THRAKOS

CORNELL CONCRETE CANOE

2015-2016

Thrakos

2016 Concrete Canoe Design Report
Cornell University
Ithaca, NY

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EXECUTIVE SUMMARY

Every member of the 2015-2016 Cornell University Concrete Canoe (CCC) Team is in search of perfection. As engineers, we are continuously asked to reach for that limit, though as the world grows and advances faster than ever before, the standard for perfection rises along with it. We are reminded time and again that constant iteration and refinement are needed for improvement. It may seem counter-intuitive, then, that to meet this challenge, we look to our ancient Greek roots – the island of Ithaca, our city's namesake, and home to the great explorer Odysseus.

But ancient Greece, the cradle of western civilization, was once a bastion of progress and technology. Her citizens valued creativity and innovation much as we do today, and executed their designs with flair, leading to lasting classic monuments like the Parthenon and the Arch of Hadrian. As we attempt to emulate our ancestors, we take on the symbol of the Greek dragon: in mythology, dragons consistently present challenges and risks to heroes, gods, and demigods — we as engineers are destined to conquer them as well. With our 2015-2016 entry, *THRAKOS*, the Cornell University Concrete Canoe team hopes to cast a new, stronger foundation with which we can continue our pursuit of perfection.

Founded in 1865, Cornell University certainly has a long history of raising the bar. Located in the rolling hills of Ithaca, New York, Cornell attracts the nation's best students, and its College of Engineering consistently ranks among the top undergraduate programs worldwide. Since the team's return to the ASCE Upstate NY Student Conference in 2008, the team has experienced its share of ups and downs. Over the past three years, Cornell has finished in 3rd (*RINGLEADER, 2013*), 2nd (*URSA MAJOR, 2014)*, and 5th (*EMPIRE, 2015*) place overall at the regional competition. Having recently celebrated Cornell's Sesquicentennial Birthday, it is the perfect time for CCC to reflect on the past and push forward into the future.

TABLE 1. SPECIFICATIONS	
Name	*THRAKOS*
Length	19 ft – 5 in
Maximum Width	26 in
Maximum Depth	12.0 in
Average Hull Thickness	0.5 in
Estimated Total Weight	180 lbs
Colors	Willow Green

TABLE 2. CONCRETE PROPERTIES		
	Structural Mix	**Patch Mix**
Compress. Strength	1835 psi	2750 psi
Tensile Strength	308 psi	175 psi
Flexural Strength	650 psi	510
Wet Unit Weight	73.6 pcf	82.0 pcf
Dry Unit Weight	65.7 pcf	80.0 pcf
Air Content	16.2 %	13%
Reinforcement	Fiberglass Mesh, PVA Fibers	

CCC began the new school year by moving into a new laboratory, giving the team a chance to deep clean all the old clutter that had accumulated over the years. Fourteen returning members recruited heavily from all majors to bring the team total to thirty-four, a 25% increase from the previous year. With such a large number of new members and limited space constraints, team leaders focused heavily on communication, efficiency, and simplicity. Educating and training of new members was and will be crucial to the continued success of the team.

This new generation of CCC engineers brings progressiveness and modernity into the competition. The hull was redesigned from the ground up to be sleeker and faster, and a new mold was built with clear cedar and epoxy; this mold doubles as a practice boat for paddlers and reduces waste. In addition, the mix design features Type III Portland cement and other new components such as a shrinkage-reducing admixture — then curing of the concrete took place underneath an automatic misting system. Because of these changes, CCC's problems with shrinkage cracking the previous year were virtually eliminated. Our final product is stronger in tension and compression, and weighs slightly more than the previous year's entry.

CCC's final product is an homage to ancient Greek values and ideals; it is a reflection of the modern project team structure and a foundation for future teams; it is a celebration of Cornell's 150th Anniversary; it is an attempt at perfection through iteration and improvement. Above all, however, *THRAKOS* is a dragon which CCC is proud to have challenged and defeated.

PROJECT MANAGEMENT

Project management activities began in early May 2015 for the selection of team leaders and preliminary project scheduling. The team's primary goals for project management this year were increased transparency between leaders and subteam members, a more balanced workload distribution between members, and an increased emphasis on acquisition of knowledge. With that in mind, the team implemented group messaging services for better communication and made a push for more movement between subteams, allowing any member to work with any subteam. CCC also attempted to follow a model of servant leadership, with the leaders focusing on supporting team members, rather than the other way around. This required a commitment to consistency and a willingness to help others, as well as taking responsibility for team goals. This is exemplified with the upside-down organizational chart.

After losing half of last year's team heading into the year, fourteen returning team members recruited heavily in the Fall and Spring to bring the total to thirty-four, making it the largest team in Cornell history. With so many new members, safety training was more important than ever, and CCC expanded on the usual lab protocol (Figure 2 outlines the normal personal protective equipment) by establishing proper waste disposal rules for expired materials like superplasticizer. A paddling protocol was also created. A lab safety training course was required for all new members and a buddy system was created for larger lab tools like the concrete compression machine and the belt sander. New safety procedures were created for working with electrical components and soldering, both of which can lead to burns. MSDS were provided for all materials.

Team members were distributed across six subteams: Mold Design, Mix Design, Analysis, Aesthetics, Logistics, and Paddling. Changes to ASCE Competition Rules this year resulted in a smaller Aesthetics team and an increased focus on Analysis. Each subteam was led by a senior leader, and, if necessary, a junior leader for support and continuity. Biweekly general body meetings were held to update team members on the progress of the team, and leaders' meetings were held as needed throughout the year. Each subteam met roughly twice weekly, and an estimated total of 2082 person-hours[1] were contributed to the project this year, as shown in Figure 1. This number is noticeably higher than in recent years, being a 25% increase from last year, but is representative of time spent creating an entirely new mold, rather than reusing an old one, and time spent moving into a new lab.

CCC therefore planned an aggressive project schedule determined at the beginning of the Fall semester. Our critical path depended on three things: first, moving into the new lab completely in order to begin work; second, the completion of the wooden form; and third, the successful design and testing of a lightweight concrete mix. Because the duration of Winter Break stretched longer than a month and extended into February, it also became increasingly clear to the team that CCC would be better off casting in December, before Winter Break, where previously the team had always cast after break. This meant that CCC would have to leave enough time before Winter Break to take the cast canoe off of the mold following an initial curing period. While CCC got off to a slow start, having been sidetracked by Cornell's Sesquicentennial Celebration, our Cast Day goal was met admirably thanks to a fast-tracked mix testing schedule and dedicated team members.

A total budget of $9,500 was allocated to the team by the University. The majority of the expenses went towards the Regional Competition. Project management estimated the budget for the rest of the project (construction, mix design, and miscellaneous) to be $4,698. CCC kept tightly to the budget and spent a total of $4,143.80, which was slightly higher than *EMPIRE*'s operational costs. In-kind donations also greatly reduced the cost of mix design, and CCC collaborated with other Cornell project teams in order to combine resources and reduce cost. A distribution of the allocated funds is presented in Figure 3.

TABLE 3. PROJECT MILESTONES

Milestone	Variance	Reason
Hull Design	None	
Moving to a New Lab	None	
Mold Completion	None	
Mix Design Completion	+ 7 days	Late start due to college sesquicentennial celebration
Cast Day	None	Accelerated mix testing

[1] Thus far. The project is still ongoing.

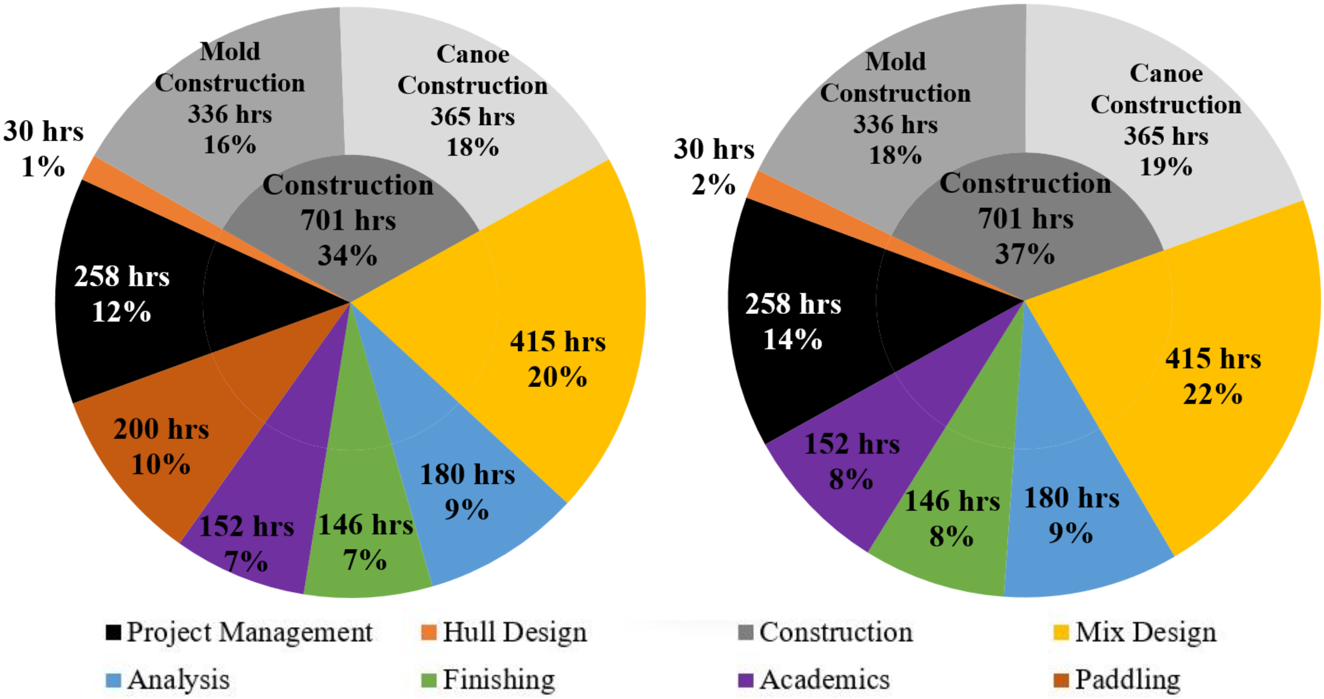


Figure 1. Person Hour Distribution (2082 Total). The majority of hours went towards construction.

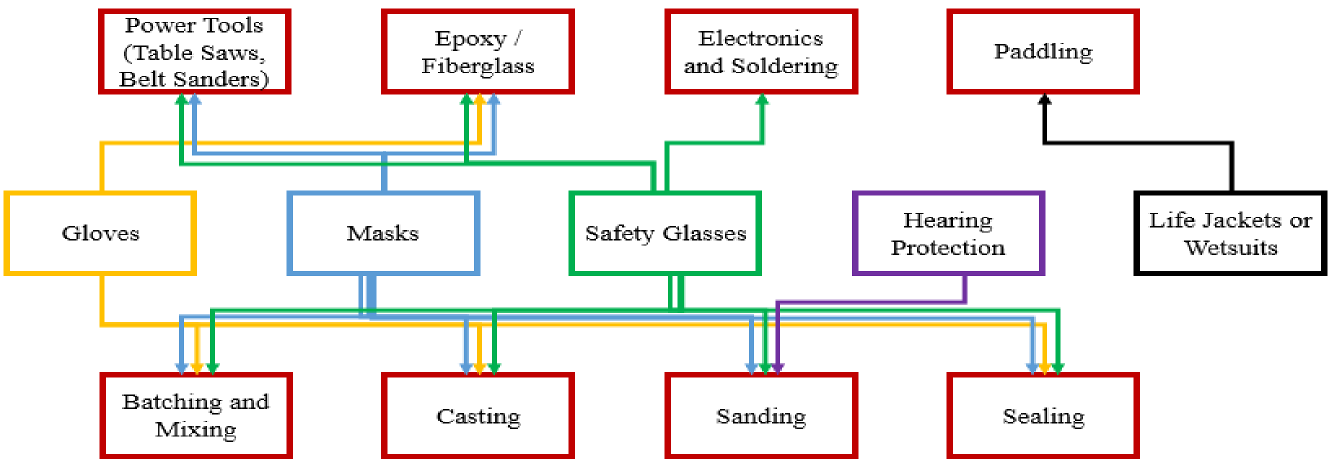
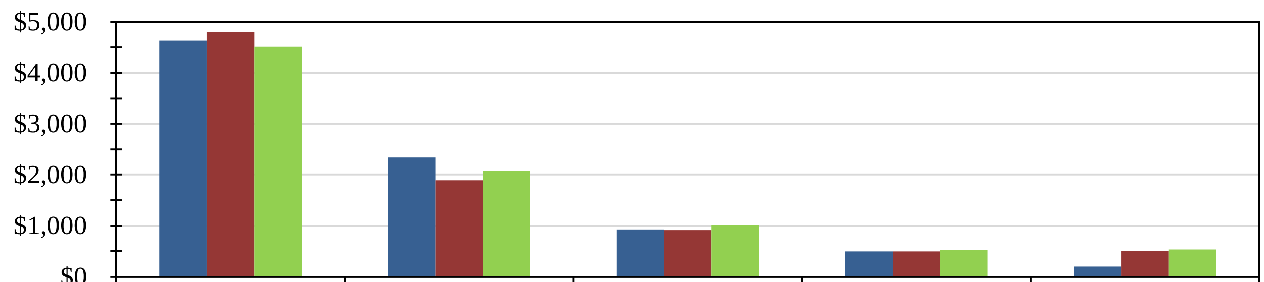


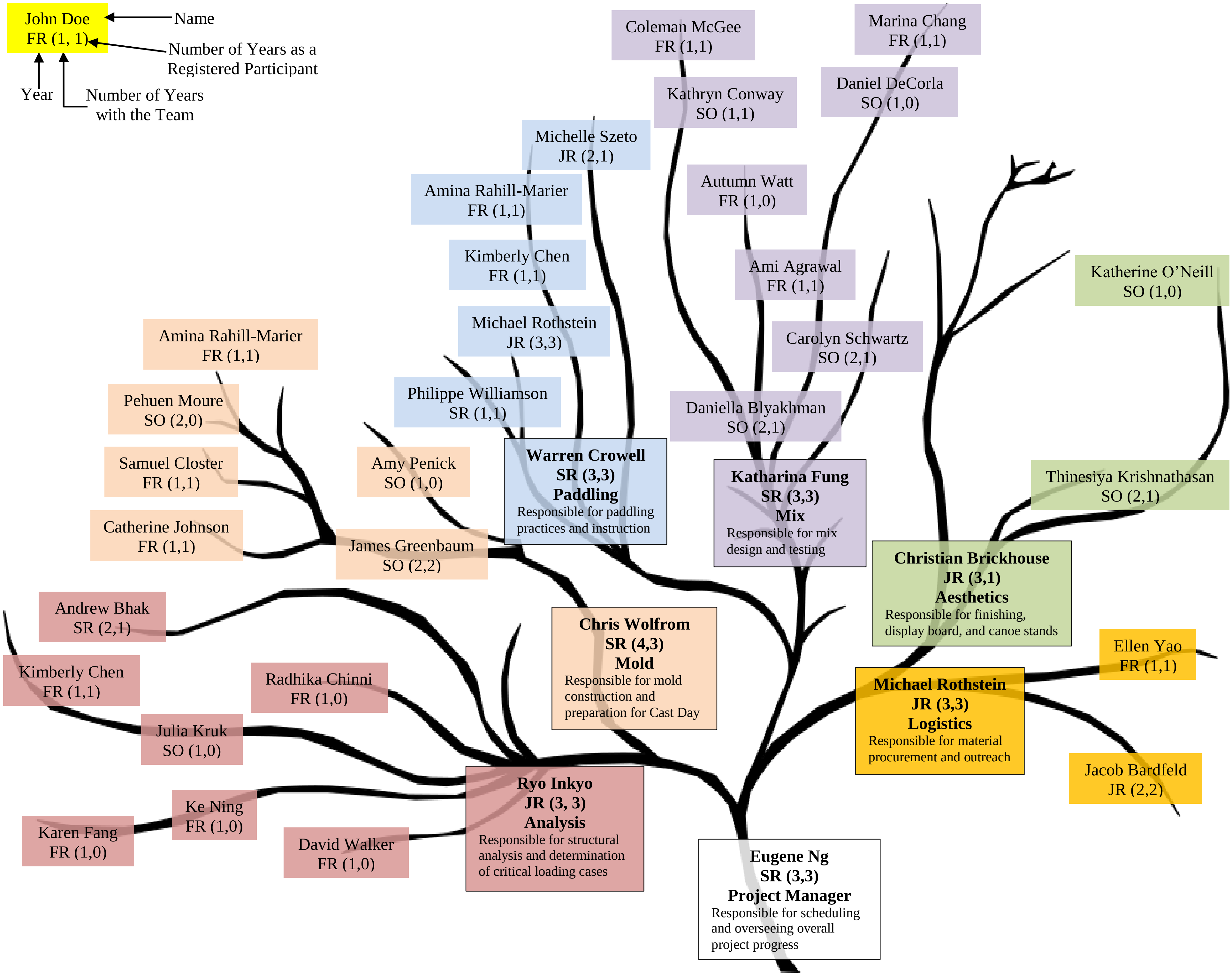
Figure 2. CCC Safety Flowchart, with Personal Protective Equipment. Members also wore closed-toe shoes at all times and members with long hair were required to tie their hair back.



	Competition	Mix Design	Construction	Finishing	Other
2015 Expenses	$4,635.77	$2,342.01	$920.09	$498.38	$200.00
2016 Budget	$4,802.88	$1,890.30	$909.17	$495.72	$500.00
2016 Expenses	$4,514.98	$2,072.68	$1,011.44	$529.43	$530.25

Figure 3.CCC Budget Distribution and Comparison (2016 Total : $8658.78)

Organizational Chart



HULL DESIGN AND STRUCTURAL ANALYSIS

Last year, *EMPIRE* came in third in most of its races despite having paddlers on par with the top teams, and design measures taken to improve turning. CCC decided that the boat was simply not competitive enough, and redesigned the boat from the ground up to create a more race-caliber canoe. The greatest change was a sharp decrease in the beam from 29.25 in. to a sleek 26 in, resulting in an extremely high length to beam (at the waterline) ratio of 9.3. *THRAKOS* also attempted to continue an earlier maneuverability initiative by emphasizing turning and mobility. CCC did this by increasing rocker, which results in less of the canoe sitting in the water, thus allowing the boat less resistance when turning. Finally, *URSA MAJOR (2014)* and *EMPIRE (2015)* had problems with waves breaking over the bow and gunwales, so the design this year also focused on reducing water taken in by the canoe. To mitigate these problems, CCC increased the freeboard slightly, resulting in greater depth, which prevents waves from crashing over the gunwales. A summary of these changes is presented in Table 4.

TABLE 4. PHYSICAL PROPERTIES			
	URSA MAJOR	*EMPIRE*	*THRAKOS*
Length	228 in	232 in	235 in
Width	28 in	29.25 in	26 in
Depth	10.5 in	10.25 in	12 in
Weight	278 lbs	170 lbs	180 lbs
Compress. Strength	1780 psi	1360 psi	1835 psi
Tensile Strength	240 psi	190 psi	308 psi

The displaced volume of water remains independent of area ($F_{buoy} = mg = \rho V_{displaced} g$) and a decrease in beam width makes the canoe ride lower in water. However, the decrease in beam width reduces the reference area much more than the increase in depth raises the area. This area corresponds to the reference area A in the drag equation $F_D = \rho u^2 C_D A$. Therefore, a decrease in the reference area results in a decrease in drag force. The beam decrease also directly increases the acceleration ($a = \frac{F_M - F_D}{m}$) and allows the canoe to reach its maximum velocity faster. These increases in speed come at a cost, and often result in a payoff of less stability in the canoe. However, in response to these improvements in maneuverability, the boat has maintained much of its stability through the soft, rounded chine. This soft chine allows the canoe to stay very stable even when tilted sideways in the water, due to the fact that there are only minimal differences in how the canoe planes through the water at different angles. This secondary stability comes as a tradeoff with less primary stability, so the canoe is not as stable when just sitting in the water or tracking straight. This is especially apparent when we examine our prismatic coefficient (C_P). C_P has a major impact on wave-making resistance (Winters, 2005), and a lower C_P results in less drag and decreased initial stability (*THRAKOS* has a C_P of 0.64). Fortunately, CCC considers its Paddling team to be top-notch and confident in their abilities. The bow and stern remain asymmetric by design: the stern features less rocker for ease of control. Given the overall amount of rocker in the design, emphasis was placed on developing skilled steersmen.

Canoe hull design and modeling was completed in the new Autodesk Fusion 360 CAD software, after initial consultation with a professional canoe designer. Cross sections were initially hand drawn and then scanned into Fusion 360, which were then lofted to create the hull form. Using initial estimates from the Mix Design team as to the density of the concrete, CCC was able to determine the amount of freeboard the canoe would have before the mold had even been built, and updated numbers once the final mix had been decided upon. Similar hull design characteristics are presented in Table 5.

Analysis team members this year focused on accurate representation of loading conditions to find and mitigate worst-case scenarios. Structural analysis was carried out using an Euler Beam Theory-based routine in MATLAB, in which the canoe was modeled as a simply supported beam with piecewise varying cross sections. The canoe was modeled using 16 different cross-sections to more accurately reflect the contour of the boat. Special attention was given to modeling the bow and stern of the canoe so that analysis could be more exact.

The team employed the code to analyze four loading conditions of the canoe: two paddlers in the canoe, four paddlers in the canoe, the canoe on display stands, and the canoe during transport. Each paddler was modeled as a 160 lbf point load, and the buoyant force was assumed to act as a uniformly distributed load along the bottom of the canoe. When the canoe was analyzed on stands in display, the

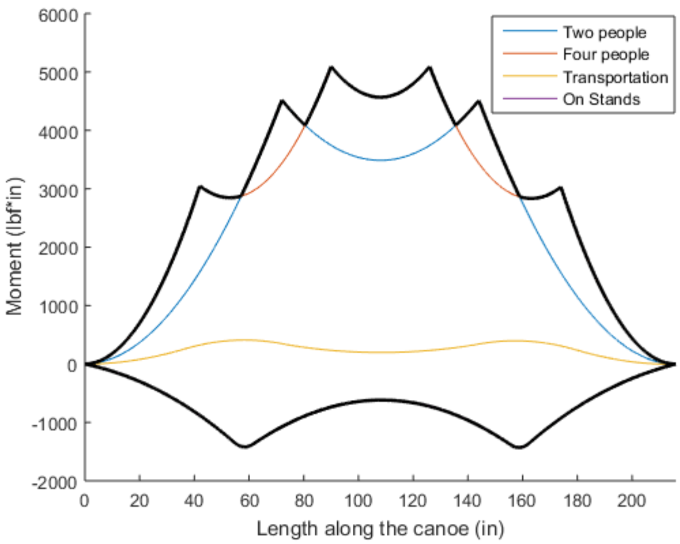


Figure 4. Moment Envelope Diagram

TABLE 5. HULL DESIGN CHARACTERISTICS[2]			
Number of Paddlers	0	2	4
Density of Concrete	65.67 pcf		
Volume of Concrete	2.74 ft^3		
Total Mass	180 lbs	500 lbs	820 lbs
Volume Water Displaced[3]	2.89 ft^3	8.02 ft^3	13.13 ft^3
Draft	2.79 in	5.35 in	7.60 in
Freeboard	9.25 in	6.69 in	4.45 in
Waterline Length[4]	193.5 in	226.3 in	231.3 in
Waterline Beam	20.74 in	23.34 in	24.1 in
Length/Beam (LWL/BWL)	9.328	9.691	9.600
Block Coefficient	0.447	0.490	0.543
Prismatic Coefficient	0.643	0.619	0.656
Section Coefficient	0.695	0.791	0.828
Wetted Surface Area	21.58 ft^2	31.77 ft^2	39.20 ft^2

[2] See Appendix C for example calculations.
[3] Note that the volume of water displaced is greater than the volume of the concrete – but not greater than the volume of the entire enclosed boat.
[4] The waterline length is not a tip-to-tip length. Rather, it follows the waterline curve of the boat.

weight of the canoe was assumed to be uniformly distributed within each of the sixteen sections. The weight was calculated by multiplying the volume of the model by the concrete's dry unit weight.

For the load condition of two paddlers, each paddler was placed 6 ft from the ends of the canoe. The maximum moments under this condition were found to be 4518 lbf-in and were located where the paddlers were placed. The maximum stress was compressive and occurred along the gunwales at 139.9 psi. For the loading condition of four paddlers, the outer and inner paddlers were taken as point loads placed 3.5 ft and 7.5 ft from the ends of the canoe, respectively. Continuing in this way, the team found that the maximum stress occurred during the four person race along the gunwales, due to the large point loads applied. The maximum stress here was calculated to be 159.3 psi. Since the maximum stress was well below the Mix Design subteam's design parameters, the team was assured that the design would enable the canoe to carry each condition's static load with significant margin to account for dynamic loads and other variations from the model's assumptions.

TABLE 6. MAXIMUM VALUES				
	Stress [psi]		**Shear [lbf]**	**Moment [lbf-in]**
	Bottom	**Top**		
2 Paddlers	73.44	139.9	122.4	4518.6
4 Paddlers	78.36	159.3	143.5	5093.6
Stands	-23.68	-43.80	40.85	-1420.0
Transport	6.87	12.18	14.07	409.6

Finally, in order to provide *THRAKOS* with additional strength and a built-in safety factor, measures of tensile reinforcement or foam endcaps were not taken into account in our analysis. Because the mix design is slightly denser than water, CCC calculated bulkhead foam volume by a direct mass ratio. *THRAKOS* continued to employ fiberglass mesh throughout the canoe, which works to hold the canoe together if significant cracks develop. The strength contribution from this mesh is ignored during maximum stress analysis in an effort to provide our canoe with a safety factor.

DEVELOPMENT AND TESTING

The Mix Design team addressed two primary goals. First, produce a low-density concrete mixture, and second, meet or exceed the strength and workability standards established by the Analysis team. The Analysis team provided target strengths of 1600 psi in compression and 236 in tension. The Mix team also designed a patch mixture as a precaution to fill cracks that typically form during the curation of the canoe. The goal of the patch mixture was to maximize workability and appearance in order to best match the canoe's color, with less of a focus on strength. Lastly, an aesthetic mix was designed purely for decorative purposes. Rule changes prevented CCC from staining the boat as we had in previous years. The goal of the aesthetic mix was to obtain vivid colors through the addition of pigment while minimizing added weight. Finally, the Mix team had both the largest number of new members and the lowest number of returning members, making knowledge transfer a priority for this year.

The structural mixture design from *EMPIRE* (2015) was adopted as a baseline due to its successful workability and low density. *EMPIRE*'s mixture had a density of 56 pcf, compressive strength of 1360 psi, and tensile strength of 190 psi. However, the concrete mixture suffered from shrinkage cracks during curing and high porosity, compromising both the structural stability of the canoe as well as the overall appearance.

With this in mind, the Mix Design team made significant changes to the baseline composition in order to reduce shrinkage cracks by introducing Type III Portland Cement and shrinkage reducing admixture (SRA). Type III Portland cement has higher early strength than Type I Portland Cement, which allowed for earlier removal of the concrete from the mold. The probability of shrinkage cracks arising was thus reduced because the concrete was allowed to shrink freely without the tension of the mold beneath it. Grace Eclipse 4500 shrinkage reducing admixture (SRA) was introduced as an additional safeguard against shrinkage cracks. Additionally, a shrinkage test was modeled after the ASTM C1581/C1581M Standard Restrained Ring Test, but adapted to mimic the stress conditions the canoe undergoes during curing (see Figure 5). The results of this test determined the appropriate ratio of SRA to use in the structural mixture, as different specimens formed cracks at different ages.

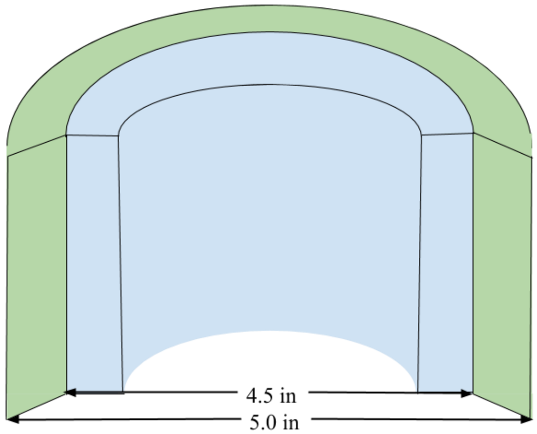


Figure 5. A cross-section schematic of the Modified Restrained Ring Test. The inner rigid ring acts as a "mold" for the outer concrete to shrink around, mimicking the conditions the canoe undergoes during curing.

To improve the canoe's finish and save time, the Mix team also integrated pigment into the concrete mixture, rather than relying solely on a topical aesthetic finishing. The structural mixture provided a uniform, subtly colored background for the topmost black aesthetic mix. The integrated pigment actually highlighted areas of the boat which needed more sanding (these areas would be a lighter color than the rest of the canoe), which was helpful but also lengthened the sanding schedule by an additional two weeks. The separate black aesthetic mixture was painted on the canoe using stencils.

Each week, the Mix team met three times and designed and prepared approximately three new concrete mixtures. This allowed for frequent testing

Figure 6. Applying the aesthetic mixture to the canoe.

Type	Cenospheres	Poravers	3M Glass Bubbles	Fibers
Source	Byproduct of Coal Production	Made from Recycled Glass	Produced by 3M	Made of Polyvinyl Alcohol
Specific Gravity	0.35	0.3	0.15/0.25	1.3
Size	140 ± 30 μm	0.5-1 mm 1-2 mm 2-4 mm	30-105 25-90 μm	130/40 Denier 1.25 in/0.75 in

TABLE 7. AGGREGATE CHARACTERISTICS.

of new mixtures to better understand the effects of the new materials being introduced. The final concrete mixture was determined using an iterative process of varying the batch proportions of aggregates, cementitious materials, and admixtures and then comparing the strength, density, workability, and cracking of each concrete mixture.

During each meeting, twelve 3x6 in concrete cylinders were made: six using Type I Portland cement and six using Type III Portland cement. The cylinders were made according to the ASTM C192 standard for testing. After 14 days of curing in a moist environment, half the cylinders were tested using the ASTM C496 standard for split tensile testing and the other half were tested using the ASTM C39 standard for compression testing. Mix and Mold team members also spent time practicing casting, testing the workability and cohesion of the concrete to gain initial insights into what the mix would be like on Cast Day.

The Mix team also took into consideration the environmental impact of the concrete while selecting materials. Portland Cement production emits enormous amounts of carbon dioxide, so it was supplemented with other cementitious materials that are less ecologically damaging: ground-granulated blast-furnace slag and Class F fly ash. Blast-furnace slag is a byproduct of steel manufacturing and produces no carbon dioxide emissions. It also assists the structural mix by reducing slump and providing high gain in late strength, which Type III Portland Cement lacks. Fly ash, a waste residue from coal combustion, was incorporated into the structural mix because it increases the workability of concrete. Proportions of slag and fly ash were adopted from the previously-optimized baseline mix and adjusted for workability.

Besides cementitious materials, Poraver expanded glass and Cenospheres were also chosen for use as aggregates for sustainability purposes. Both are silica materials; Poravers are made of post-consumer recycled glass and Cenospheres are a byproduct of coal production at power plants. The Mix team tested the use of a smaller size of Poravers this year, but they were eliminated from the final mix design because other small aggregates proved more useful due to higher strength.

While Type III Portland Cement helped the canoe reach its desired strength faster, thus reducing the formation of cracks and improving its structural stability, it also required the addition of more water than the baseline mixture had entailed, thus increasing overall paste volume. In order to minimize paste volume, iterative testing was done to increase the proportion of aggregates with higher surface area. Cenospheres and graduated sizes of Poravers (0.5-4mm) were increased rather than lightweight 3M Glass Bubbles as they had larger surface areas. Aside for their surface area, the amount of Cenospheres was also increased due to their high strength. The proportion of Glass Bubbles was not increased because they constituted a large volume of *EMPIRE*'s mix and caused many of the issues found in that mix.

TABLE 8. GOALS AND RESULTS

	Baseline Properties	Goal Properties	Actual Results
Density	56 pcf	68 pcf	65.67 pcf
Compressive Strength	1360 psi	1600 psi	1835 psi
Tensile Strength	190 psi	236 psi	308 psi

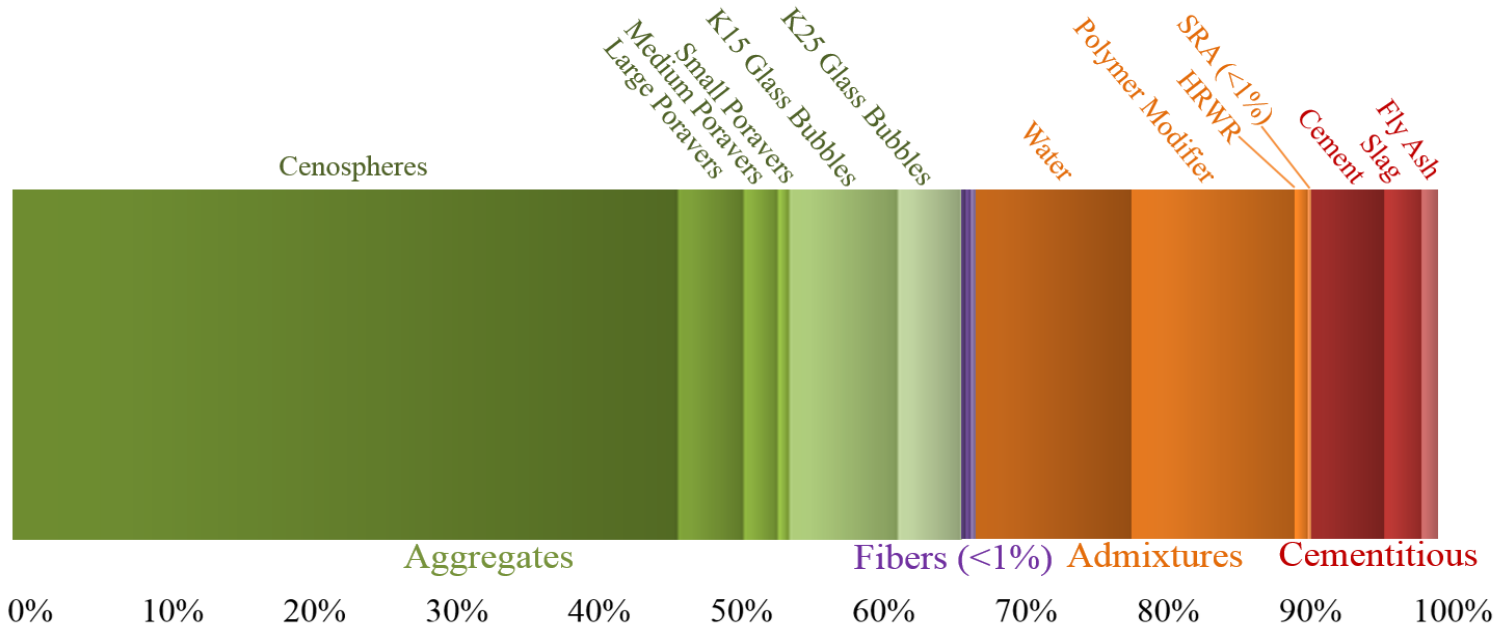


Figure 7. Concrete Mixture Proportions by Volume. The Mix Design team introduced new materials in all categories this year (aggregates, cementitious, admixtures, and reinforcement). Note that fibers were added in equal proportions.

Grace ADVA Cast 575 high-range water reducer (HRWR) improved the workability of the concrete mixture and reduced the amount of water needed, thus increasing the mixture's overall strength. A higher amount of HRWR was used to adhere to the new addition of Type III Portland cement and its tendency to dry faster than the Type I Portland cement previously used in *EMPIRE*. Increasing the amount of HRWR decreased the amount of additional water while maintaining maximum workability and strength. Another way to reduce the paste volume was by using DOW latex redispersable powder (polymer modifier). It strengthened the bond between the two layers of concrete and increased tensile strength without using additional cement or water. Testing from previous years found that the optimal weight percent of polymer modifier was 7.9% and was applied to this year's mixture.

Several changes were made to primary and secondary reinforcement materials. New to this year's concrete mixture were NYCON RECS 15 PVA fibers, which are shorter and thinner than previously used fibers, but have 150% of the tensile strength of NYCON RF4000 fibers used in previous years. Further testing found that RECS-15 did increase the strength of concrete mixtures. However, preliminary casting practices exposed a flaw; too high a concentration of these fibers would cause them to clump together and create large holes in the concrete. Through iterative testing, the Mix team determined that the most effective ratio of RECS 15 fibers to use was in equal amounts to the NYCON RF4000 and RFS400 fibers used in previous years. In addition to new internal fibers, CCC acquired a new fiberglass mesh (Glasgrid 8501) after exhausting the supply of Glasgrid 8511. The new mesh has a smaller aperture size, but an almost identical percentage of open area. CCC applied the mesh in sections with eight inches of overlap to minimize the time between casting the layers of concrete on either side of the mesh.

Results (Table 8) demonstrate that the Mix team was successful in designing a concrete mixture with greater tensile strength and lower density than that of *EMPIRE*. CCC experienced virtually no cracks from shrinkage. The team also succeeded in meeting the tensile strength and density set forth by the Analysis team. The incorporation of Type III Portland Cement into the concrete mixture proved an extremely effective alternative to Type I Portland Cement in this time-constrained project, while still allowing the freedom to tailor the concrete mixture's properties.

CONSTRUCTION

THRAKOS's sleek, new form was created by a method of boat building called cedar-stripping. The Mold team decided on a wooden mold over a foam CNC mold for sustainability purposes as well as reusability from year to year. The cedar-stripped mold also acts as a practice canoe for paddlers. CCC recycled the old wooden cross sections of the previous canoe - the new cross section patterns were traced on and cut out of the old wood with a jig saw. The curve of these new cross sections were sanded via belt sander to remove any rough edges and ensure roundedness of the boat. These were then secured to the strongback with screws in 14 inch increments.

¼ inch by ¾ inch strips of 20 ft long cedar strips were laid across the length of the canoe onto this backbone. The strips were laid and cut in an alternating pattern - one strip would be laid on the port side and then a strip would be laid on the starboard side - to ensure that the pieces would fit together evenly at the bow and stern. The cross-sectional shape of the cedar strips are parallelograms to fit the contour of the boat and to provide a tongue and groove system for increased strength and decreased gaps between strips. This was achieved by using a table saw with the blade angled at 8 degrees. Each strip was glued on the top side to the adjacent strip, moving from the gunwales to the keel. Then, the two were stapled to each other and to the joints. The final pieces on the underside of the wooden mold were cut into progressively smaller and angular shapes to fit the remaining area using hand planes. Once the glue had dried, the staples were removed with pliers. A level was used to remove any large bumps and to smooth edges between the wooden strips.

Figure 8. Male mold under construction. The Mold team removed a total of 532 staples upon completion.

Several stages of sanding were completed after all cedar strips had been applied. Starting on the outside, the team used 120-grit sandpaper to remove glue and splinters, and to smooth edges between the cedar strips. 220-grit sandpaper was used to finish the outside of the mold. The mold was then flipped over and laid on cut pieces of foam so that the inside of the mold could be sanded. The sharper angles inside of the boat were sanded by hand at first. Just as on the outside of the boat, CCC progressively reached 220-grit smoothness.

After sanding the canoe, large sheets of mesh fiberglass cloth were laid over the outer hull of the mold. The pieces were cut to size and left to drape over the canoe so they could begin to form to the shape of the mold. The team mixed two-part epoxy resin and applied it to the fiberglass using foam brushes and squeegees. After it hardened, the excess fiberglass and epoxy was cut off and the exterior sanded to reduce the texture of the fiberglass cloth and to eliminate any hardened drips. A second layer of epoxy was applied. The mold was flipped and the process was then repeated on the interior of the canoe. This proved to be a harder process; gravity would pull the fiberglass and epoxy mixture towards the center of the boat before the epoxy had time to harden. The team was careful to apply the epoxy slowly and held the fiberglass in place. The inside of the boat was again sanded smooth.

Once this process was complete, CCC set out to test the canoe mold. The team hoped to get a sense of its maneuverability and speed, which would allow for a better approximation of how the concrete version of the boat would behave once it was complete. Preliminary tests on the lake proved it to be extremely fast and very light, though unstable. Better stability was achieved by sitting lower in the boat and lowering paddler center of gravity. Videos of the test runs were taken so that they would be available for reference.

In preparation for Cast Day, 2.97 oz. Dacron® cloth was layered over the exterior of the inverted mold. The fabric was pulled taut over the surface of the mold and was secured in place with staples. The team hand-sewed the fabric on the mold for a body-hugging fit and then ironed it flat to ensure that no creases or wrinkles would be passed into the texture of the boat. Two extra ¼-inch cedar strips were placed along the length of the gunwales of the canoe in order to create an edge that would help apply the correct thickness of concrete. Four sections of 1x1-in and four sections of ½ x ½ -in semi-rigid fiberglass structural mesh sections were measured, cut, and laid onto the mold to allow it to contour to the hull shape before casting.

Cast Day proceeded on schedule just two weeks after the mold was completed. CCC started the day off with a preliminary briefing and made sure all the necessary preparations were ready. Members were assigned to different roles, including casting, mesh placing, slump boarding, and hydrating. All members wore full body suits, masks, gloves, and protective eyewear. These measures protected us from fine dust, chemically basic concrete, and other particulates. The team worked in assembly line fashion from bow to stern, casting a first layer of ¼-in concrete and then moving forward; the mesh placement team came in behind them and then the second layer of ¼-in concrete was placed by a second casting team. The mix and hydration teams kept the humidity of the room high to prevent the concrete from becoming unworkable. Quality control involved using marked toothpicks as depth gauges and a ¼-in diameter rope moved along the surface of the mold. These measures allowed the team to make sure the boat was not too thick, making it unnecessarily heavy, and not too thin, leading to weakness and increased cracking.

After completion of casting, a plastic tent was placed over the canoe to help keep the environment within the ideal humidity and temperature ranges. This year, the team took both an active and passive approach; buckets of water were placed inside the tent, humidifiers were regularly refilled, and a brand new sprinkler system was set up above the canoe to automatically mist the air at predefined time intervals. This allowed us to keep the canoe at near 100% relative humidity while the curing process occurred.

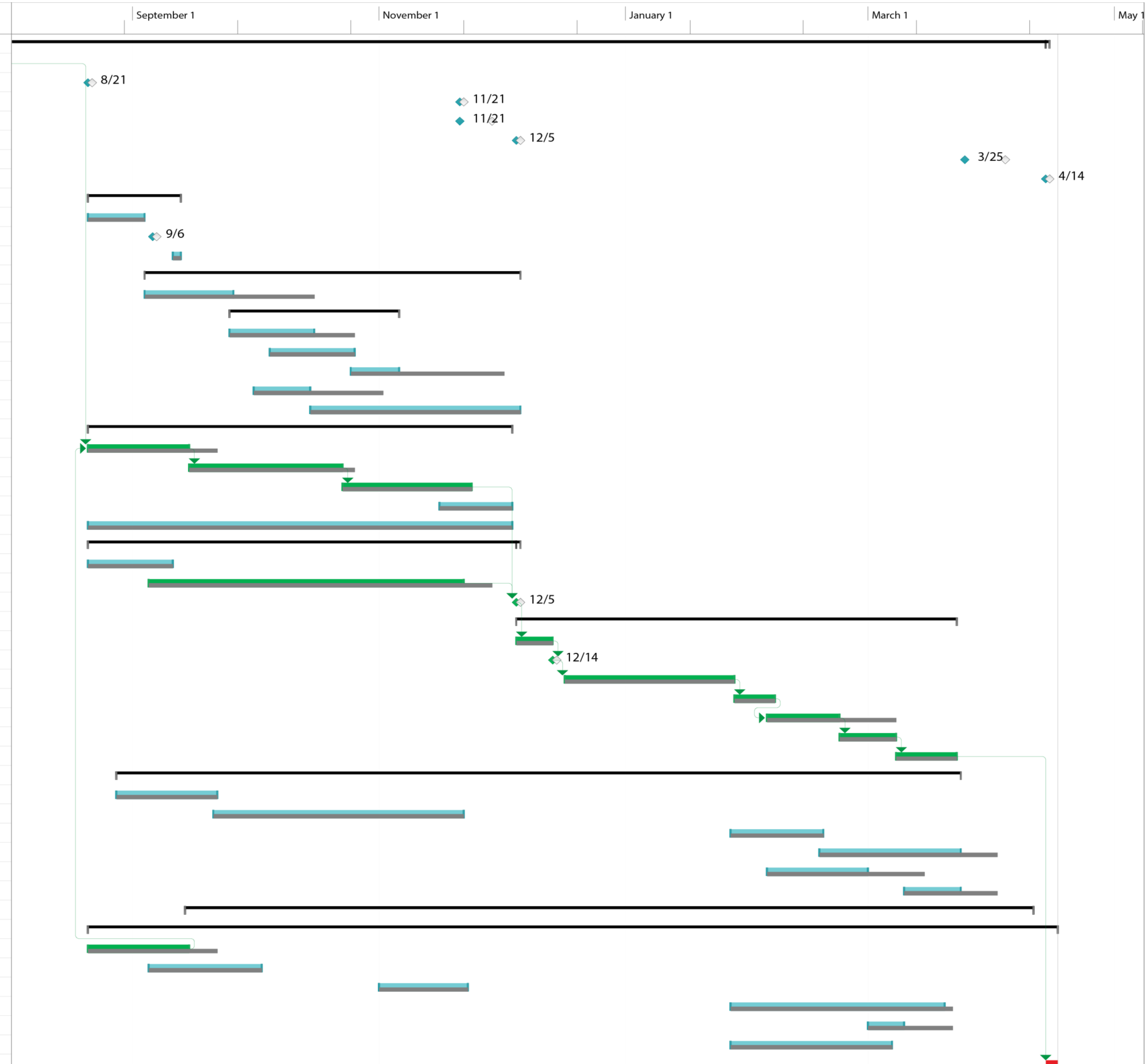
Figure 10. Plastic tent set up. Note the sprinkler hose running along the top of the tent.

Figure 9. Placement of the Concrete after Mesh Section. Members at the far end of the canoe continue slump boarding and misting the air. Note the ¼ -in rope on the bottom left of the image.

After curing for a week, the boat was flipped onto foam cut-outs so that the mold and canoe could be separated. The team took two long plastic sheets and pushed them between the mold and *THRAKOS*, and these were shimmied from bow to stern of the two boats. Then team members on both sides of the boat gripped the edges of the plastic and simultaneously lifted the mold out of the canoe. The mold was set off to the side and the demolded. *THRAKOS* was placed on the strongback – just in time for Winter Break. *THRAKOS* spent nearly a month dry curing during Winter Break. When the team returned in February, several weeks' worth of sanding ensued. A sanding tent was erected around our lab area to prevent concrete dust from spreading throughout the shared lab space, and members followed strict safety protocol by wearing masks, gloves, and goggles during sanding. A patch mix was applied and sanded before moving on to the other side of the boat. CCC reached up to 220 grit sandpaper to create a smooth surface for optimal performance.

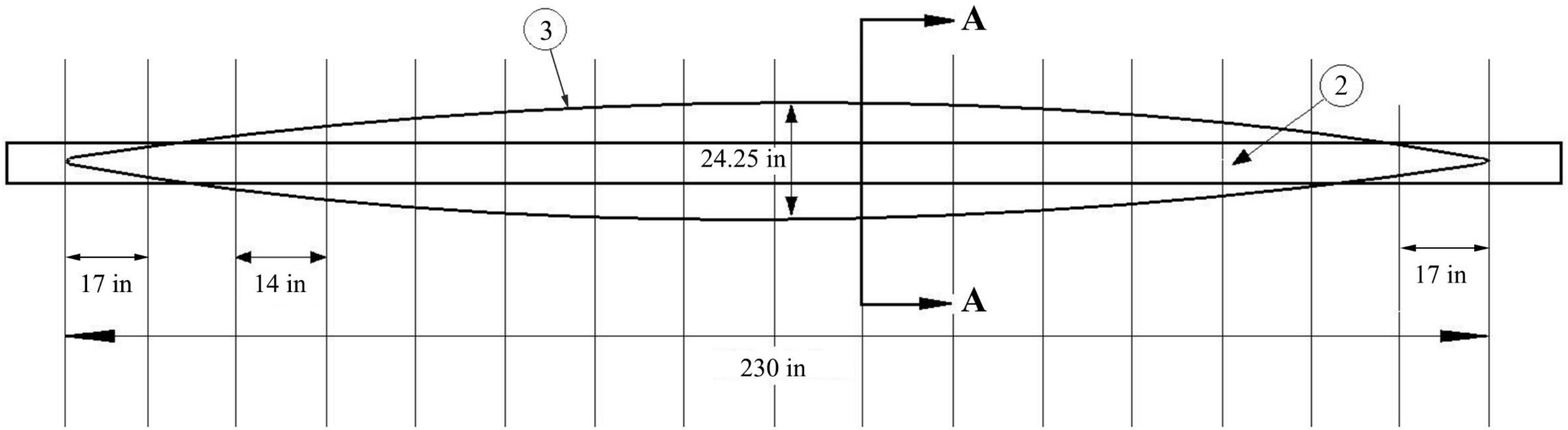
Once the team had finished sanding the surface of the boat, the Mix and Aesthetics team used stencils to strategically place the aesthetic concrete mixture on the surface of the boat. Multiple one-inch thick cross sections were traced out of polystyrene foam board and cut out to fit in the bow and stern of the canoe – these foam sections were then encased in concrete. The concrete design was again sanded smooth. Finally, two layers of sealant were applied and *THRAKOS* was completed.

ID	Task Name	Start	Finish	Actual Finish
1	Project Milestones	Tue 5/19/15	Thu 4/14/16	Thu 4/14/16
2	Hull Design	Tue 5/19/15	Tue 5/19/15	Tue 5/19/15
3	Project Start	Fri 8/21/15	Fri 8/21/15	Fri 8/21/15
4	Mold Completion	Sat 11/21/15	Sat 11/21/15	Sat 11/21/15
5	Mix Completion	Sat 11/21/15	Sat 11/21/15	Sat 11/28/15
6	Cast Day	Sat 12/5/15	Sat 12/5/15	Sat 12/5/15
7	Finishing Completion	Fri 3/25/16	Fri 3/25/16	Sun 4/3/16
8	Regional Competition	Thu 4/14/16	Thu 4/14/16	Thu 4/14/16
9	Recruitment	Fri 8/21/15	Sat 9/12/15	Sat 9/12/15
10	Create Recruitment Materials	Fri 8/21/15	Thu 9/3/15	Thu 9/3/15
11	Fall Clubfest	Sun 9/6/15	Sun 9/6/15	Sun 9/6/15
12	Interviews	Fri 9/11/15	Sat 9/12/15	Sat 9/12/15
13	Analysis	Fri 9/4/15	Sat 12/5/15	Sat 12/5/15
14	3D Modeling	Fri 9/4/15	Fri 9/25/15	Thu 10/15/15
15	Structural Analysis	Fri 9/25/15	Thu 11/5/15	Thu 11/5/15
16	Hull Design Characteristics	Fri 9/25/15	Thu 10/15/15	Sun 10/25/15
17	Loading Case Analysis	Mon 10/5/15	Sun 10/25/15	Sun 10/25/15
18	Sample Calculations	Sun 10/25/15	Thu 11/5/15	Tue 12/1/15
19	Configure Moisture/Temperature Sensors	Thu 10/1/15	Wed 10/14/15	Sun 11/1/15
20	Tent/Sprinkler/Heater System Setup	Thu 10/15/15	Sat 12/5/15	Sat 12/5/15
21	Construction	Fri 8/21/15	Thu 12/3/15	Thu 12/3/15
22	Strongback and Form Creation	Fri 8/21/15	Mon 9/14/15	Mon 9/21/15
23	Cedar Stripping of Hull	Tue 9/15/15	Thu 10/22/15	Sun 10/25/15
24	Sanding and Fiberglassing	Fri 10/23/15	Mon 11/23/15	Mon 11/23/15
25	Test release agents	Mon 11/16/15	Thu 12/3/15	Thu 12/3/15
26	Concurrent Practice Casting	Fri 8/21/15	Thu 12/3/15	Thu 12/3/15
27	Mix Design	Fri 8/21/15	Sat 12/5/15	Sat 12/5/15
28	Material Procurement	Fri 8/21/15	Thu 9/10/15	Thu 9/10/15
29	Trial Batches and Testing, Structural Mix	Sat 9/5/15	Sat 11/21/15	Sat 11/28/15
30	Cast Day	Sat 12/5/15	Sat 12/5/15	Sat 12/5/15
31	Canoe Finishing	Sat 12/5/15	Tue 3/22/16	Tue 3/22/16
32	Hydration (Wet Curing)	Sat 12/5/15	Sun 12/13/15	Sun 12/13/15
33	Mold Removal	Mon 12/14/15	Mon 12/14/15	Mon 12/14/15
34	Dry Cure	Thu 12/17/15	Wed 1/27/16	Wed 1/27/16
35	Patching	Thu 1/28/16	Sat 2/6/16	Sat 2/6/16
36	Sanding	Fri 2/5/16	Mon 2/22/16	Mon 3/7/16
37	Graphics Application	Tue 2/23/16	Mon 3/7/16	Mon 3/7/16
38	Sealing	Tue 3/8/16	Tue 3/22/16	Tue 3/22/16
39	Aesthetics	Fri 8/28/15	Wed 3/23/16	Wed 3/23/16
40	Theme Development	Fri 8/28/15	Mon 9/21/15	Mon 9/21/15
41	Graphic Designs	Mon 9/21/15	Sat 11/21/15	Sat 11/21/15
42	Stand Design	Wed 1/27/16	Thu 2/18/16	Thu 2/18/16
43	Stands	Thu 2/18/16	Wed 3/23/16	Fri 4/1/16
44	Mini-Mold	Fri 2/5/16	Mon 2/29/16	Mon 3/14/16
45	Display Board	Thu 3/10/16	Wed 3/23/16	Fri 4/1/16
46	Paddling	Mon 9/14/15	Sun 4/10/16	Sun 4/10/16
48	Logistics	Fri 8/21/15	Sat 4/16/16	Sat 4/16/16
49	Laboratory Moving	Fri 8/21/15	Mon 9/14/15	Mon 9/21/15
50	Website	Sat 9/5/15	Fri 10/2/15	Fri 10/2/15
51	Apparel	Sun 11/1/15	Sun 11/22/15	Sun 11/22/15
52	Design Report	Wed 1/27/16	Sat 3/19/16	Mon 3/21/16
53	Engineer's Notebook	Tue 3/1/16	Wed 3/9/16	Mon 3/21/16
54	Canoe Transport Module	Wed 1/27/16	Sun 3/6/16	Sun 3/6/16
55	Competition	Thu 4/14/16	Sat 4/16/16	Sat 4/16/16

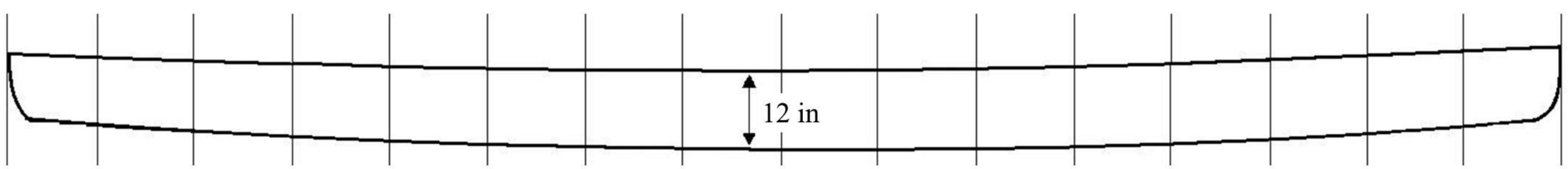


LEGEND

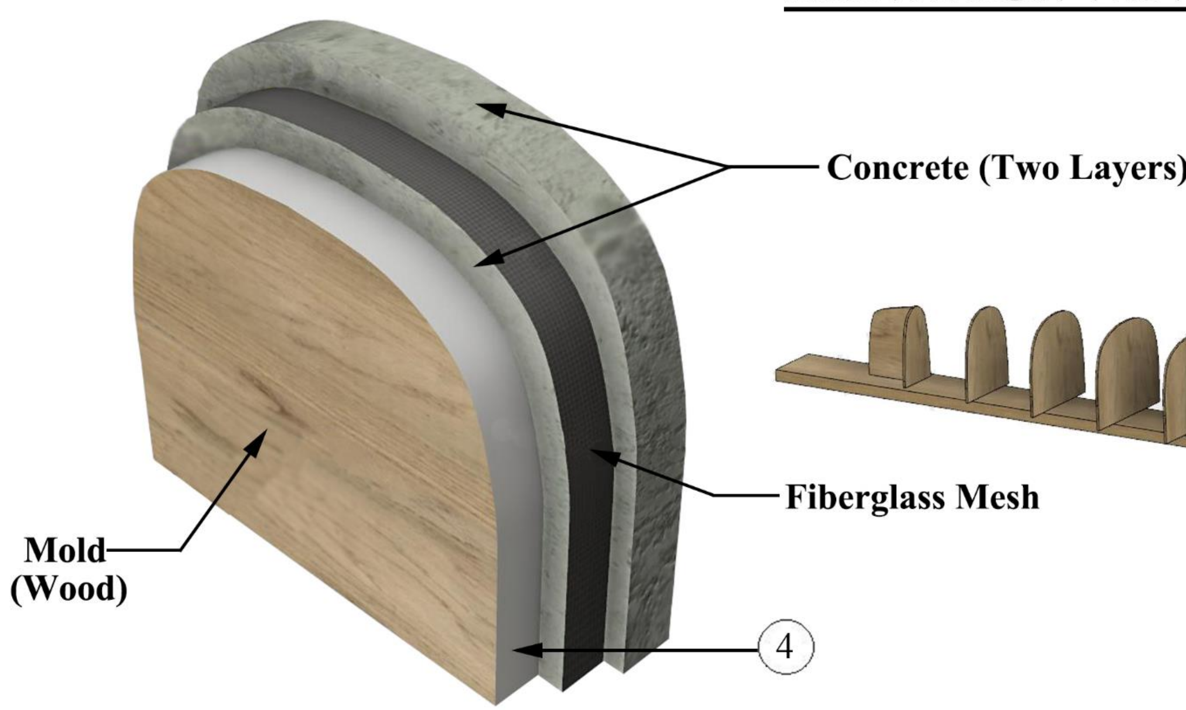
- Baseline Milestone
- Actual Finish Date
- Baseline Path
- Actual Path
- Critical Path



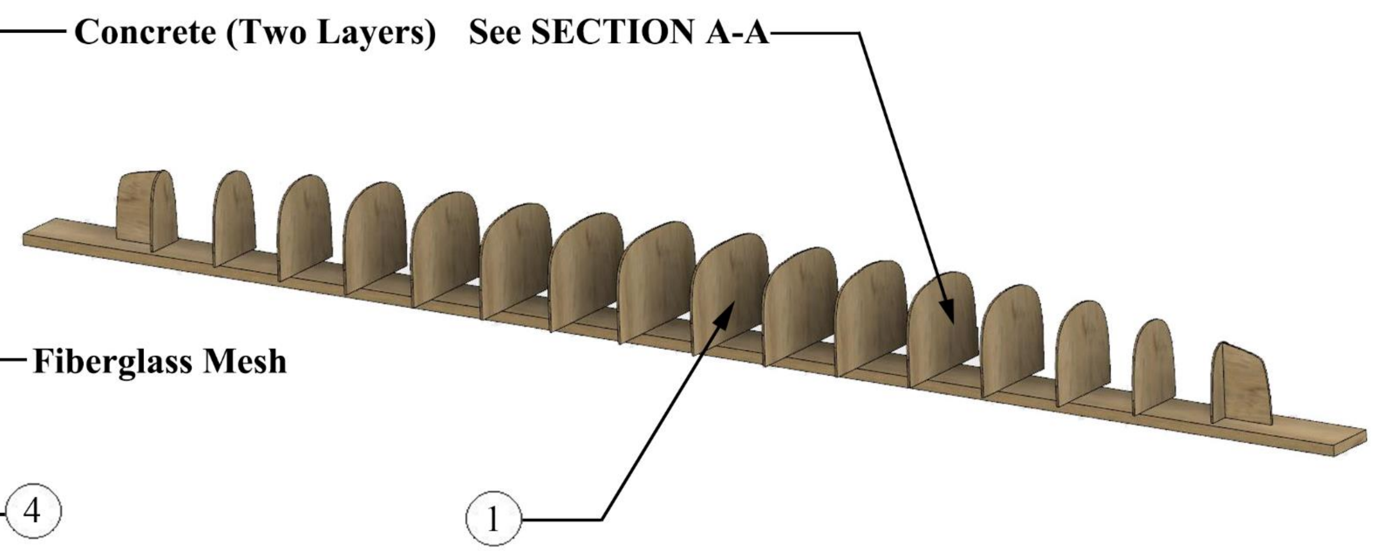
PLAN VIEW



ELEVATION VIEW



SECTION A-A



STRONGBACK VIEW

CORNELL UNIVERSITY concrete canoe

Bill of Materials

Concrete Materials				
Material	Quantity		Unit Price	Total Price
Type I Portland Cement	20	lbs	$0.11	$2.20
Type III Portland Cement	62	lbs	$0.16	$9.92
Ground Granulated Blast Furnace Slag	38.1	lbs	$0.05	$1.91
Fly Ash (Class F)	12.6	lbs	$1.20	$15.12
SphereOne Extendospheres SG-900	88	lbs	$4.54	$399.52
Poraver Recycled Glass (0.5 – 1.0 mm)	33	lbs	$0.70	$23.10
Poraver Recycled Glass (1.0 – 2.0 mm)	27	lbs	$0.70	$18.90
Poraver Recycled Glass (2.0 – 4.0 mm)	24	lbs	$0.70	$16.80
Nycon PVA RECS100 Fibers	1	lbs	$15.00	$15.00
Nycon PVA RFS400 Fibers	1	lbs	$15.00	$15.00
Nycon PVA RF4000 Fibers	1	lbs	$20.00	$20.00
3M K15 Glass Bubbles	20	lbs	$6.50	$130.00
3M K25 Glass Bubbles	15	lbs	$5.19	$77.85
Grace ADVA Cast 575 HRWR	2	gal	$35.05	$70.10
Grace Eclipse 4500 SRA	2	gal	$26.42	$52.84
DLP 212 Polymer Modifier	22.64	lbs	$2.00	$45.28
Davis Pigments Willow Green Pigment	2	lbs	$11.91	$23.82
Davis Pigment Black Pigment	1	lbs	$3.90	$3.90
		Concrete Materials Total		$941.26
Construction Materials				
Material	Quantity		Unit Price	Total Price
Plywood Cross Sections (1)	30	Sq. Ft.	$0.68	$20.49
Strongback (2)	25	Ft	$5.00	$125.00
¼" x ¾" x 20` Clear Cedar Strips (3)	1	Lump Sum	$372.00	$372.00
2.97oz Dacron Cloth (4)	21	yds	$3.95	$82.95
MAS Slow Hardener	½	Gal	$91.51	$91.51
MAS Epoxy	1	Gal	$117.51	$117.51
JPS Racing Hull 6oz Fiberglass Cloth	10	yds	$8.49	$84.90
3" Screws	1	Pack	$6.47	$6.47
Fiberglass Mesh	10	Sq. Yd.	$3.34	$33.40
		Construction Materials Total		$934.23
Finishing Materials				
Material	Quantity		Unit Price	Total Price
Contact Paper	1	Roll	$9.74	$9.74
24x48x1 in Polystyrene Foam Sheet	4	Sheets	$9.00	$36.01
Vinyl Lettering	1	Lump Sum	$140.00	$140.00
ChemMasters Crystal Clear-A Sealant	1	gal	$32.86	$32.86
		Finishing Materials Total		218.61
Total Production Cost of *THRAKOS*				$2094.10

General Notes: Drawings not to scale. Dimensions shown represent dimensions of the form and not the concrete canoe.

Date: 3/13/2016

Engineer: Ke Ning

Drawn By: David Walker, Kimberly Chen

Checked By: Ryo Inkyo, James Cramer

Appendix A: References

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Appendix B: Mixture Proportions

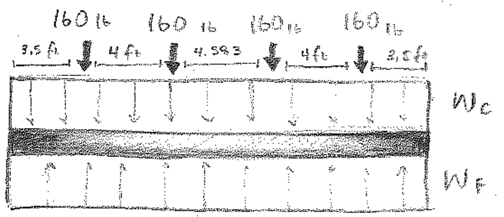
	Mixture ID: Structural Mix				**Design Proportions (Non SSD)**		**Actual Batched Proportions**		**Yielded Proportions**	
YD	Design Batch Size (ft3):		1.00							
Cementitious Materials				SG	Amount (lb/yd3)	Volume (ft3)	Amount (lb)	Volume (ft3)	Amount (lb/yd3)	Volume (ft3)
CM1	Portland Cement (Type III)			3.15	259.46	1.320	9.61	0.049	405.76	2.06
CM2	Fly Ash Class F			2.50	52.25	0.335	1.94	0.012	81.71	0.52
CM3	Slag			2.90	118.74	0.656	4.40	0.024	185.70	1.03
Total Cementitious Materials:					430.45	2.31	15.94	0.09	673.18	3.61
Fibers										
F1	Large PVA Fibers			1.30	3.86	0.048	0.15	0.002	6.16	0.08
F2	Medium PVA Fibers			1.30	3.86	0.048	0.15	0.002	6.16	0.08
F3	Small PVA Fibers			1.30	3.86	0.048	0.15	0.002	6.16	0.08
Total Fibers:					11.57	0.14	0.44	0.01	18.47	0.23
Aggregates										
A1	Cenospheres	Abs:		0.35	280.54	12.845	10.39	0.476	438.73	20.09
A2	Large Poravers	Abs:		0.30	23.32	1.246	0.86	0.046	36.47	1.95
A3	Medium Poravers	Abs:		0.30	11.66	0.623	0.43	0.023	18.24	0.97
A4	Small Poravers	Abs:		0.30	4.32	0.231	0.16	0.009	6.75	0.36
A5	K15 Glass Bubbles	Abs:		0.15	18.77	2.006	0.70	0.074	29.36	3.14
A6	K25 Glass Bubbles	Abs:		0.25	18.77	1.203	0.69535	0.04457	29.36	1.88
Total Aggregates:					357.39	18.15	13.24	0.67	558.91	28.39
Water										
W1	Water for CM Hydration (W1a + W1b)			1.00	62.70	1.005	2.32	0.037	97.96	1.57
	W1a. Water from Admixtures				0.00		0.00		0.00	
	W1b. Additional Water				62.70		2.32		97.96	
W2	Water for Aggregates, SSD			1.00	0.00		0.00		0.00	
Total Water (W1 + W2):					62.70	1.00	2.32	0.04	97.96	1.57
Solids Content of Latex, Dyes and Admixtures in Powder Form										
S1	Polymer Modifier			2.20	217.00	1.581	8.05	0.059	339.91	2.48
S2	Green Pigment			1.20	5.71	0.076	0.21	0.003	8.94	0.12
Total Solids of Admixtures:					222.71	1.66	8.26	0.06	348.85	2.60
Admixtures (including Pigments in Liquid Form)				% Solids	Dosage (fl oz/cwt)	Water in Admixture (lb/yd3)	Amount (fl oz)	Water in Admixture (lb)	Dosage (fl oz/cwt)	Water in Admixture (lb/yd3)
Ad1	HRWR	*8.8*	*lb/gal*	0.00	18.00	0.00	8.60	0.000	18.00	0.00
Ad2	SRA	*7.7*	*lb/gal*	0.00	14.00	0.00	2.23	0.000	14.00	0.00
Water from Admixtures (W1a):						0.00		0.00		0.00
Cement-Cementitious Materials Ratio					0.603		0.603		0.603	
Water-Cementitious Materials Ratio					0.15		0.146		0.146	
Slump, Slump Flow, in.					0.00		0.000		0.000	
M	Mass of Concrete. lbs				1103.61		40.90		1716.16	
V	Absolute Volume of Concrete, ft3				23.27		0.86		36.40	
T	Theoretical Density, lb/ft3 = (M / V)				47.43		47.45		47.15	
D	Design Density, lb/ft3 = (M / 27)				40.87					
D	Measured Density, lb/ft3						63.960		63.960	
A	Air Content, % = [(T - D) / T x 100%]				13.82		34.81		35.65	
Y	Yield, ft3 = (M / D)				**27**		0.639		**27**	
Ry	Relative Yield = (Y / YD)						0.639			

	Mixture ID: Patch Mix				Design Proportions (Non SSD)		Actual Batched Proportions		Yielded Proportions	
YD	Design Batch Size (ft3):		1.00							
	Cementitious Materials			SG	Amount (lb/yd3)	Volume (ft3)	Amount (lb)	Volume (ft3)	Amount (lb/yd3)	Volume (ft3)
CM1	Portland Cement (Type III)			3.15	537.83	2.736	19.92	0.101	974.82	4.96
CM2	Fly Ash Class F			2.50	0.00	0.000	0.00	0.000	0.00	0.00
CM3	Slag			2.90	0.00	0.000	0.00	0.000	0.00	0.00
	Total Cementitious Materials:				537.83	2.74	19.92	0.10	974.82	4.96
	Fibers									
F1	Large PVA Fibers			1.30	0.00	0.000	0.00	0.000	0.00	0.00
F2	Medium PVA Fibers			1.30	0.00	0.000	0.00	0.000	0.00	0.00
F3	Small PVA Fibers			1.30	0.00	0.000	0.00	0.000	0.00	0.00
	Total Fibers:				0.00	0.00	0.00	0.00	0.00	0.00
	Aggregates									
A1	Cenospheres	Abs:		0.35	0	0.000	0	0.000	0.00	0.00
A2	Large Poravers	Abs:		0.30	0.00	0.000	0.00	0.000	0.00	0.00
A3	Medium Poravers	Abs:		0.30	0.00	0.000	0.00	0.000	0.00	0.00
A4	Small Poravers	Abs:		0.30	179.99	9.615	6.67	0.356	326.23	17.43
A5	K15 Glass Bubbles	Abs:		0.15	65.395	6.987	2.422	0.259	118.53	12.66
A6	K25 Glass Bubbles	Abs:		0.25	179.99	11.538	6.6664	0.42733	326.23	20.91
	Total Aggregates:				425.38	28.14	15.75	1.04	770.99	51.00
	Water									
W1	Water for CM Hydration (W1a + W1b)				116.00	1.859	4.28	0.069	209.45	3.36
	W1a. Water from Admixtures			1.00	0.00		0.00		0.00	
	W1b. Additional Water				116.00		4.28		209.45	
W2	Water for Aggregates, SSD			1.00	0.00		0.00		0.00	
	Total Water (W1 + W2):				116.00	1.86	4.28	0.069	209.45	3.36
	Solids Content of Latex, Dyes and Admixtures in Powder Form									
S1	Polymer Modifier			2.20	38	0.277	1.41	0.010	69.00	0.50
S2	Green Pigment			1.20	1.648	0.022	0.061	0.001	2.99	0.04
	Total Solids of Admixtures:				39.65	0.30	1.47	0.01	71.99	0.54
	Admixtures (including Pigments in Liquid Form)			% Solids	Dosage (fl oz/cwt)	Water in Admixture (lb/yd3)	Amount (fl oz)	Water in Admixture (lb)	Dosage (fl oz/cwt)	Water in Admixture (lb/yd3)
Ad1	HRWR	8.8	lb/gal	0.00	18.00	0.00	8.60	0.000	18.00	0.00
Ad2	SRA	7.7	lb/gal	0.00	14.00	0.00	2.23	0.000	14.00	0.00
	Water from Admixtures (W1a):					0.00		0.00		0.00

		Design	Actual	Yielded
	Cement-Cementitious Materials Ratio	1.000	1.000	1.000
	Water-Cementitious Materials Ratio	0.22	0.215	0.215
	Slump, Slump Flow, in.	0.00	0.000	0.000
M	Mass of Concrete. lbs	1156.85	42.84	2065.25
V	Absolute Volume of Concrete, ft3	33.03	1.22	59.86
T	Theoretical Density, lb/ft3 = (M / V)	35.02	35.02	34.50
D	Design Density, lb/ft3 = (M / 27)	42.85		
D	Measured Density, lb/ft3		77.639	77.639
A	Air Content, % = [(T - D) / T x 100%]	22.35	121.71	125.03
Y	Yield, ft3 = (M / D)	**27**	0.552	**27**
Ry	Relative Yield = (Y / YD)		0.552	

Mixture ID: Aesthetic Mix					Design Proportions (Non SSD)		Actual Batched Proportions		Yielded Proportions	
YD	Design Batch Size (ft3):		1.00							
Cementitious Materials				SG	Amount (lb/yd3)	Volume (ft3)	Amount (lb)	Volume (ft3)	Amount (lb/yd3)	Volume (ft3)
CM1	Portland Cement (Type III)			3.15	304	1.547	11.259	0.057	342.38	1.74
CM2	Fly Ash Class F			2.50	0.00	0.000	0.00	0.000	0.00	0.00
CM3	Slag			2.90	0.00	0.000	0.00	0.000	0.00	0.00
Total Cementitious Materials:					304.00	1.55	11.26	0.06	342.38	1.74
Fibers										
F1	Large PVA Fibers			1.30	0.00	0.000	0.00	0.000	0.00	0.00
F2	Medium PVA Fibers			1.30	0.00	0.000	0.00	0.000	0.00	0.00
F3	Small PVA Fibers			1.30	0.00	0.000	0.00	0.000	0.00	0.00
Total Fibers:					0.00	0.00	0.00	0.00	0.00	0.00
Aggregates										
A1	Cenospheres	Abs:		0.35	14.216	0.651	0.5265	0.024	16.01	0.73
A2	Large Poravers	Abs:		0.30	0.00	0.000	0.00	0.000	0.00	0.00
A3	Medium Poravers	Abs:		0.30	0.00	0.000	0.00	0.000	0.00	0.00
A4	Small Poravers	Abs:		0.30	0.00	0.000	0.00	0.000	0.00	0.00
A5	K15 Glass Bubbles	Abs:		0.15	65.395	6.987	2.422	0.259	73.65	7.87
A6	K25 Glass Bubbles	Abs:		0.25	53.311	3.417	1.9745	0.12657	60.04	3.85
Total Aggregates:					132.92	11.05	4.92	0.41	149.70	12.45
Water										
W1	Water for CM Hydration (W1a + W1b)				102.00	1.635	3.78	0.061	114.95	1.84
	W1a. Water from Admixtures			1.00	0.00		0.00		0.00	
	W1b. Additional Water				102.00		3.78		114.95	
W2	Water for Aggregates, SSD			1.00	0.00		0.00		0.00	
Total Water (W1 + W2):					102.00	1.63	3.78	0.061	114.95	1.84
Solids Content of Latex, Dyes and Admixtures in Powder Form										
S1	Polymer Modifier			2.20	441	3.212	16.3	0.119	495.67	3.61
S2	Green Pigment			1.20	10.662	0.142	0.3949	0.005	12.01	0.16
Total Solids of Admixtures:					451.66	3.35	16.69	0.12	507.68	3.77
Admixtures (including Pigments in Liquid Form)				% Solids	Dosage (fl oz/cwt)	Water in Admixture (lb/yd3)	Amount (fl oz)	Water in Admixture (lb)	Dosage (fl oz/cwt)	Water in Admixture (lb/yd3)
Ad1	HRWR	8.8	lb/gal	0.00	18.00	0.00	8.60	0.000	18.00	0.00
Ad2	SRA	7.7	lb/gal	0.00	14.00	0.00	2.23	0.000	14.00	0.00
Water from Admixtures (W1a):						0.00		0.00		0.00
Cement-Cementitious Materials Ratio					1.000		1.000		1.000	
Water-Cementitious Materials Ratio					0.34		0.336		0.336	
Slump, Slump Flow, in.					0.00		0.000		0.000	
M	Mass of Concrete. lbs				1023.98		37.90		1148.11	
V	Absolute Volume of Concrete, ft3				17.59		0.65		19.81	
T	Theoretical Density, lb/ft3 = (M / V)				58.21		58.19		57.97	
D	Design Density, lb/ft3 = (M / 27)				37.93					
D	Measured Density, lb/ft3						42.682		42.682	
A	Air Content, % = [(T - D) / T x 100%]				34.85		26.65		26.37	
Y	Yield, ft3 = (M / D)				**27**		0.888		**27**	
Ry	Relative Yield = (Y / YD)						0.888			

Shear and Bending Moment:



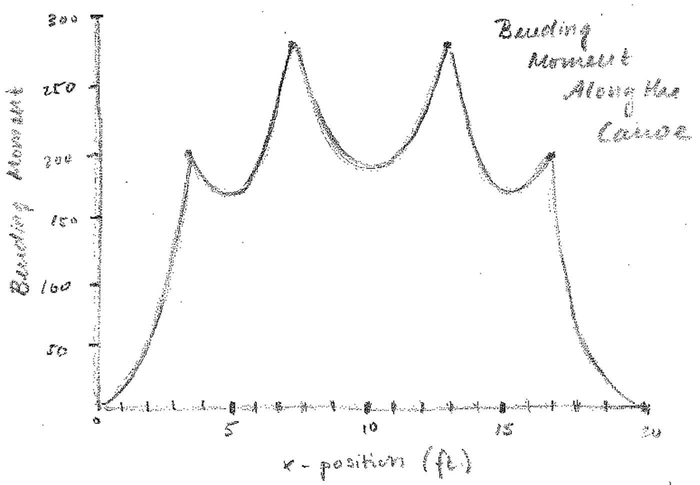
The canoe is approximated to a beam

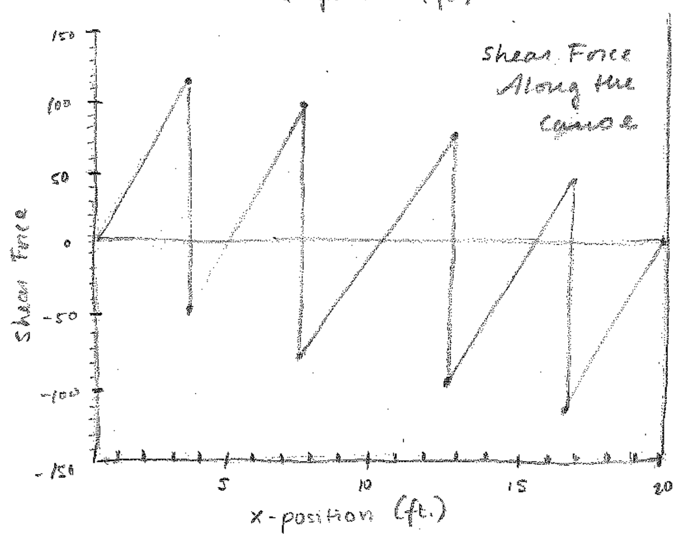
Four people on the boat, 160 lbs each

$$W_c = \frac{\text{weight of canoe}}{\text{length canoe}} = \frac{-180 \text{ lbs}}{19.583 \text{ ft}} = \boxed{-9.192 \text{ lbs/ft}}$$

$$W_F = \frac{\text{weight}_{\text{canoe}} + 4(160)}{\text{length}_{\text{canoe}}} = \frac{180 + 4(160)}{19.583}$$

$$\boxed{W_F = 41.873 \text{ lbs/ft}}$$





V_i = shear force

M_i = bending moment

$$V_1(x) = 41.873(x) - 9.192(x) = \boxed{32.681(x)}$$

$$M_1(x) = \int V_1\,dx = \left(\tfrac{1}{2}\right)32.681(x)^2 + C$$

$$M_1(x) = 16.341x^2 + C$$

initial condition: $M_1(0) = 0 \rightarrow C = 0$

$$\boxed{M_1(x) = 16.341x^2 \quad (0 \le x \le 3.5 \text{ ft})}$$

$$V_2(x) = 32.681(3.5) - 160 + 32.681(x - 3.5)$$

$$\boxed{V_2(x) = 32.681(x) - 160}$$

$$M_2(x) = \int V_2\,dx = 16.341x^2 - 160x + C$$

initial condition: $M_1(3.5) = 200.177$

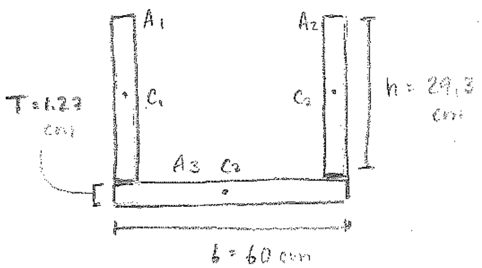
$$M_2(3.5) = 200.177 = 16.341(3.5)^2 - 160(3.5) + C$$

$$C = 560$$

$$\boxed{M_2(x) = 16.341x^2 - 160x + 560 \quad (3.5 < x < 7.5)}$$

This process is repeated V_3, V_4 and V_5, as well as M_3, M_4 and M_5. For each interval, the initial condition for M is construed from the theorem of continuity.

Interval	Shear Force	Bending Moment
[0, 3.5]	32.681 x	16.341 x²
[3.5, 7.5]	32.681 x - 160	16.341x² - 160x + 560
[7.5, 12.08]	32.681 x - 320	16.341x² - 320x + 1760
[12.08, 16.08]	32.681 x - 480	16.341x² - 480x + 3693
[16.08, 19.58]	32.681 x - 640	16.341x² - 640x + 6267



A_i = Area
C_i = centroid
b = base
h = height
T = thickness

$A_1 = A_2 = hT = (29.3)(1.27)$

$A_1 = A_2 = 37.21$ cm

$A_3 = bT = (60)(1.27)$

$A_3 = 76.2$ cm

$C_i = \frac{\text{length}}{2}$

$C_1 = 15.3$ cm

$C_2 = 15.3$ cm

$C_3 = 0.64$ cm

This form was modeled from the largest cross-section, of width 60 cm and length of 39.6 cm.

Nuetral Axis:

$$\bar{y} = \frac{\Sigma A_i C_i}{\Sigma A_i} \qquad \bar{y} = \frac{2(37.21)(15.3) + (76.2)(0.64)}{2(37.21) + (76.2)}$$

$$\boxed{\bar{y} = 7.88\text{ cm}}$$

Moment of Inertia of Area:

$$I_x = \Sigma\left(I_{xi} + A_i(\bar{y} - c_i)^2\right)$$

$$I_{xi} = \frac{b_i h_i^3}{12}$$

$$I_{x_1} = I_{x_2} = \frac{(1.27)(29.3)^3}{12} = 2662.11\text{ cm}^4$$

$$I_{x_3} = \frac{(60)(1.27)^3}{12} = 10.24\text{ cm}^4$$

$$I_{x_1}' = I_{x_2}' = 2662.11 + (37.21)(15.3 - 7.88)^2$$

$$I_{x_1}' = I_{x_2}' = 4710.76\text{ cm}^4$$

$$I_{x_3}' = 10.24 + (76.2)(7.88 - 0.64)^2$$

$$I_{x_3}' = 4004.46\text{ cm}^4$$

$$I_x = 2(4710.76) + 4004.46$$

$$\boxed{I_x = 13425.98\text{ cm}^4 \quad I_x = 322.56\text{ in}^4}$$

Peak Stresses

$$\sigma_{top} = \frac{M_{max}\,\bar{y}_{top}}{I_x} \qquad \sigma_{top} = \frac{(279.72)(0.7454)}{0.015556}$$

$$\sigma_{bottom} = \frac{M_{max}\,\bar{y}_{bottom}}{I_x} \qquad \sigma_{bottom} = \frac{(279.72)(0.2585)}{0.015556}$$

$\bar{y}_{top} = 22.72\text{ cm} = 0.7454$ ft

$\bar{y}_{bottom} = 7.88\text{ cm} = 0.2585$ ft

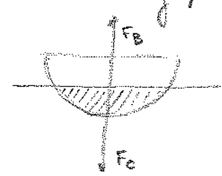
$M_{max} = M_3(7.5) = 279.208$ lbs·ft

$I_x = 322.56\text{ in}^4 = 0.015556\text{ ft}^4$

$$\boxed{\sigma_{top} = 13378.866\text{ lbs/ft}^2 \quad \sigma_{bottom} = 4639.706\text{ lbs/ft}^2}$$

Volume Desplaced

Assuming four people are on the canoe.



$\Sigma F_y = F_B - F_c = 0$

$F_c = W_c + W_p$

$0 = F_B - W_c - W_p$

$F_B = \rho_{H_2O} V_{dis}$

F_c = Force (canoe)
F_B = Buoyancy Force
W_c = weight of canoe
W_p = weight of people

$\rho_{H_2O} V_{dis} = 180 + 4(160)$
$= 820$ lbs
$= 371.95$ kg

$\rho_{H_2O} = \frac{1000\text{ kg}}{\text{m}^3}$

$\therefore V_{dis} = \frac{371.95}{1000}$

$= 0.372\text{ m}^3$

$$\boxed{V_{dis} = 0.372\text{ m}^3 \quad V_{dis} = 13.14\text{ ft}^3}$$

These are the definitions of the variables used in the calculation of the following coefficients:

V_{dis} = Volume displaced
V_{dis} = 0.372 m³

LWL = Waterline Length
LWL = 5.875 m

OLWL = Overall Waterline Length
OLWL = 5.788 m

H = Draft = 0.193 m

BWL = Waterline Beam
BWL = 0.612 m

$A_{c\text{-}s}$ = Area of Largest Cross-Section
$A_{c\text{-}s}$ = 0.098 m²

L_c = Canoe Length
L_c = 5.969 m

Block Coefficient

$$\text{Block Co.} = \frac{V_{dis}}{(OLWL)(BWL)(H)}$$

$$= \frac{0.372\ m^3}{(5.788)(.612)(.193)\ m^3}$$

$$\boxed{\text{Block Co.} = 0.544}$$

Waterline Length to Beam Ratio

$$\frac{LWL}{BWL} = \frac{5.875\ m}{0.612\ m}$$

$$\boxed{\frac{LWL}{BWL} = 9.60}$$

Prismatic Coefficient

$$\text{Prismatic Co.} = \frac{V_{dis}}{(A_{c\text{-}s})(L_c)}$$

$$= \frac{0.372\ m^3}{(0.098)(5.969)\ m^3}$$

$$\boxed{\text{Prismatic Co.} = 0.636}$$

Section Coefficient

$$\text{Section Co.} = \frac{A_{c\text{-}s}}{(BWL)(H)}$$

$$= \frac{0.098\ m^2}{(0.612)(0.193)\ m^2}$$

$$\boxed{\text{Section Co.} = 0.830}$$