Arizona State University

2015 Concrete Canoe Design Report

MANDJET

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Long before the technology of today's modern world, ancient Egyptians were among the first to harness the methods of civil engineering. Building pyramids, temples, fortresses, dams, and canals, ancient Egyptians engineered an empire that has become a model for modern innovation. Arizona State University's 2014-2015 Concrete Canoe, *Mandjet*, was inspired by the human ingenuity of this great civilization. *Mandjet*, whose name means "growing strong", but often referred to as the morning, solar boat of Ra, ferried the sun god across the sky turning night into day. Mandjet fittingly represents team's belief of growing stronger each year through continuous innovation and creativity.

Territorial Normal School at Tempe was founded March 12, 1885, but was later renamed to Arizona State University in 1958. Located in Tempe, Arizona, ASU is home to more than 82,000 graduate and undergraduate students in its 24 independent colleges. Among these colleges, the Ira A. Fulton School of Engineering ranks in the top 15% of all accredited engineering programs throughout the United States (U.S. News and World Reports). Of the 3,000 students in the Ira A. Fulton School of Engineering, approximately 1,100 are enrolled in the School of Sustainable Engineering and the Built Environment (SSEBE), which includes civil, environmental, sustainable, and construction engineering students.

The ASU Concrete Canoe Team participates in the competitive Pacific Southwest Conference, featuring two nationally elite schools in Cal Poly Pomona and Cal Poly San Luis Obispo. Arizona State's performance has stayed consistent the last three years placing ninth with *Kraken* (2012), seventh with *Clockwork* (2013), and tenth with *Avanyu* (2014). The 2015 team strived to improve upon past years' performance through innovations to the hull design & analysis, construction, and mix design processes. The hull design team developed two new design techniques to modify the National Concrete Canoe hull design. Racing performance was enhanced by reducing the beam to improve paddler efficiency and decrease fluid drag.

Table 1: *Mandjet* Specifications

Wet Unit Weight	59.1 pcf
Dry Unit Weight	57.0 pcf
Compressive Strength	1290 psi
Composite Flexural Strength	520 psi

Table 2: *Mandjet* Specifications

Estimated Weight	248 lbs
Length	20'-0"
Maximum Width	2'-4"
Maximum Depth	1'-4"
Average Thickness	1/2"
Main Colors	Black, Gold, Red, Blue
Reinforcements	Fiberglass Mesh

The mix design team addressed sustainability by incorporating recycled materials, including Class F fly ash, cenospheres, and Poraver, and reducing the amount of cement in the mix. *Mandjet's* well-graded aggregate blend, and 50% replacement of Portland cement with supplementary cementitious materials minimized CO_2 emissions proportional to the amount removed from the mix. Construction improved quality control by fabricating wooden guides to regulate thickness during the casting and sanding process. The guides decreased typical casting time by 3 hours, while also improving the efficiency of the sanding process since more focus could be placed on finishing instead of concentrating on thickness.

Just as Ra used Mandjet to raise the morning sun, the Arizona State Concrete Canoe team hopes to use *Mandjet* to raise the Sun Devils to a new level of success.

The success of a project is measured by the effectiveness of project management to define the scope and objectives. The scope is simple; build a canoe out of concrete. The challenge was developing tangible objectives. The team met in early August to establish project objectives, a preliminary budget, and a project schedule based on previous knowledge and experience. Tasks that were essential to completing the project on time were identified as key milestones (Table 3), establishing the critical path on page 10. One of our essential activities was hull design because it controlled when cutting of the cross sections occurred, which directly affected mold completion and canoe casting.

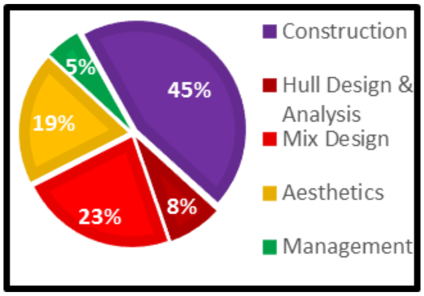


Figure 1: Division of Man-Hours

The project was divided into four main branches: construction, mix design, hull design & analysis, and aesthetics. Captains, assigned to each branch, were responsible for planning work sessions, training members, and procuring materials. Since most of the team from last year departed, the project manager recruited and trained new members until they were able to handle the responsibility of the position. Any unfilled position was absorbed by the PM. This unconventional organizational structure can be seen on page 2. The team dedicated a total of 2,000 man-hours towards completion of *Mandjet* (Figure 1).

Table 3: Key Milestones

Milestone	Delay	Cause
Hull Design Selection	None	Proper Scheduling
Structural Analysis	4 weeks	Inexperience
Final Mix Selection	5 weeks	Additional Testing
Mold Completion	4 weeks	Lack of Manpower
Canoe Casting	1 week	Repair Mold

Winter break was used as a 5 week buffer to account for any unexpected delays seen during the first half of the project. This buffer allowed the team to efficiently address all delays (Table 3), resulting in casting a week earlier than last year. Additionally, the sanding process began after a 14-day cure to offset remaining lost time.

The budget objective this year was to reduce CNC costs since this accounted for 60% of last year's $5,000 production cost. The construction team achieved this goal by developing a no-cost, in-house operation through ASU's partnership with TechShop Chandler. TechShop provides free training and access to their CNC equipment for ASU students, thus eliminating CNC costs entirely. Production cost totaled approximately $1,200 for *Mandjet* (See Appendix C).

Construction errors from previous years revealed the need for a quality assurance and control officer. Two years ago, improper placement of reinforcing mesh led to *Clockwork* breaking. Last year, CNC issues led to *Avanyu* being 19 ft. instead of 20 ft. To mitigate these errors, QA/QC officers were responsible for reviewing calculations and design drawings, and developing quality control measures. These measures ensured construction accurately followed the proposed design.

The health and safety of the team remains a major concern every year. To ensure a safe work environment, each team member was required to attend a safety training program, addressing potential safety hazards and proper use of equipment, before they were allowed to participate on the project. The safety officer coordinated with captains to procure necessary personal protective equipment (PPE), update material safety data sheets (MSDS), and maintain a clean workspace. As a result of these practices, the team was able to avoid accidents and injuries.

Organization Chart

Project Manager
Steven Sherant (Sr./3/3)*

Kept schedule & budget; Supervised hull analysis, mix design & construction; Ensured compliance with industry standards & competition Rule and Regulations

Hull Analysis Captain
Steven Sherant

Researched design properties & analyzed structural design; Used computer programs to aid design and calculations.

Contributors: Ashraf Abukhalaf (Jr./1/0) | Brent Allman (Grad./1/0)

Mix Design Captains
Victoria Flys (Jr./1/0)
Jacob Bauchmoyer (Jr./1/1)

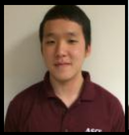

Material research; Developed concrete mix design for structural & finishing layers; Performed laboratory testing.

Mix Contributors: Ashraf Abukhalaf (Jr./1/0) | Jordan Rodriguez (Jr./1/0) | Steven Sherant (Sr./3/3) | Miriam Woolley (Sr./4/1)

Safety Captain
Steven Sherant

Obtained MSDS for materials; Oversaw proper material handling and storage; Oversaw PPE of all team members.

Construction Captains
Wei Hii (Sr./1/0)
Mackenzie Hagan (Sr./3/2)
Brooke Ridley (Jr./1/0)



Canoe mold preparation & form cutting; Research & selection of fiber glass reinforcement mesh; Concrete casting; Sanding & finish.

Construction Contributors: Ashraf Abukhalaf (Jr./1/0) | Brent Allman (Grad./1/0) | Jeffrey Capaci (Jr./2/0) | Dylan Curet (Jr./1/0) | Jacob Bauchmoyer (Jr./1/1) | Mark Daniel (Sr./2/0) | Jesus Esquivel (Grad/4/0) | Victoria Flys (Jr./1/0) | Omar Gloria (Sr./2/2) | Hajar Husainy (Jr./1/1) | Cody Langlois (Soph./1/1) | Jordan Rodriguez (Jr./1/0) | Hoyong Ryou (Sr./1/1) | Steven Sherant (Sr./3/3) | Miriam Woolley (Sr./4/1)

Paddling Captain
Victoria Jimenez (Jr./2/2)

Scheduled weekly practices; Coordinated with Tempe Parks & Recreation for Lake permits & canoe storage.

Paddling Team

Men	Women
Omar Gloria	Mackenzie Hagan
Cody Langlois	Victoria Head
Hoyong Ryou	Hajar Husainy
Steven Sherant	Victoria Jimenez

Aesthetics Captain
Mackenzie Hagan (Sr./3/2)

Oversaw theme of final product including canoe graphics, display table & stands; Design Paper & Presentation graphics/formatting.

Aesthetics Contributors: Jeffrey Capcaci (Jr./2/0) | Veronica Head (Jr./1/1) | Victoria Jimenez (Jr./2/2) | Adrien Orlowski (Jr./1/0)

QA/QC
Mackenzie Hagan | Brooke Ridley


Reviewed project deliverables; Ensured compliance with industry standards and competition Rules and Regulations; Oversaw concrete casting and finishing.

(Year/# of years participating in Concrete Canoe Competition/# of years as a registered participant)

The key to producing a competitive canoe is through an effective hull design process. The process involves modifying previous designs in order to optimize the performance of the canoe. This design process, however, has remained stagnant at Arizona State University; the standard NCCC hull has been used the last 4 years. According to Albert Einstein, the definition of insanity is doing the same thing over again and expecting different results. Based on our declining performance at the last three conferences, the design process demands innovation for ASU to become a serious competitor once again.

Preliminary research began in August to understand the important factors incorporated in canoe design, leading to the development two new design techniques: Scaling and Splining. In scaling, a factor is used to scale the length, depth, and/or width of existing designs. This allows each dimension to be modified while still maintaining the original shape. In splining, quadratic splines were used to join key points of a canoe. First, plan and profile views were created using coordinates of the bow, stern, and widest/deepest point. Then, intermediate points, between the gunnels and belly, were used to shape the walls and bottom of the cross-sections.

The standard NCCC design was used as a baseline because of ASU's familiarity with this design. Before altering the NCCC hull design, the team consulted with previous paddlers. The consensus was that the NCCC hull felt too wide to paddle efficiently. Research of top performing teams at nationals revealed that their canoes had narrower beams with similar lengths and depths as the NCCC hull. Based on this information, the team focused on altering the canoe's beam, or width.

The width affects several key performance characteristics, including, length-to-beam ratio (L/B), beam-to-draft ratio (B/T), and wetted surface area (A_w). The L/B ratio, B/T ratio, and A_w all directly affect the overall speed and wave-making resistance of the canoe (Winters). In order to increase speed, the B/T ratio and A_w should be minimized to reduce water contacting the canoe, which lowers fluid drag. The L/B ratio should be maximized to produce a hull that is longer than it is wide, similar to an arrow. This allows that canoe to track well at high speeds, however, large L/B ratios can decrease stability and hinder performance. Typical L/B ratios range from 8 to 11 for racing boats (Winters).

Table 4: 2 Male Performance Comparison

Characteristic	Model 1	Model 2	NCCC	*Mandjet*
Beam (in)	28	27	31	28
Wetted Surface Area (ft²)	37.4	31.18	38.9	32.5
Length-to-Beam Ratio	8.73	9.06	8.23	9.13
Beam-to-Draft Ratio	4.01	3.7	4.71	3.92

Several designs were analyzed in DELFTship™ free, a 3D hull modeling program, to quantify the performance (Table 4). Model 2 performed well, but was rejected as it provided 4 in. of freeboard when fully loaded, compared to 5 in. for *Mandjet*. Freeboard is known as the distance from the waterline to the top of the gunnels. A lower freeboard reduces unnecessary weight and improves ease of paddling, however, the team concluded that 4 in. was not enough to prevent waves generated during paddling from entering the canoe, especially during the co-ed sprint.

Mandjet was designed by scaling the beam of the standard NCCC down to 28 in., an 11% reduction. This modification improves the performance due to a higher L/B ratio, and lower B/T ratio and A_w. The length and depth were kept at 20 ft. and 14 in., respectively. The overall shape is asymmetrical with a moderate rocker, and shallow arch bottom. The design team is confident these characteristics will allow *Mandjet* to track well in long straightaways for sprints, while still maintaining the ability to maneuver the staggered buoys in the slalom portion of the endurance.

Upon finishing the hull design, a two-dimensional structural analysis was performed to evaluate the internal stresses *Mandjet* will experience during competition; these stresses then determined the minimum required compressive and tensile strength of the concrete mix. Internal stresses were calculated using the theory of simple bending,

$$\sigma = Mc/I_x$$

Where, M is the bending moment, c is the distance from the neutral axis to the outer most fiber, and I_x is the moment of inertia about the neutral x-axis. A longitudinal analysis was performed to determine the magnitude and location of the maximum bending moment under six loading conditions, assuming the canoe acts as a simple beam. Cross-sectional properties were determined at 1 ft. intervals by integrating quadratic splines generated for the inner and outer coordinates of each cross section. The six load conditions taken into account: (1) display, (2) transportation, (3) carrying, (4) two female paddlers, (5) two male paddlers, and (6) coed.

For load cases on land, only self-weight, modeled as a uniformly distributed load, was placed on the canoe. Pin supports were assumed to represent the supporting devices since they provide no moment resistance. On display, the canoe has two supports located 3 ft. inward from the bow and stern. During transportation, the canoe has 10 support spaced equally along the length. While carrying, the canoe was only supported at the bow and stern.

For load cases on water, self-weight, weight of the paddlers, and a buoyant distributed load acted on the canoe. Point loads represented paddlers, while a cubic function was used to represent the buoyant load. Static equilibrium was maintained by balancing downward forces with the resultant buoyant force, while eliminating residual moments. This balance was achieved by using the magnitude and location of the resultant downward force as a constraint when computing the coefficients of the cubic distributed load (Appendix D).

Table 5: Maximum Stresses

Load Case	Compressive	Tensile
2 Female	49.6 psi	134.8 psi
2 Male	60.9 psi	165.6 psi
Coed	31.7 psi	86.0 psi
Carrying	84.6 psi	31.2 psi
Display	33.3 psi	12.3 psi
Transportation	0.2 psi	0.1 psi

Bending moment diagrams were created for each loading scenario, assuming 200 lbs for male paddlers, 150 lbs for female paddlers, and 250 lbs for *Mandjet* (Figure 2). A dynamic load amplification (DLA) factor was applied to account for momentum generated by paddlers (Paradis and Gendron 2006). Noting the study by Paradis and Gendron determined a DLA of 1.25, our team applied a conservative factor of 2 to account for the variability in natural frequency resulting from differences in our shape and thickness. The maximum compressive stress (84.6 psi) occurs in the gunnels at the center of the canoe while carrying, and the maximum tensile stress (165.6 psi) occurs in the same location during the 2 male loading condition (Table 5).

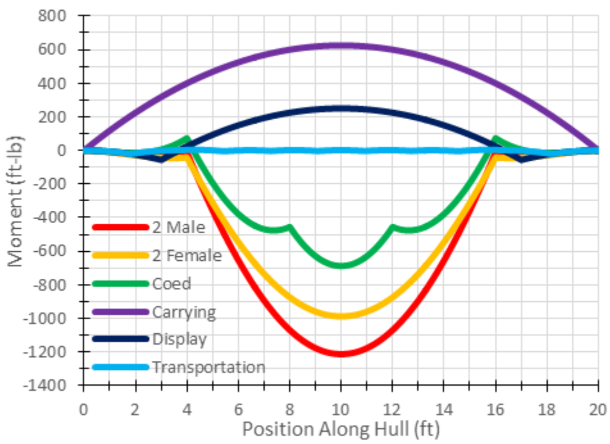


Figure 2: Bending Moment Envelope

The goals for mix design this year were to create a concrete mix that was simultaneously lightweight and strong enough to withstand all possible stresses throughout competition. Another major goal was to design a concrete mix that was easy to place and finish, as this had been a consistent problem with mixes in previous years. These goals were met using a systematic, iterative approach. The effects of each material and mix property were studied. This information was then utilized to create a final mix that met the all of the competition goals.

Due to its low unit weight, last year's mix, *Avanyu*, was used as a baseline for *Mandjet*. *Avanyu* possessed a 55.7 pcf wet unit weight, a 49.3 pcf dry unit weight, an 1100 psi compressive strength, and a 280 psi flexural strength. *Avanyu's* mix consisted of Type I White Portland Cement, Class F fly ash, metakaolin, 3M Glass Bubbles, Extendospheres, Poraver (0.25-1.0 mm), AEA-92 (air entrainer), Acryl 60 (latex), SRA+ (shrinkage reducer), and DS (set retarder). Focus was placed on improving ease of placement and workability without compromising strength or unit weight since *Avanyu's* main difficulty was casting.

Testing began by determining proper aggregate gradation. A smooth gradation curve was desired to achieve a strong, economical mix since well-graded blends minimize voids between aggregate particles typically filled with cement and water. The aggregates studied were 3M Glass Bubbles, cenospheres, and Poraver (varying in size from 0.1-2.0 mm). Sieve analysis tests were conducted for each aggregate, according to ASTM C136, to estimate the gradation of the composite blend. For each test mix, a particle size distribution chart was developed and recorded in order to determine which gradation provided desirable properties (Figure 3). The team initially developed composite blends by fitting them to a Fuller curve (0.5 power curve). This produced mixes that were difficult to place and finish due the increase in 1.0-2.0 mm Poraver. The team switched to utilizing gradations from top performing universities as a new comparison method. Minor modifications were made to the finer aggregates in *Avanyu* to generate a smoother curve. *Mandjet's* gradation consists of Cenospheres, Poraver (varying from 0.25-1.0mm), and 3M Glass Bubbles. Poraver 1.0-2.0 mm was omitted because it typically produced too granular of mixes with low finishing potential. Poraver 0.1-0.3 mm was also excluded to maintain a balanced particle distribution.

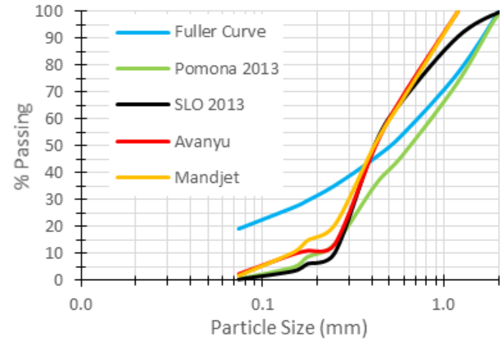


Figure 3: Gradation Curve

Once the desired gradation was achieved, the mix team focused on studying the effects of blending cementitious materials. The materials tested were Type I White Portland Cement, Class F fly ash, metakaolin, and VCAS^{TM}. The properties of each material were researched and proportioned into the mix accordingly. Mixes were created with varying percentages of each cementitious material in order to compare strength, workability, and finishing texture. Type I White Portland Cement (ASTM C150) was kept between 40-60% by weight. Class

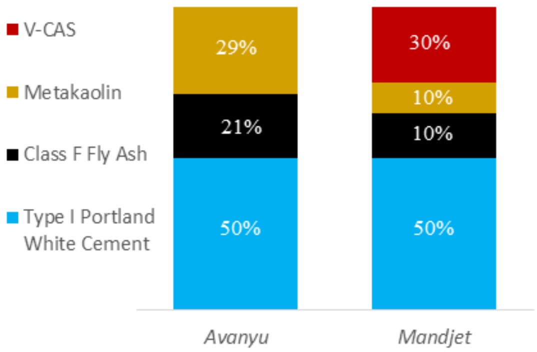


Figure 4: Cementitious Materials

F fly ash (ASTM C618) was added between 10-20% to improve workability while reducing water demand. Metakaolin (ASTM C618) was implemented between 10-15% to improve strength and mitigate cracking developed from the alkali-silica reaction between calcium hydroxide in Portland cement, the alkali, and glass aggregates, the silica (Optipozz). VCAS™ (ASTM C618), known for its improved retention of mold detail, was incorporated between 25-30% to increase the durability of hardened concrete (Vitro Minerals). A combination of 50% Type I White Portland Cement, 15% Class F fly ash, 10% metakaolin, and 25% VCAS™ was determined to provide optimal strength, texture, and workability.

The design process shifted towards admixtures to improve workability, increase strength, and reduce unit weight of the mix. Admixtures taken into consideration were Daraweld C, a bonding agent, Airalon 3000 and AEA-92, air entertainers, SRA+, a shrinkage reducer, ADVA Cast 575, a high-range water-reducer, and DS, a set retarder. Each admixture was first tested individually in order to study the properties it provided to the mix. Then, it was tested in combination to obtain the desired properties. AEA-92 was used to develop an air-void system in the concrete matrix with the main purpose of lowering unit weight. Dosages higher than recommended were needed to achieve the desired 59 pcf unit weight (Table 6). However, the large volume of air-voids created discontinuity in the concrete matrix, which reduced strength by 20%. To offset the strength loss, ADVA Cast 575 was added to maintain the desired workability while lowering the water-to-cement ratio; lower w/cm correlate to higher strengths.

Table 6: Admixture Dosage Rates

Admixture	Type	Recommended Dosage	Structural Mix	Patching Mix
ADVA Cast 575	HRWR	2-10 fl oz/cwt.	5 fl oz/cwt.	3 fl oz/cwt.
AEA-92	AEA	0.1-7 fl oz/cwt.	12 fl oz/cwt.	8 fl oz/cwt.
Daraweld C	Latex	N/A	-	145 fl oz/cwt.

ADVA Cast 575 helped with early strength gain by reducing the w/cm from 0.65 to 0.40. Under guidance from graduate students, superplasticizer (HRWR) was highly recommended with mixes containing metakaolin in order to disperse the particles homogeneously. Metakaolin causes concrete to become sticky, making placement difficult without use of a superplasticizer. Daraweld C was used as an admixture only for the patching mix due to its ability to improve adhesion and cohesion. Since the rules prohibit coating the surface with a bonding admixture, the team incorporated Daraweld C as a constituent in the mix. This improved bond strength of the cold joint formed between the patching and structural mix. Other admixtures were eliminated early in the testing process, as their benefits were not required.

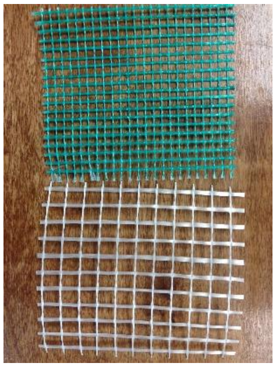


Figure 5: Fiberglass Mesh

Finally, reinforcement was analyzed to enhance tensile strength since concrete is much stronger in compression than in tension. Primary reinforcing carried the structural loads while secondary reinforcing provided resistance to cracking and shrinkage. The team considered two types of fiberglass mesh for primary reinforcing (Figure 5). To compare effectiveness, mesh was placed in concrete plate samples subjected to three-point bending. The white fiberglass mesh was chosen as it promoted better bonding of concrete layers separated by the mix. The smaller openings of the green fiberglass mesh weakened bonding between successive layers promoting susceptibility to cold joints. The white fiberglass mesh provided a 31% increase in flexural strength, as well. Two fibers were tested for secondary reinforcement: Sigrafil C-Type fibers and Grace MicroFibers. Grace fibers were chosen over the Sigrafil fibers due to difficulty dispersing them within the mix. Sigrafil fiber mixes experienced significant clumping which negatively affected strength, placement, and finishing properties. On average, Grace fiber mixes experienced little clumping and were 16% stronger than mixes containing Sigrafil fibers.

Cylinder and plate molds were made for compressive and flexural strength testing according to ASTM C39 and ASTM C78, respectively. Test cylinders were downsized from 3x6” to 2x4” in an effort to conserve materials by producing smaller batch sizes. As a result, the team was able to save an estimated 5 ft^3 of concrete while testing over 60 unique mixes. It is important to note that decreasing cylinder size may cause misleading test results. Smaller sized cylinders are less representative and tend to possess fewer defects within the sample, which can yield higher strength values. The team compared both cylinders, and observed an 8% increase in strength and a 6% increase in unit weight from downsizing the cylinders. It was decided that the economic benefit of utilizing smaller cylinders outweighed the variation in results. Cylinders and plates were cured according to ASTM C31 and tested at 7-day strength. Testing at 7-days was chosen over 14-days or 28-days based on results from last year, confirmed with initial tests this year. Results showed that our concrete reaches 80-85% strength at 7-days, whereas normal concrete typically reaches 60% strength at 7-days. Testing early also increased the effectiveness of the design process since the results of altering the mix were obtained sooner. The team concluded that 7-day strength was a good representation of the ultimate strength, and the additional strength gained by further curing was an inefficient use of time.

Sustainability was incorporated throughout the design process by utilizing recycled materials, downsizing compression cylinders, and reducing cement content. Firstly, recycled materials including cenospheres and fly ash, byproducts of coal combustion, and Poraver, made from post-consumer recycled glass, comprised 95% of aggregates and 15% of cementitious materials by weight. Secondly, the team conserved approximately 5 ft^3 of concrete materials by using 2x4” cylinders instead of standard 3x6” cylinders, which require more than 3 times the material to produce. Thirdly, the team optimized gradation to minimize voids between aggregate particles, and also replaced 50% Portland cement with supplementary cementitous materials to reduce cement content. This decreased CO_2 and other air-emissions generated from cement production proportional to the amount of cement eliminated from the mix (Concrete Sustainability Initiative).

The final concrete mix for *Mandjet* met all of the design team’s goals. The mix exceeded the required compressive and tensile strength with a factor of safety of 14.3 and 2.2, respectively. The unit weight was less than water, 59.1 pcf. And, the mix remained workable for 20 minutes longer than *Avanyu*, allowing for easy placement and finishing on the mold.

Table 7: Final Testing Results

Property	Required Value	Actual Value
Compressive Strength	90 psi	1290 psi
Tensile Strength	170 psi	380 psi
Unit Weight	-	59.1 pcf

The planning process began with the issuance of the rules and regulations. Weekly meetings were held during the hull design phase to determine the most viable materials and methods for constructing *Mandjet*. The team decided to use a male mold made from 1.5 pcf expanded polystyrene (EPS) foam due to the ease of construction last year. This year's aim was to improve upon last year's construction process by reducing cost, and implementing new construction techniques and quality control methods. The entire process was spread out over a five month period beginning with mold construction, casting, and lastly, concrete finishing.

Figure 6: ShopBot CNC

Mold construction began by drafting the finalized hull design in AutoCAD. The hull was offset by ½" to account for the thickness of the canoe, then cross section cuts were taken at two inch intervals generating a stair stepping pattern in the mold. Upon drafting completion, cross sections were imported into VCarve Pro, a toolpathing software, where they were ready to cut. Team captains developed a no-cost, in-house cutting operation by capitalizing on ASU's partnership with TechShop Chandler. TechShop offered ASU students free access and training to their ShopBot CNC (Computer Numeric Control) machine (Figure 6). Construction team managers personally operated the CNC machine, resulting in a cost savings of $3000 towards the construction budget compared to last year. A total of 118 cross sections were cut to assemble the male mold.

Figure 7: Applying Joint Compound

After cutting was completed, the 118 sections were adhered using Elmer's Rubber Cement and fitted on top of a continuous steel bar to achieve proper alignment between cross sections. The stair stepping pattern was then sanded flush with 50 grit sand paper to create a smooth transition between adjacent sections. Any defects occurred during initial sanding were fixed through a continuous process of applying a 1/16" thick layers of joint compound (Figure 7), then sanding with 120 grit sand paper until the mold met quality control specifications. This process attributed to more than half of the 900 man-hours dedicated towards construction.

Contact paper and vinyl sheeting were analyzed as releasing agents to facilitate form removal. Vinyl sheeting was chosen since it provided a smooth finish with minimal patching. However, the vinyl began separating from the mold a day after placement due to uneven drying of the adhesive. After being unable to reapply the releasing agent, the vinyl was removed causing minor damage to the mold (Figure 8). Casting was delayed a week in order to repair the mold and apply a new releasing agent. Elmer's Glue was suggested by alumni for its low surface energy and high contact angle compared to the vinyl used previously. Acting as a barrier release agent, Elmer's Glue reduced moisture loss and facilitated removal of the mold. Releasing agent was not applied to the bow and stern as 3 feet of foam was intended to be left in place to provide additional floatation.

Figure 8: Damage to Mold

Mandjet incorporates one layer of fiberglass mesh to resist tensile forces and protect against puncture. The mesh was draped along the length of the mold and contoured to fit the mold prior to casting. Additional mesh reinforcing was required along the walls since the mesh could not span over the entire canoe. A four inch overlap was provided between the meshes to ensure the reinforcement acted as a continuous system. A layer of chicken wire, extending three inches inward from the tip of the bow and stern, was also placed to reduce slumping while forming the sharp, streamlined shape of the bow and stern.

The construction team implemented an innovative quality control method to gauge thickness during and after casting. Wooden guides, spaced at one foot intervals along the canoe, were fabricated using a CNC machine to measure the outer thickness (Figure 9). This improved casting efficiency by reducing typical casting time from 6 hours to 3 hours, while ensuring a high quality product with uniform thickness. The team also constructed a new curing chamber (Figure 10) made out of plastic canvas, misters, and humidifiers. This created a controlled environment providing proper hydration and humidity for an efficient wet curing process, safe from the dry Arizona air.

Figure 9: Wooden Guides

Figure 10: Curing Chamber

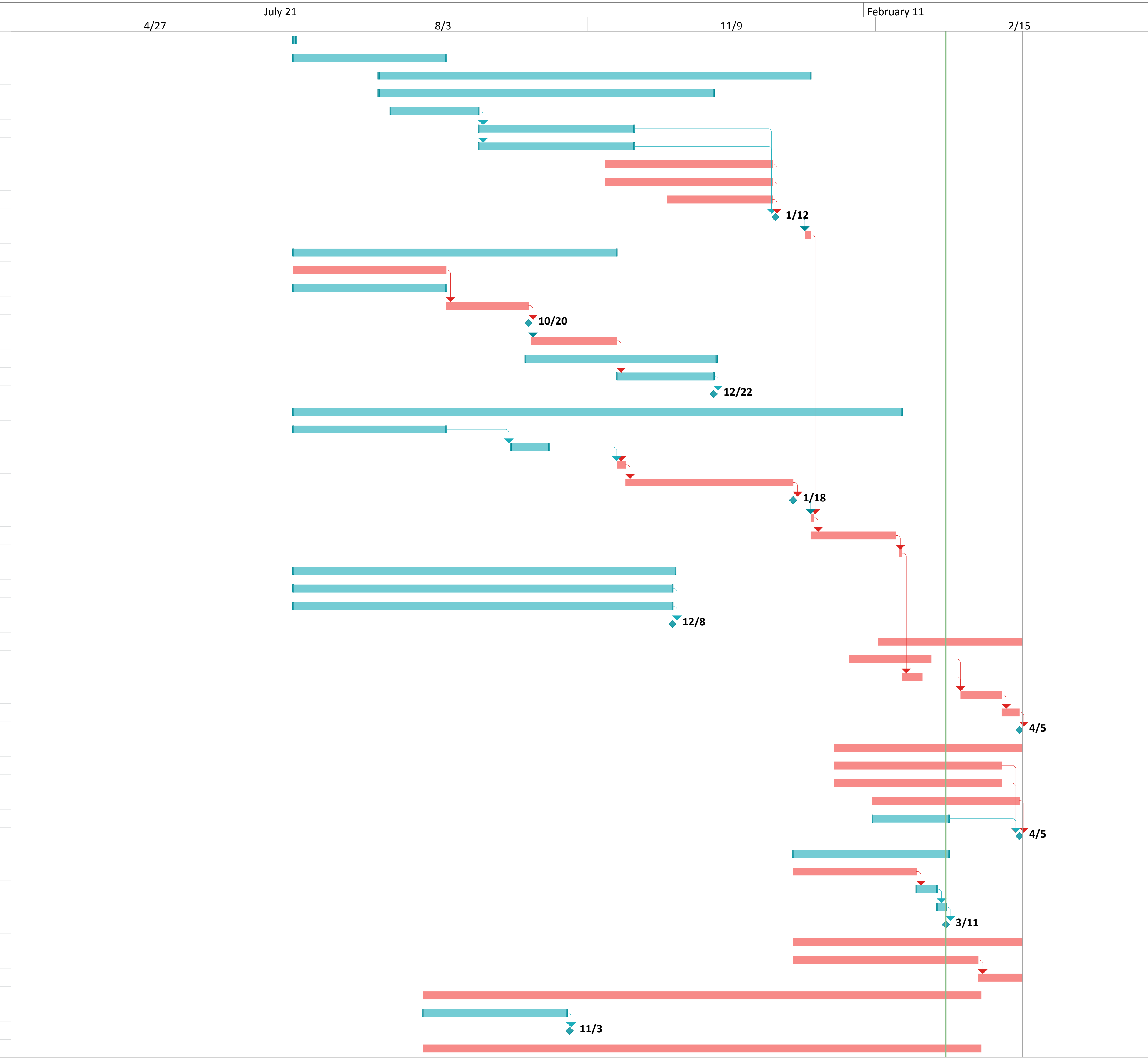
A total of twenty six team members, alumni, and faculty cast *Mandjet* in three steps. First, a ¼" layer of structural mix was applied by hand using tire tread gauges to regulate thickness. Second, the pre-fitted fiberglass mesh was placed over the first layer of concrete. Finally, an additional ¼" layer of structural mix was applied by hand using wooden guides to regulate thickness and finished smooth by troweling.

To offset time lost from repairing the mold, the sanding process was initiated after a 14-day cure. The team performed a wet sand with 50 grit sand paper on the outside using the wooden guides to ensure constant thickness throughout. A patching mix was applied to the outside at 21-days to fill any inconsistencies, and then left to cure for another 7 days. *Mandjet* was removed from the mold after the initial 28-day curing period. The bulkheads and inside were patched, and then the entire canoe was wet sanded using 120 grit sand paper to create a smooth surface. Wet sanding was utilized, instead of dry sanding, to reduce exposure to dust particles containing calcium hydroxide and crystalline silica, providing a safer work environment.

Sustainability was incorporated by efficiently utilizing resources to reduce and properly dispose of waste. The team utilized VCarve's optimization tool to fit as many section cuts as possible on one sheet of foam. This reduced the amount of foam needed by six sheets. The team also utilized Arizona State University's hazardous waste disposal program to properly dispose of expired admixtures, old concrete specimens, and other waste from mold construction.

Overall, the team succeeded in improving upon last year's construction techniques, saving time, materials, and cost, while improving upon quality. *Mandjet* is ready once again to turn night into day and demonstrate the growing strength of the Sun Devils.

ID	Task Name	Duration	Start	Finish	Baseline Start	Baseline Finish	Predecessors
1	**First Meeting and Start**	**1 day**	**Fri 8/1/14**	**Fri 8/1/14**	**Fri 8/1/14**	**Fri 8/1/14**	
2	**Planning and Organizing**	**37 days**	**Fri 8/1/14**	**Sun 9/21/14**	**Fri 8/1/14**	**Sun 9/21/14**	
3	**Concrete Mix Design**	**106 days**	**Sat 8/30/14**	**Fri 1/23/15**	**Sat 8/30/14**	**Fri 1/16/15**	
4	Research	82 days	Sat 8/30/14	Sun 12/21/14	Sat 8/30/14	Sun 12/7/14	
5	Material Procurement	22 days	Wed 9/3/14	Thu 10/2/14	Sat 8/30/14	Fri 9/26/14	
6	Aggregate Testing	37 days	Fri 10/3/14	Mon 11/24/1	Sat 10/18/14	Sun 12/7/14	5
7	Cementitious Material	37 days	Fri 10/3/14	Mon 11/24/1	Sat 10/18/14	Sun 12/7/14	5
8	Admixture Testing	42 days	Sat 11/15/14	Sat 1/10/15	Sat 11/1/14	Sun 12/7/14	
9	Fiber Testing	42 days	Sat 11/15/14	Sat 1/10/15	Sat 11/1/14	Sun 12/7/14	
10	Reinforcement Testing	27 days	Sat 12/6/14	Sat 1/10/15	Sat 11/1/14	Sun 12/7/14	
11	Final Mix Selection	0 days	Mon 1/12/15	Mon 1/12/15	Mon 12/7/15	Mon 12/7/15	6,7,8,9,10
12	Pre-Weigh Materials	2 days	Thu 1/22/15	Fri 1/23/15	Thu 1/15/15	Fri 1/16/15	11
13	**Hull Design**	**78 days**	**Fri 8/1/14**	**Tue 11/18/14**	**Mon 7/14/14**	**Sat 11/1/14**	
14	Learn Software	37 days	Fri 8/1/14	Sun 9/21/14	Fri 8/1/14	Sun 9/21/14	
15	Research	37 days	Fri 8/1/14	Sun 9/21/14	Fri 8/1/14	Sun 9/21/14	
16	Design in DELFTship	21 days	Mon 9/22/14	Sun 10/19/14	Sun 9/21/14	Sun 10/19/14	14
17	Finalize Hull Design	0 days	Mon 10/20/1	Mon 10/20/1	Mon 10/20/14	Mon 10/20/14	16
18	Complete Drafting for CNC	21 days	Tue 10/21/14	Tue 11/18/14	Tue 10/21/14	Sat 11/1/14	17
19	**Structural Analysis**	**47 days**	**Sun 10/19/14**	**Mon 12/22/1**	**Sun 10/19/14**	**Sat 11/22/14**	
20	2D Beam Analysis	24 days	Wed 11/19/1	Sun 12/21/14	Sun 10/19/14	Sat 11/22/14	18
21	Finalize Analysis	0 days	Mon 12/22/1	Mon 12/22/1	Sat 11/22/14	Sat 11/22/14	20
22	**Construction**	**147 days**	**Fri 8/1/14**	**Mon 2/23/15**	**Fri 8/1/14**	**Sat 2/14/15**	
23	Construction Planning	37 days	Fri 8/1/14	Sun 9/21/14	Fri 8/1/14	Sun 9/21/14	
24	Material Procurement	10 days	Tue 10/14/14	Sun 10/26/14	Sun 10/12/14	Sun 10/26/14	23
25	CNC Form	3 days	Wed 11/19/1	Fri 11/21/14	Sun 10/26/14	Fri 10/31/14	18,24
26	Construct Mold	42 days	Sat 11/22/14	Sat 1/17/15	Sat 11/1/14	Sat 12/13/14	25
27	Complete Mold	0 days	Sun 1/18/15	Sun 1/18/15	Sat 12/13/14	Sat 12/13/14	26
28	Canoe Casting	1 day	Sat 1/24/15	Sat 1/24/15	Sat 1/17/15	Sat 1/17/15	12,27
29	Concrete Curing	22 days	Sat 1/24/15	Sat 2/21/15	Sat 1/17/15	Sat 2/14/15	28
30	Form Removal	1 day	Mon 2/23/15	Mon 2/23/15	Sat 2/14/15	Sat 2/14/15	29
31	**Aesthetic Design**	**92 days**	**Fri 8/1/14**	**Mon 12/8/14**	**Fri 8/1/14**	**Sun 12/7/14**	
32	Theme Selection	92 days	Fri 8/1/14	Sun 12/7/14	Fri 8/1/14	Sun 12/7/14	
33	Design Skething	92 days	Fri 8/1/14	Sun 12/7/14	Fri 8/1/14	Sun 12/7/14	
34	Finalized Canoe Design	0 days	Mon 12/8/14	Mon 12/8/14	Mon 12/8/14	Mon 12/8/14	32,33
35	**Finishing**	**36 days**	**Mon 2/16/15**	**Sun 4/5/15**	**Sat 2/14/15**	**Sun 4/5/15**	
36	Patching/Sanding Exterior	20 days	Fri 2/6/15	Thu 3/5/15	Sat 2/14/15	Fri 3/6/15	
37	Patching/Sanding Interior	5 days	Tue 2/24/15	Mon 3/2/15	Sun 3/8/15	Mon 3/16/15	30
38	Staining	11 days	Mon 3/16/15	Sun 3/29/15	Mon 3/16/15	Sun 3/29/15	36,37
39	Sealing	6 days	Mon 3/30/15	Sat 4/4/15	Sun 3/29/15	Sun 4/5/15	38
40	Canoe Finished	0 days	Sun 4/5/15	Sun 4/5/15	Sun 4/5/15	Sun 4/5/15	39
41	**Display**	**47 days**	**Sun 2/1/15**	**Sun 4/5/15**	**Sun 2/1/15**	**Sun 4/5/15**	
42	Construct Stand	42 days	Sun 2/1/15	Sun 3/29/15	Sun 2/1/15	Sun 3/29/15	
43	Construct Display Table	42 days	Sun 2/1/15	Sun 3/29/15	Sun 2/1/15	Sun 3/29/15	
44	Construct Cutaway	37 days	Sat 2/14/15	Sat 4/4/15	Sat 2/14/15	Sun 4/5/15	
45	Engineer's Notebook	19 days	Sat 2/14/15	Wed 3/11/15	Sat 2/14/15	Wed 3/11/15	
46	Complete Display	0 days	Sun 4/5/15	Sun 4/5/15	Sun 4/5/15	Sun 4/5/15	42,43,44,45
47	**Design Paper**	**39 days**	**Sun 1/18/15**	**Wed 3/11/15**	**Sun 1/18/15**	**Tue 2/24/15**	
48	Rough Draft	32 days	Sun 1/18/15	Sun 2/28/15	Sun 1/18/15	Sun 2/22/15	
49	Peer Review	7 days	Sun 3/1/15	Sat 3/7/15	Fri 2/13/15	Wed 2/18/15	48
50	Final Draft	3 days	Sun 3/8/15	Tue 3/10/15	Wed 2/18/15	Tue 2/24/15	49
51	Send Paper	0 days	Wed 3/11/15	Wed 3/11/15	Tue 2/24/15	Tue 2/24/15	50
52	**Presentation**	**57 days**	**Sun 1/18/15**	**Sun 4/5/15**	**Sun 1/18/15**	**Sun 4/5/15**	
53	Powerpoint Development	47 days	Sun 1/18/15	Sat 3/21/15	Sun 1/18/15	Sat 3/21/15	
54	Rehearsal	12 days	Sun 3/22/15	Sun 4/5/15	Sat 3/21/15	Sun 4/5/15	53
55	**Paddling**	**137 days**	**Sun 9/14/14**	**Sun 3/22/15**	**Sun 9/14/14**	**Sun 3/22/15**	
56	Tryouts	37 days	Sun 9/14/14	Sat 11/1/14	Sun 9/14/14	Sat 11/1/14	
57	Team Selection	0 days	Mon 11/3/14	Mon 11/3/14	Sat 11/1/14	Sat 11/1/14	56
58	Conditioning	137 days	Sun 9/14/14	Sun 3/22/15	Sun 9/14/14	Sun 3/22/15	



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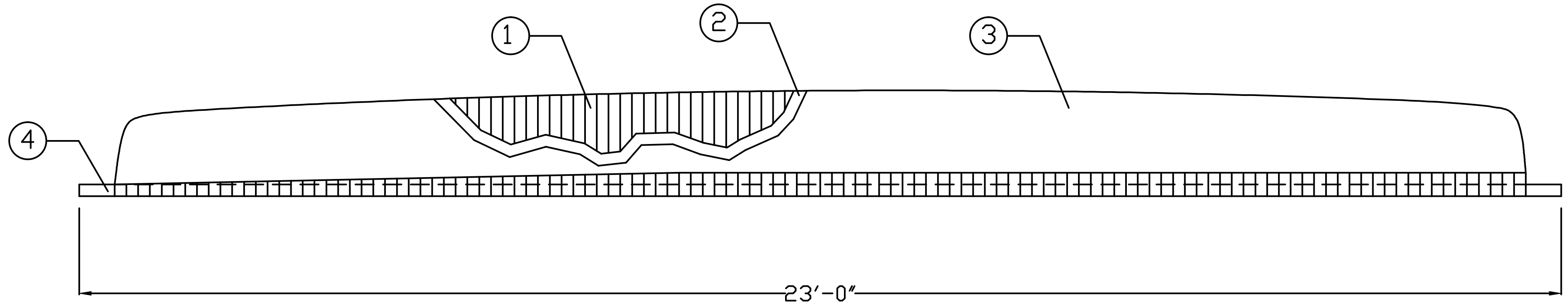
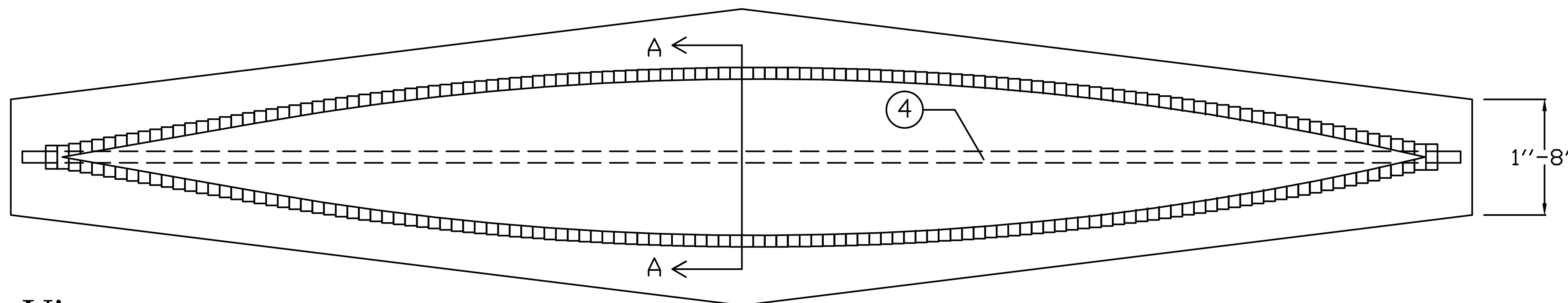
Task

Milestone

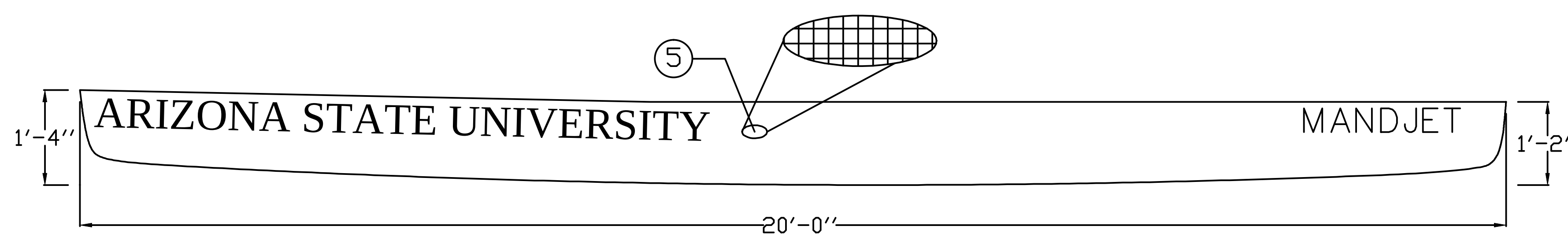
Critical Path

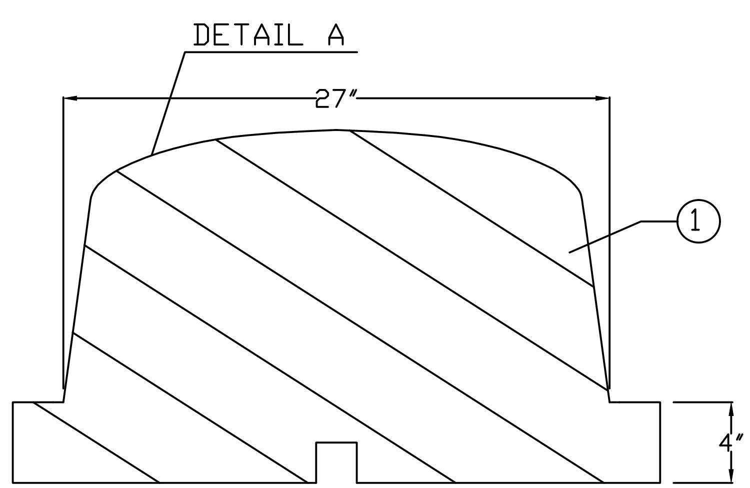


Elevation View

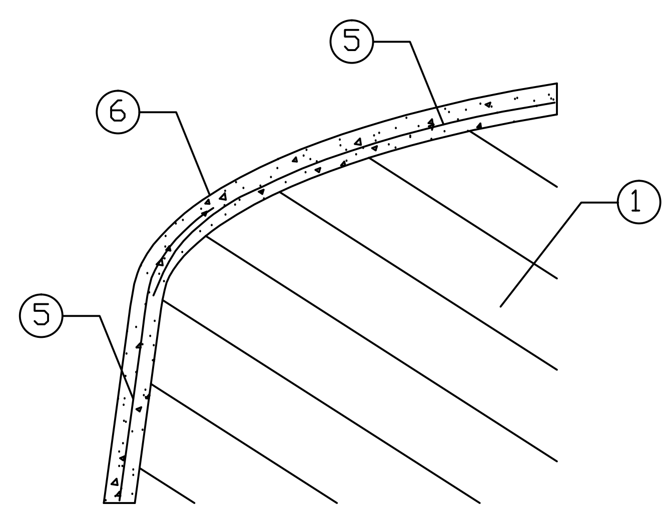


Plan View





Section A-A (WIDEST SECTION)



DETAIL A
REINFORCEMENT WITHIN CONCRETE

BILL OF MATERIALS

Part	Qty	Description
1	120	Expanded Polystyrene Foam
2	5 gal	Joint Compound
3	65 sf	Releasing Agent
4	1	HSS 2"X2"X23'-0"
5	80 sf	Fiberglass Mesh
6	4.16 ft^3	Concrete (Per Mix Design Appendix B)

MANDJET

Form Design Drawings

Design By:	Steven Sherant
Drawn By:	Steven Sherant
Approved By:	Mackenzie Hagan
Scale:	Not To Scale
Submittal Date: 3/11/2015	Page: 10

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Appendix B – Mixture Proportions (Structural Mix)

	Mixture ID:		Design Proportions (Non SSD)		Actual Batched Proportions		Yielded Proportions	
Y_D	Design Batch Size (ft^3):	0.13						
Cementitious Materials		SG	Amount (lb/yd^3)	Volume (ft^3)	Amount (lb)	Volume (ft^3)	Amount (lb/yd^3)	Volume (ft^3)
CM1	White Portland Cement	3.15	362.50	1.844	1.745	0.009	384.76	1.957
CM2	Class F Fly Ash	2.30	108.75	0.758	0.524	0.004	115.43	0.804
CM3	Metakaolin	2.50	72.50	0.465	0.349	0.002	76.95	0.493
CM4	VCAS-8	2.60	181.25	1.117	0.873	0.005	192.38	1.186
	Total Cementitious Materials:		725.00	4.18	3.491	0.02	769.51	4.44
Fibers								
F1	Grace MicroFiber™	0.91	2.00	0.035	0.010	0.000	2.12	0.037
	Total Fibers:		2.00	0.04	0.010	0.00	2.12	0.037
Aggregates								
A1	Cenospheres Abs: 5%	0.70	80.00	1.832	0.385	0.009	84.91	1.944
A2	3M Glass Bubbles Abs: 0%	0.15	20.00	2.137	0.096	0.010	21.23	2.268
A3	Poraver (0.25-0.5) Abs: 28%	0.68	130.00	3.064	0.626	0.015	137.98	3.252
A4	Poraver (0.5-1) Abs: 20%	0.47	180.00	6.137	0.867	0.030	191.05	6.514
	Total Aggregates:		410.00	13.17	1.974	0.06	435.17	13.98
Water								
W1	Water for CM Hydration (W1a + W1b)	1.00	290.00	4.647	1.40	0.022	307.80	4.933
	W1a. Water from Admixtures		6.92		0.03		7.34	
	W1b. Additional Water		283.08		1.36		300.46	
W2	Water for Aggregates, SSD	1.00	76.40		0.37		81.09	
	Total Water *(W1 + W2)* **:**		366.40	4.65	1.76	0.02	388.89	4.93
Solids Content of Latex, Dyes and Admixtures in Powder Form								
S1	Latex	1.04	0.00	0.000	0.00	0.000	0.00	0.000
	Total Solids of Admixtures:		0.00	0.00	0.00	0.00	0.00	0.00
Admixtures (including Pigments in Liquid Form)		% Solids	Dosage (fl oz/cwt)	Water in Admixture (lb/yd^3)	Amount (fl oz)	Water in Admixture (lb)	Dosage (fl oz/cwt)	Water in Admixture (lb/yd^3)
Ad1	AEA 92 (Air Entrainer) *8.5* *lb/gal*	6.00	12.00	5.41	0.41889	0.02607	12.7	5.75
Ad2	ADVA® Cast 575 (Superplasticiz *9.1* *lb/gal*	41.00	5.00	1.51	0.17454	0.00729	5.3	1.61
Ad3	DARAWELD® C (Latex) *8.6* *lb/gal*	28.00	0.00	0.00	0.00000	0.00000	0.0	0.00
	Water from Admixtures *(W1a)* **:**			6.93		0.03		7.35
	Cement-Cementitious Materials Ratio		0.500		0.500		0.500	
	Water-Cementitious Materials Ratio		0.400		0.400		0.400	
	Slump, Slump Flow, *in* .		0.00		0.0		0.0	
M	Mass of Concrete. *lbs*		1504.80		7.24		1595.70	
V	Absolute Volume of Concrete, ft^3		22.04		0.11		23.39	
T	Theorectical Density, lb/ft^3 = (M / V)		68.29		68.22		68.22	
D	Design Density, lb/ft^3 = $(M / 27)$		55.73					
D	Measured Density, lb/ft^3				59.100		59.100	
A	Air Content, % = $[(T - D) / T \times 100\%]$		18.39		13.37		13.37	
Y	Yield, ft^3 = (M / D)		**27.000**		0.122		**27.000**	
Ry	Relative Yield = (Y / Y_D)				0.942			

Appendix B – Mixture Proportions (Patching Mix)

	Mixture ID:		Design Proportions (Non SSD)		Actual Batched Proportions		Yielded Proportions	
Y_D	Design Batch Size (ft^3):	0.13						
Cementitious Materials		SG	Amount (lb/yd^3)	Volume (ft^3)	Amount (lb)	Volume (ft^3)	Amount (lb/yd^3)	Volume (ft^3)
CM1	White Portland Cement	3.15	362.50	1.844	1.745	0.009	411.83	2.095
CM2	Class F Fly Ash	2.30	108.75	0.758	0.524	0.004	123.55	0.861
CM3	Metakaolin	2.50	72.50	0.465	0.349	0.002	82.37	0.528
CM4	VCAS-8	2.60	181.25	1.117	0.873	0.005	205.91	1.269
	Total Cementitious Materials:		725.00	4.18	3.491	0.02	823.65	4.75
Fibers								
F1	Grace MicroFiber™	0.91	0.00	0.000	0.000	0.000	0.00	0.000
	Total Fibers:		0.00	0.00	0.000	0.00	0.00	0.000
Aggregates								
A1	Cenospheres Abs 5%	0.70	80.00	1.832	0.385	0.009	90.89	2.081
A2	3M Glass Bubbles Abs 0%	0.15	20.00	2.137	0.096	0.010	22.72	2.427
A3	Poraver (0.25-0.5) Abs 28%	0.68	130.00	3.064	0.626	0.015	147.69	3.481
A4	Poraver (0.5-1) Abs 20%	0.47	180.00	6.137	0.867	0.030	204.49	6.973
	Total Aggregates:		410.00	13.17	1.974	0.06	465.79	14.96
Water								
W1	Water for CM Hydration (W1a + W1b)	1.00	275.50	4.415	1.33	0.021	312.99	5.016
	W1a. Water from Admixtures		55.59		0.27		63.15	
	W1b. Additional Water		219.91		1.06		249.83	
W2	Water for Aggregates, SSD	1.00	76.40		0.37		86.80	
	Total Water *(W1 + W2)* **:**		351.90	4.42	1.69	0.02	399.78	5.02
Solids Content of Latex, Dyes and Admixtures in Powder Form								
S1	Latex	1.04	19.87	0.308	0.10	0.001	22.58	0.350
	Total Solids of Admixtures:		19.87	0.31	0.10	0.00	22.58	0.35
Admixtures (including Pigments in Liquid Form)		% Solids	Dosage (fl oz/cwt)	Water in Admixture (lb/yd^3)	Amount (fl oz)	Water in Admixture (lb)	Dosage (fl oz/cwt)	Water in Admixture (lb/yd^3)
Ad1	AEA 92 (Air Entrainer) 8.5 lb/gal	6.00	8.00	3.61	0.27926	0.01738	9.1	4.10
Ad2	ADVA® Cast 575 (Superplasticiz 9.1 lb/gal	41.00	3.00	0.91	0.10472	0.00437	3.4	1.03
Ad3	DARAWELD® C (Latex) 8.6 lb/gal	28.00	145.00	51.10	5.06157	0.24606	164.7	58.06
	Water from Admixtures *(W1a)* **:**			4.52		0.02		5.13
Cement-Cementitious Materials Ratio			0.500		0.500		0.500	
Water-Cementitious Materials Ratio			0.380		0.380		0.380	
Slump, Slump Flow, *in* .			0.00		0.0		0.0	
M	Mass of Concrete. *lbs*		1507.62		7.25		1711.80	
V	Absolute Volume of Concrete, ft^3		22.08		0.11		25.08	
T	Theorectical Density, lb/ft^3 = *(M / V)*		68.29		68.25		68.25	
D	Design Density, lb/ft^3 = *(M / 27)*		55.84					
D	Measured Density, lb/ft^3				63.400		63.400	
A	Air Content, % = *[(T - D) / T x 100%]*		18.24		7.11		7.11	
Y	Yield, ft^3 = *(M / D)*		**27.000**		0.114		**27.000**	
Ry	Relative Yield = (Y / Y_D)				0.880			

Appendix C – Bill of Materials

Material	Quantity	Units	Unit Price	Total
Cementicious Materials				
Type I Portland White Cement	73.31	lbs	$0.27	$19.79
Class F Fly Ash	21.99	lbs	$0.43	$9.46
Metakaolin	14.66	lbs	$0.81	$11.88
V-CAS 8™	36.65	lbs	$0.76	$27.86
Aggregates				
Cenospheres	16.18	lbs	$4.00	$64.71
3M™ K15 Glass Bubbles	4.04	lbs	$12.50	$50.55
Poraver® 0.5-1.0mm	26.29	lbs	$0.70	$18.40
Poraver® 0.25-0.5mm	36.40	lbs	$0.70	$25.48
Admixtures				
ADVA® Cast 575	6.64	fl oz	$0.09	$0.60
AEA-92	16.19	fl oz	$0.12	$1.94
DARAWELD®	50.62	fl oz	$0.10	$5.06
Concrete Fibers				
Grace MicroFiber™	0.308	lbs	$7.14	$2.20
Reinforcement				
Fiber Glass Mesh	67.5	sq ft	$2.70	$182.25
Mold Construction				
2 pcf EPS foam	20	cu ft	$19.20	$384.00
Oriented Strand Board	3	sheets	$10.05	$30.15
Joint Compound	4	gal	$14.48	$57.92
Elmer's Glue	3	gal	$19.49	$58.47
Finishing				
Vibra-Stain Concentrate (WB)	32	fl oz	$2.50	$80.00
Crystal Clear VOC Sealer	2	gal	$10.80	$21.60
Vinyl Lettering	184	sq in	$0.11	$20.24
			Total Production Cost	$1,072.56

Internal stresses were computed by first developing a free body diagram (Figure A-1). For the 2-male loading condition, the following assumptions were made: canoe acts as a beam, $w_c = 12.5\ \mathrm{lb/ft}$, $L = 20\ \mathrm{ft}$, $W_M = 200\ \mathrm{lb}$, $L_1 = 4\ \mathrm{ft}$, $L_2 = 16\ \mathrm{ft}$, and the buoyant distributed load is cubic. The coefficients of the cubic load were computed using a system of equations by setting the magnitude and location of the downward resultant force equal to the magnitude and centroid for a cubic function. The distributed load was also constrained to equal zero at the bow and stern. The following integrals compute the magnitude and centroid of a cubic function,

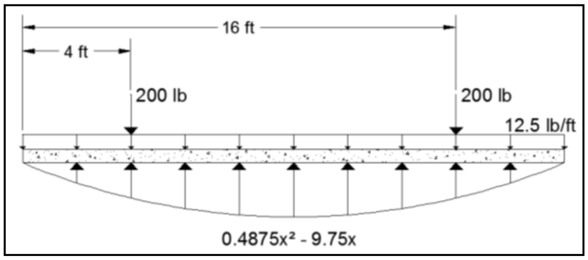

Figure D-I: Free Body Diagram

$$R = \int_0^L [ax^3 + bx^2 + cx]dx = aL^4 + bL^3 + cL^2$$
$$\bar{x}R = \int_0^L x[ax^3 + bx^4 + cx^3]dx = aL^5 + bL^4 + cL^3$$

Sum the vertical forces and moments from the FBD to compute the magnitude and location of the resultant buoyant force, then solve the system of equations.

$$+\uparrow \Sigma F_y = R - w_c L - 2W_M = 0 \qquad \Rightarrow \quad R = 650\ \mathrm{lb}$$
$$+\circlearrowleft \Sigma M_{bow} = \bar{x}R - 0.5 w_c L^2 - W_M(L_1 + L_2) = 0 \qquad \Rightarrow \quad \bar{x}R = 6500\ \mathrm{ft\cdot lb}$$

$$\begin{aligned} aL^3 + bL^2 + cL &= 0 \\ aL^4 + bL^3 + cL^2 &= R \\ aL^5 + bL^4 + cL^3 &= \bar{x}R \end{aligned} \quad \Rightarrow \quad \begin{bmatrix} 20^3 & 20^2 & 20 \\ 20^4 & 20^3 & 20^2 \\ 20^5 & 20^4 & 20^3 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 0 \\ 650 \\ 6500 \end{bmatrix} \quad \Rightarrow \quad \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 0.000 \\ 0.4875 \\ -9.75 \end{bmatrix}$$

Note: taking the inverse will not work since the matrix is singular; another method, such as, least-squares is required to find a solution. MATLAB was used to compute the coefficients.

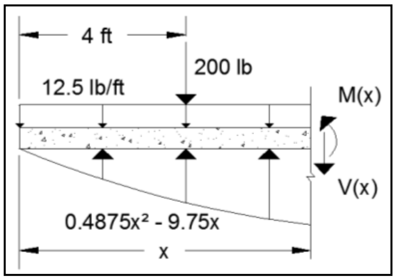

Figure D-2: FBD of 2nd

Shear force and bending moment diagrams were computed from the FBD by taking three cuts, then summing vertical forces and moments for each cut. One cut was taken before the 1st point load, one in-between the 1st and 2nd point load, and one after the 2nd point load. Example calculations for the 2nd cut are shown below. The equations for the other cuts are computed in a similar manner, the only difference being the contribution from the point loads.

$$V_2(x) = w_c x + \int_0^x [0.4875x^2 - 9.75x]dx - W_M$$
$$V_2(x) = (0.4875/3)x^3 - (9.75/2)x^2 - 12.5x - 200 \qquad 4\ \mathrm{ft} \le x \le 16\ \mathrm{ft}$$

$$M_2(x) = -0.5 w_c x^2 - x\int_0^x [0.4875x^2 - 9.75x]dx + \int_0^x [0.4875x^3 - 9.75x^2]dx - W_M(x - L_1)$$
$$M_2(x) = (-0.4875/12)x^4 + (9.75/6)x^3 - 6.25x^2 - 200(x - 4) \qquad 4\ \mathrm{ft} \le x \le 16\ \mathrm{ft}$$

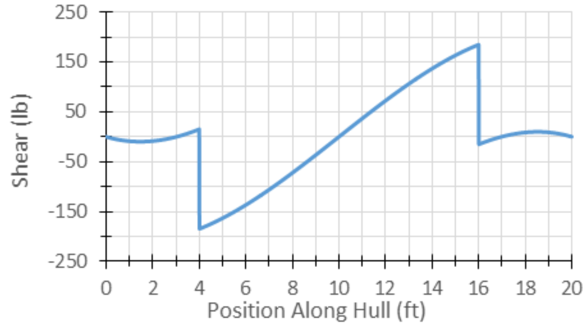

Figure D-3: Shear Force Diagram

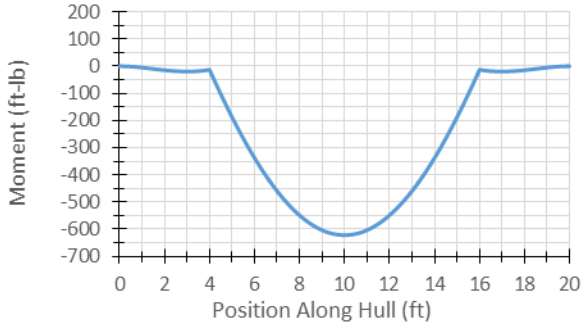

Figure D-4: Bending Moment Diagram

The largest shear (185 lbs) occurs at the location of the paddlers, and the largest moment (622 ft-lb) occurs at the center of the canoe. Stresses are computed by applying these forces and moments to the cross-section. Cross-sectional properties were found by first taking the outer coordinates of the hull, then offsetting by the thickness of 1/2" to obtain the inner coordinates. Quadratic splines were fit to the inner and outer coordinates to generate equations that could be integrated between each coordinates to determine all cross-sectional properties, including, moment of inertia and location of the neutral axis. Parallel axis theorem was used to shift the moment of inertia to act through the neutral axis. This process involves iterative and repetitive calculations; MATLAB was used to execute these calculations using the following integrals:

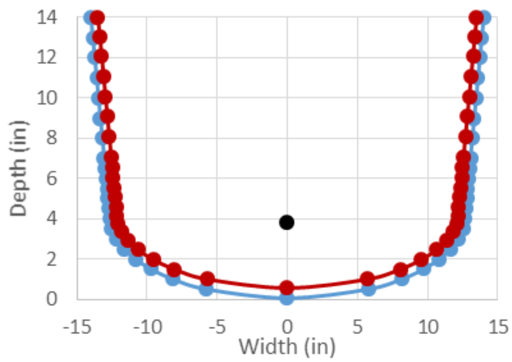

Figure D-5: Location of Centroid

$$I_{xx} = \frac{1}{2}\int ([f_{out}(x)]^2 - [f_{in}(x)]^2)dx + A\bar{y}^2 \qquad I_{yy} = 2\int x[f_{out}(x) - f_{in}(x)]dx$$

$$\bar{x} = \frac{I_y}{A} \qquad \bar{y} = \frac{I_x}{A} \qquad A = \int f_{out}(x) - f_{in}(x)$$

Stress were then computed by applying the theory of simple bending, $\sigma = Mc/I$, where M is the bending moment, c is the distance from the neutral axis to the outermost fiber, and I is the moment of inertia (about the x-x axis for longitudinal analysis). Since the maximum bending moment is negative, the belly of the canoe is in compression and the gunnels are in tension. A DLA factor of 2 was assumed to amplify the stress due to the dynamics effects of paddling.

Table D-1: Cross-Sectional Properties

Property	Value
Centroid (in)	(0, 3.8)
Area (in²)	21.7
I_{xx} (in⁴)	895.6
I_{yy} (in⁴)	57.7

$$\sigma_c = \frac{2(622\text{ ft}\cdot\text{lb})(3.8\text{ in})(12)}{895.6\text{ in}^4} = 63.3\text{ psi}$$

$$\sigma_t = \frac{2(622\text{ ft}\cdot\text{lb})(14\text{ in} - 3.8\text{ in})(12)}{895.6\text{ in}^4} = 170\text{ psi}$$