Raising Calculations and Prep

CALCULATION OF FRAME WEIGHT. As simple as it sounds, the total weight of a frame assembly is the sum of the weights of the individual pieces in that assembly. So it's possible to estimate the weight of a bent by estimating the weight of each timber in that bent and then adding up all the weights. Further, the weight of a timber is directly related to its volume. A timber's weight can be estimated by calculating its volume and then multiplying that volume by the appropriate unit weight for the wood species at a certain moisture content:

Length × Width × Depth = Volume
Volume × Unit Weight = Weight

The one trick is to be sure the measurements are all in the same units. Lengths should all be in either inches or feet, unit weights in pounds per cubic inch (lb/in^3) or pounds per cubic foot (lb/ft^3). As long as the units are consistent, the answers will be accurate.

To start the process, let's calculate the weight of the girt in the model bent (Fig. 1). The girt is an 8x8 timber connecting two 8x8 posts spaced 12 ft. outside to outside. The length of the girt should be taken as the length from shoulder to shoulder along the centerline of the timber. (The weight of the tenons will be included in their receiving members, the posts.)

Converting to inches for consistency, the length of the girt is then 144in − 8in − 8in, or 128in. The volume of the timber, Length×Width×Depth, is then 128in × 8in × 8in, or 8192in^3. As most unit weights are given in lb/ft^3, it will now be easier if the timber volume is converted into cubic feet (ft^3). One cu. ft. is the volume of a box 1 ft. to a side: (1ft)(1ft)(1ft) or (12in)(12in)(12in). So 1ft^3 = 1728in^3. The volume of the timber in cu. ft. is then 8192in^3 × 1 ft^3 ÷ 1728in^3, or 4.74ft^3.

From Dr. Bruce Hoadley's book, *Identifying Wood* (Taunton Press, 1990), we find that white oak has a unit weight when wet of approximately 55 lb/ft^3. The weight of the bent girt (Volume × Unit Weight) is then (4.74ft^3)(55lb ÷ ft^3), or 260 lb.

These calculations can be set up easily in a spreadsheet. Table 1 shows the calculation of the total weight of the bent. The completed spreadsheet gives the weight of each individual timber and the total weight of the bent. In this case, the bent weighs approximately 1638 lb. Note that accuracy to a single pound is a snare and delusion. This is an estimate.

Timber	pcs	Lgth (in)	Width (in)	Depth (in)	Vol (cu in)	Vol (cu ft)	Unit Wt of wood (lb/cu ft)	Wt of 1 pc (lb)	Wt of all pcs (lb)
girt	1	128	8	8	8195	4.74	55	261	261
post	2	158	8	8	10112	5.85	55	322	644
rafter	2	119	8	10	9520	5.51	55	303	606
brace	2	45	4	6	1080	0.63	55	34	68
collar	1	78	4	6	1872	1.08	55	59	59
Total weight of bent in lbs =1,638									

TABLE 1. SPREADSHEET OF MEMBER WEIGHTS.

CALCULATION OF FRAME CENTER OF GRAVITY. The center of gravity (CG) of an object is the imaginary point through which the total weight of the object would act. Our bent girt just described is a timber of constant section. If

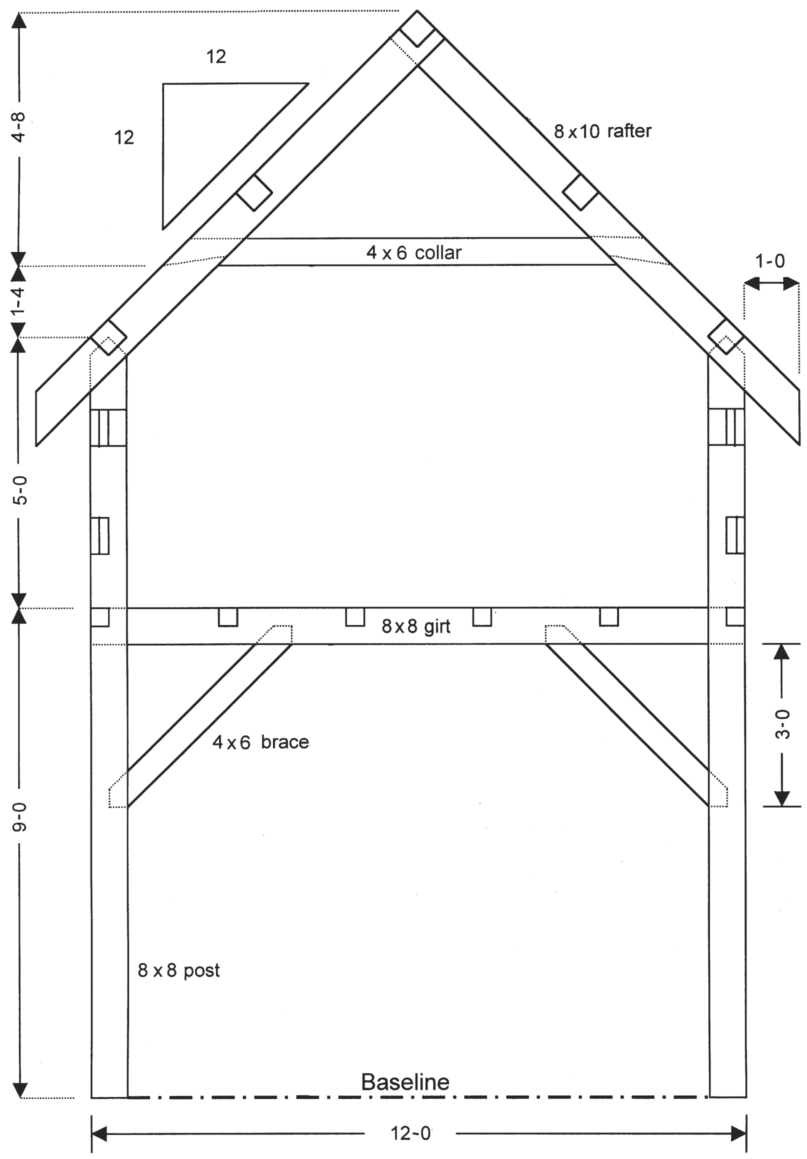

FIG. 1. MODEL BENT FOR WEIGHT, CENTER OF GRAVITY AND LIFTING CALCULATIONS. WOOD SPECIES IS UNSEASONED WHITE OAK. TIMBERS SIZED TO FULL DIMENSION.

you were to put a roller under this timber, it would balance at its middle, since the CG within the timber would be just over the center of the roller (Fig. 2). Let's take the idea a little further and stand an imaginary 10-ft. 8x8 next to an imaginary 14-ft. 8x8 (Fig. 4). Common sense would indicate that the vertical center of gravity of the two timbers combined would be somewhere between the centers of gravity of the two individual timbers.

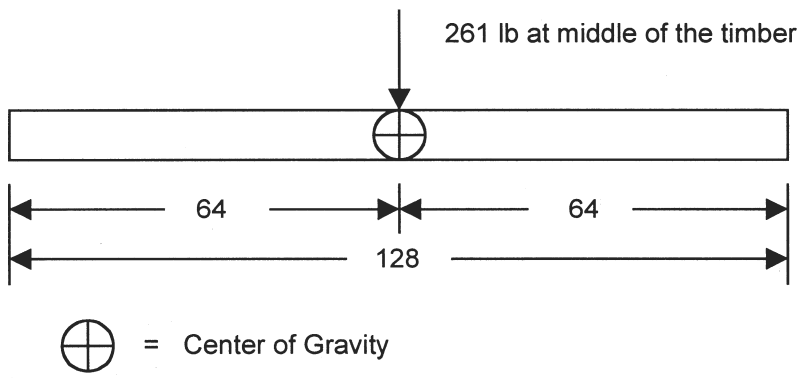

FIG. 2. CENTER OF GRAVITY OF BEAM OF UNIFORM SECTION.

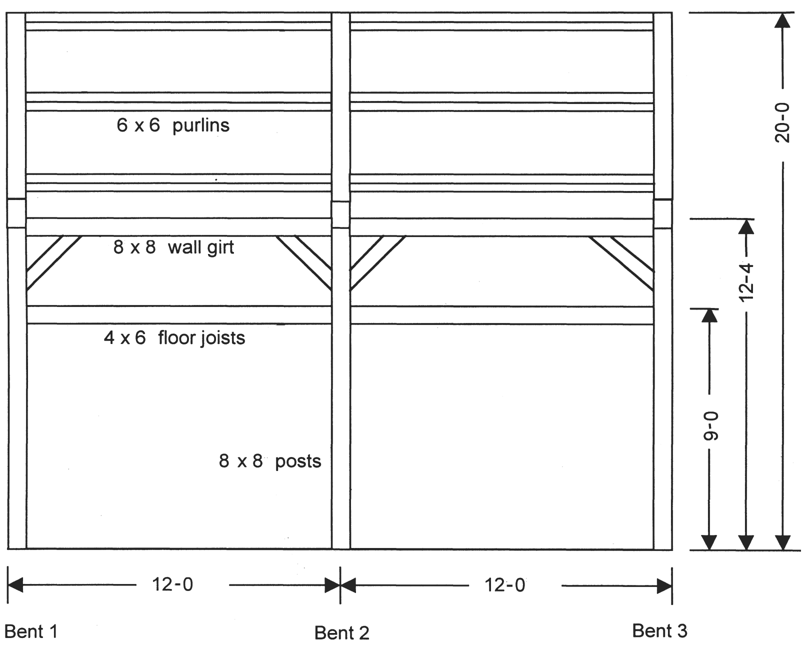

FIG. 3. ELEVATION OF A THREE-BENT MODEL FRAME.

Mathematically, the vertical center of gravity of the two timbers can be found by multiplying the weight of each timber by the height of its CG above the baseline, adding up the answers and then dividing by the combined weight of both timbers.

Our 10-ft. timber weighs 245 lb. and its CG is at half the height or 60 in. above the baseline:

$$W \times H = (245\text{lb})(60\text{in}) = 14{,}700\text{in-lb}$$

Our 14-ft. timber weighs 343 lb. and its CG is at 84 in. above the baseline:

$$W \times H = (343\text{lb})(84\text{in}) = 28{,}812\text{in-lb}$$

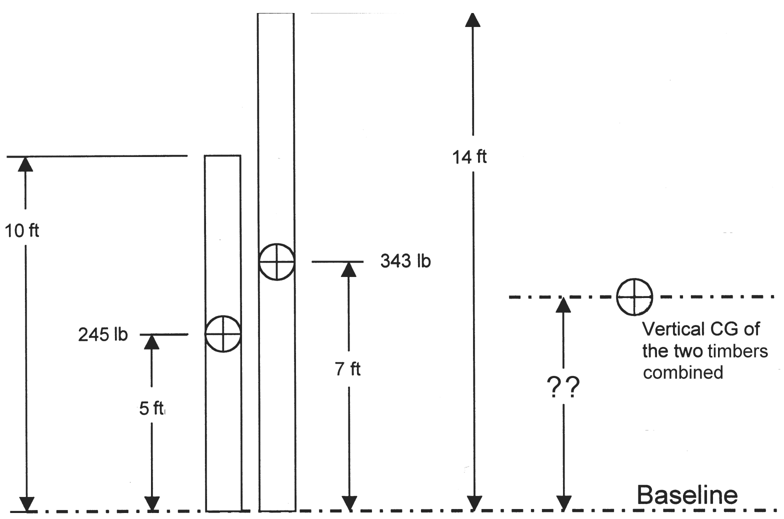

FIG. 4. COMBINED CENTERS OF GRAVITY FOR TWO TIMBERS.

The sum of Weight × Height for the two timbers is then 43,512 in-lb. The sum of Weight for the two timbers is 588 lb.

43,512in-lb ÷ 588lb. = 74in. (6 ft. 2 in.) above baseline

The process is the same for an entire bent. There are just more timbers involved, including horizontal and diagonal members. But since it is of uniform section, each timber in the bent can be treated as if its weight acted through its midpoint. The timber weight is multiplied by the height of the midpoint of that timber above the baseline. Then all the answers of Weight × Height are added up and divided by the total weight of the bent. The individual timber weights in our model bent have already been calculated. Likewise, the total weight of the bent is already known. All that is needed is the height of the center of gravity of each timber above the baseline. A spreadsheet again facilitates the calculation:

Timber	pcs	Weight of one pc (lb)	Weight of all pcs (lb)	Height of center above Baseline (in)	Weight x Height
girt	1	261	261	104	27,144
post	2	322	644	79	50,876
rafter	2	303	606	191	115,746
brace	2	34	68	84	5712
collar	1	59	59	187	11,033
				Total of Weight x Height (in-lb) =	210,511
				Total Weight (lb) =	1638

TABLE 2. SPREADSHEET OF CENTERS OF GRAVITY OF MEMBERS.

Bent CG is then 210,511in-lb ÷ 1638lb = 128.5in

The center of gravity of the bent is about 128½ in. above the baseline. That means that the total weight of the bent, about 1638 lb., is acting at a point 10 ft. 8½in. above the post bases, or about midway between the girt line and the top of the wall.

CALCULATION OF LOADS IN THE LIFTING TACKLE.

If a crane line or block and tackle were attached to the bent at its center of gravity, a vertical lifting force equal to the weight of the bent would be required to lift it off the ground. With a crane, a vertical lifting force is easily applied: position the end of the boom directly above the center of gravity, drop the cable, hook to the bent and lift. As long as the bent weight is below the safe working capacity of the crane, the lift is safe and the load in the cable is equal to the weight of the bent.

But if the lift point is not at the CG (and usually it isn't), the calculation of load is a bit more involved. In a hand raising, for example, the tackle is usually attached to a gin pole or another bent in the frame and can be far from the center of gravity of the bent. Indirect pull significantly increases the load in the lifting tackle.

The first problem is to calculate the vertical load required at the collar to lift the bent. Since the collar is above the center of gravity of the bent, the vertical load required should be less than the total bent weight. The problem (Fig. 5) is much like the force needed to lift a wheelbarrow, where the post bases are the wheel, the bent weight at the CG is the load in the wheelbarrow pan and the vertical lifting load is the lift on the handles.

When the bent just starts to lift, the product of the bent weight times the distance from the post bases to the CG is equal to the vertical lifting force times the distance of the attachment point above the post bases. In engineering terms, the sum of the moments around the post bases is zero. Moment is the product of a force

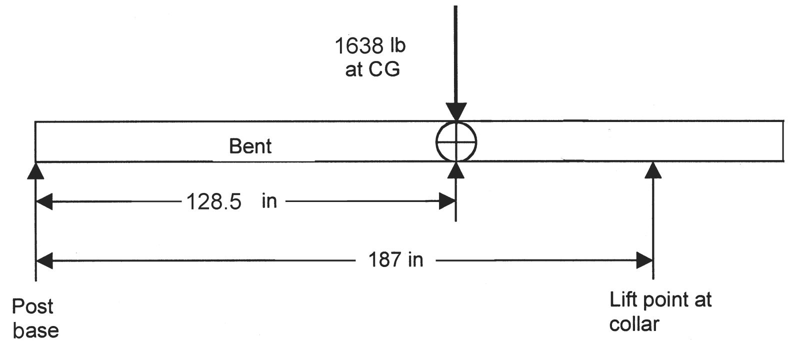

FIG. 5. DISTANCES FROM FULCRUM OF LIFT POINT AND BENT CG.

(bent weight) times its distance (height to CG) from a point (post base). When the bent starts to lift, the moment due to the weight just counteracts the moment due to the lifting force at the collar. The two moments are of equal magnitude. From Fig. 5:

(1638lb)(128.5in) = (vertical lifting force)(187in)
Vertical lifting force = (1638lb)(128.5in) ÷ 187in
Vertical lifting force = 1125lb

Let's now do calculations for a hand raising using a 15-ft. gin pole set vertically 5 ft. back from the post bases and a single set of block and tackle to raise the model bent (Fig. 6). The problem now becomes to calculate the loads that the 1125-lb. vertical load at the lifting point produces in the rest of the lifting system.

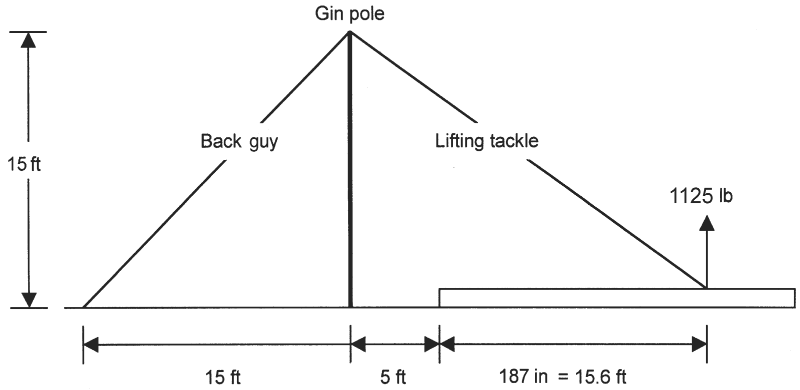

FIG. 6. GIN POLE LIFT DIAGRAM FOR CALCULATING LOADS.

To solve for the load in the tackle, it's possible to use similar triangles (Fig. 7). A triangle representing the vertical gin pole, the horizontal distance to the lift point and the inclined tackle has the same proportions as a triangle of the vertical lift load, the horizontal load along the bent and the inclined load in the tackle

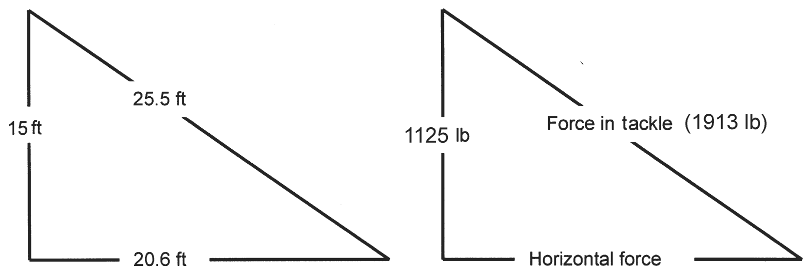

FIG. 7. CALCULATION BY METHOD OF SIMILAR TRIANGLES.

Height of gin pole = 15ft
Horizontal distance = 5ft + 15.6ft = 20.6ft
Length of tackle = $\sqrt{(15\text{ft})^2 + (20.6\text{ft})^2}$ = 25.5ft

By similar triangles:

20.6ft ÷ 15ft = horizontal force ÷ 1125lb
Horizontal force = 1545lb

And:

25.5ft ÷ 15ft = tackle force ÷ 1125lb
Tackle force = 1913lb

The tension in the 45-degree back guy can also be calculated by the same method (Fig. 8 above right). The lift tackle applies a horizontal force of 1973 lb. at the tip of the gin pole. The horizontal force is resisted by the tension in the angled back guy. Thus:

21.2ft ÷ 15ft = guy force ÷ 1545lb
Guy force = 2184lb

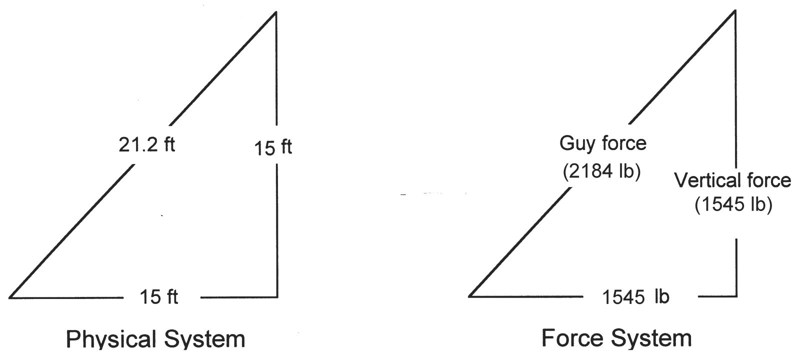

FIG. 8. CALCULATION BY SIMILAR TRIANGLES OF TENSION IN A GUY.

The lift tackle also produces a vertical force on the guy of 1973 lb. So, the overall forces in the lifting system are as follows:

Tension in the lift tackle = 1913lb
Tension in the back guy = 2184lb

And compression in the gin pole is the sum of the vertical forces from the tackle and the back guy (1125lb + 1545lb):

Compression in the gin pole = 2670lb

One more question. Is it possible to safely raise the frame by hand using one set of four-part block and tackle (see illustration at bottom of page 7) as the lifting tackle? The two-sheave blocks sized for 5/8-in. rope available for the lift have a safe working load of 3000 lb. The safe working load is greater than the tackle load of 1913 lb., so the blocks themselves are up to the job.

The nominal load in the rope will be 1913 lb. divided by the four parts (the lines between the blocks), or 478 lb. Braided 5/8-in. nylon rope available for the lift has a breaking strength of 7000 lb. Using a factor of safety of 5:1, the rope has a safe working load of 1400 lb. At 478 lb., the actual load in the rope will be well below the safe working load, so the rope is acceptable for the lift.

Finally, how many people are needed to exert 478 lb. of pull on the raising line? A safe estimate is that one person can comfortably exert 50 lb. of pull on a rope. Using that figure, the number of people required is 9.6 people. Looks like a minimum of 10 people on the pull line. Finding the 0.6 person would be difficult, and the sight would probably prevent the other nine from pulling.

PREPARATION OF THE FRAME FOR RAISING. During the raising, it's highly desirable that the frame fit together well and that the lifting process not destroy it. Once the raising starts, there should be no surprises about the fit of the joinery. Completely prefitting the frame assemblies before the raising eliminates unexpected problems. Assemble the sections on a flat surface and ensure that all the joints fit, the frames are square and the assemblies dimensionally correct. Connecting pieces not accounted for in the major preassemblies for the crane should be individually tested in their joints. Adjusting a thick tenon or a shallow mortise is far easier and safer on the ground than in the air.

During a raising, the joinery will see higher stresses than it ever will in service. Also, the stresses will be in directions that the joinery was not intended to resist. Examine each assembly and determine if additional bracing is needed. For example, the lifting system for the model frame is designed to pull at the level of the collar, which puts extreme stress in the post-to-rafter joint. If the joint is not reinforced, the frame could hinge at that joint and fail. The joint can be reinforced with strongbacks such as 4x6 timbers or built-up sections of dimension lumber (include their added weight in the lift load). The strongbacks run from near the post bottoms across the bent girt and end at the rafter-to-collar joint (Fig. 9).

Heavy-duty ratchet straps work well for attaching the strongbacks to the frame. Wrap the strap several times around the frame member and the strongback, and then tighten it securely. In this example, the strongback should be strapped at its crossing with the bent girt. As the frame tries to hinge at the rafter joint, the ends of the strongback will press against the rafter and the post while the strap causes the strongback to lift the bent at the girt level, keeping the bent in plane. Metal clamps should not be used to attach strongbacks. Clamps can loosen or bend and open up, thereby falling off in the middle of the lift, with undesirable consequences.

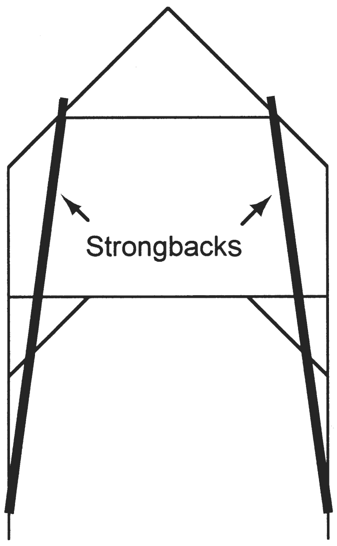

Fig. 9. Strongbacks fitted to assembly to prevent unwanted hinging.

For the rigging to work properly, it must remain in place at its attachment points on the bent. The bent also must be constrained so that it finishes the lift in the proper position. Rope (or rigging) only works in a straight line. If that line is not perpendicular to its attachment point, the tension in the rigging will try to move the attachment point along the timber. Slings will slip along the timber if they are not physically restrained. In our model bent, the sling would try to slip down the rafter as the bent came up, and so it should be choked around the rafter at the middle purlin pocket so that it will be restrained by pulling into the pocket. If such an anchor point is not available, blocks can be nailed to a hidden face of the timber to secure the rigging.

In the calculation of the lifting forces on the bent, we determined a horizontal force of almost 2000 lb. Because of that force, at the start of the lift the bent will try to slide horizontally along the deck. The post feet must be blocked to prevent that movement and to position them so that they drop into their mortises as the bent becomes vertical. For the first bent, these kicker blocks can be braced to stakes in the ground, clamped to the deck or otherwise secured. For interior bents, the kickers can be braced to the posts of the previous bent.

DEVELOPING A RAISING SCRIPT. The easiest way to avoid confusion and errors during a raising is to think through the whole process beforehand. This procedure is important enough that it warrants writing a formal raising script. The people leading the raising should sit down with a set of frame plans, talk through the necessary steps and record them. The idea is to have all the necessary equipment at hand for each step of the raising. That way, no one is frantically searching for something as the crew tries to stabilize the piece of the frame that has just been raised. The general raising sequence for our three-bent frame (Fig. 3), which has drop-in purlins and joists, would be to set the gin pole, raise bent one, add wall girts between bents one and two, raise bent two, add wall girts between bents two and three, then raise bent three; finally, with the bents connected, drop in the purlins and drop in the joists. Following is the model raising script.

1. *Raise Bent 1*
   - Set the gin pole
   - Assemble the bent on the deck with the post feet positioned at their appropriate mortises
   - Install the kicker blocks for the post feet
   - Attach the strongbacks to the bent
   - Attach the rigging between the gin pole and the bent
   - Attach a safety haul-back line to the top of the bent
   - Attach 2x4 or 2x6 braces at sides of posts to brace the bent once it is raised. Nail braces for now to outside of bent with one 16d (or 20d) duplex nail so braces can rotate into position as the bent is raised
   - Set a commander near the post bases for positioning the posts as the bent approaches vertical
   - Set a level near the post bases
   - Provide pike poles
   - Clear the deck of all unnecessary material to avoid tripping
   - Recheck the rigging
   - Stop and explain the lift to the crew
   - Raise the bent
   - Using the level, plumb one post and nail off the 2x4 brace
   - Plumb and brace the second post
   - Add two additional 16d nails at each end of the braces
   - Remove strongbacks
   - Remove haul-back rope
2. *The wall girts and outer floor joists between bents one and two are fitted in preparation for raising Bent 2 (see Fig. 3)*
   - Place the girts with braces in Bent 1
   - Using dimension lumber, prop the other ends of the girts at the correct height to mate with Bent 2
   - Using comealongs, tie the girts safely back to Bent 1
   - Repeat the procedure for the outer floor joists
3. *Raise Bent 2*
   - Reposition gin pole and lifting tackle (or lift off Bent 1 with the installation of appropriate back guys)
   - Install kicker blocks between Bent 1 and Bent 2 post bases
   - Position Bent 2 on the deck against the kicker blocks
   - Attach the strongbacks to the bent
   - Attach the rigging between the gin pole and the bent
   - Attach a safety haul-back line to the top of the bent
   - Position braces for installation as Bent 2 is raised
   - Hang comealongs from slings near ends of Bent 1 bent girt
   - Attach matching slings near ends of Bent 2 bent girt
   - Extend comealong cables so they will easily reach Bent 2
   - Position a level and pike poles at the ready
   - Recheck the rigging and explain the lift to the crew
   - Begin raising Bent 2
   - As bent approaches vertical, hook up to comealongs
   - Insert wall girt braces
   - Bring bent closer to vertical and engage brace and girt tenons
   - Use comealongs to pull Bent 2 into position
   - Check for plumb and peg off Bents 1 and 2
   - Bents 1 and 2 now form a braced, stable assembly
4. *Repeat Steps 2 and 3 to Raise Bent 3*
5. *Install Purlins*
   - Use a rolling stage (safest way) to install purlins
   - Position stage, feed purlins up to people on the stage and install
   - Alternatively, set purlins singly using the gin pole
6. *Install Floor Joists*
   - Set what floor joists are possible from the stage
   - Remove stage or decrease its height
   - Set remaining joists from ladder or lowered stage
7. *Last*
   - Fasten the wetting bush
   - Take picture of entire crew on the frame

—Grigg Mullen

Grigg Mullen teaches engineering at the Virginia Military Institute. He has served on the Guild's Board of Directors and been a crew leader on many Guild projects, as well as helping to teach the Guild's Raising and Rigging course. He recently worked on the development of the Guild's Apprenticeship Curriculum.