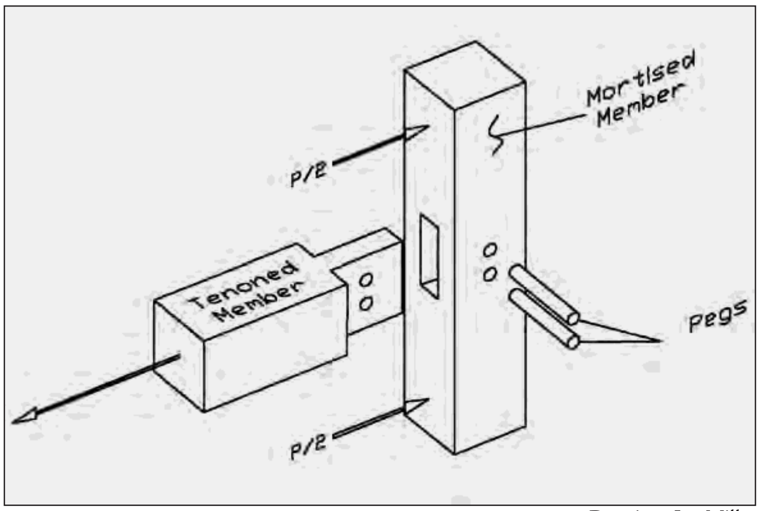
Michael Margulies

Fig. 5. Conjectural reconstruction of the Tremblay ceiling in place.

Capacity of Pegged Connections

TIMBER FRAME structures typically rely on pegged mortise and tenon connections to secure their members. Wood pegs, while large in diameter, are considerably more flexible than steel dowels of the same size. Engineering design of these pegged tension connections is not addressed in the *National Design Specification for Wood Construction* or *NDS* [1]. In an effort to standardize the design procedure used for timber frame structures, the Timber Frame Engineering Council has developed *TFEC 1-10, Standard for Design of Timber Frame Structures* [2], which includes a straightforward approach for analyzing the allowable capacity of pegged mortise and tenon tension connections. The design process included in *TFEC 1-10*, described in more detail in this article, is based on *NDS* yield model equations and provides a similar level of performance to steel dowel connections. The TFEC approach is based on physical testing and numerical modeling of connections, coupled with corresponding reliability analyses.

In a pegged mortise and tenon joint, a tension load on the tenoned member is transferred into the mortised member by the pegs acting in double shear, as shown in Fig. 1.



Drawings Joe Miller

Fig. 1. Exploded view of a representative mortise and tenon joint.

R. L. Brungraber was perhaps the first in recent times to investigate these connections [3]. R. J. Schmidt et al. conducted significant research at the University of Wyoming, which included substantial physical testing along with a new proposed peg shear yield mode [4, 5, 6, 7]. Further physical testing by others yielded similar results [8, 9].

The existing *NDS* yield model and dowel-bearing equations are based on steel dowel connections. Steel dowels have a substantially higher bearing strength than wooden pegs, so a different set of dowel-bearing equations is required. Church and Tew investigated the effects of grain orientation on dowel-bearing capacity, although substantial testing was required to account for all of the various parameters [10]. A spring-in-series approach was instead used to combine the various orientations [11].

Bill Bulleit investigated the levels of performance expected from the current *NDS* yield model equations using steel dowel connectors [12]. A similar analysis was conducted on pegged connections to ensure that a similar level of performance could be expected when designing both pegged and steel dowel connections [13].

Lateral Design Procedure. The yield limit equations included in the *NDS* as well as *TFEC 1-10* are used to design mortise and tenon connections where the applied load causes the tenon to withdraw from the mortise. Pegs in mortise and tenon connections are loaded in double shear, with the corresponding yield mode equations shown in Table 1.

The *NDS* Mode IV (not shown in Table 1) cannot occur in normal configurations of mortise and tenon joints. This limitation occurs because the Mode IV dowel yield points occur well outside the mortise cheek bounds [4]. Thus, Mode IV does not need to be analyzed in pegged connections. This paper focuses on using the existing yield mode equations included in the *NDS* coupled with the new peg shear yield mode (Mode V) to determine a design capacity of pegged connections.

The nominal design capacity for a single peg in a connection is the minimum of the four yield modes shown in Table 1. The nominal design capacity must be multiplied by all applicable NDS adjustment factors to achieve an allowable design capacity. For a connection consisting of multiple pegs, the capacity is multiplied by the total number of pegs in the connection to arrive at the total joint design capacity. Application of the yield mode equations in Table 1 will result in a similar level of reliability to steel-bolted timber connections [13], provided the requirements of *TFEC 1-10* are maintained. Here are three of the more notable requirements:

1. The mortise cheeks (side walls) must be at least as thick as the tenon.
2. The peg specific gravity must be greater than or equal to the timber specific gravity, and at least 0.57. The limits on specific gravity are a result of full-scale testing conducted on pegged joints. Because of limits in the test data, the upper bounds of peg specific gravity must not exceed 0.73. When denser pegs are used, a specific gravity of 0.73 may be assumed for analysis purposes.
3. Mortise and tenon connections must be loaded such that the tenoned (main) member is loaded by the pegs parallel to the grain. Pegs may not be used to transfer load to a tenon at any other angle to the grain.

The yield mode equations were developed for peg diameters between 0.75 in. and 1.25 in. As rigorous testing and modeling have not been conducted on peg diameters outside of this range, the equations may not be valid for smaller or larger pegs. The use of smaller or larger diameter pegs is not precluded by *TFEC 1-10*, although no design guidance is provided.

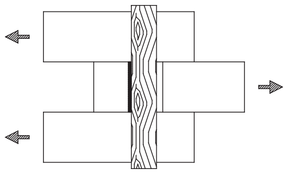
Dowel-Bearing Capacity. Dowel-bearing equations included in Section 11 of the *NDS* are based on steel dowels. However, wooden dowels (pegs) are more compliant than steel dowels, resulting in different dowel-bearing equations [11]. These equations are listed within Table 1, and should always result in a lower dowel-bearing capacity than a same-sized steel dowel connection. The yield model's bounds on peg diameter (0.75 in. $\leq D \leq$ 1.25 in.) and specific gravity ($G_T < G_P$) apply to dowel-bearing capacity as well.

Peg equations are based on the assumption that pegs are always being compressed perpendicular to their grain, regardless of grain orientation in the connecting timbers. When the connecting timber is loaded parallel to the grain (typically the tenoned member), the timber dowel-bearing strength greatly exceeds that of the peg (it acts essentially as a rigid interface), leaving a dowel-

Table 1.
Yield Limit Equations for Pegged Double Shear Connections

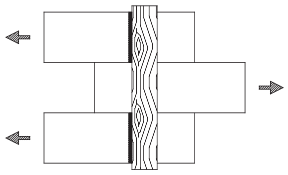
Yield Mode — *Capacity*

I_m $$Z = \frac{D\, l_m\, F_{em}}{R_d}$$



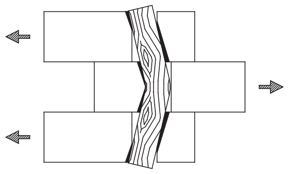
(1)

I_s $$Z = \frac{2D\, l_s\, F_{es}}{R_d}$$



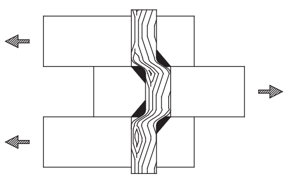
(2)

III_s $$Z = \frac{2k_3\, D\, l_s\, F_{em}}{(2+R_e)R_d}$$



(3)

V $$Z = \frac{\pi D^2 F_{vy}}{2R_d}$$



(4)

F_{em} = tenon dowel-bearing strength (psi)

F_{es} = mortise dowel-bearing strength (psi)

$F_{e\parallel}$ = $4770 G_P^{1.32}$, parallel to grain dowel-bearing strength (psi)

$F_{e\perp}$ = $4900 G_P \sqrt{G_T}$, perpendicular to grain dowel-bearing strength (psi)

$F_{e\theta}$ = $\frac{F_{e\parallel} F_{e\perp}}{F_{e\parallel}\sin^2\theta + F_{e\perp}\cos^2\theta}$, angle to grain dowel-bearing strength (psi)

G_P = specific gravity of the peg material (from *NDS* Table 11.3.2A [1])

G_T = specific gravity of the timber material where $G_T < G_P$ (from *NDS* Table 11.3.2A [1])

F_{vy} = $4850 G_P G_T^{0.75}$, effective dowel shear strength (psi)

F_{yb} = bending yield strength of the peg (psi)

= $24850 G_P^{1.13}$ (approximated from *Wood Handbook* [14])

k_3 = $-1 + \sqrt{\frac{2(1+R_e)}{R_e} + \frac{2F_{yb}(2+R_e)D^2}{3F_{em} l_s^2}}$

K_θ = correction factor to account for loading at angle to the grain = $1 + \frac{\theta}{360}$ $(1 \le K_\theta \le 1.25)$

l_m = tenon thickness (in.)

l_s = mortise cheek thickness (in.)

R_e = main-to-side-member dowel-bearing ratio = F_{em} / F_{es}

R_d = reduction term to calibrate yield capacity to allowable capacity, where

= $4K_\theta$ (Modes I_m, I_s)

= $3.2K_\theta$ (Mode III_s)

= 3.5 (Mode V)

θ = maximum angle of load to any timber grain (deg.) $(0° \le \theta \le 90°)$

bearing relationship independent of the timber properties. When the connecting timber is loaded perpendicular to the grain (commonly the mortised member), both connecting timber and peg have dowel-bearing strengths in the same order of magnitude, resulting in both materials affecting the joint dowel-bearing strength (11).

Design Examples. The following design examples show the yield mode equations and how they are commonly used to analyze a typical pegged mortise and tenon joint subjected to withdrawal loads.

1. *Problem Statement.*

Determine the withdrawal capacity of a connection consisting of two 1-in.-dia. red oak pegs securing a tying joint in an Eastern white pine frame, as shown in Fig. 2. The tendency for withdrawal is caused by wind loading.

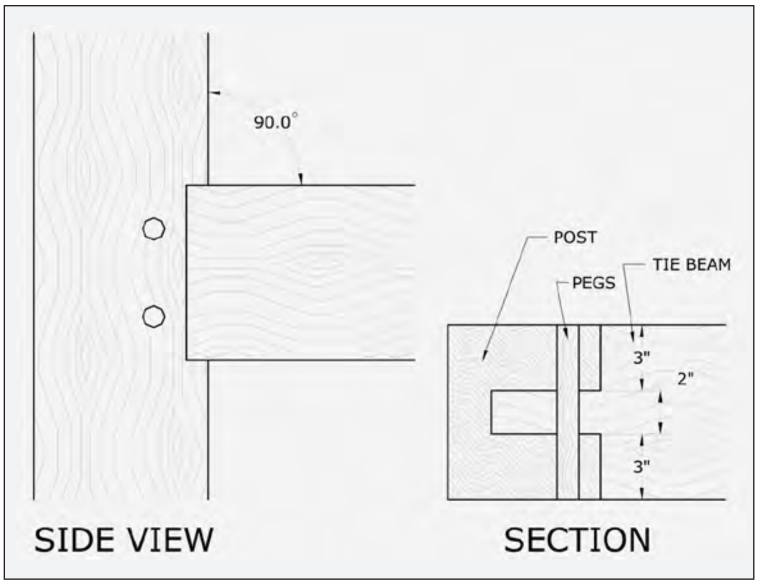


Fig. 2. View and section of typical double-pegged mortise and tenon joint, with 1-in. pegs.

Given:

D = 1 in.
G_P = 0.68 (*NDS* Table 11.3.2A)
G_T = 0.36 (*NDS* Table 11.3.2A)
l_m = 2 in.
l_s = 3 in.
θ = 90 degrees
C_D = 1.6 for wind (*NDS* Table 2.3.2)

The solution is obtained thus:
The main member (tie beam) is loaded parallel to the grain, so the dowel-bearing strength is calculated as

$$F_{em} = F_{e\parallel} = 4770(0.68)^{1.32} = 2867.0 \text{ psi}$$

The side member (mortised post) is loaded perpendicular to the grain, so the dowel-bearing strength is calculated as

$$F_{es} = F_{e\perp} = 4900(0.68)\sqrt{0.36} = 1999.2 \text{ psi}$$

The yield shear strength of the peg is

$$F_{vy} = 4850(0.68)(0.36)^{0.75} = 1532.8 \text{ psi}$$

and the yield dowel-bending strength of the peg is

$$F_{yb} = 24850(0.68)^{1.13} = 16071.7 \text{ psi}$$

In order to obtain the yield mode equations, several constants need to be found.

They are:

$$R_e = \frac{2867.0}{1999.2} = 1.434$$

$$k_3 = -1 + \sqrt{\frac{2(1+1.434)}{1.434} + \frac{2(16071.1)(2+1.434)1^2}{3(2867.0)(3)^2}} = 1.196$$

$$K_\theta = 1 + \frac{90}{360} = 1.25$$

$$R_d(I_m, I_s) = 4(1.25) = 5$$

$$R_d(III_s) = 3.2(1.25) = 4$$

From here, the nominal capacity of each mode is calculated:

$$Z_{I_m} = \frac{(1)(2)(2867.0)}{5} = 1146.8 \text{ lb.} \qquad (\textit{TFEC 1-10}, \text{3.4-1})$$

$$Z_{I_m} = \frac{2(1)(3)(1999.2)}{5} = 2399.0 \text{ lb.} \qquad (\textit{TFEC 1-10}, \text{3.4-2})$$

$$Z_{III_s} = \frac{2(1.196)(1)(3)(2867.0)}{(2+1.434)(4)} = 1497.2 \text{ lb.} \qquad (\textit{TFEC 1-10}, \text{3.4-3})$$

$$Z_V = \frac{\pi(1)^2(1532.8)}{2(3.5)} = 687.9 \text{ lb.} \qquad (\textit{TFEC 1-10}, \text{3.4-4})$$

The nominal design capacity per peg is the minimum yield mode capacity

$$Z = \min(1146.8,\ 2399.0,\ 1497.2,\ 687.9) = 687.9 \text{ lb.}$$

which is limited by a Mode V peg shear failure (see Table 1). The design capacity per peg can be adjusted for load duration, such that the capacity of each peg is

$$Z' = C_D Z = 1.6(687.9) = 1100.7 \text{ lb.}$$

The tying connection consists of two pegs, so the maximum allowed withdrawal force that can be resisted by this connection is calculated as

$$P = nZ' = 2(1100.7) = 2201.4 \text{ lb.}$$

2. *Problem Statement.*

Determine the nominal capacity for a 1-in.-dia. white oak peg used to connect a knee brace to a post in a Douglas fir frame (Fig. 3).

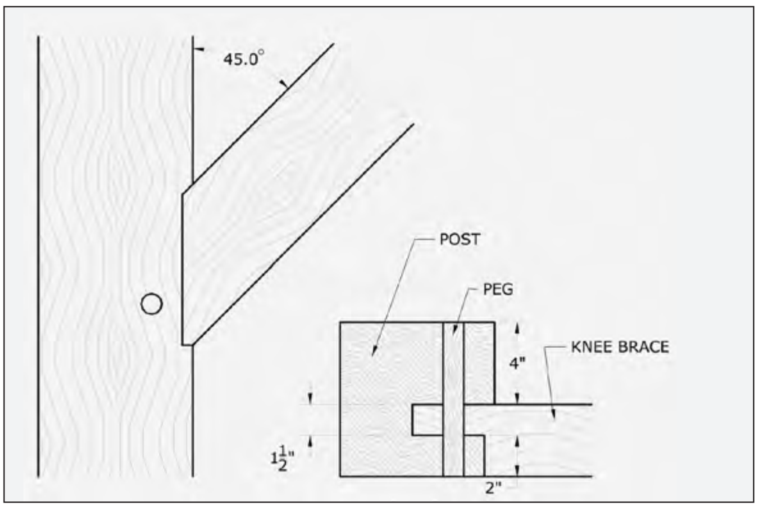


Fig. 3. Typical single-pegged knee brace in post.

Given:

D = 1 in.
G_P = 0.73 (*NDS* Table 11.3.2A)
G_T = 0.50 (*NDS* Table 11.3.2A)
l_m = 1.5 in.
l_s = minimum(2 in., 4 in.) = 2 in.
θ = 45 degrees

The solution is obtained thus:

The main member (tenoned knee brace) is loaded parallel to the grain, so the dowel-bearing strength is calculated as

$$F_{em} = F_{e\parallel} = 4770(0.73)^{1.32} = 3148.5 \text{ psi}$$

The side member (mortised post) is loaded at an angle to the grain, so the dowel-bearing strength needs to be calculated using Hankinson's formula as

$$F_{es} = F_{e\theta}$$

$$F_{e\perp} = 4990(0.73)\sqrt{0.5} = 2529.3 \text{ psi}$$

$$F_{es} = F_{e\theta} = \frac{(3148.5)(2529.3)}{(3148.5)\sin^2 45 + (2529.3)\cos^2 45} = 2805.2 \text{ psi}$$

The yield shear strength of the peg is

$$F_{vy} = 4850(0.73)(0.5)^{0.75} = 2105.2 \text{ psi}$$

and the yield dowel-bending strength of the peg is

$$F_{yb} = 24850(0.73)^{1.13} = 17413.3 \text{ psi}$$

Again, to calculate the yield mode equations, several constants need to be found:

$$R_e = \frac{3148.5}{2805.2} = 1.122$$

$$k_3 = -1 + \sqrt{\frac{2(1+1.122)}{1.122} + \frac{2(17413.3)(2+1.122)1^2}{3(3148.5)(2)^2}} = 1.581$$

$$K_\theta = 1 + \frac{45}{360} = 1.125$$

$$R_d(I_m, I_s) = 4(1.125) = 4.5$$

$$R_d(III_s) = 3.2(1.125) = 3.6$$

From here, the nominal capacity of each mode is calculated:

$$Z_{I_m} = \frac{(1)(1.5)(3148.5)}{4.5} = 1049.5 \text{ lb.} \qquad (\textit{TFEC 1-10}, \text{3.4-1})$$

$$Z_{I_m} = \frac{2(1)(2)(2805.2)}{4.5} = 2493.5 \text{ lb.} \qquad (\textit{TFEC 1-10}, \text{3.4-2})$$

$$Z_{III_s} = \frac{2(1.581)(1)(2)(3148.5)}{(2+1.122)(3.6)} = 1771.0 \text{ lb.} \qquad (\textit{TFEC 1-10}, \text{3.4-3})$$

$$Z_V = \frac{\pi(1)^2(2105.2)}{2(3.5)} = 944.8 \text{ lb.} \qquad (\textit{TFEC 1-10}, \text{3.4-4})$$

The nominal design capacity of the joint is the minimum yield mode capacity,

$$Z = \min(1049.5,\ 2493.5,\ 1771.0,\ 944.8) \ = \ 944.8 \text{ lb.}$$

which is limited by a Mode V peg shear failure.

Therefore, the nominal capacity of the knee brace in tension is 945 lb. Any applicable adjustment factors may be made at this time according to Section 3.4.9 of *TFEC 1-10*. Note that a Mode V peg shear design equation is based on empirical and numerical testing data, where the yield point was defined using the 5 percent dowel diameter offset method [15]. This method can often limit joint capacity on the basis of serviceability issues (excessive joint deformation), rather than the basis strength issues of ultimate capacity [7].

To achieve the nominal capacity of the joints in the above examples, the peg locations must be properly detailed to ensure that there is adequate relish, tenon edge distance and mortise side distance. This process of joint proportioning is outlined in Section 3.4.8 of *TFEC 1-10* [2] with additional recommendations provided in the Commentary to Section 3.4.8.

Conclusion. The design capacity of pegged mortise and tenon joints subjected to withdrawal loads is obtained using the method outlined in *TFEC 1-10*. This method uses equations similar to yield-mode design equations included in the *NDS* for steel dowel connectors, and it provides a similar level of reliability.

Detailing pegged mortise and tenon joints to achieve full design withdrawal capacity will be discussed in a future Technical Bulletin produced by the Timber Frame Engineering Council. Table 2 below provides a sampling of peg capacities according to combined timber and peg species.

The information in this article is meant to be used only in conjunction with competent engineering design, accurate fabrication and adequate supervision of construction. The design of engineered structures is within the scope of expertise of licensed engineers, architects or other licensed professionals for applications to a particular structure. —Joe Miller

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Table 2. Peg Capacities for Certain Peg and Timber Species Combinations

Frame Species

Peg Species (3/4" Dia / 1" Dia)	Eastern White Pine G=0.36	Lodgepole Pine G=0.38	Eastern Hemlock G=0.41	Ponderosa Pine Yellow Poplar G=0.43	Baldcypress G=0.46	Douglas Fir - Larch G=0.50	Southern Pine G=0.55	Red Oak G=0.67	White Oak G=0.73
G=0.58 Red Maple	330 / 587	244 / 611	364 / 647	377 / 670	397 / 705*	422 / 751*	454 / 806*		
G=0.63 Birch	358 / 637	373 / 664	395 / 703	410 / 728	431 / 766	459 / 815*	493 / 876*		
G=0.64 White Ash	364 / 647	379 / 674	401 / 714	416 / 740	438 / 778	466 / 828*	500 / 890*		
G=0.68 Sugar Maple Red Oak	387 / 688	403 / 716	427 / 758	442 / 786	465 / 827	495 / 880*	532 / 945*	617 / 1096*	
G=0.71 Locust	404 / 718	421 / 748	445 / 792	462 / 821	486 / 863	517 / 919*	555 / 987*	644 / 1144*	
G=0.73 White Oak	415 / 738	433 / 769	458 / 814	475 / 844	499 / 888	531 / 945	571 / 1015*	662 / 1177*	706 / 1255*

1. G = Specific Gravity.

2. Tabulated design values (Z) in lb. may be multiplied by all applicable adjustment factors per NDS *Table 10.3.1.*

3. Proper detailing for end, edge and spacing distances is required to achieve tabulated values. See TFEC 1-10, *Section 3.4.8.*

*4. Tabulated values are based on 1½-in.-thick tenons with 2-in.-thick mortise cheeks except where designated by *, signifying that 2-in.-thick tenons are required.*

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