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Introduction and Executive Summary

“Cal students have never been quiet. Since the first class, the “12 Apostles” of 1873, Cal men and women have been creating their own identity, creating their own activities and lore, some of which have survived over the years. Some of our traditions have even been adopted by other universities around the world.”¹

The University of California, Berkeley (UC Berkeley) was established in 1868, when the College of California and the Agricultural, Mining, and Mechanical Arts College were merged. Located in the heart of the culturally diverse San Francisco Bay area, UC Berkeley has grown to include 300 degree programs, 32,000 students, world-renowned faculty, and it is a university known for incubating original ideas and social movements.

In keeping with the innovative nature of UC Berkeley’s student body, the UC Berkeley Concrete Canoe team was the first to host a Regional Concrete Canoe Competition in the 1970s. In the years that followed, this idea spread around the country and in 1988, the Concrete Canoe became a National Competition. Since that time, UC Berkeley has captured four national championship titles, one second-place and four third-place finishes.

UC Berkeley hopes to reclaim the gold at the 150th Anniversary celebration of ASCE with **CALCATRAZ**. Weighing in at 578 N (130 lb) **CALCATRAZ** has a black interior, and a striped black and gray exterior. The canoe is 6.40 m (21 ft) long, has a maximum depth of 330 mm (13 in), a maximum beam width of 670 mm (2.20 ft), and a constant thickness of 14.7 mm (0.58in). **CALCATRAZ** was constructed using two concrete mixes; a 1043 kg/m³ (65 pcf) mix with a compressive strength of 20.7 MPa (3000 psi), and a 480 kg/m³ (30 pcf) mix with a compressive strength of 1.70 MPa (250 psi). Two layers of fiberglass scrim combined with carbon fibers were placed in the interface of the two mixes.

Numbers, however, cannot describe how **CALCATRAZ** distinguishes itself in competition. This year’s innovative features include: (1) a flared stern section which allows for more efficient strokes, and decreases turning time; (2) two types of concrete and two types of reinforcement, which together produce a rigid, lightweight composite with large surface crack initiation toughness; and (3) an effective Organizational Breakdown Structure and improved fundraising efforts.

Hull Design

Goals

CALCATRAZ’s hull design team consists of former paddlers with first hand knowledge of how UC Berkeley’s past canoe designs can be improved. This group set design goals based on research, time trials of past canoe designs, and paddling experience. The team’s focus was to create a more paddler-friendly canoe by improving maneuverability, initial stability, drag resistance, and paddler placement.

Implementation

Maneuverability: Through research, we established that shortening a canoe’s length improves its maneuverability, while increasing it improves straight-line speed and directional stability (Appendix 1.1). To improve turning characteristics, the designers shortened **CALCATRAZ** to 6.40 m (21 ft), from last year’s 7.0 m (23 ft). This length was selected because the fastest speed attained by the paddlers during the time trials corresponded to a theoretical hull length of 6.40 m (21 ft) (Appendix 1.2). Also, the second longest canoe at last year’s National competition was about 6.40 m (21 ft) so the UC Berkeley paddlers will

¹ ‘Bear Traditions’, Days of Cal, www.berkeley.edu, Accessed 03/20/2002

maintain competitive straight-line speed while decreasing turning times. After **CALCATRAZ**'s hull design was completed, the team created a Torque Test to evaluate maneuverability data (Appendix 1.3). This inexpensive test measures the time a canoe takes to rotate over a 120 degree angle under a constant torque of 50 ft-lbs. Future teams will be able to use this test to assess and refine characteristics of past canoes desirable in future designs.

Initial stability: Last year's canoe, Bearrier Reef, benefited from its V-shaped cross-section with straight-line speed; however, our paddlers were uncomfortable with the canoe's tendency to heel. By incorporating a flatter bottomed cross-section, the paddlers can now focus more on their stroke and less on their balance.

Drag resistance: There are two components to the total drag force on the canoe: frictional and wave. Frictional drag is a function of wetted surface area, which cannot be altered significantly once the hull length is chosen. Thus, the design team focused on lowering wave drag (R_r), which is dependent on geometry below the water line. **CALCATRAZ**'s beam (β) was kept to a narrow 670 mm (2.20 ft) because decreasing the width lowers wave drag exponentially ($R_r \propto \beta^2 L$). The team also modified design stations until an optimum wave drag was achieved (Appendices 1.4, 1.5). **CALCATRAZ**'s total drag resistance at 11.0 km/h (6.0 knots) is 75.6 N (17 lb), nearly thirty-five percent less than what it was for last year's Bearrier Reef 115.6 N (26 lb).

Paddler placement: Paddler placement was a strong consideration for **CALCATRAZ**'s hull design. Last year's canoe pitched toward the bow because the heavier front paddler created a greater moment about the canoe's center than the back paddler (Appendix 1.6). Incorporating a flared stern section allows the back paddler to sit closer to the stern end to equalize the moments. Other advantages of the flared section, along with all the hull features, are outlined in Figure 1.

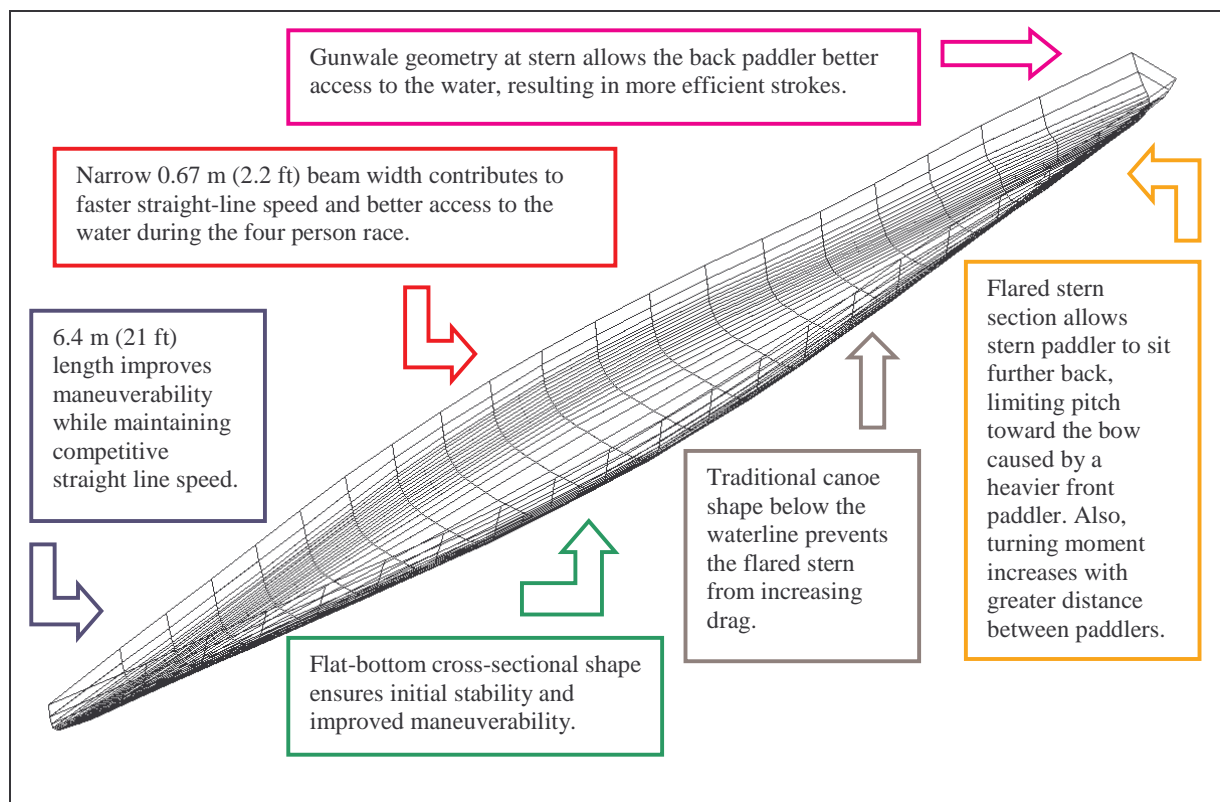


Figure 1: **CALCATRAZ** Hull Design

Structural Design

Concrete Mix Design

Goals

Last year the UC Berkeley Concrete Canoe, Bearrier Reef, was constructed with a 8.27 MPa (1200 psi) concrete and weighed 534 N (120 lb). To improve structural strength of the canoe and reduce unit weight, we established four concrete mix design goals:

- Minimize cracking in the canoe by increasing the tensile strength of concrete. We calculated the required tensile strength to be 1.37 MPa (200 psi). Using the ACI empirical formula for lightweight concrete: $6.5(f_c')^{1/2}$ we determined that this would be achieved by using a concrete mix with a compressive strength greater than 13.8 MPa (2000 psi) for a factor of safety of 1.5.
- Use two concrete mixes for a layering effect of a low weight concrete filler sandwiched between two high strength skins. The high strength skins were designed to have a compressive strength greater than 13.79 MPa (2000 psi) and the low strength filler was designed to weigh as little as possible.
- Construct a canoe that weighs approximately 534 N (120 lb) which has been the average weight of the canoe for the past few years.
- Allow adjustment of concrete workability to accommodate a variety of construction techniques such as hand placement and shotcrete by designing for easy adjustment of workability.

Implementation:

Material Selection: Since cementitious materials provide the strength in the concrete mixes, we selected cement replacements to decrease overall weight while maintaining high strength. Silica fume slurry, latex, fly ash, and epoxy were investigated as binders (Appendix 2.1.1, 2.1.2). We investigated percentages for which binders are typically used, and performed individual tests to confirm this data in accordance with ASTM C-39 using 0.05 m x 0.102 m (2x4 in) cylinders (Appendix 2.1.3). Silica fume slurry (5%), latex (20%), and cement (75%) were selected as the binders for both concrete mixes because this configuration yielded the highest strength to weight ratio.

Aggregates chosen to be tested for use in this year's mixes included Macrolite Ceramic Spheres[®], Baypor F-3[®] expanded shale, Perlite, and K46 and K25 3M[®] glass bubbles based on the ranges of their weights and particle sizes (Appendix 2.1.4). During initial testing, it was found that the Baypor F-3[®] did not maintain its particle shape or size; therefore Macrolite[®] was used for the high strength mixes. The low weight of the 3M[®] glass bubbles led to their selection for aggregate in the lightweight mixes since the Perlite absorbed 100% of its volume of water and lost its low-density attribute.

Testing Procedure: We created a spreadsheet of mix designs to study proportioning of aggregate-to-binder (by mass) and water-to-binder ratios that would produce concrete with the desired properties. Mixes were tested in general accordance with ASTM C-39 using 0.05 m x 0.102 m (2x4 in) cylinders and tested at 7 and 14 days. During actual casting of the final canoe, in-situ cylinders were cast and cured to verify the final strengths of the canoe elements.

Final Mix Selection: Final concrete mix selection was based on compressive strengths and unit weights of the mixes. The thickness of each concrete layer was determined such that the canoe would have a composite density of 881 kg/m³ (55 pcf) and weigh 524 N (120 lb). To achieve this we developed a computer program that calculated the composite density and weight of the canoe for varying values of the thickness and density of each mix. Our final design consisted of two 3.2 mm (0.125 in) thick outer layers of the strong mix and a middle layer of 6.4 mm (0.25 in) of the lightweight mix. We optimized the

combination of concrete mixes based on total weight and strength in accordance to this thickness design. The final high strength concrete mix ('The Rock') has a compressive strength of 20.7 MPa (3000 psi) and a unit weight of 1043 kg/m³ (65 pcf). The low weight filler ('Birdman Stroud') has a compressive strength 1.7 MPa (250 psi) and a unit weight of 480 kg/m³ (30 pcf) (Appendix 2.1.6).

Reinforcement

Goals

- Reduce cracking in the canoe by using a stiffer reinforcing material than previous years.
- Reduce the number of reinforcement layers to two for ease of construction.

Implementation

Material Selection: Reinforcing materials considered include: steel, carbon fiber, Spectra[®], and Twaron[®] meshes and fiberglass, and Kevlar[®] scrim. Despite the impressive properties offered by Spectra[®] and Twaron[®], we were unable to locate a mesh with the desired spacing. Strength-strain relationships for the materials (Appendix 2.2.1) show that carbon fiber and steel have the greatest stiffness, and carbon fiber and Kevlar[®] are the strongest. Steel was not considered because of its low specific strength [stress/density] and Kevlar[®] was eliminated because of its low stiffness and high cost. The selected materials were carbon fiber mesh, which offered the optimum mechanical properties, and fiberglass scrim, which offered intermediate properties but was readily available.

Stress distribution: Before selecting a final reinforcing scheme, we needed to determine the forces in the canoe during the critical load cases. First, we determined the moment envelopes in the canoe for each race. The negative moment demand was 820 N-m (605 lb-ft) while the positive moment demand was 941 N-m (700 lb-ft) (Appendix 2.2.2). We then modified the principles used for the design of reinforced concrete structures and applied them to evaluate several reinforcement schemes that used combinations of carbon fiber and fiberglass (Appendix 2.2.3). For each configuration, we calculated the ultimate flexural capacity. Two reinforcement schemes offered adequate capacity (safety factor of at least 2 compared to demands):

- Two layers of carbon fiber mesh.
- Two layers of fiberglass mesh combined with carbon fiber strands at variable spacing.

We then proceeded to perform testing to determine which configuration was more suitable for the canoe.

Testing: To verify the strengths of the carbon fiber and fiberglass, we performed tension tests. A single carbon fiber was tested in tension and failed at 734 N (165 lb), which is consistent with the nominal strength. The tension test of a 127 mm (5 in) wide strip of the fiberglass scrim (consisting of 14 double fibers) using a standard grab test failed at 1135 N (255 lb). The fiberglass scrim, failed at a higher load than expected, because during the test, the scrim became distorted and the horizontal fibers were able to take some of the load.

Since all the reinforcements considered were either a mesh or a scrim, we had to devise a way to fit the two-dimensional reinforcement on the three-dimensional canoe. This problem was solved for the carbon fiber mesh by using a 2x2 Twill weave, which drapes easily over three-dimensional surfaces. The fiberglass scrim was more challenging because it does not drape well due to the chemical bonding of the fibers. The best way to fit the scrim was to place it on the canoe and make transverse cuts where required. However, it had to be decided whether to overlap or cut and tie the scrim at the cuts. To study the difference, we cast two 0.61 m x 0.3 m (2 ft x 1 ft) test plates, one with the scrim tied and the other with the scrim lapped. The test results showed that overlapping the pieces is a superior technique because the plates failed at 178 N (40 lb) versus the 44 N (10 lb) fracture strength exhibited by the tied reinforcement.

Before selecting the final reinforcement configuration for the canoe, we had to investigate the composite action that each scheme has with our concrete mixes.

Composite Action

Goals

- Minimize cracking.
- Resist critical loads without delaminating.

Implementation

Once the two concrete mixes were determined, we needed to test the interaction of the two mixes with the two reinforcement schemes we had developed. The first set of tests were three-point tests of 0.3 m x 0.3 m (1 ft x 1 ft) plates to test flexural capacity. The plates with the fiberglass/carbon fiber combination failed at 735 N (165 lb) and the plates reinforced with the carbon mesh failed at 665 N (150 lb). These tests showed that either option produced a similar flexural capacity. All test plates failed in the manner anticipated by the structural design team: the inside layer started cracking first; at high loads and after significant deflections a dominant crack formed in the strong outer layer and the plates failed.

For the reinforcement to work effectively with the two concrete mixes, delamination had to be considered. We performed pullout tests, using the equipment for a standard grab test, on the reinforcement embedded in 0.51 m x 0.13 m (20 in x 5 in) test plates. All plates delaminated severely, and this was found to be due largely to the graphite coating on the carbon fibers (Appendix 2.3.1). We eliminated this problem by sanding the surface of the carbon fibers before casting new test plates. Sanding the fibers proved beneficial since the carbon fibers formed a strong bond with the concrete mix. We then performed a three-point test on test plates containing the sanded carbon fibers. These plates were able to withstand the load even after the dominant crack had formed due to the increased bonding.

The fiberglass/carbon fiber combination was selected because it allowed the flexibility to better reinforce locations of higher stress concentrations by decreasing the spacing of the carbon fibers. The composite design provides a negative moment capacity of 1627 N-m (1200 lb-ft) (Safety Factor of 2), and a positive moment capacity of 6915 N-m (5100 lb-ft) (Safety Factor of 7).

Construction

Goals

- Reduce the amount of cracking.
- Improve the finish through quality control.

Implementation

Three techniques for constructing **CALCATRAZ** were considered:

- Hand placement of concrete over a male mold.
- The “sandwich method”, in which portions of the canoe are cast onto both a female and male mold, then inverted within one another and filled to a desired thickness.
- Shotcrete over a male mold.

Each method had its own challenges, but after testing all three methods, hand placement emerged as the most efficient method, both in terms of feasibility and cost (Appendix 3.1).

We began construction by milling a male mold of the hull design from foam. Next we applied joint compound to fill the divots left by the computer-controlled bit and a layer of epoxy to harden and seal. We then applied a layer of wax to ease the removal of the mold. Casting began by placing 3.17 mm (0.125 in) diameter wire spacers on the mold every 203.2 mm (8 in). The team placed the high strength concrete mix over the wire spacers and used trowels to level it to the thickness of the spacers. Once a uniform thickness was achieved, the wire spacers were removed and the remaining impressions filled. We then placed the carbon fibers by incorporating them into the mix, over which we draped the fiberglass

scrim. The same procedure was used with the light weight mix to form the interior layer, except 6.38 mm (0.25 in) wire spacers were used. We then added the second reinforcement layer and placed the final 3.17 mm (0.125 in) layer of the strong mix. The canoe was then fog cured for fourteen days (Appendix 3.2). We placed sprinklers inside the curing tent to maintain a high humidity. We started sanding the exterior of the canoe at seven days while it was curing. Twenty-one days after casting, we removed the canoe from the mold and sanded the interior. The canoe was then painted by the team, leaving a 76.2 cm (30 in) section of the canoe unfinished. The unpainted band was water-sealed and graphics were applied.

Project Management and Cost Assessment

Organizational Structure

At the beginning of the year, the returning members from last year's team decided to eliminate the position of 'Chair' and developed a more efficient Organizational Breakdown Structure (OBS) which distributed the responsibilities among several team members. We elected a Project Manager, four Engineers responsible for hull, concrete mix, reinforcement, and construction, and five Coordinators for fundraising, paddling, display, technical paper, and oral presentation (Appendix 4.1).

Project Management

In August 2001, the Project Manager and Engineers developed a budget and a detailed schedule for the year, with the critical path for the canoe identified (Appendix 4.3). The schedule and budget were posted in our work area. In September, the team held an informational presentation and a picnic to recruit new members. After eight new recruits joined our team, we set up scheduled work-sessions and paddling practices. Every week the Project Manager and the Engineers held meetings to discuss the progress of the project and to resolve problems that were encountered in each area. The Project Manager also held individual meetings with the coordinators, when necessary. To avoid time consuming team meetings, a team e-mail list and website kept all the members and sponsors informed of the progress and assignments.

Cost Assessment

Material and tool purchases were recorded by the team treasurer. All members submitted monthly timesheets and the Project Manager compiled them in a spreadsheet. The expected labor cost, which was the average of the labor costs from past teams, was \$55,700. The expected materials costs, as listed in the budget, were \$4,500. Actual labor costs came out to \$57,727 and material costs were \$4,502. The grand total for the development and construction of **CALCATRAZ** was \$62,229, which is within 5% of the initial estimates. Detailed cost assessments are included in Appendix 4.2.

Summary

After nine months of research, innovation, and hard work, the 2002 Concrete Canoe team presents their final product, **CALCATRAZ**. Equipped with a brand new hull, an efficient structural design, a smooth finish, and an enthusiastic team of engineers, **CALCATRAZ** has been vested with the responsibility of bringing the National title back to the University of California, Berkeley.