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Lifting Apparatus Calculations

IT'S all very nice to know about rope, knots and rigging, but it's even better to be able to do something useful with them. Of the several types of lifting apparatus, shear legs are the most stable, but the least adaptable in use. A gin pole is more adaptable, but requires more guys to ensure stability. Finally, a derrick is the most adaptable assembly, but requires the most complicated construction. Safe design of the three different lifting systems comes down to these basic considerations:

The poles have to be strong enough to carry the compressive loads.

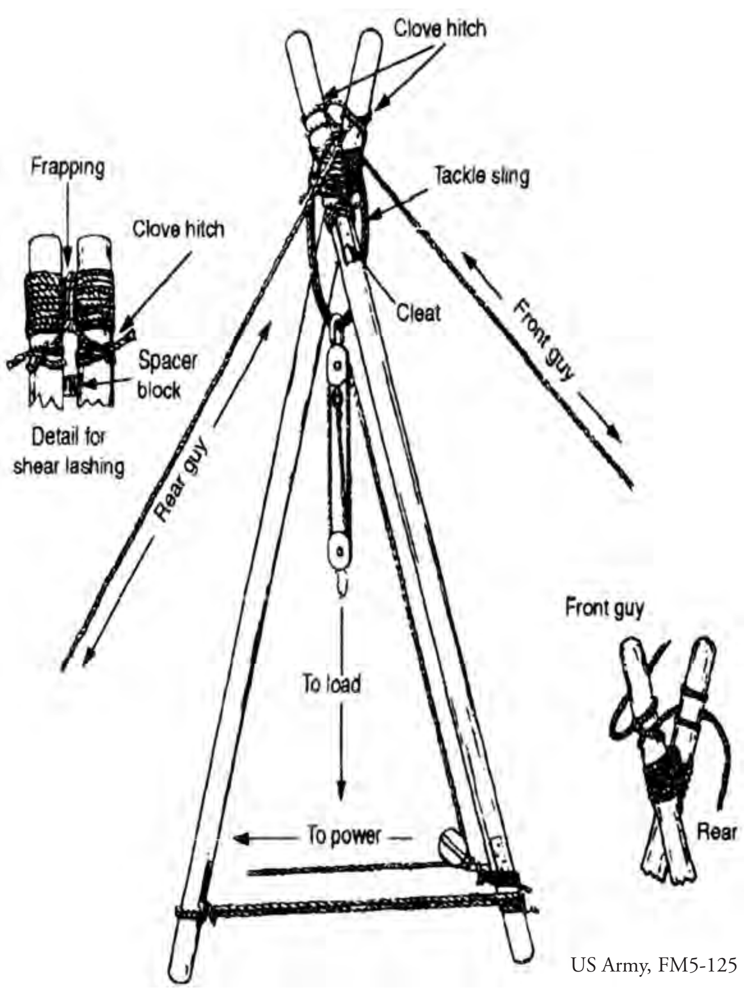
The guys have to be strong enough to handle the tension within the safe working capacity of the line.

There must be sufficient guys to stabilize the apparatus and prevent movement in the wrong direction if something should fail.

The lifting tackle must have adequate safe lifting capacity.

Finally, guy anchors must have sufficient capacity to resist the guy loads, and the poles must be prevented from sinking into the ground. (Calculations to meet these reqirements form a subject unto itself, to be taken up in a future article.)

Before you can check for safe design, you have to know the loads in the various parts of the system.



US Army, FM5-125

FIG. 1. SHEAR LEGS, RIGGED.

SHEAR LEGS. Shear legs are made by lashing or bolting together two legs crossed at the top, with the hoisting tackle suspended from the intersection. A heavy back guy running from the intersection to a ground anchor and a similar but lighter front guy complete the assembly. The spread of the poles at the base stabilizes the shear legs in the plane perpendicular to the guys.

Compression in the poles and tension in the heavy back guy does the work of holding the tackle in the air as a load is lifted. The lighter front guy prevents the assembly from falling backward should the back guy be overtightened or a load be released too quickly. Adjusting the length of the guys can move the top of the shear forward or back. This allows the load to be positioned forward or backward, but not side to side.

Rigging Shears. When shear legs are erected, the spread of the legs should be equal to about one-half the height of the shears. The procedure: Lay two timbers together on the ground in line with the guys, with the butt ends pointing toward the back guy and close to the point of erection. Place a large block under the tops of the legs just below the point of lashing and insert a small spacer block between the tops at the same point. The separation between the legs at this point should be equal to one-third the diameter of one leg to make handling of the lashing easier.

With sufficient 1-in. rope for 14 turns around both legs, make a clove hitch (see TF 68, "Ropes and Knots") around one leg and take eight turns around both legs above the clove hitch. Wrap the turns tightly so that the lashing is smooth and without kinks. Finish by taking two frapping turns (see upper left corner of Fig. 1) around the lashing between the legs and securing the end of the rope to the other leg just below the lashing. For handling heavy loads, increase the number of lashing turns. To prevent the poles from slipping in the lashing, a cleat should be spiked to each pole just below the lashing. Or a hole can be drilled through each pole and a steel pin inserted.

Of course, it's much simpler to attach lifting tackle, guys and any safety lines to the shear legs before they're up in the air. Take a minute and consider what rigging might be useful once the shear legs are standing.

To begin, place a sling of appropriate strength around the top of the shear legs. The sling should be choked around the poles and positioned so that the loose end comes across the top of the lashing and hangs between the legs. If the sling hangs to one side or comes around the outside of one leg, the shear legs will twist when a load is lifted. This can cause a premature and dramatic failure.

Reeve a set of blocks and place the hook of the upper block through the sling. Secure the sling in the hook by mousing. Fasten the lower snatch block to one of the legs near the butt so that it will be in a convenient position when the shears have been raised but will be out of the way during erection. Rig another tackle in the back guy near its anchorage if you intend to use the shears on heavy lifts. Using clove hitches, secure the two guys to the top of the shears above the lashing, attaching to the legs opposite their anchorages. A clove hitch is the preferred knot for this application as it is stronger than a loop made with a bowline. Once all the rigging is in place, the shear legs can be erected.

The descriptions of constructing, rigging, and raising shear legs, gin poles and derricks are substantially taken from the public-domain US Army Field Manual FM 5-125, Rigging Techniques, Procedures, and Applications, *modified somewhat to fit with timber framing practices. The sections on load calculations for each device and the sections on safe design were developed by the author.*

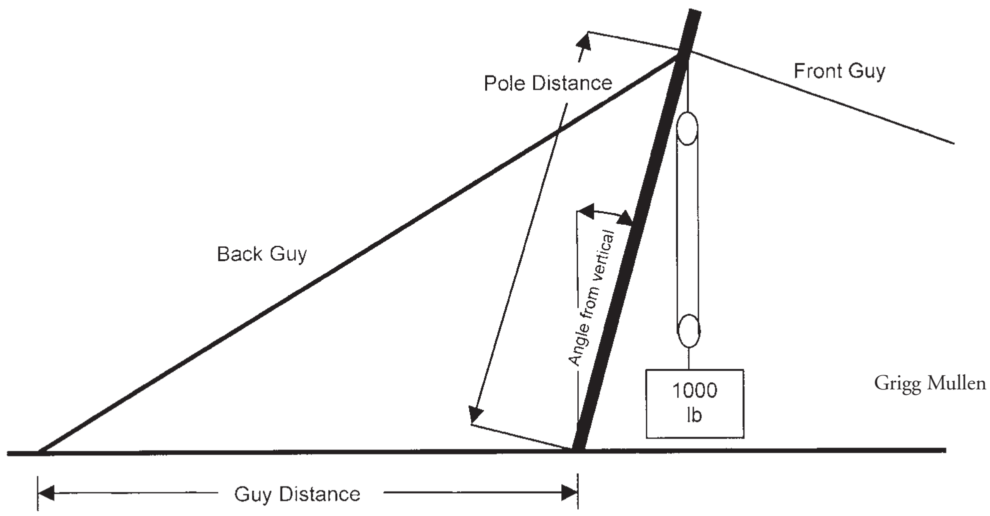


FIG. 2. SHEAR LEGS DIMENSIONS.

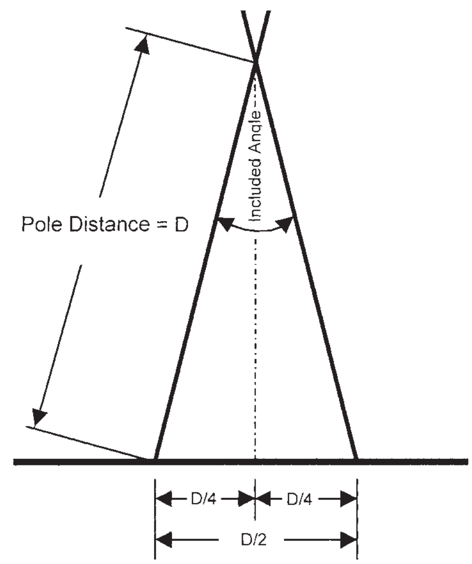


FIG. 3. SHEAR LEGS INCLUDED ANGLE.

Load Calculations for Shear Legs. To be sure the various parts of the system are properly sized, we must know the loads in the system. The following information allows us to calculate the compression in each of the shear legs and the tension in the back guy, and thus pole and guy size. The calculations are the same for a set of shear legs, a gin pole or a derrick.

Using regular engineering, the calculation of compression in the shear legs and tension in the back guy is a fairly ugly matter. However, the graphs that follow make it possible to calculate the loads using several dimensions of the shear legs assembly (Fig. 2):

Pole Distance is the distance from the ground to the attachment point for the guys and tackle if the pole is standing vertical. In the case of a single pole, it would be simply the length along the pole from the butt to the attachment point. The splayed shear legs complicate things slightly.

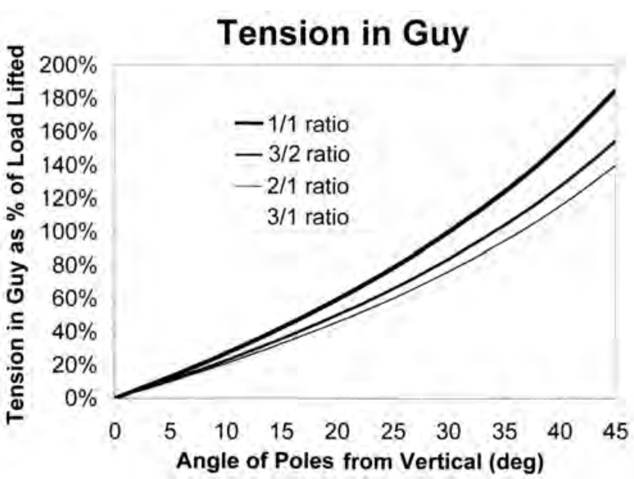
Guy Distance is the horizontal distance along the ground from the butt of the pole to the guy anchor.

Angle from Vertical is the angle of forward lean in the shear legs.

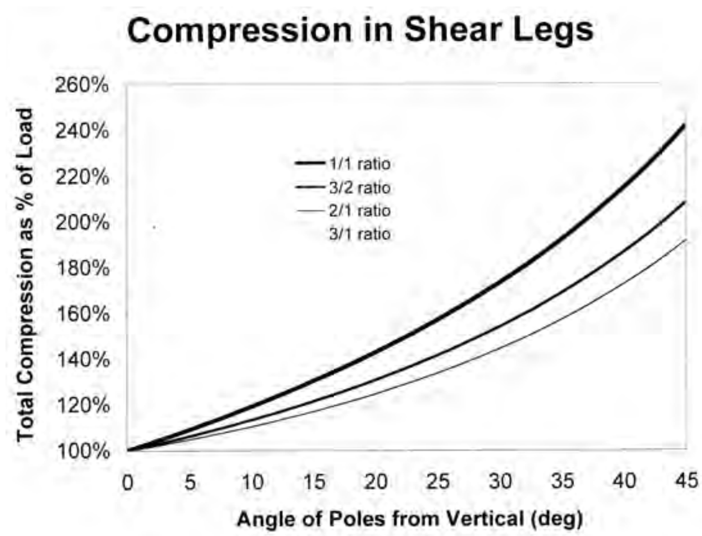
Ratio is *Guy Distance* divided by *Pole Distance*.

For an example, let's plug in the following values:
Guy Distance = 30 ft.
Pole Distance = 20 ft.
Angle from Vertical = 15 degrees
Spread between legs at base = 10 ft.
Ratio = (Guy Distance)/(Pole Distance) = (30 ft.)/(20 ft.)=1.5

Determining the Guy Tension. Start at the 15-degree point on the horizontal axis of the graph. Go up to the curved line for a ratio of 1.5. Then go horizontally over to the vertical axis. Read off the load in the guy as a percentage of the total load. The guy load as a percent of total load is 37 percent, and the load is thus 370 lbs.



Determining the Compression in the Shear Legs. Start at the 15-degree point on the horizontal axis of the graph. Go up to the curved line for a ratio of 1.5. Then go horizontally over to the vertical axis. Read off the total compression in both shear legs as a percentage of the total load.



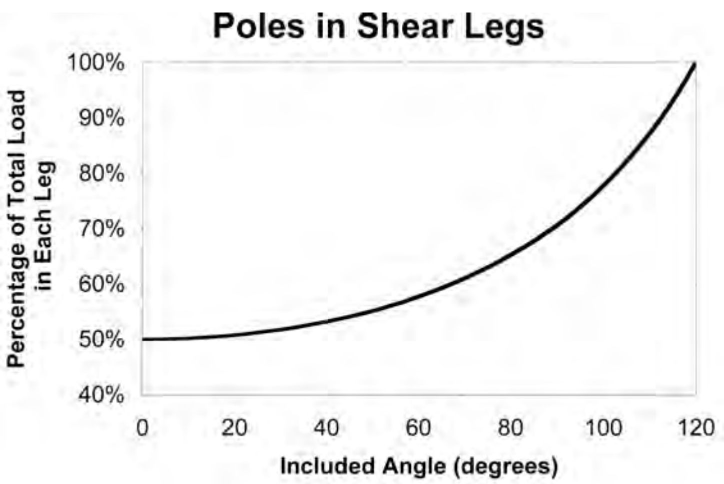
Total compression as a percent of total load is 122 percent and thus total compression is 1220 lbs.

But you're not done yet! The 1220 lbs. is the total compression carried by both shear legs. If the two poles making up the shear legs were standing parallel, then the load in each leg would be half the total compression. But the legs stand at an angle to each other, so the answer takes a bit more work.

A method used for determining sling loads based on included angle works well for this problem. If the legs are splayed to half the leg length as described earlier in the text, the included angle shown in Fig. 3 can be found using trigonometry. Since the sine value of an angle can be calculated in a right triangle by dividing the side of the triangle opposite the angle by the hypotenuse of the triangle, then, for half the angle,

Sine = D/4 ÷ D = 0.25.

From trigonometric tables, or by using the inverse function on a suitable calculator, we find that 0.25 is the sine of 14.4 degrees. The included angle between the shear legs is then 28.8 degrees. Using 30 degrees is close enough, and slightly conservative.



Using the chart above for percentage of load versus included angle, start at the 30-degree point on the horizontal axis of the graph. Go up to the curved line. Then go horizontally over to the vertical axis. Read off the load in each pole as a percentage of the total load. The total load is the total compression carried by the two poles in the shear legs. Pole load as a percent of total compression load is 52 percent and thus equals .52 x 1220 lbs. or 634 lbs.

GIN POLES. A gin pole comprises a single upright pole guyed at the top to maintain a vertical or nearly vertical position and equipped with suitable hoisting tackle. The gin pole is used widely in erection work because of the ease with which it can be rigged, moved and operated. It is suitable for raising loads of medium weight where only a vertical lift is required.

The gin pole may also be used to drag loads horizontally toward the base of the pole when preparing for a vertical lift. It should not be inclined more than 45 degrees from the vertical.

The gin pole offers a bit more freedom in positioning the lift than a set of shear legs. The pole is secured by both a set of fore and aft guys and a set of side guys. By adjusting the four guys, it is possible to move the tip of the pole both forward and back and side to side. Any positioning should be done before the lift, and then the lift performed vertically. *Note well that if the pole is to be moved side to side, the side guys must have the same capacity as the back guy.*

Rigging and Raising a Gin Pole. This procedure follows much the same process as setting shear legs: attach all the rigging, set the base of the pole and then raise it into position. The major difference is that there are four guy lines to control during the raising. Unlike shear legs, the gin pole is not stable in one plane. All four guys must constantly be tightened and adjusted to keep the pole in position during its raising. The spread at the base of shear legs keeps them from flopping sideways. The side guys on the gin pole perform the same function.

Load Calculations for a Gin Pole. The load calculations for a gin pole are almost exactly the same as those for the shear legs. The only difference is that the total compression load is being carried by one pole instead of being split between two poles. When lifting the same load, a single gin pole must then be a heavier pole than either leg of a pair of shear legs.

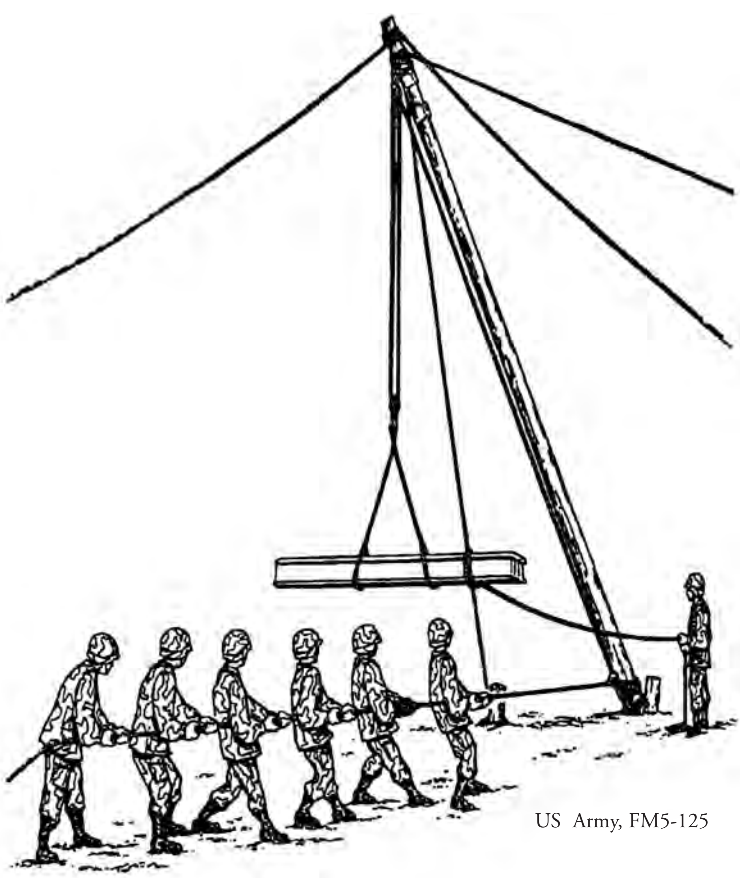


FIG. 4. A GIN POLE IN USE.

DERRICKS. A derrick is a vertical gin pole or mast combined with a second, movable pole called a boom. The major advantage of a derrick is that the load can easily be moved in and out and side to side as well as up or down. The general arrangement of a derrick is shown in Fig. 5.

The boom tackle lifts the load. The mast tackle is used to position the load in or out from the mast, and the entire boom can be pushed sideways to position the load from side to side.

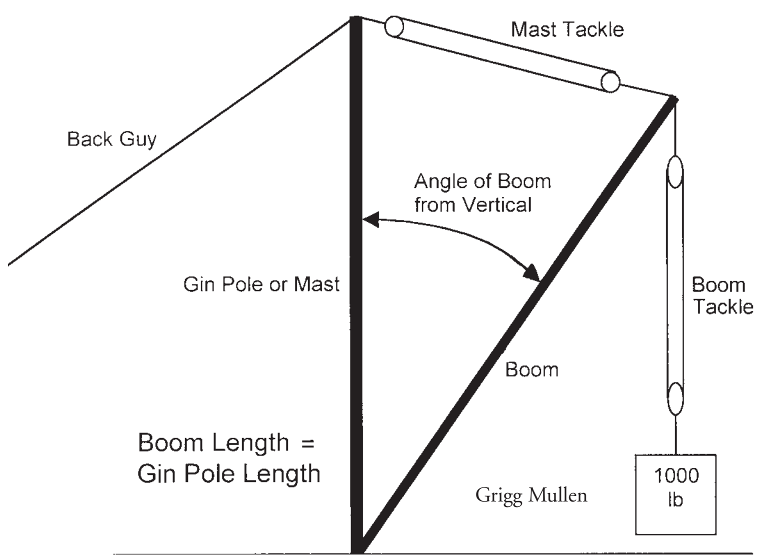


FIG. 5. SCHEME OF A DERRICK WITH LOAD. SIDE GUYS NOT SHOWN.

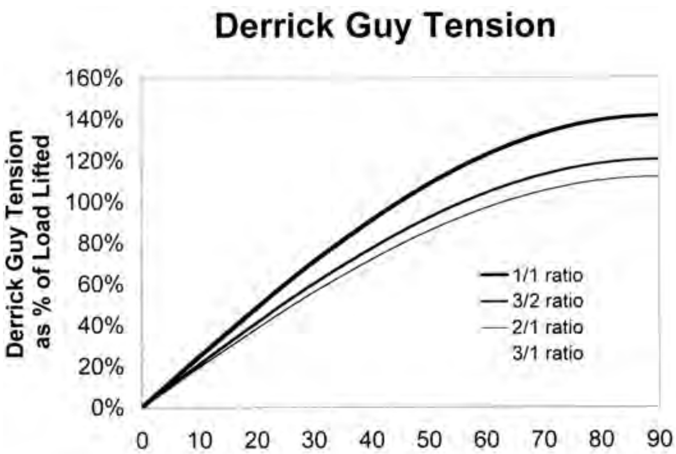
Rigging Boom Derricks. Initially, rigging a derrick is almost the same as rigging a gin pole. The gin pole is raised and secured, then the boom is added to the system. However, the addition of the boom does increase the loading on the guys. And the ability to swing the load sideways also means that the back guy or either of the side guys could carry the entire guy load. The guys need to be sized accordingly.

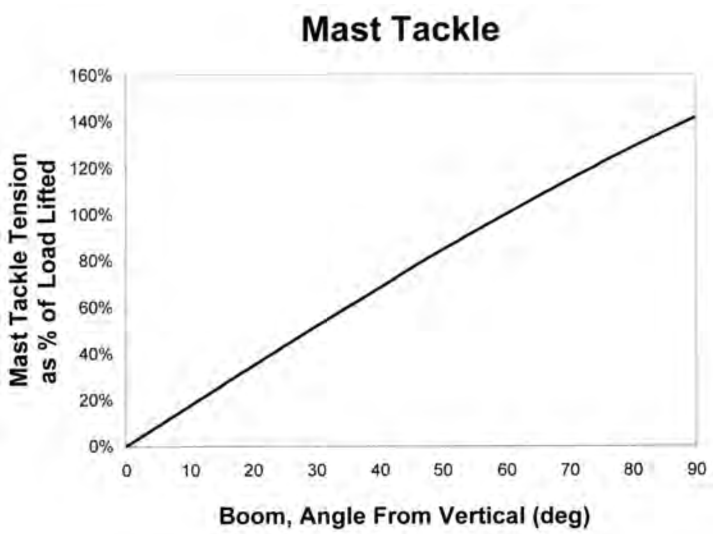
The major consideration in attaching the boom is to ensure that the end of the boom remains resting at all times against the bottom of the gin pole. The bottom of the boom can be forked to nestle against the pole, and then constrained by a loose lashing between the two poles.

Once the gin pole is in position, place the boom in position against the bottom of the gin pole. Rigging the end of the boom is the same as rigging the top of the gin pole with the addition of a second sling to attach the mast tackle to the boom. Once the rigging is in place, attach the tackle from the gin pole to the end of the boom and lift the boom into position.

Boom Derrick Load Calculations. For a sample calculation, let's use the following dimensions in the derrick drawing at the start of this section:

Guy distance = 60 ft.
Pole distance (length from base to guy) = 30 ft.
Boom length from base to tackle attachment = 30 ft.
Angle of the boom from vertical = 20 degrees
Ratio = Guy Distance ÷ Pole Distance = 60 ft. ÷ 30 ft. = 2.0





To determine the derrick guy tension, start at the 20-degree point on the horizontal axis of the graph. Go up to the curved line for a ratio of 2.0. Then go horizontally over to the vertical axis. Read off the load in the derrick guy as a percentage of the total load. Guy load as a percent of total load is 39 percent and thus equals 390 lbs. for our total load of 1000 lbs.

Bear in mind, however, that the boom is movable by intent. The limiting case of the guy tension would be reached as the boom approached horizontal. For the guy:pole distance ratio of 2:1 in this example, the maximum guy tension would be 110 percent of the load being lifted, or 1100 lbs. in our illustration. And, again, all of the guys would have to be sized to resist this load.

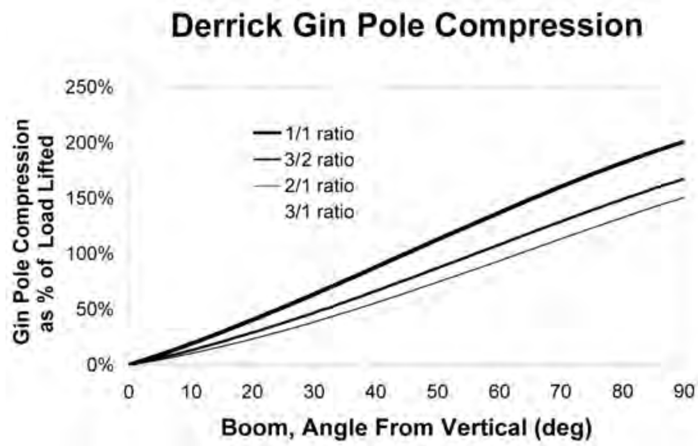
The process for determining the tension in the mast tackle is the same. But, since the boom is designed to move, the tackle has to be sized to resist the maximum load. Using trig again, with the gin pole and boom of equal lengths, the maximum tension in the mast tackle (the boom at horizontal, the tackle at 45 degrees) is $\sqrt{2}$ times the load to be lifted.

Maximum mast tackle load = ($\sqrt{2}$) 1000 lbs. = 1414 lbs.

Easier to remember than $\sqrt{2}$ or 1.414 would be a rule of thumb to size the mast tackle for 150 percent of the load to be lifted. That would also provide a bit of additional safety.

Determining Compression in the Derrick Gin Pole and Boom. To determine the compression in the derrick gin pole, start at the 20-degree point on the horizontal axis of the graph. Go up to the curved line for a ratio of 2.0. Then go horizontally over to the vertical axis. Read off the pole compression as a percentage of the total load. Compression as a percent of total load is 25 percent and thus equals .25 x 1000 lbs. or 250 lbs.

Again, the load on the system changes with the position of the boom. The gin pole must be sized to resist the maximum possible load. Reading the graph, the maximum compression in the gin pole for a 2:1 guy ratio is 150 percent of the load to be lifted, or 1.5 x 1000 lbs. = 1500 lbs.



Compression in the Boom. There is no graph for compression in the boom because that force remains constant for the amount of load to be lifted. When the boom is vertical, the load acts directly downward on the boom, causing a compression equal to the load. As the boom swings downward, the mast tackle begins to pick up some of the load. But the tackle is angled in relation to the boom, so a portion of the mast tackle load acts along the boom, inducing some compression. When the boom length is equal to the mast length, the decrease in direct compression from the load is exactly offset by an increase in compression from the mast tackle.

SAFE DESIGN. For a lifting system to be safe, all of its components must be safe. The important items to consider are the strength of the poles, the bearing capacity of the soil under the pole butt, the capacity of the ropes and tackle and guys and, finally, the capacity of the guy anchors.

The following are appropriate factors of safety for the various parts of the system:

Wood poles: Use the allowable stresses in the *National Design Specification for Wood Construction* (NDS-1997).
Ropes and tackle: Use 5 to 1 as a minimum.
Ground anchors and pole bases: Use 2.5 to 1.

Strength of Poles. The poles carry the tension in the lifting or mast tackle into the ground as compressive load. The poles are the only compression pieces in the system; everything else works in tension.

There are two ways that a pole can fail. Either the wood can crush from being overloaded (not likely), or the leg can buckle like a bow. The buckling tendency depends on the overall length of the pole, its diameter and how the ends are constrained. A long, skinny flagpole buckles at a lower load than a short, wide column captured top and bottom in a floor system.

Checking Pole Size for Safety. The worst-case example in the various systems is the mast in the derrick. The 30-ft. pole carries a compressive load of 1500 lbs. As a first check, we'll use an oak pole with a 6-in. tip diameter.

For No. 1 mixed oak, the NDS gives an allowable compressive stress parallel to the grain of 775 psi. Two failure methods need to be checked: compression and buckling.

Checking first for failure in compression, the actual compressive stress in the pole has to be below the allowable 775 psi.

Stress =Load ÷ Area
Load = 1500 lbs.
Sectional area of a pole = πr^2
Minimum section of a 6-in.-dia.-tip pole = 28.3 sq.in.
Stress = 1500 lbs. ÷ 28.3 sq. in. = 81.3 psi
81.3 psi < 775 psi

But compressive failure of the poles is not going to be the prime failure mode. A much bigger concern is buckling of the poles. The longer and skinnier a pole is, the more it's likely to fail in buckling. The way to quantify "long and skinny" is through a number called the slenderness ratio:

Slenderness ratio = length ÷ diameter = l/d
Length = length of the pole (true for our cases with poles restrained at each end)
Diameter = the minimum diameter of the pole

The higher the slenderness ratio, the less load a pole can carry before buckling. Reducing the allowable compressive stress in the pole to account for the slenderness ratio ensures an adequate factor of safety. The following chart is used to determine the allowable stress in the pole to prevent buckling. The chart is conservative as it is based on low-strength wood (No. 2 white pine). Better quality wood would allow for higher loads in the poles.

For our sample 30-ft. mast with 6-in. tip, the capacity in compression is simply checked: if *l* = 30 ft. or 360 in. and *d* = 6 in. (minimum dimension), our slenderness ratio is then

l/d = 360 in ÷ 6 in = 60.

Note that if the mast were a 6x8 timber instead of a pole, *d* would be the minimum dimension of the timber, or again 6 in., despite the greater section of the rectangular timber.

To determine the allowable compression in the gin pole, start at the *l/d* = 60 point on the horizontal axis of the graph. Go up to the curved line. Then go horizontally over to the vertical axis. Read off the allowable compressive stress in the pole for buckling as a percentage of allowable compressive stress parallel to the grain.

Allowable compressive stress against buckling as percent of total load is found to be 11 percent. Allowable compressive stress against buckling is then 11 percent x 775 psi or 85 psi.

We had previously computed the actual compressive stress in the 6-in.-dia. pole as 81.3 psi, less than the allowable stress of 85 psi. A higher margin of safety would be preferable. It is common practice to limit the slenderness ratio to a value less than 50. For our case,

l/d desired = 50
l = 360 in.
d = l/50 = (360 in)/50 = 7.2 in.

So the safe conclusion is to use an 8-in.-dia. pole, which would produce a slenderness ratio of 360/8, or 45. Rechecking allowable stress in buckling for *l/d* = 45, allowable compressive stress against buckling as a percent of total load = 18 percent, and allowable compressive stress against buckling is then .18 x 775 psi or 140 psi.

Sectional area of an 8-in.-dia. pole = 50.3 sq. in.
Actual compressive stress = 1500 lbs. ÷ 50.3 sq. in. = 29.8 psi
29.8 psi < 140 psi = Safe.

Notice how a small increase in pole size makes a major difference in the safety factor against buckling.

CAPACITY of the ropes and tackle and guys. The ropes, tackle and guys must also be sized to carry the expected loads. The common minimum safety factor in rope for block and tackle and guys is 5:1. For a critical application such as an elevator, the minimum factor of safety is 10:1.

Guy Ropes. For the derrick, at our Ratio of 2.0 (p.32), the maximum tension in the guy rope to lift the 1000-lbs. load would be 1118 lbs. Multiplying by the safety factor of 5, we arrive at a minimum required breaking strength of 5600 lbs. for the guy rope.

From the chart of rope strengths (see TF 68, "Ropes and Knots"), we know that breaking strength of 1-in. 3-strand Manila rope is 8100 lb and of ½-in. Dacron (polyester) double-braid is 8200 lbs. Either would work as a guy rope.

Rope used in block and tackle. With a rope load of, say, 245 lbs. and the safety factor of 5, the minimum required breaking strength for the rope is then 1225 lbs. From our chart in TF68, the breaking strength of ½-in. three-strand Manila is 2380 lbs., more than we need, but anything smaller than ½-in. rope would be hard on the hands of the folks pulling on the rope.

Capacity of blocks. Often the safe working capacity of a block is less than the total capacity of the number of strands of rope that can be threaded through the block. For example, a commonly available three-sheave wood-shell block for 1-in. fiber rope has a safe working capacity of 4800 lbs. But the safe capacity of the six strands of 1-in. Manila rope (one on either side of each sheave) that can be reeved through this block is 9700 lbs. *Note that the only way to determine the safe capacity of a block is to refer to the manufacturer's literature.*

Calculating for safe rigging, if it seems a lot of work, is really a simple process of solving individually for each part of the system and then putting all the parts back together. Don't get spooked, just start with the load to be lifted and work forward from there.

—Grigg Mullen

Grigg Mullen teaches engineering at the Virginia Military Institute in Lexington. This article is third in a series on timber frame rigging. Previous articles appeared in TF 67 ("Raising Calculations and Prep") and TF 68 ("Ropes and Knots"). A final article on ground anchors and soil considerations will appear in a future issue.