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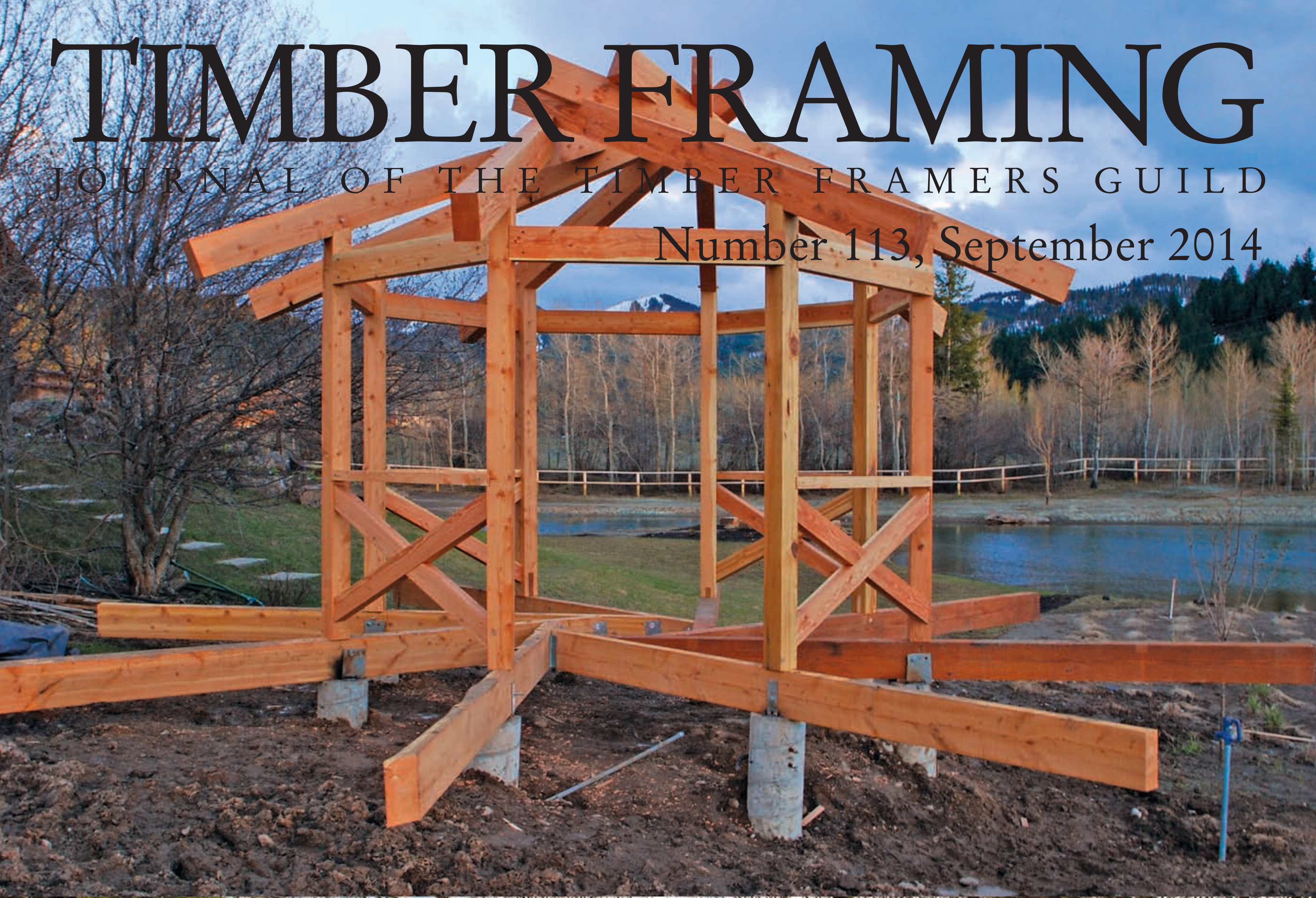

Reciprocal Frame Gazebos

Two Reciprocal Frame Gazebos

1. Square Timber, Eight-Sided Plan

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Photos Adam Riley

IN the spring of 2009, TF 91 began with a review of Olga Popovic-Larsen's excellent book, *Reciprocal Frame Architecture*. The reviewer, engineer Ben Brungraber, included photos of American reciprocal roof frames and recommended the book "to any timber framers still on their irresistible quest for another cool way to lose money." These fascinating structures and Ben's humorous challenge sang to me like sirens to a sailor.

For me, reciprocal frames conjure memories of M. C. Escher prints on my college dorm room walls and of structurally indeterminate systems from my engineering classes. Reciprocal frames can be elegant, inspiring and challenging to design and assemble. Popovic-Larsen defines a reciprocal frame as "a three-dimensional grillage structure mainly used as a roof structure, consisting of mutually supporting sloping beams placed in a closed circuit. The inner end of each beam rests on and is supported by the adjacent beam. At the outer end the beams are supported by an external wall, ring beam or by columns." I read her book cover to cover and began looking for opportunities to build reciprocal frames.

My first attempt was a simple three-legged stand for a large African drum. This was a chance to start small and sneak up on the topic. I used three 2x2 cedar legs 40 in. long, braced them at the required angles to cradle the drum (60-degree angle from horizontal, 120 degrees apart in plan) and scribed plumb and level bearing surfaces into the adjacent faces. I feared the drum would drive the joints apart or the legs would "unwind" under its weight. I was delighted to find that the weight of the drum actually tightened the joints and the slender tripod was remarkably stable, even with kids of all ages banging on the drum.

Not long after this experiment, a neighbor asked me to design and build a gazebo near a small pond on her property. She wanted something unique and beautiful which might someday be enclosed as a writer's cabin or a guest room. I showed her photos of reciprocal roof and floor systems and we agreed to incorporate those elements into the design, which eventually became the structure in Fig. 1.

Design I collaborated with two talented colleagues, Al Klagge and Jake Amadon, to design a frame in SketchUp using fir timbers on hand, with a 2D reciprocal floor and 3D reciprocal roof. There were several geometrical, joinery and assembly riddles to solve. Using available timber, we chose to build an octagonal frame with 8-ft. 5x5 posts and 12-ft. 5x9 rafters. The floor system would be repetitive: 12-ft. 6x8 joists would support each other in a single plane around a 36-in. opening and cantilever over concrete piers at each post location (Fig. 2).

We explored a few different roof slopes in SketchUp and found that steep roofs allow for a smaller framing aperture (or oculus, as it eventually became) but require the removal of more material from adjacent rafters than lower angled roofs. We wanted to preserve as much cross-section of the rafters as possible, so we settled on a slope of 6:12 measured along the axis of each rafter. Because the eaves are not level and the rafters do not converge on a central point, the roof slope varies depending on where it is measured and the roof segments thus curve slightly, although that may not be apparent in Fig 1. In other words, because the rafters are not parallel, the slopes of successive purlins differ. We used 2x6 purlins parallel to the eaves, which run over the timber rafters on one end and hang from the face of the adjacent rafter.

We chose to rotate the posts to keep them square to the rafters in plan. This made for compound brace housings on the sides of the posts, but that was easier to execute than compound joinery where the rafters meet the posts (cover photo). Since the rafters do not converge at the peak, that would have been necessary if we had oriented the posts toward the true center of the gazebo (square to the hips of a normal hexagon). If we were to build the gazebo again, I think we would rip pentagonal posts to make both brace and rafter bearing surfaces perpendicular to post faces.

The gazebo stands at the western base of 8432-ft. Teton Pass between Wilson, Wyoming, and Victor, Idaho, and at 6520 ft. it sees some extraordinary snow, wind and seismic loads. We knew there would be large shear forces where the rafters intersect so we wanted large bearing surfaces and plenty of relish beyond those joints to the ends of the rafters.

Popovic-Larsen addresses member and joint loads in her book and presents shear and moment diagrams to graphically display those concepts. While such analysis is beyond the scope of this article, good information may be found there if needed.

Raising and assembly challenges When it came time to raise the frame, the building site was deep with soft, sucking mud. After burying the forklift to its axles, we delivered timbers by hand while the mud tried to pull our boots off. The first seven floor joists teetered over the piers, scarcely able to hold themselves level. At this point a man's weight would have collapsed the assembly. It was not until the eighth joist locked the first and seventh together and provided some moment capacity that the whole floor system became quite rigid. What a relief! With that platform in place, we propped the first rafter at its 6:12 slope with a pair of 2x6 "kickstands" (Figs. 3 and 4). By design the rafters were directly above the reciprocal joists, and they all fit nicely until it was time to install the eighth and final rafter.


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1 Completed reciprocal frame gazebo, 14 ft. in dia., Victor, Idaho.

2 Floor framing. Eighth joist grants rigidity.

3 Rafter raising started on props.

4 Detail of stepped-notch joints in rafter assembly, with large bearing surfaces and adequate relish.

5 First and seventh rafters spread to allow insertion of eighth, Jake Amadon considering next move. Repositioning and application of appropriate force won the day.

6 Rick Neier and Jake survey completed and rigged rafter cluster from safe distance. Truck straps between slings and forks help set rafters level.

7 As expected, rafters spread slightly during raising. Posts lean out to receive them and tension will be applied to bring them plumb and rafters to 6:12. Ring of girts around post tops will maintain tension and may serve as window and door headers.

We knew we would have to sneak that last rafter between the first and seventh rafters and pivot it into position rather than dropping it straight down like all the others. The angle of the notched housing allowed for this but the twisted and out-of-square timbers did not. But Jake Amadon studied the matter (Fig. 5) and was ultimately persuasive. We were eventually able to get the forklift close enough to pick up the roof and lower it onto the posts for an eight-point landing (Figs. 6 and 7). It took some faith to work beneath this unlikely assembly and trust that our notches would hold it all together.

Estimating, roof framing and trim details In terms of job satisfaction and remuneration, this would have been a great place to stop. We basically broke even on the frame and learned a lot about reciprocal structures. But of course we had also agreed to provide the owner with a deck over the joists and a roof to shield her from the elements. Both were surprisingly hard to price. The decking, fairly straightforward, was less difficult: 2x6 cedar mitered on each joist to express the spiraling structure below, and a 36-in. octagonal parquet over the opening in the center. But the roof framing and flashing, on the other hand, were another time-consuming opportunity for learning.

Popovic-Larsen presents two approaches to framing and flashing reciprocal roofs. One is to express the structure inside and out with a faceted roof. Graham Brown, a designer and builder in the UK who coined the term *reciprocal frame*, is a proponent of this form. The other approach is to set the fascia level around the eaves and over-frame the roof with regular hips that hide the spiraling rafters from the exterior. The reciprocal designs of Japanese architect Kazuhiro Ishii and structural engineer Yoichi Kan employ this form beautifully. Popovic-Larsen provides extensive case studies of each.

Since our gazebo would initially be open walled and we had a limited budget to finish the roof, we chose the faceted form with a polycarbonate yurt dome over the opening at the center. This is where Ben Brungraber's challenge became prophetic. It took twice as long to frame and flash that roof as I had estimated (20 man-days, not 10). We learned more about curving roof planes and compound jack purlins—and we concluded that the level fascia and over-framed hips would have taken even longer to build!

Possible failure modes The gazebo's cedar shakes and unheated roof hold snow for months at a time. I've seen it over 4 ft. deep, looking like a big white mushroom. So far, the joinery and rafters have held up well through five winters, but the owner resisted my attempts at additional bracing or low shear walls, and I fear an earthquake or big wind event in conjunction with the snow load will someday topple this gazebo.

My other concern is asymmetric loading of the roof when snow melts off the south side in spring but remains deep and heavy on the north side. I've seen that load condition crush a neighbor's yurt by snapping a few rafters on the snowy north side of the roof. In most reciprocal designs, there is little or no redundancy in the frame. When one member fails the others will be loaded in unpleasant ways and fall like dominoes. Still, I encourage framers seeking inspiration and a challenge to explore reciprocal structures. Many beautiful forms await to be built, and there is much to be learned. —Adam Riley

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