Introduction/Executive Summary

After ten months of clever and clandestine work, the Clemson Concrete Canoe Team (3CT) returns to the National Concrete Canoe Competition with **Accomplice**. This fast and maneuverable canoe is constructed of an ultra thin lightweight concrete composite reinforced with polypropylene mesh and pretensioned polyethylene tendons.

Length: 6.5 m (21.4 ft.)
Weight: 59.0 kg (130 lb.)
Thickness: 10.2 mm (0.4 in.)
Depth: 29.2 cm (11.5 in.)
Beam at Gunwale: 73.7 cm (29 in.)
Beam at Waterline: 66.0 cm (26 in.)
Color: Dark Green

Clemson University is a public, land grant institution located in a small, college town setting in western South Carolina. The University started in 1889 in the vision of Thomas Green Clemson and today fulfills its mission of teaching, research and public service. The University's enrollment is approximately 14,000 undergraduate and 3,000 graduate students. The department of civil engineering is comprised of 270 undergraduate and 65 graduate students and 18 faculty.

The Clemson Concrete Canoe Team has evolved greatly since its start in 1975. The team participates in Carolinas' Conference, which includes schools from North Carolina, South Carolina, and Georgia. This year 3CT is making its tenth consecutive appearance at the National Concrete Canoe Competition, where the team has finished 6th, 5th, 4th 5th, 11th, 3rd, 1st, 1st, and 2nd each year since 1993, respectively.

This year's canoe is the product of innovative research and continued meticulous attention to detail. An improved concrete mixture based on new shrinkage research and a stronger reinforcement scheme with increased pretension force produce a stronger and significantly lighter canoe. Subtle improvements to a proven hull design enhance paddler performance. Meanwhile, innovative construction techniques and a new systematic decision-making process have resulted in a higher quality product in a shorter construction time. This research and diligent work have produced a sleek and fast **Accomplice** capable of escaping competition.

Hull Design

Designing a hull for the concrete canoe competition involves many factors due to the requirements of the two types of races. The straight-aways require the straight-line speed of a sprint canoe, while the buoy turns and slalom require the maneuverability of a whitewater canoe. Through the years, 3CT has determined that there is not one optimum design for a concrete canoe, rather many good designs that are based around the paddlers' strengths. 3CT paddlers have always been fast in the straight-aways, but somewhat inconsistent in the turns.

To improve on last year's canoe, *Good Fortune*, the team considered either developing an entirely new hull design or making modifications to last year's hull design. A hull design software program was used to design a hull that would theoretically produce slightly less drag during the starts of the races. Team leaders performed a cost-benefit analysis by weighing the cost and construction time for a new form against the slight increase in speed that the paddlers may achieve with this new hull design. Based on the costs and benefits associated with the options of constructing a new form or modifying last year's form, team leaders decided to make several improvements to last year's form.

To modify the existing hull design, this year's team eliminated 2.5 cm (1 in.) of freeboard from the canoe, which reduced the weight of the canoe and improved paddler ergonomics. In order to mitigate the problem of waves entering the front of the canoe, the depth of the canoe was increased gradually from a depth of 29.2 cm (11.5 in.) at a distance of 1.5 m (5 ft.) from the bow to a depth of 35.6 cm (13 in.) at the bow. The length of the canoe was decreased by 17.8 cm (7 in.) to increase maneuverability.

This year's canoe, which is shown in Figure 1, is the ideal **Accomplice** for 3CT's 2002 paddlers. It has excellent straight-line speed that comes from a length of 6.5 m (21.4 ft.) and a narrow beam of only 66.0 cm (26 in.), which reduces the wetted surface area. A 22.7 kg (50 lb.) reduction in weight from 2001 decreases the canoe's draught and enables the paddlers to make quicker turns. Rocker in the bow and stern—6.5 cm (2.5 in.) and 3.8 cm (1.5 in.), respectively—also enhance the maneuverability of the canoe.

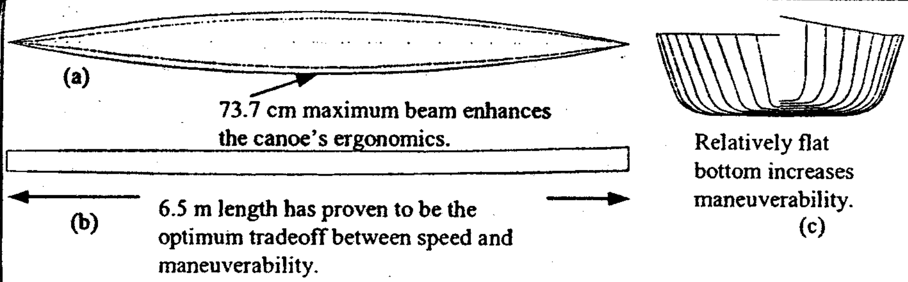

Figure 1: Views of Accomplice's (a) plan view, (b) elevation, (c) and cross-sections

Structural Design

In evaluating the structural performance of *Good Fortune*, 3CT determined that eliminating the cracks that appeared at regular intervals along the gunwales and reducing the boat's weight should be the main goals of this year's concrete and reinforcement research. To create an improved concrete composite, 3CT considered ways to reduce concrete shrinkage, reduce the unit weight and volume of concrete, and increase the flexural strength and toughness of the concrete composite, all while maintaining the constructibility of the structural designs from previous years.

Concrete Mixture Design

To eliminate the cracking that occurred in *Good Fortune* and to reduce the weight of the canoe, 3CT needed to develop a concrete mix with high flexural strength, low elastic modulus and little shrinkage. Based on experience from past years and design priorities for this year, the target properties for **Accomplice**'s concrete mixture were a 28-day compressive strength of 6.89 MPa (1000 psi), a wet unit weight of 769 kg/m^3 (48 lb/ft^3), a 28-day flexural strength of 2.76 MPa (400 psi), a shrinkage strain at 28 days of less than 0.002, low elastic modulus, impact resistance, and workability.

To characterize the relevant properties of each trial concrete mixture, 3CT employed both standardized and custom tests. Compressive strength was measured with 50 mm (2-in.) cubes in accordance with ASTM C109. Flexural response was characterized according to ASTM C1018 by applying a load at the third points of a 5.08 cm (2 in.) deep, 3.18 cm (1.25 in.) wide, and 20.32 cm (8 in.) long beam. For this test, the areas under the load-deflection curve pre- and post-peak load were determined to quantify toughness. Shrinkage was evaluated based on ASTM C157 by measuring the shrinkage strains of unrestrained prisms over a period of 28 days. Workability was assessed qualitatively.

The concrete research began by determining an optimum blend of glass bubbles for the concrete mix. While 3CT has successfully used glass bubbles in the previous years, the team wanted to select a new combination of glass bubbles that would permit a lower unit weight. Since unit weight and concrete strength are correlated, 3CT had to determine the appropriate tradeoff between unit weight and strength. Based on unit weights, shrinkage data, and compressive strengths of trial mixes consisting of varying proportions of five different types of glass bubbles, each with different specific gravity (SG), size, and strength, the team chose a combination of K25 bubbles (SG=0.25) and S32 bubbles (SG=0.32) for a base mix with a wet unit weight of 806 kg/m^3 (50.3 lb/ft^3).

With the base concrete mixture selected, the team began evaluating fibers and admixtures to improve flexural response, reduce weight, increase abrasion resistance and reduce shrinkage. The final mixture uses type III cement for high early strength, which allows the canoe to be sanded earlier.

Based on the design target properties, the team tested six different latexes, which are analyzed in Table 1. The acrylic latex selected for the final mixture, designated in Table 1 as L6, increased the flexural strength of the base mix by nearly 350%,

Table 1: Comparison of properties of latex modified mixtures

Latex Designation	Percentage Improvement Over Control (polymer/cement=0.10)					Weighted Score
	Modulus of Rupture	Toughness	W/C	Unit Weight	Compressive Strength	
L1	95.2	217.5	-22.9	-7.7	16.4	104.7
L2	123.2	249.9	-28.3	-6.8	-1.3	124.4
L3	41.9	63.0	3.4	-4.1	11.5	33.9
L4	93.4	198.2	-43.4	-5.4	-12.0	100.8
L5	11.6	53.1	53.8	-11.5	-45.6	8.1
L6	139.5	321.0	-19.9	-7.9	5.7	150.1
Weight	35	30	20	10	5	

while only decreasing compressive strength by 20% when added at a polymer to cement (p/c) ratio of 0.25.

Polypropylene and carbon chopped fibers were added to the concrete mix to reduce plastic shrinkage cracking and increase flexural strength by bridging microcracks and redistributing internal forces in the concrete. Carbon fibers increase ultimate flexural strength, while polypropylene fibers enhance post-peak performance, as shown in Figure 2. The low denier and short length of the multifilament polypropylene fibers make them well suited for placement in the 1.6 mm (1/16 in.) layers of the canoe. Carbon fibers are more difficult to disperse, but require fewer fibers for a comparable increase in ultimate flexural strength.

Shrinkage tests performed by 3CT indicated that the concrete for the canoe initially expands in the first 2-3 days, before shrinking. The rate of shrinkage declines after approximately 15 days. The key to controlling shrinkage cracking is to reduce shrinkage strains while allowing the concrete to develop early strength.

To reduce shrinkage, 3CT used a latex that did not increase shrinkage, increased the median particle size of the glass bubbles to reduce particle surface area and added chopped fibers. The final mix also incorporates a shrinkage reducing admixture, which works by decreasing capillary tension in the concrete pore water. Tests conducted by 3CT indicated that this shrinkage reducing admixture did reduce shrinkage but also reduced compressive and flexural strength. The reduction in shrinkage justified the reduction in strength.

The final concrete mixture (Table 2) features a compressive strength of 9.41 MPa (1365 psi) a flexural strength of 3.90 MPa (565 psi), and a shrinkage strain of 0.00194, all measured at 28 days and all exceeding team goals.

Once the final mix was placed, 3CT used a different concrete mixture (Table 2) to patch the canoe. To be successful, the patch mix needed to bond well to hardened concrete and gain strength quickly. Like the final mix, the patch mix needed to be workable and easy to spread into thin layers. As compared to the latex in the final mix, the acrylic latex selected for the

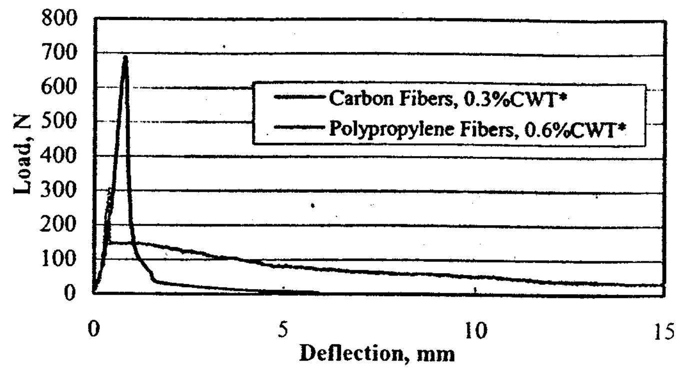

Figure 2: Load-deflection curve for discrete fiber reinforcement (*Percent cement by weight)

patch mix provided a lower increase in flexural strength but produced a more workable concrete.

Reinforcement

To build a thinner, lighter canoe that would not exhibit cracking under anticipated loading conditions, 3CT needed to design a reinforcement scheme to add stiffness and strength to the final composite. Reinforcement materials should have high modulus and strength to allow the stress in the concrete to be transferred to the reinforcement. While the reinforcement itself contributes little to the overall weight of the canoe, a stronger reinforcement scheme allows for a thinner, lighter canoe. The reinforcement must be selected in order to resist forces acting both in the plane of the

Table 2: Concrete mixture proportions, kg/m^3 (lb/ft^3)

	Base Mix	Final Mix	Patch Mix
Binding Materials			
Type III Cement	327 (551)	341 (575)	359 (605)
Acrylic Latex (L6)		183 (308)	
Acrylic Latex (L4)			87 (146)
Aggregates			
K1 Glass Bubbles (SG=0.125)			57 (96)
K25 Glass Bubbles (SG=0.25)	62 (105)	65 (110)	
S32 Glass Bubbles (SG=0.32)	80 (134)	83 (140)	
Fibers			
Carbon Fibers		1.2 (2.1)	
Polypropylene Fibers		2.0 (3.5)	
Admixtures (Wet)			
Shrinkage Reducer		6.8 (11.5)	
Defoamer		1.8 (3.1)	
Water	336 (567)	88 (149)	169 (285)
Engineering Properties			
Water/Cement Ratio	1.03	0.54	0.60
Water/Binder Ratio	1.03	0.43	0.54
Air Content, %	6.1	9.9	17.9
Wet Unit Weight, kg/m^3 (lb/ft^3)	806 (50.3)	772 (48.2)	671 (41.9)
28-Day Compressive Strength, MPa (psi)	9.86 (1430)	9.41 (1365)	5.17 (750)
28-Day Flexural Strength, MPa (psi)	0.90 (130)	3.90 (565)	2.45 (355)

composite and out of the plane of the composite. The team tested each trial reinforcement scheme in a control concrete mixture consisting of cement and glass bubbles. 3CT set a target improvement of 80% for the effect of pretensioning on in-plane strength and an improvement of 100% for the effect of mesh reinforcement on out-of-plane strength, both as compared to the strength of a control unreinforced member.

Reinforcement research began with an evaluation of the four most feasible types of reinforcement for concrete canoes: carbon fiber, aramid, fiberglass, and polypropylene. 3CT needed both a woven mesh to serve as the main reinforcement throughout the canoe and individual strands of reinforcement to add strength at the gunwales.

To evaluate these four reinforcement materials, 3CT collected information from manufacturers and the literature. Further, the bond strength in concrete of each material was evaluated using pullout tests. The results of this research, which are presented in Table 3, show that polypropylene is sufficiently stiff and strong and is significantly more cost effective and constructible than alternative types of reinforcement. Therefore, 3CT selected a polypropylene leno weave for use as the main reinforcement throughout the canoe.

With the type of reinforcement selected, 3CT tested the flexural strengths of various configurations of three different types of polypropylene meshes. These flexural specimens, tested in accordance with ASTM C293, measured 1.0 cm (0.4 in.) deep, 7.6 (3 in.) wide, and 30.5 cm (12 in.) long. Based on these tests, 3CT selected the strongest polypropylene of the three types to be used in three layers. This reinforcement scheme features less reinforcement than last year's canoe yet exhibits higher strength.

Next, 3CT examined the pretensioned reinforcement placed above the neutral axis of the canoe near the gunwales. The team considered the use of different types of reinforcement and different pretension forces. The effect of pretensioning was evaluated using beams measuring 7.6 cm (3 in.) deep, 2.5 cm (1 in.) wide, and 25.4 cm (10 in.) long and containing four pretensioned strands. These beams were tested in third point bending. Although samples containing carbon fiber produced slightly higher flexural strengths than samples with polyethylene, the use of carbon fiber was eliminated due to constructibility problems. After identifying a loss in pretension force in polyethylene strands over time, an attempt was made to increase the pretension force to offset this stress relaxation. An increase in the pretension force in each strand results in an increase in composite strength, but also causes the strands to slip along the side of the boat during placement. It was determined that increasing the force in each strand to 18.1 kg (40 lbs.) from last year's 9.1 kg (20 lbs.) would not create this problem of tendon slippage during construction.

The final reinforcement scheme includes twelve pretensioned polyethylene strands on each side of the canoe. These strands are spaced 1.3 cm (0.5 in.) apart and are placed in alternating layers with six strands in each of the two inner layers of concrete. Placing the strands in alternating concrete layers increases the capacity for out-of-plane loading without any decrease of in-plane strength. The final pretensioning reinforcement selected for the canoe increased in-plane strength by 88%, while the final polypropylene mesh reinforcement increased out-of-plane strength by 121%, exceeding the preset goals of the team.

Composite Action

The canoe must be capable of resisting the forces subjected by construction, transportation, and racing. The concrete and reinforcement must work together to resist these design forces. Since the ultimate composite flexural strength is significantly above the first-crack composite flexural strength, 3CT focused on eliminating flexural cracking. The boat will experience cracking at the gunwales at loads above the design loads but well before catastrophic failure occurs. The team set a target first-crack composite flexural strength of 4.83 MPa (700 psi) and an ultimate

Table 3: Ratings of reinforcement properties

	Tensile Strength	Modulus of Elasticity	Constructibility	Bond Strength	Cost	Weighted Score
Carbon Fiber	8	12	10	8	16	54
Aramid	10	20	10	10	4	54
Fiberglass	7	8	12	8	28	63
Polypropylene	2	4	20	6	40	72
Total Weight	10	20	20	10	40	100

composite flexural strength of 8.27 MPa (1200 psi).

Based on an analysis of anticipated loading conditions, the center third of the boat was determined to contain the critical design section due to the negative moment induced by the buoyant force when two paddlers are in the boat, as shown in Figure 3. The precise location of the maximum moment varies based on paddler locations and relative weights. A spreadsheet structural model was developed for the center sections to quantify the effects of changes in material and geometric properties. In this model, the thickness and depth of the boat, reinforcement type and location, and the concrete material properties were varied to determine the optimum final structural design.

Using this spreadsheet structural model, 3CT could quickly evaluate the relative importance of various design parameters. The model showed that while large reductions in unit weight would decrease the weight of the canoe, the attendant strength reduction would make this option undesirable. By contrast, reducing the thickness of the canoe would significantly decrease the weight of the canoe, while not having a substantial impact on structural capacity.

The final concrete mixture and reinforcement scheme has a first-crack composite flexural strength of 5.24 MPa (760 psi) and an ultimate composite flexural strength of 9.41 MPa (1365 psi), which are in-line with team goals. These values are based on plates measuring 1.0 cm (0.4 in.) deep by 7.6 cm (3 in.) wide by 30.5 cm (12 in.) long and tested at 28 days.

Construction

As the research phase of the project neared completion in November, the construction phase of the project began. The team selected a laminate method for construction of the canoe, where alternating layers of concrete and reinforcement are placed by hand on the form. A male mold is best suited for this construction procedure because the interior of the canoe is more difficult to shape after placement than the exterior of the canoe. The male mold allows the interior of the canoe to be formed instead of sculpted.

After modifying last year's wooden form, which was constructed to high standards to be

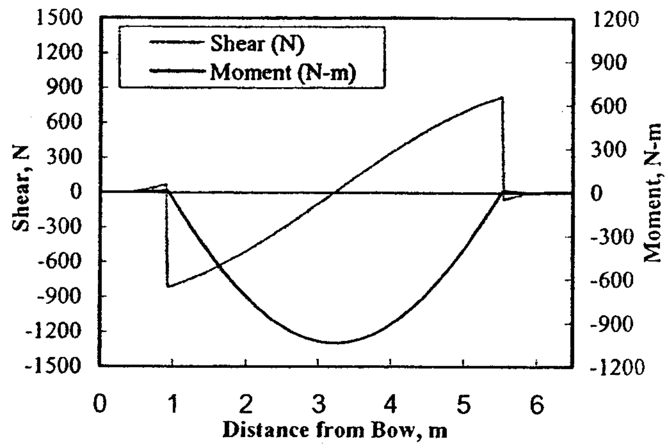

Figure 3: Shear force and bending moment in canoe for 2-person loading

durable and precise, the team was ready to place the canoe. The form was covered with a thin sheet of plastic to act as a release agent. A 1.6 mm (1/16 in.) layer of concrete was first placed by hand, with thickness monitored using nylon spacers that were removed once the desired thickness was achieved. Next, the team laid the first layer of polypropylene mesh atop the fresh concrete and scoured a thin coat of concrete across this first layer of reinforcement to ensure a strong bond between the concrete and the reinforcement. This procedure was repeated for a total of four layers of concrete and three layers of reinforcement. Six pretensioned polyethylene strands were placed on each side of the canoe in each of the middle two layers of concrete. The team applied tension to each tendon by using a turnbuckle. The force in each tendon was monitored by measuring the extension of a calibrated spring attached between the end of the tendon and the turnbuckle. The canoe was finished by hand troweling. The sequence of layers in the canoe is shown in Figure 4.

Although the polymer included in the final mix promotes curing and eliminates the need for moist curing, the canoe was covered with an opaque polyethylene sheet and kept moist for 7 days to prevent rapid loss of water, which could have resulted in shrinkage cracking. With the canoe still on the form, the outside was sanded and patched once a day. When the outside took shape, the canoe was removed from the form and the inside was sanded. Special attention was given to the shape and finish of the gunwales, chines and ends.

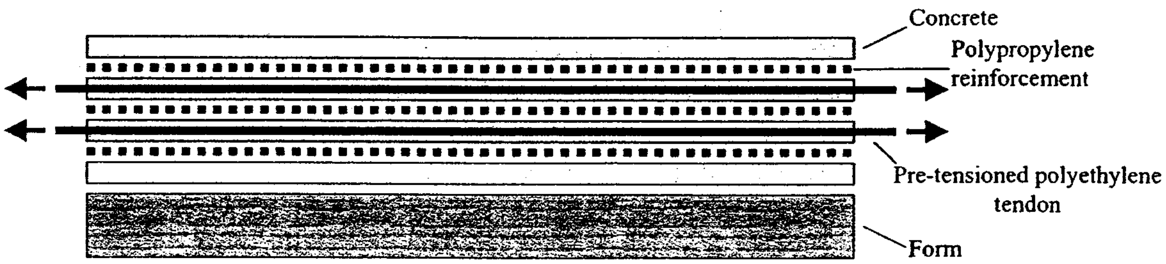

Figure 4: 3CT's Accomplice layer by layer

When 3CT was satisfied with the sleek shape and smooth finish of the concrete, the team applied an automotive primer and paint to the boat, with the exception of the 76.2 cm (30 in.) unpainted band. Finally, vinyl graphics were applied to complete 3CT's **Accomplice**.

Project Management/Cost Assessment

Completing a project of the magnitude of the concrete canoe requires detailed planning, diligent implementation, and constant communication. This year's project was split into two stages with the research conducted during the fall semester and the construction completed during the spring semester.

Two project managers oversaw all aspects of research and construction. The project was broken into the main parts and individual team members focused on their areas of interest. All team members were encouraged to be involved with each aspect of construction to develop a full understanding of the project. Team leaders made use of email, message boards, and meetings to keep the entire team apprised of the project's progress.

Last year, 3CT leaders found that creating a long-term schedule was critical to keeping the project on track. This year, team leaders developed a thorough schedule in mid-August for the research stage and a new schedule in early-December for the construction stage. These schedules, which were updated regularly throughout the year, were based on actual construction times and feedback from previous years. Critical path tasks were identified, labor availability was considered, and material lead times were determined. Despite the inevitable delays and complications, 3CT was able to largely remain on schedule throughout the project.

After losing several key 2001 team members to graduation, the returning team leaders identified recruiting and retaining new team members as a key goal to ensure a smooth, complete project this year and to benefit future teams. The team leaders worked to get new members involved in the project at early stages. Research and construction were carefully documented for the benefit of future teams.

At each stage in the project, the project managers made decisions only after a careful and systematic consideration of costs and benefits. In this way, decisions were based on the effects on team performance, not on personal preference. Although this project management strategy is utilized by businesses of all sizes, it has historically been overlooked too frequently in the design of concrete canoes. The costs of all features in this year's canoe were justified by improvements in performance.

Based on experience from previous years and a desire to reduce costs, the team set a goal of reducing total project costs by 10% to $125,700 from last year's cost of $139,710. The final total cost of designing and constructing **Accomplice** was $120,401, which the team achieved through a more extensive consideration of costs and improved construction techniques that were based on greater experience.

Summary

Thorough research, careful planning, clear communication, constant attention to quality, and diligent consideration of costs have helped 3CT to produce a greatly improved canoe for the 2002 National Concrete Canoe Competition at the ASCE 150th Anniversary National Student Conference. This year's canoe is stronger and lighter due to an improved concrete mix design and a stronger reinforcement scheme. The Clemson Concrete Canoe Team has proven that hard work, dedication, creativity and innovation make a great **Accomplice**.