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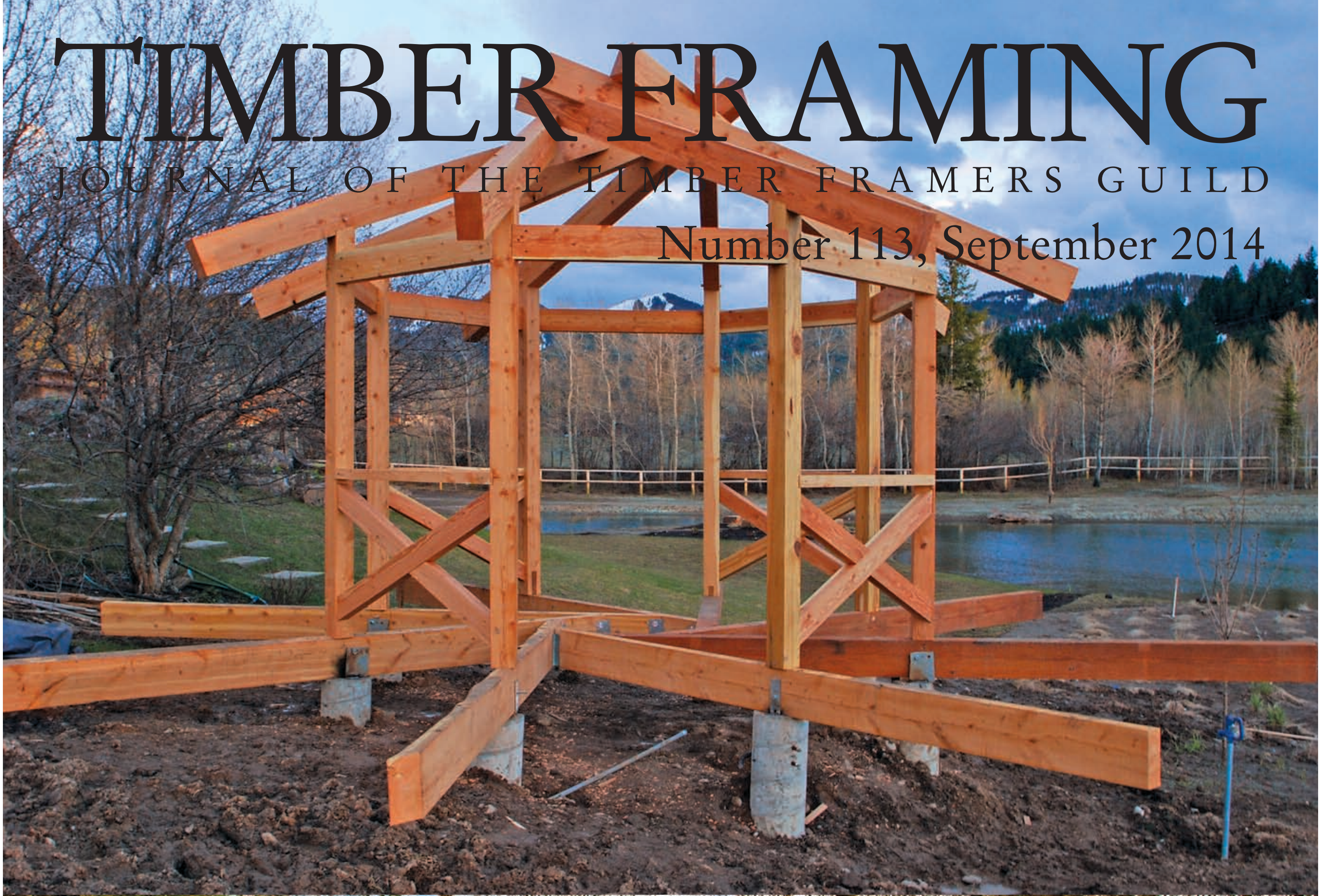

Reciprocal Frame Gazebos

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

Adam Riley (adam@tetontimberframe.com) operates Teton Timberframe in Driggs, Idaho.

2. Round Timber, 12-Sided Plan

Photos Daniel Girard except where noted

RECIPROCAL roofs offer ample opportunity for bracing directly across the frame, in this case provided by forked-post joinery (Figs. 1 and 2), but they are trickier to brace around the ring. In squared-timber work, five-sided posts are necessary to avoid compound-angled connections. In our case of timber in the round, I considered affixing cables or chains from perhaps 3 ft. up the side of the forks down to the sills at 45-degree angles, but settled instead on shear walls every other panel.

In polygonal-plan buildings, there is a dance between more and fewer posts. With our 32-ft. diameter, 12 posts resulted in about a 10-ft. span for the outer purlins but a relatively crowded scene at the aperture in the roof. Dropping to eight posts, the next elegant number in terms of shear walls and openings, would have made for a more spacious connection at the aperture but a significantly heavier loading of the rafters themselves, along with a 15-ft. span for the outer purlins.

Because each rafter rests on top of its neighbor, while all the rafter butts are at the same height at the eaves line, any pitched reciprocal roof creates nonplanar segments defined by top of rafter (Fig. 2). Decking and roofing these twisted surfaces is a challenge. Tapered-width boarding over short lengths can help.

Generous overhangs offer a cantilever offset of the load in the primary rafter span, to the extent that the rafters are stiff enough to do so, perhaps reducing stresses in the aperture joinery. Pitch and aperture must be adjusted to work with intended rafter size,

1 At top, reciprocal-framed gazebo 32 ft. in diameter, winter-built of Eastern white pine logs in northern New England, purlins in place before roofing over. Forked posts provide transverse bracing, low walls shear bracing in alternate panels. Not part of original design, two-tiered stainless steel cupola 8 ft. 6 in. dia. covers aperture and will be supported by temporary posts during winter months to resist added snow load.

2 Above, tops of rafters bound twisted surfaces since peaks are stacked. Rings of purlins, to come, will shorten sheathing spans.

3 First two rafters supported by future temporary winter post.

4, 5 Challenge was getting innermost purlin ring for cupola to meet rafter peaks nicely. Initially rafters were tacked with structural screws. After assembling purlin ring, screws came out and the commander was used to adjust for best fit before replacing screws and adding heavy lags. Finally, rafter tips were trimmed in place at plane of lower cupola roof.

such that the joints where rafters cross have enough bearing while retaining sufficient material in the upper rafter. In this case, we chose not to remove any additional material from the flattened lower rafters at each crossing, though in other designs I have seen there is some notching of the lower rafter to provide a positive lock. Paired ¾-in. lag screws do that work here and allowed some positioning flexibility as described below. The flat cut in the underside of the upper rafters is swept (rather than notched) to full round section, to reduce shear stress (Fig. 3).

This is complicated geometry! Wondering how it would all fit, and needing the innermost purlin ring to meet the rafter peaks nicely, I considered leaving one of the innermost purlins uncut to be able to adjust on site. Ultimately I decided instead to make round tenons on the bottoms of the forked posts to allow them to rotate as necessary, and to precut the whole purlin ring exactly.

I assembled rafters to match scribe lines when raising but left them tacked with 10-in. structural screws, then assembled the innermost purlin ring, tacking to rafter peaks as I went. I then untacked all the rafter joints (all hands cleared the deck for this procedure, though friction kept the rafters from going anywhere on this relatively low 3:12 pitch) and used the commander to nudge the rafters to achieve the best possible fit with the innermost purlin ring. The ring meets each rafter peak cut with paired structural screws. The purlin ring itself has plywood splines at its butt joints (Figs. 4 and 5).

Setup for scribing the rafter-to-rafter joints was the most interesting shop aspect of the project. Originally I thought to simply set up the rafters at their final pitch with one above the other. Even with the low 3:12 pitch, however, that would have put the 24-ft.-long, 600-lb. rafters something like 7 ft. in the air at their peaks and required accurately holding them above floor layout and at pitch angle. My colleague Shannon McIntyre wondered, Why couldn't we scribe them flat?

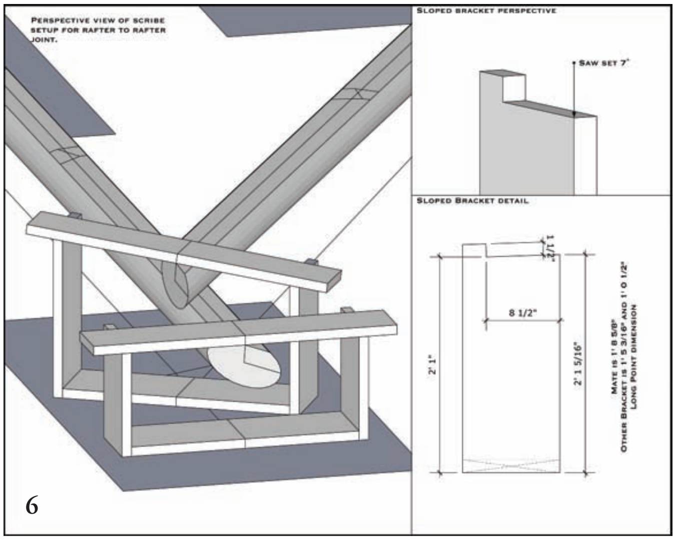
Of course we could! I could take a pair of the rafters in SketchUp and rotate them down along the hinge point defined by the butt cut of the lower rafter until the latter's top surface was level. This left the upper rafter pitched both longitudinally and transversely. Then, in the 3D model, I built brackets to support the rafters in that attitude using the same crosspieces we had used in the rafter-to-forked-post scribe setup, with the lower rafter dropped 6 in. for scribing. In the layout of the real logs, with the support brackets screwed to the shop floor, the rafters cycled through, and alignment was taken care of by marriage marks on the crosspieces (Figs. 6 and 7).

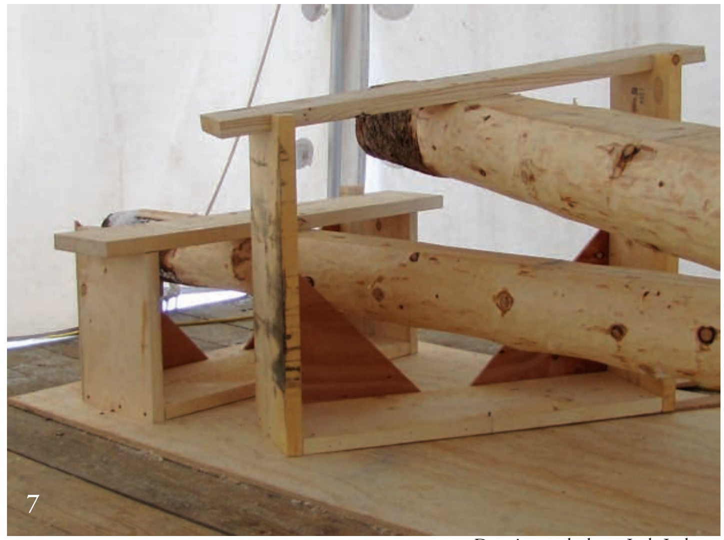
The joints at the tops of the forked posts, meanwhile, required relatively straightforward scribing operations (Fig. 8).

Late in the game, the client decided to cover the large roof aperture, a smokehole for the central firepit, with an exhaust hood that would allow campfires even in inclement weather. We designed a two-tiered stainless steel cupola for the purpose and added a top purlin ring at the peak to carry it (Figs. 1 and 9). Under a 70-lb. snow load, and neglecting dead weight, the 8 ft.-6-in.-dia. aperture cover adds nearly 4000 lbs. to the inner purlin ring, or a 330-lb. point load at each rafter peak. While the frame could have been re-engineered to handle the situation and larger rafters ordered, given the seasonal use of the building we specified temporary supports to be installed each fall for the winter months.

—Josh Jackson

Josh Jackson (josh@timberhomesllc.com) is a partner at Timber-Homes LLC in Vershire, Vermont.





Drawing and photo Josh Jackson

6 SketchUp drawing showing setup with support sticks and custom alignment jigs for rafter-peak scribe.

7 Jigs aligned to floor drawing with pair of rafters set in place, hanging from support sticks. Same sticks had been used earlier in scribing rafter to fork and were reattached to rafter using same holes.

8 Joinery at fork-to-rafter connection. Housing is cut square to mortise from scribe line as is tenon shoulder, providing accurate bearing while avoiding fragile shoulders and splitting tendency of coped joinery or sharp housing edges, and difficult router work of fully housed joints. Over time such joinery also performs well as pieces shrink, while fully housed joints in round work tend to develop large gaps.

9 Finishing up purlins and starting on shear walls. Twisted surfaces of roof can be seen most easily between upper two purlin rings and present sheathing fitting problems at cupola ring.