RUSHIN'BLUE

A PRODUCT OF THE

UNIVERSITY OF MICHIGAN CONCRETE CANOE TEAM

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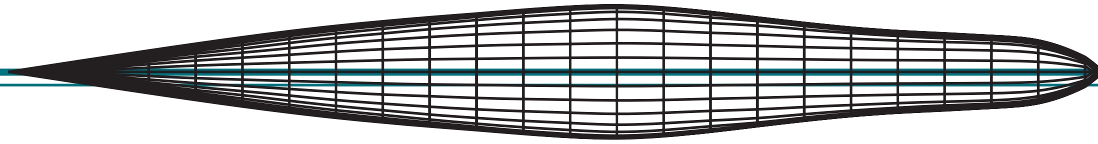
EXECUTIVE SUMMARY

When University of Michigan's progressive education paths expanded into the versatile field of engineering, Civil Engineering was the first department to be created in 1854. Since then, our department has taught students to be at the forefront of engineering technology and advancements. The participation of the Michigan Concrete Canoe Team (MCCT) in the A.S.C.E. North Central Regional Conference is our chance to demonstrate the quality of this education. Each year, leading individuals combine forces to form a small yet tremendously strong and dedicated team. Inspired by the strength of its members, MCCT 2007 strived to achieve a strong, durable concrete composite through investigative and innovative means.

The result: The Rushin' Blue, a 260 lbs. canoe measuring 19 feet 6 inches long, 28-1/2 inches wide, and 18 inches in depth. The Rushin' Blue's name is a pun on the vessel's blue-gray coloration, a product of high silica fume cement replacement. Our hull features two 3/8 inch thick layers of concrete enclosing a single layer of fiberglass mesh. While the mesh ensures the overall structural integrity of the canoe, localized damage is controlled with the inclusion of PVA fibers at 0.6 percent of the total canoe volume. The resulting 62.2 pound per cubic foot (p.c.f.) mix has a compressive strength of 2250 pounds per square inch (p.s.i.) at 16 days and exhibits an average residual compressive strength of 1500 p.s.i. through a strain of 3 percent. The splitting test flexural strength of the composite is approximately 1300 p.s.i.



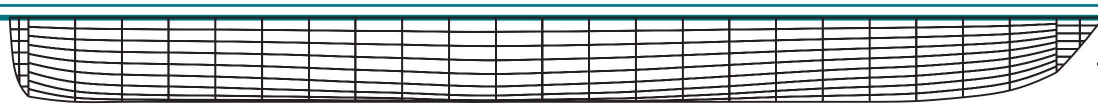
HULL DESIGN

The Rushin' Blue's shape and streamlines were inspired by Michigan concrete canoes of the past, but featured modifications to promote stability and paddling efficiency. Toward this end the canoe features a long bow that gradually tapers into a wide center paddling station. The bow section was not intended to seat paddlers and merely provides the smoothest possible transition between the foremost submerged point and the wide central paddling station.

Amidships, the near-tumblehome design of the canoe's gunwales allows for a more efficient paddling position. This efficiency is gained by allowing the canoeist to have a vertical stroke into the water, an angle that provides the most power transmission towards forward motion of the canoe. Also, by not requiring the canoeist to lean over the gunwale to paddle, stability is greatly enhanced when trying to orchestrate the movements and positions of a four-person paddling team. Finally, the steep walls and flat bottom of the central paddling station increase the volume of displaced water located away from the vessel's centerline, further increasing the canoe's resistance to roll.

The stern-section of the Rushin' Blue was also designed with high, straight sides, though with a much narrower beam than that at the center station. Alike to the forward sections, this design allows the canoeist to have a vertical stroke and thereby maximizes locomotive power. In addition, the extremely narrow beam in the stern allows paddlers there to easily reach out over the gunwale to make a sweep or pull stroke while performing technical maneuvers, accurate turns, and rapid directional changes. This ability to apply a substantial amount of power and control over the canoe's movement from the stern paddling station is advantageous in two ways: first, it represents an overall increase from the 2006 design in maneuverability (to be exploited during the sprint and slalom races); and second, it places control of this maneuverability in the hands of a select number of experienced canoeists paddling from the stern.

With the general cross sections determined from a practical standpoint, the canoe streamlines were derived through an extensive series of iterations under the guidance of an experienced naval architect. A hydrostatic analysis of the final design – using approximations for the canoe thickness, density, and canoeist weights – was carried out to ensure the displaced volume provided sufficient buoyancy and freeboard. This analysis was completed in the same program that modeled the canoe shape and from which the formwork cutpaths were extracted: Rhinoceros 3D by McNeel Software.



ANALYSIS

Initial determinations for the structural hull and composite requirements for the Rushin' Blue were based on experience gained during the 2006 competition. A desire to used leftover reinforcement coupled with concrete placement concerns kept our overall hull construction unchanged – 3/8 inch concrete, 1 layer of fiberglass mesh, 3/8 inch concrete (see Mix Design for explanation). Additionally, the 2006 canoe successfully weathered a number of pseudo-static and impact loading conditions without any noticeable damage. Given that the main goal of our mix development program was to increase the composite strength, we saw no pressing need to thoroughly analyze a similarly constructed, similarly loaded 20 foot long structural shell.

Nevertheless, there was some concern about the effects of the canoe "hip" – the sudden decrease in vessel width just aft of amidships - on a simply supported loading condition. This condition was occasionally necessary in 2006 for transporting the canoe with a limited number of people. The worry was that offset compression forces in the gunwales on either side of the "hip" would form couples and thereby induce additional flexural compresive stresses in the composite.

To determine the magnitudes of these stresses, we extraced the 3D canoe geometry from Rhinoceros and conducted a simple finite element analysis in SAP2000. The canoe was supported on two simple supports at bow and stern and loaded under 150% of its own weight. The additional 50% self weight was to account for deviation in hull thickness and for situations where the canoe would be moved while wet. Figure 1 shows the distribution of various stresses throughout the Rushin' Blue. Material properties used in analysis and critical stresses are summarized in Table 1.

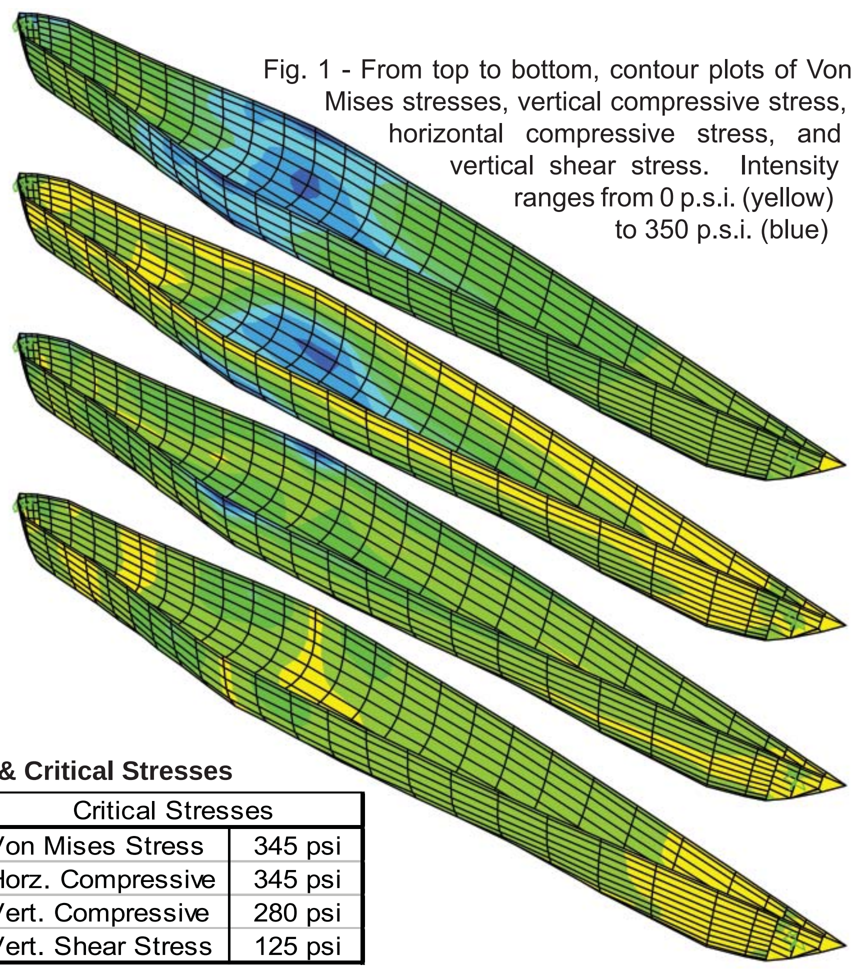


Fig. 1 - From top to bottom, contour plots of Von Mises stresses, vertical compressive stress, horizontal compressive stress, and vertical shear stress. Intensity ranges from 0 p.s.i. (yellow) to 350 p.s.i. (blue)

Table 1 - Material Properties & Critical Stresses

Material Properties		Critical Stresses	
Density	65 pcf	Von Mises Stress	345 psi
Elastic Modulus	450 ksi	Horz. Compressive	345 psi
Shear Modulus	188 ksi	Vert. Compressive	280 psi
Poisson's Ratio	0.2	Vert. Shear Stress	125 psi

MIX DEVELOPMENT

This year's mix was developed to improve the compressive and flexural strengths of last year's mix while maintaining its residual strength. Additionally, construction of the canoe would require a stiff mix that could be placed up the sides of the formwork. Improved finish quality was a tertiary goal. We began with the 2006 U-M mix:

Cementations Materials (CM) – Option 1

- Portland Cement, Type 1: no high-early strength or coloration desired.
- Fly Ash (FA), Class C: required by the rules; useful for filling voids, decreasing permeability and increasing long-term strength.
- Silica Fume (SF): stiffens mix for placement; similar to FA but less dense.

Aggregates

- 3M S-38 Glass Bubbles: high isostatic crush strength, low specific gravity.
- Haydite A Expanded Slate: similar strength to 2NS sand, 30% less dense.
- Expanded Polystyrene (EPS): miniscule density, zero crush strength.

Reinforcing Fibers

- PVA 3/8": used to control damage and provide residual strength.

Admixtures

- Superplasticizer: reduced water and helped disperse fibers.
- Latex Modifier: reduced water; increased fibers-mesh-matrix bond.
- Air Entrainer: regulated void size in very stiff mix.

The baseline compressive strength of this mix was a mere 600 p.s.i. An improvement in strength required a thorough reevaluation of our aggregate selections. Once selected, samples of promising aggregates were ordered and their effect on our baseline mix's behavior parametrically studied. Below is a summary of our studies.

Our first step was the volumetric reduction of Expanded Polystyrene. A replacement was found in the form of slightly denser, slightly stronger 1-2 mm Poraver Spheres (crush strength approx. 300 p.s.i.). Mixes were conducted and tested to determine the appropriate Poraver-EPS ratio and to limit the overall volume of large, weak particles. The resulting ratio was about 10:1 by mass (4:3 by volume) of Poraver to EPS.

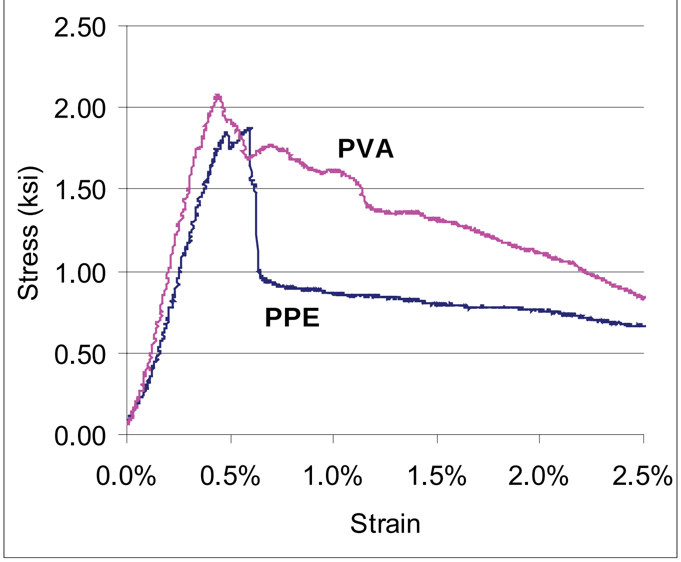
We continued to use 3M S38 Glass Spheres because of their low density and relatively high crush strength (approx. 2000 p.s.i.). We replaced Haydite fines with 3M G-3500 sand because of its lower density and comparible crush strength (approx. 2000 p.s.i.). To smooth the composite gradation curve, Haydite A was selectively sieved to remove those particles coarser than sieve No. 30 and those finer than sieve No. 50.

Tecfil 300 spheres were originally used as a higher-strength replacement for portions of our S38. However, they were later discovered to be a lightweight Class F fly ash and thereby ineligible as an aggregate. Because of its low density, Tecfil 300 was ultimately used as a partial replacement for Class C FA. Though we were unable to extensively test the effects of this replacement, we felt our project schedule allowed enough time for all pozzolans to react beneficially with cement hydration products.

Reinforcing

Experience has shown that the required flexural strength of the hull composite could be achieved using one layer of 4.3 oz. fiberglass mesh (with P.O.A. of ~75%) between two 3/8 inch layers of concrete. This choice was based as much on composite strength as on constructability – our mix is hard to place consistently in layers thinner than 3/8 inch.

Fig 2: PVA & PPE Stress-Strain Curves



Fibers were required to maintain the residual strength enjoyed with the 2006 mix. A canoe-to-canoe collision last year demonstrated that a few fibers can go a long way in controlling crack size and propagation. Both polyvinyl alcohol (PVA) and polypropylene (PPE) fibers were evaluated. PVA fibers were chosen over PPE fibers because of their even dispersion throughout the mix. Further, the chemical bond between PVA fibers and concrete is more effective than the PPE physical bond at achieving large residual strengths and multiple- or micro-cracking. Figure 2 compares compressive stress-strain results of the same mix, one containing PPE fibers and the other PVA.

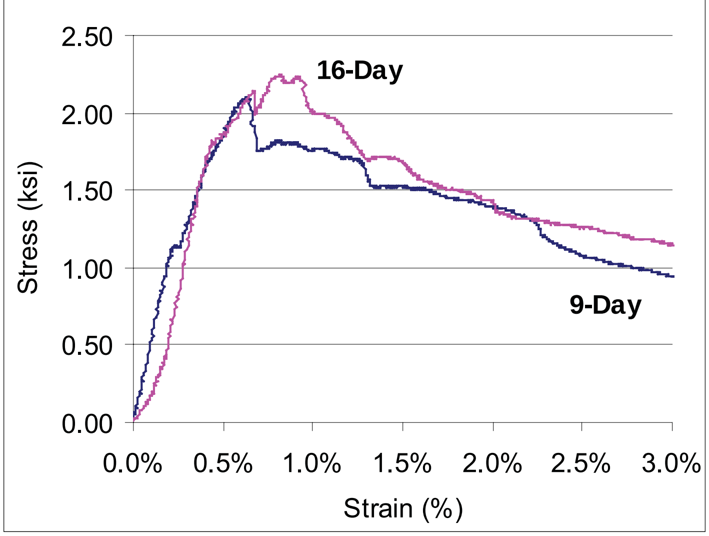
Admixtures

Our final admixture selection changed very little from the baseline mix. However, there were slight increases in the admixture volumes as the overall cementitious material density decreased. Less dense CM implies a greater number of cementitious particles per pound, requiring a more admixture to produce the desired results. Exact amounts of admixture can be found in Appendix B; the reasoning behind admixture selection is covered above.

Final Results

Figure 3 shows the compressive response (including residual strength) of our final mix. Once again, the composite compression, flexure, and shear properties exceeded the demands predicted by analysis.

Fig 3: Final Mix Comp. Stress vs. Strain



PROJECT MANAGEMENT & CONSTRUCTION

The approach to designing and constructing this year's canoe focused on A) building on the successes of the 2006 season and passing them on to a new set of leadership; and B) selecting specific aspects of last year's project for research and improvement. This method allowed our team to easily define the major project phases early in the season. These phases are as follows:

- Phase 1 (Sept. & Oct.) – Fundraising, Hull Design, Aggregate Research
- Phase 2 (Nov. & Dec.) – Formwork Design, Analysis, Aggregate Evaluation
- Phase 3 (Jan.) – Formwork Construction, Mix Refinement
- Phase 4 (Feb.) – Canoe Pouring & Curing
- Phase 5 (Feb. & Mar.) – Finishing, Report & Display Creation, Paddling Practice

With a horizontally-integrated 7-person core, coordination and the division of responsibilities were relatively straightforward tasks. Please reference the organizational chart and project schedule for definitions of groups and associated tasks. There was no significant deviation from the outlined assignments and their respective time frames.

The funds allocated for each group's operation was determined in a large part from money spent last year. Additions and subtractions were made based on altered construction practices and aggregate procurement. For example, we determined that the MDF spacers between formwork sections were unnecessary this year so the cost of materials and router time required to produce them was eliminated. Similarly, we included several hundred additional dollars into the mix design budget to allow for purchase and shipping of new aggregate. Our major funding sources included the University of Michigan College of Engineering, the U-M Department of Civil and Environmental Engineering, and corporate sponsors. Funding requests and letters were submitted in the beginning of October 2007.

The independent nature of our project teams limited the number of zero-float tasks in our schedule to two: formwork routing and canoe pouring. The CNC router we used is managed by the U-M College of Architecture. Because architecture students frequenting the router mid-semester received priority, we needed to cut within the first weeks of January. Also, the canoe needed to be poured the first weekend in February to allow sufficient time to cure. Both of these critical tasks were completed on time: the formwork was cut on January 13th and the canoe was poured on February 3rd.

The estimated time committed by each project team throughout the 5 phases were approximately as follows: 80 man-hours for mix design & development, 40 hours for hull design, 30 hours for formwork design, 30 hours for formwork construction, 60 man hours for canoe pouring and 50 hours for finishing.

Deciding to build on last year's successes, we again chose a routed-foam female mold for the 2007 canoe formwork. This system was well-suited for the placement of our stiff fiber reinforced mix. What's more, we were very familiar with the costs and construction time associated with construction of foam formwork.

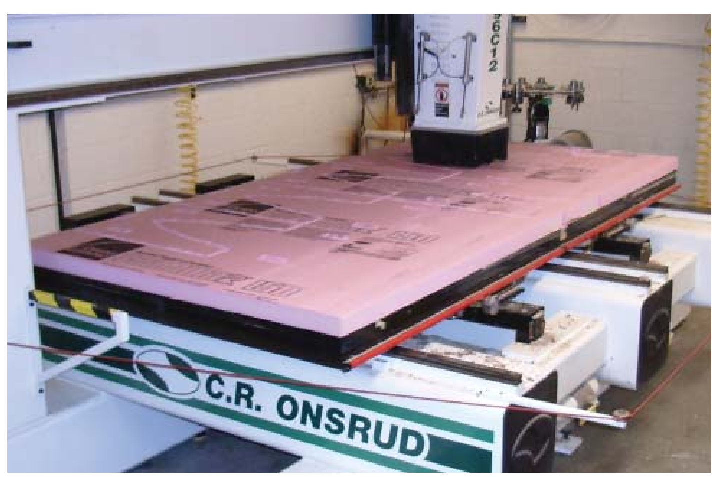
After designing the canoe, the 3D model was converted in Rhinoceros into two dimensional contours. We decided to use 2 inch foam, so contours were taken at 2 inches on center. It was determined that the first 18 inches and last 16 inches of the canoe would be best routed as 3D surfaces to properly capture their complex geometry.

To ensure efficient use of the costly foam insulation, the width of the formwork varied along the length of the canoe (see Formwork Design Drawing). Sections of equal width and approximately 4 foot in length were glued and lined-up by placing structural grade 2x4's through pre-cut keys. Three keys were also cut along the bottom of the formwork to assist in placement of adjacent sections. Once all the sections were assembled, Bondo was used to seal the interior surface of the formwork and to fill any imperfections. The Bondo was sanded and oiled prior to the placement of concrete.

4 foot fiberglass sheets cut to fit the mold, with approximately 6 inches of overlap between sheets and approximately 1-1/2 inches below the rough gunwale height (see Canoe Design Drawing for finished gunwale diagram). During pouring, concrete was placed in a 3/8 inch layer and "finished from above" by working it hard into the formwork with trowels. Reinforcement was laid after a sufficient surface of form was covered, whereafter an additional crew followed behind and placed the final 3/8 inch layer of concrete. The interior of the canoe was smoothed with moistened trowels.

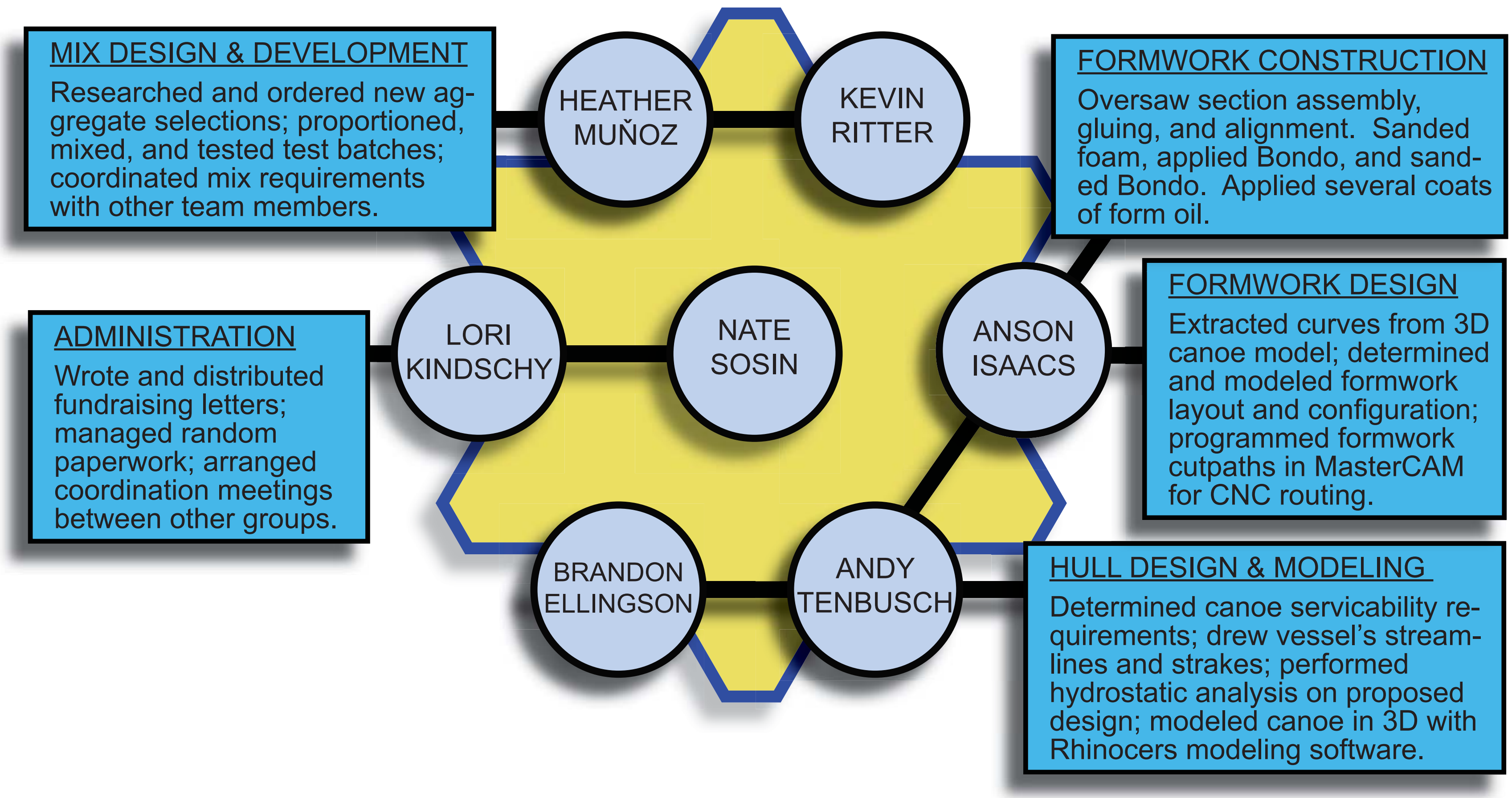
After pouring, cups full of water were placed inside the canoe and the entire formwork was covered in plastic. The canoe was then cured for 18 days and occasionally misted with water. After demolding, the interior and exterior surfaces were coated with a slurry mix and the entire hull thoroughly sanded.

Proper safety training was required before any work or research could be conducted in the U-M laboratory facilities. Each member of the team was responsible for attending safety training by the beginning of October, so that he/she could proceed with his individually assigned tasks and so that the team as a whole remained on schedule. Furthermore, face masks were worn during the application of Bondo and the sanding of the foam, Bondo, and concrete. Safety glasses were worn at all levels of construction.



Figures 4 and 5: Formwork sections on and just off the router. Notice the 2x4 keys in the cut pieces.

ORGANIZATIONAL CHART for ***The Rushin' Blue***



APPENDIX A - REFERENCES

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