Firebolt

Arizona State University

2017

Concrete Canoe

Design Report

Table of Contents

Executive Summary……………………………………………………………………………….ii
Project Management………………………………………………………………………………1
Quality Assurance and Control……………………………………………………………………2
Organization Chart……………………………………………………………………………...3
Hull Design and Structural Analysis………………………………………………………………4
Development and Testing…………………………………………………………………………6
Construction…………………………………………………………………………………………9
Project Schedule……………………………………………………………………………………11
Construction Drawing and Bill of Materials……………………………………………………..12
Appendix A: References………………………………………………………………………..A-1
Appendix B: Mixture Proportions………………………………………………………………B-1
Appendix C: Structural Calculations……………………………………………………………C-1
Appendix D: Percent Open Area Calculations…………………………………………………D-1

List of Figures

Figure 1: MATLAB Canoe Model……………………………………………………………...4
Figure 2: Hull Profile………………………………………………………………………………4
Figure 3: Longitudinal Analysis FBD……………………………………………………………..5
Figure 4: FBD of Forces……………………………………………………………………………...5
Figure 5: Cementitious Composites…………………………………………………………………7
Figure 6: Shopbot CNC……………………………………………………………………………9
Figure 7: Mold Assembly……………………………………………………………………………9
Figure 8: Concrete Casting………………………………………………………………………10
Figure 9: Canoe in Curing Chamber…………………………………………………………...11

List of Tables

Table 1: Mix Properties……………………………………………………………………………ii
Table 2: Canoe Properties…………………………………………………………………………ii
Table 3: Major Project Milestones…………………………………………………………………1
Table 4: Performance Comparison (2 Male Race)……………………………………………...4
Table 5: Maximum Stress……………………………………………………………………………5
Table 6: Final Mix Properties……………………………………………………………………...8

Executive Summary

J.K. Rowling's *Harry Potter* is a coming of age tale that encompasses themes of magic, friendship, adventure, and even death. The series of novels follows Harry Potter and his close friends, Ron Weasely and Hermione Granger on their seven-year journey as students at the Hogwarts School of Witchcraft and Wizardry. Throughout their journey they harnessed the powers of magic, friendship, and bravely defeat the dark lord of the wizarding world, Lord Voldemort (*Harry Potter*). Much like Harry, Ron, and Hermione were able to harness their strengths and defeat darkness, *Firebolt* seeks to overcome darkness and find victory.

Arizona State University was established in 1885 as the Territorial Normal School on a 20-acre plot with 33 students. Since then, the university has grown to become the largest public university by enrollment at 83,000 students ("Enrollment"). The Ira A. Fulton Schools of Engineering had 20,275 students enrolled in Fall 2016, of which approximately 1,300 are enrolled in the Fulton School of Sustainable Engineering and the Built Environment as civil engineering, construction engineering, or construction management majors (Ira).

The ASU Concrete Canoe team is part of the American Society of Civil Engineers chapter on campus, and each year ASCE ASU competes in the Pacific Southwest Conference each year. The ASCE ASU Concrete Canoe team had placed tenth with *Avanyu* (2014), eleventh with *Mandjet* (2015), and third with *Pondicherry* (2016). The 2017 team hopes to follow up on last year's success and rank as the best team from Arizona. This year, the team hopes to improve through efficient leadership, increased funding, and continued innovations in hull design and structural analysis, construction, and mix design.

Table 1: Mix Properties

Mix Properties	
Wet Density	61.3pcf
Dry Density	47.2pcf
28-Day Compressive Strength	1877 psi
14-Day Tensile Strength	560 psi
14-Day Composite Flexural Strength	1730 psi
Air Content	11.78%

With the help of alumni, an existing MATLAB code was improved and used to perform all structural analysis calculations to drastically accelerate the hull design and analysis process. Due to this innovation, multiple hull designs could be tested and immediately analyzed to determine the optimal design. The mix design team experimented with new sand and shale aggregate materials, in order to conform to the changes in the 2016-17 NCCC competition rules. The final mix incorporates a well graded aggregate mix of lightweight clay shale and recycled glass Poraver.

Table 2: Canoe Properties

Canoe Properties	
Name	Firebolt
Length	20ft
Width	28 in
Depth	14 in
Avg. Thickness	0.75 in
Estimated Weight	250lb
Colors	Gray, Maroon, Gold
Primary Reinforcement	Fiberglass Mesh
Secondary Reinforcement	Glass Fibers

The construction team sought improvements from last year's releasing agent – Elmer's Glue – as it reactivated during curing causing it to adhere to the concrete. To determine an optimal releasing agent, leftover concrete from mix testing was used on prepared test sections of Styrofoam. Through this experimentation, it was determined that Thompson's water seal and Klean Kote oil would be used as releasing agents for the mold. Improvements were also made to the semi-permanent curing chamber to ensure that water does not leak from the chamber during the curing process.

Project management is a vital aspect to the overall success of the project, and ensures that the project is completed successfully. The role of the project manager is to oversee the schedule, finances, and engineering of the project. For *Firebolt*, we elected to have two project managers in order to create a stronger and dynamic leadership. As a team, we sought to create a lightweight canoe with enough strength to withstand stresses from racing, but one that will perform well in races. With the help from a strong group of captains, selected from the 2015-16 *Pondicherry* team and from other exemplary peers within ASCE, we are confident we have accomplished our goal. The selection process began immediately following the 2016 Pacific Southwest Conference; we began project planning to reflect on necessary improvements to place higher for the 2016-17 PSWC Concrete Canoe Competition.

The majority of our funds for *Firebolt* has come from fundraising events and donations made by local engineering and materials companies. In addition, we received cement and aggregate donations which helped significantly with our budgeting. The estimated budget for *Firebolt* was $2,400, and the final cost was $2,000. In order to track our expenditures, we created a detailed budget and utilized a ledger to keep track of spending.

Table 3: Major Project Milestones

Milestone	Delay	Cause
Hull Design Selection	None	Use of MATLAB program
CNC the Foam	None	Accurate CNC machine programming
Finalize Mix Design	3 weeks	New aggregate experimentation
Casting the Canoe	None	Proper scheduling

After the 2016-16 PSWC competition, we created a schedule for *Firebolt* so that we could begin work on the project as soon as possible, allowing us to utilize the summer for research. The schedule was distributed to all of the captains to ensure our goals were met and to have an efficient progress for their aspects of the project. Our major milestones included: (1) final hull design selection, (2) CNC cutting of foam mold, (3) final mix design selection, and (4) canoe casting. The schedule and critical path can be found on page 11. These major milestones can be found in Table 3. The project experienced few changes between the proposed and actual schedule, indicating our starting early paid off. Our team implemented a new online project management platform, Asana, in order to keep track of project deadlines and tasks. We were able to complete the hull design and structural analysis program using a MATLAB program that significantly reduced the amount of time required for hull design selection. During the CNC process, we experienced few setbacks and were able to complete the task on time. Our longest project delay was in the final mix design selection due to the new sand and shale aggregates. Even with the setback in mix design, we were still able to cast the canoe according to schedule. The total hours spent on *Firebolt* was approximately 1,400 hours, 480 of which are from time spent on paddling practice.

Throughout the entire project, the utmost attention was paid to the safety of all *Firebolt* team members. During all mix design and construction sessions, members were required to wear the appropriate PPE, including gloves and respirators. Safety data sheets were kept available at all times in the canoe workspace and we also made sure to adhere to ASU's environmental health and safety standards and participate in related safety training provided by the university. We also made an effort to practice sustainability during the project. An effort was made to include sustainable materials in our concrete mixture, such as Poraver and Fly Ash. While performing mix design testing, we used 2"x4" cylinders to minimize the amount of material needed for testing, and created creative objects with excess material such as small pots. We also used leftover foam from mold construction for our canoe display to reduce the materials used.

Throughout the duration of the *Firebolt* project, the utmost attention was paid to the quality control and quality assurance of multiple project aspects. Quality control and assurance measures were put into place during all aspects of the project including: hull design and structural analysis, mix design, mold construction, canoe casting, and canoe finishing. Peer review was incorporated to ensure the accuracy and quality of calculations and written work such as the design report.

During the project, multiple materials were used for the mix design of the concrete and the construction of the canoe. A wide variety of materials were required, and it was important to apply guidelines for the procurement of these materials to ensure that they were of acceptable quality and in compliance with the rules. When new materials were required, they were sought from certified suppliers to ensure their quality. Furthermore, the material data sheets for the materials were checked to ensure that they were compliant with the rules. This process carried more importance for this year's canoe as several new aggregates were tested in the mix design process and each of these new materials had to be reviewed for compliance.

Peer review was utilized during the project to ensure that documents were of acceptable quality and correct. Before all major deliverables for the project, such as the project schedule and design report, were submitted, they were subjected to review by other team members, alumni of the concrete canoe project, and university professors. All calculations were checked by another team member to ensure that they were correct. In special cases, we requested our faculty advisor to check our calculations due to his expertise and research in concrete. A file sharing platform, Dropbox, was used to allow for an efficient distribution of pertinent project files to all members. In addition, Dropbox was utilized to facilitate document tracking such as having multiple versions of each project document after proper edits and revisions were made. A project management platform – Asana – was also used to delegate tasks and track project progress. The implementation of this new platform helped to ensure that tasks were completed in a timely manner and that adequate time was dedicated to review.

Once the national competition rules were released, they were distributed to each captain for review. Each captain was held responsible for assuring they followed the rules in their aspect of the project The project managers then provided an additional check, to ensure that all aspects of the project were in compliance with the rules.

Throughout the duration of the project, the CNCCC's Facebook page for RFI responses was checked occasionally. The intent of these checks was to determine if any RFIs contained information helpful to the project. The RFIs were also check to ensure that we were aware of any new project information.

For physical work products, quality control and assurance was performed in multiple ways. During the mix design process, materials were kept in clean, water tight containers to ensure that they were not subject to cross contamination. Testing of the materials was performed in strict accordance with ASTM standards to ensure the accuracy and consistency of results. Work surfaces and areas were kept clean. During the construction of the mold, quality was ensured through checks from project management. This was vital to acquire a construction of the upmost quality. During the casting of the canoe, project management and other team members provided routine checks during the process to ensure quality.

Organization Chart

Project Managers (Headmasters)


Veronica Head, Sr   Cesar Castro, Sr

Primary Roles: Created and maintained project schedule and budget, oversaw all areas of project, ensured compliance with competition rules

House of Hull Design & Analysis


Veronica Head, Sr   Natalie Miller, So

Primary Roles: Performed the design and analysis of various hull shapes using computer programs

House of Mix Design


Cesar Castro, Sr   Quinn Beauparlent, Sr

Primary Roles: Developed final concrete mix design through series of testing

Contributors: Nathan Reisenaur (Jr), Ian Contreras (Jr), Hilary Merline (So), Ana Repta (Jr), Joseph Garcia (Jr), and Miranda DeSimone (Jr)

House of Construction

Natalie Miller, So

Primary Roles: Led the mold construction including CNC machining, led casting process, led sanding of the canoe after curing

Contributors: Connor Fegard (So), Allie Charles (So), Victoria Flys (Grad), others

House of Aesthetics

Joseph Garcia, Jr

Primary Roles: Designed the theme for the canoe, designed and created the stands and display table, oversaw final product

Contributors: Marisol Luna (Sr), others

House of Paddling


Hoyong Ryou, Sr   Allie Charles, So

Primary Roles: Created and maintained project schedule and budget, oversaw all areas of project, ensured compliance with competition rules

The hull design team decided it was best to continue the utilization of last year's MATLAB code working early in the summer to develop a hull design in MATLAB. The 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.

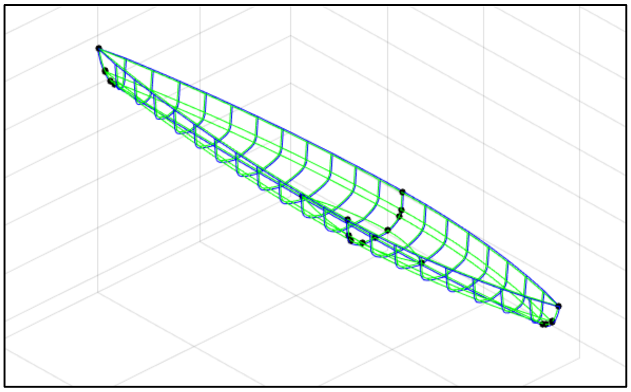


Figure 1: MATLAB Canoe Model

Pondicherry's hull design was utilized as the baseline for *Firebolt's* design. Last year's canoe, *Pondicherry*, was chosen as the baseline design due to its fast straight-line speed and ease of paddling. The team kept the stern rocker at 4" and bow rocker at 4". These parameters were kept since it was notable that Pondicherry had success in turning with ease in respect to the canoe's midpoint (EoHD).

Table 4: Performance Comparison (2 Male Race)

Canoe	Wetted Surface Area	Prismatic Coefficient	GM_T
Firebolt (2017)	37.0 ft^2	0.59	1.10
Pondicherry (2016)	37.0 ft^2	0.59	1.10

The team addressed initial stability by giving the profile a rounder transition between the bottom and walls of the hull. This helped widen the hull at higher waterline levels, which increased the transverse metacentric height (GMT) 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, the increased stability was achieved with little change to the wetted surface area and prismatic coefficient (Table 4), indicating *Firebolt* will have a similar performance to *Pondicherry*.

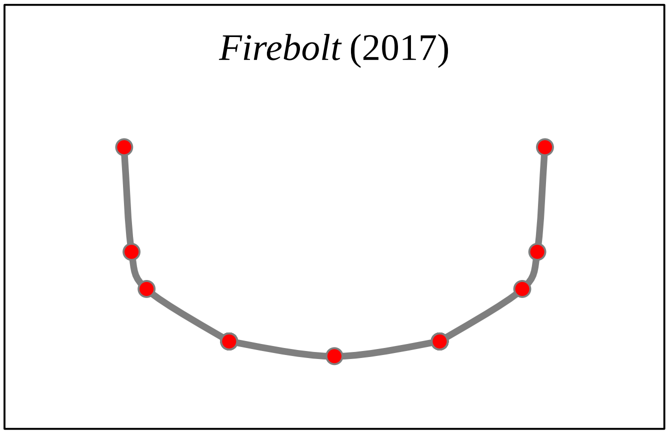


Figure 2: Hull Profile

Firebolt's hull design dimensional properties consisted of an overall length of 20', 28" width and 15" depth at mid span, 16" depth at the bow and stern, and a ¾" thickness. Ribs were added to the canoe at the center, and three feet from each bulkhead of the canoe, thus at 6', 10', and 14'. The canoe's unique design characteristics included the addition of ribs, a shallow arch bottom and slightly flared walls.

Upon completing the hull design, the team performed a two-dimensional longitudinal and lateral analysis to ensure Firebolt's 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) transporting, (3) two female paddlers, (4) two male paddlers, and (5) coed paddlers.

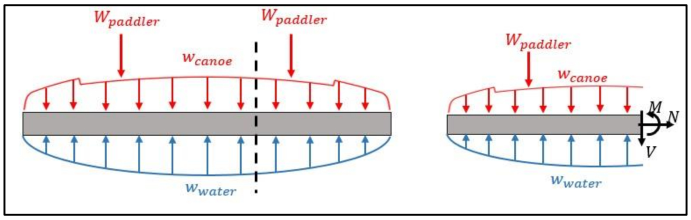


Figure 3: Longitudinal Analysis FBD

For the longitudinal analysis, the canoe's geometry and uniform placing in the water allowed the assumption that it can be modeled as a simply supported beam. To acquire an accurate representation of the canoe as a beam, its self- weight and paddler weight acting in the gravity direction and the buoyant force acting in the positive gravity direction (Figure 4) were applied. Then cuts were taken at 2" intervals to compute the internal forces and moments. Concrete unit weight was conservatively estimated as 62 pcf as initial mix design testing was done to give weights around this value. With a unit weight of 62 pcf, the canoe weighed 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: $\sigma = Mc/S_x$. 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.

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 3. Stress was then determined using curved beam formula:

$$\sigma_{\theta\theta} = \frac{N}{wt} + \frac{M(wt - rwln(r_o/r_i))}{wtr(Rwln(r_o/r_i) - wt)}$$

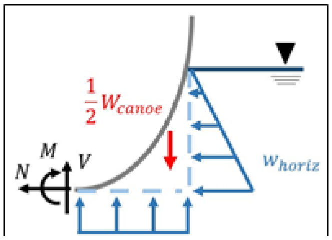


Figure 4: FBD of Forces

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).

The team decided to add 3 - 1" diameter semi-circular ribs to provide stability during paddling. Last year, the paddlers had an issue of remaining at their respective spots, which caused the paddlers to slide into each other.

Table 5: Maximum Stress

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

The primary objective of this year's mix design team was to successfully adapt a baseline mix to incorporate the required volume of 25 % non-glass aggregate and to demonstrate engineering properties favorable for the construction of a canoe. One specific goal was to avoid creating a mix which was overly buoyant, as last year, the *Pondicherry* could not be easily submerged for the swamp test and was damaged through excessive effort. Additionally, the mix design team sought to re-evaluate the sensibility of all design choices made by the past year's team, specifically regarding admixtures dosages in the context of manufacturer recommendations.

Due to last year's strong performance (ASU placed 3rd), *Pondicherry*'s mix was chosen as a baseline. *Pondicherry* 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 entraining agent), Grace short glass fibers, and ADVA Cast 575 (high range water reducer). The proper utilization of these mixes obtained a canoe with a fresh unit weight of 60.0 pcf, dry unit weight of 45.5 pcf, a 28-day compressive strength of 1590 psi, and a tensile strength of 430 psi. Due to the change in mix design rules, its entirely-glass aggregate composition had to be redesigned.

The design process began with selecting new aggregates that could be utilized to meet the 25% volume of non-glass aggregates rule. As previously mentioned, Pondicherry's mix does not meet the mix design rules for this year because the aggregate content was pure glass. To meet the requirement, three alternative aggregates were acquired and tested: UTELite Clay Shales with size variations, Trinity Lightweight Sand, and 3M Ceramic Microspheres. To fulfill their purpose inside the canoe they had to: have a low specific gravity, benefit the gradation of the aggregate blend, and have a high compressive strength. Technical data sheets provided by the manufacturers revealed Trinity Lightweight sand had the highest specific gravity at 1.72, while the largest size clay shale size had a specific gravity of 0.854. The clay shales also spanned a wider range of particle sizes, which allowed for fine-tuning of the mix's particle size distribution (using a 0.45 power chart). Based on the goal of obtaining a lightweight and well-structured mix, Trinity Lightweight sand was deemed unsatisfactory.

To further evaluate the potential usefulness of the clay shales and the ceramic microspheres, trial mixes with all variables except for aggregate blend held constant were constructed. After conducting 7-day testing on the concrete samples with the new aggregates, it was determined that the clay shale would be a suitable choice to compensate for the 25% volume of non-glass aggregates. Since the microspheres at 25% replacement produced a mix which was far too heavy and did not contribute to the strength.

With only the clay shales left to fulfill the 25% non-glass aggregate requirement, the mix design team collaborated in order to minimize the unit weight of the mix, while increasing the compressive strength. The first approach was to adjust the volumetric distribution of the other aggregates to acquire a higher volume output, and a better graded mix. This theoretical approach was executed by creating a 0.45 power chart in Excel which was used to analyze a wide distribution of possible volume fractions. Performing the initial gradation selection digitally rather than through trial mixes reduced man-hours and material wastes. A nearly linear 0.45 power chart distribution was achieved using 11.1% of Crushed Fine Clay Shale, 14.6% 10 Mesh Clay Shale, 26.8% 3M Glass Bubbles, 8.9% Poraver (0.1-0.3), 7.9% Poraver (0.25-0.5), 28.5% Poraver (0.5-1.0), and 2.0% Poraver (1.0-2.0) by volume. Trial cylinders cast with this distribution had an average compressive strength of 1007 psi and a wet unit weight of 62.43 pcf.

Previous canoe mixes had used latex admixtures to reduce unit weight, and so liquid Acryl-60 was considered as a buoyancy enhancer. Incorporating 50 mL of latex into the mix caused it to be essentially self-consolidating and therefore unsuitable for placement on the canoe mold. At the time, the mix was developed for a water/cement ratio of 0.4, so rather than give up on latex as an option, all workability-modifying options were first considered.

The mix design team decided to completely reevaluate the dosage amounts of admixtures and fibers. Through a series of single-factor experiments, the following beneficial changes were made: air entraining agent increased from 8.00 fl oz/cwt to 12.00 fl oz/cwt to improve the pore structure and reduce the unit weight; superplasticizer decreased from 7 fl oz/cwt to 5 fl oz/cwt to reduce workability and allow for the use of latex; a doubling of distributed fiber content was also implemented to improve strength. The last step was to reconfigure the weight distribution of the cement and reduce the water content since the improved mix was still facing placing issues. After multiple tests, the best performing weight distribution was 50% white cement, 25% Fly Ash, 10% Metakaolin, and 15% VCAS-8. Notable changes to the cement content was increasing Metakaolin from 5% to 10% in order to obtain a better placing through the clay and decreasing Fly Ash from 30% since it was at the recommended max for general concrete mixes. Due to the workability improvement caused by the addition of latex, water content was decreased from 0.4 to 0.32 to ensure the concrete's strength would increase. These changes led to obtaining the final mix.

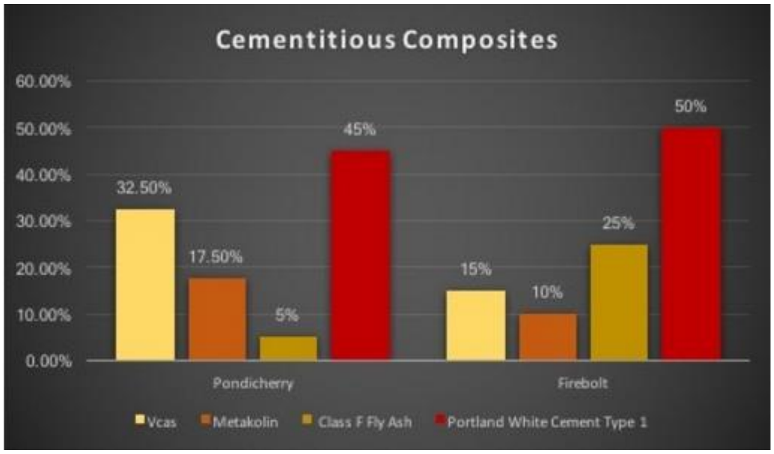


Figure 5: Cementitious Composites

Implementing fiber reinforcement into the canoe was further examined to improve tensile strength because of concrete's known characteristic of being weak in tension. The canoe had two types of reinforcement: the primary reinforcement withstood stress from structural loads such as the paddlers, while a secondary reinforcement bridged and resisted possible fracturing and shrinkage. For the primary reinforcement, this canoe had the same reinforcement as Pondicherry, which was a dual layer green fiberglass mesh. The green mesh was placed in layers at 0.25 intervals to acquire an equal fiber distribution, and improve tensile and flexural strength. To successfully implement this mesh, the mix was adjusted to be more workable and adhesive to allow a secure impregnation. This adjustment to the mix was tested by creating 14 inch by 4 inch by 0.75 inch beams, which resulted in a 300% increase in flexural strength compared to a beam with no primary reinforcement. In addition, the green mesh is finer compared to other tested mesh, meaning it had a higher volume fraction of textile that provided more bridging to minimize crack propagation through the matrix.

For the secondary reinforcement, the mix design team continued to incorporate GRACE short glass fibers. These fibers were ideal for this mix because of their light weight, and optimizing capabilities by better dispersing in the concrete due to their length. This effective fiber distribution was able to minimize the fractures, and allow the concrete to withstand higher stress values. Different amount of fibers (lb/yd3) in the concrete were tested to determine the appropriate amount of fibers. The purpose of varying amounts was to determine when the fibers would begin to clump in the concrete and result in inhomogeneities. This phenomenon was present in a 6 lb/yd3 fiber content. It was then determined that adding 4 lb/yd3 was ideal in acquiring an optimal distribution. The implementation of both reinforcements was successful in improving the tensile and flexural strength of concrete without compromising weight.

The heavy use of supplementary cementitious materials contributed greatly to the sustainability of the mix. Ordinary Portland cement (OPC) is incredibly energy-intensive to manufacture, and the calcination reaction which is used to manufacture it from limestone has carbon dioxide as a 1:1 stoichiometric product. Any material which can offset the need for OPC therefore significantly offsets the carbon impact of the concrete mix. In addition to reducing OPC usage, Fly Ash and VCAS both have their own sustainability benefits. Fly ash is a waste product of coal-burning power plants, and it is far more environmentally friendly to use its low heat-of-hydration pozzolanic reaction to bind concrete than it is to disperse it throughout the air or sequester it to landfills. VCAS is manufactured from industrial by-products, which helps to divert waste from landfills. The increased durability it adds to concrete reduces the future need for repairs and replacements.

Several measures were taken in order to minimize the quantity of waste generated by the mix design process. Before any trial designs were mixed and cast, they were subject to peer review to ensure that each mix was logically designed and had a clear investigatory purpose. Additionally, whenever the effect of varying a single mix component was a desired quantity, the mixes were cast as 2"x 4" cylinders rather than 3"x6". As a result, the design process reduced the total amount of concrete and preserved 6.5 ft^3 of concrete.

Overall, the mix design team extensive research and testing led to the acquiring a final mix that exceeded the set goals. The final design achieved a high compressive and tensile strength compared to the canoe's predecessors. This final mix led to the creation of Firebolt, with the following design properties.

Table 6: Final Mix Properties

Property	Required Value	Actual Value
Compressive Strength	231 psi	1877 psi
Tensile Strength	224 psi	560 psi
Dry Unit Weight	<62.4pcf	47.2pcf

After the assurance of the rules and regulations, weekly meetings were held during the hull design to determine the most viable materials and methods for the construction of *Firebolt*. 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.

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, gunnels were added. After requests from the paddling team, two rails were added seven and fourteen feet into the canoe. Upon completion of drafting, cross sections were imported into VCarve Pro, a tool pathing 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 6) due to the shop's partnership with ASU. The construction team operated the CNC machine, resulting in a cost savings of $3,000 towards the construction budget compared to previous years.

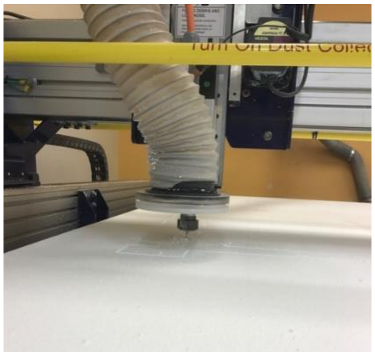


Figure 6: ShopBot CNC

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 7). The stair-step pattern was sanded flush with 60-grit sand paper to create smooth transitions between adjacent sections. A VBS-Heavy Duty Hot Knife (130-watt) was used to carve two rails from the mold. 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 year's releasing agent was Thompson's water seal and Kleen Kote oil. The Rosco Foamcoat™ layer was sanded using 120-grit sand paper until imperfections were minimized so that the mold met quality control specifications. Since previous year's attempt with Elmer's glue proved extremely unsuccessful, the Rosco Foamcoat™ was the final layer prior to concrete pouring. Releasing agent was not applied to the bow and stern as three feet of foam was intended to be left in place to provide additional floatation.

Figure 7: Mold Assembly

Firebolt incorporates two layers of fiberglass mesh to resist tensile forces and protect against rupture. The mesh was draped along the length of the mold and contoured to fit the mold prior 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 as a continuous system.

After last year's team constructed a steel framed curing chamber used to support a PVC pipe misting system completely enclosed by plastic sheeting and tarps. The misters that were previously placed along the length of the pipes to ensure even misting had to be adjusted due to many leaks that caused uneven water coverage throughout the canoe. Misters were scheduled to turn on every 6 hours. This created a controlled environment providing proper hydration and humidity for an efficient wet curing process, safe from the dry Arizona air. The curing chamber that was constructed by last year's team has proven to be a very efficient and effective method used to cure the canoe.

Figure 8: Concrete Casting

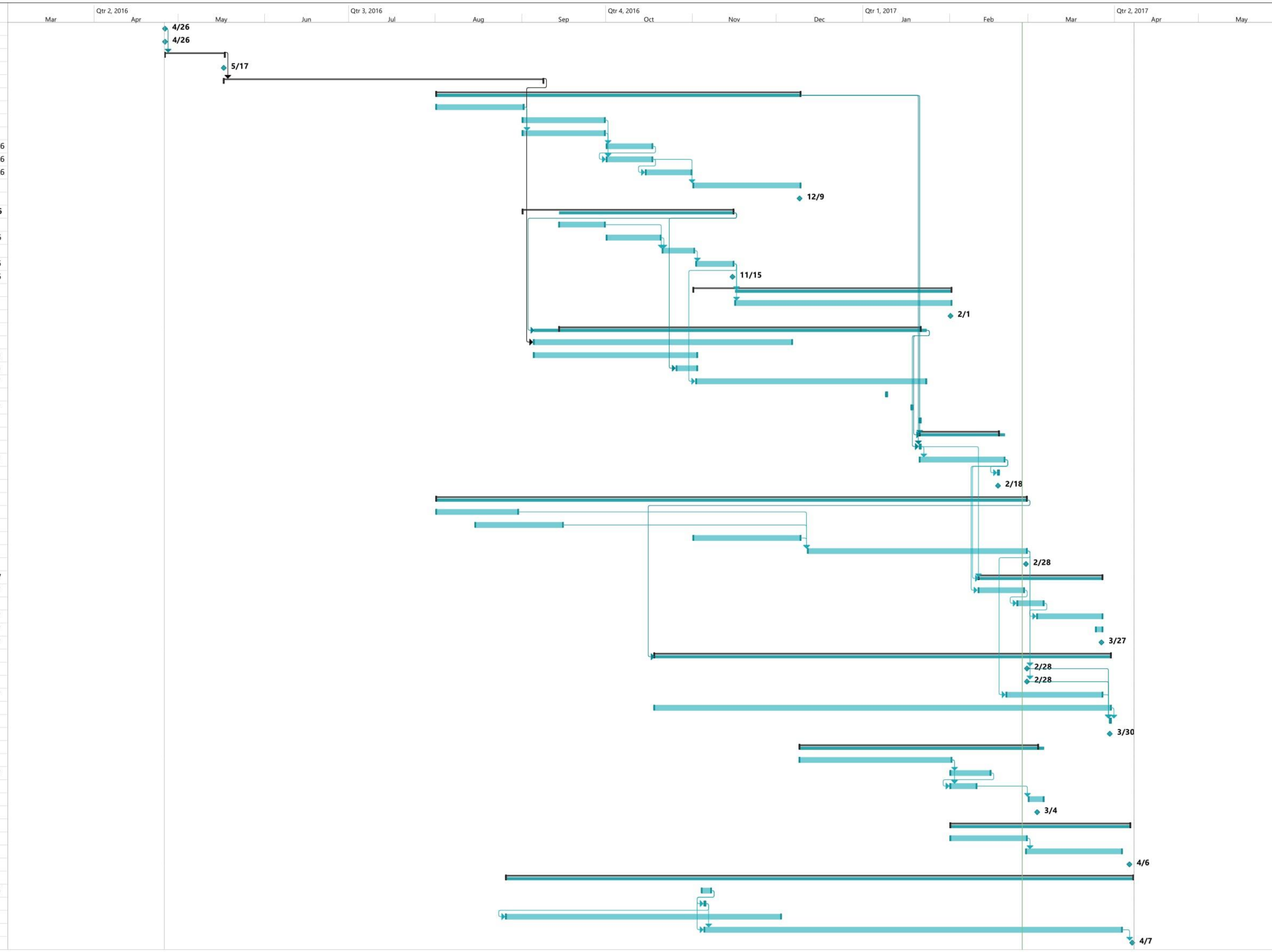
Due to constraints on the use of strain and acrylic paint, pigment was added to a portion of the concrete. Since the theme of the canoe was based on Harry Potter, it was decided that the inside of the canoe would be red with featured gold gunnels and rails, and the outside of the canoe would be gray. The different colored concrete as well as the inclusion of gunnel rails and rails resulted in a more complicated concrete application process than previous years, requiring strategic planning before concrete casting. *Firebolt* was casted in a six-step process (Figure blank). First, the rails and gunnel rails were filled with gold 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 rails and gunnel rails and using tired tread gauges to regulate thickness. Third, pre-fitted fiberglass mesh was placed over this layer of concrete. Then a 1.4" layer of gray structural mix was applied, followed by another fiberglass mesh layer. Finally, another ¼" layer of gray 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).

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 the fill inconsistencies at 28-days. *Firebolt* 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 complete. These appliques were applied by hand and additional detail was added to the bulkheads using a Dremel.

Figure 9: Canoe in Curing Chamber

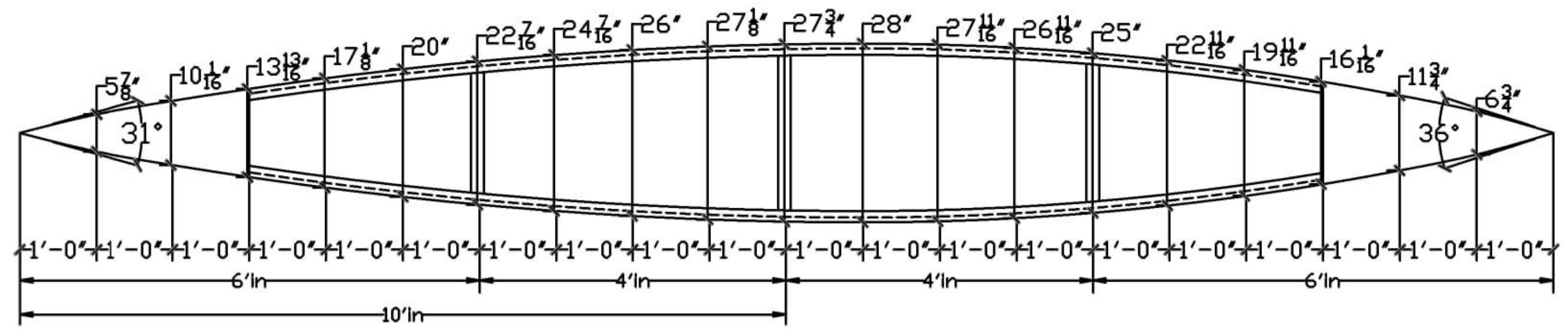
Sustainability was incorporated by efficiently utilizing resources to reduce waste. The team utilized VCarve's optimization tool to fit as many section cuts as possible on one sheet of foam. This reduced the amount of foam needed by six sheets. The team also utilized Arizona State University's hazardous waste disposal program to properly dispose of expired admixture, old concrete specimens, and other waste from mold construction. The semi-permanent curing chamber was amended to be more effective for future years. Overall, the team succeeded in improving upon last year's construction techniques, saving time, materials, and cost, while improving upon quality. *Firebolt* will not fly like Harry's lightning-fast broom, but instead will slice through the water and carry the Sun Devils to victory!

ID	Task Mode	Task Name	Duration	Start	Finish
1		**2016 Performance Review**	**0 days**	**Tue 4/26/16**	**Tue 4/26/16**
2		Performance Review Complete	0 days	Tue 4/26/16	Tue 4/26/16
3		**Leadership Selection and Transition**	**16 days**	**Tue 4/26/16**	**Tue 5/17/16**
4		Leadership Selection and Transition Comple	0 days	Tue 5/17/16	Tue 5/17/16
5		**Project Planning and Research**	**83 days**	**Tue 5/17/16**	**Thu 9/8/16**
7		**Mix Design**	**95 days**	**Mon 8/1/16**	**Fri 12/9/16**
8		Materials Procurement	24 days	Mon 8/1/16	Thu 9/1/16
9		Materials Testing	22 days	Thu 9/1/16	Fri 9/30/16
10		Baseline Mixes	22 days	Thu 9/1/16	Fri 9/30/16
11		Cementitous Materials Testing	12 days	Sat 10/1/16	Mon 10/17/16
12		Aggregate Testing	12 days	Sat 10/1/16	Mon 10/17/16
13		Admixture Testing	12 days	Sat 10/15/16	Mon 10/31/16
14		Fiber & Mesh Testing	29 days	Tue 11/1/16	Fri 12/9/16
15		Final Mix Selection	0 days	Fri 12/9/16	Fri 12/9/16
16		**Hull Design**	**54 days**	**Thu 9/1/16**	**Tue 11/15/16**
17		Develop & Learn MATLAB Program	13 days	Wed 9/14/16	Fri 9/30/16
18		Drafting & Modeling	15 days	Sat 10/1/16	Thu 10/20/16
19		Finalize Design	8 days	Fri 10/21/16	Tue 11/1/16
20		CNC Drafting	10 days	Wed 11/2/16	Tue 11/15/16
21		Hull Design Complete	0 days	Tue 11/15/16	Tue 11/15/16
22		**Structural Analysis**	**67 days**	**Tue 11/1/16**	**Wed 2/1/17**
23		Finalize Analysis	56 days	Wed 11/16/16	Wed 2/1/17
24		Structural Analysis Complete	0 days	Wed 2/1/17	Wed 2/1/17
25		**Construction**	**94 days**	**Wed 9/14/16**	**Sat 1/21/17**
26		Small Scale Testing	67 days	Mon 9/5/16	Tue 12/6/16
27		Material Procurement	43 days	Mon 9/5/16	Wed 11/2/16
28		CNC Form	6 days	Wed 10/26/16	Wed 11/2/16
29		Mold Construction	59 days	Wed 11/2/16	Mon 1/23/17
30		Finish Mold	1 day	Mon 1/9/17	Mon 1/9/17
31		Prebatching for Cast Day	1 day	Wed 1/18/17	Wed 1/18/17
32		Construction Complete	1 day	Sat 1/21/17	Sat 1/21/17
33		**Cast Day**	**22 days**	**Sat 1/21/17**	**Sat 2/18/17**
34		Cast Day	1 day	Sat 1/21/17	Sat 1/21/17
35		Curing	22 days	Sat 1/21/17	Mon 2/20/17
36		Form Removal	1 day	Sat 2/18/17	Sat 2/18/17
37		Casting Complete	0 days	Sat 2/18/17	Sat 2/18/17
38		**Aesthetics**	**152 days**	**Mon 8/1/16**	**Tue 2/28/17**
39		Theme Selection	22 days	Mon 8/1/16	Tue 8/30/16
40		Design Sketching and Planning	24 days	Mon 8/15/16	Thu 9/15/16
41		Pigment Testing	29 days	Tue 11/1/16	Fri 12/9/16
42		Finalize Theme Designs	57 days	Mon 12/12/16	Tue 2/28/17
43		Aesthetics Complete	0 days	Tue 2/28/17	Tue 2/28/17
44		**Finishing**	**32 days**	**Sat 2/11/17**	**Mon 3/27/17**
45		Patching/Sanding Exterior	12 days	Sat 2/11/17	Mon 2/27/17
46		Patching/Sanding Interior	7 days	Sat 2/25/17	Mon 3/6/17
47		Sealing	17 days	Sat 3/4/17	Mon 3/27/17
48		Finished Product	2 days	Sat 3/25/17	Mon 3/27/17
49		Canoe Finished	0 days	Mon 3/27/17	Mon 3/27/17
50		**Display**	**118 days**	**Tue 10/18/16**	**Thu 3/30/17**
51		Construct Stand	0 days	Tue 2/28/17	Tue 2/28/17
52		Construct Table Display	0 days	Tue 2/28/17	Tue 2/28/17
53		Construct Cutaway	25 days	Tue 2/21/17	Mon 3/27/17
54		Engineer's Notebook	118 days	Tue 10/18/16	Thu 3/30/17
55		Complete Display	1 day	Thu 3/30/17	Thu 3/30/17
56		Display Complete	0 days	Thu 3/30/17	Thu 3/30/17
57		**Design Paper**	**62 days**	**Fri 12/9/16**	**Sat 3/4/17**
58		Rough Draft	39 days	Fri 12/9/16	Wed 2/1/17
59		Peer Review	11 days	Wed 2/1/17	Wed 2/15/17
60		Final Draft	8 days	Wed 2/1/17	Fri 2/10/17
61		Send Paper	4 days	Wed 3/1/17	Mon 3/6/17
62		Paper Complete	0 days	Sat 3/4/17	Sat 3/4/17
63		**Presentation**	**47 days**	**Wed 2/1/17**	**Thu 4/6/17**
64		Powerpoint Development	20 days	Wed 2/1/17	Tue 2/28/17
65		Rehearsal	25 days	Tue 2/28/17	Mon 4/3/17
66		Presentation Day	0 days	Thu 4/6/17	Thu 4/6/17
67		**Paddling**	**161 days**	**Fri 8/26/16**	**Fri 4/7/17**
68		Tryouts	2 days	Fri 11/4/16	Mon 11/7/16
69		Team Selection	1 day	Sat 11/5/16	Sat 11/5/16
70		Information Sessions and Technique Trainin	71 days	Fri 8/26/16	Fri 12/2/16
71		Practice	107 days	Sat 11/5/16	Mon 4/3/17
72		Race Day	0 days	Fri 4/7/17	Fri 4/7/17

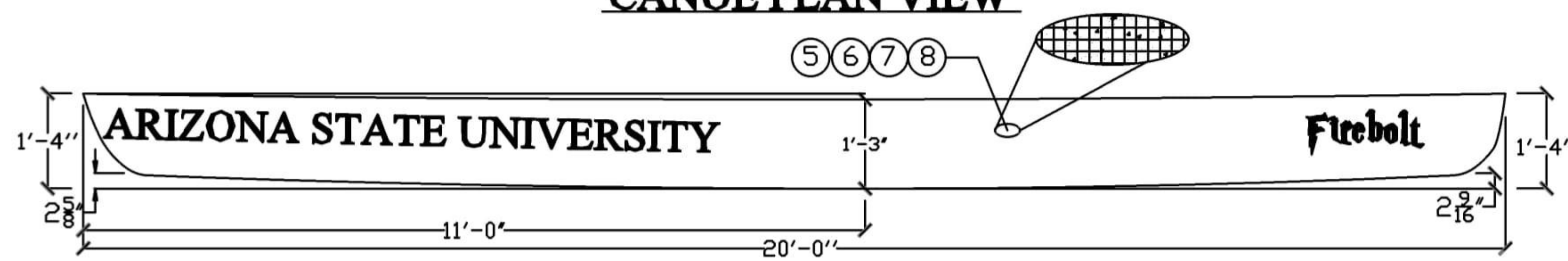


Project: Concrete Canoe 2016-1
Date: Mon 2/27/17

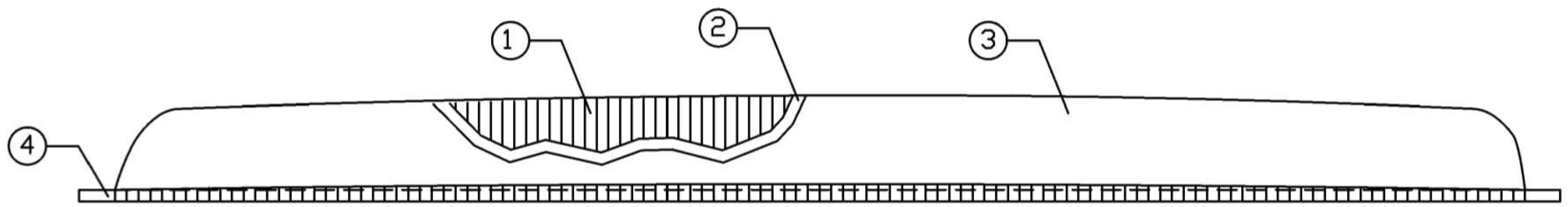
Task	Milestone	Project Summary	Inactive Milestone	Manual Task	Manual Summary Rollup	Start-only	External Tasks	Deadline	Manual Progress
Split	Summary	Inactive Task	Inactive Summary	Duration-only	Manual Summary	Finish-only	External Milestone	Progress	



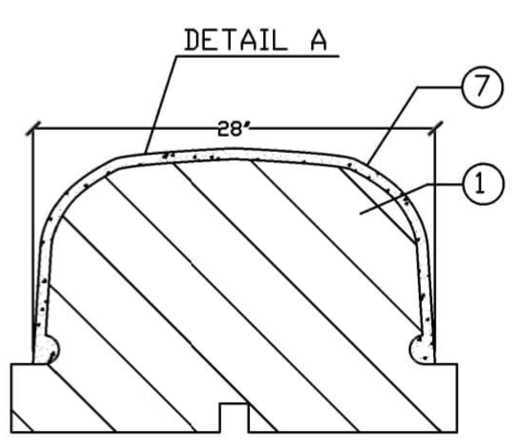
CANOE PLAN VIEW



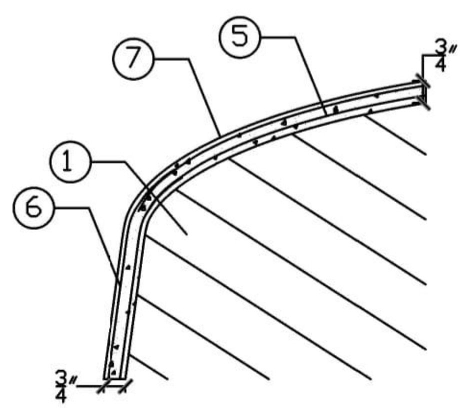
CANOE ELEVATION VIEW



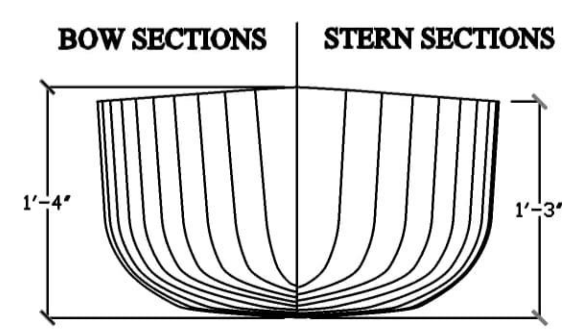
MOLD ELEVATION VIEW



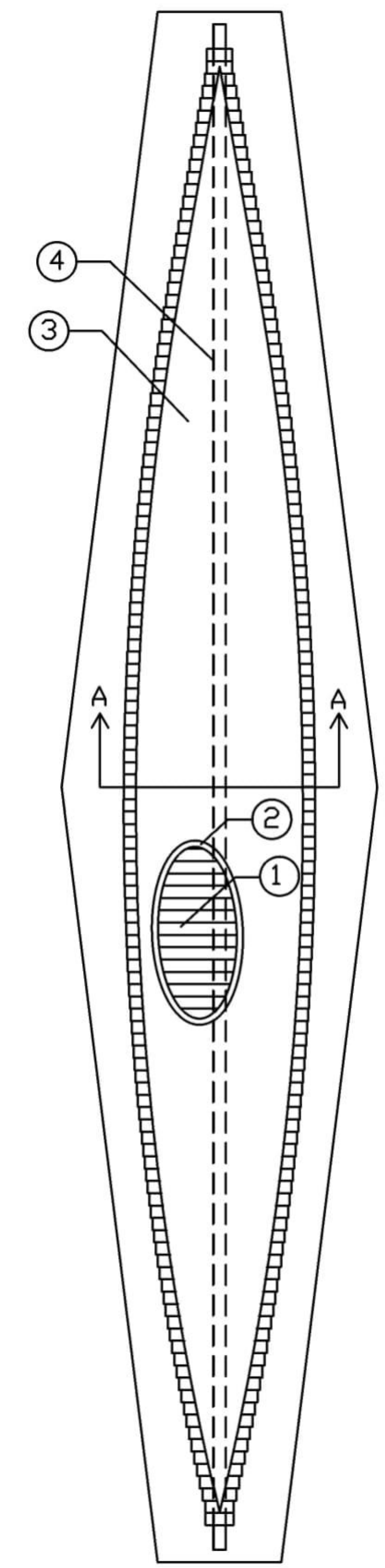
SECTION A-A (WIDEST SECTION)



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	5.11 ft^3	Concrete (Per Mix Design Appendix B)
8	2 gal	BARACADE WB 244 SEALER

FORM DESIGN DRAWINGS

Design By:	NATALIE MILLER
Drawn By:	VERONICA HEAD
Approved By:	CESAR CASTRO
Scale:	Not To Scale
Submittal Date: 2/27/2017	Page: 12

Appendix A - References

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MIXTURE DESIGNATION: Structrual Mix – Without Pigment

Cementitious Materials					
Component	*Specific Gravity*	*Volume (ft³)*	*Amount of CM (mass/volume) (lb/yd³)*		
White Portland Cement, ASTM Type I	3.15	1.653	*9*		*Total Amount of cementitious materials* **650 lb/yd³** *c/cm ratio* **0.32**
Class F Fly Ash	2.30	1.132	*165.5*		
Metakaolin	2.50	0.417	*65.0*		
VCAS-8	2.60	0.601	*97.5*		

Fibers					
Component	*Specific Gravity*	*Volume (ft³)*	*Amount of Fibers (mass/volume) (lb/yd³)*		
Grace MicroFibers	0.91	0.070	*4.00*		*Total Amount of Fibers* **4.00 lb/yd³**

Aggregates							
Aggregates	*Abs (%)*	*MC_{stk} (%)*	*SG_{SSD}*	*Base Quantity (lb/yd³)*		*$Volume_{SSD}$ (ft³)*	*Batch Quantity (at MC_{stk}) (lb/yd³)*
				OD	*SSD*		
Clay Shale (Fine)	80.0	6.62	0.85	*60.85*	109.53	*2.055*	109.53
Clay Shale (Crushed Fine)	80.0	9.33	0.84	*40.79*	73.43	*1.393*	73.43
Clay Shale (10 Mesh)	80.0	8.39	0.83	*20.05*	36.09	*0.701*	36.09
3M Glass Bubbles	0.0	0.42	0.15	*24.89*	24.89	*2.659*	24.89
Poraver (0.1 – 0.3)	70.0	0.31	0.90	*58.57*	99.57	*1.773*	99.57
Poraver (0.25-0.5)	60.0	0.31	0.68	*23.34*	37.34	*0.880*	37.34
Poraver (0.5 – 1.0)	50.0	0.31	0.47	*99.57*	149.36	*5.093*	149.36
Poraver (1.0 – 2.0)	40.0	0.31	0.41	*35.56*	49.79	*1.946*	49.79

Admixtures					
Admixture	*lb/gal*	*Dosage (fl oz/cwt)*	*% Solids*	*Amount of Water in Admixture (lb/yd³)*	
AEA 92	*8.5*	*10.0*	*6.0*	*4.04*	*Total Water from Admixtures, $\sum w_{admx}$* **21.19 lb/yd³**
ADVA Cast 575	*9.1*	*5.0*	*41.0*	*1.36*	
ACRYL 60		*50.0*	*28.0*	*15.79*	

Solids (Latex, Dyes and Powdered Admixtures)			
Component	*Specific Gravity*	*Volume (ft³)*	*Amount (mass/volume) (lb/yd³)*

Water			
	Amount (mass/volume) (lb/yd³)		*Volume (ft³)*
Water, lb/yd³		*602.7*	*9.66*
Total Free Water from All Aggregates, lb/yd³		*186.7*	
Total Water from All Admixtures, lb/yd³		*21.19*	
Batch Water, lb/yd³		*602.7*	

Densities, Air Content, Ratios and Slump						
	cm	*fibers*	*aggregates*	*solids*	*water*	*Total*
Mass of Concrete, M, (lb.)	*650*	4	580	0.96	602.7	*1837.66*
Absolute Volume of Concrete, V, (ft³)	3.803	*0.07*	*16.5*	*0.11*	*9.66*	*30.143*
Theoretical Density, T, (=∑M / ∑V)	68.5	*lb/ft³*	*Air Content [= (T – D)/T x 100%]*			*11.78 %*
Measured Density, D	61.3	*lb/ft³*	*Slump, Slump flow*			*0 in.*
water/cement ratio, w/c:	0.64		*water/cementitious material ratio, w/cm:*			*0.32*

MIXTURE DESIGNATION: STRUCTRUAL MIX – WITH PIGMENT

CEMENTITIOUS MATERIALS

Component	Specific Gravity	Volume (ft^3)	Amount of CM (mass/volume) (lb/yd^3)		
White Portland Cement, ASTM Type I	3.15	1.653	9		Total Amount of cementitious materials **650 lb/yd^3** c/cm ratio **0.32**
Class F Fly Ash	2.30	1.132	165.5		
Metakaolin	2.50	0.417	65.0		
VCAS-8	2.60	0.601	97.5		

FIBERS

Component	Specific Gravity	Volume (ft^3)	Amount of Fibers (mass/volume) (lb/yd^3)		
Grace MicroFibers	0.91	0.070	4.00		Total Amount of Fibers 4.00 lb/yd^3

AGGREGATES

Aggregates	Abs (%)	$MC_{[illegible]}$ (%)	SG_{SSD}	Base Quantity (lb/yd^3) OD	Base Quantity (lb/yd^3) SSD	$Volume_{SSD}$ (ft^3)	Batch Quantity (at $MC_{[illegible]}$) (lb/yd^3)
Clay Shale (Fine)	80.0	6.62	0.85	60.85	109.53	2.055	109.53
Clay Shale (Crushed Fine)	80.0	9.33	0.84	40.79	73.43	1.393	73.43
Clay Shale (10 Mesh)	80.0	8.39	0.83	20.05	36.09	0.701	36.09
3M Glass Bubbles	0.0	0.42	0.15	24.89	24.89	2.659	24.89
Poraver (0.1 – 0.3)	70.0	0.31	0.90	58.57	99.57	1.773	99.57
Poraver (0.25-0.5)	60.0	0.31	0.68	23.34	37.34	0.880	37.34
Poraver (0.5 – 1.0)	50.0	0.31	0.47	99.57	149.36	5.093	149.36
Poraver (1.0 – 2.0)	40.0	0.31	0.41	35.56	49.79	1.946	49.79

ADMIXTURES

Admixture	lb/gal	Dosage (fl oz/cwt)	% Solids	Amount of Water in Admixture (lb/yd^3)	
AEA 92	8.5	10.0	6.0	4.04	Total Water from Admixtures, $\sum w_{[illegible]}$ 21.19 lb/yd^3
ADVA Cast 575	9.1	5.0	41.0	1.36	
ACRYL 60		50.0	28.0	15.79	

SOLIDS (LATEX, DYES AND POWDERED ADMIXTURES)

Component	Specific Gravity	Volume (ft^3)	Amount (mass/volume) (lb/yd^3)	
Direct Colors Powdered Pigment	4.80	0.0136	38.2	Total Solids from Admixtures 38.2 lb/yd^3

WATER

		Amount (mass/volume) (lb/yd^3)	Volume (ft^3)
Water, lb/yd^3		602.7	9.66
Total Free Water from All Aggregates, lb/yd^3		186.7	
Total Water from All Admixtures, lb/yd^3		21.19	
Batch Water, lb/yd^3		602.7	

DENSITIES, AIR CONTENT, RATIOS AND SLUMP

	cm	fibers	aggregates	solids	water	Total
Mass of Concrete, M, (lb)	650	4	580	0.96	602.7	1837.66
Absolute Volume of Concrete, V, (ft^3)	3.803	0.07	16.5	0.11	9.66	30.143
Theoretical Density, T, ($=\sum M / \sum V$)	68.5	lb/ft^3	Air Content [= (T – D)/T x 100%]			11.78 %
Measured Density, D	61.3	lb/ft^3	Slump, Slump flow			0 in.
water/cement ratio, w/c:	0.64		water/cementitious material ratio, w/cm:			0.32

Longitudinal Analysis

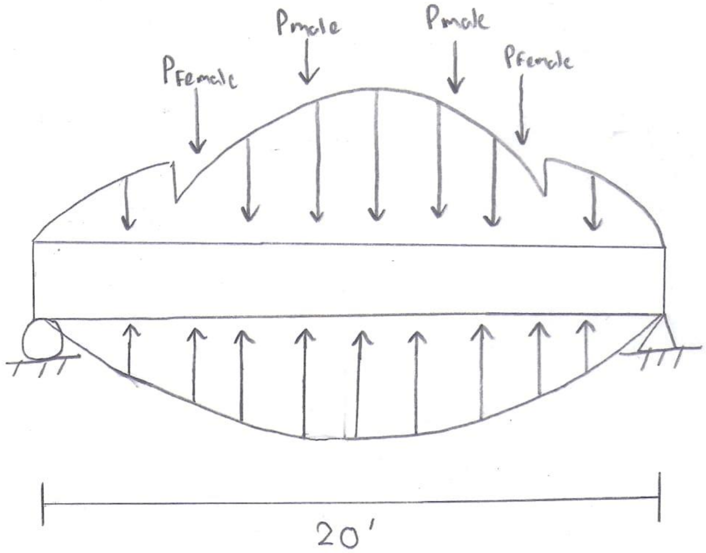
Assumptions: γ_{canoe} = 62 pcf W_{canoe} = 260 lbs.

P_{male} = 190 lbs P_{female} = 130 lbs @ 4' O.C.

Center of Gravity = 10.16'

Simply - Supported Case

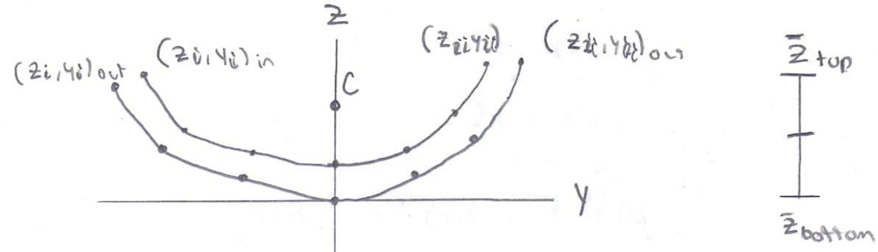
Free Body Diagram:



Structural Analysis Approach:

The weight of the canoe distributed load was computed by integrating spline equations of each cross section at 2in. intervals to find the net cross sectional area, which was multiplied by 2in intervals and unit weight to compute cross sectional weight. Moment of Inertia and centroid were also computed by integrating spline equations. To perform the analysis, more than 10 splines were used for each cross section. This analysis was performed on MATLAB and the following page demonstrates the algorithm.

Numerical Integration Procedure:



General Spline Equation $= \quad y_i = a_i z^2 + b_i z + c_i$

Cross-Sectional Area $= \sum_{i=1}^{n} \left[\frac{1}{3} a_i (z_{i+1}^3 - z_i^3) + \frac{1}{2} b_i (z_{i+1}^2 - z_i^2) + c_i (z_{i+1} - z_i) \right]$

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

Centroid $(\bar{z}) = \frac{1}{A} \sum_{i=1}^{n} \left[\frac{1}{4} a_i (z_{i+1}^4 - z_i^4) + \frac{1}{3} b_i (z_{i+1}^3 - z_i^3) + \frac{1}{2} c_i (z_{i+1}^2 - z_i^2) \right]$

From MATLAB, the canoe's center cross sections properties were found

$I_y = 787 \text{ in}^4 \qquad \bar{z}_{bot} = 5.07 \text{ in} \qquad \bar{z}_{top} = 9.94 \text{ in}$

The bouyant force was computed using a system of equations. A cubic function was chosen in order to meet three criteria: (1) Force is zero at the ends, (2) down force equates to area under cubic function, and (3) the Centroid of the cubic function aligns with the downward center of gravity.

$$W_{bouyant} = ax^3 + bx^2 + cx + d$$

Bow

1) $0 = a(0)^3 + b(0)^3 + c(0) + d \qquad \Rightarrow d = 0$

2) $2P_{male} + 2P_{Female} + W_{canoe} = a(20)^4 + b(20)^3 + c(20)^2$

3) $C.O.G\ (\Sigma P + W_{canoe}) = a(20)^5 + b(20)^4 + c(20)^3$

Stern

1) $0 = a(20)^3 + b(20)^2 + c(20)$

2) $900 = a(20)^4 + b(20)^3 + c(20)^2$

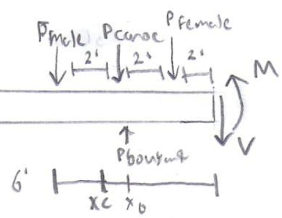
3) $9144 = a(20)^5 + b(20)^4 + c(20)^2$

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

$a = -7.681 \times 10^{-5}$
$b = -1.986 \times 10^{-4}$
$c = 0.0521$

Internal Forces:
Cut was taken at the center and distributed loads were converted to point loads.

Cut Free Body Diagram



$x_c = 4.35'$ $x_b = 4.00'$ $P_{bouyant} = 442.3$ lb

$+\uparrow \Sigma F_y = 0 = -V + 442.3\text{ lb} - 190\text{ lb} - 130\text{ lb} - 127.6\text{ lb}$
$V = -5.3$ lb

$\circlearrowleft + \Sigma M_{cut} = 0 = -M + 442.3\text{ lb}(4.00') + 190\text{ lb}(2') + 130\text{ lb}(6')$
$+ 127.6(4.35')$
$M = -54.14$ lb·ft

Bending Stress:

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

$\sigma_c = 4.19$ psi

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

$\sigma_t = 8.21$ psi

Hull Thickness/Reinforcement Calculations

Thickness:

Layers

Three (3) structural laywers at [0.25”] each

Reinforcement

Two (2) layers of Fiberglass Grid Green Mesh = (2)(1/128”) = 0.0156”

Gunwale Rails

Rail radius = 1.0”

Ribs

Rib radius = 1.0”

Wall:

Total wall thickness: (3)(0.25”) + (0.0156”) = 0.7656”

Total Mesh

Total reinforcement thickness = 0.0156”

Total reinforcement thickness/Total wall thickness = 0.0204 < 0.5 ***Acceptable Ratio***

Gunwale Rails and Ribs:

Total rail/rib thickness = 1.0” + 3(0.75”) + 0.0156” = 1.7656”

Total Mesh

Total reinforcement thickness = 0.0156”

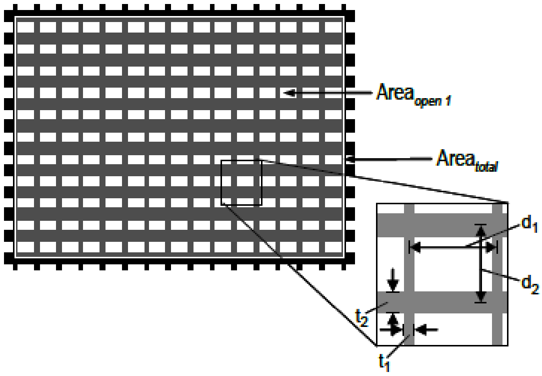
Total reinforcement thickness/Total rail/rib thickness = 0.009 < 0.5 ***Acceptable Ratio***

Bulkhead:

Total bulkhead thickness = 1”

No reinforcement

Percent Open Area



Annotation:
n_1: Number of apertures along sample length
n_2: Number of apertures along sample width
d_1: Spacing of reinforcing (center-to-center) along the sample length
d_2: Spacing of reinforcing (center-to-center) along the sample width
t_1: Thickness of reinforcing along sample length
t_2: Thickness of reinforcing along sample width

Equations:

$$d_1 = \text{aperature dimension} + 2(t_1/2)$$
$$d_2 = \text{aperature dimension} + 2(t_2/2)$$
$$\text{Length}_{\text{sample}} = n_1 d_1$$
$$\text{Width}_{\text{sample}} = n_2 d_2$$
$$\sum \text{Area}_{\text{open}} = n_1 \times n_2 \times \text{Area}_{\text{open 1}}$$
$$\text{Area}_{\text{total}} = \text{Length}_{\text{sample}} \times \text{Width}_{\text{sample}}$$
$$\text{POA} = \sum \text{Area}_{\text{open}} / \text{Area}_{\text{total}} \times 100\%$$

Green Mesh: Mesh is made up of fiber glass and thread. The thread is woven between the fiberglass strands.

$$t_1 = 2.0 \text{ mm} \quad t_2 = 1.0 \text{ mm}$$
$$d_1 = 4.0 \text{ mm} + 2(2.0 \text{ mm}/2) = 6.0 \text{ mm}$$
$$d_2 = 4.0 \text{ mm} + 2(1.0 \text{ mm}/2) = 5.0 \text{ mm}$$
$$\text{Length}_{\text{sample}} = 19(6.0 \text{ mm}) = 114.0 \text{ mm}$$
$$\text{Width}_{\text{sample}} = 14(5.0 \text{ mm}) = 70.0 \text{ mm}$$
$$\sum \text{Area}_{\text{open}} = 19 \times 14 \times 16.0 \text{ mm}^2 = 4{,}256 \text{ mm}^2$$
$$\text{Area}_{\text{total}} = 114.0 \text{ mm} \times 70.0 \text{ mm} = 7{,}980 \text{ mm}^2$$
$$\text{POA} = \frac{4{,}256 \text{ mm}^2}{7{,}980 \text{ mm}^2} \times 100\% = 53.33\ \%$$

$$t_1 = 0.067 \text{ in} \quad t_2 = 0.033 \text{ in}$$
$$d_1 = 0.167 \text{ in} + 2(0.067 \text{ in}/2) = 0.234 \text{ in}$$
$$d_2 = 0.15 \text{ in} + 2(0.033 \text{ in}/2) = 0.183 \text{ in}$$
$$\text{Length}_{\text{sample}} = 4(0.234 \text{ in}) = 0.936 \text{ in}$$
$$\text{Width}_{\text{sample}} = 4(0.183 \text{ in}) = 0.732 \text{ in}$$
$$\sum \text{Area}_{\text{open}} = 4 \times 4 \times 0.025 \text{ in}^2 = 0.4 \text{ in}^2$$
$$\text{Area}_{\text{total}} = 0.936 \text{ in} \times 0.732 \text{ in} = 0.685 \text{ in}^2$$
$$\text{POA} = \frac{0.4 \text{ in}^2}{0.685 \text{ in}^2} \times 100\% = 58.4\ \%$$