



A Multidisciplinary Re-evaluation of the Fabrication and Operation of the 4th Century CE Roman Artillery Engine known as the Onager

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Introduction

Multidisciplinary projects provide unique opportunities to foster critical thinking in undergraduate engineering students and to allow them the opportunity to determine and use applicable engineering analysis methods. In addition, multidisciplinary projects which combine engineering analysis and a study of technological history are an interesting way to increase student interest in the engineering design process.

To motivate and reinforce the targeted engineering skill sets/learning outcomes of critical thinking and the ability to determine and apply applicable engineering analysis techniques at the University of X, a small engineering school in the south, a multi-disciplinary student project, called the “Onager Project”, was developed. For this interdisciplinary project a team of three undergraduate mechanical engineering seniors investigated the extant historical technical information concerning the 4th Century CE Roman siege weapon known as the Onager and then determined and applied appropriate modern engineering analysis, design, and testing methods to recreate an Onager design that satisfied the constraints documented or implied by the historical documents. The procedure has become known as experimental archeology, since an attempt is made to actually reconstruct historical artillery about which very little is known. The students then fabricated and fully tested their Onager design.

In this paper, the authors present a detailed case study of the interdisciplinary Onager project that mirrors the interwoven historical and engineering pathways that the student team had to traverse to produce their final Onager design and fabrication. Through a detailed description of this interwoven engineering and history-based project the authors hope to illustrate the critical thinking skills and appropriate engineering analysis and testing methods that the student team were required to identify and use in order 1) to determine the historical-based technical ‘constraints’ of what the Onager did and looked like, 2) to determine the applicable engineering analysis techniques, 3) to fill, through application of their engineering analysis, the critical gaps between the scant historical information and the engineering constraints, indicated through their analysis, to create an Onager design, and 4) to then to fabricate and test their design to determine if it did, indeed, satisfy both the historical and engineering constraints. The process the students followed was not linear, but required a back-and-forth interweaving between historical records and appropriate engineering analysis. Therefore, the authors’ description of the project and of the skill sets used by the students within the project follows that same interwoven pathway. The authors also include the Onager project description at length to inform and guide engineering faculty who are particularly interested in developing similar types of historically-based engineering course projects. The authors also include in the paper a discussion of their assessment of the project with respect to the targeted skill sets and of their plans for future work.

The Onager Project

The students found that the historical information referencing the Onager is rather sparse. Little is known about this machine despite its supposed frequent appearance at sieges during the late

Roman Empire. One armed throwing machines are mentioned as early as 3rd century BCE by Philon, and again by Emperor Trajan's famous engineer, Apollodorus of Damascus, 2nd century CE. But these sources don't provide much insight into the structure, design, or operation of one-armed torsion powered machines as there exists for two-armed ballista type machines. It is suspected from references to one armed throwing machines, that their use peaked during the 4th Century CE. The only useful description of the machine from this period was written by the Roman soldier and historian Ammianus Marcellinus.¹ To Ammianus this torsion engine was known as a Scorpion; but he also states that Onager was the vernacular name. There are no pictures of the Onager described by Ammianus. Some believe that one armed throwing machines continued to be used into The Middle Ages, where they were known as catapults or mangonels.² The advent of trebuchets in the ninth century apparently replaced these Onager type machines for a time.

The description of the Onager by Ammianus is the primary source used by the students to guide their reconstruction efforts in design and fabrication. Also taken into account by them were known principles that hold true for two armed throwing machines of an earlier period, since the Onager performs in a similar way. The historical approach they used in their current design tries to keep the model as true to the description by Ammianus as possible while maintaining simplicity and battlefield practicality. Because of the non-technical nature and lack of proportions in the Ammianus description, some engineering design assumptions had to be made by the students using engineering principles. Validation of this design and subsequent insight would hopefully come from dynamics and solid mechanics when they tested the completed engine. The design as derived by the students has some variables that are necessary and other aspects that rely on aesthetic proportions. As they learned throughout this project, engineers sometimes have to rely on what 'looks right' aided by engineering principles. It is known that the two-armed machines usually used a sizing formula to determine the size of the machine based on the weight of projectile the artilleryman wished to throw.³ The lack of a sizing formula or other design guidelines for the Onager caused the students to rely on the sizing principles from two-armed machine when creating their design. From this perhaps it would be necessary for them to derive another algorithm that could be formulated from an assumed range. Beyond Ammianus, most of the information used by the students comes from attempts by Schramm, Payne-Gallwey and Marsden to recreate this type of machine. These are summarized by Marsden⁴. Other modern studies of the Onager have influenced the student design decisions of the Onager presented here and hence a much more simplistic approach was taken than just using the considerations mentioned by Marsden.⁵ Computational and experimental results were used by the students to determine if the engineering assumptions and interpretation of Ammianus' description were a viable method for recreating a Roman Onager.

The description of the Onager by Ammianus as translated by Marsden⁶ is as follows:

"The design of the scorpion, which they now call onager, is as follows. Two beams of oak or holm-oak are fashioned and given a moderate curvature so that they seem to bulge into humps, and the beams are connected as in a frame-saw, having quite large holes bored in each side; between these beams, through the holes, powerful ropes are stretched, preventing the structure from falling apart.

From the middle of the cords a wooden arm rises at an angle and, being set upright in the manner of a yoke pole, is so inserted in the twists of sinew that it can be raised higher and lowered; to its tip iron hooks are fastened, from which hangs a sling of tow or iron. A huge buffer is placed in front of this arm, a sack stuffed with fine chaff, secured by strong binding. The engine is placed on piles of turf or brick platforms. You see, if put on a stone wall, a mass of this sort smashes whatever it finds underneath because of its violent recoil, not its weight.

When it comes to combat, a round stone is put in the sling and four young stalwarts on each side, by pulling rearwards the bars to which the withdrawal ropes are connected, draw the arm down almost horizontal; finally, when all this has been done, and only then, the master artilleryman, standing loftily beside it, strikes the pin, which secures the ropes of the whole machine, with a heavy hammer; whereupon the arm, released by the sharp blow and meeting the softness of the sack, projects the stone which will smash whatever it hits.

It is called a torsion engine because its whole power is derived from torsion, and scorpion because it has an upraised sting; modern times have also applied the name of Onager to it because wild asses, when hunted in the chase, throw up stones so high behind their backs by kicking that they penetrate the chests of their pursuers or actually break their bones and smash their skulls.”

Ammianus mentions that the beams are slightly curved in the middle to form humps and large holes are cut through these sides. The size of the holes is not known, but there was a formula, mentioned above, for the two armed torsion ballista described by Philon⁷ that related the weight of the projectile to the size of the holes in the ballista through which the torsion ropes are stretched. It is given as $D = 1.1 \sqrt[3]{100M}$, where M is in mina (1 mina = 0.96 lb) and D is in dactyls (1 dactyl = 0.76 inch). The use of this formula by the students seems reasonable, since the two armed ballista had its arms pulled back through 45 degrees and the one armed Onager will be pulled back through approximately 90 degrees. Payne-Gallwey⁸ found that he could throw projectiles of the size predicted by this formula and even greater, and still obtain reasonable distances. The students also came to the conclusion that it will be easier to change the weight of the projectile rather than adjust the hole size. Therefore a new relationship could be determined by them from the resulting range of the projectile.

In their design work, the students also had to take account of the rope size and tension. Philon mentions what size rope will be used to thread, around iron bars on each side, between the two oak beams. The original diameter of the rope is to be $d_0 = (1/4 + 1/12)D = (1/3)D$. Marsden disputes this as he says that this is too large. He believes that a mistake in transcription was made at some time and that Philon should be read as $d_0 = (1/4 - 1/12)D = 1/6D$, to give smaller ropes.⁹ The choice was made to regard the original byzantine text as being correct. The reasoning here is that a larger rope would be able to support a larger tension and therefore would present a stiffer torsion bundle¹⁰. It would not be as flexible as a larger number of ropes under lower tension. Philon goes to some length to say that twisting the bundle is not the way that the majority of tension is derived in the torsion engines. He notes that usually during a battle if the ropes become slack they can be tightened somewhat by twisting so as to slightly increase the tension. According to Philon, this is just a temporary method to increase the tension a little. To emphasize this lack of need for generating the majority of tension by twisting, he proposes an engine that

would derive its tension from using wedges at either end of the tensioned torsion bundles of the engine. For the two armed torsion ballista the tension is derived in a factory away from the battlefield, where the tension in each bundle is created by using large winches or capstans and the tightened torsion bundles are then taken to the battlefield and assembled into the whole completed engine.¹¹ For a large engine on the battlefield it would have been very difficult to do this tightening by twisting on the top and bottom of each torsion bundle; so they would have to be disassembled and taken back to a factory to be restrung and tensioned. There does not appear to be any evidence that the wedge ballista was ever used or even built, it still stands that the tension in all torsion devices, used in the ancient world, came principally from tensioning the ropes by stretching. Philon states that the tension needed to tighten the rope would be determined when the diameter of the rope is reduced to $\frac{2}{3}$ of the original diameter; $d = (\frac{2}{3})d_0$. Therefore $d = (\frac{2}{9}) D$.¹² Philon also states that the iron bars supporting the rope on each side of the oak sides will be $(\frac{1}{5}) D$ wide and $(\frac{2}{5}) D$ deep. These are placed vertically across the hole. Since 1 inch rope was on hand to use and is fairly easy to obtain, the hole would be $D = (\frac{9}{2})d = 4.5d$ plus a little more to allow for the width of the bar, and therefore the diameter of the hole was taken as $D = 4.67$ inch. This would mean that 4 ropes could be laid in on each side of the bars, with another three forced in outside these, giving 7 in back and 7 in front of the bars, or 14 total ropes between the oak beams. Using the formula which relates the weight of the projectile to the hole diameter the students determined that they would need a 1.67 lb projectile to get a 4.67 inch hole diameter.

The students learned that sinew rope was the preferred type of rope used by the ancient artificers, although hair rope was a second choice.¹³ Therefore, the students made tensile test measurements that allowed them to compare handmade sinew rope to some modern manufactured and handmade ropes. These ropes were tested on a tensile testing machine using 0.25 inch diameter ropes. The results of these tests are shown in Figure 1. In Figure 2 is shown that only handmade ropes are able to reduce to $\frac{2}{3}$ of the original rope diameter before breaking. Using the results for the sinew rope gave the students an idea of the loads needed in other ropes to simulate the sinew.

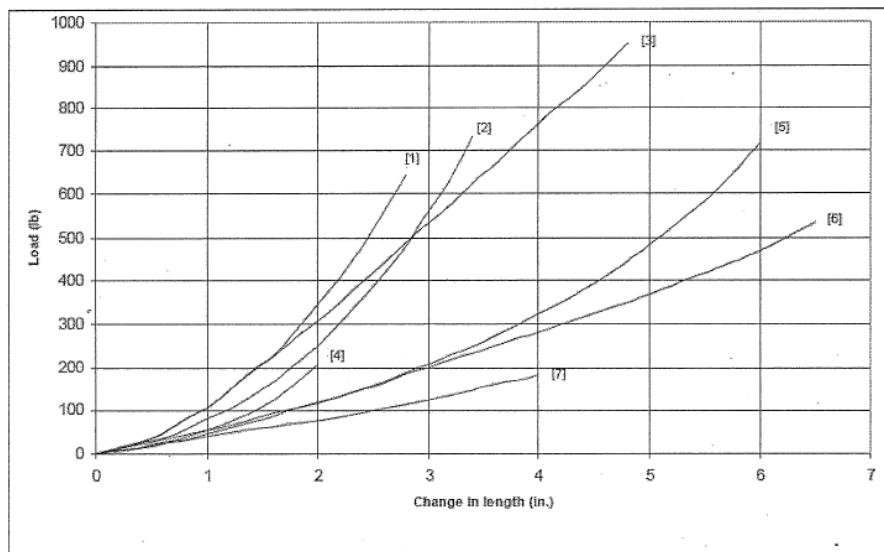


Figure 1 Tension versus change in length for quarter inch diameter rope. [1] Manufactured Sisal, [2] Manufactured Manila. [3] Manufactured Polypropylene, [4], Handmade Jute, [5] Manufactured Nylon, [6] Manufactured Polyester, [7] Handmade Sinew

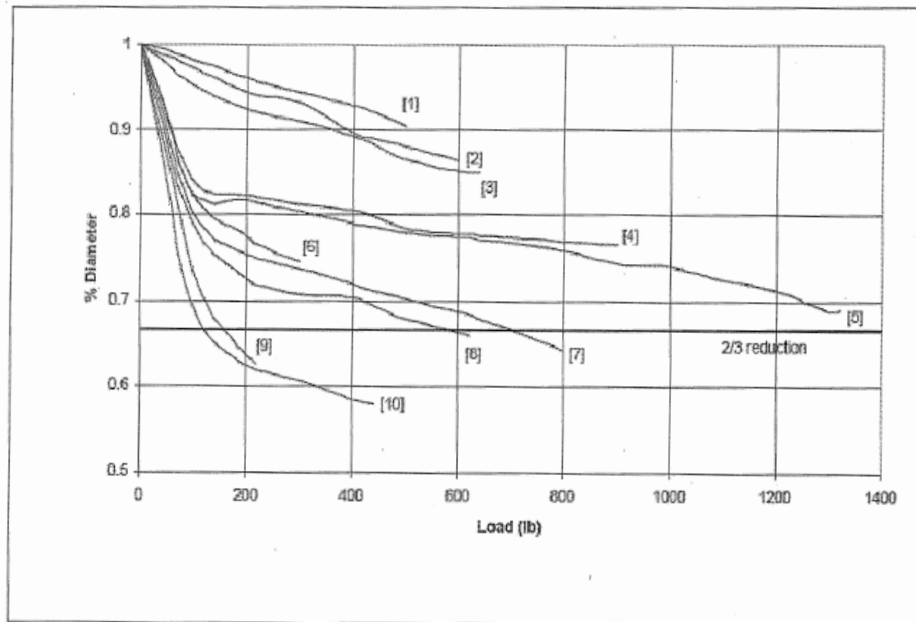


Figure 2 Reduction to 2/3 of the rope diameter versus the applied tension when taken to the breaking point. [1] Manufactured Sisal, [2] Manufactured Manila, [3] Manufactured Polyester, [4] Manufactured Nylon, [5] Manufactured Polypropylene, [6] Handmade Jute, [7] Handmade Hemp, [8] Handmade Polypropylene, [9] Handmade Sinew, [10] Handmade Polyester.

Once the students had determined the hole size D , every other dimension of the Onager is given in terms of this hole size; as is done in the construction of the ballistae of Philon, Heron and Vitruvius¹⁴. The overall dimensions of the Onager were determined through educated ‘guesses’ made by the students, due to the limited information available to them, based approximately on the golden mean and the dimensions of the individual pieces were determined by the students loosely guided by the construction of the better known ballista and aided by engineering principles.

The very early ballistae used a height of $5.5 D$ for the side stanchions, and these were positioned vertically.¹⁵ By the 4th century CE the distance was reduced.¹⁶ Therefore, since the students are dealing with a 4th century CE engine, the distance between the two oak beams was taken as $4.5 D$. The width of the oak beam sides was determined to be $1.25 D$, which the students determined was able to support the bending moment generated by the rope bundle during the loading process. This gives an overall width of $7 D$. The braces on either side of the torsion bundle separate the oak sides which are held together only by the tensioned ropes, as mentioned by Ammianus. The back brace adds stability by slight dovetails into the sides. It will also hold the trigger rope and is useful when operating the winch. Instead of a ratchet to hold the arm in any position the haul down levers can be rested against the back brace. There is no need for the vertical framework normally used in constructions and reconstructions. These engines relied totally on the forward twisting of the torsion bundle in order to achieve a high tension in the torsion bundle and the vertical structure was subsequently used to absorb the large torque left

after the projectile was released. Figure 3 shows a 15th century mangonel¹⁷ and Figure 4 shows Payne-Gallwey's¹⁸ 20th century reconstruction.

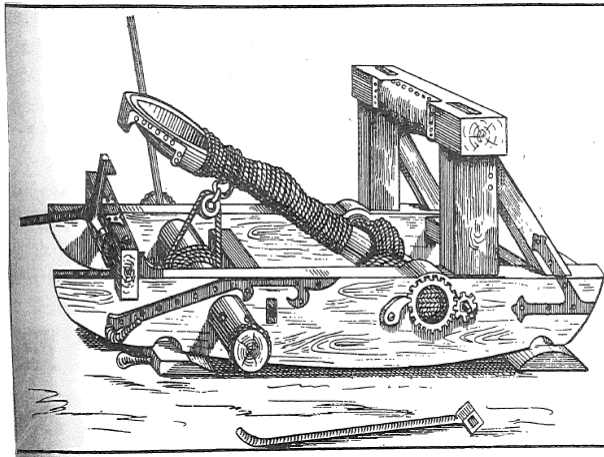


Figure 3 A late medieval siege catapult.

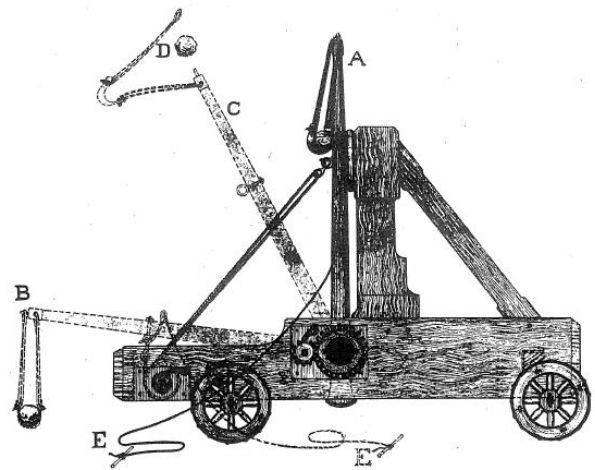


Figure 4 A sling catapult by Payne-Gallwey.

As may be seen from Figures 3 and 4 the total stretching of the torsion ropes, at the bottom of the arm, is produced by the forward twisting of the rope bundle using the gearing in the middle to help put a high torque on the bundle, which makes the arm press very tightly against the vertical crossbar. As will be discussed later, in the students' new design there is only a forward half twist given to the torsion bundle and then stretching along its length to develop the necessary resistive torque, needed to throw the projectile. Basically the half twist is to help hold in the arm when uncocked. Drawing down the throwing arm is resisted mainly by the torque generated by the high tension in the rope bundle. After the projectile is released most of the energy that was put into the throwing arm has been carried away and the angular speed of the arm is fairly low. Ammianus says that a large sack of chaff is placed in front of the arm. In their design the buffer is placed on the forward brace in front of the arm. From reconstructions it is known that a common problem is that the large residual torque, due to the twisting, causes the end of the arm to snap off when the arm encounters the high crossbar.¹⁹ The current reconstruction developed by the students is shown in Figure 5.

The students found that Ammianus says that a sling was attached to the end of the throwing arm. In some of the medieval pictures the end of the throwing arm has a spoon like cup to hold the projectile (See Figure 3). While this will work, a sling is much more efficient by developing a higher speed than just the speed of the tip of the throwing arm. This is well known by the author from experience and computer analysis of the operation of trebuchets. Payne-Gallwey tried both of these methods with his engine and he found that the sling produced consistently greater distance.²⁰

The main innovation of the current student design is the way the tension is generated in the torsion bundle as it is along the bundle and not generated totally from twisting of the bundle. The picture from the 14th century, shown in Figure 4, shows what looks like an Onager; but with the bundle positioned vertically.²¹ Figure 6 shows two interesting points. The torsion bundle has

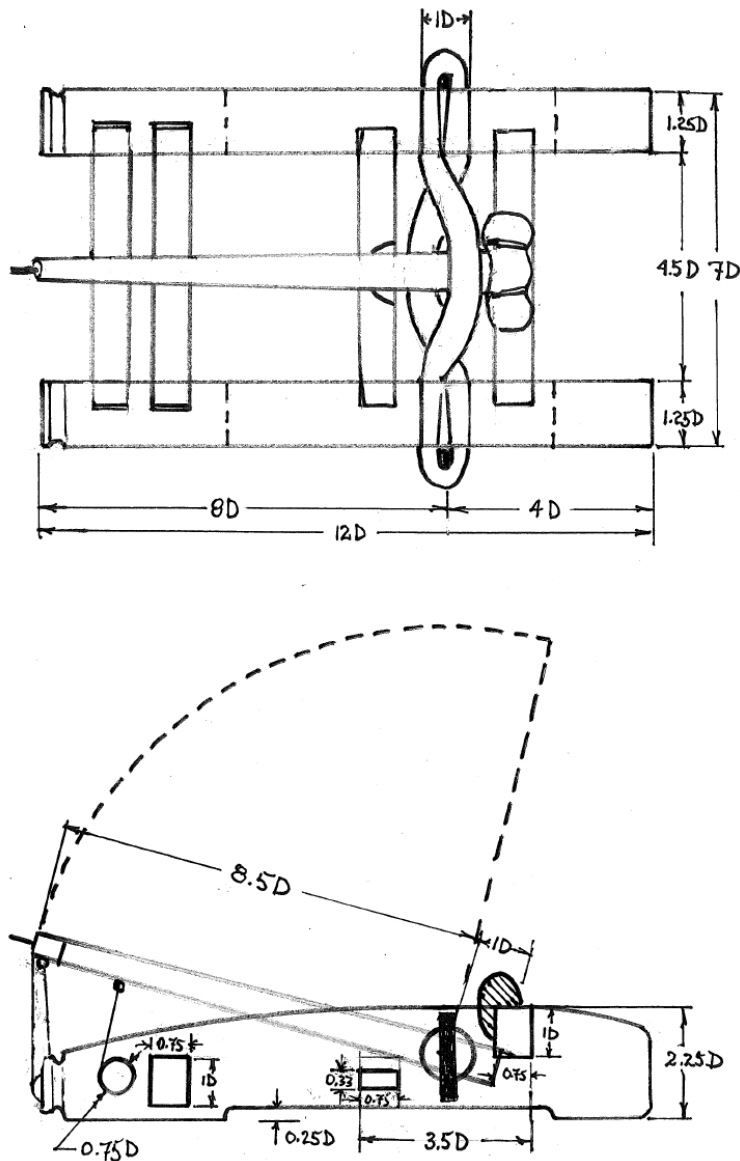


Figure 5 Top view and elevation of the reconstruction. All dimensions are in terms of the hole diameter, D .

just a 180 degree twist and the only way that tension can be applied to the torsion bundle is to first form the bundle by wrapping around what will be the two verticals or sides while they are on the ground, with the sides forming a V. The students decided that the key is to use some method to draw the top of the V together so that the sides are parallel. This drawing together of the two sides could be most simply and easily accomplished by wrapping another rope near the top of the V and using a lever, twist the rope to tighten, thereby pulling together the sides into the parallel configuration. The whole frame could then be placed vertically into two holes in the ground and the twisted rope near the ground removed. The students at this point remembered that Ammianus had said that the Onager was configured like a frame saw.²² (See Figure 7) For this

project, that is exactly what the students incorporated into their design. In Figure 8 is a model of the larger Onager. The tensioned rope bundle is where the sawblade would be in Figure 7.

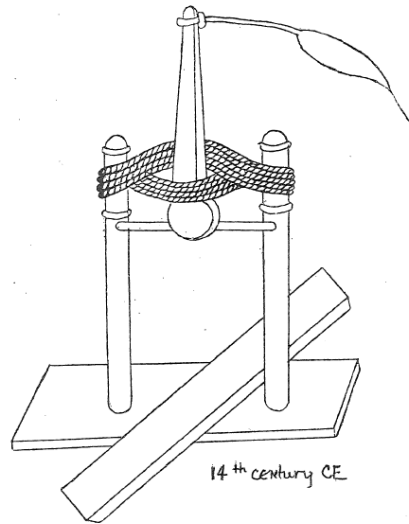


Figure 6 A 14th Century CE Onager

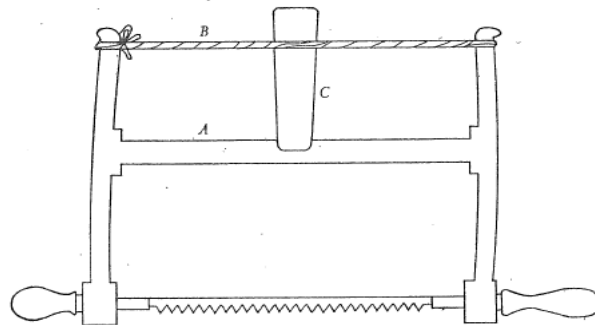


Figure 7 A frame saw

By measuring the elongation of the rope under load the students calculated the maximum tension in the ropes. For example, the students measured the force per elongation for a 1 inch Nylon rope, which they would use in the full sized Onager, and which is shown in the Figure 9 graph.

From this the students were able to determine the total load that is applied to the sides; based on there being 14 ropes. By calculating the bending moment for oak, the cross section of the oak beam was ascertained by limiting the stress to the maximum bending stress for oak. For a given strength of rope the angles of each side relative to each other was set, and the tension could be varied by spacing the forward ends of the oak beams to different distances. A 1D distance was

used. This gives about 18% elongation for the 1 inch Nylon rope of Figure 9 which yields 100 lb/rope when the sides are parallel. The reason that the two sides can pivot on the cross brace is that the students cut a mortise and tenon parallel to each oak side, so the oak sides may pivot horizontally and the front edge of this brace is the pivot point that is 1 D from the center of the torsion bundle. When the tension is loaded the bending moment is the largest on the sides at the pivoting brace. This is where the side thickness of 1.25 D was determined by the students from the bending moment of oak using this total load. When the forward brace is inserted in front of the throwing arm, most of the bending moment on the sides goes away.

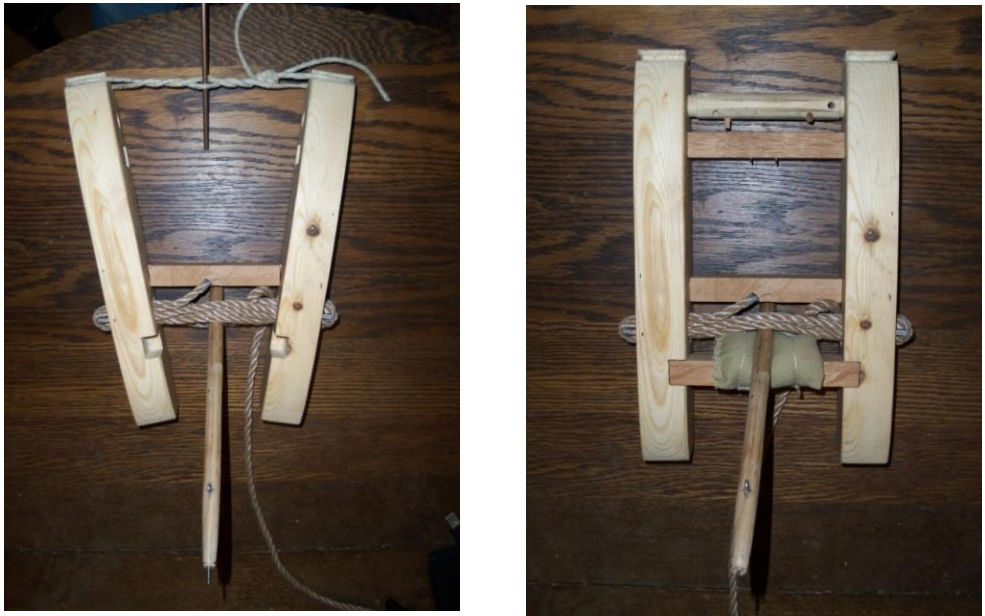


Figure 8 Method of tensioning the rope bundle that holds the throwing arm.

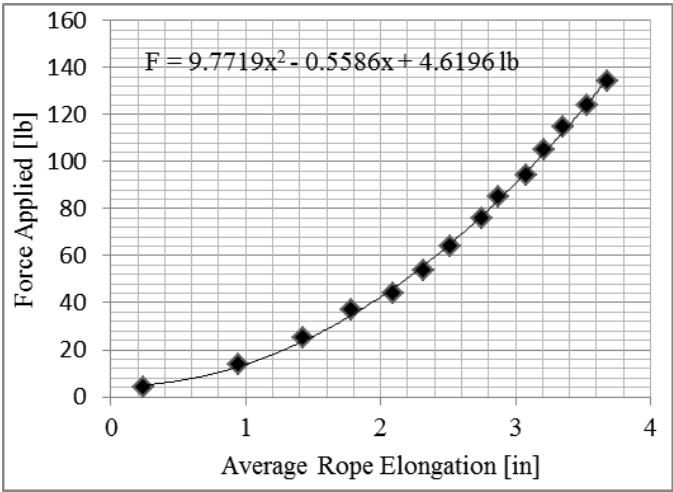


Figure 9 The loading of a single nylon rope as a function of elongation.

The moment that the torsion bundle supplies to the throwing arm was measured to obtain the moment as a function of the angle of the throwing arm. This gives a torque of approximately 2150 ftlb at 15 degrees and 0 ftlb at 113 degrees for Nylon rope. The relationship shown in Figure 10 was used to drive the computer model. As may be noted this is almost linear.

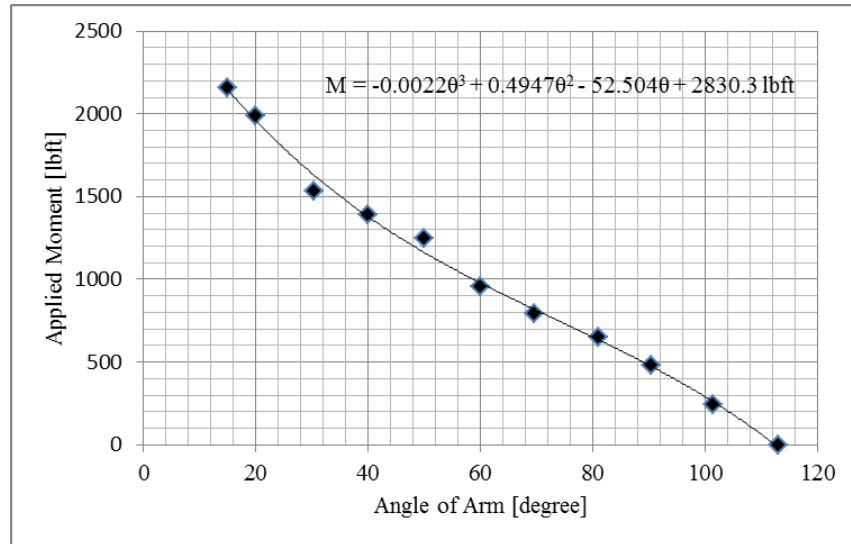


Figure 10 Moment applied to the arm by a nylon rope bundle as a function of the angle of the throwing arm.

Dynamic Analysis

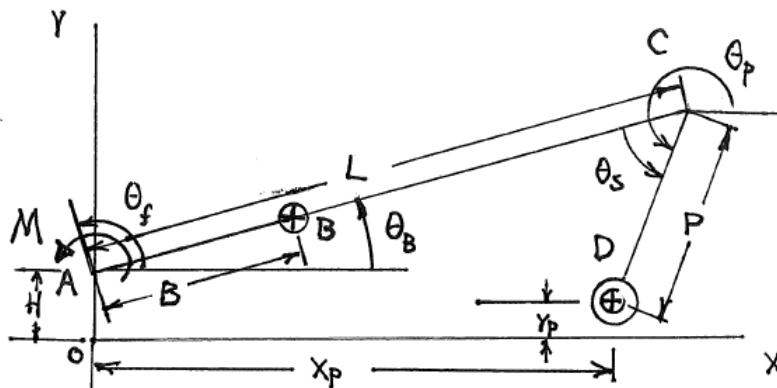


Figure 11 The Sling (P) and throwing arm (L).

The dynamic components of the Onager as determined by the students are shown in Figure 11. The equations derived by the students, to describe the positions and motion of these components, are as follows:

Position of center mass of the arm

$$\begin{aligned}x_B &= B \cos \theta_B \\y_B &= H + B \sin \theta_B\end{aligned}$$

Position of the projectile

$$\begin{aligned}x_P &= L \cos \theta_B + P \cos \theta_P \\y_P &= H + L \sin \theta_B + P \sin \theta_P\end{aligned}$$

If $H + L \sin \theta_B + P \sin \theta_P \leq r$ then $y_P = r$, where r is the radius of the projectile.

Velocity of center mass of the arm

$$\begin{aligned}v_{xB} &= -B \omega_B \sin \theta_B \\v_{yB} &= B \omega_B \cos \theta_B\end{aligned}$$

Velocity of the projectile

$$\begin{aligned}v_{xP} &= -L \omega_B \sin \theta_B - P \omega_P \sin \theta_P \\v_{yP} &= L \omega_B \cos \theta_B - P \omega_P \cos \theta_P\end{aligned}$$

Acceleration of center mass of the arm

$$\begin{aligned}a_{xB} &= -B \alpha_B \sin \theta_B - B \omega_B^2 \cos \theta_B \\a_{yB} &= B \alpha_B \cos \theta_B - B \omega_B^2 \sin \theta_B\end{aligned}$$

Acceleration of the projectile

$$\begin{aligned}a_{xP} &= -L \alpha_B \sin \theta_B - L \omega_B^2 \cos \theta_B - P \alpha_P \sin \theta_P - P \omega_P^2 \cos \theta_P \\a_{yP} &= L \alpha_B \cos \theta_B - L \omega_B^2 \sin \theta_B + P \alpha_P \cos \theta_P - P \omega_P^2 \sin \theta_P\end{aligned}$$

The force and moment equations are functions of θ_P , θ_B . The moment is taken about point A. This is of course assuming that point A does not move. I_A is the moment of inertia about point A.

$$I_A \alpha_B + m_P L a_{yP} \cos \theta_B - m_P L a_{xP} \sin \theta_B - M + B m_B g \cos \theta_B + m_P g L \cos \theta_B = 0$$

From the moment about point D and where I_P is the moment of inertia of the projectile with the sling considered rigid and massless.

$$I_P \alpha_P - m_P P a_{xP} \sin \theta_P + m_P P a_{yP} \cos \theta_P + m_P g P \cos \theta_P = 0$$

From these moment equations are obtained the following two equations

$$\alpha_B (I_A + m_P L^2) + \alpha_P m_P L P \cos (\theta_P - \theta_B) + \omega_B^2 m_P L^2 \sin 2\theta_B - \omega_P^2 m_P L P \sin (\theta_P - \theta_B) - M + m_B g B \cos \theta_B + m_P g L \cos \theta_B = 0 \text{ and}$$

$$\alpha_B m_P L P \cos (\theta_P - \theta_B) + \alpha_P (I_P + m_P P^2) + \omega_B^2 m_P L P \sin (\theta_P - \theta_B) + m_P g P \cos \theta_P = 0$$

M is approximated from measurements of the moment supplied by the bundle (Nylon is given in Figure 10) and is used in the above moment equations. The students solved for the angular

accelerations of the arm α_B and sling α_P , using numerical computer methods, and then used these to update all the positions, velocities and accelerations as a function of θ_B , the angular position of the throwing arm. At the point of release of the projectile, this becomes a trajectory problem that allowed the students to determine the range. The air resistance is taken into account. The point of release may vary, but usually the sling is approximately $\theta_S = 135$ degrees with respect to the throwing arm. The prong at the end of the beam is straight out from the end of the arm. These equations were useful since the students were able to use them, through simulation, to determine the best values for the length of the sling with respect to the throwing arm length, the initial angle of the throwing arm and the angle of the arm when the projectile was released. These values subsequently turned out to work well.



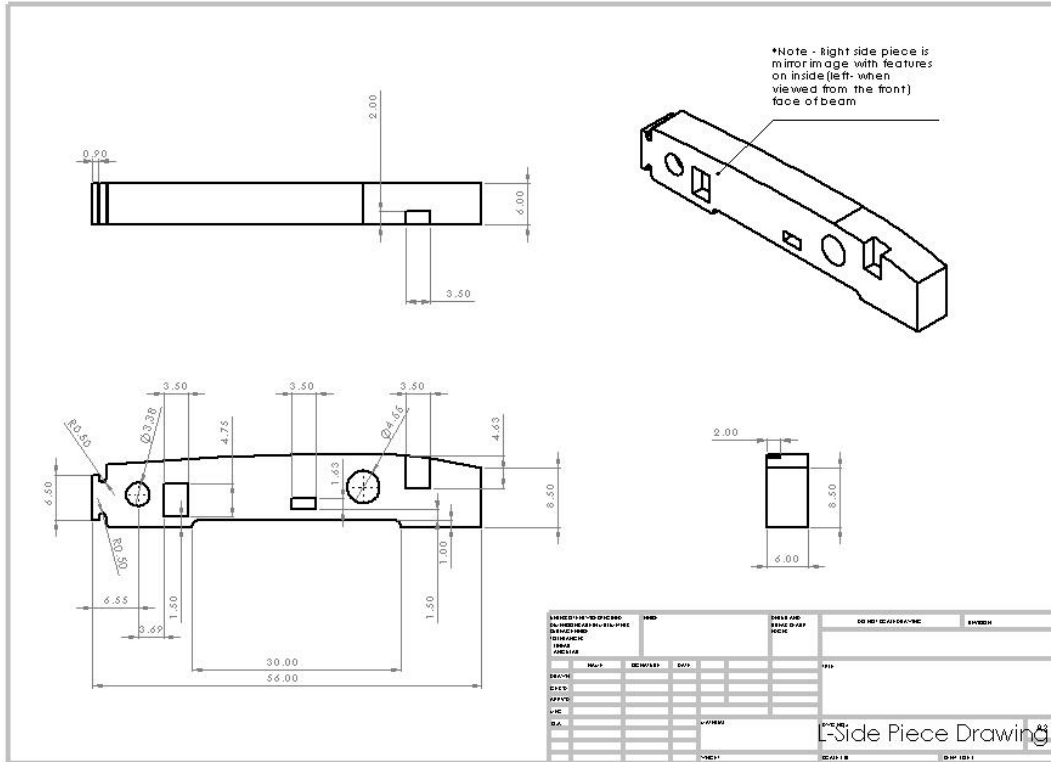
Figure 12 Components during manufacturing.

Construction of Components

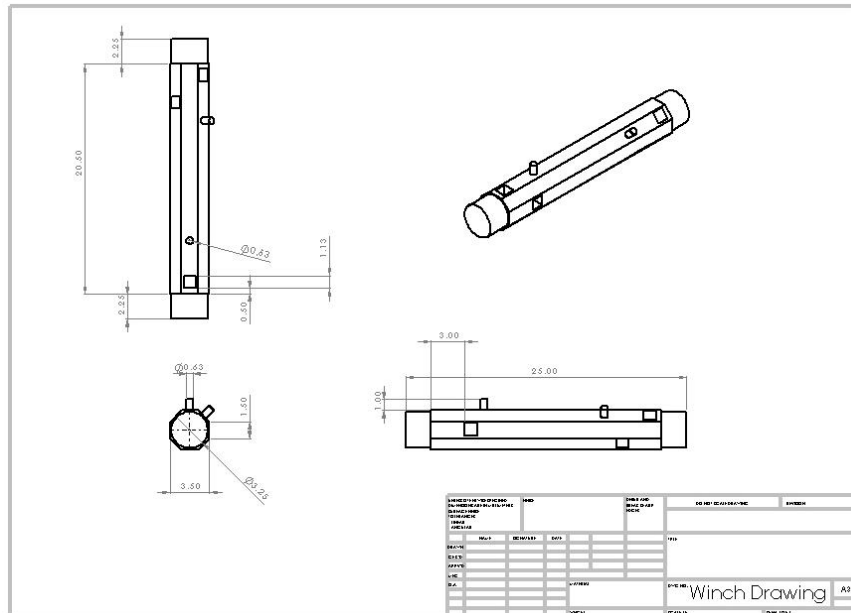
Starting with two 4.67 ft beams of oak the students formed the outside profile using an adze, planes and framing chisels. After the outside profile was formed, the main holes on each side were drilled through and then shaped with gouges and files. Mortises were made that would receive the front and back center pieces, a back brace and the winch. These do not go through. The ends of the winch were formed using a lathe. The winch rope was eye sliced at the ends to provide strength and an easy loop to fasten to the winch pegs. All parts are made from oak except the throwing arm which is yellow pine, with a cylindrical iron fitting and a short metal prong at the top end. The following drawings created by the students show the major components for an Onager with a hole of diameter $4 \frac{2}{3}$ inch. The mid Crossbar and the front bar need to have indentations cut into the bars to allow the arm to recline to 15 degrees; See Figures 5 and 13.

Drawings of the Major Components:

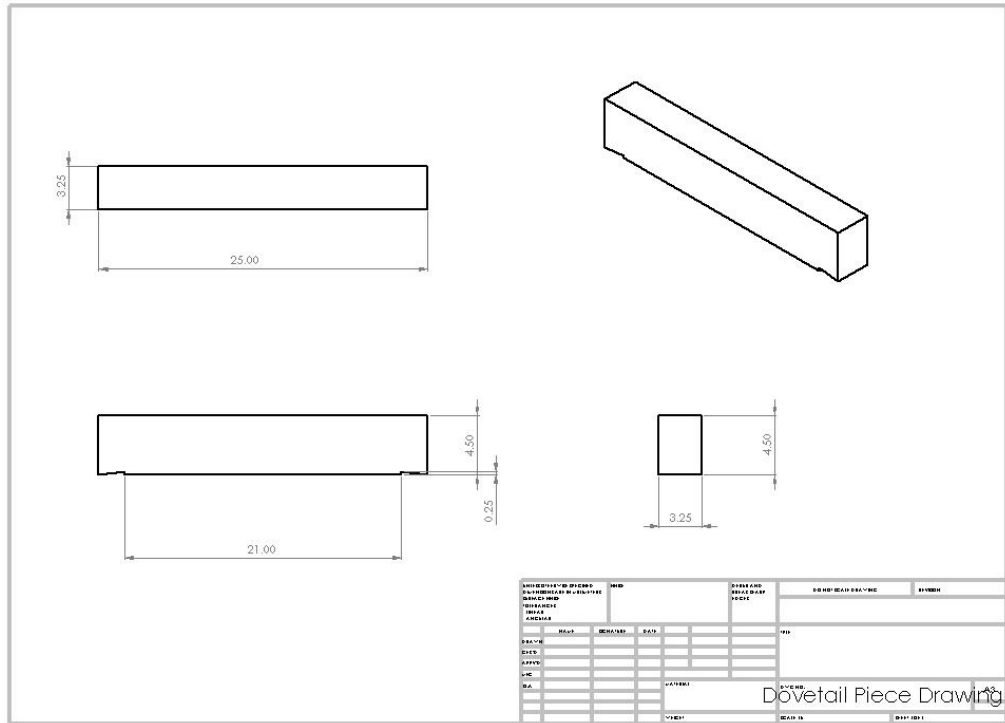
1. Side Pieces



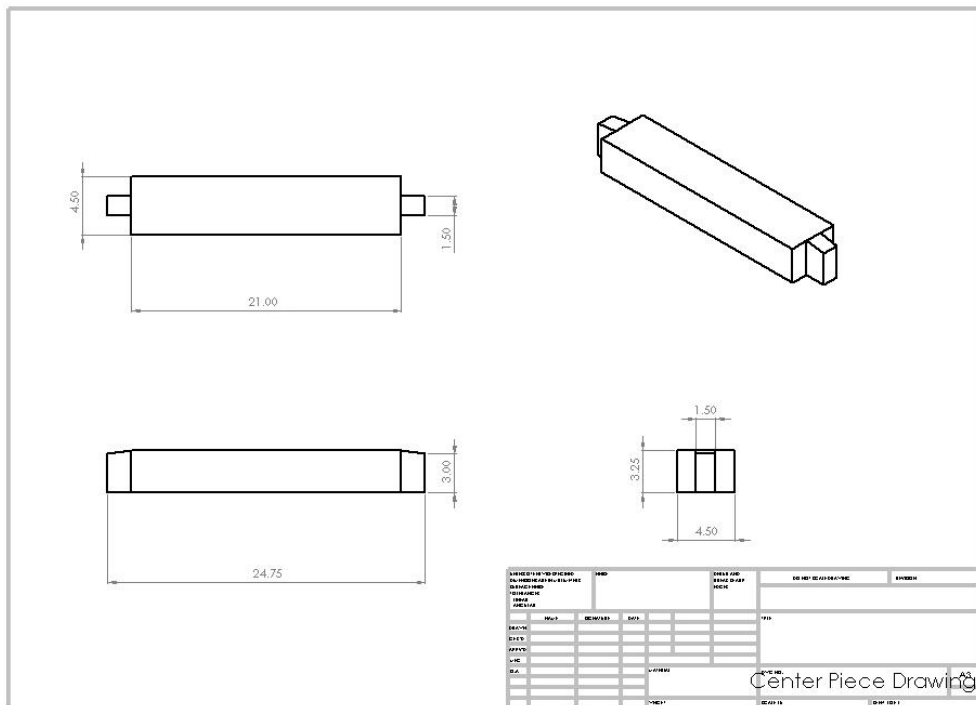
2. Winch



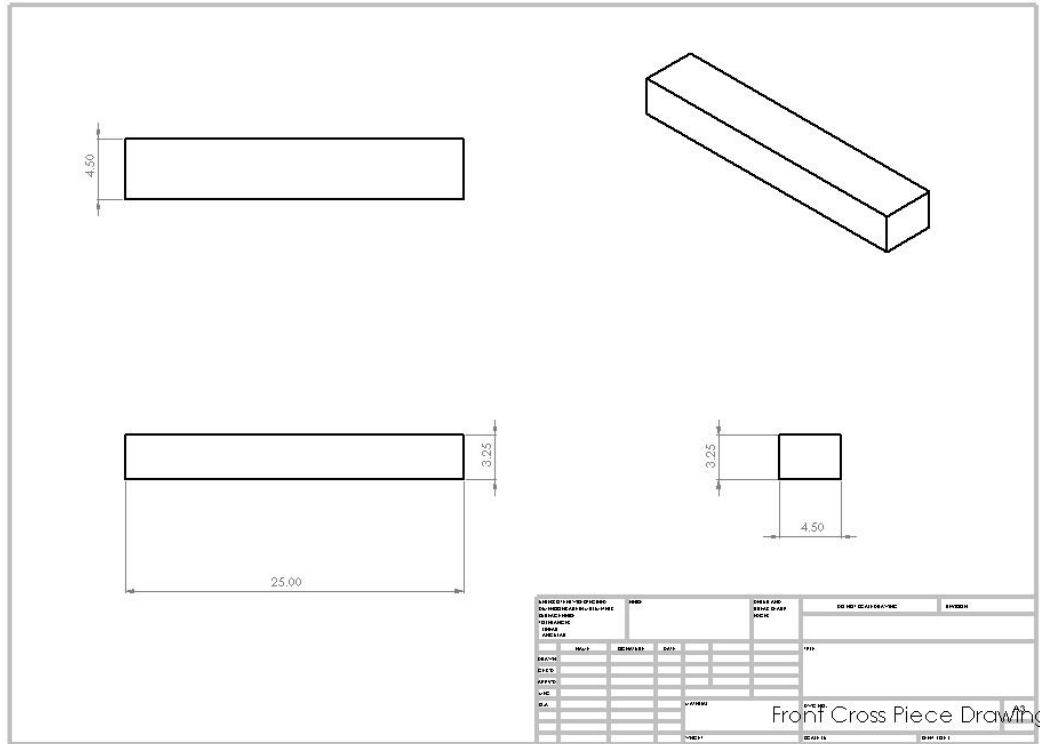
3. Rear Crossbar with Dovetail



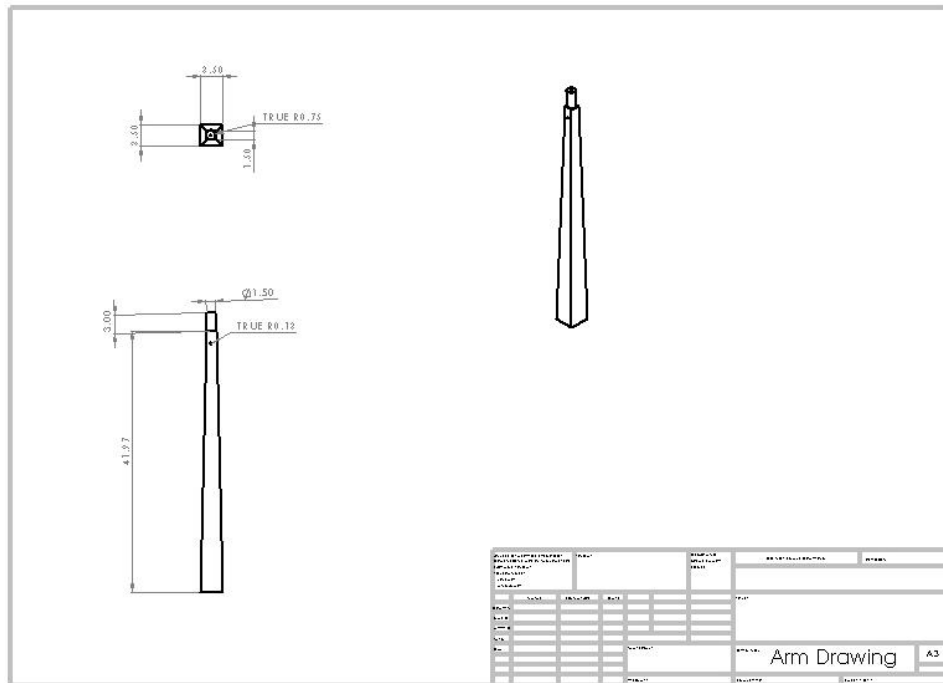
4. Mid Crossbar with Tenon



5. Front Crossbar



6. Throwing Arm



The students also developed and implemented the following assembly plan:

1. The two large sleepers (side pieces - drawing 1), are set about 4.5 hole diameters apart with the recesses on the inside.
2. The cross brace with the tenons at each end (mid crossbar with tenons – drawing 4) is put into the mortises (small rectangular tenons in side pieces –drawing 1). With the cross brace as a pivot point, the forward ends of the sleepers are angled together. The ends are to be set a distance of one hole diameter apart. This is best achieved by a block of wood of this length.
3. Iron bars ($1/5 D \times 2/5 D \times 2 D$) are placed in their respective positions, centered on the outside of each large through hole. Wooden blocks are used to hold these in place before the ropes are looped around them.
4. The torsion bundle consists of seven complete loops of a diameter of slightly smaller than $2/9$ of the hole diameter. Four loops can be easily placed next to the iron bars and the final three loops lay on top of the first four. Pull snug the cords with each pass from side to side. The cord is not tied, but at the beginning a length of cord is left so that it can be incorporated into the completed bundle, and the final end of the cord is also passed through the bundle which will be held in place by the tensioning of the entire bundle.
5. Insert the throwing arm in between two sides of the torsion bundle. Rotate both iron bars one half of a turn (the tops of the bars are rotated forward). This was found to be the easiest way to string the ropes, by looping them straight and then given a half twist. One can put the half twist in when stringing by going in front of and in back of the throwing arm, but this was harder to do.
6. Put a spacer above the cross brace that has the tenons (drawing 4) so as to maintain the spacing of the tops of the sleepers, as they tend to rotate inward upon being loaded as the ropes are stretched.
7. Place a tied loop of the same size cord as the torsion bundle, around the back notches. Manila works the best for this, whatever the type of rope used in the torsion bundle. Manila does not stretch much. Use a square metal tube cross and two levers, which fit into this cross. These are used to wind the loop of the cord which tightens the loop and thereby draws the rear of the engine together. The metal cross is just two short lengths of square tubing, side by side and welded together at their centers. This allows the two levers to be removed alternately and walked just as the winch is walked. These levers should be rotated backward. This allows the levers to be rested against the rear cross brace.
8. When the back is getting close together put the winch and back brace in their respective recesses.
9. Use the levers and the winch to pull the throwing arm so that it is vertical.
10. Continue drawing the back of the engine together by tightening the loop. You will need to stop a couple of times and put pieces of wood and wedges between the front ends of the engine so that the tightening loop can be retied.
11. When the two sides are parallel, put the forward cross brace, with the cushioning sack attached, in its vertical slot in front of the throwing arm.
12. Remove the any forward spacing pieces of wood, the spacer above the cross brace with the tenons and the rear tightening rope as they are no longer needed.
13. The back cross brace is wedged at the top of each side to lock in this brace, which fits into a shallow dovetail notch. This back cross brace is also what the trigger is attached to.

Operation

When the throwing arm is in the unloaded position, the loop of the winch rope is attached to the winch. The winch is rotated alternately using the two bars that fit into the winch. The levers produce a mechanical advantage of about 23:1. The winch is used to pull the arm back until it reaches approximately 15 degrees above the horizontal. The trigger rope is then looped over the arm and a firing pin is inserted to lock the arm in place, such that now the trigger is holding the arm back and not the winch. The bars are moved clear and the sling is loaded with the shot. The shot is spherical and was made of Portland cement and sand to simulate sandstone. This was cast in plastic molds that were made by the students using a 3D rapid prototyping machine. The winch cable, which is acting like a safety, is removed and the weapon is ready to discharge. The pin is pulled out using a rope lanyard and the projectile is released. Ammianus says the pin is struck out, but it was safer for the operator to be some distance from the engine, so the pin was jerked out using a lanyard.

Figure 13 and 14 show that there does not need to be some sort of ratchet device to hold the arm in any position, the bars used to rotate the winch backward can rest on the back brace, giving incremental positions. The students wrapped the arm with Gorilla® tape just in case the arm shattered.

Technical Conclusions

The Onager functioned in a manner that was determined from the computer modeling conducted by the students. However the range was less than what they expected. Their maximum

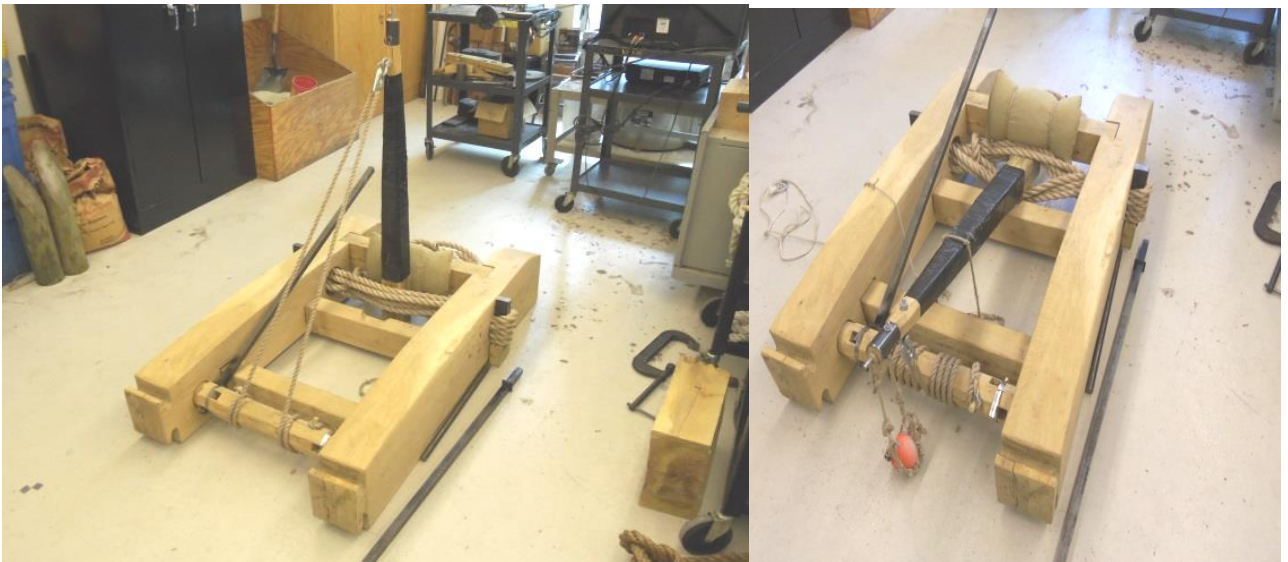


Figure 13 The Onager when un-cocked (left) and when cocked (right)

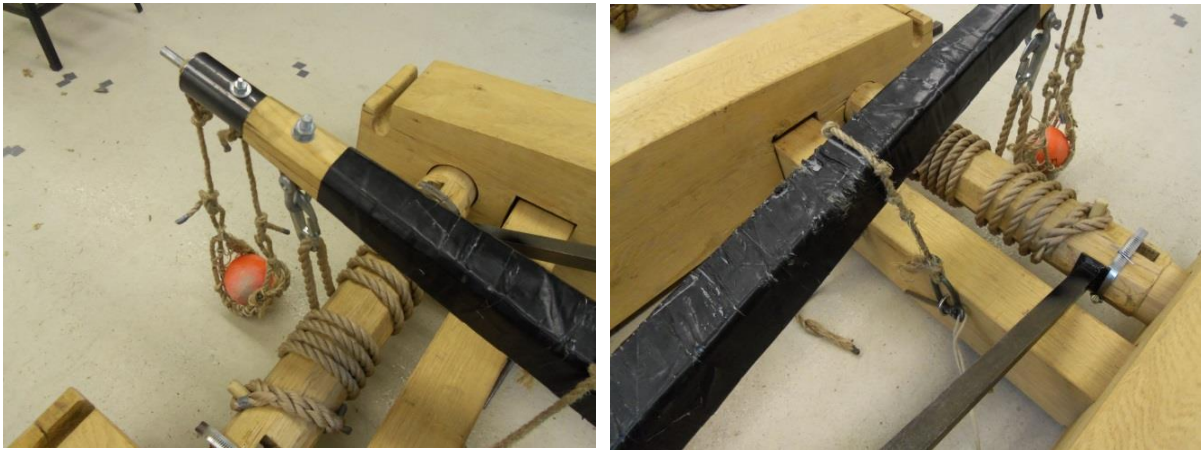


Figure 14 The sling (left) and the trigger with pin (right).

actual shot distance was approximately 150 feet when they expected 900 feet as determined from their computer model. The apparent reason for the discrepancy could be creep of the ropes, since in this case the engine was left assembled for a long period of time before it was taken outside already assembled and tested. It was later noted by the students that when assembled in the laboratory the arm could not be moved by hand, but several weeks later the arm could be easily moved by hand. The ropes need to be pre-stretched or the operation of the Onager is best right after arming. As the ropes are used and restrung upon each new deployment, the ropes will become stretched and become more stable. In a previous paper,²³ the comparison of the mathematical computer model results utilizing measurements of the torque characteristics of the actual devices and subsequent measuring of the dynamics of the actual device, were within reasonable agreement. The ropes had originally been under load for some time, had time to stretch and the torsion bundle was unchanged for the three configurations.

The initial arm angle that correlates to the maximum range seems to be between 14 and 17 degrees and anything outside that range significantly reduces the distance. The computer model worked best for 15 degrees, so 15 degrees seems to be optimum angle. Approximately a 60 degree angle of the arm at launch of the projectile will result in a 45 degree launch of the projectile. The computer also predicted that the sling length should be approximately 1/3 of the arm length L . These results also agree with the 15 degree initial angle, 60 degree arm angle and sling length of 1/3 of the arm length L of Payne-Gallwey. Refer to Figure 4. Lengthening the sling gives a lower trajectory and shortening the sling gives a higher trajectory.

The final students design was found to be a functional and practical design. It could be assembled and taken apart fairly rapidly. For future work, the performance of different one inch diameter modern ropes needs to be compared in order to ascertain what would work best. Obtaining enough animal sinew to make 50 feet of 1 inch rope, as was used by the ancients, seems to be out of the question. This would have to be made up into rope and would take more than 22 lbs. of sinew. The overall geometry and method of propulsion seems to be about right and fits the description given by Ammianus. This design project can serve as a starting point for students to determine the right modern rope to use.

Pedagogical Conclusions

As noted earlier, this historically-based multidisciplinary design and fabrication project was implemented to foster the targeted engineering skill sets/learning outcomes of critical thinking and the ability to determine and apply applicable engineering analysis techniques, and provide an interesting way to increase student interest in the engineering design process. To assess the impact of the Onager project on the reinforcement and enhancement of the targeted skill sets/learning outcomes, the authors used the open-ended indirect methods of their own targeted observation and their targeted discussions with the members of the student design team. Since this was a pilot multidisciplinary history-engineering project, the authors selected these assessment tools as better suited to provide the broad input from this pilot project that could better guide the later development of the project and of direct measurement assessment instruments.

As can be seen from the detailed project description above, the students' critical thinking and engineering analysis skills were certainly challenged in their having to do quite a bit of 'detective' work with limited clues in order to formulate and solve a complex unknown system problem based on piecing together the design constraints that they had to glean from historical and modern sources and 'common sense', their determination and use of appropriate engineering principles/analysis, their appropriate determination and use of analytical and computational analysis and materials testing, their learning of fabrication techniques (both ancient and modern), their testing of their design results, and their analysis of those results to better their design. Based on the authors' direct observations and discussions with the student team members, their skills improved over the course of the project. At the beginning of the project the authors observed, and the students explicitly expressed, that the students were very concerned that they didn't know what an Onager 'looked like', that they had no knowledge of or pre-conceived ideas about the shape, size or design of an Onager, and felt they would not be able to 'figure out' the applicable engineering modeling and analysis methods. Therefore, at the beginning of the project, the students relied more on the authors' input into their design. Yet the broad open-ended nature of the project was perhaps the best pedagogical tool of the project since the students then had to rely solely and more frequently on the functional information they found in the historical sources and their own critical thinking, analytical, and engineering skills to create their design that satisfied their historical findings. That they were designing and creating a machine that perhaps had not been seen on earth in centuries became a very motivating factor that kept them interested in their engineering work. As the students progressed through the project, they began relying less on the authors' input and began expressing more concrete and technically-based ideas about what they needed to model and what engineering principles and analysis methods seemed applicable to the numerous questions/concerns that confronted them. By the end of the project, they relied almost exclusively on their own ideas relying very little on the authors' input. The students' overwhelmingly positive response to their work on this project can be summed up in a comment one of them made at the end of the project: "Sir, we just made history come alive!"

The authors plan to continue developing this and similar interdisciplinary historical-engineering based student projects and, based on their experience with this pilot project, to develop

assessment instruments that directly measure the targeted skill sets/learning outcomes of critical thinking and the ability to determine and apply applicable engineering analysis techniques for these unique types of projects.

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