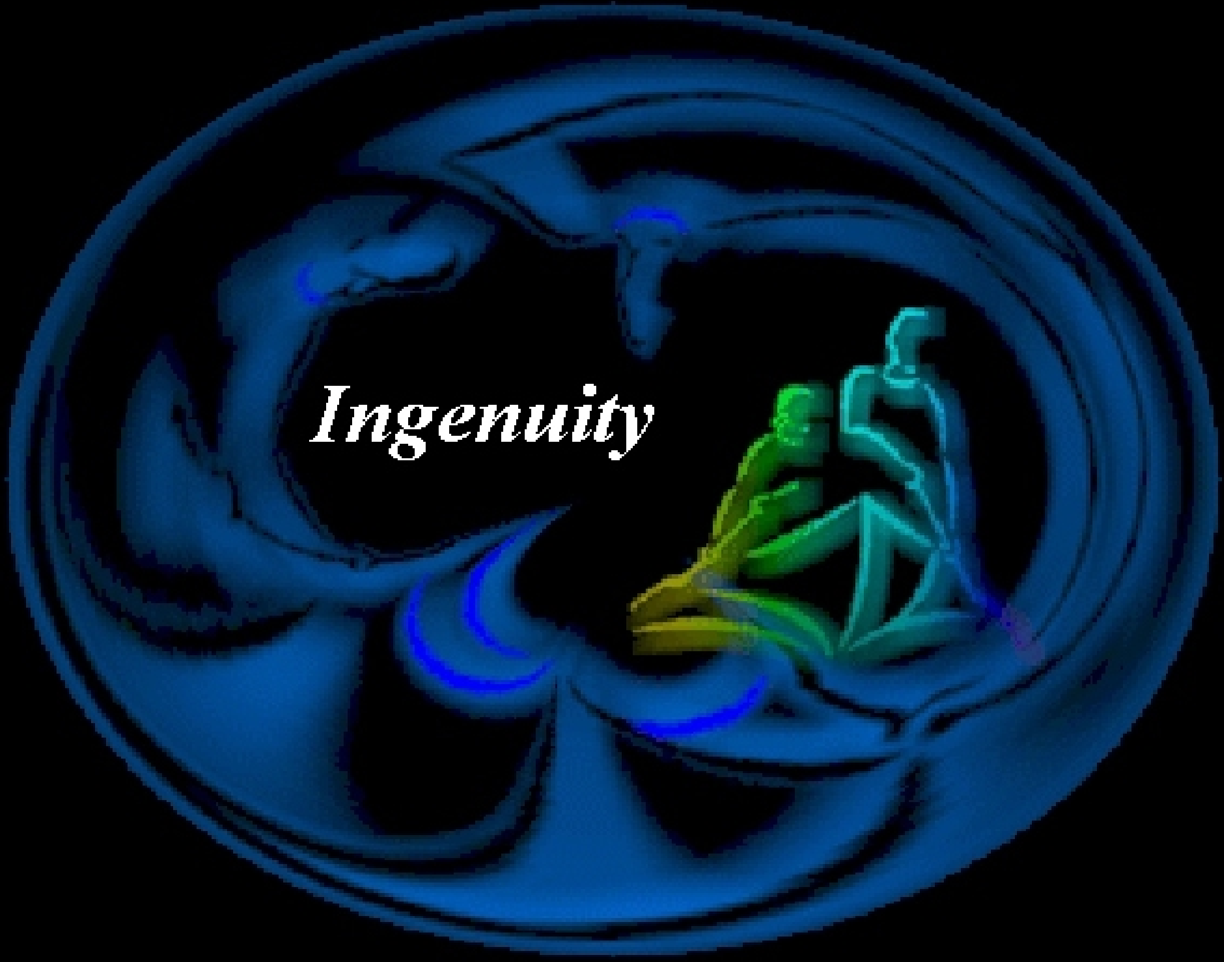
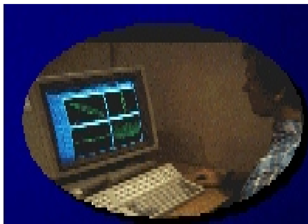
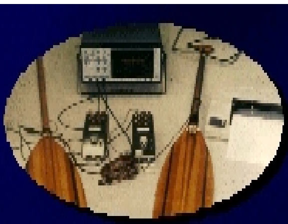
Team UAH

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



Designing reinforced concrete from a new perspective.







2000 CONCRETE CANOE DESIGN REPORT

"Ingenuity"

University of Alabama in Huntsville

Compliance Certification....................iii
1.0 Executive Summary....................1
2.0 Introduction....................1
3.0 Hull Design....................2
4.0 Concrete Mix Design....................5
5.0 Reinforcement....................7
6.0 Construction....................9
7.0 Project Management....................10
8.0 Cost Assessment....................11
9.0 Innovative Features....................11
10.0 Summary....................11
References....................12
Appendix 1: Calculations....................13
  A1.1 Mix Design Summary....................13
  A1.2 Concrete Tensile Test Calculations....................14
  A1.3 Water Resistance Measurements....................15
  A1.4 Reinforcement Thickness Measurements....................15
  A1.5 Finishing Thickness Measurements....................16
  A1.6 Flotation Measurements....................16
  A1.7 Seat Measurements....................16
  A1.8 Stress Analysis Calculations....................17
  A1.9 Reinforcement Compliance Measurements....................18
Appendix 2: Technical Data....................19
Appendix 3: Detailed Cost Assessment....................21

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Compliance Certification

On behalf of the ASCE Student Chapter at the University of Alabama in Huntsville, I hereby certify the following:

1. The construction of our 2000 concrete canoe was performed in complete compliance with the rules and regulations of the national concrete canoe competition.

2. The team members registered for the national competition are qualified student members as specified in the rules and regulations of the national competition.

3. The canoe was built within the current academic year of the competition.

4. "Team UAH" placed first in the concrete canoe competition at the regional level and proudly represents this year's Southeast Regional contingent consisting of the following schools:

University of Florida
Vanderbilt University
Univ. of Tennessee-Knoxville
Univ. of Alabama-Tuscaloosa
Univ. of Alabama in Huntsville
Southern Poly. State University
Florida International University
Christian Brothers University
University of South Florida
Tennessee Tech. University

Auburn University
University of Miami
University of Central Florida
Univ. of Puerto Rico-Mayaguez
Florida Institute of Technology
Georgia Southern University
Florida A&M/State University
University of South Alabama
Alabama A&M University
University of Memphis

Jon Coign

Jon Coign, Team Captain

1.0 Executive Summary

In the early autumn of 1999, a group of civil engineering students at the University of Alabama in Huntsville (UAH -) banded together to form yet another concrete canoe team. Our veterans felt that their hard work and technological delivery had been grossly underrated in the display category at last year's national competition, and it seemed that our chapter faced a year consumed by a lack of enthusiasm. However, as we pondered the materials sent to us by the Committee on National Concrete Canoe Competitions, we quickly realized that even the most highly competitive schools would have trouble producing a viable product. A unique opportunity had come to elevate the benchmark once again by challenging us to do something better, something revolutionary.

Beginning with this report, we invite you to scrutinize our technological and promotional deliveries, and ask you to carefully compare our efforts to those of other schools. We christened our boat "***Ingenuity***" because that's what it took to make the technological breakthroughs required to solve the exceedingly difficult engineering problems that faced us. By introducing new and better ideas, we hope to leave lasting marks on this competition and the Civil Engineering profession.

Our boat is 6.93 m (22.75 ft) long and has a mass of 35.8 kg (equivalent to 79 lb), a maximum width of 86.4 cm (34 in.), and a maximum depth of 33.7 cm (13.25 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 of the hull is 0.74 cm (0.291 in.), and the boat is painted black with multicolored designs.

This year, we expect our men's team to achieve a top speed of 4.3 m/s (14.2 ft/s). We considered momentum transfer while selecting the canoe's weight, and took several factors into account while choosing its length. We studied the kinematics to minimize deceleration and developed new design strategies and test methods to verify and tune computational engineering analyses.

Our structural design relies on adaptive reinforcement to resist the dangerous stresses produced by reverse bending. We developed an accelerated 7-day test program, and proved that concrete compressive strength is not a critical design parameter. 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 added an acrylic fortifier to the concrete mix to make it water resistant, employed a very creative management scenario, and adhered to the most rigorous physical training program in our chapter's history.

2.0 Introduction

The University of Alabama in Huntsville (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 slightly under 7000 with 104 students currently enrolled in civil and environmental engineering.[1]

Shortly after our ASCE Student Chapter was chartered in 1985, we participated in our first concrete canoe competition. We finished last in regional competition with a 3.66 m (12 ft) long boat that weighed 204 kg (450 lb)! Since then, we have improved each year's canoe, learning from past performances. As a result, we have proudly represented the highly competitive Southeast Region eleven times at the national level. In our seven most recent appearances, we have won the national competition four times and have placed second the other three. We remain the only school to have swept the competition by winning every event in 1994 and hold a majority of the national paddling records.

At the beginning of this year's concrete canoe effort, we outlined plans to develop an engineering environment that fostered innovation and creativity. Our idea was to have team leaders act as "visionaries," charged with developing seemingly unrealistic concepts without worrying about constraints such as feasibility, money, and manpower. The primary objective was to motivate our veterans. But we also wanted to break free of the design ruts imposed by a highly restrictive set of rules and the budgetary limitations imposed by being a small chapter void of significant institutionalized funding. Once the visions had been established, the rest of the team was entrusted with turning them into realities.

Our unorthodox strategy worked well. We found ways around obstacles that were initially thought to be insurmountable. While designing and building our boat, we addressed pertinent hydrodynamic and structural issues. Teams conducted extensive research and documented their findings in written and oral reports. Each of us took pride in making independent contributions while working toward a common goal. For the first time in a long time, we actually had fun. At the same time, the grueling experience made us experts in human dynamics.

3.0 Hull Design

3.1 Goal and Attributes

Our goal was to design a hull shape having the correct balance of speed, tracking, and maneuverability required to achieve maximum performance in two- and four-person races. We established and prioritized the desired attributes as (1) outstanding straight line speed, (2) good turning ability, (3) adequate freeboard, (4) ease of construction, (5) acceptable stability, (6) minimum wetted surface area, (7) advanced ergonomics, and (8) acceptable tracking.

The comprehensive research effort that followed allowed us to produce a boat that is different from its predecessors and all other commercially available canoes.

3.2 Preliminary Research and Visions

We began the hull design process by drawing from the vast knowledge base accumulated by our predecessors who compiled extensive literature surveys, experimental data, analytical results, race statistics, films, photographs, and personal recollections. After performing a preliminary investigation using commercially available software,[2] we determined that it would be difficult to produce a hull shape that could travel much faster than last year's.[3,4] Our "visionaries" suggested that we study the dynamic performance of a canoe in greater detail. **Figure 1** shows the forces generated by one of our men's teams, recorded by placing strain gages on their paddles.[5] During this run, the two men paddled one of our old practice boats in cadence on opposite sides of the boat. Similar results were obtained when the bow and stern paddlers switched places.

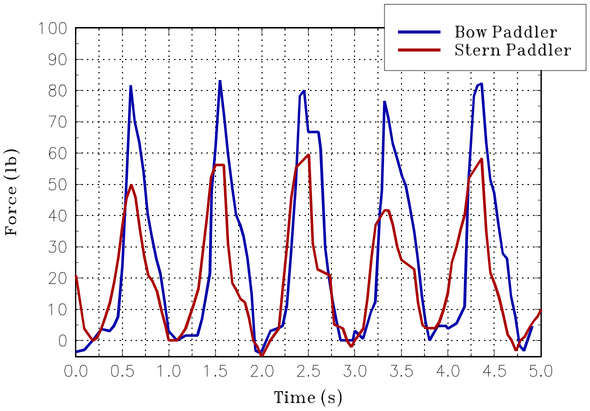


Figure 1. Performance of our paddlers.

The areas under the curves are measures of power. The plots reveal that the bow paddler is able to achieve a higher output than the stern paddler. The bow paddler uses a straight shaft paddle for power and, since the bow is narrow, can draw his paddle straight back during the stroke. The stern paddler relies on a bent shaft paddle for control. He must reach further to the side during his stroke and expends energy to steer the boat. This is evident in Figure 1 during the fourth stroke where a "J" is being executed.

The data recorded during one stroke was used as input to a customized software routine developed by our chapter to predict the velocity and acceleration of the hull. **Figure 2** shows the results obtained over a two-second interval computed by assuming that the team is traveling in rectilinear motion. The boat undulates profusely as the paddlers recover from their strokes, and therein lies our key to victory.

We envisioned building a boat that would allow us to dominate the competition, not by making the boat travel faster, but by making it travel less slowly. This would be accomplished by decreasing the deceleration during recovery, thereby increasing the boat's average velocity.

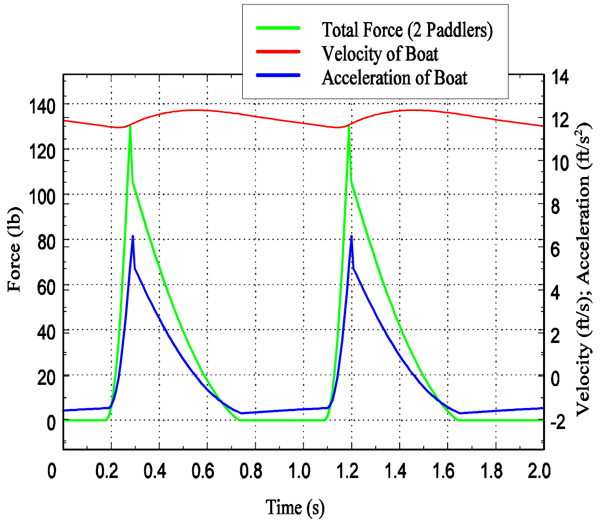


Figure 2. Kinematics of the hull.

Our “visionaries” suggested two different alternatives. The first idea came from one of our design team leaders, Brandon Whitworth, who suggested that we modify the boat’s shape to reduce drag, improve tracking, and enhance stability. The second idea came from our team captain and paddling coach, Jon Coign, who suggested that we develop a training program that included exercises and drills aimed at linking strength and endurance with speed of movement to produce more power. In some cases, we needed to reduce paddler weight to reduce drag.

3.3 Turning Visions Into Realities

The primary factors that limit the speed of a displacement hull are skin drag and wave drag. Skin drag, often referred to as frictional or shear drag, is a boundary layer effect that is linearly related to the wetted surface area. It increases roughly with the velocity squared, and was calculated for our designs using a straight-forward Reynolds number approach.[6]

Commercially available software[2] was used to predict the wave drag that results from the energy lost when the bow pushes water away from the canoe. First described by William Froude about 100 years ago, wave drag is characterized by a highly nonlinear function that is proportional to the speed, length, width, and displacement of the hull.[6]

To pursue Brandon’s idea, we computed the total drag for different velocities by simply adding the skin and wave drag components. Prior to these studies, we chose a target mass for the boat of 36.3 kg (80 lb). The mass was sufficiently large to make the canoe less susceptible to side winds and strong currents, and to avoid problems in performance and stability that occurred when the boat’s momentum was overpowered by that associated with the paddlers’ motion. Yet, it was small enough to assure that the canoe would be one of the lightest in the competition.

We took other factors, such as wind resistance, flow separation (pressure drag), water temperature, and water depth, into account by tuning our analytical models with results obtained from full scale drag tests conducted on older concrete canoes. During the tests, a 1.86 kW (2.5 hp) outboard motor was mounted at a distance of 45.7 cm (1.5 ft) behind the stern of each boat on a linear rail system equipped with a vibration isolated transducer. The transducer was used to measure the propulsive force of the motor during timed runs through a 100 m (328 ft) course. A velocity meter was used to probe the flow field.

Parametric analysis techniques were used to establish the required attributes of the hull. The first study determined the optimum hull length. We analytically studied the proposed hull shape and incrementally increased its length while maintaining a constant combined paddler/boat weight of 204 kg (450 lb) for our men’s team and 168 kg (370 lb) for our women's team. After taking into account that four paddlers had to be accommodated, we decided to lengthen our boat by 22.9 cm (9 in.) over last year’s to 6.93 m (22.75 ft).

Our second parametric study showed that subtle changes in the width and cross section of the hull drastically changed speed and stability. We decided to narrow the entry and exit lines of this year’s hull to reduce drag. To improve stability and reduce draft during the four-person race, we widened the boat by 7.6 cm (3 in.) to 86.4 cm (34 in.).

Last year’s team attributed their third place finish in the four-person co-ed sprint to a lack of freeboard coupled with low stability in wind and rough water. Our calculations showed that these factors were important but they also revealed that drag increased too quickly with draft. We corrected these problems by reducing the rocker to 7.6 cm (3 in.), increasing depth to 33.6 cm (13.25 in.), and adjusting the flare in the walls.

Figure 3 shows drag versus velocity plots for our 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. Our men's team, for example, should be able to achieve speeds ranging from 4.1 m/sec (13.4 ft/sec) to 4.3 m/sec (14.2 ft/sec). In an effort to achieve top speed, we developed the most rigorous training program in our chapter's history.

3.4 Crew Training

We pursued Jon's idea through a training program that began with six days per week in the gym. The time was split equally between weight and cardiovascular training. Team members ate six meals per day and took vitamin and nutritional supplements to increase energy levels. Whenever possible, they ate and trained together.

Weather permitting, the team paddled on the campus pond two to three hours per day, seven days per week. Relatively long river trips, often in rough water, were scheduled once per week.

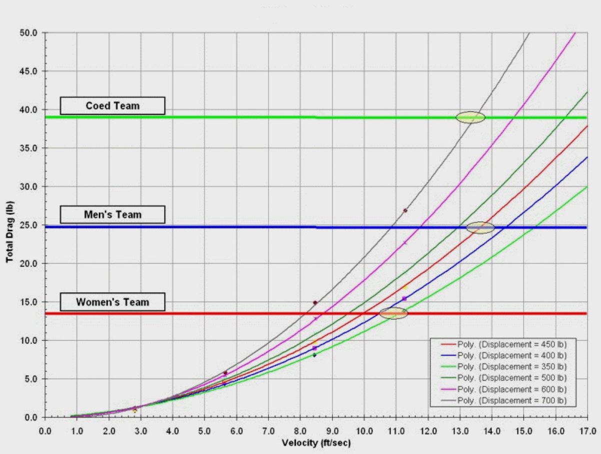
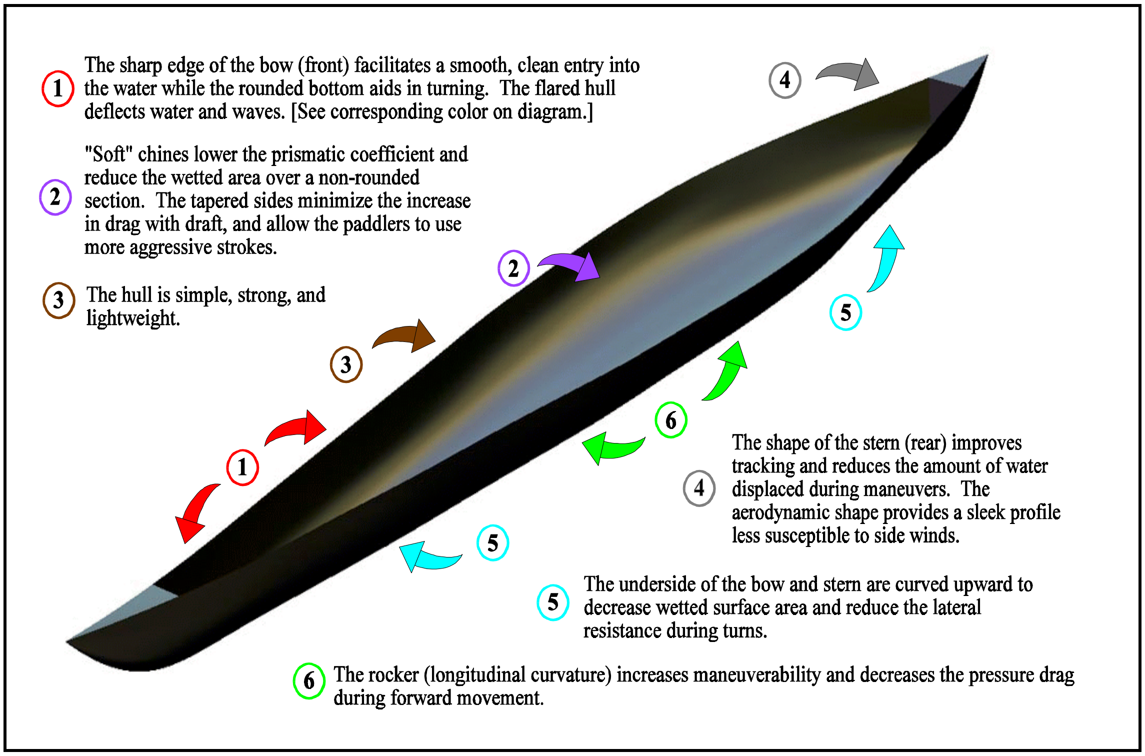


Figure 3. Performance predictions.

Our goals were to increase strength and endurance, and to minimize body fat.[7] We adjusted our strokes and body movement while paddling to transfer as much energy as possible from our paddles to the water. The performance curves in Figure 3 clearly show that reduced weight means less drag.

We conclude this section by presenting **Figure 4,** a schematic diagram that clearly shows our "***Ingenuity***."



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

② "Soft" chines lower the prismatic coefficient and reduce the wetted area over a non-rounded section. The tapered sides minimize the increase in drag with draft, and allow the paddlers to use more aggressive strokes.

③ The hull is simple, strong, and lightweight.

④ The shape of the stern (rear) improves tracking and reduces the amount of water displaced during maneuvers. The aerodynamic shape provides a sleek profile less susceptible to side winds.

⑤ The underside of the bow and stern are curved upward to decrease wetted surface area and reduce the lateral resistance during turns.

⑥ The rocker (longitudinal curvature) increases maneuverability and decreases the pressure drag during forward movement.

Figure 4. "***Ingenuity***."

4.0 Concrete Mix Design

4.1 Design Strategy and Target Properties

In past competitions, we demonstrated that a fairly low strength, polymer-enhanced concrete could be used to construct the critical sections located directly beneath the paddlers.[8] However, the concrete had to have an elastic modulus low enough to enable the reinforcement to absorb the dangerous stresses that resulted from the reverse bending that took place in these locations.[9]

Since this year's rules called for unprotected and exposed concrete surfaces, we had to make the mix durable and water resistant. To increase design flexibility, we needed to maximize tensile strength and minimize weight. As the project progressed, we found that the concrete had to have a very dense population of small and strong aggregates. Impact resistance and excellent bonding characteristics were also very important.

In short, we needed to develop a mix that exhibits all of the following properties: (1) low modulus of elasticity, (2) sufficient strength to survive the service loads, (3) water resistance, (4) light weight, (5) dense, small, and high strength aggregate composition, (6) impact resistance, (7) excellent bonding capability, and (8) good workability.

4.2 Testing Methods

After performing an analytical study on an "adaptive" section (see Section 5.0), we realized that our concrete had to be equally strong in tension and compression. Since all of the mixes tested by our chapter in the past were weaker in tension than compression, we reached the startling conclusion that ***concrete compressive strength is not a critical design parameter***. As a result, only the first few trial mixes were tested in compression. We tested 7.62 cm (3 in.) diameter by 15.24 cm (6 in.) long cylinders fabricated from the final mix but only to complete the mix table and data sheets required for the competition. We already knew, from a 7-day test program, that our mix was superb.

We determined that the critical design parameters for an "adaptive" section are the elastic modulus and the tensile strength of the concrete mix, as well as the composition and crush strength of its aggregates. The concrete must be flexible enough to enable stresses to be transferred from it to the reinforcement, and strong enough so that the concrete performs as an integral structural component in tension. The aggregates must be carefully selected to prevent local buckling of the reinforcement on the compressive side of the composite section.

We tested 77 different concrete mixes. The most promising mixes were placed over identical reinforcement configurations, and 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. A non-standard impact test was used to study denting and shattering where weights were dropped onto composite plates from an average height of 1.5 m (5 ft). Since the concrete was the only parameter varied, the plate tests provided a direct and accurate method for comparing the efficiencies of different mixes.

We used the cantilever test to evaluate the bond strength between the concrete and the reinforcement, and studied the failure of dry and wet composite sections. Wet samples were carefully dismantled so that we could study water absorption.

Many of the composite test samples were studied under a microscope, before and after failure, to evaluate the microscopic behavior of the materials. This was very helpful during a parametric study of plates constructed with mixes that contained aggregates having different crush strengths. Microscopic examinations were also performed during some of the absorption studies. **Figure 5** shows some photographs taken during the test program.

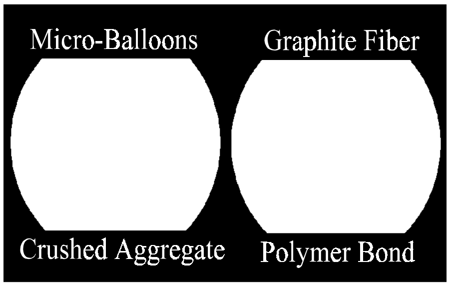


Figure 5. Microscopic examinations.

4.3. Final Mix Selection

As explained in Section 5.0, we placed our concrete over three layers of a graphite mesh. The analysis of this composite section allowed us to target the elastic modulus and the tensile strength required for our concrete.

The mix, labeled as No. 1 in **Table 1**, served as a control mix. It was selected primarily because the small and uniformly sized micro-balloons created a dense grain structure that prevented the graphite fibers from buckling on the compressive side of our composite section. The addition of latex helped keep the elastic modulus low. It also improved the bond between the concrete and the reinforcement, thereby improving the strength of cold joints. We might have used it, had it not been for the fact that unprotected composite plates, when exposed to water and tested immediately thereafter, failed miserably under the required service loads.

We tested eight different admixtures in an attempt to waterproof the concrete, and found a viable solution to this problem by combining latex with an acrylic fortifier. The acrylic fortifier stiffened the concrete but made it water resistant and increased the tensile strength.

We also tested five different kinds of micro-balloons having different crush strengths, and added three different types of free fibers to the mix (chopped carbon, chopped glass, and Kevlar pulp). The stronger micro-balloons increased the strength-to-weight ratio, improved durability, and added impact resistance. Since they held the reinforcement in place at higher loads, we had greater design flexibility. The free fibers increased the strength-to-weight ratio and improved durability but decreased workability to the point where we decided not to use them.

Table 1 includes samples of different mix designs. We selected Mix No. 4 for building and patching our canoe. Additional details for this mix are included in Appendix 1. The tests described there reveal that the final mix has an average 7-day tensile strength of 1.77 MPa (256 psi), a Poisson's ratio of 0.28, and an elastic modulus of 0.8 GPa (115 ksi). Moisture absorption studies were also performed on the concrete mixes, and the appendix includes a comparison between the control mix and the final mix. Since the central portions of our test cylinders had not fully cured, ***the results of 7-day compression tests were very misleading***. It took 21 days before a reasonable correlation was obtained between the plate and cylinder tests.

Table 1. Typical Trial Mixes [proportions in kg/m^3 (lb/ft^3) of concrete].

Mix Number	**1**	**2**	**3**	**4**
Mix Name	MB-100B	K-25K	GD-K25-2	**Super 7**
Comments	Control Mix	Highest Dry Strength/Weight	Inferior to Acrylics	Excellent Water Resistance
kg/m3 (lb/ft^3) [%]	**Binding Materials**			
Portland Cement	413 (25.8) [83.4%]	391 (24.4) [83.4%]	395 (24.7) [83.2%]	393 (24.5) [77.0%]
Latex	82.2 (5.1) [16.6%]	78 (4.9) [16.6%]	78.5 (4.9) [16.5%]	78.2 (4.9) [15.3%]
Acrylic Fortifier	-	-	-	39.4 (2.5) [7.7%]
Darapel	-	-	1.4 (0.1) [0.3%]	-
kg/m^3 (lb/ft3)	**Aggregates**			
K1 Spheres	89 (5.6)	-	-	-
K25 Spheres	-	153 (9.6)	154 (9.6)	154 (9.6)
Kevlar Pulp	-	3.5 (0.2)	-	-
Water	444 (27.7)	490 (30.6)	424 (26.5)	453 (28.3)
Water / Cement	1.08	1.25	1.07	1.15
28 Day Strength [MPa (psi)]	1.58 (229)	NA	NA	4.8 (696)
Unit Weight [kg/m^3 (lb/ft^3)]	663 (41.4)	712 (44.4)	717 (44.8)	757 (47.3)
Concrete Strength to Weight	5.5	NA	NA	14.7
Elastic Modulus [GPa (Msi)]	0.030 (0.0044)	NA	NA	0.793 (0.115)
Water Resistance	Poor	Poor	Average	Good
Workability	Good	Average	Good	Good
Dry Plate Strength / Weight	31.1	55.5	25.6	39.2
Wet Plate Strength / Weight	20.4	35.2	21.2	34.4
Percent Difference	**-34.4%**	**-36.6%**	**-17.2%**	**-12.2%**

5.0 Reinforcement

5.1 Research and Goal

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. [10,11]

We began this year's investigation by performing a parametric study on a modified version of the adaptive section employed by last year's team. They used a Mylar honeycomb to separate two layers of graphite mesh.[5,12] We decided not to include the honeycomb because of the dimensional restrictions imposed on spacers, reinforcement, and thickness in this year's rules.

Figures 6 and 7 show the maximum stresses in the concrete and graphite, respectively, as two layers of graphite mesh are progressively separated in a 7.62 mm (0.3") thick specimen. For comparison purposes, a moment of 31.2 Nm (23 in-lb) was applied to a plate of 2.54 cm (1 in.) width. The results were obtained by using the transformed section method; the "n" value is the ratio of the elastic modulus of the reinforcement divided by that of the concrete.

Our analysis showed us that we could transfer the stresses from the concrete to the graphite by increasing the elastic modula ratio. The farther apart that we spaced the layers in the section, the more efficient the transfer.

The mix developed by last year's team, for example, allegedly corresponded to an "n" value of approximately 7500.[5] Assuming that the applied moment was indicative of the maximum service load, the concrete had to withstand a stress of only 69 kPa (10 psi). The maximum stress in the graphite mesh was higher but manageable, on the order of 517 MPa (75 ksi).

Last year's team specified that their mix needed three times this strength because their plates were weaker than expected at higher loadings. To find out why, we prepared a number of composite samples using last year's mix design, and tested them in a cantilever mode. Microscopic examinations revealed that the graphite fibers in the mesh began to buckle on the compressive side of the composite section when the aggregates in the mix began to crush. Then, the compressive mesh became less stiff.

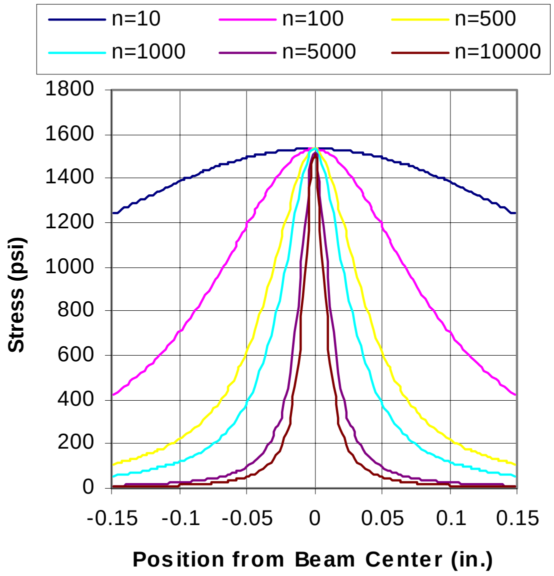


Figure 6. Stresses in concrete.

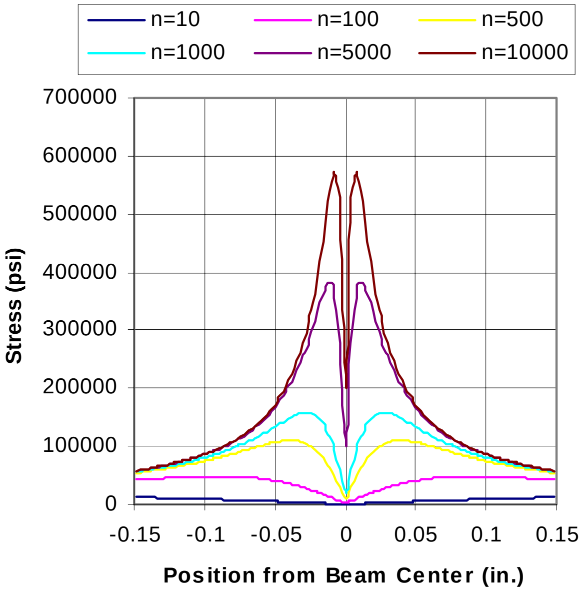


Figure 7. Stresses in reinforcement.

We quantified the reduction in stiffness by measuring the deflections during the test. They provide a measure of the flexural stiffness EI, where I is the moment of inertia of the transformed section and E is the elastic modulus of the base material (concrete). Since E is known, I can be computed. It is then a simple matter of using computer techniques to vary the unknown embedded elastic modulus of the compressed reinforcement until the moment of inertia of the transformed section agrees with the experimentally determined value.

We found the compressive layer to be as stiff as the tensile layer until the aggregates began to fail. When structural stability was compromised, the fibers began to buckle, eventually causing the section to delaminate.

Now that we understood last year's design, we set our goal to improve upon it. We needed to replace the honeycomb core and increase the structural performance.

5.2 Analysis and Testing

Before receiving a copy of this year's rules, we began testing composite plates containing as many as ten graphite layers. We found that these plates were strong but, as a result of studying the adaptive section, we realized that they were structurally inefficient. The plates were also relatively heavy and did not meet the thickness requirements established in the rules.

We tried to use fewer layers and separated them by using pegs and fishing line but these plates suffered from poor quality control and were riddled with stress concentrations. In some cases, the inclusions created tensile cracking at only twenty percent of the failure load. To make matters worse, we had not yet developed a water resistant concrete, and our plates were failing miserably after being soaked in water.

For the moment, our efforts seemed to be destined to failure and, in desperation, we turned to our "visionaries" for help. We were advised to design and build an adaptive section reinforced, as depicted in **Figure 8**, with three layers of graphite mesh. Two of the layers were to be positioned as close as possible to the upper and lower surfaces of the section with the third layer placed between.

Our predecessors had introduced this design concept in 1997 but it was not well understood and appreciated then.[13] We now know that as the section is bent 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 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. The symmetry makes the section adaptive.

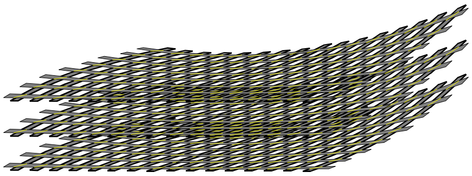


Figure 8. This year's adaptive reinforcement is simple, strong, and lightweight.

We rationalized that if a water resistant concrete could be developed to limit absorption to one side of the plate, we could make a conservative estimate of the structural performance by neglecting one layer of mesh and using the analysis described earlier. The weaker, saturated sections could be positioned in non-critical areas.

Preliminary calculations showed that our canoe would be so strong that thwarts, bulkheads, and ribs could be eliminated. These members are extremely difficult to finish, and create very high stress concentrations at points where they are attached to the hull.

With renewed vigor, we tried staggering plastic grids, honeycomb sections, and spacers to separate the meshes only to find that the layers would sag, thereby decreasing structural efficiency. Finally, our perseverance paid off when we found a way to completely eliminate permanent spacers. This *ingenious* construction method, described in Section 6.3, necessitates placing concrete in three lifts staggered at twelve-hour intervals.

During the final testing phase, we studied composite sections of different thickness, constructed using a number of different concretes. Each sample was fabricated by hand using a base mix. After it had dried (3-7 days), the sample was tested to failure using either the constant shear cantilever method, or the third-point flexural beam test. We soaked one side of some plates in water for times ranging from 0 to 15 minutes. Other plates were subjected to impact. Samples were compared for their thickness, weight, deflection, load bearing capacity, and durability. We evaluated bond strength by inspecting areas where the samples had been subjected to combinations of bending and shear stresses. Each sample was carefully dissected to see how the stresses had affected its interior. We checked for internal dryness and studied how absorption had affected the strength and bonding (see Appendix 1 for details).

Before making our final selection, we took the failure mode into account. We eliminated sections that had either delaminated or buckled. These failures were unpredictable and a canoe made from such sections would be hard to repair during the competition. Other sections that distorted in shear or displayed tensile cracks were scrapped mainly because the anomalies would destroy our paint job. The damage would be extremely hard to fix, and the repair would be obvious during the final phase of the product judging. We finally selected a plate that would fail only in compression. This failure mode was the most predictable of all 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 fibers are held in place using 0.08 mm (0.003 in.) diameter Kevlar strands. 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 our composite section is Mix No. 4 (see Table 1).

We determined the required strength of the section by placing strain gages in critical locations on our older concrete canoes. The strain gage experiments provided accurate real-time data and quantified the dynamic loads and the stress reversals that occurred during paddling. The peak strain for four paddlers was statically equivalent to a 31.2 Nm (23 in.-lb) moment applied to a 2.54 cm (1 in.) wide plate.

6.0 Construction

6.1 Mold 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.

A male mold was constructed 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. We applied a final layer of fiberglass to harden the surface.[14]

6.2 Prototype Construction

The team used established techniques to construct a composite prototype[15] and used it to evaluate the design. When tested, the original shape proved satisfactory. However, due to irreparable damage to the mold, the concrete canoe had to be placed over the prototype.

6.3 Concrete Canoe Construction

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

The concrete was placed over this configuration, and drywall knives were used to level the concrete to the upper surface of the wires. The concrete was left to dry for 12 hours. Then, the wires were removed. 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, the second set of wires was removed. The third layer of mesh was applied before a final layer of concrete was placed.

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.[11]

After only three days, the outer layer of concrete was hand-sanded smooth. The majority of the sanding was performed 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 practice canoe and repeated the process on the inner surface.

Using temporary wooden forms located around the upper rim of the canoe, we placed a gunwale. After adding flotation, we carefully selected the location for the unpainted section. We masked a continuous band around the canoe before sealing, priming, and painting the rest of the surface.[16,17] The portion of the mask on the exterior of the canoe was removed before we coated all exposed surfaces with a non-epoxy based clear coat. We removed the mask from the band located on the interior of the canoe and added graphics. Appendix 2 contains technical data for the materials and products used to produce our magnificent creation.

7.0 Project Management

7.1 Overview and Strategy

A strategic planning meeting was held at the first chapter meeting of the fall semester. We decided to reduce the number of people involved in the concrete canoe project to give us a better chance of performing well in the nine other events scheduled at the Southeast Regional Conference. This meant that we needed to revise our game plan for the concrete canoe competition by assigning team members joint responsibilities.

We reviewed the time chart used by last year's team (see **Figure 9**) and decided to follow it. Our chapter president and the concrete canoe chair assigned tasks, scheduled meetings, and kept lines of communication open. They organized ten different teams to support the effort and posted work schedules and meeting notices. We relied on a management information system including an extensive telephone and email network. The system was based on feedback from prior performances and was designed to help the team leaders make complex business decisions, especially in response to unusual developments such as last minute changes in design and strategy, personnel problems, and unexpected schedule delays.

Our president met with our faculty advisors on a regular basis 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.

One of the unique aspects of this year's program was that each team included at least one veteran, and was led by two "visionaries." The veterans' job was to avoid making past mistakes and duplicating work already done. The "visionaries" were charged with formulating new ideas without worrying about constraints such as money, manpower, and feasibility. The team's job was to turn these visions into realities. We also elected a "motivator." His job was to keep spirits high while pressing individuals and teams to their limits. Our "motivator" gained the respect of everyone by doing more than his share and worked closely with our faculty advisors to see that no one's feelings were hurt too badly.

With the exception of the "motivator," two people were put in charge at every level. This was done to make sure that no individual had autonomous control. When one manager came up with a good idea, it was the responsibility of that person's counterpart to improve upon it. The two were expected to work together to bring the scope of the work they assigned within reason before passing it off to their team.

This mode of operation worked well for us. We were always striving for greatness, continuously raising the benchmark one step at a time. We never settled for mediocrity; and since our check and balance system enabled us to pursue better ideas, we saved time.

7.2 Teams, Goals, and Responsibilities

The ten teams formed to support this year's effort were Hydrodynamic Design, Prototype, Concrete Design, Structural Design,

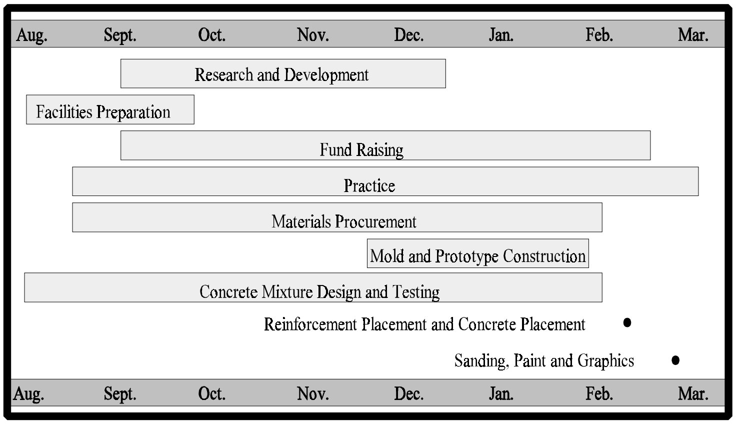


Figure 9. Time chart for the project.

Construction, Documentation, Design Report, Presentation, Crew Training, and Fund Raising.

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, recruiting, and retaining dedicated team members remained top priorities throughout the project.

8.0 Cost Assessment

The time chart shown in Figure 9 allowed team leaders and chapter members to set clear goals and plan well in advance so that they could successfully complete all tasks on time.

Appendix 3 includes tables detailing the labor and cost breakdown associated with this year's project. In constructing these tables, we used the methods and rates outlined in the 2000 rules and regulations for the national concrete canoe competition, and subsequent clarifications published on the web. The direct labor cost was $88,789. The materials used to build the mold, prototype, and concrete canoe cost $4,607. With a 10 percent markup, our total expenses amounted to $5,068. The grand total for producing our boat was $93,856.

9.0 Innovative Features

"***Ingenuity***" features innovations in seven different areas: hull design, prototype and canoe construction, crew training, concrete mixture design, composite section design, management, and final product.

The performance of a canoe was studied based on strain gage data taken while paddling.

Steps were taken to reduce deceleration and increase the average velocity of the hull.

Weight considerations took momentum transfer into account.

Parametric analyses were used to optimize the hull shape.

Design considerations included factors such as temperature, depth, wind, and waves.

Empirical results were used to verify and tune analytical models.

The design accounted for the strength and skill of our paddlers.

A prototype was produced to evaluate the hydrodynamic design and train the crew.

The team adhered to the most rigorous training program in our chapter's history.

An accelerated 7-day test program was established.

A strong, lightweight, and water resistant concrete was developed.

A simple, strong, and lightweight "adaptive" composite section was designed.

Microscopic and macroscopic analyses helped the team understand aggregate failure, bonding strength, and structural performance.

Impact and absorption tests were added.

The failure mode of the composite section was selected and controlled.

New techniques were developed for constructing the mold and canoe.

An *ingenious* construction scenario eliminated permanent spacers.

The canoe required no cross members.

A unique management scenario was used.

In addition to these innovations, we produced reinforced concrete composite sections that were formed to exact shapes (i.e., the hull and the gunwale) and finished the concrete to produce smooth surfaces. Our canoe has a sleek profile and is aesthetically pleasing. It clearly demonstrates the versatility of concrete and its effectiveness as a construction material.

10.0 Summary

In meticulously designing and optimizing our hull, we achieved performance levels well beyond our expectations. 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; a unique blend of materials for the production of a better adaptive section; and, the development of innovative construction techniques, training methods, and racing strategies.

This year's canoe is faster and better than ever. We look forward to demonstrating our "***Ingenuity***" to you at the national competition, where we will be more than pleased to entertain any questions that you may have.