Design/Build of a Concrete Canoe—*From Start to Finish Line*

Combining concrete technology with naval architecture.

BY MICHAEL CARNIVALE, III

The Drexel University Concrete Canoe Teams have participated in regional competitions since the early 1980s, and we have represented the Pennsylvania-Delaware Region at the National Concrete Canoe Competition five times. A string of four consecutive regional championships began with our 1998 entry, *Rocky Canoa*, which went on to finish 11th overall at the national competition. The *Broad Street Bully* (1999), the *Drexel Experiment* (2000), and our 2001 entry, *Obi-Wan Canoebi,* finished in 8th, 13th, and 7th place overall in the national competitions, respectively.

Throughout the years, our teams have taken valuable learning experiences back from these competitions and incorporated them into the following year's project. Success in this competition is based on a combination of factors: the ability to combine recent advances in concrete technology with the concepts of naval architecture; the use of effective management for this unique design/build project; and the motivation, creativity, and spirit of a group of young men and women who take extreme pride in their product and skills.

Hull design

With races that include straightaways, hairpin turns, and even a slalom course, designers are faced with the inevitable task of developing a canoe that can achieve conflicting objectives—namely the ability to travel straight and fast, but remain maneuverable enough to negotiate the turns. *Obi-Wan Canoebi*—our entry into the 2001 ASCE/Master Builders Technologies (MBT) National Concrete Canoe Competition (see the News section for race results)—is nearly 21-ft (6.4 m) long and weighs 140 lb (63.5 kg).

This canoe features a long, asymmetrical hull; its length falls within the range proven by several of the top schools in this event, such as Clemson, Alabama-Huntsville, and Oklahoma State, to provide superior speed and maneuverability for the current race configuration. It features a sharp bow at the entry line and a small beam width of 28.5 in. (724 mm) just aft of amidships. The sharp bow reduces the strike-through resistance at the front of the canoe, enhancing streamlining. Most sophisticated racing hulls have their fullness shifted to the rear, making the bow finer at the expense of stern fineness and providing an efficient design that balances speed, capacity, and stability.

A shallow arch cross-section provides a high resistance to capsizing. The surface-to-volume ratio decreases the wetted surface area and the resulting skin friction that is the primary contributor to resistance at paddling speeds. The arched bilge (bottom of the canoe) combines the best attributes of flat-bottomed design (maneuverability) and rounded cross-sections (tracking and speed), providing a structurally efficient and well-balanced design. The shallow arch tapers into a “whale tail” in the stern to allow the paddler to sit further back for better handling of the canoe.

Structural evaluation

The structural analysis performed on our canoe is a method commonly used by naval architects that takes into account the weight of the canoe and paddlers and buoyancy loads to determine the corresponding shear forces and bending moments. Designers generally look at the worst-case loading conditions in the water (the absolute worst-case loading occurs when the canoe is simply supported). In our case, this condition occurred when we applied the load of the men’s tandem (assuming 185 lb [823 N]/paddler) to the canoe.

By making the conservative assumption that the concrete carries no tension and the selected reinforcement would carry no compression, we checked the critical cross-sections in both bending and shear to determine the necessary concrete compressive and reinforcement tensile strengths. Using the results of the structural analysis and incorporating a safety factor of 2, the required compressive strength of 5.5 MPa (800 psi) was computed. A 1100-lb (4.5 kN) tensile load in the gunwale was also determined from the analysis, again with a safety factor of 2.

The reinforced concrete composite is required to resist all shear forces and moments generated during various loading conditions that occur while in transport, on display, and in competition. Our goals were to limit “hog” (negative moment) and “sag” (positive moment) deformations; obtain considerable impact and cracking resistance; maintain a thin, lightweight section; use reinforcing materials that are inert to reaction with the concrete mixture; and ensure that all materials and the selected reinforcing scheme conformed with the rules.

The concrete mixture

In addition to the compressive strength requirement, our designers targeted several key properties including: a maximum unit weight of 62.4 lb/ft^3 (998 kg/m^3); low water absorption; high durability; and good workability and finishing characteristics. Our team has relied on the use of a polymer-modified concrete in our canoes for the past several years. From the research conducted by competition participants during the last decade and a half, teams can draw from an extensive database on lightweight concrete design. Typically, teams continually modify previous designs to enhance performance (such as a decrease in unit weight, an increase in tensile strength, etc.).

During the 2000-2001 academic year, we focused our efforts on improving the workability of our concrete mixture compared to the design of the previous year: a 50 lb/ft^3 (800 kg/m^3) epoxy-modified concrete with a 7-day compressive strength of 6.9 MPa (1000 psi). The epoxy-modified concrete was sticky and sometimes cumbersome to use for canoe construction, so we looked into making construction easier without compromising the other concrete properties.

In addition to the epoxy resin/curing agent system used in previous mixture designs, various binders and admixtures, including silica fume, fly ash, latex, high-range water reducers, and air-entrainment products, were evaluated and tested. We created 20 different mixture designs using the Absolute Volume Method and tested them in accordance with the appropriate industry standards.

The optimum combination of desired properties was found in a 50 lb/ft^3 (800 kg/m^3) latex-modified portland cement concrete with 14-day compressive and tensile strengths of 6.5 MPa (940 psi) and 1.4 MPa (210 psi), respectively. The mixture, which we named “Tatooine,” was composed of Type III portland cement (ASTM C 150), for high-early strength, which accelerated both the testing program and canoe construction; Laticrete® 333, an acrylic mortar latex that is 31% solids by weight, which enhanced the workability and durability, and reduced both the absorption and unit weight; Q-Cel®, a low-density, hollow, sodium borosilicate microsphere aggregate, which added volume while reducing density; and polypropylene fibers to prevent microcracking.

This year’s design team believed that latex modification provided the proper workability. Compared to last year’s design, the team achieved the same unit weight without a significant decrease in the compressive or tensile strength. While it took 14 days to reach the required strength rather than the 7 days it took last year, this didn’t have any significant impact on the construction schedule.

Reinforcement

Our designers evaluated the reinforcement available and selected a combination of fiberglass mesh and fiber-reinforced-plastic (FRP) reinforcing bars to serve as the primary reinforcement. Polypropylene fibers dispersed in the concrete served as secondary reinforcement. We selected these materials based on their proven performance, the unquestionable satisfaction of all of the design criteria as outlined in the rules and regulations, and the team’s familiarity with their use in construction.

The hull skin is a composite of latex-modified con-

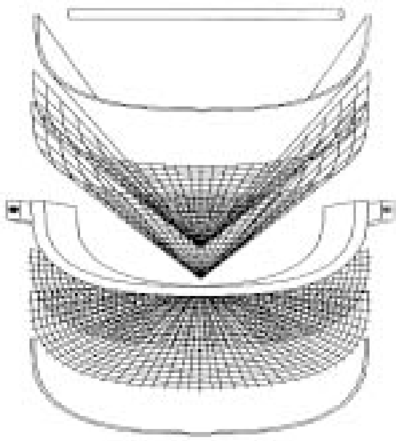

Fig: 1: 3-D exploded view of the reinforced concrete composite section of the hull skin

Fig. 2: Mold composed of cross-sectional templates and EPS block mounted on a wooden strongback

Fig. 3: The finished mold ready for concrete placement. The mold was refined and faired with spackling compound and sealed with an epoxy resin

crete sandwiched between layers of specially-treated glass fiber mesh at both the interior and exterior surfaces (Fig. 1). Wide-width tensile strength tests (ASTM D 4595) conducted on specimens of the glass fiber mesh indicated that a single layer could withstand an average tensile load of 200 lb/in. (35 kN/m), which correlated well with the strengths reported by the manufacturer. The gunwale includes lengths of 0.25-in (6.4 mm) diameter FRP reinforcing bars strategically placed at sections with high tensile forces. The precast thwarts are solely reinforced with the FRP bars. Based on the ultimate tensile strength of 140,000 lb/in^2 (950 MPa) for the 0.25 in. (6.4 mm) diameter FRP bar, the total tensile load capacity is nearly 6900 lb (30.7 kN), and exceeds the required tensile force determined from the structural analysis.

To evaluate the strength and bond effectiveness of the reinforced concrete composite, we applied a line load at the center of the simply supported plate. We measured load and deflections and computed the flexural rigidity of the plate using principles from the mechanics of materials. Coupled with the past performance and structural integrity of our previous canoes, the tests indicated that the composite could easily withstand the loads applied by the paddlers.

Construction

Mold making for *Obi-Wan Canoebi* began with 24 cross-sectional templates and two longitudinal templates for the bow and stern sections, cut out of masonite, and aligned along a wooden strongback (Fig. 2). Blocks of expanded polystyrene (EPS) foam were cut using the templates as guides. The naval architecture software used to analyze the hull geometry also generated the final full-scale plans.

We inserted the templates into dadoes cut into the strongback 12 in. (305 mm) on center, with the exception being at the last 3 ft (0.9 m) of both the bow and stern, where the templates were 6 in. (152 mm) on center. We then inserted and secured the EPS blocks in between the templates, filled in mold imperfections with drywall compound, and faired the mold by sanding with long-boards. On achieving the desired contours, our team sealed the mold and hardened it with an epoxy resin (Fig. 3). We cut and bent aluminum sheeting to the desired dimensions of the gunwale and attached it to the plywood guide with rivets to serve as a form. Finally, after six coats of mold release wax, the mold was ready for concrete casting.

Construction of the canoe began at the interior surface by placing a skim coat of concrete on the mold followed by the two layers of the glass fiber mesh that compose

Fig. 4: Hand placement of a 0.2-in. (5.1 mm) thick layer of concrete. Flexible plastic tubing (next to hand) was used to gauge the thickness

Fig 5: The final product included several layers of water sealant, automotive primer, paint and clearcoat, and stenciled vinyl lettering (photo courtesy of ASCE/MBT)

the interior reinforcement layer. The team rolled the mesh into the concrete skim coat using paint rollers fitted with PVC pipe. We then applied a 0.2-in. (5.1 mm) thick layer of concrete by hand (Fig. 4), using flexible plastic tubing to gauge and control the thickness. This layer of concrete made up the core of the composite section. After two additional layers of the glass fiber mesh were applied, an exterior skim coat of concrete provided full coverage over the reinforcement. When concrete was placed in the aluminum gunwale form, two 8-ft (2.45 m) lengths of FRP rebar, one for either side of the canoe, became encased. Throughout the casting process, we made unit weight determinations of the fresh concrete, and quality control cylinders and cubes were obtained from each batch for testing purposes.

Obi-Wan was moist cured continuously for 14 days by placing burlap under polyethylene sheeting. After curing took place and it was released from the mold, the canoe was sanded to a smooth, curvilinear finish. We applied thin patches of concrete to fill imperfections; two thwarts were installed into notches cut in the gunwale by tying the bar in the thwart to the bar in the gunwale, then filling the notches with concrete.

Finishing included providing a 20-in. (508 mm) wide continuous band of exposed concrete on the canoe, required by the rules. The interior portion of the band was left uncoated, while the exterior portion was coated with a polyurethane water sealant. The remainder of the canoe was finished with several layers of the water sealant, automotive primer, paint, and clearcoat. The final touches to the canoe were the application of stenciled vinyl lettering and decals (Fig. 5). The paint scheme represented a Star Wars Jedi knight light-saber.

In total, 1510 hours of labor went into this project from the late summer of 2000 through the final preparations for the 2001 national competition.

What's in store for the Drexel team?

Drexel's 7th place finish resulted in part from a well-rounded effort in the academic portion of the competition, which included top 10 finishes in the technical paper, display board, oral presentation, and final product categories. While our paddlers performed admirably, improvements in this portion of the competition could vault us higher.

Preparations already have begun for the 2002 team, including the construction of a new strongback, preliminary concrete testing, and an evaluation of hull-design performance, while we wait for the 2002 edition of the rules and regulations to be published (where changes could entirely change the face of the competition).

We look forward to defending our regional championship and possibly participating in the 15th ASCE/MBT National Concrete Canoe Competition, to be hosted by the University of Wisconsin-Madison. We don't plan to underestimate the participants in the regional competition, all who have shown significant improvement in recent years, and we hope that no one at the national level underestimates the ability of Drexel University's up-and-coming Concrete Canoe Team.

Selected for reader interest by the editors.

ACI member **Michael Carnivale, III,** is a civil engineer with the Geotechnical Section, Engineering and Construction Division, U.S. Army Corps of Engineers, Philadelphia District. He holds a BS in civil engineering from Drexel University, has completed graduate coursework at the University of Rhode Island (URI), and is currently enrolled in the PhD program at Drexel University. Carnivale participated in the National Concrete Canoe Competition with URI, and has served as a technical advisor to the Drexel Concrete Canoe Team since 1997.