# PONDICHERRY

## ARIZONA STATE UNIVERSITY

## 2016 CONCRETE CANOE DESIGN REPORT

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# Executive Summary

Yann Martel's *Life of Pi* is a story of survival, will power, and dominance. The main character, Pi Patel, recounts the time when he found himself stranded at sea in a lifeboat with a tiger, zebra, hyena, and orangutan from his father's zoo, Pondicherry. Patel survives 227 days at sea with the tiger. Patel describes the hunger and thirst that drove him to survive, and his territorial dominance that allowed him to live alongside a tiger in a small boat. *Pondicherry* seeks to overcome the insurmountable odds and paddle to victory, just as Pi Patel did in *Life of Pi* (Martel).

Arizona State University, originally entitled the Territorial Normal School, was founded in 1885 and had a total enrollment of 33 students. Since then, Arizona State University has grown to be the largest public university in the United States with over 83,000 students enrolled today ("Arizona State University"). The Ira A. Fulton Schools of Engineering unit within ASU enrolled almost 19,000 students this year (Ira A Fulton). Approximately 1,100 are enrolled in the School of Sustainable Engineering and the Built Environment as civil, environmental, sustainable or construction engineering majors (School of Sustainable Engineering and the Built Environment).

Table 1: Structural Mix Properties

| Mix Properties | |
|---|---|
| **Wet Density** | 60.0 pcf |
| **Dry Density** | 45.5 pcf |
| **28-Day Compressive Strength** | 1590 psi |
| **14-Day Tensile Strength** | 430 psi |
| **14-Day Composite Flexural Strength** | 1550 psi |
| **Air Content** | 36.40% |

The ASU Concrete Canoe team is a competitive team within the American Society of Civil Engineers club on campus. ASCE ASU participates in the Pacific Southwest Conference each year. ASCE ASU Concrete Canoe has placed seventh with *Clockwork* (2013), tenth with *Avanyu* (2014), and eleventh with *Mandjet* (2015). The 2016 team hopes to improve upon these scores and rank as the best team from Arizona. This improvement hopes to come from this year's experienced leadership, increased funding, and innovations in the hull design and structural analysis, construction, and mix design processes.

Table 2: Canoe Physical Properties

| Canoe Properties | |
|---|---|
| **Name** | Pondicherry |
| **Length** | 20 ft |
| **Width** | 28 in |
| **Depth** | 14 in |
| **Avg Thickness** | 0.75 in |
| **Estimated Weight** | 230 lbs |
| **Colors** | White, Red-Orange |
| **Primary Reinforcement** | Fiberglass Mesh |
| **Secondary Reinforcement** | Glass fibers |

With the help of alumni, a MATLAB code was written to perform all structural analysis calculations instantaneously to drastically speed up the hull design and analysis portion of the project. A few hull designs were created using the program, and the analysis results were immediately studied to determine the optimal design. The mix design team promoted sustainability techniques by incorporating recycled materials such as Class F Fly Ash and recycled glass Poraver. In addition, the final mix design for *Pondicherry* significantly reduced the amount of Portland White Cement and replaced it with more sustainable cementitious materials, resulting in significantly reduced $CO_2$ emissions.

The construction team saw improvements and innovation in several aspects of the process. A waterproof, rigid coating agent, Rosco's FoamCoat™ was used in place of last year's joint compound to result in a stronger, more durable mold for cast day. With the help of ASU professionals, the construction team was able to build a semi-permanent curing chamber that can be utilized for years to come. This curing chamber allowed the team to cure in a larger, temperature controlled environment, ensuring *Pondicherry* will be as strong as possible.

Just as Pi Patel's will to live allowed him to survive at sea, Arizona State University's hunger and thirst for success will guide *Pondicherry* to victory.

Project management is one of the most important aspects of a project to ensure its successful completion. Project managers are essential leaders of a team in all aspects, including scheduling, finances, and engineering. In the creation of *Pondicherry*, we elected two Project Managers to lead the team. Our objective was to create a canoe that was lightweight yet strong enough to withstand racing conditions. With several returning members from the 2014-2015 *Mandjet* team, we felt confident in our ability to create a great canoe. We assigned captains and met immediately following the 2015 Pacific Southwest Conference to begin planning for *Pondicherry*.

The majority of our funds for *Pondicherry* were acquired from donations made by local engineering and construction material companies. With these new funds, we were able to plan for a higher budget than *Mandjet* (which cost approximately $1200). While the final cost of *Pondicherry* was $1,190, we were able to put the new funds into building a semi-permanent curing chamber. We created a detailed account ledger from the beginning of the project to ensure that all funds were tracked and allocated properly.

We created the schedule for *Pondicherry* at the end of the 2015 spring semester so that we could start during the summer. The schedule was distributed to all captains and was referred to weekly to ensure that we were on track throughout the process. The major milestones were hull design selection, cutting the foam using CNC, finalizing the mix design, and casting the canoe, and the critical path can be seen on page 11. These milestones are outlined in Table 3. With the creation of a MATLAB program that performs hull design and structural analysis in one program, we were able to significantly reduce the hull design person hours. We encountered problems in the CNC programs that caused a delay in the mold construction time. With a lack of manpower during winter break, we saw a delay in the final mix design selection; however, we were still able to cast the canoe one week earlier than *Mandjet*.

Table 3: Major Project Milestones

| Milestone | Delay | Cause |
|---|---|---|
| Hull Design Selection | None | MATLAB program creation |
| CNC the Foam | 2 weeks | Improper CNC maching programming |
| Finalize Mix Design | 3 weeks | Lack of manpower |
| Casting the Canoe | None | Proper scheduling |

One challenge faced this year was the relocation to a different space a few weeks before casting day. Our club was provided with a new room to cast in over winter break, and we had to relocate into the new space without damaging the mold. Due to the fact that the new space posed unknown challenges, we had to have a backup plan for every task to ensure that the team members as well as the canoe were safe at all times.

The total man hours spent creating *Pondicherry* was approximately 1,330 hours, 480 of which are from paddling practice. The allocation of man hours can be seen in Figures 1 and 2 on page 2.

Every precaution was taken to ensure the safety of all team members during the design and construction of *Pondicherry*. During the mix design and construction phases, all members were required to wear gloves and respirators. Safety data sheets were readily available at all times as well. We made sure to make the production of *Pondicherry* as sustainable as possible. We used 2”x4” cylinders to test our mix designs so as not to waste expensive materials and discard excess concrete. We also were able to use the excess concrete from mix design to create useful objects, such as flower pots, ornaments, and other souvenirs.

# Project Management Resource Allocation

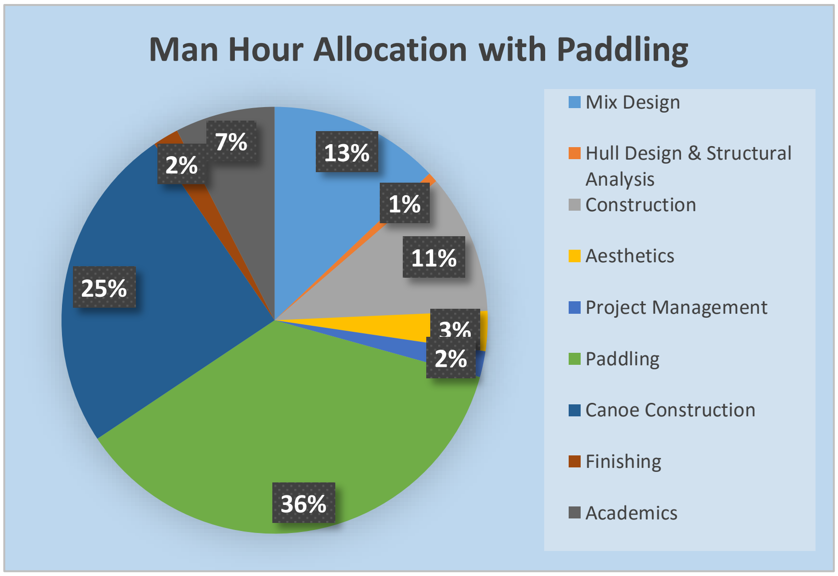



Figure 1: Man Hour Allocation with Paddling. Figure 1 shows the man hour allocation of the approximately 1,330 hours put into the project, including paddling practice. As is evident from this figure, paddling took up more than one-third of the time allocation.

Note: Some of the hours have been estimated as they are ongoing.

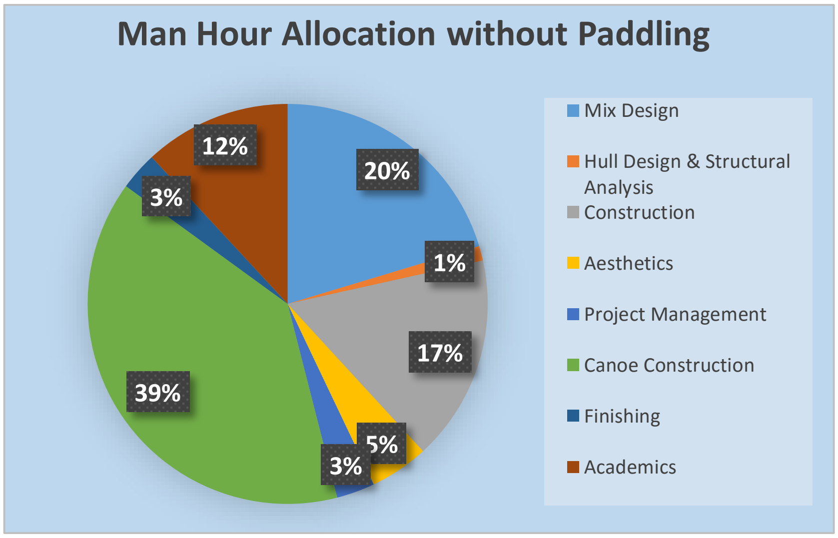



Figure 2: Man Hour Allocation without Paddling. Figure 2 shows the man hour allocation of the approximately 1,330 hours put into the project, not including paddling practice. Canoe construction (39%) and mix design (20%) took up more than half of the total time for the project.

Note: Some of the hours have been estimated as they are ongoing.

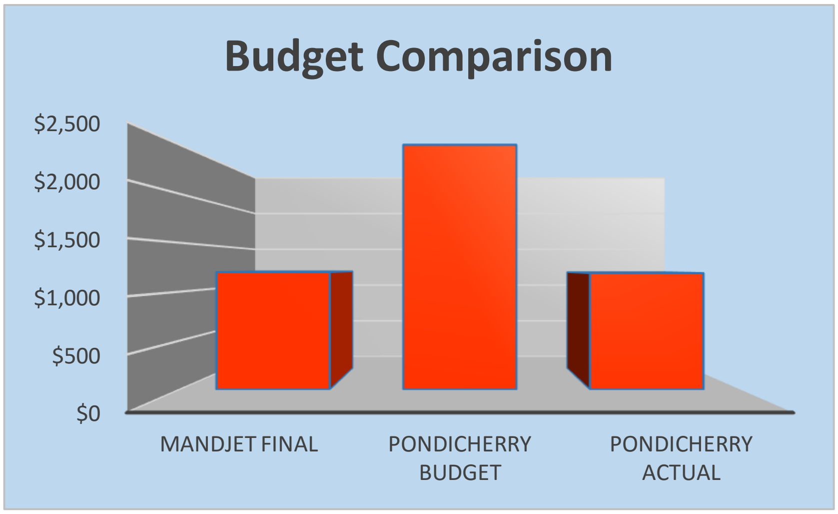



Figure 3: Budget Comparison with *Mandjet*. Figure 3 shows the budget comparison between *Mandjet* and *Pondicherry*. While the budget for *Pondicherry* was much greater than the cost of the canoe, a lot of the funds went towards the construction of a semi-permanent curing chamber that can be used for years to come.

## Project Managers

Victoria Flys, Sr

Jacob Bauchmoyer. Sr

- Created and maintained project schedule and budgets
- Ensured compliance with competition rules
- Ordered materials and managed finances
- Delegated tasks and coordinated teams

## Aesthetics

Adrien Orlowski, Sr

- Developed and designed theme of canoe
- Designed and produced canoe presentation and display
- Oversaw development of final product

Contributors: Mackenzie Hagan (Grad), Victoria Flys (Sr), Jacob Bauchmoyer (Sr)

## Mix Design

Victoria Jimenez, Sr

Dylan Curet, Sr

- Conducted concrete research and development
- Developed concrete mix design
- Performed laboratory testing

Contributors: Jeffery Spradley (So), Jordan Rodriguez (Sr), Victoria Flys (Sr), Jacob Bauchmoyer (Sr)

## Construction

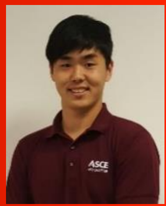
Brooke Ridley, Sr

- Organized and carried out mold construction and concrete casting and finishing
- Coordinated quality control and safety practices
- Oversaw curing chamber construction

Contributors: Jeffery Spradley (So), Jordan Rodriguez (Sr), Jeffrey Capaci (Sr), Victoria Flys (Sr), Jacob Bauchmoyer (Sr), Mackenzie Hagan (Grad), Veronica Head (Jr), Adrien Orlowski (Sr)

## Paddling

Veronica Head, Jr



Hoyong Ryou, Jr

- Coordinated paddling practices
- Conducted tryouts and organized paddling team
- Research and taught paddling techniques paddling team

Team members: Veronica Head (Jr), Hoyong Ryou (Jr), Marisol Luna (Jr), Natalie Miller (Fr), Allison Charles (Fr), Tyler Charles (Sr), Connor Fegard (Fr), Nathan Holt (Jr)

## Hull Design & Analysis

Victoria Flys, Sr
Jacob Bauchmoyer, Sr

- Performed design and analysis of hull using MATLAB and AutoCAD
- Determined strength requirements of concrete mix
- Conducted file conversion from AutoCAD to VCarve Pro

*Pondicherry's* hull design team began working early in the summer to develop a hull design program in MATLAB. The completed program requires several user specified points to form the bow, stern, keel, and widest cross-section, then uses quadratic splines to connect these points, and finally offsets the splines to create the inner and outer surfaces of the hull. Figure 4 demonstrates the program's modeling capability; key points are shown as black dots and splines are shown as the blue and green lines.

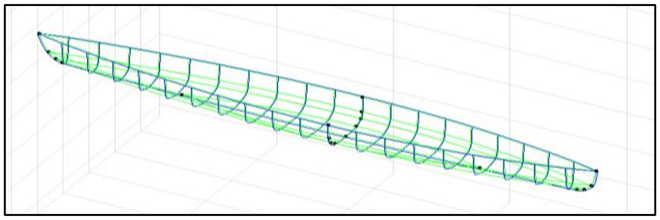


Figure 4 - MATLAB Canoe Model

Last year's canoe, *Mandjet*, was chosen as the baseline design due to its fast straight-line speed and ease of paddling. The team aimed to improve upon *Mandjet's* maneuverability and initial stability. To improve maneuverability, the team increased the stern rocker from 2½" to 4" and kept the bow rocker at 4". This lifts the ends up, which forces the center of the canoe to bear more weight, making the canoe easier to turn at its midpoint (EoHD). However, an increased rocker decreases tracking. To offset the lost tracking, the widest point was moved 1' aft of midship. This creates a longer streamlined bow, which allows the canoe to track better, and travel faster due to the sharper entry line. Figure 5 displays *Pondicherry's* 31 degree entry line compared to *Mandjet's* 40 degree entry line.

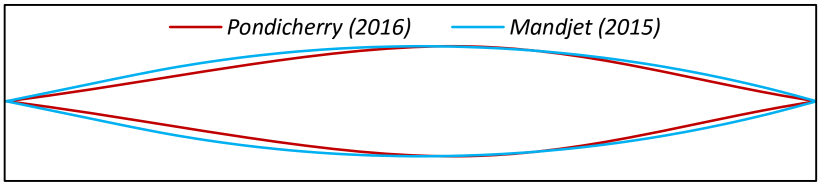



Figure 5- Entry Line Comparison

The team addressed initial stability by giving the profile a rounder transition between the bottom and walls of the hull (Figure 6). This helped widen the hull at higher waterline levels, which increased the transverse metacentric height ($GM_T$) from 1.00 to 1.10 (Table 4). Since transverse metacentric height provides a measure of the initial stability and resistance to overturning where a larger value implies greater stability and resistance, *Pondicherry* has 10% greater stability than *Mandjet*. The increased stability was achieved with little change to the wetted surface area and prismatic coefficient (Table 4), indicating a *Pondicherry* will have a similar performance to *Mandjet*, yet with improved stability.

Table 4 - Performance Comparison (2 Male Race)

| Canoe Name | Wetted Surface Area | Prismatic Coefficient | $GM_T$ |
|---|---|---|---|
| ***Pondicherry* (2016)** | 37.0 $ft^2$ | 0.59 | 1.10 |
| ***Mandjet* (2015)** | 36.7 $ft^2$ | 0.57 | 1.00 |

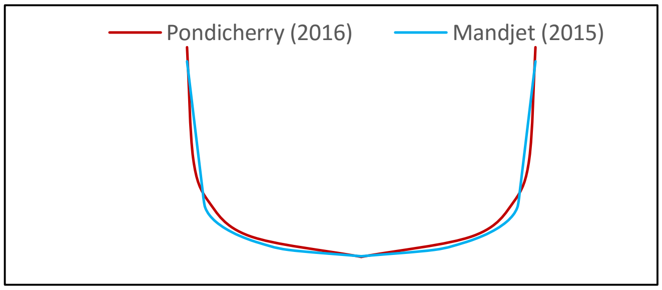



Figure 6 - Hull Profile Comparison

*Pondicherry*'s final design is asymmetric with a shallow arch bottom and slightly flared walls, a 20'-0" overall length, a 28" beam, a 15" depth at widest section, a 16" depth at the bow and stern, and a ¾" thickness.

Upon completing the hull design, the team performed a two-dimensional longitudinal and lateral analysis to ensure *Pondicherry* would endure all loading conditions. MATLAB was used in combination with Excel to compute cross-sectional properties and perform each analysis. Five loading cases were taken into account: (1) display, (2) carrying, (3) two female paddlers, (4) two male paddlers, and (5) coed.

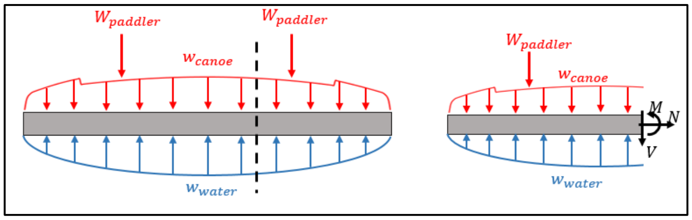



Figure 7 – Longitudinal Analysis FBD

For the longitudinal analysis, the canoe was modeled as a simply supported beam with self-weight and paddler weight acting in the negative gravity direction and the buoyant force acting in the positive gravity direction (Figure 7). Then cuts were taken at 1” intervals to compute the internal forces and moments. Concrete unit weight was conservatively estimated as 62 pcf for the analysis, resulting in a conservative canoe weight of 260 lbs. Male and female paddlers were modeled as 190 lbs and 130 lbs point loads, respectively. For paddling load cases, static equilibrium was maintained by balancing the net downward forces with the resultant buoyant force to eliminate the simple support reaction; the centroids of the upward and downward forces aligned in order to eliminate residual moments. For the display case, supports were located 4’ inward from the bow and stern. For the carrying case, supports were located at each end. Bending stresses were determined using the theory of simple bending: $\sigma = M/S_x$. Where, $M$ is the bending moment, $c$ is the distance from the neutral axis to the outer most fiber, and $S_x$ is the section modulus.

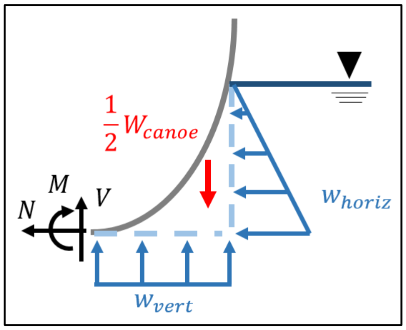



Figure 8 – Lateral Analysis FBD

The transverse analysis was only performed for the paddling load cases where the canoe was modeled as a curved cantilever beam with the same loading as the longitudinal analysis. Moments and forces were determined using the free body diagram in Figure 8. Stress was then determined using curved beam formula: $\sigma_{\theta\theta} = \frac{N}{wt} + \frac{M\left(wt - rw\ln\left(\frac{r_o}{r_i}\right)\right)}{wtr\left(Rw\ln\left(\frac{r_o}{r_i}\right) - wt\right)}$, where $N$ is the axial force, $M$ is the moment, $w$ is the width, $t$ is the thickness, $r_o$ is the outer radius, $r_i$ is the inner radius, $R$ is the radius to centroid (Bending of Curved Beams). The coed race lateral analysis controls the concrete strength where the maximum stress occurs at the widest hull section (Table 5).

Table 5 – Maximum Stresses

| Load Case | Compressive (psi) | Tensile (psi) |
|---|---|---|
| **2 Male*** | 160 | 155 |
| **2 Female*** | 127 | 123 |
| **Coed*** | 231 | 224 |
| **Carrying**** | 131 | 110 |
| **Display**** | 16 | 31 |

* Lateral Analysis Governs **Longitudinal Analysis Governs

The team decided to add a 2” diameter semi-circular gunnel rail to mitigate cracks since *Mandjet* developed several hairline cracks uniformly spaced originating from the gunnel down to the bottom during regional competition.

Three feet of bulkhead was added at the bow and stern based on *Mandjet’s* performance during the swamp test in order to improve floatation. Bulkheads were made from EPS foam encased in a layer of concrete.

The goals of the mix design team this year was to create an effective mix that could withstand the stresses brought on by competition while simultaneously being as lightweight as possible to ensure maximum buoyancy. The secondary goal was to create a workable mixture that was easy to place and finish to improve casting and to reduce the amount of necessary sanding and patching. 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 high strength, last year's mix, *Mandjet*, was used as a baseline for *Pondicherry*. *Mandjet* possessed a 59.1 pcf wet unit weight, a 55.2 pcf dry unit weight, a 1290 psi compressive strength, and a 380 psi tensile strength. *Mandjet*'s mix consisted of Type I White Portland Cement, Class F fly ash, metakaolin, 3M Glass Bubbles, Cenospheres, Poraver (0.25-1.0 mm), AEA-92 (air entrainer), Grace short glass fibers, and ADVA Cast 575 (HRWR). Focus was placed on balancing unit weight and strength as *Mandjet*'s biggest issue was distributed cracking during competition. *Mandjet* had strong workability and flow during casting, therefore the mix placement quality was relegated to a secondary goal.

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 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 and compare with results from the prior year's mix design. *Mandjet's* gradation consisted of Cenospheres, Poraver (varying from 0.25-1.0mm), and 3M Glass Bubbles with Poraver 0.1-0.3mm and 1.0-2.0mm omitted to create a smoother finishing mix. A larger range of Poraver in the mix would allow for increases in strength and reduction in weight due to the more effective packing of aggregates. In an effort to reduce weight, increase strength, and further spread the gradation range, *Pondicherry*'s mix design incorporated small amounts of Poraver 0.1-0.3mm (5.8%) and Poraver 1.0-2.0mm (2.5%). A minor amount of grains were detected in the mix when casting, but a proper finish was still easily achieved.

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 F fly ash (ASTM C618) was added between 5-20% to improve workability while reducing water demand (SRMG). Metakaolin (ASTM C618) was implemented between 10-20% 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).

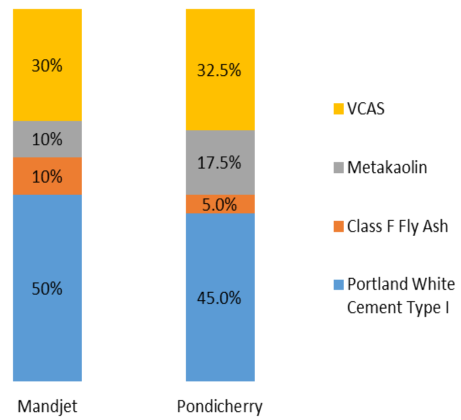


Figure 9: Cementitious Materials

VCAS™ (ASTM C618), known for its improved retention of mold detail, was incorporated between 25-35% to increase the durability of hardened concrete (Vitro Minerals). A combination of 45% Type I White Portland Cement, 5% Class F fly ash, 17.5% metakaolin, and 32.5% VCAS™ was determined to provide optimal strength, texture, and workability for *Pondicherry*. The amount of fly ash was reduced from *Mandjet*'s mix (Figure 9) in order to lighten the color of the final mix. Type I Portland White Cement content was also reduced in order to significantly reduce weight of the mixture.

The design process shifted towards admixtures to improve workability, increase strength, and reduce unit weight of the mix. Admixtures taken into consideration were AEA-92, an air entertainer and ADVA Cast 575, a high-range water-reducer. Other admixtures were eliminated early in the testing process, as their benefits were not required. Tests from previous years showed harsh interactions between different admixtures, therefore the *Pondicherry* mix team sought to reduce the number of used admixtures to prevent adverse interactions, such as foaming that can occur between latex and air entrainers. 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 a lower unit weight (Table 6). However, the large volume of air-voids created discontinuity in the concrete matrix, which reduced strength by 10%. 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. ADVA Cast 575 helped with early strength gain by reducing the w/cm from 0.65 to 0.38. 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.

Table 6: Admixtures

| Admixture | Type | Recommended Dosage | Structural Mix |
|---|---|---|---|
| **ADVA Cast 575** | HRWR | 2-10 fl oz/cwt. | 5 fl oz/cwt. |
| **AEA-92** | AEA | 0.1-7 fl oz/cwt. | 12 fl oz/cwt. |

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 10). The white mesh was used in *Mandjet*. To compare effectiveness, mesh was placed in concrete plate samples subjected to three-point bending. The green fiberglass mesh was chosen for its dramatic increase in composite strength. Two layers of the green fiberglass mesh were used and provided a flexural strength increase of nearly 400% due to the high bonding surface area and strong impregnation of the textile into the cement matrix. The reinforcement provided a higher volume fraction of textile than the white mesh which led to a significant increase in composite flexural strength. As concrete is weak in tension and flexure, the textile bridged distributed cracks and slowed crack propagation through the matrix. Two fibers were tested for secondary reinforcement: Sigrafil C-Type fibers and Grace MicroFibers. Grace fibers were chosen over the Sigrafil

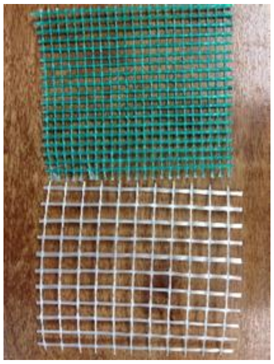


Figure 10: Fiberglass Mesh

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 50 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. This variance was likely due to the low cement content of the mix and the early strength gain provided by the HRWR. 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. First, recycled materials including fly ash, a byproduct of coal combustion, and Poraver, made from post-consumer recycled glass, comprised 5% of cementitious materials and 94% of aggregates by weight. Second, 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. Third, the team optimized gradation to minimize voids between aggregate particles, and also replaced 65% Portland cement with supplementary cementitious 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 (Cement Sustainability Initiative).

The final concrete mix for *Pondicherry* met all of the design team’s goals. The mix exceeded the required compressive and tensile strength with a factor of safety of 6.9 and 1.9, respectively. The dry unit weight was significantly less than water at 45.5 pcf. Finally, the mixture was comparatively as workable as *Mandjet* with an equally strong casting and finishing ability.

Table 7**:** Final Testing Results

| Property | Required Value | Actual Value |
|---|---|---|
| **Compressive Strength** | 231 psi | 1590 psi |
| **Tensile Strength** | 224 psi | 430 psi |
| **Dry Unit Weight** | <62.4 pcf | 45.5 pcf |

After 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 *Pondicherry*. The team decided to use a male mold made from 2 pcf expanded polystyrene (EPS) foam due to the ease of construction as well as the additional buoyancy provided when left in the bulkheads. The goal for construction was to improve upon last year's process by implementing new construction techniques based on lessons learned from last year. The entire construction process was carried out over a five-month period, beginning with mold construction, followed by casting, and lastly, concrete finishing.

Figure 11: ShopBot CNC

AutoCAD was used to draft the finalized hull design in order to begin mold construction. Cross-section cuts were taken at two-inch intervals, generating a stair-step pattern when assembled. Due to cracking along the top edges of the canoe last year, gunnel rails were added. Upon completion of drafting, cross sections were imported into VCarve Pro, a toolpathing software that converts AutoCAD cut files into files that a CNC (Computer Numeric Control) machine can read. TechShop Chandler provided free access and training on the ShopBot CNC machine (Figure 11) due to the shop's partnership with ASU. The construction team operated the CNC machine, resulting in a cost savings of $3000 towards the construction budget compared to previous years.


Figure 12: Assembling the Mold

After cutting was completed, the 120 cut-sections were adhered using waterproof carpet tape and fitted along a continuous steel bar for proper alignment of the mold (Figure 12). The stair-step pattern was sanded flush with 60-grit sand paper to create smooth transitions between adjacent sections. Any defects during initial sanding were fixed by applying 1/16" thick layers of Rosco Foamcoat™. An alternative product to joint compound was used this year because the joint compound applied last year was not waterproof, and thus reacted when Elmer's glue (the releasing agent) and concrete was applied. This caused difficulty when removing the mold. The Rosco Foamcoat™ layer was sanded using 120-grit sand paper until imperfections were minimized so that the mold met quality control specifications. Because the foam coat was extremely rigid and waterproof, discussion occurred on whether a releasing agent was necessary. Ultimately it was decided that Elmer's Glue would be used as a precaution due to unfamiliarity with Rosco Foamcoat™. 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 13: Curing Chamber Construction

*Pondicherry* incorporates two layers 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 the entire canoe. A four-inch overlap was provided between the two sheets of mesh to ensure the reinforcement acted as a continuous system.

The team constructed a new curing chamber (Figure 13). The chamber was constructed using a steel frame that supports a PVC pipe misting system which is enclosed by plastic sheeting and tarps. Misters were placed along the length of the pipes to ensure even misting. Misters were scheduled to turn on every 4 hours for 45 minutes. This created a controlled environment providing proper hydration and humidity for an efficient wet curing process, safe from the dry Arizona air. It is intended for this curing chamber to be permanent and usable for years to come, compared to last year in which the curing chamber was temporary.

Figure 14: Concrete Casting

Due to constraints on the use of stain and acrylic paint, pigment was added to a portion of the concrete. Because the theme of the canoe was based on Life of Pi, it was decided that the inside of the canoe would be a red color, and the outside of the canoe would be uncolored. The different colored concrete as well as the inclusion of gunnel rails resulted in a more complicated concrete application process than previous years, requiring strategic planning before concrete casting. *Pondicherry* was casted in a six-step process (Figure 14). First, the gunnel rails were filled with uncolored structural mix, extending ¼" from the main body of the canoe. Second, a ¼" layer of red-colored structural mix was applied by hand, excluding the gunnel rails and using tire tread gauges to regulate thickness. Third, the pre-fitted fiberglass mesh was placed over this layer of concrete. Then a ¼" layer of uncolored structural mix was applied, followed by another fiberglass mesh layer. Finally, another ¼" layer of uncolored structural mix was applied and smoothed using trowels. The tire gauges were used throughout the placement process to ensure uniform thickness. The canoe was covered in cheesecloth while curing to ensure the concrete remained moist (Figure 15).

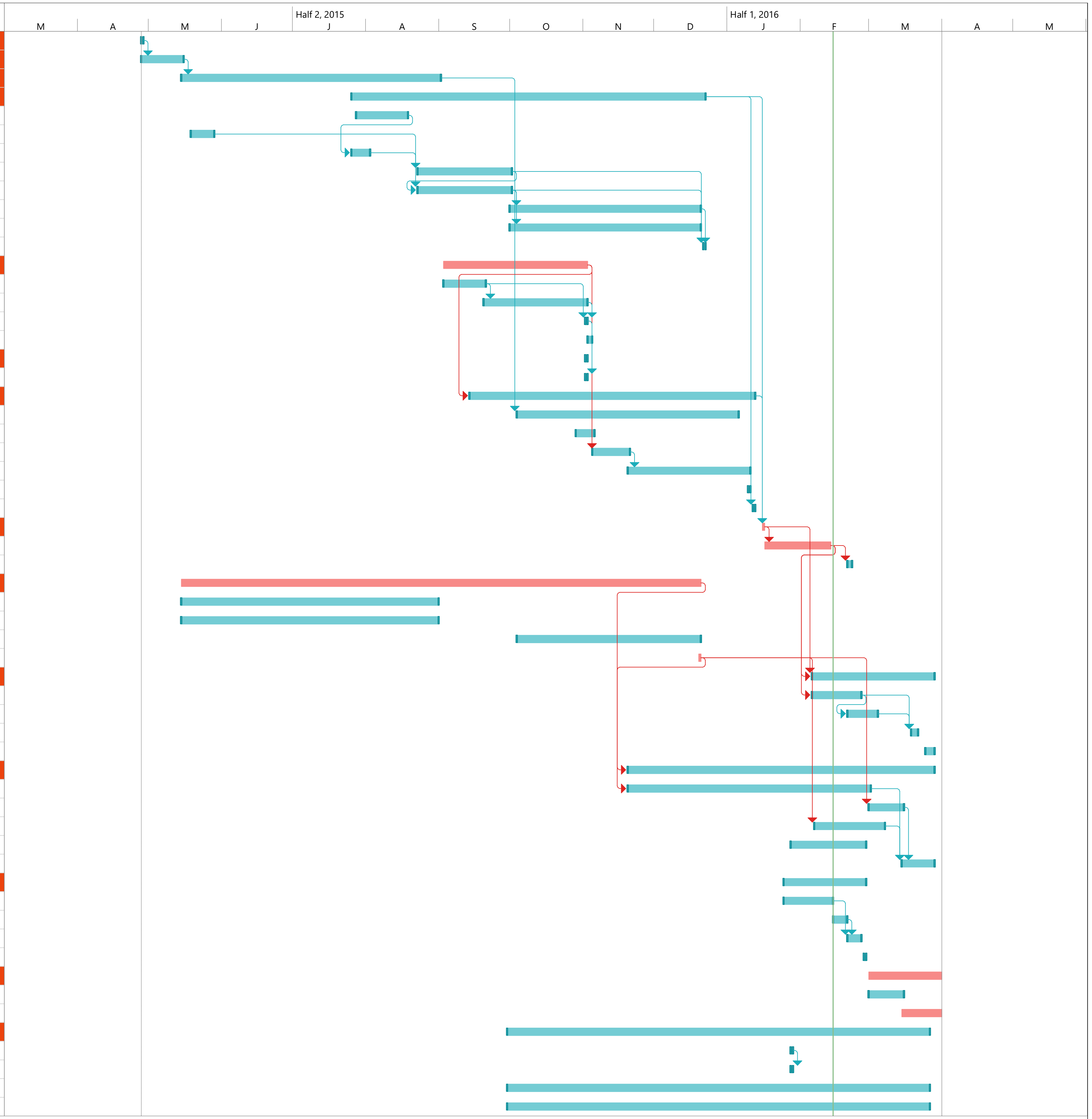
Figure 15: Curing Chamber

The sanding process was initiated after a 21-day cure. The team performed a wet sand of the outside with 80-grit, 120-grit, 180-grit, and 220-grit sandpaper. A patching mix was applied to fill inconsistencies at 28-days. *Pondicherry* was removed from the mold by hand after the 28-day curing period. The canoe was turned over so that the mold could be removed by carefully cutting the foam from the inside of the canoe, leaving 3 feet of foam in each bulkhead. The bulkheads and inside were patched and then the inside of the canoe was wet-sanded using various grits of sandpaper to create a smooth surface. Wet sanding was utilized to reduce exposure to dust particles containing calcium hydroxide and crystalline silica, providing a safer work environment. Adhesive appliques were applied to the canoe after sanding was completed. These appliques were applied by hand and additional detail was added to the bulkheads using a Dremel.

Sustainability was incorporated by efficiently utilizing resources to reduce 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. A permanent curing chamber was constructed in the team's new construction space, saving time and materials for future years.

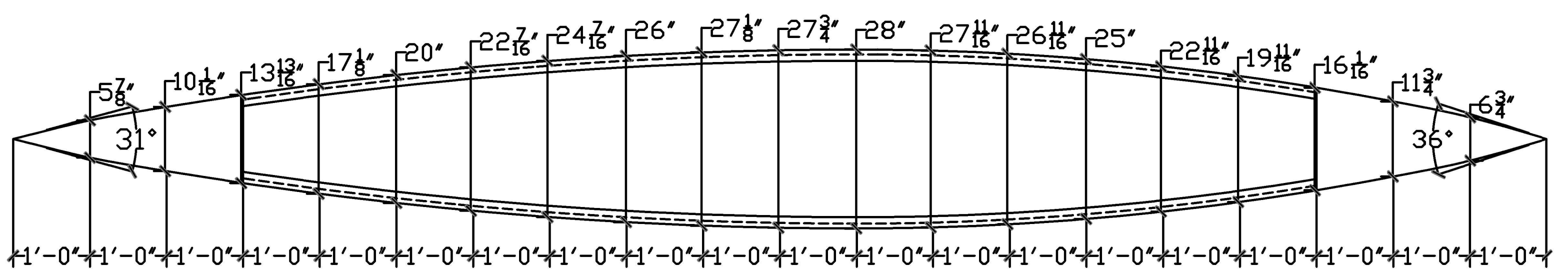
Overall, the team succeeded in improving upon last year's construction techniques, saving time, materials, and cost, while improving upon quality. *Pondicherry* will not sink like the mighty ship Tsimtsum, but instead will overcome obstacles and sustain the Sun Devils despite all odds!

| ID | | Task Mode | Task Name | Duration | Start | Finish | Baseline Start | Baseline Finish |
|---|---|---|---|---|---|---|---|---|
| 1 | | | **2015 Performance Review** | 1 day | Tue 4/28/15 | Tue 4/28/15 | Tue 4/28/15 | Tue 4/28/15 |
| 2 | | | **Leadership Selection & Transition** | 14 days | Tue 4/28/15 | Fri 5/15/15 | Tue 4/28/15 | Fri 5/15/15 |
| 3 | | | **Project Planning & Research** | 78 days | Fri 5/15/15 | Tue 9/1/15 | Fri 5/15/15 | Thu 9/3/15 |
| 4 | | | **Mix Design** | 108 days | Sun 7/26/15 | Tue 12/22/15 | Sat 8/1/15 | Sun 12/6/15 |
| 5 | | | Materials Procurement | 16 days | Tue 7/28/15 | Tue 8/18/15 | Wed 7/15/15 | Thu 8/20/15 |
| 6 | | | Materials Testing | 8 days | Tue 5/19/15 | Thu 5/28/15 | Fri 5/15/15 | Fri 5/22/15 |
| 7 | | | Baseline Mixes | 7 days | Sun 7/26/15 | Sun 8/2/15 | Sun 7/26/15 | Sun 8/2/15 |
| 8 | | | Cementitious Materials Testing | 30 days | Sun 8/23/15 | Thu 10/1/15 | Sun 8/23/15 | Sun 11/1/15 |
| 9 | | | Aggregate Testing | 30 days | Sun 8/23/15 | Thu 10/1/15 | Sun 8/23/15 | Sun 11/1/15 |
| 10 | | | Admixture Testing | 58 days | Thu 10/1/15 | Sun 12/20/15 | Sun 11/1/15 | Sun 12/6/15 |
| 11 | | | Fiber & Mesh Testing | 58 days | Thu 10/1/15 | Sun 12/20/15 | Sun 11/1/15 | Sun 12/6/15 |
| 12 | | | Final Mix Selection | 1 day | Tue 12/22/15 | Tue 12/22/15 | Sun 12/6/15 | Sun 12/6/15 |
| 13 | | | **Hull Design** | 43 days | Thu 9/3/15 | Mon 11/2/15 | Mon 9/14/15 | Mon 11/2/15 |
| 14 | | | Develop & Learn MATLAB Program | 13 days | Thu 9/3/15 | Sun 9/20/15 | Mon 9/14/15 | Mon 10/19/15 |
| 15 | | | Drafting & Modeling | 32 days | Sun 9/20/15 | Mon 11/2/15 | Mon 10/5/15 | Mon 10/19/15 |
| 16 | | | Finalize Design | 1 day | Mon 11/2/15 | Mon 11/2/15 | Mon 10/19/15 | Mon 11/2/15 |
| 17 | | | CNC Drafting | 2 days | Tue 11/3/15 | Wed 11/4/15 | Mon 10/19/15 | Mon 10/26/15 |
| 18 | | | **Structural Analysis** | 1 day | Mon 11/2/15 | Mon 11/2/15 | Mon 11/2/15 | Mon 2/1/16 |
| 19 | | | Finalize Analysis | 1 day | Mon 11/2/15 | Mon 11/2/15 | Mon 11/2/15 | Mon 2/1/16 |
| 20 | | | **Construction** | 87 days | Mon 9/14/15 | Tue 1/12/16 | Mon 9/14/15 | Sun 12/13/15 |
| 21 | | | Small Scale Testing | 68 days | Sun 10/4/15 | Tue 1/5/16 | Sat 9/5/15 | Sun 12/6/15 |
| 22 | | | Material Procurement | 6 days | Thu 10/29/15 | Thu 11/5/15 | Sat 9/5/15 | Mon 11/2/15 |
| 23 | | | CNC Form | 12 days | Thu 11/5/15 | Fri 11/20/15 | Mon 10/26/15 | Mon 11/2/15 |
| 24 | | | Mold Construction | 37 days | Fri 11/20/15 | Sun 1/10/16 | Mon 11/2/15 | Sat 1/16/16 |
| 25 | | | Finish Mold | 1 day | Sun 1/10/16 | Sun 1/10/16 | Sat 1/9/16 | Sat 1/9/16 |
| 26 | | | Prebatching for Cast Day | 1 day | Tue 1/12/16 | Tue 1/12/16 | Wed 1/13/16 | Wed 1/13/16 |
| 27 | | | **Cast Day** | 1 day | Sat 1/16/16 | Sat 1/16/16 | Sat 1/16/16 | Sat 1/16/16 |
| 28 | | | Curing | 22 days | Sun 1/17/16 | Sat 2/13/16 | Sat 1/16/16 | Sat 2/13/16 |
| 29 | | | Form Removal | 2 days | Sun 2/21/16 | Mon 2/22/16 | Sat 2/13/16 | Sat 2/13/16 |
| 30 | | | **Aesthetics** | 157 days | Fri 5/15/15 | Sun 12/20/15 | Fri 5/15/15 | Mon 2/29/16 |
| 31 | | | Theme Selection | 77 days | Fri 5/15/15 | Mon 8/31/15 | Fri 5/15/15 | Thu 9/3/15 |
| 32 | | | Design Sketching & Planning | 77 days | Fri 5/15/15 | Mon 8/31/15 | Fri 5/15/15 | Thu 9/3/15 |
| 33 | | | Pigment Testing | 57 days | Sun 10/4/15 | Sun 12/20/15 | Sun 10/4/15 | Sun 12/6/15 |
| 34 | | | Finalize Theme Designs | 1 day | Sun 12/20/15 | Sun 12/20/15 | Sun 12/6/15 | Mon 2/29/16 |
| 35 | | | **Finishing** | 37 days | Sat 2/6/16 | Mon 3/28/16 | Sat 2/6/16 | Sun 3/27/16 |
| 36 | | | Patching/Sanding Exterior | 16 days | Sat 2/6/16 | Fri 2/26/16 | Sat 2/6/16 | Mon 2/22/16 |
| 37 | | | Patching/Sanding Interior | 11 days | Sun 2/21/16 | Fri 3/4/16 | Mon 2/22/16 | Sun 3/6/16 |
| 38 | | | Sealing | 2 days | Sat 3/19/16 | Mon 3/21/16 | Sun 3/6/16 | Sun 3/27/16 |
| 39 | | | Finished Product | 2 days | Fri 3/25/16 | Mon 3/28/16 | Sun 3/27/16 | Wed 3/30/16 |
| 40 | | | **Display** | 92 days | Fri 11/20/15 | Mon 3/28/16 | Sun 10/18/15 | Sun 3/27/16 |
| 41 | | | Construct Stand | 73 days | Fri 11/20/15 | Tue 3/1/16 | Sun 12/6/15 | Mon 2/29/16 |
| 42 | | | Construct Table Display | 11 days | Tue 3/1/16 | Tue 3/15/16 | Sun 12/6/15 | Mon 2/29/16 |
| 43 | | | Construct Cutaway | 22 days | Sun 2/7/16 | Mon 3/7/16 | Sun 2/21/16 | Sun 3/27/16 |
| 44 | | | Engineer's Notebook | 23 days | Thu 1/28/16 | Sun 2/28/16 | Sun 10/18/15 | Wed 3/30/16 |
| 45 | | | Complete Display | 10 days | Tue 3/15/16 | Mon 3/28/16 | Sun 3/27/16 | Wed 3/30/16 |
| 46 | | | **Design Paper** | 26 days | Mon 1/25/16 | Sun 2/28/16 | Sun 12/6/15 | Fri 2/26/16 |
| 47 | | | Rough Draft | 16 days | Mon 1/25/16 | Sun 2/14/16 | Sun 12/6/15 | Mon 2/22/16 |
| 48 | | | Peer Review | 6 days | Mon 2/15/16 | Sat 2/20/16 | Sun 2/7/16 | Mon 2/29/16 |
| 49 | | | Final Draft | 6 days | Sun 2/21/16 | Fri 2/26/16 | Sun 1/31/16 | Mon 2/29/16 |
| 50 | | | Send Paper | 1 day | Sun 2/28/16 | Sun 2/28/16 | Mon 2/29/16 | Wed 3/2/16 |
| 51 | | | **Presentation** | 23 days | Tue 3/1/16 | Thu 3/31/16 | Sat 2/6/16 | Thu 3/31/16 |
| 52 | | | Powerpoint Development | 11 days | Tue 3/1/16 | Tue 3/15/16 | Sat 2/6/16 | Mon 2/29/16 |
| 53 | | | Rehearsal | 13 days | Tue 3/15/16 | Thu 3/31/16 | Mon 2/29/16 | Thu 3/31/16 |
| 54 | | | **Paddling** | 129 days | Wed 9/30/15 | Sat 3/26/16 | Mon 9/14/15 | Sun 3/27/16 |
| 55 | | | Tryouts | 1 day | Thu 1/28/16 | Thu 1/28/16 | Sat 10/17/15 | Sun 11/1/15 |
| 56 | | | Team Selection | 1 day | Thu 1/28/16 | Thu 1/28/16 | Sat 10/17/15 | Sat 11/14/15 |
| 57 | | | Information Sessions & Technique Training | 129 days | Wed 9/30/15 | Sat 3/26/16 | Sat 10/17/15 | Sun 3/27/16 |
| 58 | | | Practice | 129 days | Wed 9/30/15 | Sat 3/26/16 | Sun 11/1/15 | Sun 3/27/16 |

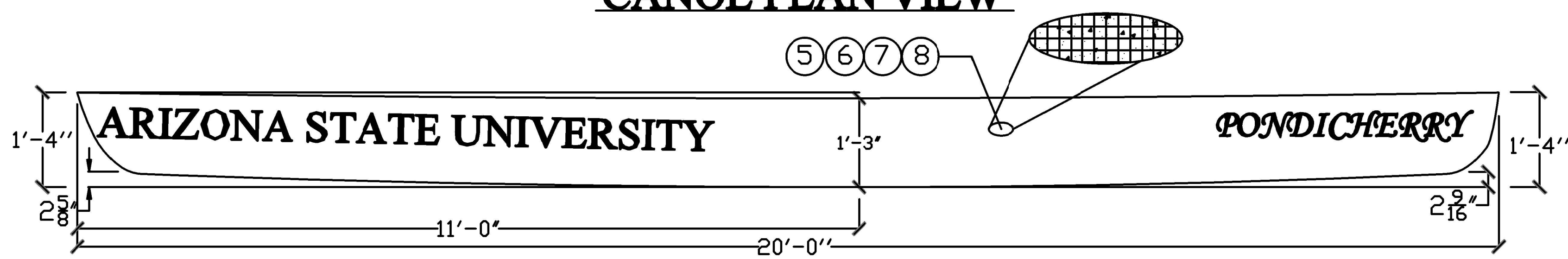



Project: Project Schedule - GAA
Date: Mon 2/15/16

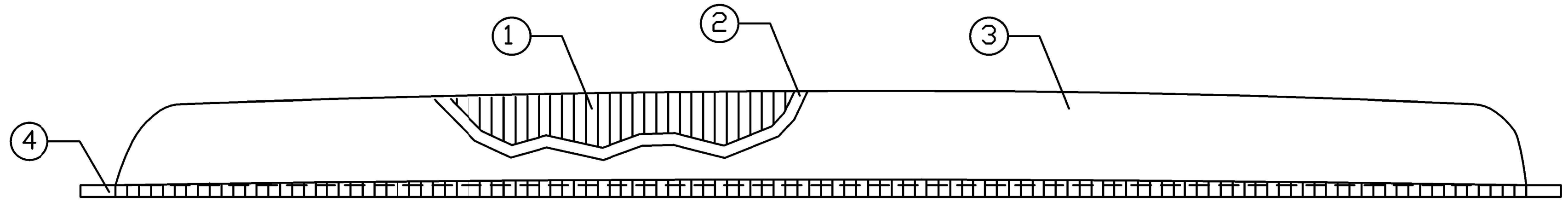
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Task | Summary | Inactive Milestone | Duration-only | Start-only | External Milestone | Critical Split | |
| Split | Project Summary | Inactive Summary | Manual Summary Rollup | Finish-only | Deadline | Progress | |
| Milestone | Inactive Task | Manual Task | Manual Summary | External Tasks | Critical | Manual Progress | |



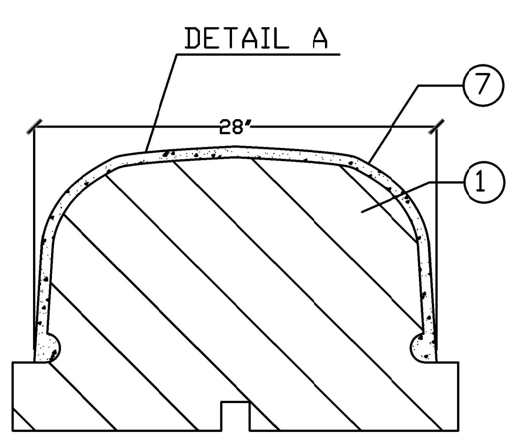

CANOE PLAN VIEW



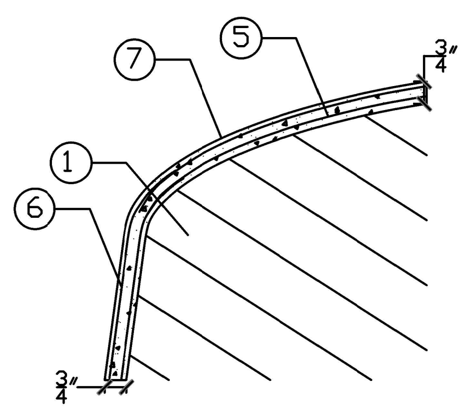

CANOE ELEVATION VIEW



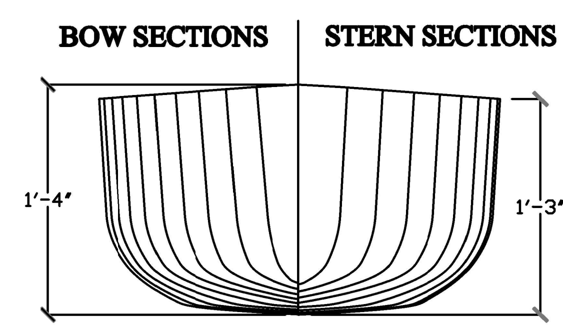

MOLD ELEVATION VIEW



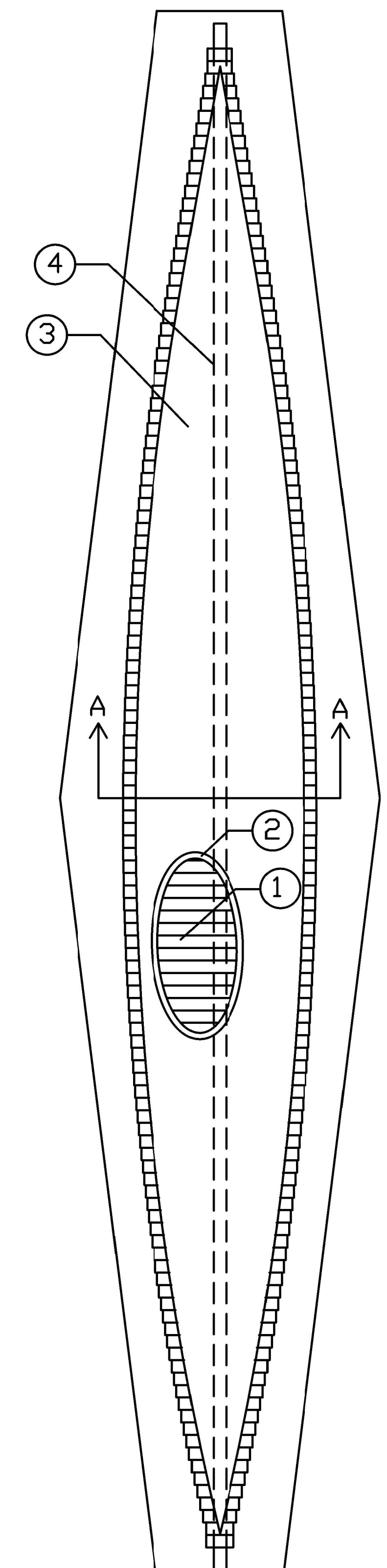

SECTION A-A (WIDEST SECTION)




DETAIL A
MESH REINFORCEMENT




CROSS-SECTIONS




MOLD PLAN VIEW

## BILL OF MATERIALS

| Part | Qty | Description |
|---|---|---|
| 1 | 120 | EXPANDED POLYSTYRENE FOAM |
| 2 | 3 gal | FOAM COAT |
| 3 | 65 sf | RELEASING AGENT |
| 4 | 1 | HSS 2"X2"X23'-0" |
| 5 | 80 sf | FIBERGLASS MESH LAYER 1 |
| 6 | 80 sf | FIBERGLASS MESH LAYER 2 |
| 7 | 4.16 $ft^3$ | Concrete (Per Mix Design Appendix B) |
| 8 | 2 gal | BARACADE WB 244 SEALER |

# *PONDICHERRY*
# FORM DESIGN DRAWINGS

| | |
|---|---|
| Design By: | VICTORIA FLYS |
| Drawn By: | BROOKE RIDLEY |
| Approved By: | VICTORIA FLYS |
| Scale: | Not To Scale |
| Submittal Date: 3/2/2016 | Page: 12 |

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# Appendix A: References


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Mix Proportions for Structural Mix – Powdered Pigment added to 1/3 of the concrete

**CEMENTITIOUS MATERIALS**

| Component | Specific Gravity | Volume ($ft^3$) | Amount (mass/volume) ($lb/yd^3$) | |
|---|---|---|---|---|
| White Portland Cement, ASTM Type | 3.15 | 1.145 | 225.0 | Mass of all cementitious materials, cm **500** $lb/yd^3$ |
| Class F Fly Ash | 2.30 | 0.174 | 25.0 | |
| Metakaolin | 2.50 | 0.561 | 87.50 | |
| VCAS-8 | 2.60 | 1.002 | 162.50 | c/cm ratio **0.45** |

**FIBERS**

| Component | Specific Gravity | Volume ($ft^3$) | Amount (mass/volume) ($lb/yd^3$) |
|---|---|---|---|
| Grace MicroFibers | 0.91 | 0.018 | 2.00 |

**AGGREGATES**

| Aggregates | Abs (%) | $MC_{stk}$ (%) | SG | Base Quantity ($lb/yd^3$) | | Volume, SSD ($ft^3$) | Batch Quantity (at $MC_{stk}$) ($lb/yd^3$) |
|---|---|---|---|---|---|---|---|
| | | | | OD | SSD | | |
| 3M Glass Bubbles | 0.0 | 0.42 | 0.15 | 20 | 20 | 2.137 | 20.0 |
| Poraver (0.1-0.3) | 70.0 | 0.31 | 0.90 | 11.32 | 19.25 | 0.343 | 19.25 |
| Poraver (0.25-0.5) | 60.0 | 0.31 | 0.68 | 72.65 | 116.25 | 2.740 | 116.25 |
| Poraver (0.5-1.0) | 50.0 | 0.31 | 0.47 | 110.83 | 166.25 | 5.669 | 166.25 |
| Poraver (1.0-2.0) | 40.0 | 0.31 | 0.41 | 5.89 | 8.25 | 0.322 | 8.25 |

**ADMIXTURES**

| Admixture | lb/gal | Dosage (fl.oz/cwt) | % Solids | Water in Admixture ($lb/yd^3$) | |
|---|---|---|---|---|---|
| AEA 92 | 8.5 | 12.0 | 6.0 | 5.41 | Total Water from All Admixtures **6.92** $lb/yd^3$ |
| ADVA Cast 575 | 9.1 | 5.0 | 41.0 | 1.51 | |

**SOLIDS (LATEX, DYES AND POWDERED ADMIXTURES)**

| Component | Specific Gravity | Volume ($ft^3$) | Amount (mass/volume) ($lb/yd^3$) |
|---|---|---|---|
| Davis Colors Powdered Pigment | 4.80 | 0.0136 | 38.2 |

**WATER**

| | | Amount (mass/volume) ($lb/yd^3$) | Volume ($ft^3$) |
|---|---|---|---|
| Water, $lb/yd^3$ | | 549 | 8.81 |
| Total Free Water from All Aggregates, $lb/yd^3$ | | 170 | |
| Total Water from All Admixtures, $lb/yd^3$ | | 4.78 | |
| Batch Water, $lb/yd^3$ | | 549 | |

**DENSITIES, AIR CONTENT, RATIOS AND SLUMP**

| | cm | fibers | aggregates | solids | water | Total |
|---|---|---|---|---|---|---|
| **Mass of Concrete, M, (lb, for1 $yd^3$ )** | 500 | 2 | 330 | 0.96 | 549 | 1382 |
| **Absolute Volume of Concrete, V, ($ft^3$)** | 2.881 | 0.018 | 11.21 | 0.01 | 8.81 | 22.9 |
| **Theoretical Density, T,** (= M / V) | 60.34 | $lb/ft^3$ | **Air Content** [= (T – D)/D x 100%] | | | 0.56% |
| **Measured Wet Density, D** | 60.0 | $lb/ft^3$ | **Slump, Slump flow** | | | 0 in. |
| **water/cement ratio, w/c:** | 0.82 | | **water/cementitious material ratio, w/cm:** | | | 0.38 |

Name:

Date:

## Longitudinal Analysis:

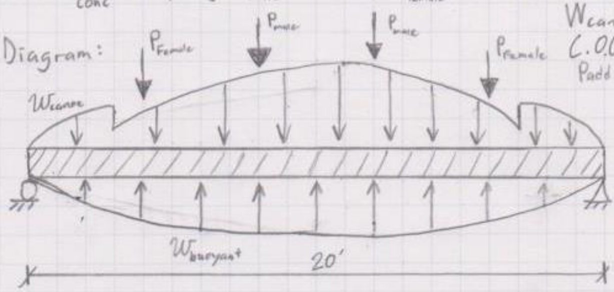
Assumptions: $\gamma_{conc} = 62\text{pcf}$, $P_{male} = 190\text{ lbs}$, $P_{female} = 130\text{ lbs}$, Simply-Supported

$W_{canoe} = 260\text{ lb}$

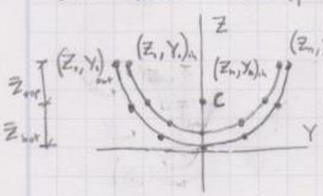
$C.O.G. = 10.16'$

Paddlers @ 4' O.C.

Free Body Diagram:




The weight of the canoe distributed load was computed by integrating spline equations of each cross-section at 2" intervals to find the net cross-sectional area, which was multiplied by the 2" interval and unit weight to compute cross-section weight. Moment of inertia and centroid were also computed by integrating the spline equations. Since 10 or more splines were used to create each cross-section, a general procedure will be shown instead to save space. MATLAB was used to perform these laborious calculations.




General Spline Eq: $Y_i = a_i Z^2 + b_i Z + C_i$

Cross-Sectional Area (A): $\sum_{i=1}^{n}\left[\frac{1}{3}a_i\left(Z_{i+1}^3 - Z_i^3\right) + \frac{1}{2}b_i\left(Z_{i+1}^2 - Z_i^2\right) + C_i\left(Z_{i+1} - Z_i\right)\right]$

Moment of Inertia $(I_y)$: $\sum_{i=1}^{n}\left[\frac{1}{5}a_i\left(Z_{i+1}^5 - Z_i^5\right) + \frac{1}{4}b_i\left(Z_{i+1}^4 - Z_i^4\right) + \frac{1}{3}C_i\left(Z_{i+1}^3 - Z_i^3\right)\right]$

Centroid $(\bar{Z})$: $\frac{1}{A}\sum_{i=1}^{n}\left[\frac{1}{4}a_i\left(Z_{i+1}^4 - Z_i^4\right) + \frac{1}{3}b_i\left(Z_{i+1}^3 - Z_i\right) + \frac{1}{2}\left(Z_{i+1}^2 - Z_i\right)\right]$

For the center cross-section, the moment of inertia and centroid were computed by MATLAB as: $I_y = 787\text{ in}^4$ $\bar{Z}_{bot} = 5.07\text{in}$ $\bar{Z}_{top} = 15.01\text{in} - 5.07\text{in} = 9.94\text{in}$

The buoyant force was computed using a system of equations. A cubic function was chosen in order to meet three criteria: (1) Force goes to zero at ends, (2) downward force equals area under cubic function, and (3) the centroid of the cubic function aligns with the downward center of gravity. $W_{buoyant} = ax^3 + bx^2 + cx + d$

| | Bow | Stern |
|---|---|---|
| (1) | $0 = a(0)^3 + b(0)^2 + c(0) + d \Rightarrow d = 0$ | $0 = a(20')^3 + b(20')^2 + c(20')$ |
| (2) | $190+190+130+130+260 = a(20')^4 + b(20')^3 + c(20')^2$ | $900\# = a(20')^4 + b(20')^3 + c(20')^2$ |
| (3) | $10.16'(900\#) = a(20')^5 + b(20')^4 + c(20')^3$ | $9144\text{ ft-\#} = a(20')^5 + b(20')^4 + c(20')^3$ |

$$\begin{bmatrix} 20^3 & 20^2 & 20 \\ 20^4 & 20^3 & 20^2 \\ 20^5 & 20^4 & 20^3 \end{bmatrix}\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 0 \\ 900 \\ 9144 \end{bmatrix}$$

$a = -7.681 \times 10^{-8}$

$b = -1.986 \times 10^{-4}$

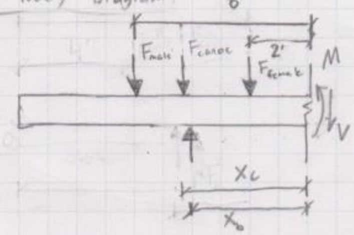
$c = 0.0521$

Name: ______________________

Date: ______________________

Moment and Shear was determined by taking a cut at the location of interest; the middle of the canoe in this case. Distributed loads were transformed into point loads.

Cut Free Body Diagram:




$F_{male} = 190\ \#$ $F_{female} = 130\ \#$

$F_{canoe} = 127.6\ \#$ $F_b = 442.3\ \#$

$X_c = 4.35'$ $X_b = 4.00'$

$\sum F_y = 0;\ V = 442.3 - 190 - 130 - 127.6$

$V = -5.3\ \#$

$\sum M_x = 0;\ M = -442.3(4.00) + 190(2) + 130(6) + 127.6(4.35)$

$M = -54.14\ \text{lb-ft}$

Bending Stress:

$$\sigma_c = \frac{M \bar{z}_{bot}}{I_y} = \frac{-54.14\ \text{lb-ft}(12)(5.07\text{in})}{787\text{in}^4}$$

$$\sigma_c = 4.19\ \text{psi}$$

$$\sigma_T = \frac{M \bar{z}_{top}}{I_y} = \frac{54.14\ \text{ft-lb}(12)(9.94)}{787\text{in}^4}$$

$$\sigma_T = 8.21\ \text{psi}$$