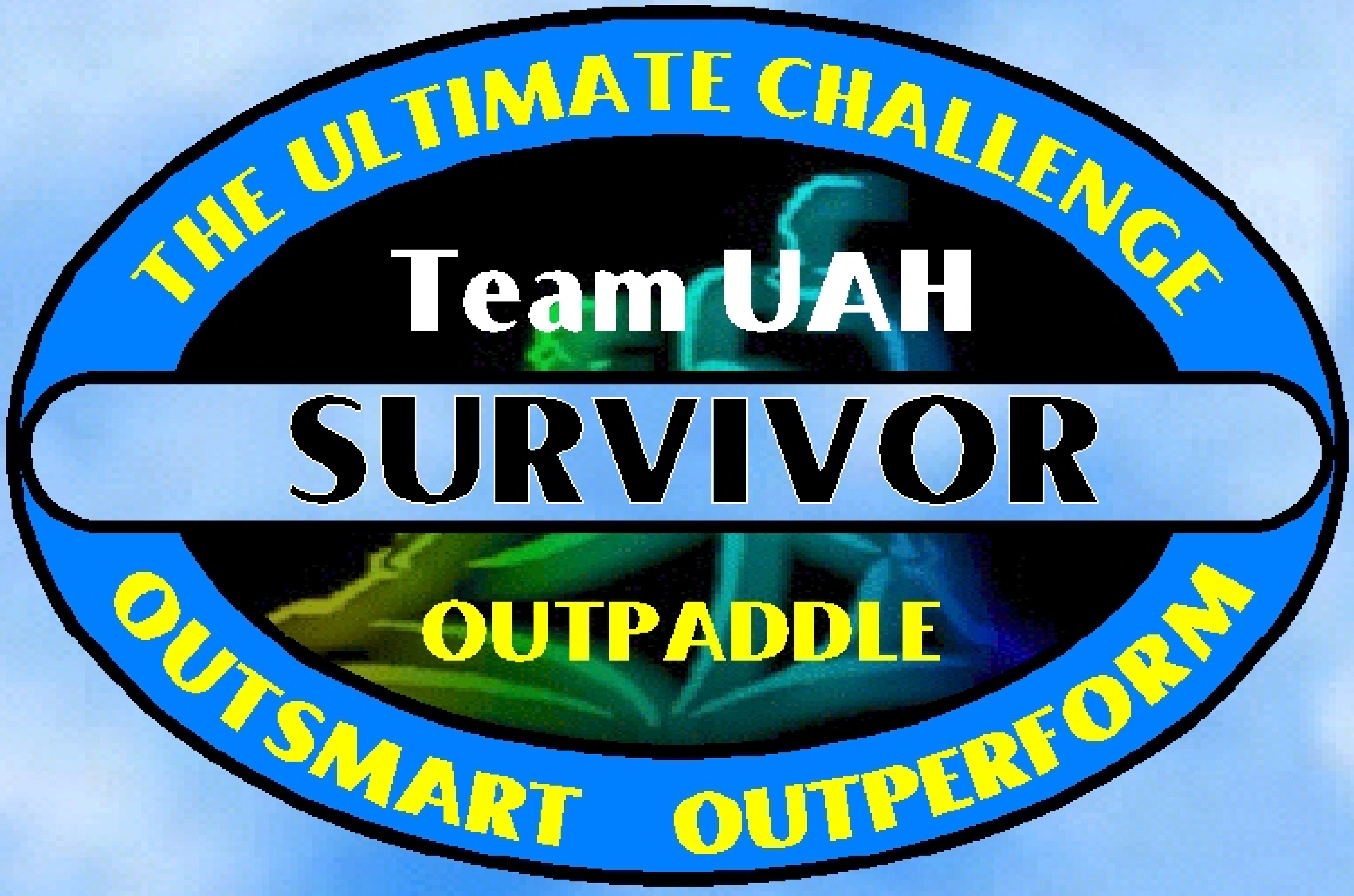
ASCE/MBT National Concrete Canoe Competition



http://www.uah.edu/student_life/organizations/ASCE/

Introduction and Executive Summary

Beginning June 14, 2001, the world will be watching as more than twenty student teams representing different regions throughout the United States and Canada face the ultimate survival challenge afforded by the ASCE/MBT National Concrete Canoe Competition. Many individuals will have already qualified as survivors after spending countless days and nights readying their entries. But the true test will come at the National Competition where they must work together with fellow team members while eliminating other teams one by one over a three-day period. The lone survivor will walk away with the first place trophy, a five thousand dollar scholarship, and the national title. Needless to say, we'll be rooting for the team from the University of Alabama in Huntsville (UAH).

UAH was founded in 1961 as a training facility for NASA's scientists and engineers. As one of three separate campuses of the Alabama System, UAH has an enrollment of 7000 with approximately 100 students enrolled in civil and environmental engineering.[1] This year marks the twelfth time that ***Team UAH*** has proudly represented the highly competitive Southeast Region at the national level. Our four national wins and three second place finishes give testament to our survival skills.

Our web site is located at http://www.uah.edu/student_life/organizations/ASCE/ . It includes tips on how to compete in the National Competition and provides links to many of the schools involved. This year, we plan to outsmart, outperform, and outpaddle our competitors with "***SURVIVOR***." Our boat is 6.8 m (22.3 ft) long and has a mass of 34 kg (equivalent to 76 lb), a maximum width of 81.3 cm (32 in.), and a maximum depth of 27.9 cm (11 in.). A 757 kg/m^3 (47.3 lb/ft^3) concrete mix, having an average 7-day *tensile* strength of 1.77 MPa (256 psi), was used to produce the hull. We placed this water-resistant concrete by hand over three layers of a graphite mesh and employed an ingenious construction scenario to eliminate permanent spacers. The nominal wall thickness is 0.74 cm (0.291 in.). Our canoe is inherently buoyant. It is blue and white with multicolored designs.

"***SURVIVOR*** " is a strategically tuned, absolutely resilient structure designed to withstand the rigors of the competition. It is arguably the best all-around human powered boat ever built and is radically different from all others because it is designed to surge forward between strokes and swim. This unique survival skill is achieved by lowering the natural frequency of the hull so that the paddlers drive it toward resonance. Adaptive reinforcement is used to resist the high strains and dangerous stress reversals that occur as strain energy is transformed into a forward propulsive component.

We developed a new method to characterize highly compliant cementitious composites and verified critical parameters as part of a very rigorous test program. Study of the microscopic and macroscopic properties of individual materials and combinations of different materials allowed us to better understand the strength, failure, and bonding characteristics of our composite section. We confirmed that concrete compressive strength is *not* a critical design parameter and combined web-based communications with a proven management scenario to produce a superior product.

Hull Design

Last year, we envisioned building a boat that would allow us to do well in the competition, not by making it travel faster, but by making it travel less slowly.[2] We began by studying the dynamic performance of a canoe. Then, we took steps to decrease the deceleration during recovery, thereby increasing the boat's average velocity. We modified the canoe's shape to reduce drag, improve tracking, and enhance stability and developed a very rigorous training program that included exercises and drills aimed at linking strength and endurance with speed of movement to produce more power. Although it was a good plan, we underestimated Clemson, who won the races and the competition with a faster boat.

This year, our canoe is a strategically tuned, absolutely resilient structure designed to withstand the rigors of the competition. We lowered the natural frequency so that the forcing function created by paddling drives the boat toward resonance. When the flexible hull deforms in response to the torsional and bending moments applied, very large stresses and strains develop. But since the materials remain elastic, strain energy is completely recovered. We envisioned converting this energy into forward momentum, thereby forcing our boat to surge forward between strokes and swim.

We began by mounting strain gages on our paddles to measure our stroke rate and the forces generated. The comprehensive research effort that followed allowed us to produce a boat that is radically different from its predecessors and from all other commercially available canoes.

Designed to satisfy conflicting objectives, “***SURVIVOR*** ” has the correct balance of speed, tracking, and maneuverability to achieve maximum performance in two- and four-person races. Parametric analysis techniques were used to establish the required attributes of the hull with the aid of commercially available software.[3]

We found it necessary to sacrifice stability to gain speed and maneuverability. We decreased the length of last year’s boat by 12.7 cm (5 in.) to improve maneuverability. The resulting reduction in hull speed was favorably offset by reducing the width by 5.1 cm (2 in.). The increased draft made the hull track better but created too much drag.[4] So we rounded the hull to decrease skin drag and modified the degree of longitudinal asymmetry to decrease wave drag. We also reduced the depth by 5.7 cm (2.25 in.) to improve ergonomics and reduce weight.

Figure 1 shows drag versus velocity plots for the canoe. Each plot represents a different combined paddler/boat weight. The horizontal lines reflect the output of our paddlers. The yellow ellipses correspond to the regimes in which we expect teams to perform. **Figure 2** shows the streamlined shape of “***SURVIVOR*** ” along with some of its attributes.

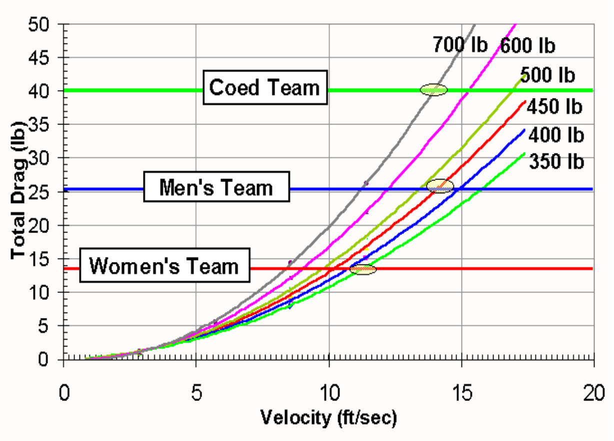
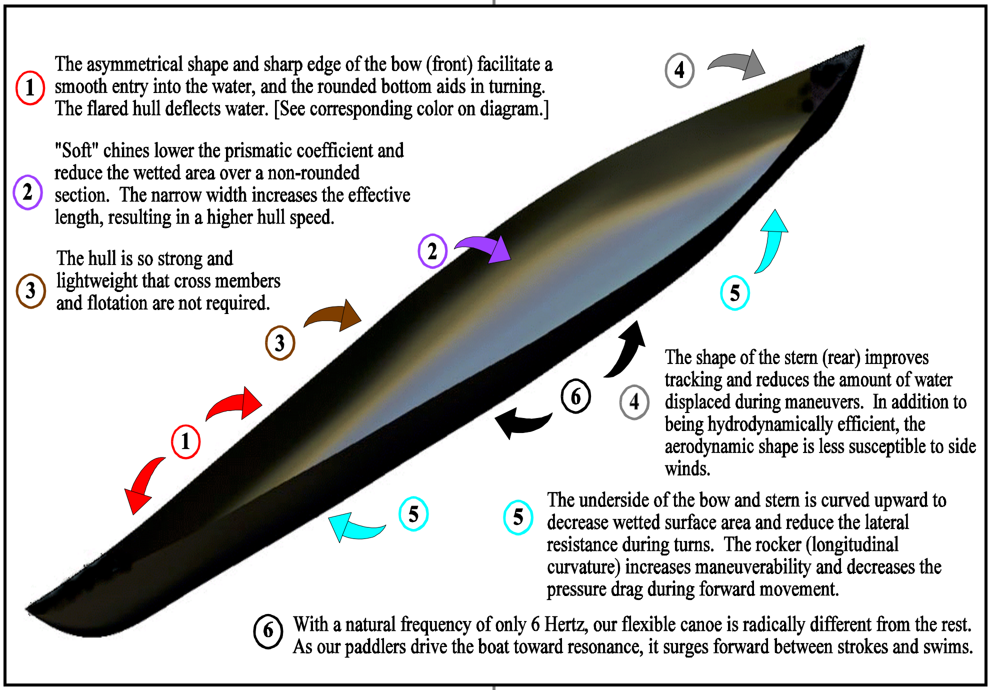


Figure 1. Performance predictions.



① The asymmetrical shape and sharp edge of the bow (front) facilitate a smooth entry into the water, and the rounded bottom aids in turning. The flared hull deflects water. [See corresponding color on diagram.]

② "Soft" chines lower the prismatic coefficient and reduce the wetted area over a non-rounded section. The narrow width increases the effective length, resulting in a higher hull speed.

③ The hull is so strong and lightweight that cross members and flotation are not required.

④ The shape of the stern (rear) improves tracking and reduces the amount of water displaced during maneuvers. In addition to being hydrodynamically efficient, the aerodynamic shape is less susceptible to side winds.

⑤ The underside of the bow and stern is curved upward to decrease wetted surface area and reduce the lateral resistance during turns. The rocker (longitudinal curvature) increases maneuverability and decreases the pressure drag during forward movement.

⑥ With a natural frequency of only 6 Hertz, our flexible canoe is radically different from the rest. As our paddlers drive the boat toward resonance, it surges forward between strokes and swims.

Figure 2. “ ***SURVIVOR***.”

Structural Design

Concrete Mixture Design - Target Properties

The production of a strategically tuned, absolutely resilient structure optimized to resist stress reversals requires an "adaptive section" where materials are placed symmetrically in the composite section. The most critical design parameters for the concrete are its elastic modulus and tensile strength. The concrete must be flexible enough to enable stresses to be transferred from it to the reinforcement so that the composite can store a large amount of strain energy. The flexibility also helps to lower the natural frequency of the hull. The concrete needs to be strong enough so that it performs as an integral structural component in tension. Since the tensile strength is less than the compressive strength, **concrete compressive strength is not a critical design parameter**.

The composition and crush strength of the aggregates must be carefully selected to control the failure mode and prevent local buckling of the reinforcement on the compressive side of the composite section.[2] Bond strength is also very important, and since the rules call for an exposed concrete surface, the mix must be durable and water resistant. To increase design flexibility, it should be as lightweight as possible.

Testing Methods and Final Mix Selection

While reviewing prior research on polymer-enhanced concretes, we discovered that our predecessors had introduced these concoctions in conjunction with a multilayered reinforcement scheme in 1996.[5] They secured their national title by being the first to report that a concrete's compliance was as important as its strength.[6] Since then, our teams have studied 206 low modulus concrete mixes, making ours one of the most comprehensive data bases on this topic in the world.

We found that last year's team did such a good job designing their concrete mix that it was perfect for our needs. Therefore, since the mix allowed us to meet all of the requirements outlined above, no other trial mixes were developed.

The only exception was a topping mix used to reduce the risk of our sanding through the reinforcement while finishing the canoe. We used as little cement as possible in this mix and added as many micro-balloons as we could to decrease weight.

As opposed to investigating different mixes, we verified the mix proportions, performance characteristics, and material properties of the primary mix described in **Table 1**.

By concentrating our efforts on a single mix design and testing multiple samples, we were able to obtain more statistically significant values for the critical parameters needed to quantify our advanced composite design. As a result, we developed a brand new method to characterize the structural behavior of the highly compliant cementitious composite section used to build our boat.

We began by testing 7.62 cm (3 in.) diameter by 15.24 cm (6 in.) long cylinders fabricated from the primary mix but only to complete the mix table and the data sheet required for the competition.

The elastic modulus [0.8 GPa (115 ksi)], Poisson's ratio (0.28), and 7-day strength [1.77 MPa (256 psi)] of this mix were measured in tension.

Composite samples [2.54 cm (1 in.) wide by 15.2 cm (6 in.) long] were tested in a cantilever mode. We conducted third-point bending tests on wider and longer composite plates, and we dropped weights onto the plates from an average height of 1.5 m (5 ft) to study denting and shattering due to impact.

Table 1. Mix Proportions
[in kg/m^3 (lb/ft^3) of concrete].

Primary Mix (No further trials were required.)	
kg/m^3 (lb/ft^3) [%]	**Binding Materials**
Portland Cement	266.2 (16.6) [80%]
Latex	51.7 (3.2) [15%]
Acrylic Fortifier	16.4 (1.0) [5%]
kg/m^3 (lb/ft^3)	**Aggregates**
K25 Spheres	104.3 (6.5)
Water	318.4 (19.9)
Water / Cement	1.20
28 Day Strength [MPa (psi)]	4.8 (696)
Unit Weight [kg/m^3 (lb/ft^3)]	757 (47.3)
Concrete Strength to Weight	14.7
Elastic Modulus [GPa (Msi)]	0.793 (0.115)
Water Resistance	Good
Workability	Good
Dry Plate Strength / Weight	39.2
Wet Plate Strength / Weight	34.4
Percent Difference	**-12.2%**

The cantilever test was used to evaluate the bond strength between the concrete and the reinforcement, and we studied the failure of dry and wet composite sections.

As illustrated in **Figure 3**, many of the composite test samples were studied under a microscope, before and after failure, to evaluate the microscopic behavior of the materials.

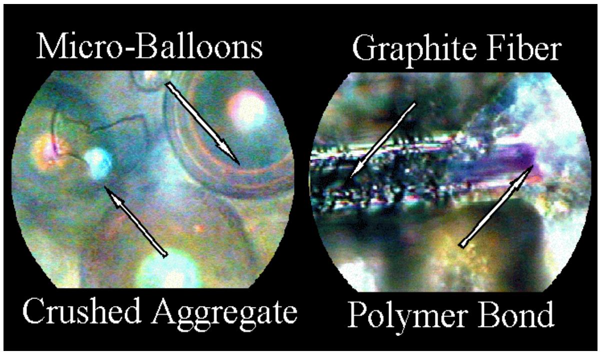


Figure 3. Microscopic examinations were performed before and after failure.

Reinforcement

The stress distribution in the hull of a concrete canoe continuously changes when the canoe is paddled. The critical sections, located directly beneath the paddlers, experience reverse bending when the canoe is transported and raced. Past research has shown that the best way to resist reverse bending is to design an "adaptive" section by placing layers of reinforcement symmetrically in the composite section.[7]

The design for our strategically tuned, absolutely resilient structure called for layers of strong, stiff, and lightweight reinforcement to be positioned accurately in the composite section. Since the boat needed to be flexible and would be driven toward resonance, we had to produce a canoe that was so strong that thwarts, bulkheads, and ribs could be eliminated. These members stiffen the structure and are extremely difficult to finish. They also create very high stress concentrations at points where they are attached to the hull.

As illustrated in **Figure 4**, we elected to reinforce the section with three layers of graphite mesh. Two of the layers are positioned as close as possible to the upper and lower surfaces of the section with the third layer placed between.

Under ordinary circumstances, the two outer layers absorb most of the stress. However, as the section is bent or weakened by moisture absorption to the point where the stiffness of the outermost compressive layer begins to decrease, the movement of the centroid forces the middle layer into compression. Assuming that the fibers in this layer are completely constrained, the embedded mesh is as stiff as it is in tension. In this case, the centroid remains close to the middle of the plate, keeping the moment of inertia high and the stresses low.

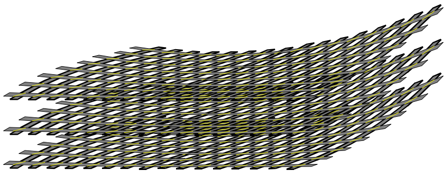


Figure 4. A strong and lightweight section.

We studied composite sections of different thickness and selected a plate that would fail in compression if the service loads were exceeded. This failure mode was predictable and resulted in localized damage that could be easily repaired. All factors considered, we chose to use a 7.6 mm (0.30 in.) thick section. Each layer of reinforcement consists of a non-impregnated graphite mesh with 3,000 fibers per tow, spaced at 3.18 mm (0.125 in.) intervals. Each tow is 0.19 mm (0.0075 in.) thick by 1.07 mm (0.042 in.) wide.

The elastic modulus and tensile strength of the graphite are 231GPa (33.5 Msi) and 3.65 GPa (530 ksi), respectively. The only other constituent used to build the main structure (topping mix excluded) is the concrete mix described in **Table 1**.

Composite Action

Last year's team demonstrated that the standard transform section method could be used to study the stress distribution in cementitious composites.[2] But while validating their work, we found that this method fails to predict deflections accurately when the elastic moduli ratio exceeds 20. Since the ratio of the elastic moduli of our reinforcement and concrete is 291, we developed a new theory that relied on material properties extracted from composite tensile specimens.

We began by placing a 1.27 mm (0.05 in.) thick concrete plate having a single layer of graphite mesh positioned midway through the thickness. A number of 25.4 mm (1 in.) wide composite tensile specimens were cut from it. When we tested the specimens, we found that the composite modulus was 3.48 GPa (504 ksi).

We modeled the section shown in **Figure 4** by assuming that our primary mix was placed around three layers, each one equivalent to the composite samples tested. We treated the layers as if they were made from a homogeneous material with a modulus equal to that measured during the tension test. We studied the system using the standard transformed section theory as developed in mechanics of materials. Since the elastic moduli ratio for our modified section was now only 4.383, the method worked very well.

We found that our predictions agreed to within a few percent error of our test data, provided that the materials remained elastic. Subsequent research has shown that it is possible to characterize the non-linear behavior of the composite section in the post-elastic range[8] by applying an iterative method developed by Balaguru.[9] This extension of our method predicted the compressive failure that we observed and built into our design strategy. We also performed a stress analysis on the critical section of "***SURVIVOR***."

We computed maximum stresses based on service loads derived from dynamic strain gage measurements taken from an older concrete canoe and determined that the maximum tensile and compressive stresses in our concrete and reinforcement are 910 kPa (132 psi) and 237 MPa (34.4 ksi), respectively. The maximum stresses in the concrete occur at the free surfaces, and the maximum stresses in the mesh occur at the outermost surface of the fibers.

Since our concrete can tolerate 1.77 MPa (256 psi), we have a safety factor of 1.94 in tension. The graphite has a tensile strength of 3.65 GPa (530 ksi), leaving little chance that the fibers will break.

As mentioned above, the results of our analysis correlate well with our plate tests where the composite sections held maximum moments ranging from 3.96 Nm (35 in.-lb) to 4.63 Nm (41 in.-lb) per 2.54 cm (1 in.). No tensile cracks were observed during these tests. Failure occurred in compression when the aggregates crushed, allowing the graphite fibers to buckle and the composite section to delaminate.

Construction

After determining the final shape, we generated full-scale computer cross sections at 46.7 cm (18.4 in.) intervals along the length. Then we used the drawings to produce plywood templates and mounted and aligned the templates on a wooden strongback.

We constructed a male mold by hot gluing 5.1 cm (2 in.) wide trapezoidal foam strips to the cross sections. We refined the mold's shape by rough sanding and applied drywall compound to fill cracks and remove discontinuities. A final layer of fiberglass hardened the surface.

The team used established techniques to construct a composite prototype and used it to evaluate the design. When tested, the original shape proved satisfactory.

The concrete boat was constructed with several small batches of concrete mixed and placed by hand. We began by coating the mold with a sheet of plastic. The first layer of graphite mesh was draped over the mold, and 2.8 mm (0.11 in.) diameter wires were positioned transversely at 7.6 cm (3 in.) intervals down the length.

The team placed the concrete over this configuration and used drywall knives to level the concrete to the upper surface of the wires. After the concrete had dried for 12 hours, we removed the wires. We repeated this process for the second layer of mesh, making sure that new wires were not placed over the freshly filled grooves left by the first set of wires. After an additional 12 hours, we removed the second set of wires and applied the third layer of mesh before placing a final layer of concrete.

Since the water required for cement hydration was held in the latex-modified system by the sealing effects of the impermeable polymer film formed, the canoe was simply left to dry.[10]

After only three days, the outer layer of concrete was hand-sanded smooth. We did most of the sanding after dark in soft lighting so that the shadows cast from oblique illumination could help us identify high and low areas. We filled voids with the same mix used during the main construction and then removed the canoe from the mold and repeated the process on the inner surface.

Using temporary wooden forms located around the upper rim of the canoe, we placed a gunwale. Since no flotation was required, we carefully selected the location for the unpainted region. We masked a continuous band around the boat and encapsulated the remainder of the canoe using a thin layer of our topping mix. Then we primed and painted the exposed area.

The team removed the portion of the mask on the canoe's exterior before we coated all exposed surfaces with a non-epoxy based clear coat. After adding graphics to complement the band, we removed the mask on the interior of the canoe. To improve aesthetics, we pigmented our mix and cast raised letters in the unfinished region.

Project Management/ Cost Assessment

We formed a Coordinating Committee at the first chapter meeting of the fall semester and elected a chair. The Committee reviewed the time chart used by last year's team and decided to follow it. Members of this group assigned tasks, scheduled meetings, and kept lines of communication open.

Chapter members organized themselves into ten different teams to support the effort, and each team posted work schedules and meeting notices weekly. We relied on a controlled access web site and a management information system. The latter included an extensive telephone and email network to help the team leaders make complex business decisions, such as last minute changes in design and strategy, personnel problems, and unexpected schedule delays.

Our president met regularly with our faculty advisors to report overall progress and to discuss critical issues that had arisen during the design and work sessions. Weekly meetings were held to allow communication and updates among individuals and teams.

Although leadership during design and construction was turned over to the individuals with the most expertise and experience, a conscientious effort was made to transfer their knowledge to our new recruits. Attracting and retaining dedicated team members remained top priorities. We used our web site to feature our key players and highlight their contributions.

We computed the labor and cost breakdown associated with this year's project. In constructing the required tables, we used the methods and rates outlined in the rules and regulations for the National Competition.

Our total direct labor cost was $99,355. The materials used to build the mold, prototype, and concrete canoe cost $4,328. With a 10 percent markup, our total expenses amounted to $5,915. Although the grand total for producing our boat was a hefty $105,270, we think that the final product is priceless.

Summary

During the project, several key areas were addressed including hull design for speed and maneuverability; the synthesis of numerical analysis and experimental testing; the use of lightweight, polymer-enhanced concretes; and the development of innovative construction techniques, training methods, and racing strategies.

We measured the natural frequency of our canoe after paint and graphics were applied. The boat vibrated in its fundamental mode at 6 Hertz.

At the regional competition, the stroke rate of our teams was approximately sixty strokes per minute (one Hertz), and we saw some dynamic coupling occur during the races. Although "***SURVIVOR*** " was faster than the other boats there, it hung in the turn and was slow during the sprint races on the return leg. These problems were attributed to improper trim and have been corrected to make this year's concrete canoe faster and better than ever. We look forward to showcasing our entry at the National Competition where we will be more than pleased to entertain any questions that you may have.

Appendix - References

1. UAH Records Department, Fall 2000.

2. Coign, J., Danson, A., Johnson, S., Redic, M., Whitworth, B., Whitworth, J., "Ingenuity," ASCE/MBT National Concrete Canoe Competition Design Report (2000).

3. Vacanti "PROLINES '98" Hull Design Software (1998).

4. Fox, R.W., McDonald, A.T., *Introduction to Fluid Mechanics*, 4th Ed., John Wiley and Sons, Inc., New York (1992).

5. Lindner, J., Roberts, L., Roberson, C., Fenwick, J., Laue, G., Shepherd, R., Tracy, L, "The Spirit of America," ASCE/MBT National Concrete Canoe Competition Design Report (1996).

6. Gilbert, J.A., "A race to innovate," *Civil Engineering*, January, 1996, pp. 46-48.

7. Biszick, K.R., Gilbert, J.A., "Designing thin-walled, reinforced concrete panels for reverse bending," *Proceedings of the 1999 SEM Spring Conference on Theoretical, Experimental and Computational Mechanics*, Cincinnati, Ohio, June 7-9, 1999, pp. 431-434.

8. Vaughan, R.E., Gilbert, J.A., "Analysis of graphite reinforced cementitious composites," *Proceedings of the 2001 SEM Annual Conference and Exposition*, Portland, Oregon, June 4-6, 2001.

9. Balaguru, P.N., Shah, S.P., *Fiber-Reinforced Cement Composites*, McGraw-Hill, New York (1992).

10. Biszick, K.R., Gilbert, J.A., "Designing reinforced concrete composite sections based on stiffness and strength," *Proceedings of the 1999 ASCE Alabama Section Meeting and Conference*, Gulf Shores, Alabama, August 4-7, 1999, p. 7.