TIMBER FRAMING

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Number 65, September 2002

Building the BBC Ballista

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CONTENTS

On the cover, preparing the BBC Ballista, a stone-throwing catapult made to Roman specifications. The machine, a kind of giant crossbow built this spring for BBC Television by Carpenter Oak & Woodland, at Theale, England, shoots a 58-lb. stone missile. The motive force is supplied by pretensioned rope in the two skeins at the top of the machine. Photo by Gordon Macdonald.

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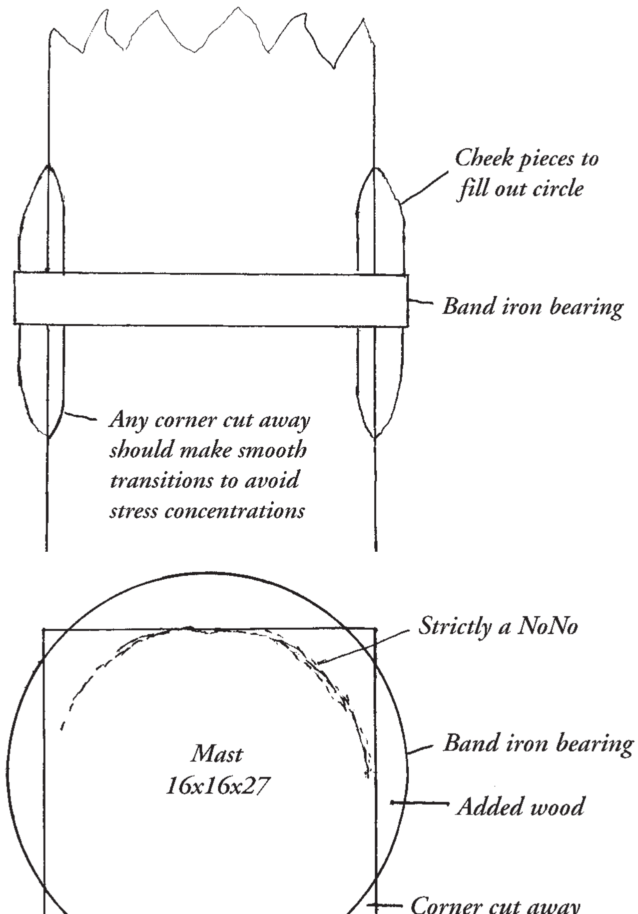
1985

LETTERS

Circles and Squares

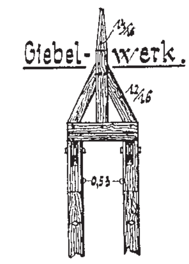
IT was with great interest that I read Mr. Ed Levin's article "Building the Norwell Crane" [TF64], but I am deeply puzzled by how anyone could cut away so much material from the most critical part of the mast as to get a round bearing. Most people would add wood here to build out a circle that could be covered with band iron to reduce wear [as shown in the drawings]. Also, the square corners around this transition from a square to a smaller cylinder will provide stress concentrations that will further weaken the mast. This whole problem is further compounded by the fact that, once built, structures almost never get adequate care, maintenance and protection from the weather. Eventually the mast will break there as the strain is shifted back and forth with the loading and unloading of the crane.



A very fine example of exactly this kind of crane has been preserved in Lüneburg, Germany, from the Middle Ages. It was used for loading and unloading ships, although now its channel has silted up. A mechanical drawing of "Der Alter Kran" (The Old Crane), as it is called, is displayed on the wall of the local youth hostel. The entire crane is covered with boards to protect it from the weather. Frequent tours of the interior are given.

Wallace M. Yater
PO Box 51
Boonsboro, Maryland 21713
June 24, 2002

Editor's note: The Norwell Crane was built carefully to the design of Jean-Rodolphe Perronet, a distinguished 18th-century French architect and civil engineer and a prolific bridge builder. Perronet was appointed the first director of the École des ponts et chaussées in Paris at the end of the century. (See TF 64.) Unlike the Lüneburg crane praised by Mr. Yater, which was meant to stand indefinitely at dockside through all weathers, the Perronet crane was designed to be used on a construction project and then struck and stored (presumably under cover) until the next one. The Lüneburg crane is illustrated here by drawings kindly supplied by Mr. Yater. His letter was edited for length.



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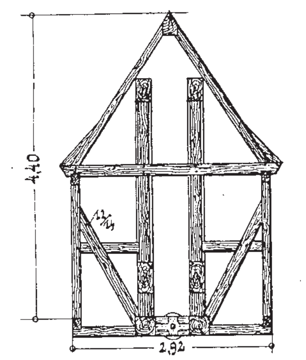
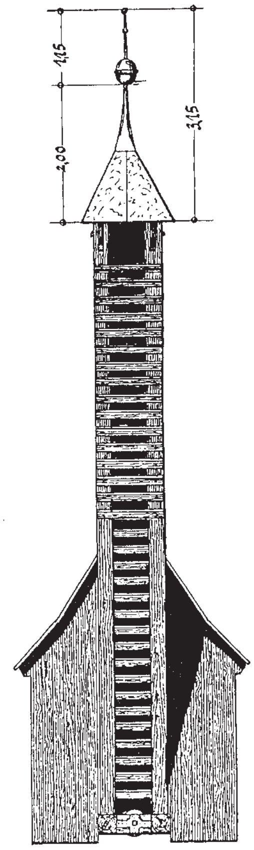
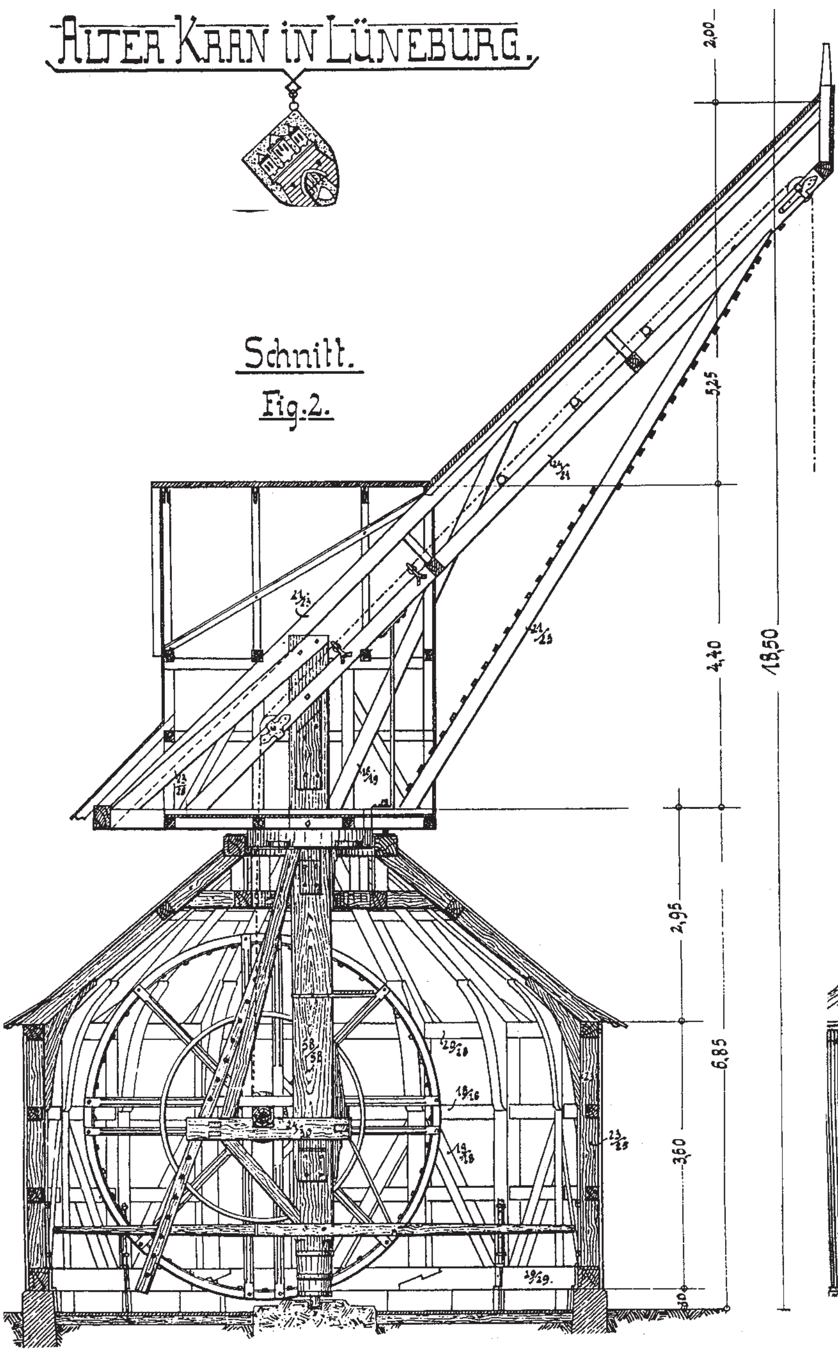
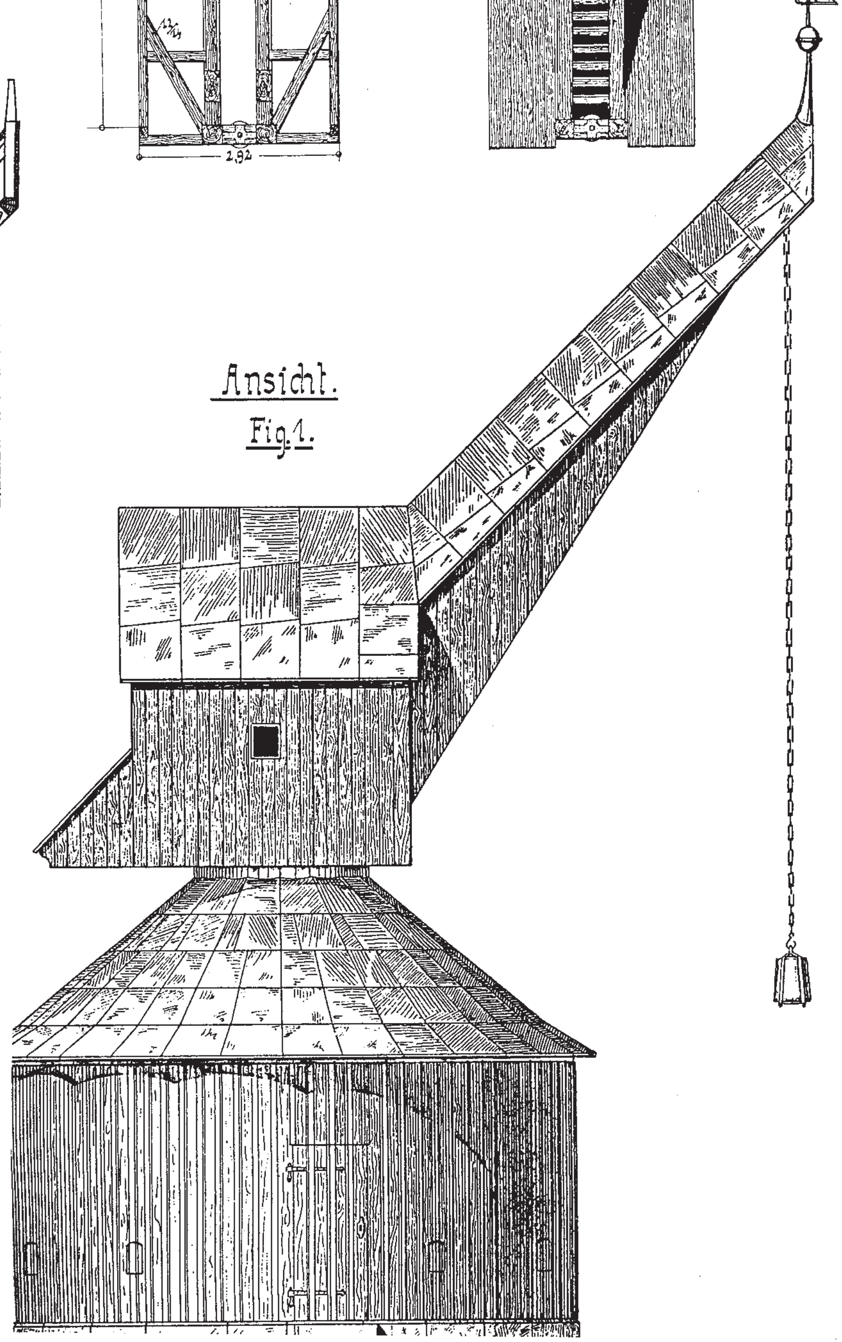




ALTER KRAN IN LÜNEBURG.



Schnitt.
Fig. 2.


Ansicht.
Fig. 1.

A Korean Pavilion in D.C.

Photos Peter Wechsler

WHEN framer Peter Wechsler recently completed a pavilion for the garden of the Korean ambassador's residence in Washington, D.C., he had to concede that the site conditions were as distinctive as the considerable technical complexities of the project. While he worked, just yards away Army Corps of Engineers contractors in moon suits carted out 700-odd canisters of World War I-era mustard gas and unexploded ordnance from a containment facility. The pavilion project is part of a complete garden reconstruction at the Korean ambassador's residence, funded by the Corps, which removed the previous garden and 2 ft. of contaminated soil as part of a cleanup of an old chemical weapons testing site near American University that has spread arsenic contamination—and related lawsuits—throughout one of the wealthiest neighborhoods in Washington.

The landscape architect's design included a rough sketch of the building, showing a temple-style hipped gable roof but with few details and no curves for the roof. Pete's research on traditional Korean building forms produced only a few books, and even fewer in English, with almost no construction details. Pavilions are open buildings with temple-style roofs. Some show elaborate bracketing and exaggerated curves while others are simple and rustic. The interiors are generally bare with a raised wooden floor and a railing. In Korea, they are usually sited in a garden or in the mountains and seem to provide an opportunity to contemplate natural surroundings.

Traditional Korean and Japanese architecture both derive from Chinese models, so they have many similarities in roof style. (Chinese building methods were transmitted to Japan through Korea.) But there are several differences from the Japanese temples with which Pete was familiar. In Japanese temples, the eaves of the hipped roof run straight along the middle of the building and flare up just at the corners. In Korea, the eaves have a continuous curve, sweeping corner to corner. Most traditional Korean roofs use round fan or radial rafters, while most in Japan use nearly square parallel rafters. Pete therefore produced a design using a curving roof line and continuous eave flares with round fan rafters. He then made a 1-in. scale model to explore the construction method.

The curving roof. Korean and Japanese temple roofs both use a curving shape that cantilevers out some distance from the wall plate. Both use heavy roof tiles. But each country employs a different engineering solution to support the roof's weight and obtain the curve.

In the 10th to 12th centuries, Japanese carpenters developed a double roof system, with two sets of rafters. The lower set of "finish"

rafters—generally heavier since they help support the cantilever—usually have about a 3:12 pitch. (The relatively shallow pitch is considered more restful seen from beneath than a steeper one, admits more light and can extend out further over the typical verandah.) A second, upper set of relatively slender "rough" rafters goes from the eave to the ridge and is bent to the purlins to define the curve (also called the sag) of the roof. The rough rafters are hidden by a ceiling on top of the finish rafters, and the space between is sometimes used for a beam to help cantilever out the eaves.

The Korean system does not use the double roof developed in Japan. Instead, there are two or more sets of straight rafters at different pitches. The upper, more-steeply pitched rafters meet the lower, more-shallowly pitched ones, forming an internal angle. To achieve the finished curve for the roof, the Koreans ease the angle by filling in with dunnage and then with 1 to 2 ft. of clay, into which roof tile is set. The weight of the materials on top of the roof supports the cantilever of the lower set of rafters, and the material can be shaped to the desired curve.

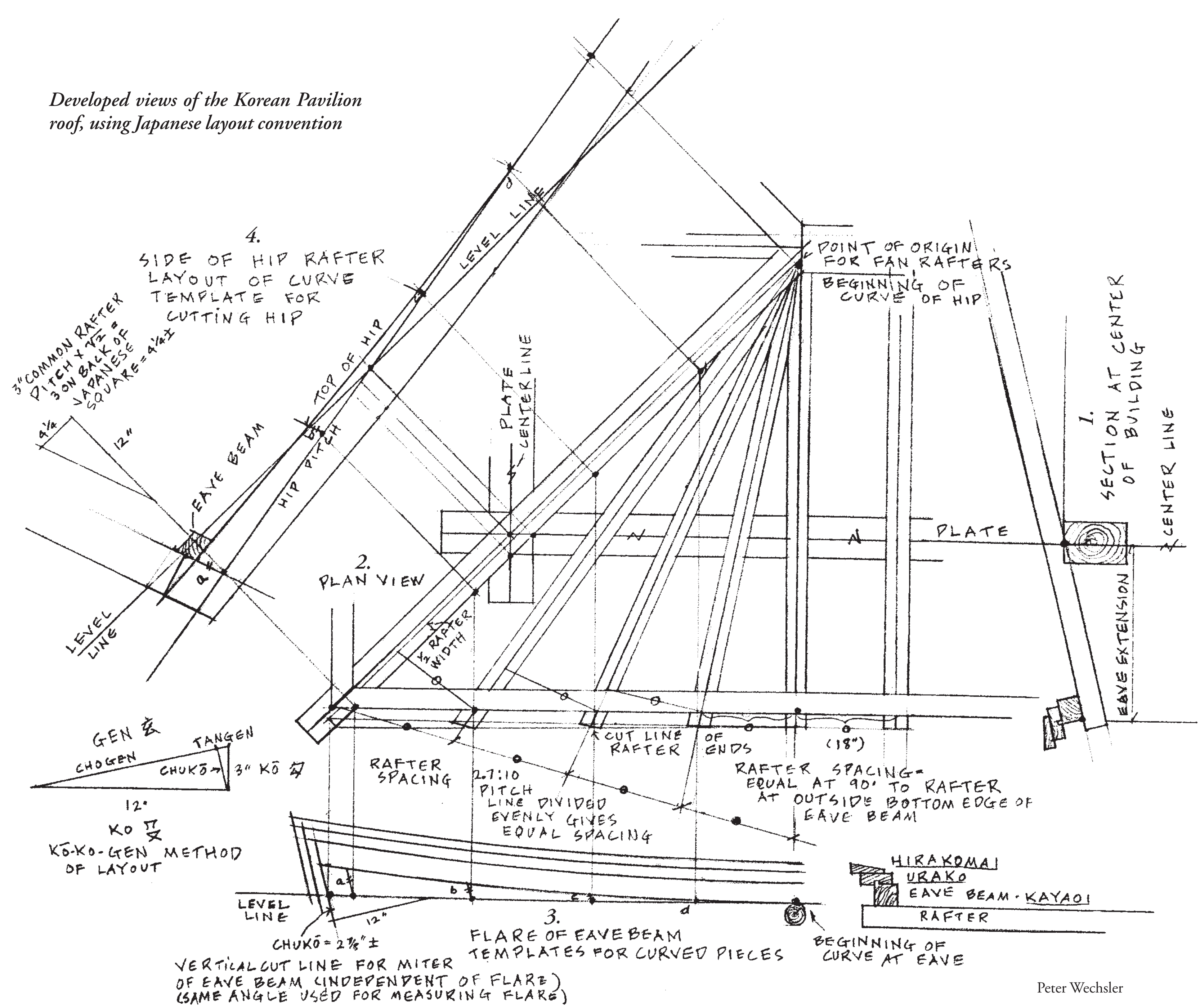
A hybrid approach. While Pete wanted the roof to look as authentically Korean as possible, he decided to use the double roof system for the pavilion since he had experience with this approach. The clients also wanted shingles, not tile, so building up clay on top of the roof was not an option. Given the relatively small size of the roof and the short spans between the purlins, Pete decided to eliminate the upper rough rafters. Instead, he ran the sheathing vertically and bent it to the purlins.

Fan rafters. Pete had been eager to try out fan rafters ever since he encountered them when he worked briefly in Japan on a reproduction of a 12th-century temple. Fan rafters are common in Korea and China, but relatively rare in Japan. Horyu-ji, the first major Buddhist temple complex in Japan, used parallel rafters in the 7th century. Its influence was so great that the use of fan rafters died out in Japan until reintroduced from China in about the 12th century. Fan rafters are described in some Japanese carpentry manuals, and thus Pete had the reference materials needed to try them out.

The pavilion design specified a wooden deck with posts set on a stone foundation. A structural engineer designed stainless steel bases with 30-in.-high collars, to set 3 ft. below the deck. Each weighed about 400 lbs. and cost about $800. The cylindrical collars are buttressed by welded external ribs and bolted to a concrete base. It may be that in traditional construction heavy wooden floor beams and decking provide enough rigidity to resist racking, but, in this case, it seemed safer to rely on the engineer's rather hefty design.

The pavilion roof rests on four 14-in.-dia. posts whose centerlines form a rectangle 9 ft. by 10 ft. 6 in. in plan. The plates are 8x12. The finish rafters have a 3:12 pitch while the overall roof pitch is 7:12. The hip rafters are bolted into a short piece in the center of the roof, concealed, along with the fan rafter peaks, by a little ceiling. To keep costs down and to achieve the rustic effect the architect wanted, Pete used peeled Eastern white cedar logs for the fan rafters, and peeled Port Orford cedar logs for the main posts. Aside from the fan rafters, all visible parts of the pavilion's frame are Port Orford cedar, a *Chamaecyparis* used often in Japanese temples in place of the traditional *hinoki* cypress native to Japan. The ceiling of the eaves is woven willow fencing, while the center ceiling is a frame with six panels.

Developed views of the Korean Pavilion roof, using Japanese layout convention



Peter Wechsler

LAYOUT. A Japanese carpenter first draws up a plan on the back of a board, showing the positions of the posts and some other structural members. Their centerlines are laid out in a grid system, with numbering vertically and lettering horizontally, showing the intersections of all the members. The alphabetical system used by Japanese carpenters on the ground is based on the first letter of each line of an ancient Buddhist poem about the impermanence of worldly existence—the transience of colors, smells and so forth. (The effect of this doubtful association upon the carpenter is unknown.) All timber layout is done from centerlines snapped on each piece of wood. The master temple carpenter with whom Pete worked in Fukushima used the reference board to work out all the layout on a job, with no other written plans.

In a building with a curved roof, a full-scale floor layout, called *gensun* in Japanese, is essential. Full-scale views of one corner of the roof as seen from four different angles are drawn using a Japanese ink line *(sumitsubo)* on plywood spread out on the floor. These four different views, if drawn on cardboard first scored and then folded up, would make a three-dimensional model of the building's corner. Gensun produces the templates needed to cut all the curved parts. The drawing reproduced here shows the same information as the gensun.

View 1 on the drawing is a section at the center of the building, showing the roof overhang, the section of the plate, the elevation of a finish rafter and the sections of the eave beam *(kayaoi)* along with the layers of eave trim on top of it.

View 2 shows the corner of the building in plan, including the intersection of the two plates, the hip rafter and the eave beam. This drawing, a rotation of the first, is generated by extending the center line of the plate beam and the lines of the eave beam from the first drawing.

This view is also used to lay out the rafter spacing. Traditional aesthetics call for the intervals between the rafters to be equal, as seen at the outside of the eave beam, including the space between the last rafter and the point where the eave beam and hip rafter intersect. This requirement is easy enough to meet with straight rafters. Determining the spacing for fan rafters is more complicated. Here the space from one fan rafter to the next is measured along a line perpendicular to the centerline of the first and originating at the latter's intersection with the outside of the eave beam. These distances ("O" in the drawing) produce the desired appearance along the eave of the building.

The spacing can be determined geometrically by drawing a line from the intersection of the hip rafter and the eave, at a slope of 2.7:10 from the eave beam, as shown in View 2. This line is divided evenly and the division points are then used to lay out the centers of the fan rafters. Since the pavilion was to be 18 in. longer than wide, the long sides would each have a single central roof bay flanked by common rafters 18 in. on center, and Pete therefore aimed to use this spacing for all the rafters. Meanwhile, a 36-in. overhang seemed provisionally a safe distance for the cantilever. But to achieve the desired rafter spacing, it was necessary to experiment with the number of rafters and the eave overhang, which ended up at about 30 in.

View 3 is a rotation of 2 and shows the side of the eave beam at a right angle to the plane of the rafters. This new view is used to determine the flare of the eave. A line is snapped parallel to the eave beam, representing a level (horizon) line. A batten is bent up from this to the desired curve and a line drawn. Another curved line is drawn parallel to this one to define the top of the eave, with additional parallel lines above it for any other trim pieces.

The sidecut lines for the miter at the ends of the eave pieces are laid out using the Japanese framing square *(sashigane)* and a unique system for finding all the angles of a hip roof. A triangle is laid out with a base or run of 12 in. (in Japan, 10 *sun*, almost identical) and a rise representing the pitch of the roof (here 3 in.). Using terms somewhat confusing to the Western ear, the base of the triangle is *ko* (short-sounded "o"), the rise is *kō* (long-sound "o"), and the diagonal or hypotenuse (the rafter length) is *gen*. The line perpendicular to *gen* bisecting the triangle is *chukō*. The short section of *gen* is *tangen* and the long section is *chogen*. Each of these dimensions can be used with the framing square to lay out various angles for a roof. This system of layout used to be secret and handed down from master to apprentice, but now carpentry manuals in Japanese explain it and offer diagrams showing how to lay out the various joints. To lay out the sidecut on the eave beam, the "reverse slope of chukō" is used. Chukō is measured and the square is laid on the level line of the drawing with this dimension on the short leg and the 12-in. mark on the long leg. A projection of the short side is the miter sidecut on the eave beam. Notice that since the top of the eave beam lies in the plane of the roof, and thus its side is perpendicular to the roof surface, the flare rotates its corner outward in two directions in addition to raising it. The end of the eave beam must extend up to follow the curve but also forward and outward to meet the end of the adjacent eave beam. The outward flare is not shown in View 2.

View 4, and the final step of the floor layout, is an elevation of the side of the hip rafter, which is used to make a template. First, a line is snapped parallel to the hip rafter in the second or plan view. The pitch of the hip then is laid out in relation to this level line. On a Japanese framing square, a special scale on the reverse side serves this purpose. On the reverse, all the dimensions from the face side are multiplied by the square root of two—about 1.4142—so that 12 on this scale is equal to almost 17 in. on the face side. (This is the unitary run of a regular plan hip.) To lay out the hip rafter pitch, the common rafter rise and 12 on the reverse scale are used. An ink line is snapped to extend this line. Because of the flare of the eave beam, the hip also must be curved the same amount, but at a different angle since it travels a different level distance to arrive at the miter.

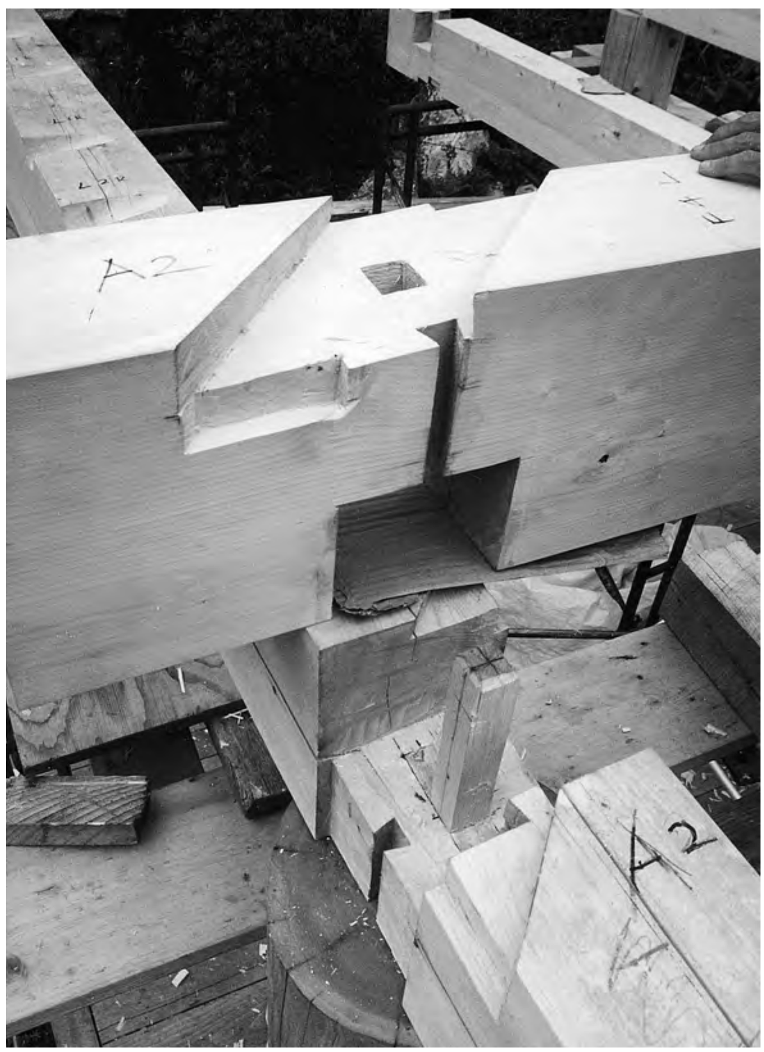
From the points where the eave beam and the plate touch the side of the hip, lines are drawn to the hip pitch line at a right angle to the hip in the plan view. Then the angle is drawn for the cut line at the end of the hip and the notch for the eave beam, as shown in the drawing; this can be laid out in various ways, one of which is shown.

Then in View 3 the distances a, b, c, d, etc. from the level line to the bottom of the eave beam, taken at the angle of the eave beam cut line, are measured at various points. On the drawing, for convenience they happen to be at projected rafter stations, but any location points suitable for bending a batten will do. These points are transferred to the hip, and then to the hip pitch line. The dimensions are then laid out from these points at the same angle as the cut line for the end of the hip.

These points are then connected with a curved batten to define the top edge of the hip. Then another line is drawn parallel and at a distance equal to the depth of the hip, defining the bottom edge of the hip. The eave beam is usually notched into the end of the hip to a depth of one half of its own thickness. Its width is then drawn using the scale on the back of the square, creating a parallelogram, the section of the eave beam cut at a 45-degree angle.

The next step is to transfer these curves to template stock. Common nails are laid flat on the floor layout, their heads registering points on the lines. Another piece of plywood is carefully placed on top and pressed down, leaving the impressions of the edges of the nail heads. These impression points are then connected using a batten and the lines redrawn.

CUTTING. Once the templates were cut out, Pete could prepare the timbers and then execute the layout and cutting. The corner joint used for the plate beams *(keta)* is known in Japan as the *neji-gumi* or "twist" joint. In brief, the plates cross at the corner via a form of halving joint, and the crossing is notched in its upper part to receive the hip rafter. To retain as much strength as possible in the hip with its lengthy cantilever, no birdsmouth is cut in the bottom of the hip. (A shallow, shouldered reduction only is made to the bottom surface of the hip, to register it on the plates.) Instead, the plates are notched to receive the hip. The depth of the notch is determined by the relative depths of the hip and common rafters, since their top surfaces have to be in the same plane. On the axis of the hip, the notch is pitched at 3 in 17.



A neji-gumi corner joint ready to assemble. The tenon formed in the post-top is reduced after it passes through the lower part of the halving, so as not to take too much of the upper part. Beam and dovetail housings in lower foreground resist twist by the outboard part of the adjoining plate. Halving lines are laid out on bisections of measurements down from sloped lines of the hip seatcut, which produces mating twisted surfaces. Note semi-elliptical fan rafter housings in the background.

The two plates (keta) partly assembled, seen from outside. The slope of the seat line on the face of each plate is at half the common rafter pitch. On the left-hand plate above, it rises from left to right and is mirrored on the right-hand plate. Analogous lines bound the rear faces of the seat.

The joint assembled, seen from inside. Though the hip is firmly registered by the rabbets at the inside and outside corners of the joint, the tenon rises from the post through both plates and enters the hip for good measure. The dovetail connection probably serves mostly as a spline.

Because of the pitch of the hip, and its plan-view 45-degree angle to the plates, the lines on the front and back faces of the plates to mark for the seatcut are not level. They are pitched at one-half the common rafter pitch—in this case, 1½:12. (In Japan, this slope is called the *han-kobai*, or half-pitch. Its relationship to the common rafter pitch is invariable.) And because of the crossing plates, these seatcut layout lines are actually mirror-imaged across the joint.

It can be helpful to think about this relationship first in terms of the hip crossing a single plate. The seatcut lines for the hip on the face and back of this plate cannot be level because the hip has been raised and turned to produce a compound intersection angle. In the case of the crossing plate, the mirror-imaged angle is produced.

To dimension the halving below the notch for the hip, the depth of plate below the seatcut lines is simply divided in two on both the fronts and backs of the plates. This ensures that the remaining material on the upper and lower plates will be equal in section for maximum strength. Because the lines for the seatcut are at different heights on the front and back of each plate, the cut for the halving joint is not level. Furthermore, halving these unequal distances changes the angles of the cutlines on the plate faces, so that the resulting surface is slightly twisted, and thus the joint name neji-gumi. The layout is the same on both the upper and lower plate; in one case the upper portion is removed, and in the other, the bottom portion. A series of sawcuts and work to the lines with a narrow chisel will produce the desired surfaces on both parts of the halving. The layout and cutting of this joint are part of the exam required to become a licensed carpenter in Japan. Of the neji-gumi, Kiyosi Sieke wrote in *The Art of Japanese Joinery* (Weatherhill, 1977): "It is in truth a delicate joint not at all reliable for major construction, yet one cannot help admiring the beauty of its composition, which is appreciated far more than its reliability." In any case, the load on the joint is fully supported by the post.

The joint shown in the photographs has sliding dovetails in two directions and a housing in one direction to stiffen the halving against twist of the outboard portions of the plates. The joint is almost completely hidden from view in the finished pavilion.

Laying out this hybrid work turned out to be more complicated than for a purely Japanese style. In a Japanese roof, all of the curve in the hip rafter takes place beyond the joint. In the Korean version, since the hip is curved over its entire length, its pitch keeps changing. In addition, the height above plate of the top of the other rafters is greater at the corner than at the center of the building. These traits led to a lot of head-scratching but were resolved by means of the floor layout.

AFTER fitting the plates and the hip rafters, the next step was to produce the curving 18-ft. eave beams (kayaoi). Once he had cut them out on the bandsaw using a half-template made from the floor layout corresponding to View 3, Pete realized that the curve looked too flat in the middle. Bending the batten only at one end, for the half-view, was the source of the effect. A Korean-style roof would need a deeper curve. Pete used the boatbuilding method of spiling boards (which work much like the two nails, a string and a pencil used to draw ellipses) to redraw the templates. Recutting the kayaoi reduced their size, but since all the fan rafters are cantilevered off the plates and offer good support for the kayaoi, this was not a problem. Cutting the kayaoi to length and notching the hip rafters where they would sit, without scribing, meant that Pete had to put his faith in his templates and his Japanese carpentry manuals. To his relief, the pieces fit precisely.

Pete installed the fan rafters starting in the middle of each side. Only the central rafters of each roof panel are straight. Because the hip is curved, each successive rafter either side of center needs to be slightly curved as well, with the curvature increasing as the hip is approached. Using round rafters avoided one problem: the top surface of each rafter would have had to twist as well, had he been using square fan rafters. And since all the natural peeled poles had varying degrees of curvature, he was able to use those with the greatest bend closest to the hip. In the center of the fan at the ridge, Pete butted the rafters together and kerfed them to fit using a chainsaw.

The second and third layers of eave trim sit on top of the kayaoi. Pete cut a tongue on the outside upper edge of the kayaoi and a groove on the bottom of the second layer (the *urako*) to ensure a uniform reveal and conceal any gaps caused by surface irregularities. The top layer (the *hirakomai*) is beveled to a nearly triangular section, which makes it easier to bend and shape to the urako. The roof sheathing is feathered at its edge so that its top surface meets the top corner of the hirakomai.

With the primary roof structure in place, it was time to build the secondary roof structure. Two sets of purlin frames sit on top of the hips, one raised up on stub posts. The third level of purlins and the ridge beam sit on posts rising from the second frame. Applied bandsawn 2x4s produce the curves on all these members, rising from the center toward the ends, roughly following the curve of the eave. The layout of the rough hip rafters on the secondary roof structure proved most difficult because it was necessary to account for not only the upward corner flare, but also the downward dip of the roof elsewhere.

The final step was to drop down the hip rafters about 2 in. from their raised position, where they had allowed the placement of all the fan rafters and their scribing to the plate. Pete roughed out the seats for the fans with an in-cannel gouge and finished with a curved-bottom plane, using carbon paper as a telltale.

When the roof was complete and ready for erection on site, a vexing obstacle emerged. Two of the four Port Orford cedar posts, when peeled, revealed shallow beetle tracks beneath the bark. At the landscape architect's insistence, Pete eventually procured 800-lb. replacement posts from Oregon. He then turned the bottom 30 in. of the posts, rotating them in a jury-rigged system, so they would slide into the hidden cylindrical steel bases.

Erecting the posts on site proved fairly painless, in spite of a tornado warning. Because of uncertainties in the elevations of the cylindrical bases, Pete cut the tenons on top of the posts once they were set by the crane, and then installed the plates and the rest of the structure, followed by the rafters and the eave pieces. Woven willow fencing went in on top of the fan rafters, the roof sheathing was bent to the purlins and screwed down and the precut gable trim pieces installed. A roofing contractor put on cedar shakes. Pete scribed the decking around the posts and made and installed the small interior ceiling pictured on the back cover.

He proposed to divide the ceiling panel into six smaller sections, but the Korean-American landscape architect rejected the proposal on the grounds that it would look "too Japanese." Pete nevertheless mocked it up with the divided panels and showed it to the Korean Embassy staff to get their opinion. To his great satisfaction, they felt the divided panel looked more authentically Korean, so he was able to prevail.

The finished building is probably unique—an American structure in traditional Korean style, built for the Army Corps of Engineers, using Japanese temple carpentry techniques. It sits on a hill at the top of the Korean ambassador's garden, where Army Corps contractors are now done with one part of their multi-million-dollar cleanup of the area.

—Heidi Welsh

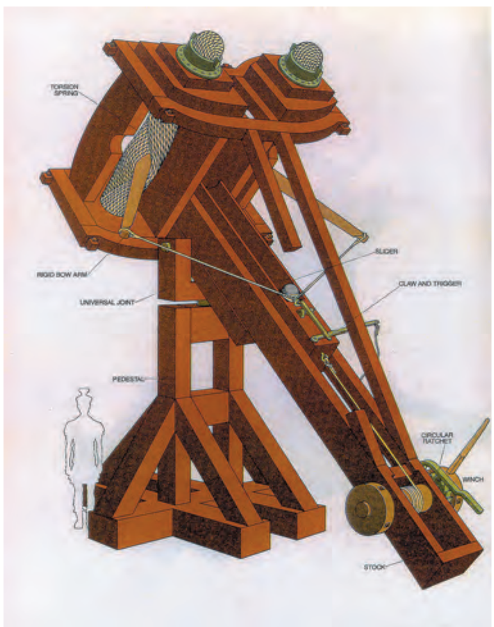
Heidi Welsh (welshwex@myactv.net) does research on corporate social responsibility and helps her husband, Peter Wechsler, run Daiku Woodworking in Boonsboro, Maryland. Peter specializes in Japanese-style buildings, rooms and shoji screens. He has lived and worked in Japan with master temple carpenters Shoji Yoshida and Hatsuo Kanomata in Fukushima prefecture. Bruce Bartol of Frederick, Md., assisted throughout the pavilion project and TFG member Tom DiGiovanni of East Berne, N.Y., also lent a hand.

Above, posts, plates, eave beams and some purlins assembled in place, having previously been prepared at Peter Wechsler's yard in Maryland. Below, remaining purlins are erected on their posts and all the shaved round fan rafters are fitted, seated in their notches in the plates and just touching the eave beams they support. At bottom, the purlins have been built up with sawn curved shims to produce the continuous sweep of the Korean style roof, the upper pitch hips and the gable frames have been installed and the fan rafters have been covered with the willow fencing. Though such double roof framing usually calls for a set of slender rough rafters to lie over the purlins, the spans here were short enough to be covered directly by sheathing bent in place to follow the curves.

Building the BBC Ballista

WHEN BBC Television approached us in June of last year to replicate a Roman siege weapon known as a ballista, we knew we would be in for long days and nights of hard work, endless trouble and little money, so we gave the only sensible answer we could think of: "Sure, we'll do it." Roman ballistas were reportedly used during the siege of Jerusalem in 70 AD and capable of launching heavy, carved stone missiles with great force and accuracy against fortified walls. The specific machine the BBC had in mind was born from the pages of Werner Soedel and Vernard Foley's 1979 *Scientific American* article "Ancient Catapults," which showed a sketch of a machine 27 ft. high by 30 ft. long, supposedly capable of launching a stone weighing one Roman talent, or about 58 lbs. Hundreds of stone missiles of various weights and sizes have been excavated from beneath the walls of ancient fortifications, a testament to the widespread use of the machines by Roman Legions.

The BBC intended to film a four-part series called "Building The Impossible," in which a team of assembled scholars and builders would design and construct historic machines according to fragments of historical text and artifacts, and the ballista was to be the subject of one segment. To its credit, the BBC had already gathered a first-class team—structural engineer Chris Wise, materials scientist Caroline Baillie, fellow Guild member Ian Ellison (who was to advise on timber selection), master bow-maker Steve Ralphs and archeologist Alan Wilkins, who specializes in Roman history. Our brief was to provide detailed design information regarding the timber and metal components and procure all of the necessary materials, and then project-manage the team in order to put the thing together for test-firing at an undetermined site in England. Our initial review of the design by London's Expedition Engineering Ltd. suggested the machine would require something like 2400 bd. ft. of fresh oak timber, and more than a ton of ironwork, so we began to assemble our own team, drawing upon a variety of disciplines and backgrounds—and calling upon friends from near and far. But first and foremost, we had to learn the terminology, tools and techniques employed to build these amazing machines two thousand years ago.



Estate of Mary E. and Dan Todd

Drawing published in* Scientific American *(March 1979 International Edition, p. 122) showing Eric Marsden's model ballista. The central slider with bowstring, missile pouch and trigger attached is drawn down by the winch. Upon trigger release, the missile alone shoots forward while the slider guides the shot.

Ballistae were the stone-throwing version of torsion artillery; the term *catapultae* was used for torsion arrow-shooters. *Catapulta* is the Latin version of the Greek word *katapaltes*, *kata* meaning downward, and the verb *pallo* meaning hurl, and so the word means a machine that would knock down anyone or anything. Greek torsion artillery probably appeared around 350 BC when Phillip II of Macedon (father of Alexander the Great) financed a program of research and development that led to the introduction of torsion-sprung engines. These new machines worked by pretensioning and rotating (hence torsion) two bundles of cords, or skeins, to form rope springs. Upon release, the springs enabled two embedded bow arms to harvest a great amount of energy efficiently and with little movement. By about 270 BC, Greek engineers in Rhodes and Alexandria had perfected catapult design and published formulas for calculating the size of the parts. The Romans began using torsion artillery in the middle of the same century during the first war against Carthage.

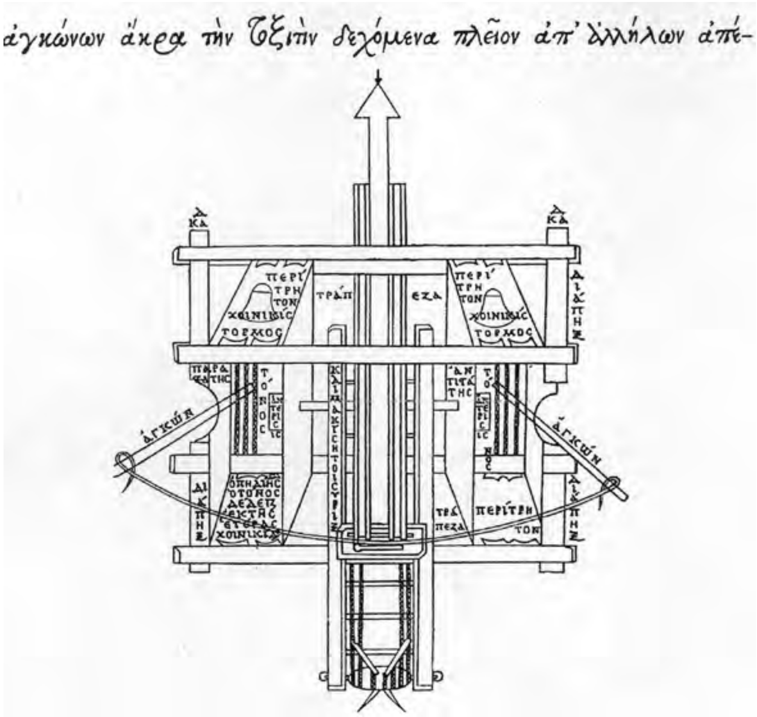
The type of stone-throwing ballista we would construct was described in detail by the Roman architect and engineer Vitruvius, writing about 26 BC, whose account includes many of the necessary dimensions. Vitruvius inherited the Greek formula for dimensioning the hole for the essential mechanism, the coiled skein, as a function of the weight of the missile that the ballista was intended to throw, and from the dimension of the skein hole all the other parts of a machine could be proportioned. We added a constant to this formula ($D = 1.1 \sqrt[3]{100M}$, where D is the skein hole diameter and M is the weight of the missile) to account for differences between ancient and modern weights and measures. In our case, the missile would weigh the equivalent of one Roman talent (26.2 kilograms), so we calculated that our machine would need a 14½-in.-dia. skein. All of the component dimensions would then be specified in skein diameters.

The dimensions given in the surviving manuscripts of Vitruvius have suffered greatly from mistakes in copying, but many can be cross-checked against those in the description of an earlier version of the same machine by the Greek engineer Philon of Byzantium. A third engineer, Heron of Alexandria, writing during the 1st century AD, gives valuable advice on constructing and operating a ballista, but no dimensions. The illustrations that originally accompanied the descriptions of Philon and Vitruvius have not survived, but there remain two illustrations attributed to Heron (one resides at the Vatican and the other in Paris) that show some of the joint details, various frame assemblies and the trigger tackle.

Inaccuracies in manuscript dimensions arise from their interpretation through the ages as numerals rather than written numbers (and vice versa). Alan Wilkins collected and translated for us the information contained in the various texts, ascribing a reliability rating from 1 to 5 for each passage. In this way we were able to select the most likely solutions when presented with a range of conflicting accounts. We would have been lost without Alan's expert and patient advice.

Other evidence exists to add to our understanding. The Hatra cast bronze washers, the surviving parts of a large fortress-mounted ballista, provide valuable clues to the tensioning method: clearly visible is a ring of index holes that would permit the washers to be rotated and then held in virtually any position (presumably by pins). The small carving known as the Cupid Gem shows an arrow-shooter atop a pedestal, in one of the only extant references to the bases of these machines. Although this device is not a ballista, its elevation at 30 degrees rather than the 45 that would obtain maximum range indicates an intention to obtain maximum force at close range, and supports the view that ballistas too were intended to "punch" at their targets from relatively close range, as when breaching a wall.

We felt confident that the historical information, taken as a



After Wescher in *La Poliorcetique des Grecs* (Paris, 1867)

Drawing after Heron, the 1st-century Alexandrian engineer, showing a ballista ready to winch down. The bow arms will be drawn down and tensioned and a missile will be discharged along the central slider, which guides the shot.

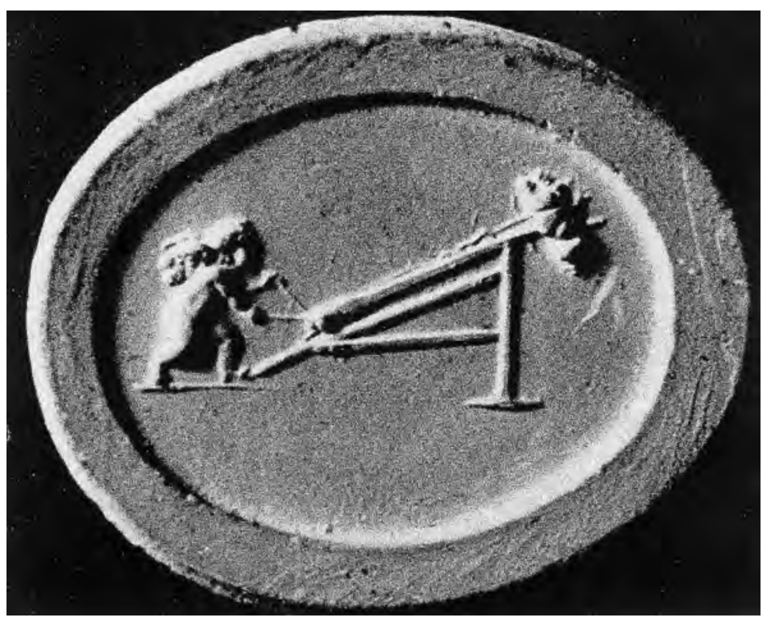
whole, was sufficient to reconstruct a reasonable facsimile of the machine, but there remained two major obstacles to overcome. First, Greek and Roman engineers usually made the torsion spring skein from sinews of oxen or deer, with horsehair regarded as an inferior alternative (it's also possible that human hair was occasionally used). A quick calculation showed that we would need to procure the sinew from over a thousand animals in order to make a machine of this size, or we could steal the tails from several hundred horses. Caroline proposed that we use instead a pre-stretched polyester rope that would perform similarly to the sinew. At such short notice, we could only find ⅝-in. stuff, meaning that we would need to wind more than three miles of it into our machine!

The second design obstacle was more intimidating. Engineer Chris Wise told us that we could expect our machine to generate loads in excess of 400 tons compression per side when fully cocked (for reference, remember that a Chieftain battle tank weighs about 70 tons), and that the ancient dimensions required some of the oak timbers to perform many times beyond their current allowable design values. In case of mishap, the Romans as professional warriors would not be nearly so worried about killing off a few of their legionaries as we would be about killing off our precious timber framers. The Romans knew what they could get away with (just) and were prepared to endanger their crews in order to get the most out of their machines. They did, however, reinforce their oak frames with far more iron than the BBC could afford. The Romans were also accustomed to working with these things (they had hundreds of them), while we were still uncertain about many of the finer design details and not entirely sure that we were interpreting the information correctly.

A COMPROMISE was reached when we agreed to build the ballista but to cycle the discharge loads in small increases until we were reasonably sure that it would work. This meant committing ourselves to a design that fell outside conventional design values, but even so called for immense oak timbers, some of them 40-in. baulks (our sawmill called the job "Sawing the

Photos Dietwulf Baatz

Views of the Hatra washers. Hatra is a fortified city in Iraq once besieged by Romans and others, with massive walls still impressive in their ruinous state. Excavations in 1972 found four washers and metal plating from a catapult that had fallen from one of the towers. The internal diameter of the washers is 16 cm. at the top, the rope skein diameter, and 17.5 cm. at the base, allowing for the spreading out of the skein. The lugs projecting inwards, features not normally found on catapult washers (the majority of those discovered may be from bolt-shooters), gave extra support to the iron bars around which the skein was wrapped.



The Cupid Gem, a plaster cast of a lost carving showing a base-mounted catapult. Low discharge angle suggests close range.

Impossible"). As a precaution, Chris also asked us to build a quarter-scale model of one torsion assembly for mechanical testing at the University of Surrey. The test results were encouraging, and showed that our trigger design was going to work, so we began to develop our final frame drawings on this basis. But precious time was slipping by. We now had just one more month in which to complete our drawings, procure the timber, build, assemble, fire and take down the whole machine. As time marched on, it became increasingly clear that we would have to build the whole machine on site—the drawings just couldn't be prepared in time for any off-site construction. I stopped sleeping.

With our preliminary timber orders placed and most of the metalwork on order, we turned our attention to the rigging and lifting plan, which the BBC had requested be a hand-raising. While we're used to making large and sometimes complicated lifts with cranes, this was going to be a much more demanding affair, so we recruited the expert advice of our friends Grigg Mullen and Dennis Platten. Grigg teaches engineering at Virginia Military Institute and helps direct the Timber Framers Guild, and in both capacities he has had extensive experience with big machines that throw rocks. Dennis is the master rigger who was asked to rig (among other things) the *Cutty Sark* during her last refit. While Grigg crunched the numbers, Dennis helped us to find the tackle, and, by the time we found ourselves on site, we had a pretty good idea that we could make it all work.

We knew that we would be safe up to a maximum lift of 10 tons, but as we left for the site the engineers issued us with their final-final revisions. With more than 6000 bd. ft. of oak now expected, they told us to expect up to 13½ tons of lift. . . ish. Clearly we would have to reduce the weight of our dead lift as much as possible in order to stay within the load limits of our tackle, so we set about reducing the machine to its bare essentials. Installing the slider and trigger tackle later would save precious pounds, and by approaching every aspect of the design in this way, we reckoned that we might reduce the overall load to a more nearly acceptable 12 tons.

As we drew closer to the fixed site date and the engineers issued their final-final-final drawing revisions, we were resigned to the reality that our machine was going to be much larger and more complicated than we had originally expected. The ballista would now stand 28 ft. high, it would be almost 40 ft. long, incorporate more than four tons of metalwork and weigh something like 20 tons all told.

OUR crew of 20 framers arrived at the site on a Sunday night, tucked into the work, and soon found itself in that traditional rhythm of long days and evenings followed by endless drafts of ale. The BBC had found us a suitable site to construct and test-fire the ballista at Englefield Deer Park, on a private estate near Theale in Berkshire. To say that this is a large estate would be something of an understatement. One night we drove from the Deer Park to our hotel (about a 15-

Alan Wilkins

Making up the component assemblies were raisings in themselves. Here a **regula** *or locating frame is flown in and lowered over the torsion cassettes. The author is on the tag line.*

Gordon Macdonald

Jon Gourley trimming the laminated bow arms to ballista-shapely form and to provide correct purchase for the bowstring. Blank ends of arms lodge in rope skeins. Arms will later be clad in steel on both vertical faces. All pieces were fabricated to engineers' drawings.

Photos Gordon Macdonald

Above left, Dan Addey-Jibb hews first four sides then four more to make the octagonal central axle on which the ballista will pivot to change elevation (see below for next stage). Above right, master rigger Dennis Platten makes an end splice in the miles-long torsion skein. Below, Gareth Bicknell adjusts the drive belt from the distinctly non-Roman Fordson Major tractor to his shade-tree turning operation.

minute drive south), showered and then drove to a pub for dinner (another 20-minute ride heading south). When we told the barman that we were working on the Englefield Estate, he just laughed and said, "Yer still on it Mate, and you've only just reached the middle!"

THE weather was incredibly good to us and added greatly to the fun of the project. There was something for everyone: in "Sleepy Hollow," our blacksmith Graham "Butty" Butler heated steel day and night on his forge and then banged it into oversized nails, bands and brackets; Dan Addey-Jibb had his axe swinging as he hewed the octagonal central axle from the round while others took turns making pegs and dowels; John Kropacsy and Gareth Bicknell turned our capstans on their Great Lathe (to which we hooked up a lovely old Fordson Major tractor); Dennis and his team spliced up a storm as they fed mile after mile of rope into the torsion assemblies; and of course there was plenty of traditional framing to go at as well as plenty of VERY BIG framing.

Jon Gourley retreated to the shade of an oak tree where he painstakingly shaped each of the laminated throwing arms to exacting tolerances. Jaime Ward and Sam Turley took charge of shaping the massive timber washers that capped the torsion assemblies, and their teams then spent many hours chiseling out the interior holes through which the rope would be passed to form the springs. Justin Pope and his crew shaped and assembled the slider, table, stock and pedestal frames, and built our lovely capstans as well. Because of the sheer size of the timbers involved, the assembly of each component became a significant frame-raising of its own. There were a few Frisbee moments along the way, but we were generally all too shagged by the end of the day (or night) for much more than beer and sleep. Ten days later (and already 2500 hours into the project) we were ready for the Big Lift.

Original lifting scheme opposed two pairs of braced shear legs over the load and ran lift lines through tackle and snatch blocks out to two remote four-person capstans. Once the main frame of the ballista was in the air, the cribbing it sat on would be removed and the pedestal, seen here ahead of the main frame, would be rolled in on the prepared wooden track, and the frame lowered to it. Failure of an incorrectly manufactered sheave in one of the blocks led to a lockup in the lift, and the job was finished by the mobile crane pictured on the previous page.

Dan Addey-Jibb

Our plan was to use two pairs of 50-ft. timber shear legs, working in tandem and guyed fore and aft with wire rope (no stretch), to lift the ballista onto its pedestal. This would entail a dead lift of about 10 tons, and because we were reluctant to slew the load once it was up in the air, we would roll the pedestal into position beneath the suspended load by means of a track. Two capstan-type windlasses, each running a set of six-fall lifting tackle, with four people (plus one to tail the rope) on each capstan, would provide the lifting power. We first raised a 30-ft. gin pole, then used it to lift the first pair of our shear legs. Once the first set of legs was up, we slid the gin pole gently down one of the rear guys and raised the second set of shear legs with the first. By noon we were ready for the real fun to begin, so we assembled our crew and, under the direction of Steve Lawrence, we began to inch the load up.

With 8½ tons hanging about 10 ft. up in the air, there was a loud *bang!* A shudder ran through all of the gear. After inspecting everything and finding it all to be okay, we inched the load up again slightly, and once more: *bang!* It was only then that we realized there was too much friction developing in one particular snatch block running line out to a windlass, and that the sheave wasn't turning freely. What's more, the shudder that had run through the system had caused the collapse of a sheave in one of our main lifting blocks, so there was no choice but to lock everything off and call in our crane. We transferred the loads to the crane, disengaged the traditional tackle and proceeded with an otherwise smooth lift, rolling the pedestal in as planned to complete the primary assembly.

The failure of our lifting gear presented something of a mystery to us. After all, we had designed our lifts with great care and had been cautious not to exceed the safe working loads of any individual pieces of tackle. We eventually discovered that the nylon sheaves in our blocks, turned especially for our 1-in. manila line, were not quite up to their work. The manufacturer has since replaced them.

IF everything worked according to plan when the ballista was discharged, the energy stored in the pretensioned skeins would almost all be transferred into the stone missile during the brief, rapid swing of the bow arms through their short arcs, leaving very little recoil toward those of us who would be pulling the trigger. This large amount of potential energy was developed in stages.

Four miles of our semi-elastic rope, factory-made from prestretched polyester fibers, was laid out in a field at the site, and then lengthened 10 percent using Turfor hand-winches. Once the loads were released, the rope recovered to very nearly its original length and was coiled in 250-ft. lays for the next phase.

The coils were then wound into the torsion spring cassettes under the load of our windlasses and again stretched about 10 percent in length. Working in two teams of six, we passed the cords back and forth through the assemblies, at each pass threading the rope past the throwing arms, which had been temporarily braced in a neutral position until enough rope had been introduced to hold them snug. End splices were made as each new length of rope was introduced to the cassette, while tension was maintained by sliding hitches fastened back to the oak frames. As much rope was fed into the assemblies as the apertures at the tops and bottoms of the washers would permit, a process that occupied about a dozen of our crew for two and a half days! Once the cassettes were fully loaded and our skeins were complete, they held the throwing arms remarkably tightly. Each cassette now weighed approximately 4½ tons, which helped keep it put during the next phase.

We braced the assemblies to prevent them from rolling and fitted a 16-ft. 10x10 oak beam onto each end of the cassette in turn, attaching the timber to the metal washers like a giant wrench. Using six-fall tackle monitored with a load cell, we then rotated these washers through 180 degrees, adding significantly to the tension of each skein. There was one property of natural sinew we could not replicate with our rope. It's supposed that Roman engineers wound their cassettes with wet sinew, and as this material dried it would become taut, adding considerably to the tension. In order to simulate this effect, we built four 100-ton hydraulic jacks into the bottom of each assembly. When controlled through a regulating manifold, these would enable us to add up to 6 in. of stretch to the final assemblies and, perhaps more important, ensure that both sides of the machine were evenly tensioned. Failure to balance the springs could lead to a misfire. It's recorded that Roman engineers achieved this balance by "plucking" at the sinew, and then "tuning" the skeins to the same pitch via rotation of the washers. This was in the days when artillerymen could presumably hear!

WE test-fired the ballista at 15, 30 and 60 percent of its capacity, by adjusting the distance of pull on the slider and correspondingly the thrust developed by the bow arms. We first moved the crowd of spectators to a distance, made a

The slider, the long channel-shaped box at the center of the machine, has been winched up and the bowstring attached, and now the crew has begun the laborious job of winching down against the vast resistance of the pretensioned skeins. Hand-carved stone ammo in the foreground.

Alan Wilkins

The missile placed, and nearly everyone (including the photographer) having withdrawn to a safe distance, the trigger has been pulled remotely and the missile has launched, guided by the slider. The bow arms travel through a remarkably short arc to accomplish their work.

safety check of the whole machine and designated crews to specific tasks. One crew then used the onboard windlass and tackle to crank the slider uphill until the trigger could be attached to the bowstring. The slider is the central, composite beam, with the trigger assembly mounted at its rear, so the slider must be drawn uphill about 14 ft. in order to make this connection. The trigger was attached to the bowstring and the safety was set to prevent accidental firing.

Reversing the direction of the windlass (but using the same tackle), a crew of six then laboriously winched (or winced, it might be said) the slider back down the stock of the machine, bringing the bowstring with it. The windlass was locked off and a stone missile was placed in the bow. All but two of the crew withdrew to a safe distance at this point. (It was never very difficult convincing people to go.) The trigger line was attached to the trigger pin and then trailed back to safety. A team of eight to ten pulled the trigger, and the missile was released. Only the bowstring and missile move during the actual discharge of the machine, while the slider stays put. The slider is grooved to guide the stone through its initial journey.

Our final shot was made at just 60 percent of the machine's capacity, but threw the 58-lb. missile almost 100 yards (producing some lovely photos for the now ecstatic BBC). We reckoned that with a little practice and a lot of nerve, a team of eight people could probably cycle a ballista through its firing sequence in about 10 to 15 minutes. Our own machine though began to show signs of wear after only three shots, and inspection revealed that the outer stanchions were beginning to fail under the impact of the throwing arms. Although the inner stanchions were protected with a padding of horsehair and leather, the repeated impact of the steel-clad arms was proving too much for the outer ones. We were reminded that Heron states that the length of the bowstring must be adjusted to absorb some shock and keep the arms from striking the outer stanchions. In our case, we decided that additional iron bands would be needed to back up the oak stanchions and prevent them from splitting. With three successful shots and so much beer cooling on ice, it wasn't a difficult decision to call it a day. —GORDON MACDONALD

Gordon Macdonald (gordmac@uk2.net) leads the Carpenter Oak & Woodland Co. Ltd. yard in Scotland. "Building The Impossible" will air in the UK on BBC2 in January 2003 and later in the US. Disassembled, the ballista fits nicely in the bed of a 40-ft. tractor-trailer, and the machine is to be reerected next at a London museum. Steve Lawrence and Alan Wilkins assisted in the preparation of this article, which appears in different form in the current issue (No. 13) of The Mortice and Tenon *(mail@morticeandtenon.org.uk), published in Totnes, Devon.*

Lifting the Ballista or, What Are You Doing Next Week?

ON April 3, I received an e-mail from Gordon Macdonald: "OK, here's the problem: the Ballista weighs 20 tons. We need to lift the machine onto its stand which is 14 ft. high. I'd like to do this by hand." It was a delightful e-mail that I immediately copied and handed out as an engineering class assignment. The lift was to happen on April 25. The challenge was to devise a lifting method using human-scale equipment that Helen Thomas of the BBC would believe and Chris Wise, the engineer, would accept. The first step was to define the problem. What materials would be available, and how much really had to be lifted? The primary consideration was crew safety, with a successful lift next on the list.

Conversation revealed the total weight to be lifted was 10 metric tons or 22,000 lbs.—thankfully not 20 tons or 44,000 lbs! We would use manila or "Handy Hemp" three-strand rope up through 1-in. dia. and appropriate tackle, with a safety factor of 5:1. Sections of log would be ground anchors (deadmen) with a safety factor of 2.5:1 (standard practice in US geotechnical engineering) and softwood utility poles would make shear legs with a safety factor of 5:1.

The approach to the lift suggested by Gordon was to use two sets of shear legs in order to position one set of tackle over each end of the ballista. The tips of the shear legs would be directly over the corresponding lift points on the ballista, allowing the tackle to hang vertically. The tackle would be used with two human-powered capstan windlasses to lift the ballista. When the ballista reached sufficient height, the stand was to be rolled under the machine and the ballista lowered into place.

At least that was the thought. However, as Gordon explains in his article on the previous pages, Mr. Murphy paid us a visit. I'll address that later. At this point, to engineer the lifting system meant sizing the various pieces of the system within their safe working limits, solving each piece one at a time and then putting all the bits back together.

Shear Legs. Shear legs work by carrying the tension in the lifting tackle into the ground as a compressive load. The legs are the only compression pieces in the system. Everything else works in tension. There are two ways the shear legs can fail. Either the wood can crush from being overloaded (not likely), or the leg can buckle like a bow. The buckling 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. Another assumption in the design of the poles is that they are straight. Curvature in the poles would give the buckling process a head start. Our legs did have some small sweep. To minimize the effect, the poles were oriented so that the curvature was in the plane of the A-frame and then collars were bolted across the two poles. The additional support cut the buckling length in half in the plane of the curvature of the poles.

Each set of shear legs consisted of two 45-ft. utility-type poles with 8-in. tip diameters, fastened together at the top. The tip of each set was leaned inward 5 ft. from the base to a position over the pick point and held by a primary back guy wire. A safety guy also ran forward to keep the legs from tipping backwards. The poles were evaluated assuming their minimum tip diameter throughout, neglecting the additional greater diameter at the butt, and, additionally, they were treated as if they were free to wiggle at the top (a conservative assumption).

With the primary guy anchored 75 ft. behind the shear legs, the axial load in each individual leg would be 7500 lbs. The K or buckling factor of 2 was used in the buckling calculations for the legs, as if they were flagpoles unrestrained at the tip. The stresses in the poles were compared with the allowable stress values for No. 1 Southern Yellow Pine. Such stresses are reasonable for a softwood utility pole in good condition. The shear leg poles would be stressed to about 40 percent of their allowable stress under the loading conditions described above. All of the assumptions were conservative, meaning actual stress levels in the poles would be lower.

Rope and Tackle. It was a given that two sets of six-part block and tackle would be used to raise the load. Total load for each set of tackle would be half of the total lift, or 11,000 lbs. With the six-part tackle, theoretical line load would be a sixth, or 1800 lbs. Allowing 5 percent friction loss per sheave in six-part tackle, the line load increases to 2450 lbs.

We intended to use Hempex synthetic manila 24 mm three-strand rope, with a minimum breaking load of 12,600 lbs., giving a safe working load of 2520 lbs. with a safety factor of 5 to 1. We actually used 26 mm rope, giving a safe working load of 2800 lbs. The new three-sheave blocks purchased for the job had a safe working load of 17,500 lbs.

The tension in the back guy was calculated at 3000 lbs. during the lift. The six-part tackle would more than adequately resist the tension. However, stretch was more of a concern than actual breaking strength. As such, it was recommended that the back guy be of wire rope to limit movement of the system.

Capstans. Two capstan windlasses, turnstile operated, were built as the primary sources of pulling power, along the lines that Ed Levin developed for our previous trébuchet-building adventures. With a 9-in. drum and 144-in. arms (ratio 16:1), to generate a total 2500 lbs. of line tension at each capstan required a push of approximately 40 lbs. at the end of each of the four arms of the turnstile. That did not seem an unreasonable amount for a healthy person.

Gordon Macdonald

The author inspects hole dug for one ground anchor. A brace of 10-ft. logs will be lashed together and buried; anchor line will enter to his left.

Foundation considerations. There were two foundation requirements. The first was to prevent the ends of the shear legs from punching into the ground. The other was that sufficiently large ground anchors (deadmen) be provided to resist the tension in the back guys and to restrain the capstans.

I was not given full advance knowledge of the soil types at the site, but I understood that they were generally sand and gravel, well drained. Support of the shear legs then would be a bearing capacity question, with some sort of timber mat under the butt of the pole. A 3-ft.-square mat would yield a contact pressure of about 710 lbs. per sq.ft. A rough assumption of allowable bearing capacity for the expected soil types was in excess of 2500 lbs. per sq. ft. For the actual lift, suitable timber offcuts were buried under the end of the legs.

Similarly, the ground anchors were designed by using passive earth pressure theory. The tension in the back guy tries to pull the anchor mostly sideways and slightly upward through the soil. The farther back the anchor is placed, the better the setup, since the soil has more resistance to sideways than to upward movement of the anchor. Roughly speaking, a 10-ft.-long log buried 3 ft. deep would safely resist a tension of 3000 lbs. A larger log or deeper burial would provide correspondingly higher capacity.

The actual anchors were pairs of 10-ft. logs with wire rope slings choked around them and leading to the ground surface. One of the anchors ended up next to a pond at the site. As the excavation reached a depth of 4 ft., the hole began to fill with water. The saturated soil would substantially reduce the capacity of the soil, hence the addition of the second log.

Gordon Macdonald

What was a pastoral scene, if with a bellicose purpose, in which the actors could hear the creak of a rope and the call of a bird, became, below, a modern industrial scene, with its costs and benefits. Author, at far left below, observes as the crane takes the 8½ tons of ballista from the shear legs.

Dan Addey-Jibb

MURPHY. The lift began well and we were able to raise the complete weight of the ballista with the rigging setup. Load cells included in the system indicated that the actual weight of the lift was 8½ metric tons or 18,700 lbs. All was going well when the sheave collapsed. Let's explore briefly what the consequences of that collapse could have been. The rope had jammed in the block, stopping all progress. The capstan crew on that side kept working to try and move things. Without the 5:1 safety factor in the rope, it could have parted under the additional strain. There would now be no connection between the capstan and the load, allowing the tackle on that side to unreeve, dropping one side of the ballista. The sudden release of load would cause the shear legs on that side to spring backward. If the forward safety guy failed, that set of shear legs would now fall over backward and hit the ground. The total weight of the lift would suddenly shift to the second set of shear legs. If they were not properly sized, the shock load would cause a buckling failure, snapping the poles in half, spraying pieces around the site. The ballista would make rapid contact with the ground from 14 ft. in the air, reducing weeks of work to splinters.

Grigg Mullen

The guilty party.

But since, in our scenario, the legs *are* properly sized, and they do hold, the full weight of the ballista (except for the part now dragging on the ground) hangs from one set of legs and tackle, almost doubling the load in the tackle. The increase is above the safe working load but still well within the failure load of the system. So the extra line load works its way downstream and tries to jerk the capstan turnstile backward. Suddenly the arms of the turnstile are slapping the crew. Injuries result.

Thanks to an alert crew, beautiful work by all involved in the rigging and assorted safety factors, nothing like this scene happened. The load held, nobody was hurt and the project continued. If all had gone as expected, a safety factor of 1.1:1 on the entire system would have been just fine. But all didn't go as expected and 5:1 for new rope seems just barely adequate. —Grigg Mullen Jr.

Col. Mullen is professor of civil engineering at Virginia Military Institute in Lexington. He is on sabbatical this year from VMI, working on special projects for the Timber Framers Guild.

The Graeco-Roman Stone-Throwing Catapult

Erwin Schramm

FIG. 1. USING BODY WEIGHT TO DRAW A STOMACH-BOW.

MACHINES capable of shooting stone missiles too large to be thrown by a sling or human arm were developed in the early 4th century BC during an arms race between the Saddam Husseins of the Greek world. Engineers employed by rulers such as Dionysius of Syracuse improved the performance of conventional war bows by fixing a much-enlarged version of the composite bow of sinew, wood and horn onto a long wooden stock. The missile, a bolt or stone, was launched along a groove on the top of the slider, a beam moving up and down the top of the stock in a sliding dovetail. A metal trigger, mimicking the archer's fingers, caught the bowstring.

The first method of drawing these enlarged bows was by using body weight through stomach pressure (Fig. 1), allowing the operative, depending on his size, to produce a pull on the bowstring of about 65 to 80 kg. As these composite bows became even larger, they required a rear-mounted windlass to draw them. The really dramatic increase in power came with the introduction of torsion catapults ca. 350 BC. Two wooden bow arms were inserted into two skeins of animal sinew rope mounted in a stout frame of hardwood reinforced with iron plates (Fig. 2). The sinew rope was prestretched by windlass around top and bottom iron bars so that it lost one-third of its diameter. The iron bars were mounted in revolving bronze cylinders that allowed the skeins to be twisted, forcing the bow arms forward. This twisting or torsion of the rope "springs" was further increased when the arms were drawn back by the windlass, storing a massive amount of energy in the sinew.

Rapid improvements were made to the design of bolt-shooting and stone-throwing catapults by the engineers of Alexandria and Rhodes, so that by 300 BC catapults were capable of shooting bolts from three span to four cubits in length (69 to 184 cm.), and stone shot from 10 *minae* to three talents weight (4.3 to 78 kg.). However, it must be stressed that throughout Greek and Roman history the three-talent size of stone-thrower is only known to have been used on rare occasions, and usually by a besieging army; few city walls could have accommodated even a half-talent (13 kg.) stone-thrower, and very few the one-talent (26 kg.) machine that we have reconstructed for the BBC.

Why have we reconstructed a one-talent rather than a three-talent size of ballista? Because it was the largest ballista used by the Roman Legions, and because the catapult engineer Philon of Byzantium describes it as "the most violent" stone-thrower, and gives detailed instructions for constructing a triple ditch system around a city to keep this deadly machine sufficiently far away to reduce its impact.

While both bolt-shooters and stone-throwing *ballistae* employed the same principle of power from torsion springs, the difference in weight of the two types of missile was considerable: the bolt for a three-span, the most popular and efficient size of bolt-shooter, weighed about 200g., whereas a stone shot of the grapefruit size commonly found on Roman sites might weigh about 4.5 kg. Therefore, a ballista had to be capable of withstanding far greater stresses. Instead of the bolt-shooter's all-in-one spring-frame (Fig. 2), each rope spring of the ballista was given a separate, hefty frame of strong timber (Fig. 3). The pair of frames was clamped in place by substantial top and bottom wooden yoke assemblies. Heron of Alexandria goes into great detail about the need to strengthen all critical points of the ballista with iron plates that must be applied to the sides of the stanchions of the spring-frames, the outside of the top and bottom spring-frame components, and even to the tenons of the stanchions inserted into mortises in the hole-carriers.

The sizes of the components of all catapults were calculated in diameters of the rope skein (or spring-hole). The Greek engineers devised the following formula for calculating this diameter based on the weight of shot the catapult was intended to throw:

$$D = 1.1 \sqrt[3]{(100\,M)}$$

where D = the diameter of the rope skein in dactyls (1 dactyl = 19.3 mm.) and M = the weight of the proposed stone shot in Attic *minae* (1 *mina* = 436.6 g.).

The impressive precision of the ballista design, worked out to cope with the variety of immense stresses involved, is amply proved by this use of a decimal point and a cube root, the first known appearance of a third-degree equation in the history of mathematics.

The evidence for a reconstruction. The chance survival of manuscript copies of Greek and Roman books on artillery construction, mostly written by professional engineers, means that we are better informed about this branch of ancient applied technology than any other. Vitruvius, the famous Roman architect-engineer, was appointed by Emperor Augustus as one of four officials in charge of manufacturing and repairing the catapults of the Roman army. His description of a stone-throwing ballista must represent the official version of the machine in use in the early Roman Empire. It is therefore the basis for our reconstruction of a one-talent machine as used by the Romans at the siege of Jerusalem in AD 70. Why choose the siege of Jerusalem? Because a graphic eyewitness description of the sight, sound and impact of the One-talent shot is given by the Jewish general Josephus in his *History of the Jewish Wars*. He had been on the receiving end of these missiles at the siege of Jotapata in AD 69, and watched the siege of Jerusalem from the Roman lines, praising the catapults built by the Tenth Legion as the most effective.

Unfortunately, Vitruvius's diagrams have not survived, and his text has suffered in transmission by hand-copying over the centuries. His Latin is often terse, and some of his numerals for the sizes of parts have been corrupted, partly because they are in Greek symbols that not all copyists would have understood. Luckily an earlier Greek version of the ballista is described in detail by the specialist catapult engineer Philon of Byzantium; his diagrams have also disappeared, but he writes in clear Greek, and many of his dimensions are written out as words. A third professional engineer, Heron of Alexandria, writing about the time of the siege of Jerusalem, provides no dimensions, but his diagrams have survived (one is shown on page 11), and he gives extremely valuable advice on constructing, arming and operating the ballista.

Several archaeological finds of parts from bolt-shooting catapults have been identified, including the complete iron plating of a spring-frame found in Spain in 1983. This matches up closely with Vitruvius's description and is the basis for my design of the machine shown in Fig. 2. No finds from Vitruvian stone-throwers have been identified, only a few parts from a different, later design found at Hatra in Iraq. Gordon Macdonald's article includes a photo of one of the Hatra bronze cylinders (page 11), similar to those used on Vitruvian catapults. The fragments of wood from the Hatra spring-frame have been identified as from the Caucasian Wingnut tree *Pterocarya fraxinifolia*, a hardwood of the walnut family, now found from Iran to the Ukraine. Undoubtedly, legionary engineers would have used whatever hardwoods were to hand, usually oak or ash.

The BBC Ballista. Previous replicas of this complex machine have been based on the impressive pioneering version by the great German experimental archaeologist Erwin Schramm. His small model was 2.6 m. long and 1.3 m. high and shot a 1 lb. (.45 kg.) lead ball over 300 m. and a 1.5-*mina* (.65 kg.) stone 184 m. Some revisions to Schramm's interpretation were suggested by Dr. Eric Marsden, who was rightly suspicious about the accuracy of the Latin version of Vitruvius's text used by Schramm. When the BBC contacted me in 2001, I had already completed an updated interpretation of the ballista with scale drawings, based on a thorough revision of the Latin text (which revealed that Schramm had indeed decided to change one-third of the dimensions found in the ms). But I had not had time to build a sizeable model, as Philon suggests, in order to discover the many problems that lay ahead. We had to go from zero to the colossal version untested.

Alan Wilkins

Fig. 2. Reconstruction of Vitruvius's bolt-shooter at three-span size. Designed by the author and built by Len Morgan.

Alan Wilkins

Fig. 3. The left-hand spring frame of the BBC Ballista.

The apparent impossibility of the BBC's challenge to build a one-talent ballista is summed up by the weight of a one-talent stone: 26.2 kg, 57 lbs., half a hundredweight. Indeed the German authority on ancient artillery, Professor Dietwulf Baatz, advised the BBC that it was impossible. The BBC employed one of the finest teams of chippies and riggers ever assembled, and experts in various fields. It was a great privilege to work with them. Did we succeed? Read Gordon's and Grigg's fascinating accounts, and watch the program.

—Alan Wilkins

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Helving a Broadaxe

The maker of the axe large and small, and the welder and temperer,
The chooser breathing his breath on the cold steel and trying
the edge with his thumb,
The one who clean-shapes the handle and sets it firmly in the socket.

The Song of the Broad-Axe
Walt Whitman

I WANTED a broadaxe in the event that I ever got around to framing the cruck building I've been dreaming about since attending Jack Sobon's one-day course on cruck framing at the '99 Lake Morey conference in Vermont. So I logged onto ebay, the online auction house, and ended up high bidder on a New England-style axe with a 6-in. laminated steel edge. It was a good bargain because the handle was fitted for a left-hander in a world in which I am (for once) in the broad majority. A year later, I spent considerably more for an 8-in. Underhill Edge Tool Co. broadaxe (pre-1890) without a handle but in near mint condition. At this point, both needed handles, since my attempts at trying to carve comfortable handles for the smaller axe out of dry, curved Pacific Madrone branches had proved less than successful. I wanted something with more offset. I did the sensible thing and called an expert.

Timber framer and hewer Dave Dauerty of Constantia, New York, uses a half-dozen broadaxes of varying sizes and ages and has had to replace several handles over time. He rips pieces of northern ash into 1/8-in. strips, then applies glue and clamps them to shape in a form. The technique represents an alternative to traditional steam-bending in the solid, which gets problematic as the curves get shorter. Laminating has also passed the test of time: one of Dave's broadaxe handles has survived seven years of heavy use. Dave, who describes himself as "fair game as a forklift" because of his 6-ft. 6-in. height and 300-lb. heft, has also shaped handles from curved branches he spots on trees while driving down the road. But he prefers to laminate his handles since he can get the precise shape he wants. His forming template allows him to shape what Eric Sloane (in *A Museum of Early American Tools*) calls a "swayed handle," a kind of flattened S-curve that bends tightly away as it exits the handle, and then comes back to relatively straight for the remaining length. Dave believes this to be the perfect shape. It immediately offsets the knuckles of the front hand (the one closest to the axe-head), safely away from the face of the timber to be hewn.

What follows is my version of Dave's method of broadaxe handle fabrication. The method would work equally well for a single-bend handle. I've added a couple of steps and variations based on my own study of handle shapes and my experience in shaping them.

Ripping and Forming. On a table saw with a sharp blade, rip some seasoned and four-sided 8/4-thick white ash to a width slightly greater than the length of the eye of your broadaxe. (Both of my broadaxes show 2½ in.). Then raise the height of the sawblade, turn the stock on edge and rip it into ⅛-in. strips. This work is potentially dangerous, and you will be working close to the blade, so I recommend using two people and stock in 6-ft. lengths to reduce the possibility of mishap. It's safest to saw the strips on the side of the blade away from the fence, moving the fence over ⅛ in. for each new cut. The 6 ft. x 2½-in. x ⅛-in. strips can be crosscut later to get the 3-ft. lengths you will need for the handle.

If the strips are cleanly sawn, they should be smooth enough for gluing. You will need five or six laminae 3 ft. long, depending on whether you want a handle thickness ⅝ to ¾ in. or ⅞ to 1 in. The four or five lines of Gorilla glue (or some equivalent waterproof, gap-filling glue) will contribute a strong ⅛ in. to the total thickness. If you are in doubt about thickness, use all six laminae. You can always remove stock later.

Janice Wormington

Dave Dauerty hewing oak with double-bend handled broadaxe at the first Trébuchet rendezvous, Lexington, Va., 1997. Axe head has single bevel; flat side is toward the work. Steel on wet oak yields blue-black stain.

Make a 2-ft. and a 3-ft. length of some stock whose width is equal to the length of the axe eye (at 2½ in., a 2x3 worked in my case), and screw them together on the flat to be flush at one end and offset 12 in. at the other. Then toe-screw them on edge and square to the work surface, making sure the screws are countersunk out of the way. Have a 2-ft. piece and a 1-ft. piece of 1x3 clamping block material ready. Soften the outside corner of the shorter 2x3 screwed down to the table and one corner of the 1- ft. clamping block. These rounded corners will be the pressure points bearing directly on the insides of the curves as the handle is bent to shape, and they should not present sharp corners to the material. (See illustrations overleaf.)

Clamping. Now you're ready for the dry run, which in this case is actually a wet run. Boil some water in a kettle. Put the strips in the form and clamp the strips to the 1-ft. section, positioning the loose 1x3 clamping block so the radiused edge will be against the handle at the point of the bend. The radiused ends of the clamping blocks

Eighth-in. ash strips sawn out of 8/4 stock 2½ in. wide and set on edge.

Doug Eaton

Wet run with boiling water (but no glue) bends the laminae to shape.

should be separated by about 1½ in. Clamp the 1-ft. section of handle tightly into the corresponding 1-ft. section of the form. Although you will only use 4 or 5 in. of this section to go into the axe eye, the extra length gives you more clamping surface.

Pour boiling water on the part of the handle to be bent. The heat and moisture will soften the fibers. Clamp the 2-ft. section of the handle loosely to the corresponding 2-ft. section of the form using the 2-ft. clamping block. Pour more boiling water on the handle at the bends. Retighten the clamps closest to the bends, then the ones further away, and repeat until you've gradually got the bends you want and the clamps are as tight as you can get them. It's best, however, to take your time and allow the wood to bend gradually. The laminae must slide over one another and the fibers within each lamina must also shift and realign if nothing is to break. At the end, you should be tightening the clamps closest to the bends to get the latter as tight as possible. The length of the double-curving section of handle should be 3 to 3½ in. between the points where it straightens out in each of the two sections. It's possible you will get some break-out of the grain opposite the pressure points, but that will likely be shallow and can be remedied later.

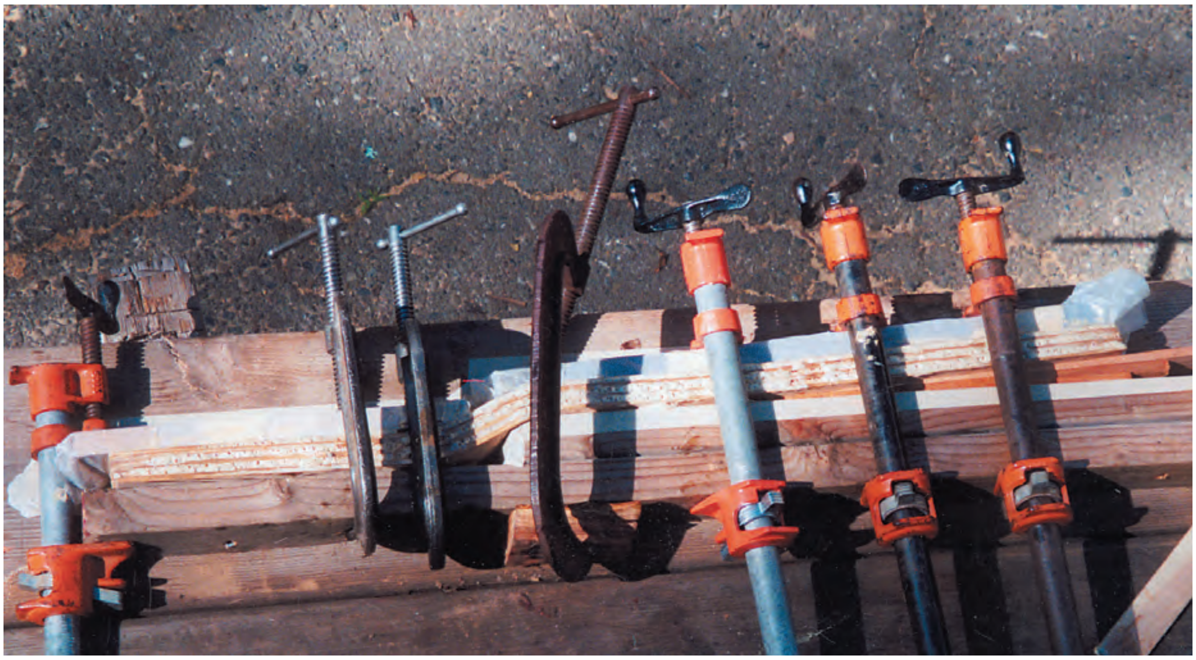
Leave the wet handle in the form overnight. This impresses memory in the wood and makes clamping less troublesome during the glue-up. Release the wood from the clamps the following day and, keeping the laminae in the order they were clamped, on edge, separate them and let them dry out a bit. If you are using Gorilla or another polyurethane glue, it's not desirable to let the wood completely dry, since such glue needs moisture to cure. For other types of glue, observe the maker's requirements for dryness.

Gluing. Use masking tape to attach wax paper to all surfaces that will come in contact with the handle during gluing, including those of the wedge (or up to four 2½-in. wide shingles) to be used in the final clamping to offset the end of the 2-ft. section of handle an extra ¾ to 1½ in. This offset will protect the rear hand from having its knuckles barked on the timber while hewing. (Dauerty doesn't do this to his handles. He hews right-handed but with the log to his right. See photo in TF 44, p. 17.)

Wear disposable rubber gloves for gluing. Setting the bent strips on edge and in order, spread glue over the near side of each lamina except the last, making sure you have reasonably thin, even coverage. Do not apply glue to the far side of the first strip or the near side of the last, because those surfaces will be the outsides of the handle. Also, do not put glue on the last 4 to 6 in. of the 1-ft. axe-head section, since this material will be cut off later. At this stage they provide a place to grip each lamina without getting glue on your hands.

With the glue dispensed, place the reassembled laminae in the form and follow the clamping procedure as before, with the additional step of placing the solid (or bundled two-to-four shim) wedge against the 2-ft. section of the form in order to offset the rear end of the handle. You've got about 20 minutes to complete the process before the glue begins to cure, so work efficiently.

Polyurethane glue will bubble up for the first hour or so, and it doesn't hurt to remove it. But don't move the clamps once they are fully tightened. The instructions for most glues say clamping time is one to four hours, with full curing time 24 hours, but I recommend leaving the handle clamped in the form overnight for maximum strength.



Lamination of pre-bent strips using polyurethane glue, which bubbles up from the joints as it cures. Group of shingles fitted between form and handle blank will add further clearance to the handle for the hewer's left (or rear) hand. Waxed paper on clamping pads prevents unwanted glue bonds. Large C-clamp in the center has lately been retired with a disability pension. Bottom left, faint smile is drawn on blank to yield customary sweep of finished handle. Bottom right, one handle shows pronounced sweep while the other appears nearly straight. Sweep helps keep rear hand of hewer clear of work.

Shaping and Fitting. Handle shape is a matter of personal taste. After removing the handle from the form, scrape off the wax paper and excess glue with a hook scraper. Figure out what section you want to make the handle. Based on the steam-bent, left-handed oak handle that I removed from my smaller broadaxe, and which appeared to be original to the axe, a traditional broadaxe handle section is an oval approximately ⅞ by 1¾ in. That size fits me well, but I found the oval of the old handle a little more pointed than I liked, so I rounded mine more. Dauerty also likes a more rounded oval because, he says, "It doesn't tend to bruise the web of my palm when I'm really pounding for long periods." (Despite the offset handles, note that a certain amount of barking of the knuckles is inevitable while hewing, so it's often done with gloved hands, a factor that could affect the section of handle you want.)

Supposing you intend a handle 1⅞ in. deep, set a pair of dividers at 2 in. and scribe a pair of lines on the side of the handle. Start high at the grip end, drop gradually down to the bottom about two-thirds of the way along and then proceed back up high at the point where the bottom of the axe head will be fixed. In other words, assuming the bit or cutting edge pointing down, draw a faint smile on the side of the handle as shown below. (The old left-handed oak handle I removed had this shape, as do the handles of the broadaxes in the catalogue of Swedish manufacturer Gransfors Bruks.) Draw the same lines on the reverse side and rough out the handle to these lines, using a bandsaw or whatever tools are to hand. Leave the handle a little larger than you think you will want it.

With scissors and cardboard, fashion a template that duplicates the shape of the axe-eye. (On both of my axes the eye is teardrop-shaped.) When you get an accurate template, trace it on a short block of 1-in. softwood and cut out the hole to give you a slightly oversized wood template that you can use to test-fit the handle as you work. Measure how much handle length will be needed to go through and extend a little beyond the end of the axe eye, then cut off the excess from the 1-ft. section of the handle. Take the cardboard template and trace it on the end of the handle, rotating it slightly out of plumb toward the flat edge of the single-beveled bit. The aim is to have the blade skewed slightly toward the work, which provides yet a little more offset to protect the knuckles.

Lay out the lines on the side of the axe head part of the handle so that they slope slightly also. (The slope is consistent with the overall smile of the handle.) The objective is to open up the angle of a bisecting line of the flat side of the axe and an imaginary straight line that runs the length of the handle. Rather than 90 degrees, you would like to make this angle more like 95 degrees, plus or minus. This further raises the rear hand up and away from the timber being hewn. (Note centerline drawn on axe head in photo above right.)

Photos Doug Eaton

Above, axe head should hang such that its centerline, visible in the photo, falls at about 95 degrees to the centerline of the handle (not drawn). At right, all clamps and paraphernalia removed, the handle blank is bent, glued up and ready for shaping and fitting to head. Unglued portion (at bottom of photo), a convenience and a means of leverage during bending, will be trimmed off. At bottom right, the finished handle posed against the jig.

A fine-toothed Japanese rip saw makes short work of rough-shaping the axe head end of the handle. I use a rasp and a file to finish the shape. Use the wood template to check periodically. When that finally slides on, use the axe head itself as the template.

In length, broadaxe handles vary from 12 in. to 30 in. or more from the point where they leave the axe head. More common lengths are 18 to 21 in. The longer handles, generally straight, are probably meant for axes used to hew railroad ties on the ground. Ordinary length handles usually come with smiles to keep your back hand above the timber while you stand beside the raised log and hew with the bit at the various angles to the grain the work might call for.

Wedging. Wedging will provide you the last opportunity to adjust the hang of the axe head on the handle. Broadaxes, like adzes, are not center wedged like felling axes and hatchets. They are wedged between the handle and the walls of the axe eye. To adjust the hang of the axe head slightly in one direction or the other, remove wood on one side of the handle and wedge the opposite side. Wedges should be of hardwood. With the handle firmly wedged, now you can go out and use the tool, reshaping the handle as necessary so that it feels completely comfortable in use.

I've hewed a couple of logs with my smaller broadaxe and very much liked the feel of the handle. But, within certain limits, shape and style of broadaxe handles, like those of any tool handle, are matters of personal preference—as is any particular method of fabrication. Dave Dauerty, who reviewed this text, warned me to brace myself for "vehement rebuttal from everyone who has ever swung an axe." That's fine with me. Maybe someone out there has a better way.

—Doug Eaton

Doug Eaton (jndpe@pacbell.net) is a contractor in Oakland, California, and a frequent contributor to this journal.

LATERALLY LOADED TIMBER FRAMES

IV. SIP Connection Behavior

This article is fourth in a series to discuss the results of research conducted at the University of Wyoming on the behavior of sheathed and unsheathed timber frames subjected to an applied lateral load. Primary funding for this research was provided by the US Department of Agriculture National Research Initiative Competitive Grants Program, with additional support from the Timber Frame Business Council, the Timber Framers Guild and individual timber framing companies who contributed the test frames and structural insulated panels (SIPs). A final article will review modeling of unsheathed and sheathed frames.

INTRODUCTION. The lateral stiffness and strength of a timber frame structure sheathed with SIPs are dependent on the characteristics of the panel-to-frame mechanical connection. The first objective of this portion of the research was to develop load-slip models that represented the SIP-to-timber interface when subjected to lateral load. The second objective was to compare statistically the effects of variation in connection details.

Test Specimens. Four-in.-wide SIP specimens were cut from panels of either 4-in. or 6-in. nominal thickness. SIP specimen length varied, but the distance from fastener to end of panel was a minimum of 2 in. or ten times the fastener diameter (10D) for all tests. Timber specimens were of Douglas fir, white oak and Eastern white pine. All timber sections were 3½ inches wide but of varying lengths and thicknesses. All specimens had sufficient thickness such that no fastener fully penetrated through the timber and, in all instances, the fastener was at least 2 in. from the end of the timber for a minimum end distance of 10D. The connections were made with either a 0.190-in.-dia. screw or a 0.180-in.-dia. ring shank nail. All fasteners were imbedded 1½ in. (or 8D) into the timber. The National Design Specification (NDS) recommends a screw penetration of 12D; however, it is common timber framing practice to use screws 1½ inches longer than the SIP thickness. All screws had 2 in. of threaded length, thus threads were included in the shear plane at the inner skin of the SIP panel. Similarly, the nail shank had annular rings along 3 in. of length, thus the shear plane at the inner skin of the nail-connected panel included the rings.

As shown in Fig. 1, load was applied in line with the panel-to-timber interface to eliminate any moment due to eccentric loading, and thus lateral restraint of the specimen was not provided. This method of load application is based on the assumption that the inner skin of a SIP carries all of the shear actions. This is a conservative assumption in that a small amount of load may be transferred to the outer skin via the cantilever action of the fastener. The testing was performed on a universal testing machine (Fig. 2). The samples were displaced at a rate of approximately 0.03 in. per minute.

Experimental Groups. Experimental testing was performed on 14 groups of specimens. The groups are designated by names of six to eight characters. The first letter indicates the fastener type: "s" for screw or "n" for nail. The last two letters indicate the timber species: "df" for Douglas fir, "wo" for white oak, and "wp" for Eastern white pine. The intermediate letters typically indicate the test that was considered to be the control group or otherwise describe a unique characteristic of the group.

Phase 1. The first phase of testing was performed on four distinct sample groups. Each group had ten connection specimens. All phase 1 test specimens consisted of a 4-in. SIP screw-connected to a white oak timber. A 5/32-in. pilot hole was drilled in each of the timber specimens, and load was applied parallel to the grain of the timber.

A summary of the variables of phase 1 is shown in Table 1. Group *sbasewo* was considered the base test group and had no washer or shim installed, and the panel was predrilled with a 5/32 drill bit. Group *swashwo* was identical to group *sbasewo* except that a 2-in. dia. washer was installed at the screw head. Group *sshimwo* included a 5/8-in. OSB shim installed between the panel and the timber. (Shims are sometimes used by panel installers to make space for later insertion of interior wall finish between the frame and the panel.) The shim was not mechanically fixed to either the panel or the timber. Group *snpdwo* was also identical to the base test, but the SIP panel was not predrilled.

Phase 2. The second phase of testing was performed on six distinct sample groups, and each group had ten connection specimens. As shown in Table 2, several variables were examined in phase 2. The combination of tests provided for comparison between a timber species of moderate specific gravity (Douglas fir) and one of low specific gravity (Eastern white pine). Both screws and nails were tested in each species but no shims or washers were used in phase 2. Load was applied both parallel and perpendicular to timber grain for the Douglas fir screw-connected specimens. For the group *sdfosb*, the outer OSB skin and the inner foam core were removed from the panel in order to examine the contribution of these elements.

Phase 3. The third phase of testing was performed on four distinct sample groups of varying size. All specimens consisted of panels screw-connected to a Douglas fir timber. The group titled *slongdf* was identical to group *sbasedf* in phase 2. Group sshortdf consisted of a countersunk 2-in. screw bearing directly on the inner skin of the panel. The *swaxdf* group had three sheets of wax paper applied between the panel and timber in order to reduce any contribution of friction on connection stiffness. The *sthickdf* group was again identical to both the *slongdf* group of phase 2 and the sbasedf group of phase 3, except that the panel was 2 in. thicker with a correspondingly longer fastener. Neither washers nor shims were used in phase 3.

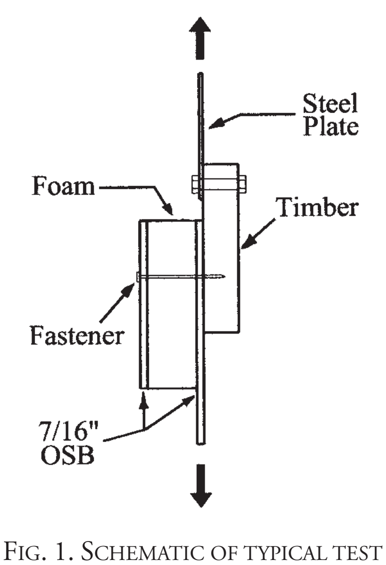


FIG. 1. SCHEMATIC OF TYPICAL TEST SET-UP.

Rob Erikson

FIG. 2. TEST SETUP.

Test Name	SIP predrill	Washer	Shim
sbasewo	yes	No	No
swashwo	yes	Yes	No
sshimwo	yes	No	Yes
snpdwo	no	No	No

TABLE 1. PHASE 1 SUMMARY OF TESTS.

RESULTS. In order to quantify and compare the results, a regression analysis was performed on the experimental data set for each specimen. (For an explanation of regression analysis, see www.nlreg.com/intro.htm.) The regression was performed on the natural log of deflection versus load. The equation has the form

$$P = a\ln\delta + b$$

where P is the applied load, δ is the fastener slip, a is the slope of the curve and b is the intercept. At a displacement of zero, the slope of this curve is undefined, therefore all data for a load less than approximately 50 lbs. was disregarded in the analysis.

The results of the regression were then used to define each dataset with an equation of the form

$$P = (A+B\delta)[1\text{-e}^{(-C\delta/A)}]$$

Test Name	Fastener	Timber species	SIP thickness	Timber Grain Orientation
sbasedf	Screw	DF	4 ½"	Parallel
nbasedf	Nail	DF	4 ½"	Parallel
sbasewp	Screw	EWP	4 ½"	Parallel
nbasewp	Nail	EWP	4 ½"	Parallel
s90df	Screw	DF	4 ½"	Perpendicular
sdfosb	Screw	DF	½"	Parallel

TABLE 2. PHASE 2 SUMMARY OF TESTS.

Test Name	Number of Tests	Screw length	SIP thickness	Timber Grain Orientation
slongdf	10	6"	4 ½"	Parallel
sshortdf	10	2"	4 ½"	Parallel
swaxdf	12	6"	4 ½"	Parallel
sthickdf	11	8"	6 ½"	Parallel

TABLE 3. PHASE 3 SUMMARY OF TESTS.

where P is the applied load, δ is the fastener slip, C is the initial slope of the curve, B is the final slope of the curve and A is the point at which a line drawn tangent to the final slope intercepts the load axis. This equation is graphically demonstrated in Fig. 4 .

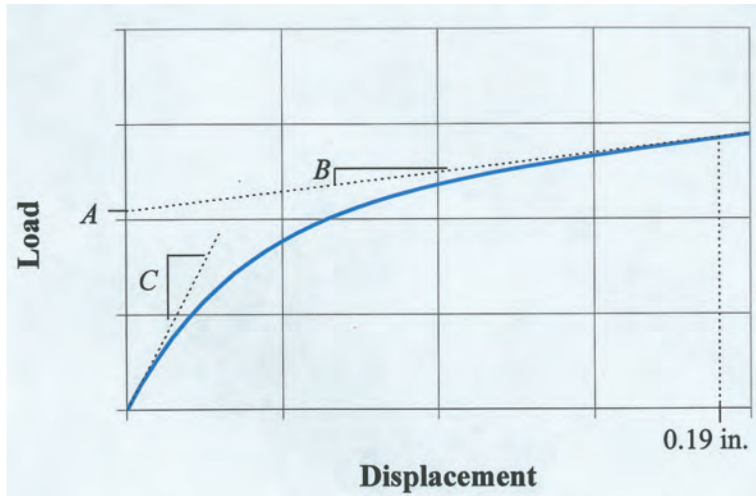


FIGURE 4. GRAPHICAL DEFINITION OF COEFFICIENTS FOR $P = (A+B\delta)[1\text{-e}^{(-C\delta/A)}]$.

The initial slope coefficient C was determined based on a linear regression of δ versus P over the range of P greater than 25 percent and less than 50 percent of design load for a given connection. Tangent slope coefficient B was determined based on the slope of the natural logarithm regression $P = a\ln\delta + b$ at a displacement of 0.19 in. (approximate fastener dia.). The intercept A was then derived by extrapolating the tangent line determined by B to the vertical axis. Graphical results of a typical group are shown in Figure 5.

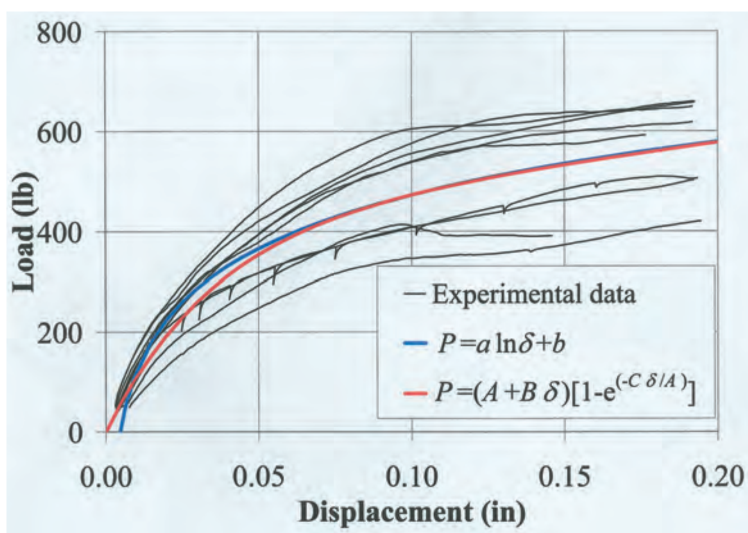


FIGURE 5. TYPICAL EXPERIMENTAL DATA AND FITTED CURVES.

Determination of a yield value is highly subjective. The 5-percent offset method is often used, but this approach results in a yield load that is dependent on the initial stiffness. In order to establish an independent analysis of the yield value for statistical comparison between specimen groups, yield load was determined simply by finding the load at a deflection of 0.95 in. (one-half of the screw diameter). Since the results of this experiment are used for comparative purposes, the yield load of nail-connected specimens is also based on 0.95 in. (rather than half of the nail diameter or 0.90 in.).

Regression Coefficients and Yield Load. The regression coefficients and yield value of each test were averaged to provide a single regression equation for each group. The mean values for all test groups are shown in Table 4.

Test Name	$P=a\ln(\delta)+b$			$P=(A+B\delta)[1-e^{(-C\delta/A)}]$			$F_{D/2}$
	a	b	R^2	A	B	C	
sbasewo	150	905	0.98	507	787	19822	564
swashwo	162	956	0.99	525	852	17993	583
sshimwo	155	706	0.99	301	796	6686	341
snpdwo	132	783	0.99	431	696	15796	472
sbasedf	153	825	0.98	418	807	12381	480
nbasedf	187	871	0.97	373	984	7582	430
sbasewp	146	783	0.98	395	767	12204	452
nbasewp	173	844	0.98	384	909	9161	440
sperpdf	137	737	0.99	372	723	10373	419
sosbdf	117	608	0.99	296	618	7040	341
slongdf	149	824	0.97	429	782	16363	470
sshortdf	167	902	0.94	458	878	21739	501
swaxdf	180	828	0.94	467	686	9174	398
sthickdf	153	713	0.95	306	806	7585	346

TABLE 4. REGRESSION COEFFICIENTS AND YIELD LOAD.

Statistical Comparisons. The statistical comparisons have been limited to two critical variables: the initial connection stiffness C and the yield load $F_{D/2}$ defined as the resisting force at a displacement of one-half of the fastener diameter (0.95 inches). The statistical analysis was limited to comparisons within each phase. One of the groups within each phase was identified as the base specimen set and the remaining groups were compared to the base group.

Phase 1. The test group *sbasewo* was considered the base group. The three variables examined included the addition of a washer at the screw head, the use of a shim between the SIP and the timber, and the omission of predrilling the SIP panel. Based on differences in both initial slope and yield load, the use of a shim and omission of SIP predrilling significantly reduced both connection stiffness and yield strength. The addition of a washer did not significantly affect connection performance.

Phase 2. The test group *sbasedf* was considered the base group. The variables examined included comparison between Douglas fir and Eastern white pine, nail versus screw fastener, removal of the outer portion of the SIP and loading perpendicular to the timber grain. Removal of the outer sheet of OSB and the foam core significantly reduced both connection stiffness and yield strength. Neither timber species nor type of fastener had a significant effect on connection performance, with one exception: the nailed Douglas fir connection had a significantly lower initial stiffness. Although the rigorous statistical analysis did not indicate a significant difference in initial stiffness of the Eastern white pine specimen, a review of the mean values for the pine specimens indicates the likelihood of some actual difference. The screw-connected pine sample had a mean initial stiffness of 12,204 lbs. per in. while the nail-connected one had an initial stiffness of 9161 lbs. per in.—a reduction of nearly 25 percent. Base samples loaded parallel to the grain showed no significant difference from those loaded perpendicular to the grain.

Phase 3. The test group *slongdf* was considered the base group. The parameters of this group were identical to those of phase 2 group *sbasedf.* The intermediate designation *long* merely indicates that the primary objective of this phase was to investigate the potential advantage of using a short screw countersunk such that the head bears on the interior OSB sheet. In addition to investigating the short screw, this phase also included a sample group *(swaxdf)* with several sheets of waxed paper between the panel and timber, and a sample group *(sthickdf)* using 6-in. nominal SIP specimens rather than the 4-in. SIPs all other groups used. The addition of a low-friction waxed paper interface significantly reduced connection properties, and the group with 6-in. SIP panels also had significantly reduced properties. The use of a countersunk screw did not affect connection properties.

Ultimate and Design Load. Failure of the joint was typically exhibited by plowing of the screw shank through the OSB skin, along with bending of the screw. This failure mechanism is Mode III_S as shown in Appendix I of the 2001 NDS, and the equation for nominal design load Z is provided in NDS section 11.3. A summary of design and ultimate loads is shown in Table 5.

TABLE 5. DESIGN LOAD AND ULTIMATE LOAD.

Test Name	Z (lb)	P_{ult} (lb)
sbasewo	158	697
swashwo	158	760
sshimwo	*	603
snpdwo	158	706
sbasedf	144	587
nbasedf	111	633
sbasewp	121	564
nbasewp	106	591
sperpdf	144	517
sosbdf	144	414
slongdf	144	589
sshortdf	144	689
swaxdf	144	622
sthickdf	144	553

*No design value is provided for the shimmed connection

SUMMARY. Comparison of the various connection parameters indicates that the addition of a shim between the SIP and timber will significantly reduce connection strength and stiffness. If a shim is used in construction, it should be mechanically fastened to the timbers at regular intervals, and the strength and stiffness characteristics of the shim-to-frame interface must also be considered in the overall design. Connection properties are also dependent on the thickness of the SIP panel. The results indicate that the outer skin contributes to both stiffness and strength, and a connection with a thicker panel has reduced properties. The connection that used a 2-in. screw countersunk through the SIP panel to bear on the inner skin did not have improved strength or stiffness. Given this result and the inherent practical difficulty in applying this technique, countersinking should not be considered an alternative construction method. Timber orientation had no effect on connection properties and can be ignored. Friction between the panel and timber increases both strength and stiffness.

The regression equations for load slip can be directly imported into a two-dimensional modeling program to predict nonlinear lateral load behavior of a sheathed timber frame. Although the connection properties due to timber species and fastener type may not always be statistically different, the model should include average values of these parameters. —ROB ERIKSON and DICK SCHMIDT

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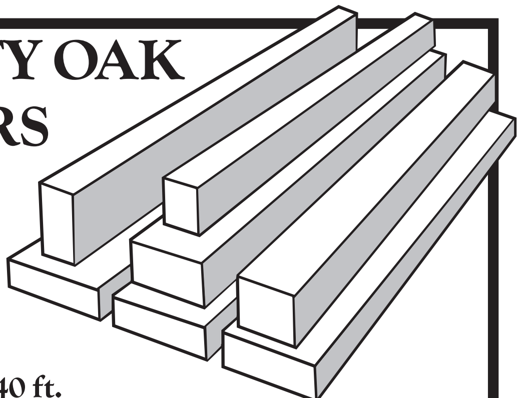

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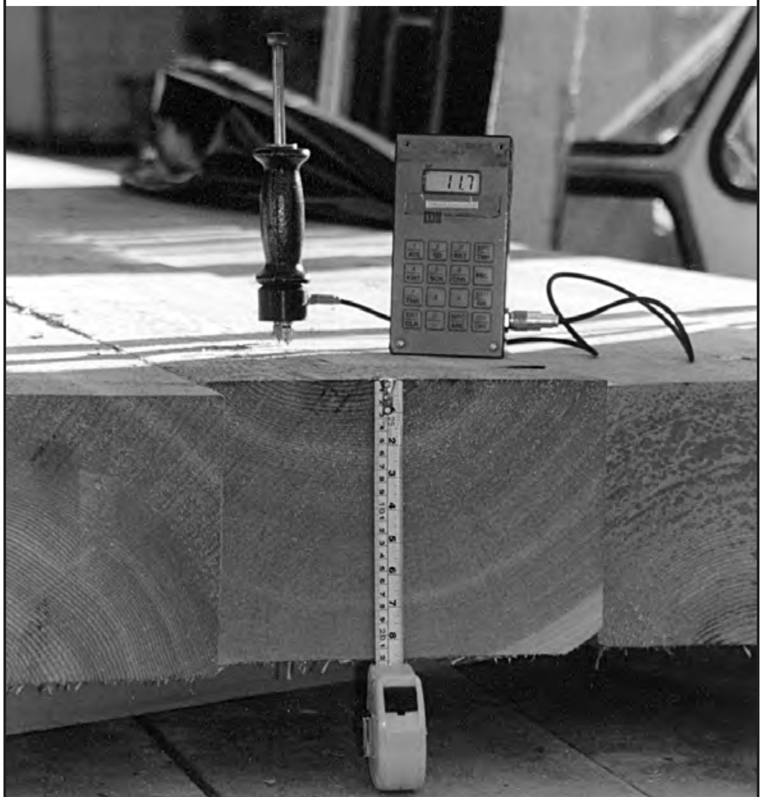

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THE pavilion in the Korean ambassador's garden in Washington, D.C., designed and built by Peter Wechsler of Daiku Woodworking, Boonsboro, Md. Framing and trim material is Port Orford cedar excluding the round fan rafters of Eastern white cedar. The ceiling is lined with woven willow fencing, the curved roof covered with Western red cedar shakes. The posts are supported beneath the deck by cylindrical steel bases bolted to the foundation. In the lower photo, the apparently empty bay in the ceiling when seen from below is a consequence of the correct rafter spacing at the eave when the eave is seen from the outside (upper photo), the controlling design consideration. Story page 4.