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Design and Construction of the Concrete Canoe *California II*

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Student chapters of the American Society of Civil Engineers participate annually in a competition for the design, construction and performance of concrete canoes that meet certain minimum rule restrictions. This paper reports on the craft entered in the 1984 competition by students at the University of California/Berkeley. The Berkeley team came in second in the men's and women's races and placed first in both design and construction.

Introduction

EACH YEAR many student chapters of the American Society of Civil Engineers (ASCE) construct and race concrete canoes. The competitions, encouraged by the Association of General Contractors and the American Concrete Institute (ACI), are for the promotion of new applications and development of concrete, as well as for giving students practice in team projects. More schools participate annually in what started as a rather light-hearted pursuit and has evolved into a competition that produces some fairly sophisticated craft. Concrete-canoe races are held regionally at about 17 host schools around the country and have been going on since the early 1970's [1].[3]

These competitions have produced some innovative ideas for concrete applications such as the downhill and cross-country races, using concrete skis, organized by Montana State University when severe weather conditions make the concrete-canoe races impossible [2].

Concrete canoe competition has two phases. The first phase is the determination of the best designed and constructed canoe by a team of judges. The second phase is the actual race, which is often held on lakes over a distance of about 1000 yards with four or five quarter, half, and full turns. In some instances races are held on smooth rivers, including portages, and they have even been held in whitewaters.

This paper describes the design and construction processes used for University of California/Berkeley's 1984 concrete canoe *California II* that participated in the mid-Pacific region competitions.

Hull design

According to the 1984 concrete canoe design rules [3] of the ASCE student chapters, there are no restrictions on the length and width of the canoe. However, the rules state that "the entry must be classified as a canoe," and add that "the American Canoe Association requirements for a canoe specify that the width should not be less than 14% of the length." Other design related rules are as follows:

1. No form of propulsion other than paddles may be used.
2. No steering devices of any kind are permitted.
3. Each canoe must be paddled by a crew of four.
4. The canoe must float when filled with water.

The last rule is for the safety of the crew during the race and it can be realized by using flotation foams, as will be discussed later on.

One of the most important design inputs to a concrete canoe is the racecourse. Obviously, knowing the racecourse before beginning the design aids in determining the main dimensions of the canoe. However, the information on the racecourse is rarely given or known to the participating schools well in advance of the race date. Therefore our design started four months before the race without the course being known, but in anticipation from past experience of two quarter, one half, and one full turn.

In the beginning of the design of any hull, a naval architect should have an idea about the approximate characteristic hull dimensions such as the length, breadth, draft and displacement. Having these dimensions closely established, a designer can move with experience which, in most cases, can be gained by reviewing past designs. The 1984 ASCE concrete canoe's characteristic dimensions were established through feedback from the past year's crews and by studying past designs, as well as by considering the weight of the anticipated crew. As a result of this study it was determined that the breadth of the canoe had to be wider to increase lateral stability; the length had to be longer to decrease wave resistance and also to further increase the displacement for a larger crew; and the sheer had to be increased, especially around the bow section, to reduce splashing. Some of the other design changes that we felt necessary were the reduction of deck height to keep weight down, an increase in the sharpness of the "vee" in the stern section and, lastly, addition of bilge keels that we hoped would provide some roll damping.

As in past years, it was felt that an efficient racing hull based upon a sailboat design was preferable to the standard symmetric canoe hull, at least for the purposes of the competition. With the main dimensions of the hull known, the design started with the drawings of the midship section profile and continued with the remaining fore and aft section profiles to obtain the body plan as shown in Fig. 1. A few iterations were necessary to correct the displacement obtained from the section-area curve. The two other projections of the hull, namely the sheer plan and the half-breadth plan, were generated simultaneously to ensure that a smooth 3-dimensional surface was generated.

The design was aided by a microcomputer (Tektronix 4051) equipped with a graphics tablet for digitizing and a plotter. A perspective view of the concrete canoe plotted by the Tektronix plotter is shown in Fig. 2. All the hydrostatic properties of the canoe were computed by a program written for the Tektronix computer. As an aid to future designs, the main dimensions and

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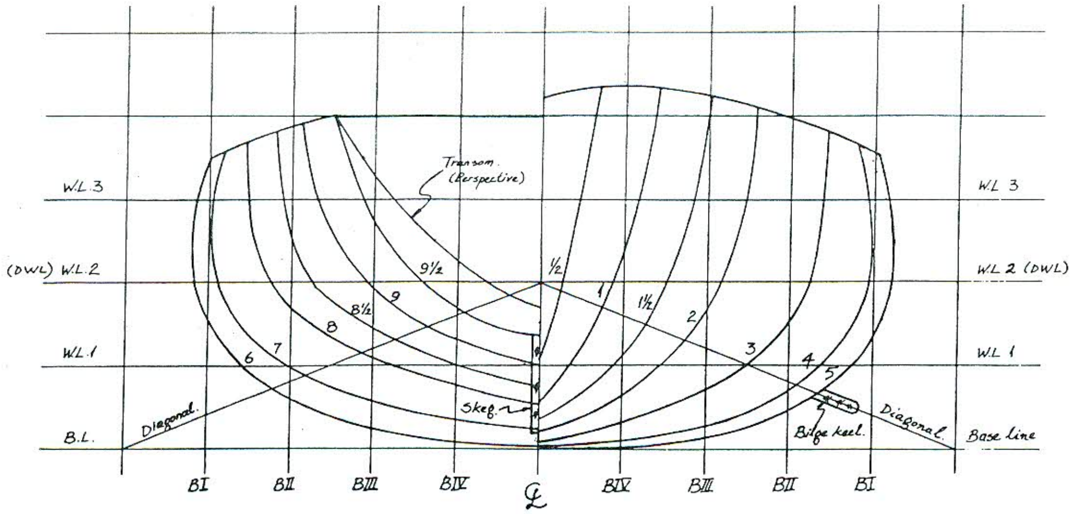

Fig. 1 Body plan of *California II*

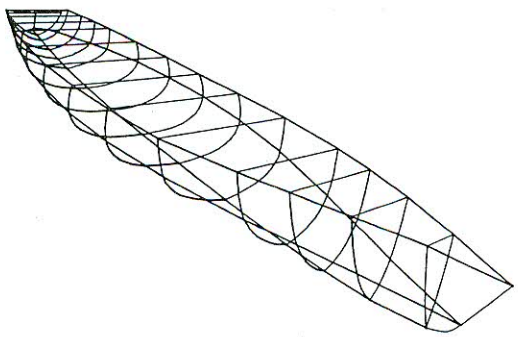

Fig. 2 Perspective view

some hydrostatic properties and form coefficients of the concrete canoe are given in Table 1. Note that the form coefficients are close to the ones for a typical destroyer rather than a cargo liner, as expected. The variation of the displacement (in fresh water) with the draft is shown in Fig. 3. The fully loaded weight of the canoe was determined to be 970 lb, which may be broken down as follows:

hull + skeg + bilge keels	= 220 lb
crew	≅ 720 lb
foam + paddles + life jackets + water intake due to splashing	≅ 30 lb

Since the depth of the canoe is 14 in., a draft of 8 in. leaves a minimum freeboard of 6 in. as shown in Fig. 3.

Because the design drawings were done at 1:4 scale the actual templates had to be scaled up in order to obtain the male-mold sections. Note that the lines in the drawings are the lines of water contact surface; this means that the lines must be reduced for the thickness of the hull (just over ¼ in.) and the mold-form skin thickness (longitudinal laths), typically ½ in. total (see Fig. 4). First the sections taken from the body plan were scaled up with reference to the baseline. Then enough points were drawn at full scale to construct a fair curve. A second line was drawn about ½ in. inside of the first; this would serve as the male-mold station template, the ½ in. being measured orthogonally to the original lines. All the male-mold stations were referenced to a new line as shown in Fig. 4. The design was then ready for construction.

Table 1 Principal dimensions and some hydrostatic properties and form coefficients of the concrete canoe

Length overall	L_{OA}	224	in.
Length at DWL	L_{WL}	217.1	in.
Breadth	B	34	in.
Depth	D	14	in.
Draft	d	8	in.
Displacement (fresh water)	Δ	978	lb
Vertical center of buoyancy	KB_T	5	in
Longitudinal center of buoyancy	LCB	15.5 (aft of midship)	in.
Waterplane area	A_{WP}	35	ft^2
Center of flotation	F	20.7 (aft of midship)	in.
Vertical metacentric radius	BM_T	13	in.
Longitudinal metacentric radius	BM_L	38.7	ft
Weight (hull + skeg + bilge keels)	W	220 (measured on finished hull)	lb
Midship section coefficient	C_M	0.813	
Block coefficient	C_B	0.458	
Prismatic coefficient	C_P	0.563	
Waterline coefficient	C_{WP}	0.684	

Construction

The construction of the canoe can be broken down into four main activities:

1. Hull mold fabrication
2. Reinforcement positioning
3. Concrete design and placement
4. Hull finishing

Since most of the work done on concrete canoes is performed by student groups, the information presented here is applicable to just such a group, although the general construction procedure would be similar for any small "lightweight" concrete boat. Most construction crews consisted of about two to six people; the work rarely required any special carpentry skills beyond the use of common handtools. Working a few afternoons a week, we completed in three to four months, including the time required for the concrete to cure.

The rules established by the hosting ASCE student chapter, as related to the construction of the concrete canoe, were as follows [3]:

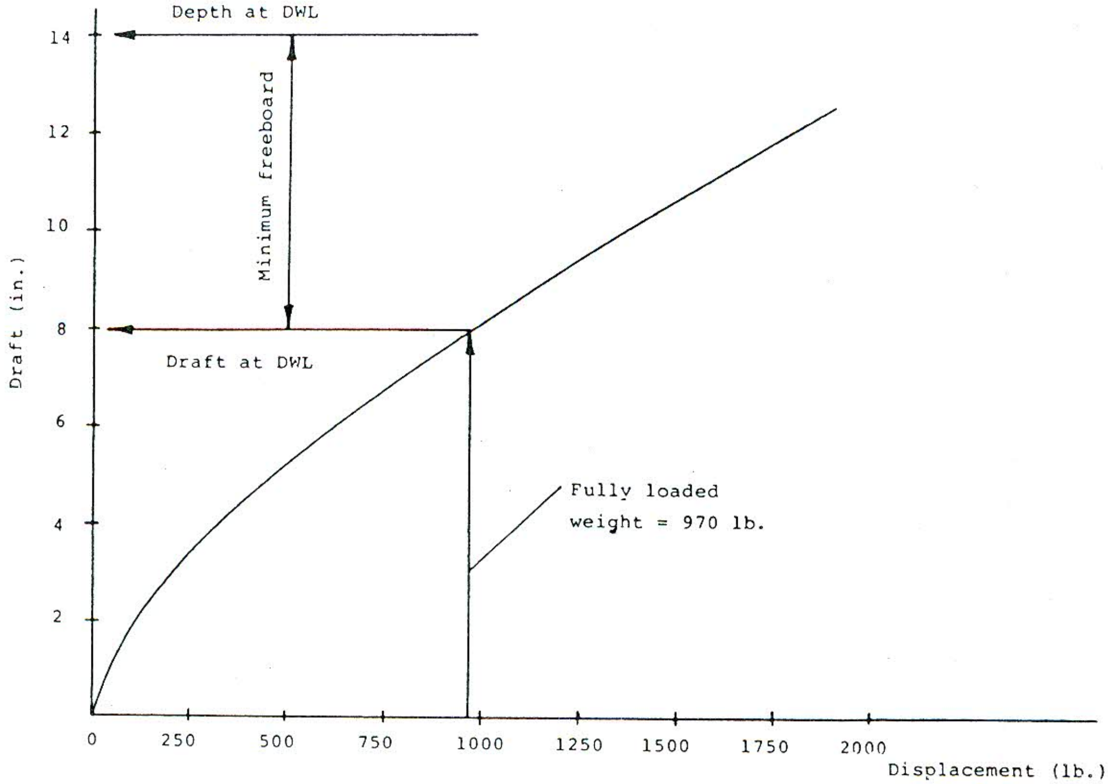

Fig. 3 Displacement-draft relationship

1. Primary binding material must be hydraulic cement.
2. Admixtures may be used by up to 20 percent by weight of cement.
3. Reinforcement must be ferrous.
4. Any keel, if used, must be made of the same material as the hull.
5. Exterior coating may not be a structural material such as fiberglass or any material that would add substantially to the structural strength.

Although there is some latitude in the type of concrete that may be used, it still has to be a steel-reinforced Portland cement concrete. An effective mix design for this special application required that it be lightweight, strong, flexible and impervious. In addition to reproducing accurately the hull design, the canoe had to be constructed within the rules and be a functional boat.

The first step in construction was the fabrication of the mold for the hull. There are two types of molds used on concrete canoes: a mold over which the concrete is placed (male mold) and a mold in which the concrete is placed (female mold). Generally, the side of the concrete which touches the mold will be the smoother side. This would seem to indicate the use of a female mold, which would make smoother the more visible exterior of the hull. However, if a male mold is used, the canoe can be built to scale, only smaller by any amount equal to the thickness of the concrete, which turns out to be the more straightforward method than building the "negative image" of the canoe as would be the case with a female mold.

Construction of the male mold started by cutting out the stations and placing them in a line. Near the bow and stern, half-stations were used to reproduce accurately the large curvatures that occurred at these locations. The actual construction of the stations used in the mold was accomplished by tracing the full-scale drawing of each station onto a sheet of ½- to 1-in.-thick plywood and then cutting it out on a bandsaw. A notch was cut into the bottom of each station so that it could be positioned on a rail on its proper location as seen in Fig. 4. Commonly two 2 × 4 fir rails 20 ft long were spaced about 1 ft apart and the plywood stations were placed normal to the rails—the rail fitting into the notch.

The positioning and the exact shape of the stations were crucial, since a little deviation would be glaringly obvious once the canoe was completed. With the "ribs" in place the next thing to do was to place the "skin."

The skin-like covering material of the mold needs to be very flexible so that it can make the transition from almost a horizontal bottom amidships to almost a vertical hull cross section at the bow. In addition, it must have flexural strength between the stations for the application of the concrete with trowels. Most common materials of this specification come in a planar form such as steel, aluminum or plywood. Because of its avail-

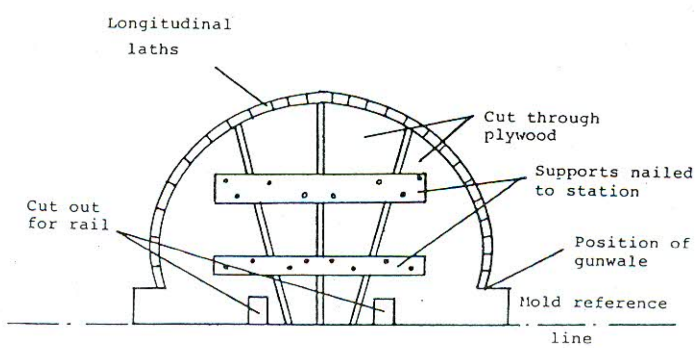

Fig. 4 Male-mold station detail

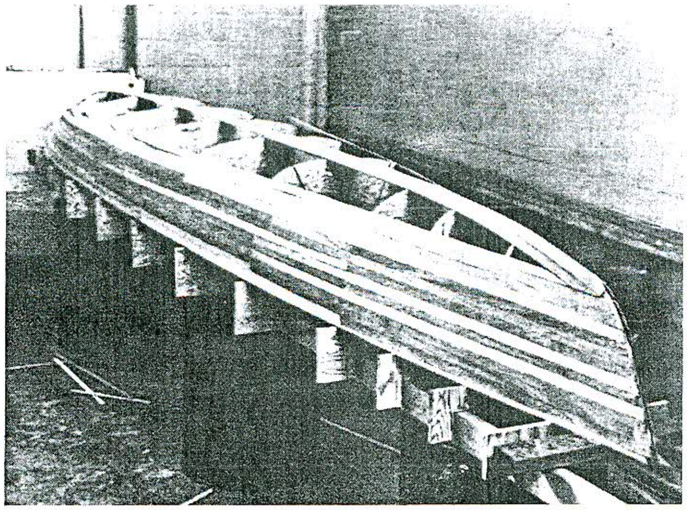

Fig. 5 Male mold under construction

ability, low cost and ease of workability, $\frac{3}{8}$-in.-thick mahogany plywood was used as the skin material by cutting it into thin strips about 1 in. wide. These strips were placed stern to bow and nailed to the stations. This method served to make a very smooth mold, and essentially a beautiful wooden boat which would have to be destroyed after the concrete was placed and had cured (see Fig. 5). It would be desirable to reuse the canoe mold since a considerable portion of the construction time was spent constructing the mold as can be seen in Fig. 6. However, the form couldn't be lifted out without breaking it because of the tumblehome of the midship section and the reverse transom. If one wants to reuse the mold then an answer would seem to be to have the mold on the outside and place a joint in it along the keel. This would be a split female mold. It has its own drawbacks in that it is difficult to place concrete from the inside; it is also tough to get the seam to match precisely. Because of these difficulties, a male mold was preferred to a female mold. The mold was covered with plastic sheeting so that it would not absorb any of the water from the concrete, and then reinforcement was placed.

Because the hull was so thin—nominally $\frac{1}{4}$ in. by design—there was insufficient thickness to develop anchorage of standard reinforcement bar. Therefore, wire mesh or hardware cloth of various grid sizes was used. Based upon previous flexural testing done on wire mesh reinforcement in thin slabs [4], it was determined that the use of two layers of wire mesh, $\frac{1}{4}$ in. and 1 in., would be suitable. But there was the problem of making a plane (wire mesh comes in a roll) conform smoothly to the curved surface of the mold; even $\frac{1}{4}$ in. wire mesh is quite stiff. The solution was to cut the rolls into 6- to 10-in.-wide strips to make for greater flexibility, just as with the wood slats. The final solution to the problem of no tension reinforcement along the seams was to place the $\frac{1}{4}$-in. mesh strips stern to bow and the 1-in. mesh strips gunwale to gunwale, thus providing tension and shear reinforcement in all directions and a flexible and workable reinforcement scheme. Once the reinforcement was tacked down to the mold it was ready for what we all came to do.

Concrete!

In combination with the reinforcement scheme, a relatively high-strength, lightweight and impervious mix had to be developed to complete an effective ferrocement hull. In addition, workability was crucial as the placement had to be done entirely by hand on nearly vertical surfaces with high curvatures, dictating a very stiff plastic mix. The significant deviations from a standard portland cement concrete were the use of micro silica fume, polystyrene beads as lightweight aggregate, and 1-in. stainless steel fibers.

The use of the silica fume, for the first time in UC/Berkeley's concrete canoe efforts, improved significantly the strength of the concrete. Silica fume is an efficient pozzolanic material being used only rather recently as an admixture to concrete [5]. It has a high reactivity with portland cement, primarily due to its very high specific surface: 4000 ft^2/lb. By reacting with the hydrated lime, silica fume can produce a higher strength in the concrete than would be otherwise obtained. As shown in Fig. 7, the silica fume replaced the cement by about 14 percent by weight and yielded a compressive strength of about 3900 psi with unit weight of 90 lb/ft^3; this was 30 percent higher strength than had ever been achieved before. Nevertheless, silica fume does increase the water demand in general so plasticizers must

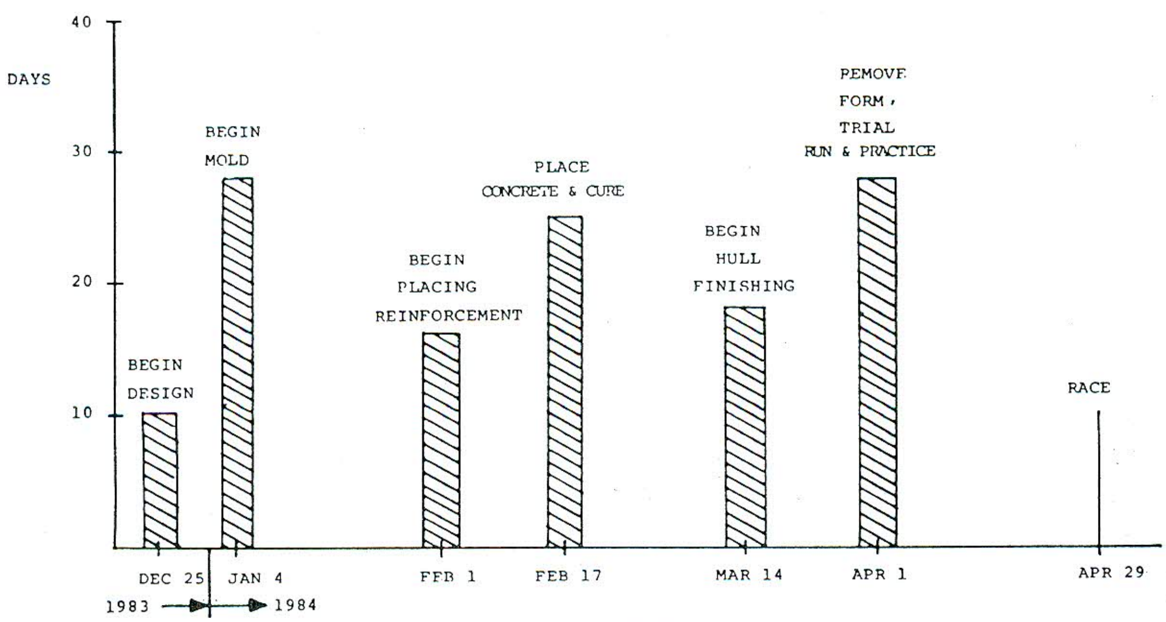

Fig. 6 Work schedule

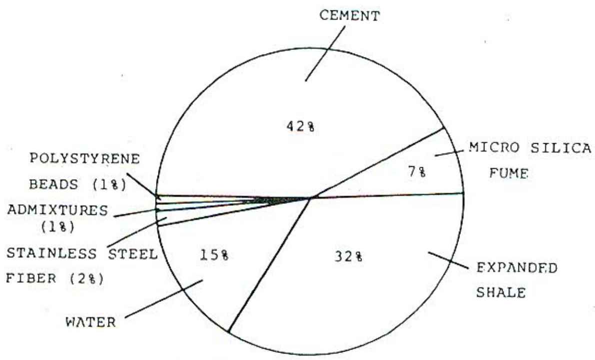

Fig. 7 Concrete mix (% by weight)

be used to keep the mix workable. This was not such a large concern since we wanted a very stiff mix—a slump of zero inches. The type of cement used was a blend of portland Type I and Type K. This was done to reduce shrinkage and resultant cracking upon curing.

In order to achieve a lightweight mix, two types of aggregates were used: expanded shale and polystyrene beads. The shale was used as the fine aggregate and the polystyrene was used as the coarse, the latter having no contribution to the strength but providing uniform air voids and a lightweight mix.

Flexural strength was very important because of the thinness of the hull. In order to accomplish this, 1-in. stainless steel fibers [6] were added to the concrete mix to provide outstanding shear reinforcement. Even after a complete local failure, that is, after a punching shear, the concrete stayed intact. This property is very desirable; it is a sort of fail-safe, particularly below the waterline.

The concrete was placed using metal trowels and worked and reworked until a smooth finish was obtained, about seven hours from initial mixing. This portion required about ten workers as only a small area can be worked effectively by one person. The concrete hull was then covered with wet burlap and plastic, and allowed to cure for 28 days. The resultant cured hull was quite smooth. Then the most boring job started: sanding and filling and resanding and refilling.

The Canoe Committee has long been upon the quest for the ultimate filler that complies with the rules. Fillers that are waterproof are hard to sand; those that sand easily are water soluble. The solution was neat cement paste, which was used for the first time. It sanded easily for a few days after placement and was waterproof. Nevertheless, it was tricky to work with. By wetting the hull and covering the fill with plastic we were able to avoid any significant cracking. This technique has not been perfected by any means, but it was felt that it was the solution to the filler problem—especially since it worked and allowed us to complete the canoe.

Once the hull was smooth on the outside, the form was removed from the inside, and then the dramatic moment arrived: What did it weigh? *California II* weighs 220 lb. This is heavier than the previous year's canoe but it is also larger. On the basis of the surface area to weight ratio, it is similar to the previous year's. After weighing, the inside was filled and sanded and polyurethane foam was installed near the bow and stern for adequate buoyancy that provided an unsinkable boat. At that point we took the canoe out for a trial run by the women's, faculty and men's crews. Being able to see how the canoe handled before the race was a great advantage. The performance was everything we had hoped for—much greater stability and tracking.

Once back from the trial run the canoe was painted with a hull-type paint (Z-Spar brand); then the design was masked off and painted (see Fig. 8).

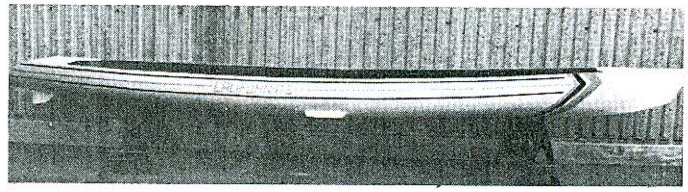

Fig. 8 *California II* after completion

Summary and conclusions

The 1984 ASCE concrete canoe *California II* has drawn upon the success of past canoes: the type of mold, method of fabrication, the use of steel fibers and the general sailboat-type hull. It has also some new features: bilge keels, micro silica fume concrete and no reinforcing bars. Even though the main body of the ASCE concrete canoe rules remain the same, every year a few changes are made. One of these changes in 1985 rules [7] will be permission to use nonferrous fibers (maximum of 1.5 lb/yd^3 of total mix) in the hull mix.

In addition to the time spent on the design and construction (see Fig. 6), practice for the concrete canoe race started in early April 1984. Four crews (two men's teams, two women's teams) of four people each took the time to practice once a week. The 1984 ASCE concrete canoe (mid-Pacific region) races were organized by the ASCE student chapter of California State University at Chico. *California II* helped UC/Berkeley crews win second place in both men's and women's races and third place in the faculty races among about 12 universities that participated. As in the last four years, UC/Berkeley's 1984 concrete canoe was chosen as the best designed and constructed canoe in the mid-Pacific region and was awarded as such by the ACI.

Over 30 students helped make *California II* possible by giving their time. Therefore, we dedicate this paper to each and every one of them. It is also hoped that this paper may serve to encourage others, at all universities, to participate in future concrete-canoe competitions.

Acknowledgment

We wish to thank Professor William C. Webster of UC/Berkeley for providing us with the hydrostatic computations and plotting programs.

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Metric Conversion Factors

1 ft = 0.3048 m
1 in. = 25.4 mm
1 lb = 0.45 kg
1 psi = 6.895 kPa
1 lb/ft^3 = 16.018 kg/m^3