MAJESTY

University of Michigan
2018 Concrete Canoe Design Paper

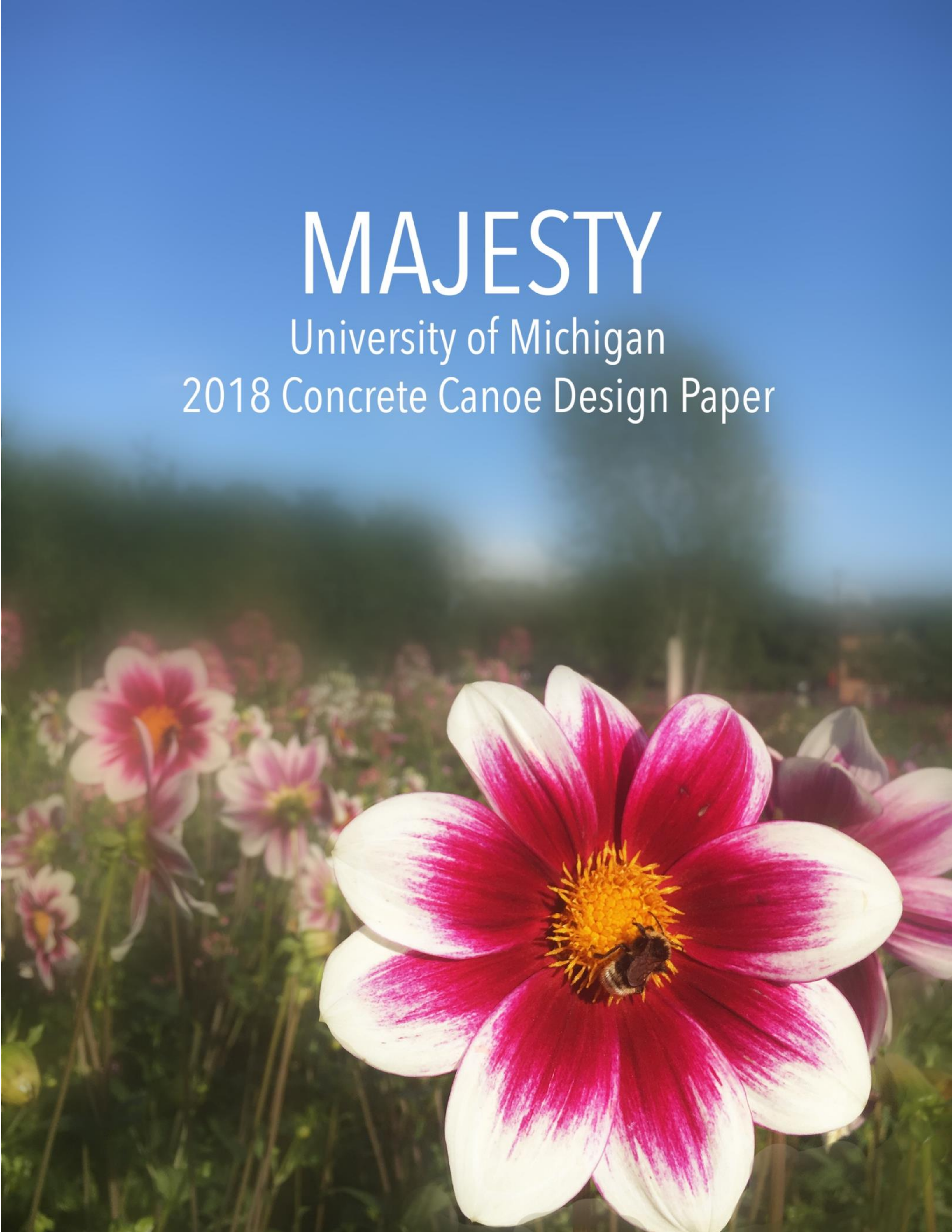


Table of Contents

List of Appendices

List of Tables

List of Figures

Executive Summary

In their hives, individual honeybees work tirelessly as a small part of a greater whole to better their colony and improve the ecosystem around them. In a growing world where climate change puts amplified stress on society's food production, honeybees are increasingly important to the agricultural infrastructure and the world's biodiversity as a whole. The determined teamwork of honeybees inspires the members of the Michigan Concrete Canoe Team (MCCT) to be socially and environmentally conscious engineers and emulate bees' qualities of synergy, communication, and persistence. MCCT is constantly pushing to innovate while being mindful of how technical innovations impact their surroundings. Working together in a colony to create a product that is greater than the sum of its parts, the 2018 canoe, *MAJESTY*, celebrates the contributions and vital importance of bees to an industrialized society, a diverse ecosystem, and recognizes the strategic vision of the University of Michigan "to anticipate the global, technological and educational changes ahead" (Regents of the University of Michigan 2017).

Located in Ann Arbor, Michigan, the University of Michigan is the number one public research university in the United States (National Science Foundation 2017). The College of Engineering's mission prompts MCCT to "create collaborative solutions" and foster an "inclusive and innovative community" inspiring future leaders through a challenging, hands-on project (Regents of the University of Michigan 2017). The Michigan Concrete Canoe Team competes in the ASCE North Central Conference. The past three years have seen incredible growth with the 2017 Canoe *VALIANT* placing second in the regional competition, 2016 *EXTINCTION* placing third, and the 2015 canoe *ALLEGRO* placing second. The growth and continued success of MCCT was brought about by dedicated members who have passed down their expertise so that MCCT can continue to improve and build on the success of previous teams.

With a returning team of approximately one half graduating seniors, a project management emphasis was placed upon team sustainability which included recruitment, member retention, and knowledge transfer between team members. For this reason, the transition procedure was overhauled to include a more rigorous documentation and mentorship system. Specifically, a new sub-team system for technical leadership was instituted to include additional meeting times for technical knowledge transfer and training.

To achieve an innovative and high performing mix design, many new ASTM C330 compliant lightweight natural aggregates were evaluated for their effect on concrete properties. The restructuring of the technical portions of the team into sub-teams allowed for more efficient design, double the mixes tested, and prompted younger members to be more involved. Polypropylene fibers were replaced with PVA fibers to prevent clumping and for the first time, blended pigments were tested and incorporated to produce an aesthetically pleasing canoe.

In 2017, the paddling team achieved its best ever finish. The experienced paddlers helped the hull design sub-team implement a feedback centered approach to create *MAJESTY's* hull by modifying the 2017 canoe form. Paddlers were most pleased with the stability and ease of turning, desiring a faster canoe that was better at straight line tracking. Members used rapid 3D modeling and analysis with Rhinoceros 5.0 and Maxsurf to design a canoe with the desired properties. To showcase honeybee like efficiency, teamwork, and to demonstrate the importance of bees to the growing world, MCCT proudly presents its 2018 canoe, *MAJESTY*.

Table 1. Canoe specifications including hull and mix parameters.

MAJESTY				
			Structural Mix	*Finishing Mix*
Weight	235 lb	Compressive Strength	1170 psi	N/A
Length	20 feet 4 inches	Split Tensile Strength	270 psi	N/A
Width	28 inches	Flexural Strength	260 psi	N/A
Depth	13 inches	Concrete Colors	Golden	Yellow, White
Average Hull Thickness	0.82 inches	Concrete Unit Weight	58.8 lb/ft^3 (dry) 59.0 lb/ft^3 (wet)	109 lb/ft^3 (dry) 111.9 lb/ft^3 (wet)
Reinforcement	Fiberglass Mesh PVA Fibers	Air Content	1.5 %	1.1 %

Project and Quality Management

In order to maintain the steady improvement MCCT has seen in recent years, project management activities in 2018 focused on recruiting and retaining new members while developing a sustainable leadership and team structure. Technical leadership positions determined individual goals that aligned with the overall project management objectives (Table 2). A significant project management innovation was the introduction of sub-teams that were able to facilitate knowledge transfer, improve overall productivity, and serve as technical mentorship for younger members.

Table 2. Project goals for team subsections.

Project Area	Project Goals
Mix Design	Involve new members in the design process to facilitate knowledge transfer.
Construction	Improve quality control to expedite finishing.
Hull Design	Use paddler feedback and testing to modify existing hull design.
Aesthetics	Oversee the use of a comprehensive theme.
Academics	Introduce a new drafting, review, and approval process.

The 2018 scheduling process involved a review of the project schedule and records generated by the 2017 team. The most critical milestone for the project was the casting day for *MAJESTY*, as curing was scheduled to take place over the winter recess in order to make the best use of that time. Critical path items were determined to include recruitment events, hull testing, finalized hull and mix designs, canoe casting, canoe curing, sanding and sealing, demolding, display pieces, and the regional competition. These milestones were scheduled after fixing the dates for casting and the regional competition. Once the critical milestones were scheduled, buffer time was added to account for unforeseen circumstances and responsibilities and deadlines for MCCT leadership were assigned.

Over the course of the project, general meeting time was used, in part, to review the schedule, deadlines, and to ensure the project was being completed on time.

Exceptional casting day quality control allowed the sanding and finishing processes for the canoe to be completed 2 weeks ahead of schedule and allowed a greater emphasis to be placed on the aesthetics and display aspects of the project.

Along with the critical path items, activities were selected as intermediate milestones to aid in the completion of the project. Intermediate milestones for the first semester included a kickoff mass meeting, theme selection, concrete testing, name selection, and mold assembly. These milestones allowed members to make sure the project was on schedule and critical path items would be completed.

With a work schedule in place and responsibilities assigned, financial resources were allocated to the different areas of the project by using budget records from previous teams while taking into account areas that would require additional funds like CNC routing and material purchasing. $8,750 was allocated for the project, however only $7,750 was used. A majority of the budget went to the registration for the regional competition and material purchasing. MCCT achieved a $1,000 cost savings by sharing paddling facility time with a local kayak club, designing the canoe mold to use 20% less foam, and building relationships with aggregate donors to contribute to economic sustainability. A budget breakdown can be seen in Figure 1. After the regional competition an additional $14,700 was allocated and raised to pay for national conference expenses including transportation and registration.

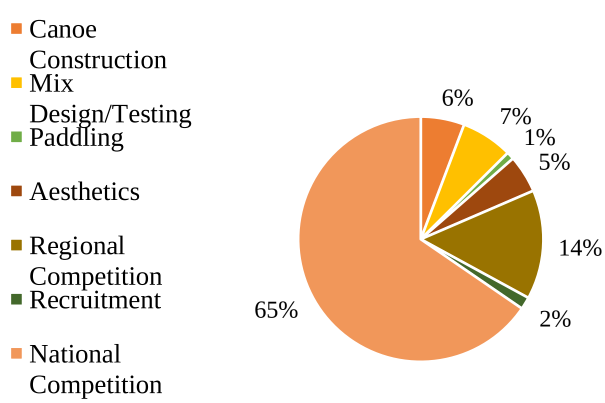


Figure 1. Financial resource allocation for *MAJESTY*.

The new sub-team organizational structure allowed the 30 active members of MCCT to be more efficient. Like individual worker bees, MCCT members each played an important role in accomplishing the 2696 person hours needed to complete an excellent final product (Table 3).

Table 3. Person-hour allocation for 2018 canoe *MAJESTY*.

Project Area	Person-hour Allocation
Project Management	618
Hull Design	90
Structural Analysis	50
Mixture Design Development	484
Mold Construction	180
Canoe Construction	260
Finishing	618
Academics	396
TOTAL OVERALL	**2696**

MCCT's Safety Officer led the team in following strict safety guidelines outlined by ASTM, MSDSs, University of Michigan facilities, team specific SOPs, hazard analyses, and trainings. Trainings include project area training, respirator training, and concrete mixer training that all members must complete. Materials used in the construction of the canoe are labeled with the hazards they present and required PPE for handling.

Figure 2. New members receiving concrete mixer training.

MCCT believes that a sustainable team requires many different viewpoints and perspectives, and for this reason membership includes 10 different areas of study and the percentage women in leadership positions matches team membership at 55%, higher than any other design team at U of M. To contribute to an environmentally sustainable project, materials were sourced from local companies when possible to eliminate shipping. Also, recycled materials were used in the construction of the canoe and a portion of the portland cement was replaced with materials having a lower carbon output.

In order to ensure full rules and regulations compliance in 2018, the Quality Control leadership position was restructured to include responsibility for rules and regulations agreement in addition to construction quality. Final design review meetings were required to verify that designs met the requirements outlined in the 2018 CNCC rules document as a form of risk management.

When the CNCC rules were released in September, the QC lead broke the document down into easy to follow checklists for the technical leads as an additional resource so no rules were overlooked. Additionally, RFIs were reviewed and presented as a part of the weekly project management meetings. When designs were ready to be finalized, the quality control lead held design review meetings with the mix design and hull design sub-teams to ensure that they met all regulations prior to canoe casting.

As a form of document tracking, archive, and review MCCT used cloud based collaborative documents for mixture design, safety documentation, hull design, academics, and scheduling. This documentation allowed project managers and QC leadership to review and approve work quickly and from anywhere.

Project management and quality control activities complimented each other and allowed MCCT to achieve an excellent final product that follows CNCC rules and was completed ahead of the proposed schedule.

Organization Chart

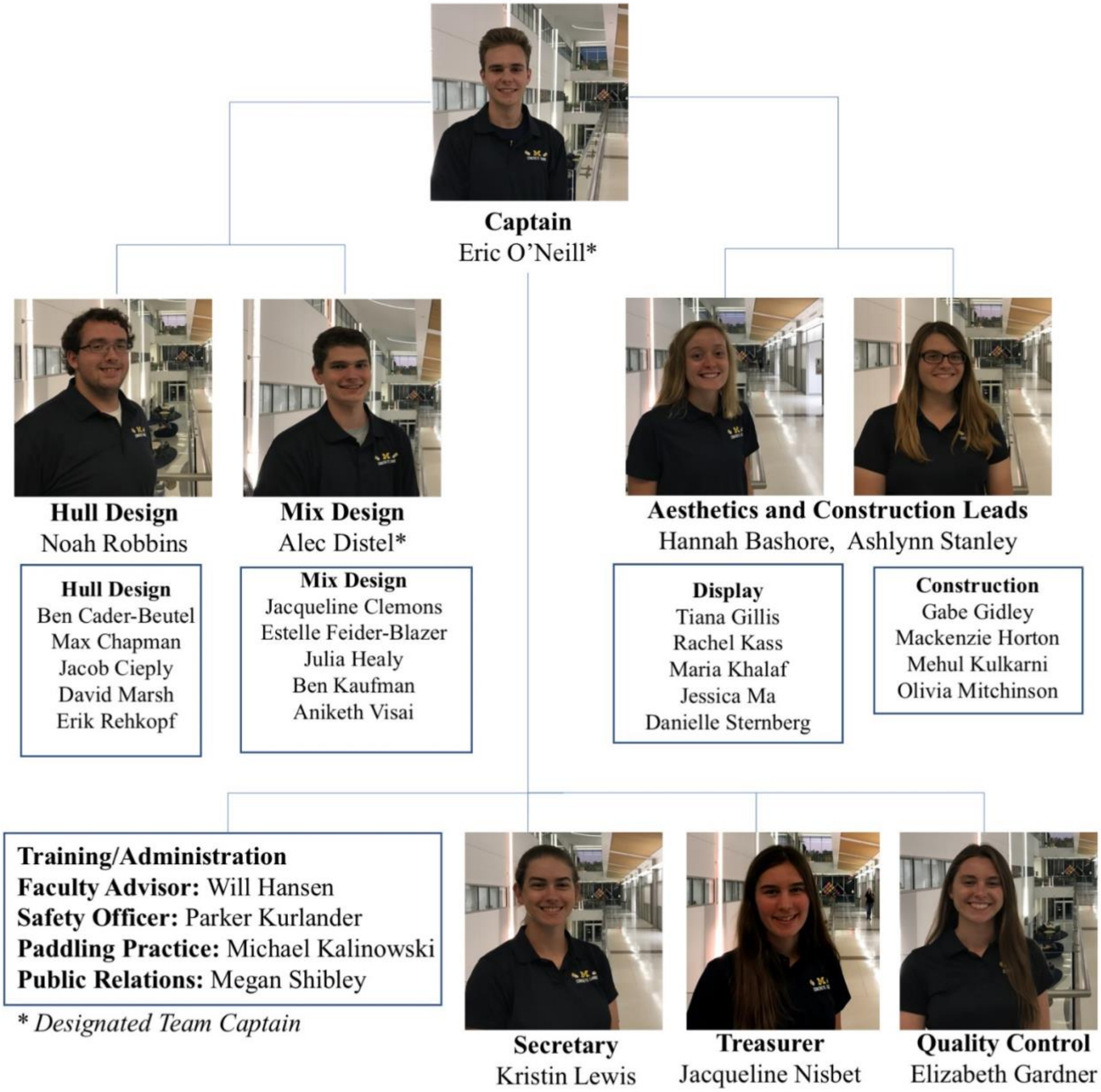


Table 4. List of team members including current academic standing.

Name	Year	Name	Year	Name	Year
Gabe Gidley	Grad	Alec Distel*	Jr.	Ben Cader-Beutel	Fr.
Hannah Bashore	Sr.	Estelle Feider-Blazer	Jr.	Max Chapman	Fr.
Elizabeth Gardner	Sr.	Jacqueline Nisbet	Jr.	Jacob Cieply	Fr.
Mackenzie Horton	Sr.	Jessica Ma	Jr.	Jacqueline Clemons	Fr.
Michael Kalinowski	Sr.	Tiana Gillis	So.	Julia Healy	Fr.
Mehul Kulkarni	Sr.	Kristin Lewis	So.	Rachel Kass	Fr.
Parker Kurlander	Sr.	Noah Robbins	So.	Ben Kaufman	Fr.
Olivia Mitchinson	Sr.	Megan Shibley	So.	Maria Khalaf	Fr.
Eric O'Neill*	Sr.	Danielle Sternberg	So.	David Marsh	Fr.
Ashlynn Stanley	Sr.	Aniketh Visai	So.	Erik Rehkopf	Fr.

Hull Design and Structural Analysis

MCCT's Hull design took multiple approaches to gauge the results of previously designed hulls to improve for the 2018 competition including data driven design and qualitative feedback approaches.

During the 2017 season, the team began a new approach of relying on computer aided 2D hydrostatics calculations for hull analysis. With more time and resources allocated to testing *VALIANT* over the summer break, the hull design team incorporated significantly more feedback from the paddlers, which gave insight into potential focus areas for design.

Figure 3. Hull testing of *VALIANT* to determine accurate waterlines and load cases.

Hull design project goals involved the recruitment of new talent to teach the principles of design and useful software tools. The goals for the canoe design were to improve tracking, speed, and the overall efficiency of paddling while maintaining stability.

VALIANT performed exceptionally well in the 2017 competition earning high praise for its stability, turning, and ergonomics from the paddling team. However, due to quality issues during casting, *VALIANT* struggled with tracking due to an imperfection on the port side of the bow, requiring constant course adjustments. From paddler feedback, it was learned that the stability of *VALIANT* was a great advantage over previous hulls. However, the opportunity cost to this design feature was a lower overall speed. To achieve the desired design modifications and make sure experienced paddlers were still familiar with the hull shape, the overall cross sectional profile was retained while the beam and length were modified from *VALIANT*.

Team members made hull modifications in Rhinoceros 5.0 (Rhinoceros, 2017) and the hydrostatics data, collected from Maxsurf Stability Suite (Maxsurf, 2017), was compared across different design iterations to find an optimal solution that accomplished the hull goals.

The team attempted to keep the same low center of gravity, but decrease the Block Coefficient, C_B, in order to increase the speed of the vessel. The team augmented the Length-to-Beam Ratio which resulted in an increase in top speed without sacrificing the stability preferred by the paddling team.

MAJESTY maintained a similar geometry to *VALIANT* with a U-shaped hull for stability and a sharp square bow to pierce through the water. In the final design, the maximum beam of the vessel was decreased to 27.85 inches from 31.85 inches while the length was increased by 4 inches to 20 feet 4 inches (MCCT, 2017). The depth of *MAJESTY* was retained from *VALIANT'S* hull because it provided a desirable freeboard that did not produce a noticeable wind heel arm and was comfortable for the paddlers. The adjustments increased the overall speed and increased the prismatic coefficient. The increase in prismatic coefficient indicates the canoe will operate more efficiently when traveling at higher speeds.

Using Maxsurf Stability Suite, the team used GM_T and GZ curves as a way to quantify the initial stability. Stability data from the various design iterations were compared to the values from *VALIANT*. After running stability calculations for *VALIANT* with load cases corresponding to accurate paddler weights, it was found that *MAJESTY* possessed a slightly lower Transverse Metacentric Height, GM_T, for the male, female, and co-ed racing conditions. The GM_T was 20.89 inches, 23.33 inches, and 16.37 inches for each load case respectively; a decrease of roughly 5%. The Block Coefficient was also decreased from 0.48 to 0.44 allowing for a greater maximum speed. The tipping angles of *MAJESTY* were found using the GZ curve calculated with Maxsurf and resulted in 38.2°, 40.5°, and 27.3° for male, female, and coed load cases. The team noted an average decrease in the tipping angle of 6.7% with the new hull design. The decrease in GM_T and tipping angle were viewed as an acceptable opportunity cost for the increase in speed and paddling efficiency predicted by the prismatic and block coefficients.

Table 5. Hydrostatic comparison of *VALIANT* and *MAJESTY*.

	VALIANT	*MAJESTY*
Prismatic Coefficient	0.568	0.580
Block Coefficient	0.48	0.44
Tipping Angle	44.2°	38.2°
GM_T	21.98	20.89
Frictional Resistance	2.42 lb	3.89 lb

Further analysis was completed with the load cases from 2018 to determine the resistance that the hull would experience. Implementing the assumption that the outside of the hull would be smooth after the vessel was sanded and sealed, the frictional resistance coefficient, C_F, was approximated by employing the skin friction line developed by the International Towing Tank Conference (ITTC 1978). The frictional resistance, R, was calculated by using Equation 1, where C_F is the resistance coefficient, S is the wetted surface area, and ρ is the density of water. The value of frictional resistance was used along with initial stability and the block coefficient to weigh pros and cons for each hull modification considered. The resistance faced a slight increase due to the increased wetted surface area and length of the waterline. Table 5 shows a comparison of the hydrostatic data for the 2 male load case.

$$R = C_F \frac{1}{2} \rho S V^2 \qquad (1)$$

To analyze the required strength of *MAJESTY*, the team used five load cases: two male, two female, four coed paddlers, two stands for display, and transportation (Figure 4.). For transportation, the canoe was considered continuously supported by the positive form fitting mold pieces used to cast and transport the canoe yielding a maximum moment of zero. The tensile strength in the gunwales was calculated with Equation 2 where *d* is the maximum distance from the neutral axis, *I* is the moment of inertia, and *M* is the global bending moment.

$$\sigma = \frac{Md}{I} \qquad (2)$$

As a way to validate the assumptions, Maxsurf Stability Suite was employed to analyze the difference between the buoyant force and distributed weight to calculate the tensile strength along the length of the canoe while taking into account the point loads from paddlers or display stands, and the asymmetrical geometry of the canoe. The moments calculated with Maxsurf were within 15% of the hand calculations and the assumptions for the structural calculations were deemed valid. Using the maximum moment along with the stress formula (Equation 2), the maximum compressive (291.5 psi) and tensile (54.9 psi) stresses are experienced during the 2 male load case. With a concrete compressive strength of 1170 psi and a tensile strength of 270 psi, the canoe has safety factors of 4.0 and 4.9, respectively.

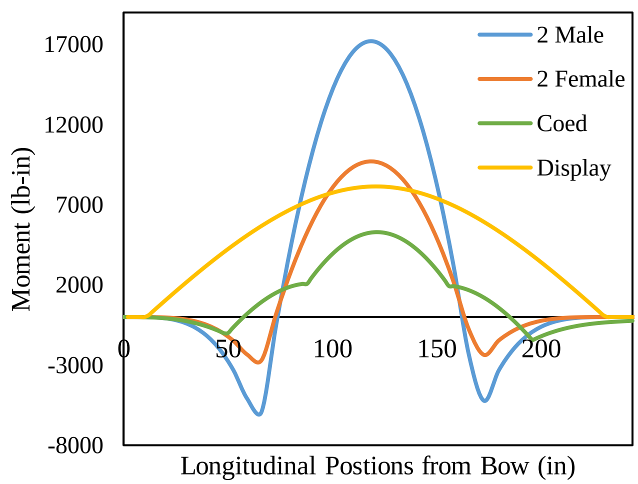


Figure 4. Moment diagram for the four load cases considered: 2 male, 2 female, 4 person co-ed, and display.

Development and Testing

Results from the 2017 structural mix were used as a baseline for the structural mix for *MAJESTY* due to its sufficient strength and buoyancy even with added pigment (University of Michigan, 2017). However, the 2017 structural mix did not use a natural aggregate that met ASTM standard C330 and was thus penalized. The main focus of 2018 was to add 25 percent natural aggregate by volume to the mix to meet the standard and still manage to keep the density of concrete lower than water.

To reach this goal, several commercially available natural aggregates that met ASTM standard C330 were selected and ordered for testing. Materials were selected by considering local availability, specific gravity, and particle size. Each natural aggregate was introduced to the 2017 baseline mix and other aggregate amounts were decreased until the natural aggregate made up 25 percent of the mix by volume. This produced multiple baseline mixes with which to adjust design parameters like aggregate to cementitious ratio, gradation, and natural aggregate composition. An iterative process was then used to alter the design parameters in order to find the most buoyant mix without sacrificing strength.

The 2018 final mix used lightweight glass microspheres and ASTM C330 compliant Haydite shale to meet the natural aggregate requirement and still manage to make the concrete float. In the final design, the aggregate to cementitious ratio by weight was increased to 0.6, up from 0.5 in previous years to lower the unit weight.

Many components of the structural mix from *VALIANT* were used in the structural mix for *MAJESTY*. Portland cement was used as the primary cementitious material, Ground Granulated Blast Furnace Slag (GGBFS) was used to partially replace the portland cement and had the added benefit of a lower specific gravity and lower carbon output, VCAS 160 was also used as an environmentally sustainable replacement for some of the portland cement, and Komponent was included at the manufacturers specifications to prevent shrinkage cracking during curing.

All aggregates from *VALIANT* were retained because of their low specific gravity, excellent gradation (Figure 5), and MCCT's knowledge and surplus of the materials. MCCT selected three sizes of Poraver expanded glass because of their low specific gravity and strength. The three sizes created a smooth gradation and provided a ball bearing effect which improved the workability of the concrete. SG-300 and K20 provided smaller grain sizes to the gradation and had the lowest specific gravity of any aggregate. Haydite shale, the only new aggregate introduced, had a larger particle size and accounted for 25% of the aggregates by volume.

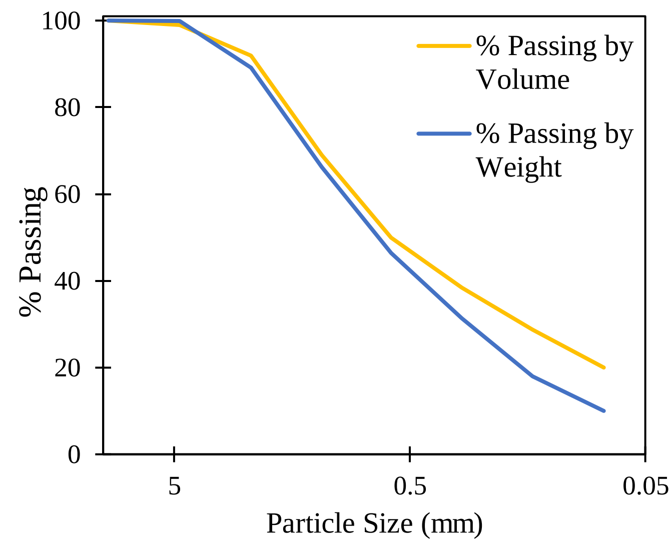


Figure 5. Aggregate gradation of the structural mix by weight and volume.

The natural aggregates Pumice, True Lite, and Haydite Shale were used during the iterative testing process, alone or in combination with each other, to determine which combination of aggregates would create a concrete with the lowest unit weight.

After curing, sixteen of seventeen mixes had a unit weight deemed too high by the Mix Design Lead. The mix that used only Haydite Shale was re-tested to verify strength and unit weight data as it was the only mix with the desired unit weight. Once the mix properties were verified, Haydite Shale was chosen over other natural aggregates that met ASTM C330 because of its low specific gravity and an improved tensile strength of 4.5 percent over the other natural aggregates. More detailed physical properties of each material in the final mix can be found in Table 6.

To keep the iterative process simple and to isolate the variable changed in each mixture iteration, all admixtures except for pigment were kept constant from the 2017 structural mix. Water reducer was used to minimize the amount of water needed for each mix and to improve the workability and strength. Air entrainer was used to increase the air content of the mix and decrease the density.

Table 6. Aggregate properties; composition, specific gravity, absorption percentage, and particle size.

Aggregate/ Composition		Specific Gravity	Abs (%)	Particle Size (mm)
Poraver	Glass Microsphere	0.40	19	1-2
Poraver	Glass Microsphere	0.50	18	0.5-1
Poraver	Glass Microsphere	0.70	21	0.25-0.5
SG-300	Cenosphere	0.72	1	0.01-0.3
K20	Cenosphere	0.20	1	.03-.09
Haydite Shale	Expanded Shale	0.84	10	2.4-0.6

Water reducer and air entrainer were kept at 8 and 3 fl oz/cwt. respectively as these dosages were found to be optimal by previous teams (University of Michigan, 2015). Sika Latex was used to create a polymer modified concrete that improved the overall workability of the mix. While the amount of pigment was kept constant in each mix, the proportions of different colors were adjusted to make the structural mix resemble honey. It was determined through testing that the different pigment color proportions did not significantly affect mixture properties.

The previous year's progress on preventing plastic shrinkage cracking was expanded upon as well. In past years concrete secondary reinforcement consisted of a combination of both polypropylene and PVA fibers. The polypropylene fibers, while decent at preventing shrinkage cracking, had issues with clumping in the mix and the fibers required extensive manual separation. The quality issues prompted the mix design team to test mixes that used only the PVA fibers (University of Michigan, 2017). The PVA fibers were not separated prior to mixing. The mix design team found no adverse effects such as excessive shrinkage, fiber clumping, strength, or setting time when fibers were not separated. This saved the mix design sub-team considerable time and allowed the team to prepare and test 17 mixes before the final mix was selected in December of 2017. After a review of manufacturer recommendations and national winning designs, the amount of PVA fibers was also increased from 5.5 to 6.5 lb/yd^3.

The increased fiber loading increased both the compressive and tensile strength of the structural mix, and the inclusion of the natural aggregate slightly increased the tensile strength. Test results from mix iterations can be found in Table 7.

Table 7. Comparison of strength values for mixture iterations.

	Baseline (2017)	With Fibers	Final with Pigment
Unit Weight (lb/ft^3)	57.4	57.6	57.7
Compressive Strength (psi)	883	1151	1168
Tensile Strength (psi)	232	282	273

Before the final structural mix for *MAJESTY* was decided, a pigment was chosen to accurately reflect elements of the theme and to limit the negative effect concrete pigment can have on the buoyancy of the mix. Yellow pigment was used in the structural mix of *VALIANT* and was found to minimally affect buoyancy. Therefore, the same color was used for the majority of the pigment, however, orange pigment was added to give the concrete a more amber color reminiscent of honey.

The final structural mix for *MAJESTY* had a density of 59.0 lb/ft^3 (wet) which was higher than the mix from 2017, but still had sufficient buoyancy. The compressive and tensile strengths of the final mix were 1170 psi and 270 psi respectively which are between 5-10% higher than the 2017 mix, tested according to ASTM C39 and ASTM C496.

After the final mix was selected, the canoe was constructed and allowed to cure. The canoe was reinforced with Spiderlath Fiberglass Mesh in between 3/8" layers of concrete for the majority of the canoe and 1.5" of concrete at the gunwales. Fiberglass mesh was selected because the material is more lightweight than other options tested in the past (University of Michigan, 2015) and provides adequate increases to composite flexural strength.

The layering scheme was chosen to achieve the required percent open area and meet strength requirements determined by the structural analysis calculations presented above.

Once the canoe was constructed, the mix design team focused on creating a suitable finishing mix for *MAJESTY*. To create a workable and aesthetically pleasing finishing mix, the mix design team made adjustments to the 2017 mix by adding ASTM C330 compliant pumice to the mix. Design goals for the finishing mix included a gradation that allowed for easy application, a color that could be manipulated with various pigment proportions to create artistic elements, and a durability that would prevent chipping and stand up to normal wear and tear.

Although Haydite shale was selected for the final structural mix because of its specific gravity and strength properties, it was not included in the finishing mix because of its dark color and large particle size. To achieve a desirable aggregate size distribution, the mix design team crushed Grade 7 ASTM C330 compliant pumice using a mortar and pestle into a fineness that was suitable for the team's workability standards.

Figure 6. Crushed natural aggregate for use in the finishing mix.

Ground Granulated Blast Furnace Slag was the only cementitious material used in the finishing mix due to its white color and environmental benefits. Aggregates were limited to a maximum size of 0.5 mm and included Poraver size 0.25-0.5 mm and pumice crushed to a fine powder less than 0.5 mm. The small spherical aggregates allowed the mixture to be spread thin and applied in an even coat by the aesthetics team to create designs in accordance with the theme.

Most admixtures were not present in the finishing mix as the strength, air content, and unit weight were not design goals; however, latex was used in the place of batch water to help the mix adhere to the already cast canoe.

In order to test the finishing mixes and ensure that they met the design goals described above, mixes were applied to a test sections of the canoe as a qualitative test of the durability, ease of application, and color characteristics (Figure 7).

Figure 7. Aesthetic testing using various pigment proportions in the finishing mix.

The mix design team considered sustainability of their actions as it relates to the team's budget and the environment. The mix design team sourced 50% of materials purchased in 2018 from local vendors to eliminate the cost and environmental impact of shipping. Additionally, in alignment with the overall project management goal of sustainable team knowledge and leadership, the mix design sub-team placed an emphasis on educating new members throughout the design process. Knowledge transfer involved technical presentations, design reviews, and specific mixing and testing training sessions.

Through careful planning and testing, the mix design team managed to meet all goals set from the beginning of the year. Considerable time went into creating a structural mix for *MAJESTY* with sufficient strength and minimal density. Similar effort was put into creating an aesthetically pleasing and ASTM C330 compliant finishing mix. Just as honeybees work as a team to grow their hive, the mix design team worked tirelessly to create the best mix possible.

Construction

MAJESTY's construction innovations were primarily focused on increasing the efficiency of casting day operations and improving the aesthetic elements of the canoe. A secondary focus was to improve quality control measures and safety during casting.

Hull Design team members modeled the canoe form in Rhinoceros 5.0 (Rhinoceros, 2017) to prepare for CNC routing. 78, 3-inch thick cross-sections with flat bases and three alignment pieces with gunwale forms were CNC routed from expanded polystyrene foam (EPS) to ensure the precision of the positive canoe form. EPS foam was chosen for multiple reasons, primarily that it is relatively inexpensive, easy to cut with a CNC router, and available locally.

A positive canoe form was chosen over a negative mold to accurately shape the gunwales, decrease the slumping seen in past use of negative molds, and require less EPS foam making it a more sustainable option. This decision was made with the sacrifice of exterior precision, particularly keel quality, prompting the team to take additional quality control measures during casting. Quality measures included two members constantly using hand trowels to smooth the outer layer of concrete to the desired form. Another downside of using a positive mold is the stress from plastic shrinkage during curing. The mix design team used a Type K shrinkage compensating cement and PVA fibers to remediate some of the stresses from the positive mold and prevent cracking.

Figure 8. Applying release coating to the exterior of the mold.

The individual cross-sections were lightly sanded to remove imperfections, glued together, and aligned over three wooden reinforcement beams on the EPS alignment pieces to increase stability. The base pieces were leveled and clamped to tables before concrete placement as a quality control measure and to improve ergonomics. Once the mold was assembled and the glue dried, a layer of spackling paste was placed over any exterior voids in the foam and over the seams between cross-sections to improve the appearance of the interior. The exterior of the mold was sanded once the spackling paste was dry and a thin layer of release coating (Figure 8) was applied to aid in the demolding process.

As an innovative quality control measure, MCCT members constructed one-foot test sections of the canoe prior to casting day. New members were supervised and guided by more experienced individuals to transfer quality control and construction knowledge. EPS foam pieces were reused from the 2017 canoe mold to reduce waste and minimally affect the 2018 budget. The new members were instructed in using quality control devices, how to apply reinforcement mesh between layers, and how to use trowels to smooth the outer layer of concrete. Creating test sections allowed the new members to prepare for casting day and be able to implement best practices before working on the actual canoe. Because the entire team was trained in construction techniques, casting proceeded without errors and more efficiently than in previous years.

Figure 9. Thickness gauges for quality control. Different colors represent 0.375", 0.75", and 1.5".

Once the structural mix was determined and prior to casting, the Mix Design Team pre-measured all of the necessary cementitious materials and aggregates into individual 0.35 ft^3 batches to increase the efficiency of the mixing process during casting. Pre batching also gave the team more time to ensure that all mixes were identical and were able to be mixed exactly when they were needed during casting. When construction began, designated team members measured fibers, liquids, and pigments for each mix as needed and concrete was mixed using a Hobart D300 mixer. Mixes were scheduled during casting based on communication between the mix team and the quality team who were monitoring the placement of the concrete.

Executive board members were assigned designated positions throughout the process and new members rotated through the different work areas in order to experience every part of the casting process. Every work area always had a specific number of members assigned to it. Work areas included mixing, placement, quality control, troweling, material measurement, reinforcement, and safety. By having an experienced member at each work area, safety practices were followed and the project management goal of efficient knowledge transfer was achieved.

Construction involved a continuous process of mixing and placement of concrete batches. First, the Quality Control Team confirmed the first layer of concrete was the correct 3⁄8" thickness with gauges made out of nails painted with the correct depths (Figure 9). The mesh was placed over the first layer and members sprayed Sika Liquid Latex onto the concrete while wearing latex gloves to incorporate the mesh by hand and prevent delamination. The second layer of concrete was then placed on top of the mesh and carefully incorporated with more latex before being checked for the correct 3⁄4" thickness and troweled smooth.

MCCT used the chasing method (Figure 10) in which the second 3/8" thick layer of concrete was placed on top of the reinforcement mesh while the first layer was still plastic in order to fully incorporate the reinforcement mesh. The second layer of concrete lagged behind the first by 3 ft while casting. The fiberglass mesh was cut into 3 ft sections to fit the mold before concrete placement began in order to expedite the placement process and prevent the concrete from setting before mesh could be placed and incorporated. In this fashion, concrete was placed down the length of the canoe until completed.

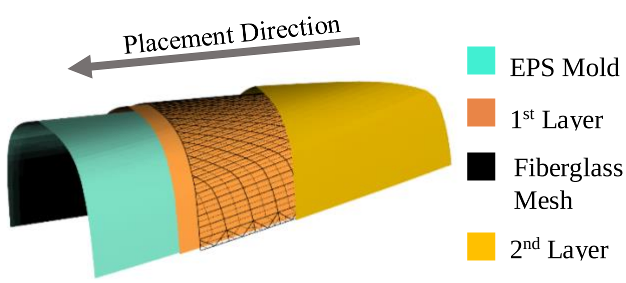


Figure 10. Diagram showing the method of applying concrete using the chasing method and layering scheme.

MAJESTY was cured over 28 days under damp sheets that were replenished twice daily. The full 28 day cure with humid conditions ensured the strength of the concrete developed completely. A significant innovation in the curing process from 2017 was the addition of a temperature control system to the curing room. Over the 28 days of curing, *MAJESTY* was kept at a constant 70°F to prevent any thermal expansion or shrinkage effects.

After *MAJESTY* was cured, it was removed from the mold. First, the canoe was flipped and placed in negative form pieces for support. Then, the canoe form was removed. Removing the mold began with taking out one cross-section piece in its entirety and using that vacancy as leverage to remove the rest of the cross-sections in larger pieces by hand. The release agent applied prior to casting allowed the easy removal of the form. The cross section pieces were saved to fully support the canoe during transportation, and additional cross section pieces were CNC routed to construct the cross section for the display.

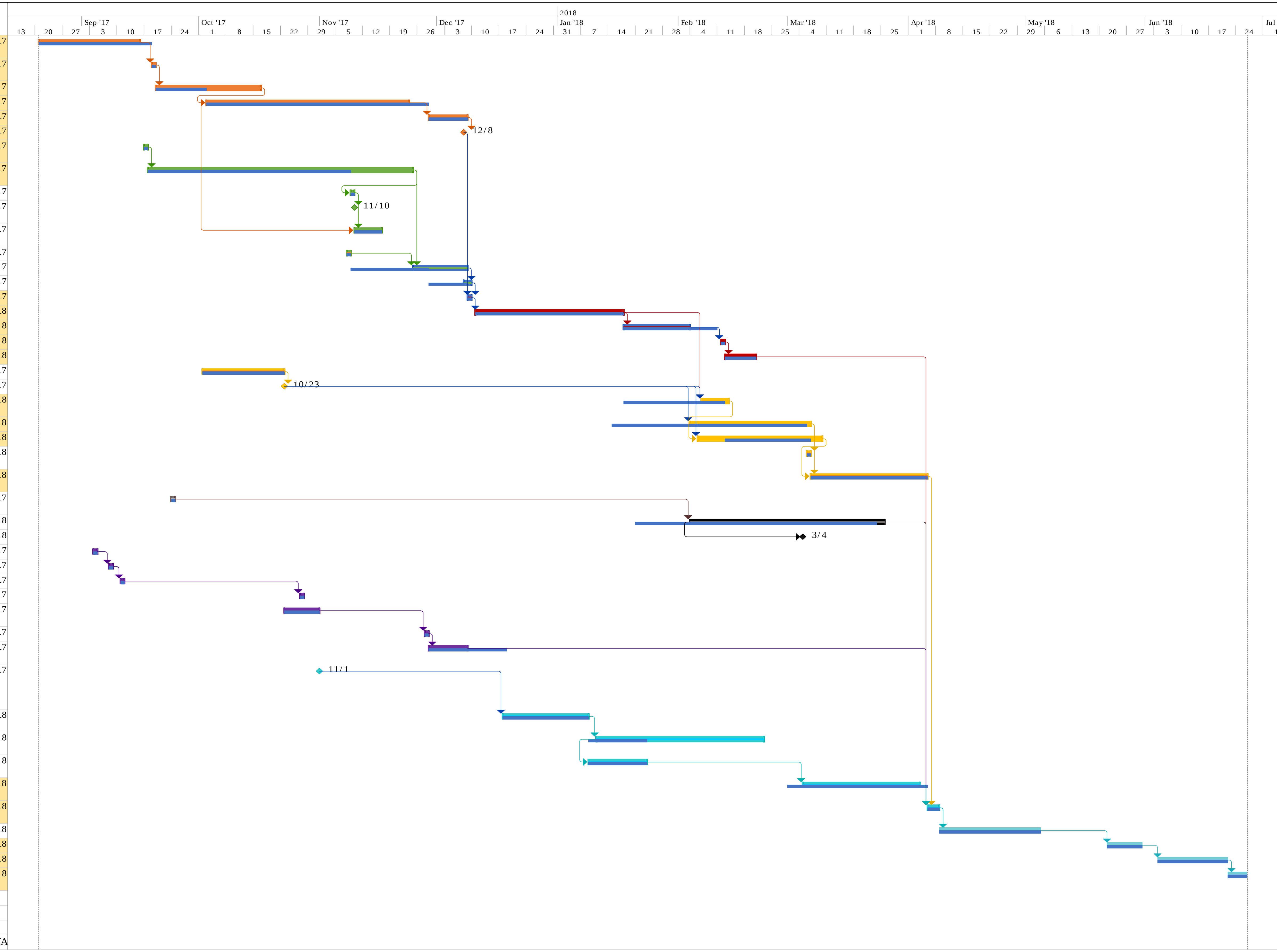
After the canoe had finished curing and was removed from its form, it was hand sanded. Sanding was completed in stages on both the interior and exterior of the canoe beginning with 100 grit sandpaper and stepping down to 240 grit paper. The mix design team used a concrete finishing mix of the same color as the canoe to fix any imperfections that occurred during casting.

In accordance with the theme and to improve the appearance of *MAJESTY*, an aesthetic finishing mix was also applied. While the mix remained the same, the proportions of different colored pigments were altered to create an artistic design. Construction team members used duct tape stencils and nitrile gloves to apply the aesthetic slurry by hand. The finishing mix was sanded smooth and two coats of ASTM C1315 compliant sealer were applied to the entire canoe.

With an emphasis on knowledge transfer and team sustainability across all aspects of the project, the Michigan Concrete Canoe Team is proud to present its innovative and aesthetically pleasing canoe *MAJESTY*.

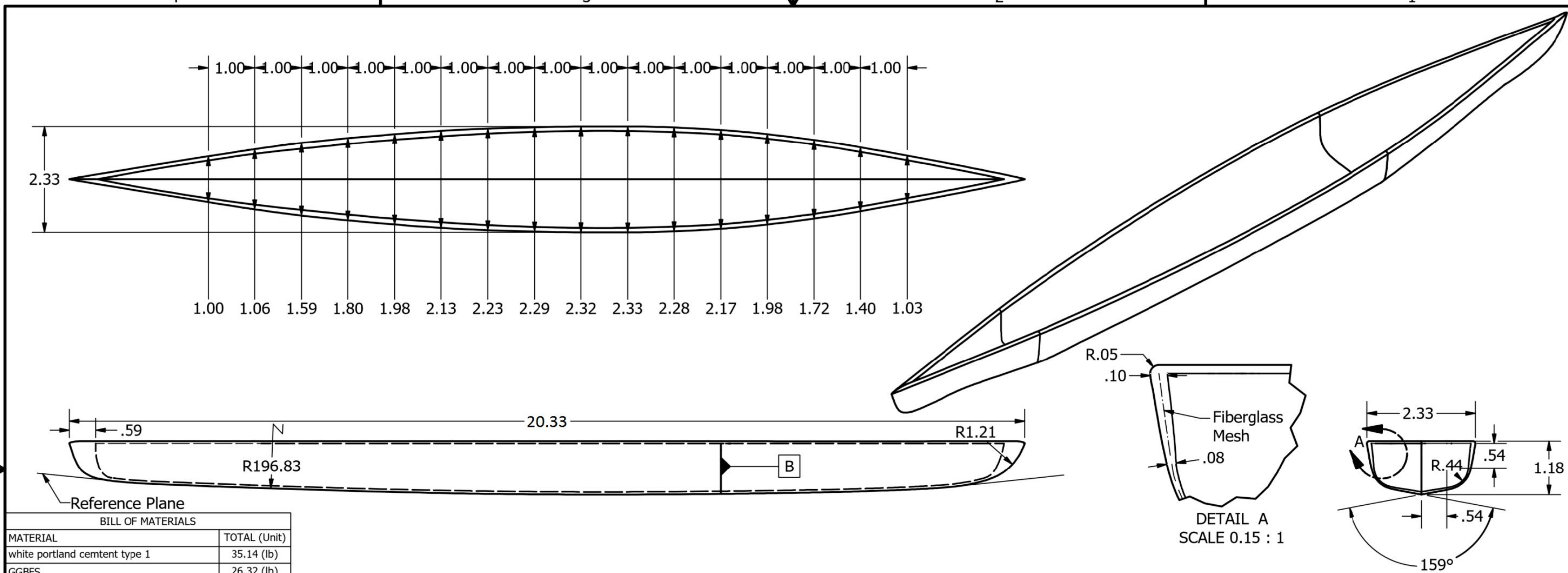
Project Schedule

ID	Task Name	Baseline Start	Baseline Finish	Act. Start	Act. Finish
2	Research New Materials	Mon 8/21/17	Mon 9/18/17	Mon 8/21/17	Fri 9/15/17
3	Clean and Organize Space	Tue 9/19/17	Tue 9/19/17	Tue 9/19/17	Tue 9/19/17
4	Order Materials	Wed 9/20/17	Mon 10/2/17	Wed 9/20/17	Mon 10/16/17
5	Mix Testing	Tue 10/3/17	Tue 11/28/1	Tue 10/3/17	Thu 11/23/17
6	Data Analysis	Wed 11/29/1	Fri 12/8/17	Wed 11/29/17	Fri 12/8/17
7	Mix Design Chosen	Fri 12/8/17	Fri 12/8/17	Fri 12/8/17	Fri 12/8/17
9	Hull Testing of 2017 Canoe	Sun 9/17/17	Sun 9/17/17	Sun 9/17/17	Sun 9/17/17
10	Design and Prototyping	Mon 9/18/17	Wed 11/8/17	Mon 9/18/17	Fri 11/24/17
11	Design Review	Thu 11/9/17	Thu 11/9/17	Thu 11/9/17	Thu 11/9/17
12	Hull Design Chosen	Fri 11/10/17	Fri 11/10/17	Fri 11/10/17	Fri 11/10/17
13	Structural Calculations	Fri 11/10/17	Thu 11/16/17	Fri 11/10/17	Thu 11/16/17
15	Purchase Foam	Wed 11/8/17	Wed 11/8/17	Wed 11/8/17	Wed 11/8/17
16	CNC Cut Mold	Thu 11/9/17	Tue 11/28/1	Sat 11/25/17	Fri 12/8/17
17	Assemble Mold	Wed 11/29/1	Fri 12/8/17	Fri 12/8/17	Sat 12/9/17
18	Casting Day	Sat 12/9/17	Sat 12/9/17	Sat 12/9/17	Sat 12/9/17
19	Canoe Curing	Mon 12/11/1	Wed 1/17/18	Mon 12/11/17	Wed 1/17/18
20	Sand and Slurry	Thu 1/18/18	Sat 2/10/18	Thu 1/18/18	Sat 2/3/18
21	Apply Lettering	Mon 2/12/18	Mon 2/12/18	Mon 2/12/18	Mon 2/12/18
22	Seal Canoe	Tue 2/13/18	Tue 2/20/18	Tue 2/13/18	Tue 2/20/18
24	Brainstorming	Mon 10/2/17	Sun 10/22/1	Mon 10/2/17	Sun 10/22/17
25	Theme Chosen	Mon 10/23/1	Mon 10/23/1	Mon 10/23/17	Mon 10/23/17
26	Canoe Aesthetic Slurry Design	Thu 1/18/18	Mon 2/12/18	Tue 2/6/18	Tue 2/13/18
27	Stand Construction	Mon 1/15/18	Mon 3/5/18	Sun 2/4/18	Tue 3/6/18
28	Prepare Poster	Tue 2/13/18	Tue 3/6/18	Tue 2/6/18	Fri 3/9/18
29	Complete Cross Section	Tue 3/6/18	Tue 3/6/18	Tue 3/6/18	Tue 3/6/18
30	Display Construction	Wed 3/7/18	Thu 4/5/18	Wed 3/7/18	Thu 4/5/18
32	Paddling Introduction	Sun 9/24/17	Sun 9/24/17	Sun 9/24/17	Sun 9/24/17
33	Paddling Practice	Sun 1/21/18	Fri 3/23/18	Sun 2/4/18	Sun 3/25/18
34	Teams Selected	Sun 3/4/18	Sun 3/4/18	Sun 3/4/18	Sun 3/4/18
36	NorthFest	Mon 9/4/17	Mon 9/4/17	Mon 9/4/17	Mon 9/4/17
37	Festifall	Fri 9/8/17	Fri 9/8/17	Fri 9/8/17	Fri 9/8/17
38	Mass Meeting	Mon 9/11/17	Mon 9/11/17	Mon 9/11/17	Mon 9/11/17
39	Social Event	Fri 10/27/17	Fri 10/27/17	Fri 10/27/17	Fri 10/27/17
40	Draft and Send Sponsor Letters	Mon 10/23/17	Tue 10/31/17	Mon 10/23/17	Tue 10/31/17
41	Giving Blue Day	Tue 11/28/1	Tue 11/28/1	Tue 11/28/17	Tue 11/28/17
42	Funding Applications	Wed 11/29/17	Mon 12/18/17	Wed 11/29/17	Fri 12/8/17
44	Project Schedule and Acknowledgment Form	Wed 11/1/17	Wed 11/1/17	Wed 11/1/17	Wed 11/1/17
45	Write Design Paper First Draft	Mon 12/18/17	Mon 1/8/18	Mon 12/18/17	Mon 1/8/18
46	Finalize Design Paper	Tue 1/9/18	Tue 1/23/18	Thu 1/11/18	Thu 2/22/18
47	Complete Project Overview	Tue 1/9/18	Tue 1/23/18	Tue 1/9/18	Tue 1/23/18
48	Make and Practice Presentation	Thu 3/1/18	Thu 4/5/18	Mon 3/5/18	Tue 4/3/18
49	Regional Conference	Fri 4/6/18	Sun 4/8/18	Fri 4/6/18	Sun 4/8/18
50	Funding Search	Mon 4/9/18	Mon 4/30/18	Mon 4/9/18	Fri 5/4/18
51	Canoe Crating	Tue 5/22/18	Thu 5/31/18	Tue 5/22/18	Wed 5/30/18
52	Shipping	Mon 6/4/18	Thu 6/21/18	Mon 6/4/18	Thu 6/21/18
53	National Conference	Fri 6/22/18	Tue 6/26/18	Fri 6/22/18	Tue 6/26/18
54					
55					
56					
57		NA	NA	NA	NA



MCCT Project Schedule Critical Path (Highlight) Actual Project (Half Bar) Planned Project (Full Bar)

Construction Drawing



BILL OF MATERIALS	
MATERIAL	TOTAL (Unit)
white portland cemtent type 1	35.14 (lb)
GGBFS	26.32 (lb)
Komponet	11.34 (lb)
VCAS	13.16 (g)
PVA Fibers 6 mm	175 (g)
PVA Fibers 8 mm	175 (g)
PVA Fibers 12 mm	175 (g)
Proraver 1-2mm	18.2 (lb)
Poraver .5-1mm	16.94 (lb)
Proraver .25-5mm	15.68 (lb)
SG 300	18.06 (lb)
K20	10.22 (lb)
Haydite Shale	49.84 (lb)
ADVA cast 555	300.58 (mL)
DAREX II	112.7 (mL)
SiklaLatex	7622.16 (g)
Fiberglass Mesh	45 (sq. ft)
ChemMasters Crystal Clear Sealer	2 (gal)
Huron Technologies Release Coating #7410	0.33 (gal)
Foam Mold Complete	1 (mold)
Sand Paper	1 (pkg)
Vinyl Letters (School Name)	2 (unit)
Vinyl Letters (Canoe Name)	2 (unit)

DRAWN Parker	12/17/2017	MCCT
CHECKED		TITLE MAJESTY
QA		
MFG		
APPROVED		SIZE B / DWG NO / REV
		SCALE 1 / 25 / SHEET 1 OF 1

Appendix A – References

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Appendix B – Mixture Proportions

MIXTURE DESIGNATION: STRUCTURAL MIX

CEMENTITIOUS MATERIALS

Component	*Specific Gravity*	*Volume (ft³)*	*Amount of CM (mass/volume) (lb/yd³)*	
Portland Cement Type 1	3.15	0.98	192.71	*Total Amount of cementitious materials* **470.1** lb/yd³ *c/cm ratio* **0.41**
Ground Granulated Blast Furnace Slag	2.90	0.39	70.50	
Komponent	3.10	0.32	61.11	
VCAS 160	2.60	0.90	145.75	

FIBERS

Component	*Specific Gravity*	*Volume (ft³)*	*Amount of Fibers (mass/volume) (lb/yd³)*	
NYCON PVA RMS702 6mm	1.30	0.03	2.13	*Total Amount of Fibers* **6.39** lb/yd³
NYCON PVA RECS15 8mm	1.30	0.03	2.13	
NYCON PVA RECS100 12mm	1.30	0.03	2.13	

AGGREGATES

Aggregates	*ASTM C330**	*Abs (%)*	*SG_OD*	*SG_SSD*	*Base Quantity (lb/yd³)*		*Volume (ft³)*
					OD	*SSD*	
Poraver 1.0-2.0mm	N	19.0	0.41	0.50	99.27	118.13	3.26
Poraver 0.5-1.0mm	N	18.0	0.50	0.59	92.32	108.93	2.51
Poraver 0.25-0.5mm	N	21.0	0.70	0.85	85.92	103.96	1.63
SG300	N	1.0	0.72	0.73	99.12	100.11	2.18
K20	N	1.0	0.20	0.20	55.59	56.15	4.41
Haydite Expanded Shale	Y	10.0	0.84	0.92	272.99	300.29	4.73

ADMIXTURES

Admixture	*lb/gal*	*Dosage (fl. oz / cwt)*	*% Solids*	*Amount of Water in Admixture (lb/yd³)*	
Sika Liquid Latex Modifier	8.8	200.0	47.0	34.26	*Total Water from Admixtures,* $\sum w_{admx}$ **37.65** lb/yd³
High Range Water Reducer	8.9	8.0	5.0	2.48	
Air Entrainer	8.7	3.0	5.0	0.91	

SOLIDS (LATEX, DYES AND POWDERED ADMIXTURES ONLY)

Component	*Specific Gravity*	*Volume (ft³)*	*Amount (mass/volume) (lb/yd³)*	
Latex Solids	1.12	0.40	30.38	*Total Solids from Admixtures* **34.58** lb/yd³
Orange Pigment	5.24	0.00	0.51	
Yellow Pigment	5.24	0.01	3.69	

WATER

	Amount (mass/volume) (lb/yd³)		*Volume (ft³)*
Water, lb/yd³		*w*: 235.03	**3.77**
Total Free Water from All Aggregates, lb/yd³		$\sum w_{free}$: -82.37	
Total Water from All Admixtures, lb/yd³		$\sum w_{admx}$: 37.65	
Batch Water, lb/yd³		w_{batch}: 279.75	

DENSITIES, AIR CONTENT, RATIOS AND SLUMP

	cm	*fibers*	*aggregates*	*solids*	*water*	*Total*
Mass of Concrete, M, (lb)	470.06	6.39	787.57	34.58	235.03	$\sum M$: 1533.63
Absolute Volume of Concrete, V, (ft³)	2.58	0.08	18.72	0.45	3.77	$\sum V$: 25.6
Theoretical Density, T, *(=∑M / ∑V)*	*59.9 lb/ft³*		***Air Content*** *[= (T – D)/T x 100%]*			*1.5 %*
Measured Density, D	*59.0 lb/ft³*		***Slump, Slump flow***			*4.0 in.*
water/cement ratio, w/c:	*1.22*		***water/cementitious material ratio, w/cm:***			*0.5*

MIXTURE DESIGNATION: Finishing mix

Cementitious Materials

Component	*Specific Gravity*	*Volume (ft^3)*	*Amount of CM (mass/volume) (lb/yd^3)*	
Ground Granulated Blast Furnace Slag	2.90	5.30	959.90	*Total Amount of cementitious materials* **959.90** *lb/yd^3* *c/cm ratio* ***0.00***

Fibers

Component	*Specific Gravity*	*Volume (ft^3)*	*Amount of Fibers (mass/volume) (lb/yd^3)*	
				Total Amount of Fibers ***0.00*** *lb/yd^3*

Aggregates

Aggregates	*ASTM C330**	*Abs (%)*	*SG_{OD}*	*SG_{SSD}*	*Base Quantity (lb/yd^3)*		*Volume (ft^3)*
					OD	*SSD*	
Poraver 0.25-0.5mm	N	21.0	0.70	0.85	*132.16*	159.91	3.03
Pumice	Y	30.0	2.72	3.53	*252.86*	278.15	6.07

Admixtures

Admixture	*lb/gal*	*Dosage (fl. oz / cwt)*	*% Solids*	*Amount of Water in Admixture (lb/yd^3)*	
Sika Liquid Latex Modifier	8.8	1059.50	47.0	370.57	*Total Water from Admixtures, $\sum w_{admx}$* ***370.57*** *lb/yd^3*

Solids (Latex, Dyes and Powdered Admixtures Only)

Component	*Specific Gravity*	*Volume (ft^3)*	*Amount (mass/volume) (lb/yd^3)*	
Latex Solids	1.12	4.70	328.62	*Total Solids from Admixtures* ***344.62*** *lb/yd^3*
Pigment (color proportions vary)	5.24	0.05	16.00	

Water

	Amount (mass/volume) (lb/yd^3)		*Volume (ft^3)*
Water, lb/yd^3		*w*: 370.57	*5.94*
Total Free Water from All Aggregates, lb/yd^3		$\sum w_{free}$: -281.08	
Total Water from All Admixtures, lb/yd^3		$\sum w_{admx}$: 370.57	
Batch Water, lb/yd^3		w_{batch}: 0.00	

Densities, Air Content, Ratios and Slump

	cm	*fibers*	*aggregates*	*solids*	*water*	*Total*
Mass of Concrete, M, (lb)	959.90	0.00	1161.61	344.62	370.57	*$\sum M$: 2836.70*
Absolute Volume of Concrete, V, (ft^3)	5.30	0.00	9.09	4.75	5.94	*$\sum V$: 25.1*
Theoretical Density, T, *(=$\sum M$ / $\sum V$)*	*113.1 lb/ft^3*		***Air Content*** *[= (T – D)/T x 100%]*			*1.1 %*
Measured Density, D	*111.9 lb/ft^3*		***Slump, Slump flow***			*10.0 in.*
water/cement ratio, w/c:	*N/A*		***water/cementitious material ratio, w/cm:***			*0.39*

Detailed Step by Step Calculation

Design parameters:

Portland Type I Cement	192.7 lb	SG = 3.25
Blast Furnace Slag	70.5 lb	SG = 2.90
Komponent	61.1 lb	SG = 3.10
VCAS 160	145.8 lb	SG = 2.60

Fibers, PVA (6mm)	2.13 lb	SG = 1.30
Fibers, PVA (8mm)	2.13 lb	SG = 1.30
Fibers, PVA (12mm)	2.13 lb	SG = 1.30

w/cm ratio	0.50

Aggregate	SG_{OD}	W_{OD} (lb)	W_{SSD} (lb)	W_{stk} (lb)	Abs (%)	MC_{stk} (%)
Expanded Shale (meets C330)	0.84	272.99	300.29	272.99	10.0	<1.0%
Poraver (1-2mm)	0.40	99.27	118.13	99.27	19.0	<1.0%
Poraver (0.5-1mm)	0.50	92.32	108.93	92.32	18.0	<1.0%
Poraver (0.25-0.5mm)	0.70	85.92	103.96	85.92	21.0	<1.0%
SG 300	0.72	99.12	100.11	99.12	1.0	<1.0%
K20	0.20	55.59	56.15	55.59	1.0	<1.0%

8 fl oz/cwt	HRWR Admixture (5% solids by weight, 8.9 lb/gal)
3 fl oz/cwt	Air Entraining Admixture (5% solids by weight, 8.7 lb/gal)
200 fl oz/cwt	Latex (47% solids by weight, 8.8 lb/gal)

Measured Unit Weight Wet	**59.0 lb/ft^3**

Cementitious Materials:

Absolute Volume = mass/ (SG x 62.4)
$V_{portland}$ = 192.7/(3.15 x 62.4) = **0.98 ft^3**
V_{slag} = 70.5/(2.90 x 62.4) = **0.39 ft^3**
$V_{komponent}$ = 61.1/(3.10 x 62.4) = **0.31 ft^3**
V_{VCAS} = 145.8/(2.60 x 62.4) = **0.90 ft^3**
V_{fibers} = 2.13/(1.30 x 62.4) = **0.03 ft^3**
V_{fibers} = 2.13/(1.30 x 62.4) = **0.03 ft^3**
V_{fibers} = 2.13/(1.30 x 62.4) = **0.03 ft^3**

Aggregate Absolute Volume(ft^3) = mass(lb)/ (SG_{SSD} x 62.4(lb/ft^3))
V_{shale} =272.99/(0.92 x 62.4) = **4.73 ft^3**
$V_{poraver\ 1\text{-}2}$ = 99.27/(0.49 x 62.4) = **3.26 ft^3**
$V_{poraver\ 0.5\text{-}1}$ = 92.32/(0.59 x 62.4) = **2.51 ft^3**
$V_{poraver\ 0.25\text{-}0.5}$ = 85.92/(0.85 x 62.4) = **1.63 ft^3**
V_{SG300} = 99.12/(0.73 x 62.4) = **2.18 ft^3**
V_{K20} = 55.59/(0.21 x 62.4) = **4.41 ft^3**

Aggregates: All aggregate stock moisture contents are less than the Abs.

$\text{Abs} = \dfrac{W_{ssd} - W_{od}}{W_{od}} \times 100\%$
Expaded Shale = (300.29 lb – 272.99 lb) / (272.99 lb) x 100% = **10.0%**
Poraver 1-2mm = (118.13 lb – 97.27 lb) / (97.27 lb) x 100% = **19.0%**
Poraver 0.5-1.0mm = (108.93 lb – 92.32 lb) / (92.32 lb) x 100% = **18.0%**
Poraver 0.25-0.5mm = (103.96 lb – 85.92 lb) / (85.92 lb) x 100% = **21.0%**
SG 300 = (100.11 lb – 99.12 lb) / (99.12 lb) x 100% = **1.0%**
K20 = (56.15 lb – 55.59 lb) / (55.59 lb) x 100% = **1.0%**

Water: As all aggregates are stored at approximately their oven dried condition, it is assumed that the total moisture content is 0. In the equation above $(0)/W_{od} \times 100\% = 0$.

Water = w/cm x cm
Water = 0.50 x 470.10 lb = **235.03 lb**
$MC_{total} = \frac{W_{stk} - W_{od}}{W_{od}} \times 100\%$
For all aggregates used $MC_{free} = MC_{total} - A$
MC_{total} = **0**
MC_{free} = **-A**

$W_{free} = W_{OD}$ x (MC_{free}/100%)
$W_{free,\ haydite}$ = 272.99 lb x (-10/100%) = **-27.3 lb**
$W_{free,\ poraver\ 1\text{-}2}$ = 99.27 lb x (-19/100%) = **-18.9 lb**
$W_{free,\ poraver\ 0.5\text{-}1}$ = 92.32 lb x (-18/100%) = **-16.6 lb**
$W_{free,\ poraver\ 0.25\text{-}0.5}$ = 85.92 lb x (-21/100%) = **-18.0 lb**
$W_{free,\ SG300}$ = 99.12 lb x (-1/100%) = **-1.0 lb**
$W_{free,\ K20}$ = 55.59 lb x (-1/100%) = **-0.6 lb**
Combined free water = SUM(W_{free}) = **-82.4 lb**

Water in admixture = dosage x cwt of cm x % water x (1 gal/128fl oz) x (lb/gal of admixture)
W_{HRWR}=8 fl oz/cwt x 470.1 lb/yd^3/100 x (100-5% solids) x (1 gal/128fl oz) x (8.9 lb/gal)= **2.48 lb**
$W_{AirEntr}$=3 fl oz/cwt x 470.1 lb/yd^3/100 x (100-5% solids) x (1 gal/128fl oz) x (8.7 lb/gal)= **0.91 lb**
W_{Latex} = 200 fl oz/cwt x 470.1 lb/yd^3/100 x (100-47% solids) x (1 gal/128fl oz) x (8.8 lb/gal)= **34.26 lb**
Total Water from admixtures = 2.30 + 0.84 + 31.73 = **37.65 lb**

$W_{batch} = w - (w_{free} + \Sigma w_{admx})$
W_{batch} = 235.03 lb – (-82.37 lb + 37.75 lb) = **279.75 lb**
$V_{water} = Mass_{water}$/62.4 lb/ft^3
V_{water} = 217.74 lb / 62.4 lb/ft^3 = **3.77 ft^3**

Solids: Neglecting all admixtures except for pigments and latex.

Solids in admixtures = dosage x cwt of cm x solids content x (1 gal / 128fl oz) x (lb/gal of admixture)
From Latex = 200 fl oz/cwt x 470.10 lb/yd^3/100 x (47% solids) x (1 gal/128fl oz) x (8.8 lb/gal)= **30.38 lb**
V_{Solids} = 28.14 lb / (1.12 x 62.4 lb/ft^3) = **0.44 ft^3**
$V_{pigment}$ = 4.20 lb/(5.24 x 62.4 lb/ft^3) = **0.01 ft^3**

Densities, Air Content, Slump, and Ratios:

Mass of Concrete = $Amount_{cm} + Amount_{fibers} + Amount_{aggregate} + Amount_{water} + Amount_{solids}$
M = 470.0 lb + 6.4 lb + 787.6 lb + 235.0 lb + 34.6 lb = **1533.6 lb**
Volume of Concrete = $Volume_{cm} + Volume_{fibers} + Volume_{aggregate} + Volume_{water} + Volume_{solids}$
V = 2.6 ft^3 + 0.1 ft^3 + 18.7 ft^3 + 3.8 ft^3 + 0.4 ft^3 = **25.6 ft^3**
Theoretical Density T = M/V
T = 1533.6 lb/25.6 ft^3 = **59.9 lb/ft^3**
Measured Density D = **59.0 lb/ft^3** (Measured in the plastic state)
Air Content = (T-D)/T x 100%
Air Content = (59.9 – 59.0)/59.0 x 100% = **1.5%**
Cement to Cementitious Materials Ratio c/cm = 178.5/435.4 = **0.41**
Water to Cementitious ratio w/cm = 217.7/435.4 = **0.50**
Slump (Measured) = **4.0 in**

Concrete Ratios:

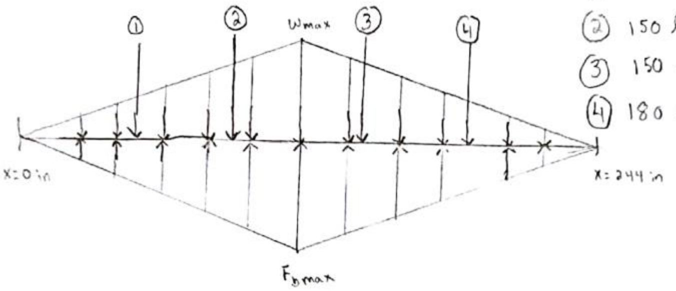
Aggregate Ratio (%) = $V_{aggregate}$ / 27 x 100%
Aggregate Ratio (%) = 18.7 ft^3 / 27 ft^3 x 100% = **69.3 %** > 25% OK!
ASTM C330 Aggregate Ratio (Volumetric) (%) = $V_{aggregate\ C330} / V_{aggregates}$
ASTM C330 Ratio = 4.7 ft^3 / 18.7 ft^3 x 100% = **25.1%** > 25% OK!

Appendix C – Example Structural Calculation

Assumptions

- Canoe Weight = 235 lb, Canoe length = 244 in.
- Bouyancy and canoe weight are approximated as triangular distributed loads
- Canoe is Symmetric
- Cross Section is assumed to be a Simple 3-beam U shape
- Paddlers are point loads male = 180 lb Female = 150 lb

Free body diagram



① 180 lb; 48.8 in
② 150 lb; 85.4 in
③ 150 lb; 158.6 in
④ 180 lb; 195 in.

$F_b = 2(150\text{ lb}) + 2(180\text{ lb}) + 235\text{ lb}$ $W_c = 235\text{ lb}$

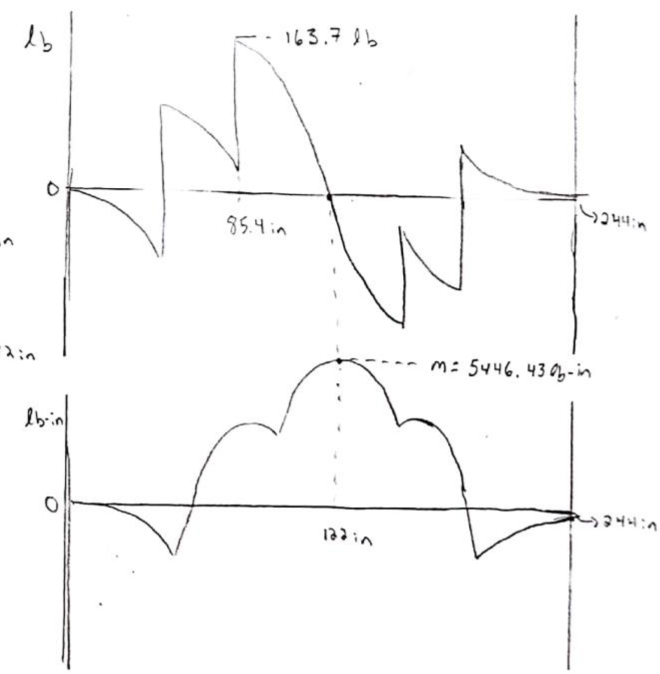
$F_b = 895\text{ lbs}$

$W_c = \int_0^L w(x)\,dx$ W_{max}: $235\text{ lb} = \frac{W_{max}}{2} \cdot 122\text{ in} + \frac{W_{max}}{2} \cdot 122\text{ in}$

$W_{max} = 1.92\text{ lb/in}$

$F_b = \int_0^L F_b(x)\,dx$ $F_{b\,max}$: $895\text{ lb} = \frac{F_{b\,max}}{2} \cdot 122\text{ in} + \frac{F_{b\,max}}{2} \cdot 122\text{ in}$

$F_{b\,max} = 7.34\text{ lb/in}$



Moment

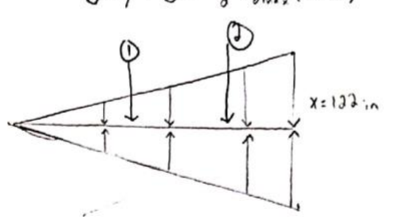
$$\Sigma M = 0 = -(180\text{ lb})(48.8\text{ in}) - (150\text{ lb})(84.4\text{ in}) - \tfrac{1}{2}(1.92\text{ lb/in})(122\text{ in})(\tfrac{2}{3})(122\text{ in}) + \tfrac{1}{2}(7.34\text{ lb/in})(122\text{ in})(\tfrac{2}{3})(122\text{ in}) + M(122\text{ in})$$

$M(122) = 5446.43\text{ lb}\cdot\text{in}$

Vertical Forces

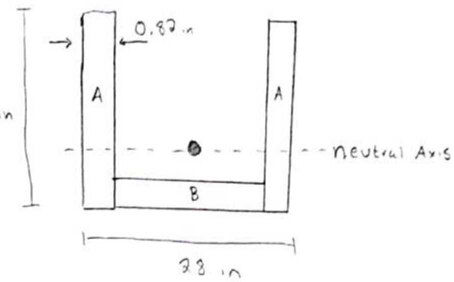
$$\Sigma F_y = 0 = \tfrac{1}{2} F_{b\,max}(122\text{ in}) - \tfrac{1}{2} W_{max}(122\text{ in}) - F_m - F_f - V(122\text{ in})$$

$V(122) = 0\text{ lb}$



Cross Section

- approximated as 3-beam U-shape, 2D analysis



$\bar{y} = \frac{\Sigma \bar{y}_i A_i}{\Sigma A_i}$ $\quad y_A = \frac{(13\text{in} - 0.82\text{in})}{2} = 6.09 \text{ in.}$

$\bar{y} = \frac{y_A + y_B}{A_A + A_B}$ $\quad y_B = \frac{0.82 \text{ in}}{2} = 0.41 \text{ in}$

$A_A = (13\text{in} - 0.82\text{in})(0.82\text{in}) = 9.99 \text{ in}^2$

$A_B = (28\text{ in})(0.87\text{ in}) = 24.36 \text{ in}^2$

$\bar{y} = \frac{(6.09\text{in})(9.99\text{in}^2) + (0.41\text{in})(24.36\text{in}^2)}{(9.99\text{in}) + (24.36\text{in}^2)} = 2.06 \text{ in}$ from bottom

Moments

From the Parallel Axis thm $\qquad I = I_\alpha + A d^2$

$I_{cx_B} = \frac{(28\text{ in})(0.82\text{in})}{12} = 1.28 \text{ in}^4$ $\qquad I_A = 123.47\text{in}^4 + (9.99\text{ in}^2)(6.09\text{in} - 2.06\text{in})^2 = 285.72 \text{ in}^4$

$I_{cx_A} = \frac{(13-0.82)^3(0.82\text{in})}{12} = 123.47 \text{in}^4$ $\qquad I_B = 1.28\text{in}^4 + (24.36\text{in}^2)(2.06\text{in} - 0.41\text{in})^2 = 67.60 \text{ in}^4$

Total $I_x = \Sigma I_i = 2(285.72\text{in}^4) + 67.60\text{in}^4 = 639.04 \text{ in}^4$

Stress

- Canoe is in compression at the top, tension at bottom

$\sigma_{Flex} = \frac{-M}{I}$

$\sigma_{Comp} = \frac{-(5446.43\text{ lb in})(13\text{in} - 2.06\text{in})}{639.04\text{ in}^4} = 93.24 \text{ psi}$ Compression

$\sigma_{tens} = \frac{-(5446.43\text{ lb in})(2.06\text{in})}{639.04\text{ in}^4} = 17.56 \text{ psi}$ tension

Comparison of load cases:

Table C- 1. Comparison of maximum moments and maximum stresses.

Load Case	Maximum Moment	Compressive Stress	Tensile Stress
2 Male	17209	291.5	54.9
2 Female	9709	166.2	31.3
4 Person Co-ed	5446	93.2	17.6
Display	8115	138.9	26.2

The four load conditions 2 Male, 2 Female, 4 Person Co-ed, and Display were also analyzed using excel. The maximum compressive and tensile stress are experienced during the 2 Male load case. The maximum stress and maximum moment were also analyzed using Maxsurf Stability Suite for a more accurate representation of the moment for the specific canoe geometry and found to be reasonably close (within 15%) to the hand calculations which validated the above assumptions. With a concrete compressive strength of 1170 psi and a tensile strength of 270 psi, the canoe will have safety factors of 4.0 and 4.9 respectively.

Appendix D – Hull Thickness/Reinforcement and Percent Open Area Calculations

Hull Thickness:

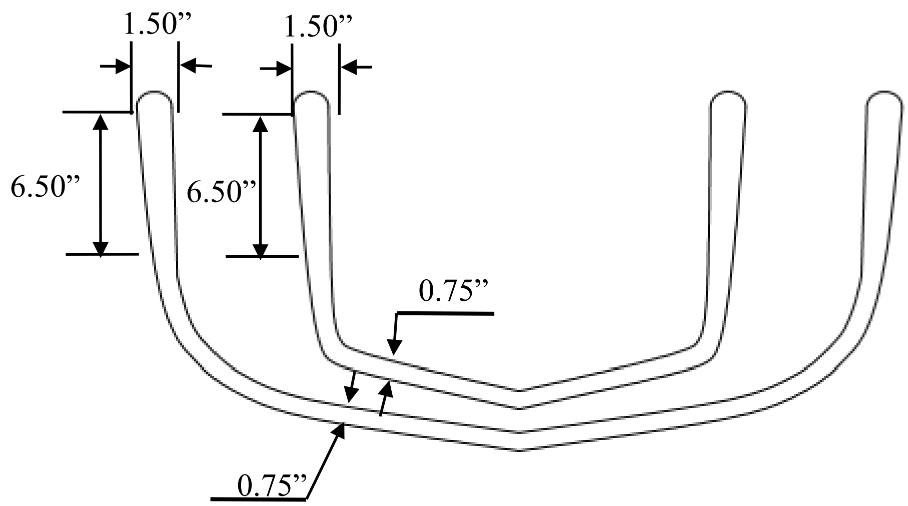


Figure D- 1. Representative cross sections for *MAJESTY* located 25% and 75% from the bow.

MCCT used a gradient similar to the 2017 gradient to strengthen the area below the gunwales which was determined to be the area experiencing the most stress. The width and height of the gradient is maintained throughout the entire length of the canoe. The ThicknessAnalysis() function was used in Rhinoceros 5.0 to find the average thickness between the outer and inner polysurfaces of the canoe design. Representative cross sections are shown above in Figure D-1. The gunwale thickness was 1.5” and the thinnest part of the canoe was 0.75” with the gradient between the two thicknesses spanning 6.5”. The ThicknessAnalysis() function provided an average thickness of 0.82”.

The Spiderlath fiberglass reinforcement used in the canoe has a thickness of 1/16”. Only one layer of reinforcement was used through the entire canoe. The example calculation below confirms that the reinforcement is less than 50% of the total thickness of the canoe. The reinforcement is incorporated into the concrete so that the final hull thickness is 0.75 inches.

1st Layer of concrete:	0.375 inches
Reinforcement:	0.0625 inches
2nd Layer of concrete:	0.3125 inches

Total Thickness = 0.375” + 0.3125” + 0.0625” = 0.75 inches

% of Thickness that is reinforcement = 0.0625”/0.75” = 8.3%

Percent Open Area:

One layer of fiberglass mesh was used in the layering scheme chosen for *MAJESTY*. Calculations are presented below.

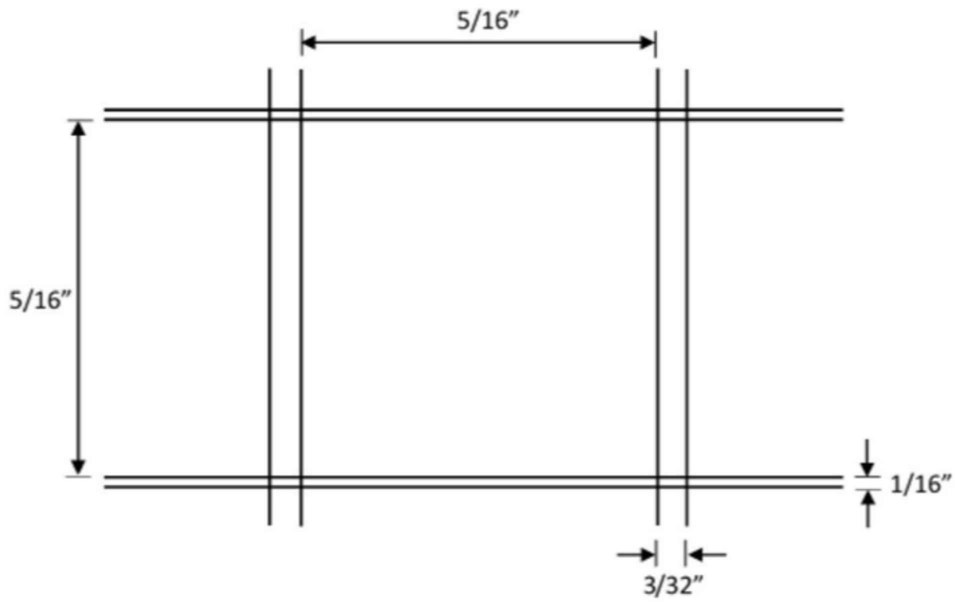


Figure D- 2. Schematic of the fiberglass mesh used as reinforcement.

Number of apertures along sample width = 20

Number of apertures along sample length = 20

$$\text{Open Area} = 20 \times 20 \times {}^{5}/_{16} \times {}^{5}/_{16} = 39.06\ \text{in.}^2$$

$$\text{Aperture Area (consider } {}^{1}/_{2} \text{ of strand thickness)}$$

$$W = {}^{5}/_{16}" + {}^{1}/_{2}(2 \times {}^{3}/_{32}") = {}^{13}/_{32}"$$

$$L = {}^{5}/_{16}" + {}^{1}/_{2}(2 \times {}^{1}/_{16}") = {}^{6}/_{16}"$$

$$\text{Width of Sample} = 20 \times {}^{13}/_{32}" = 8.13\ \text{in.}$$

$$\text{Length of Sample} = 20 \times {}^{6}/_{16}" = 7.50\ \text{in.}$$

$$\text{Total Sample Area} = 8.13" \times 7.50" = 60.98\ \text{in}^2$$

$$\text{Percent Open Area} = \frac{39.06\ \text{in.}^2}{60.98\ \text{in.}^2} \times 100 = \mathbf{49.3}\%$$