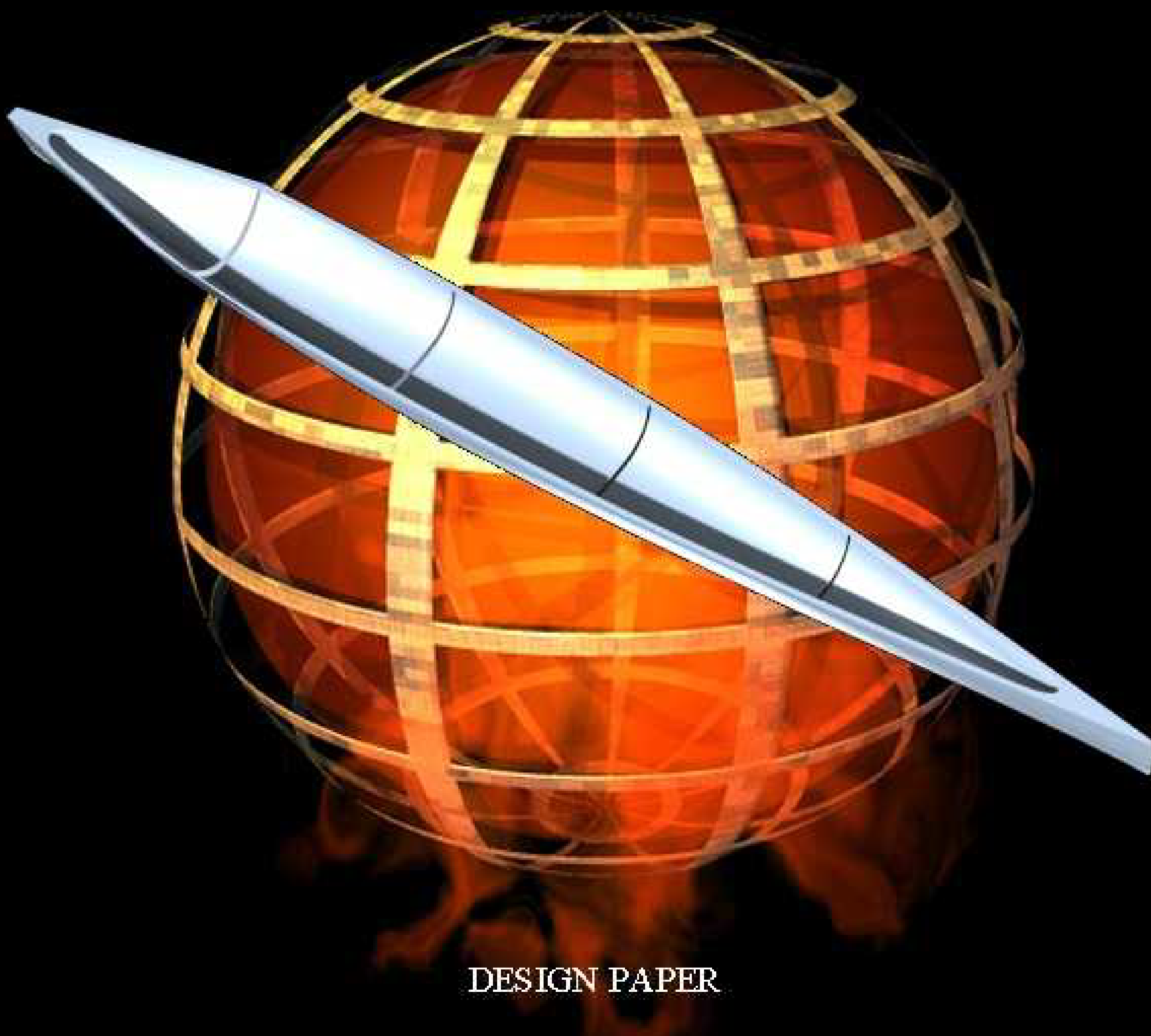
@pocalypse 2001

C O N C R E T E   C A N O E



DESIGN PAPER

UNIVERSITÉ
LAVAL

1. Introduction

Université Laval was the fourth university founded in America and is the oldest one in Canada. Each year, it welcomes more than 30 000 students in its 12 faculties, 8 schools and many research centers. Its engineering programs appeared in 1947 and are continuously ahead with new technologies and, through the years, its outstanding teaching quality has always been maintained. Université Laval is located in Quebec City known especially for its cultural, historical and tourist attractions.

In its first two years of existence, Université Laval's Concrete Canoe Team won the Canadian competition and also did well at the North American level finishing 21st in 1996 and 12th in 1997. In 1998 and 1999, the team has reached the second place at the Canadian competition. Last year, with *SC Minnow* [1], the team won the Canadian competition and finished 9th overall in Colorado with an outstanding 2nd place for the final product. For the past five years, Université Laval's team has carried off the award for "Exceptional Quality of the Final Product" at the Canadian level.

This year, the dark blue shade of the canoe and the red and yellow letters symbolizes darkness and fire representing the *Apocalypse*; the end of the world and the beginning of a new era. With its 6.40 m length, its 0.70 m width and its depth, from bottom to gunwale, of 0.29 m, *Apocalypse* has a total weight of only 39.5 kg (87.1 lb). The development of two extremely light concrete mixes has contributed to obtain, once in place, specific dry weights of 520 kg/m³ (32.5 lb/ft³) and 675 kg/m³ (42.2 lb/ft³) with compressive strengths of 7 and 25 MPa (1015 and 3625 psi) and tensile strengths of 1.2 and 2.2 MPa (174 and 319 psi). *Apocalypse*'s hull has a thickness of 8.5 mm and is composed of a multi-layer concrete composite. The interior and exterior layers are made of HIGH RESISTANCE concrete reinforced with carbon fiber mesh and the middle layer is made of LIGHTWEIGHT concrete in order to optimize the strength/weight ratio. Furthermore, considering the poor performance of last year's team during the races in Colorado, the dimensions of the hull and the asymmetrical design were completely changed to improve straight-line speed, maneuverability and directional stability.

2. Hull Design

2.1. Theory

The first parameter to consider is straight-line velocity. The total drag force of the canoe in racing is equal to the sum of the wave drag and the skin drag. The wave drag is mostly related to the length and the shape of the hull while the skin drag is proportional to the wet surface [2]. Several factors must be accounted for. First of all, the smaller the surface under the water line, the less friction there will be and therefore creating less skin drag, which translates into a gain in speed. Secondly, a higher submerged length to width ratio helps to create a more hydrodynamic hull that will slice through water more easily, thus reducing wave drag and producing a gain in speed.

The second parameter is maneuverability. The longer the canoe, the more resistance there will be while turning. The most radical solution to increase tacking maneuverability is to reduce the length of the canoe. However, since the main objective is to privilege speed, the optimization of the rockers is the most practical alternative in order to achieve good tacking capability.

The last parameter to consider is the stability of the canoe. It is defined as the ability of the hull to resist heeling over. In effect, for small heeling angles, buoyancy principle comes about. Buoyancy force will generate bigger moments on the canoe than the moments generated by the heeling [2].

2.2. Canoe Configuration

Following the disappointing performances during last year's races, the paddlers team has decided to adopt a more aggressive style of paddling. To achieve this purpose, the shape of the canoe had to follow the same tendency. In such a case, *Apocalypse*'s dimensions were inspired by a C-2 Olympic canoe (see Appendix A-1). *Apocalypse* is 6.4 m long and 0.7 m wide with a high length to width ratio of 9.14. In comparison with last year's canoe, *S.C. Minnow* [1] offered a length to width ratio of only 7.85. In order to maintain good maneuverability, the designers decided to keep the same draft and proportional rockers. Besides, the stern « V » shape allows to heel the canoe and to keep it stiff during tacking motions. Heeling distorts the wet surface asymmetrically, permitting easier and faster turns. This way, the canoe itself can go faster and it still has good maneuverability.

The preliminary design was made with the help of a computer program created by the designers. The main parameters obtained were then used in a specialized design software to proceed with the design of the final shape. Final characteristics of the canoe are presented in Appendix A-2.

The construction and testing of a fiberglass prototype allowed the team to notice and correct mistakes made during the construction of the mould. These imperfections were revised and changed before the concrete canoe construction. Also, comparative tests between last year and this year prototypes permitted to conclude that the new design is approximately 3 seconds faster on a 100 m stretch.

3. Concrete Mix Design

3.1. Objectives

From the beginning of the development of the concrete mix, the following objectives were established in order to respect the modifications on rules and regulations and to solve problems observed with the previous year mix design:

- Decrease the specific weight of the concrete to eliminate sealed cavities;
- Control compaction and air loss during casting;
- Improve concrete binding to facilitate the construction and to eliminate debonding risks between layers;
- Decrease the absorption and permeability of concrete.

3.2. Research and Development Procedure

The first step was to determine the concrete properties in order to optimize the total specific weight (and therefore the total mass) of the canoe while preserving the hull strength. Two different options were studied: using the same concrete mix for the whole hull or a multi-layered disposition with stronger concrete on the surfaces and lighter concrete in the middle. Calculations demonstrated that a multi-layered disposition permitted reaching a lower total specific weight for the same hull strength.

In order to solve the problem of compaction and air loss during casting, the concrete mix design team studied a new approach. Instead of increasing the air volume to obtain a lighter concrete mix, the objective was to use more effective and lighter aggregates while keeping a minimum air volume. This approach allowed to have a better control of the concrete properties during casting while directly increasing concrete performances.

The second step consisted of material research necessary to the development of concrete mixes, particularly lightweight aggregates and supplementary binders to cement. Aggregate research led to glass bubbles with density varying from 0.25 to 0.46. The particle size distribution of this material (particle diameters from 15 to 105 micrometers) permitted an excellent compactness of the granular skeleton recalling the basic principles of the development of high-strength concrete (HSC). These bubbles also possess noticeable mechanical resistance; therefore, they don't behave as shortcomings in the matrix, they increase the concrete strength.

Since the concrete mixes had to reach good performances, several combinations of binders have been studied. Silica fume, because of its pozzolanic properties, reacts during the cement hydration to form an additional binder and to increase concrete strength. Moreover, it decreases concrete porosity, reducing water absorption of concrete. The latex solution (45% of solid binder by mass) increased the workability of concrete as well as its tensile strength while reducing permeability of the hardened concrete. Latex and silica fume also permitted to increase the quality of the binding between concrete layers and to decrease the specific weight.

Testing took place until the desired properties were obtained. Compressive strength of different mixes were tested on 50 mm side cube specimens according to ASTM C519 standard. Tensile strength was also verified with the help of a center-point loading flexural test on prisms of 40x40x160 mm according to ASTM C293 standard. These tests were performed after 7 days of curing and at 28 days to determine the strength gain progression of those new concrete mixes. For the last mixtures, a more representative testing method was necessary to support the hull resistance calculation model that will be explained in the composite action section. Therefore, the final concrete mixes were tested in compressive strength according to ASTM C39 standard, in tensile strength according to ASTM C496 splitting tensile test and Young's modulus was determined according to ASTM C469 standard on cylindrical specimen of 50x100 mm. The detailed results are presented in Appendix B-2.

3.3. Concrete Mix Selection

The final concrete mixes presented in Appendix B-1 are composed of Type I cement, silica fume, water and latex as binding materials, of K46 glass bubbles as lightweight aggregate and of superplasticizer. As mentioned previously, a composite section made of a HIGH RESISTANCE concrete at both interior and exterior surfaces and LIGHTWEIGHT concrete mix in the middle appeared as a better solution to optimize the total specific weight of the canoe and the hull strength.

Table 1: Trial Mixtures *vs* Final Mixtures

	2000 Mix		Mix #7		Mix #34		HIGH RESISTANCE		LIGHTWEIGHT	
	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days
Compressive (MPa)	6.7	10.4	3.3	5.1	7.7	10.1	14.0	24.6	4.1	7.2
Tensile (MPa)	0.75	1.25	0.35	0.55	1.10	1.65	1.65	2.20	0.89	1.22
Modulus (MPa)	2100	2720	1450	1820	2300	2620	3950	5280	1010	1343
Air content (%)	22		22		12		1.45		1.7	
Spec. Weight Dry (kg/m^3)	728		703		721		675		520	

After 28 days of curing, the HIGH RESISTANCE concrete has a compressive strength of 24.6 MPa (3567 psi) and a tensile strength of 2.20 MPa (319 psi) with a specific dry weight of 675 kg/m^3 (42.2 lb/ft^3). The LIGHTWEIGHT concrete has a specific dry weight of only 520 kg/m^3 (32.5 lb/ft^3) with a compressive strength of 7.2 MPa (1044 psi) and a tensile strength of 1.2 MPa (174 psi). As presented in table 1, these properties are a great improvement in comparison with the previous years and even more in relation to the range of usual lightweight concrete [4] presented in Appendix B-2. These concrete mixes allowed the construction of a very light and resistant canoe.

4. Reinforcement

4.1. Objectives

Reinforcing material selection and layout were important steps in the structural design of the canoe. In order to decrease as much as possible the total specific weight of the canoe and to satisfy the new flotation regulations, the goal was to find low-density materials that offered sufficient structural rigidity and would prevent cracking.

4.2. Material Selection

Different carbon fiber and fiberglass meshes were considered. The first research was oriented on a very light bi-directional carbon fiber mesh with a modulus of 220 GPa that allowed a good composite effect with the concrete. On the other hand, the mesh was made out of discontinuous carbon fibers that could not offer enough tensile strength to local efforts occurring under the paddlers in the canoe. Therefore, the team looked for a plain bi-directional carbon fiber mesh with continuous fibers and a high modulus of 300 GPa. With a higher modulus, reinforcement offered a better structural and local resistance. The plain carbon fiber mesh also allowed the designers the possibility to optimize the quantity and the spacing between yarns. Optimization was made in accordance with all the rules and requirements of solid mat reinforcement [3] on one hand and according to concrete shear stress requirements at the interface of reinforcement layers on the other hand.

A bi-directional carbon fiber mesh with a thickness of 0.3 mm and with continuous yarns of 0.15 x 1 mm was finally chosen because it offered the best potential of optimization in relation to a thicker and stronger mesh. Otherwise, to prevent cracking, previous year experiences have proven that a fiberglass mesh on each surface gave excellent results. The calculations of reinforcement material thickness are presented in Appendix C-1.

5. Composite Action

5.1. Objectives

The reinforcement layout was optimized in order to get better composite action with concrete and a more resistant hull while using the minimum amount of reinforcing materials.

5.2. Procedure

In the past years, a third-point loading flexural test was made on hull section specimens using a very precise procedure in order to determine a unit bending moment in kN•m/m. Combined to the behavior of the hull during races, it was possible to use the minimum limit value of 0.1 kN•m/m, permitting to avoid any cracking problems. A theoretical calculation model was elaborated according to the mechanical properties of every material. This model permitted to finalize the optimum layout without making a lot of trial sections. Comparative results between theory and experiments are presented in Appendix D-1.

5.3. Composite Section Selection

The final choice of composite section was four layers of bi-directional carbon fiber mesh designed by removing three yarns out of five in the two directions, placed on each surface of the hull and impregnated in the HIGH-RESISTANCE concrete. In order to increase the section inertia, a removable spacer of 3.8 mm diameter was used. This spacer also allowed to include flotation material (LIGHTWEIGHT concrete) between reinforcement layers and to keep uniform hull thickness. This configuration made a more rigid and resistant hull than the previous ones with a lower specific weight.

5.4. Load Distribution

To limit direct efforts on the hull, the designers judiciously placed reinforcing ribs under the paddlers knees. Therefore, more important efforts are oriented to the stronger elements of the structure. The same way, structural gunwales receive the most part of the global efforts that the canoe is submitted to during race maneuvers and transportation.

6. Construction

6.1. Mould

Apocalypse is constructed on a male mould constituted of 122 polystyrene sections with a thickness of 51.8 mm assembled on a rigid wooden base that is also used as a gunwale guide as presented in Appendix E-1. A plastic sheet covers the mould to get a good interior finish.

6.2. Fiberglass Prototype

The prototype was built on the mould and is constituted of five layers of fiberglass tissue impregnated in polyester resin. Wooden gunwales and transverse bars were used for stiffness.

6.3. Concrete Canoe

Ribs were made directly on the mould just before the canoe construction began, as illustrated in Appendix E-2. The carbon fiber mesh layers are impregnated with the HIGH RESISTANCE concrete. Carbon yarns were also placed perpendicularly to the ribs in order to anchor them to the hull.

Hull construction was made as shown on the cutaway view in Appendix E-3. The first fiberglass layer, as well as two layers of carbon fibers, are impregnated with the HIGH RESISTANCE concrete. A 3,8 mm diameter spacer was installed perpendicularly to the canoe. A layer of LIGHTWEIGHT concrete was applied with a trowel using the spacer as a glide plate to ensure constant hull thickness. Once this layer had hardened, the spacer was removed and the two layers of carbon fiber mesh as well as the last layer of fiberglass were impregnated with the HIGH RESISTANCE concrete. To avoid concrete drying during construction, the relative humidity in the construction area has been increased near 100%.

The gunwales were made with the edge extension of carbon fiber meshes and fiberglass used in the hull. These reinforcing materials were folded under the mould and impregnated with HIGH RESISTANCE concrete as shown in appendix E-4.

6.4. Curing and Finishing

The canoe was cured for 28 days. To keep the relative humidity close 100%, daily watered towels under a plastic sheet were used. The outer surface of the hull was sanded while curing and the imperfections were corrected progressively with HIGH RESISTANCE concrete mix.

Unmoulding followed the 28 days curing and minor corrections were made to the inner surface of the hull. Two thin primer coatings were sprayed and sanded in order to get a perfect surface. The products used (primer, paint and clear coat) are made of two polyurethane components.

7. Project Management and Cost Assessment

7.1. Team

At the beginning of the year, 2 captains were chosen among the team veterans. Different committee leaders were named by the captains to ensure that all the necessary tasks would be performed. Each committee had numerous task-oriented sub committees; The Fundraising committee created a promotional brochure to help sponsorship, looked for sponsors and kept an eye on the project costs. The Structural Design committee developed a concrete mix and a reinforcement layout to provide an outstanding final product. The Hull Design committee elaborated a completely new hull design to obtain excellent times in the races. The Academic committee was in charge of the design paper, the oral presentation and the display. The Paddle team was responsible for pool renting and practicing. Finally, all team members helped for canoe construction.

7.2. Project Management

In September, an information presentation was given to all new students by last year's members and by the Civil Engineering Department. After the presentation, an orientation meeting was held for people interested in the project (showing of previous canoes, lab and a canoe race between members). One week later, committee leaders were named among members from last year and new members were assigned to committees based on their interests and experience. Committee leaders had the responsibility of passing on the knowledge of past successes and failures. This method of working permitted to integrate new members in the team and to assure continuity of the project for years to come. Collaboration between the different sectors was assured by a weekly meeting of all teammates. Committee leaders reported work evolution and problems encountered in order to find some solutions to help progress in the realization of the project. A diagram shown in Appendix F-1 illustrates the schedule that was determined at the beginning of the year and which the team followed.

7.3. Cost Assessment

All year long, materials used were cataloged in an inventory notebook kept at the concrete canoe lab. A time sheet was also kept in the lab so that everyone could note his or her working hours. Every week a secretary compiled all the information. So, with this information, the costs associated with *Apocalypse* development and construction are estimated and detailed in Appendix F-2. In short, development costs added to $66 274 including $65 064 for labor. Construction costs added to $60 760 including $58 664 for labor. The total cost for the project added to 127 034$.

8. Summary

Finally, after a lot of work and efforts, research, design and development objectives were achieved with success and Université Laval's Concrete Canoe Team is proud to present to the public the outcome of their ingenuity. With its multiple innovations: Better concrete, new reinforcement and redesigned hull. *Apocalypse* has all the requirements and capabilities to reach the top 5. *Apocalypse* is lighter and more resistant than *S.C. Minnow* [1] and its new design allowed the paddlers to gain more than 5 seconds in 200 m races at the Canadian competition.