DESIGN PAPER

PRESENTED TO THE JUDGES OF THE NATIONAL CONCRETE CANOE COMPETITION
2002 EDITION

UNIVERSITY OF WISCONSIN
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Quebec today, the World tomorrow

QUEBEC CITY
MAY 2002

We, Simon Blais and Maxim Morency, Captains of Université Laval's Concrete Canoe Team, certify that the canoe we have built is in accordance with all the rules and requirements of the 2002 National Concrete Canoe Competition. We also attest that all of the official members of our team are Engineering students and that all of them have actively participated in the development and completion of this project. Furthermore, we certify that the canoe we present has been conceived, designed and built during the present academic year, 2001-2002.

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Simon Blais

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Maxim Morency

Concrete Canoe
Team Captain
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Table of Contents

1. Introduction

Université Laval was the fourth university founded in America and is the oldest in Canada. It is located in Quebec City, which is especially known for its cultural, historical, and touristic attractions. Each year, it welcomes more than 35 000 students in 17 colleges, 63 departments and schools, and many research centers. Its engineering programs were founded in 1947, and continuously stay ahead with new technologies. Through the years, its outstanding quality of teaching has always been maintained.

In its first years, Université Laval's Concrete Canoe Team won the Canadian competition twice. It also did pretty well at the North American competition finishing 21st in 1996, and 12th in 1997. In 1998 and 1999, the team earned second place at the Canadian competition. In 2000, with the *S.C. Minnow*, the team won the Canadian competition, and finished 9th overall in Colorado with a 2nd place for final product. Last year, after winning the Canadian competition, Laval's team finished 4th overall and the *Apocalypse* won the prize for the best final product. For the past six years, Université Laval's team has always earned the award for "Exceptional Quality of the Final Product" at the Canadian level and is constantly improving.

This year, the dark red shade of the canoe, the mountain and the red and yellow letters symbolize the UL-team in working to reach the highest peak; a team reaching its *Apogee*. With a length of 6.48 m (21' 3"), width of 0.70 m (27.5"), and depth, from gunwale to bottom, of 0.33 m (13"), the *Apogee* has a total mass of only 34 kg (75 lb). The development of extremely light carbon micro-fiber reinforced concrete mixes has helped to produce a HULL mix with a dry density of 670 kg/m^3 (41.9 pcf) with outstanding properties such as a 7 day tensile strength of 4.7 MPa (682 psi), elastic modulus of 4950 MPa (718 ksi) and compressive strength of 18.6 MPa (2697 psi). The *Apogee*'s hull is 7 mm thick and is reinforced with four layers of carbon fiber and two layers of fiberglass meshes in order to optimize the strength/weight ratio. The hull is also stiffened with four ribs made out of a more resistant concrete mix (RIBS), which has a 7 day tensile strength of 6.7 MPa (972 psi), and is reinforced with carbon yarns. Furthermore, considering that last year's the *Apocalypse* had a hard time turning in races, but performed very well when paddled in straight line, the hull design was modified in order to keep the *Apocalypse*'s straight-line speed, but get back the *S.C. Minnow*'s maneuverability. All things considered, the *Apogee* is the most optimized and well-designed canoe that has ever been built in Laval's laboratory.

2. Hull Design

2.1. Theory

There are three important parameters to consider when designing a canoe. The first parameter is the drag force, which limits the straight-line velocity. The total drag force is the sum of the wave drag and the skin drag. A long and narrow hull with slender ends generates less wave drag. The skin drag is directly proportional to the wetted surface area, which is decreased by using V shapes.

The second parameter is maneuverability. For a given water displacement, a long and narrow canoe has a higher keel which increases the resistance while turning. Rounder shapes help to maintain a lower keel. Although, raising the rockers increases taking capabilities but decreases tracking.

The last parameter of importance is stability. Since only very skilled paddlers will be asked to use this year's canoe, stability is not considered to be a factor in the present optimization.

The 2001 canoe, the *Apocalypse*, was a fast and easy tracking canoe, but it lacked maneuverability and nimbleness, which are necessary to perform in the slalom race and in the sprint race turn. In 2000, the *S.C.Minnow* was more maneuverable but its speed was limited. To increase performance, this year's canoe must be at least as fast as the *Apocalypse* and as maneuverable as the *S.C.Minnow* (Appendix A-1 shows both models specifications).

2.3. Canoe Configuration

The new design has the same dimensions as the *Apocalypse* in order to keep its narrowness and slenderness. The *S.C.Minnow*, which was rounder with a flatter bottom than the *Apocalypse*, has inspired new shapes. Rocker optimization is also based on the *S.C.Minnow* parameters. Appendix A-2 presents the average speed reached in 2001 races and the total drag produced at these speeds for each model. The drag force corresponds to the force that the paddlers can develop in races. The new shapes were optimized in order to increase the hull speed for a specified drag value, hence producing a faster canoe. The lateral wetted plane to length ratio is used to optimize the amount of rockers in order to obtain an easily maneuverable canoe (Appendix A-3). The 2002 model is 6.48 m long, 0.7 m wide and 0.33 m deep with bow and stern rockers of 60 mm. Its final specifications are presented in Appendix A-4.

3. Structural Design

3.1. General Objective

The main objective is to optimize the structural design in order to obtain a strong, stiff and light hull. A lighter canoe is easier to race, and hull stiffness makes paddle strokes more efficient. Since Laval started building concrete canoes, the lightest canoe was the *Arkonak* in 1997 with a mass of 32.4 kg (72 lb); the *Apogee* must match this.

3.2. Research and Development Procedure

The structural design has been studied as a big puzzle in which all pieces are interdependent. The development of the concrete mix, the reinforcement materials and the composite action must be interwoven in order to achieve the best result. A finite elements model has been used to evaluate stresses and strains in the hull structure and to assess the material properties requirements.

The total weight of the canoe can be decreased by the use of a lighter concrete mix. Since the mix developed in 2001 had an almost ideal density, it was decided to design a thinner hull. Then, the concrete must be more resistant to deformation and ribs more efficient to keep the same structural stiffness. Tensile strength and elastic modulus are the most important properties to consider when optimizing the concrete mix and the composite section.

3.3. Finite Element Model

The entire structure of the canoe, including ribs and gunwales, has been modeled using finite element analysis software. The ribs and gunwales have been redesigned in accordance with the 2002 rules, and the new dimension limitations tend to decrease their efficiency. The analyses have been made using four loading patterns: simply supported at each end, upside and upside-down (moving and display patterns), and on water with two and four paddlers (racing patterns). The model has been used to assess the least hull thickness that could be used considering the composite section and rib properties in order to keep the most critical stress below the tensile strength of the concrete. This stress criterion is a protection against the development of structural cracking. Furthermore, the deflection must be kept under 5 mm while the canoe is simply

supported. This displacement criterion, based on the past years experience, ensures that the canoe will be stiff enough and efficient on water.

3.4. Concrete Mix Development

In order to achieve the objective, the concrete mix must have a higher tensile strength while keeping almost the same density as last year High-Resistance concrete (Table 1 – Mix 2001). The elastic modulus must also be at least the same. Therefore, the new concrete mix should be an evolution of the 2001 mix.

The first step was to replace the normal cement by super-white cement and the silica fume by metakaolin respectively. These changes are motivated by aesthetic considerations for the unfinished band. Metakaolin possesses almost the same pozzolanic properties as silica fume, and reacts during the cement hydration to increase the strength and to reduce the water absorption of concrete. The second step was to replace latex by a new water-based epoxy resin in order to increase mechanical properties (Table 1 - Mix #2). The resin also increases the bonding between layers during construction and for the finish corrections. The last step was to add carbon micro-fibers (3 mm long) to replace part of the glass bubble aggregates while optimizing the particles compactness (Table 1 - Mix #11). With the addition of micro-fibers, the material has a ductile behavior; the ultimate tensile strength (flexural strength) is thus higher than the elastic limit stress corresponding to the end of the linear behavior (Appendix B-1). Concrete tensile properties are efficiently improved by micro-fibers. On the other hand, they tend to decrease the workability and the compatibility of concrete with some reinforcing meshes. Because of the particle size distribution of the lightweight glass bubble aggregates (particle diameters from 15 to 105 micrometers) it is possible to get excellent particle compactness that helps to achieve higher mechanical properties.

Tensile strength was assessed by a third-point flexural test, according to the ASTM-C1018 standard, on 160x30x7 mm thin plates in order to obtain a value corresponding to the hull resistance. Tensile strength is defined here as the stress generated when the material has reached its elastic limit. At that point, micro-cracks appear though they are not yet visible to the naked eye. Tensile strength is used as the upper limit in the finite elements analysis. The flexural strength is used in the predictive calculation of the composite section resistance (described in 3.6). Compressive strength was assessed following the ASTM-C39 standard on cylindrical specimen of 50x100 mm. Elastic modulus was measured during the flexural test according to ASTM-C1018 standards (details about the flexural analysis are presented in Appendix B-1). It was also measured in compression tests according to ASTM-C469 to check the flexural value. The whole structural design was made with the material properties measured after 7 days of curing.

3.5. Reinforcement Materials Development

The objective of the reinforcement material research was to find low-density materials that offered sufficient structural rigidity to the hull and could prevent cracking. Reinforcement also had to be compatible with the lower workability of the micro-fiber reinforced concrete mix.

Previous years experience proved that a fiberglass mesh on each surface is efficient to prevent cracking. It is also useful as a sanding guide. The fiberglass mesh has a thickness of 0.2 mm and each yarn has a 2 mm spacing and an elastic modulus of 95 GPa (138,000 ksi), measured experimentally following a tension test method based by the ASTM-E111 standard.

The carbon mesh used in 2001 had a very high modulus [300 GPa (435,000 ksi)] and was very efficient to reinforce the hull structure. Unfortunately, the yarns' pattern in the mesh was too

easy to disturb while placing the concrete and was not compatible with the new concrete mix. Research was therefore oriented towards using a manufactured scrim carbon mesh that is more consistent with the new concrete workability and allows a better composite effect. This carbon mesh is 0.5 mm thick with 6 mm spacing between yarns and has an elastic modulus of 220 GPa (319,000 ksi).

Since the ribs had to be more efficient than in the past years, it was decided that yarns from the 2001 carbon mesh should be used to reinforce these ribs. Each yarn is 1mm wide and 0.15 mm thick.

3.6. Composite Action Development

A theoretical calculation model, based on the transformed section theory taken from the mechanics of materials, has been used to design the reinforcement layout of the composite section. Considering past years experience, the section should possess a unit bending moment higher than 0.100 kN·m/m in order to avoid any cracking problems of the hull. These calculations were checked experimentally by a flexural test on composite section plates (ASTM-C1018) to assess the elastic modulus of the composite. Rib sections were also tested and the results were used in the finite element model. The hull thickness and the ribs dimensions were optimized, using an iterative process, to find the best combination, one that would comply with the concrete tensile strength and the displacement criteria for the canoe. Theoretical calculations and experimental results are shown in Appendix B-2

3.7. Materials Selection and Final Results

All factors considered, the optimum hull thickness was set to 7 mm with four carbon meshes equally distributed in the hull and impregnated in the HULL concrete mix (as shown in Appendix C-2). The outer reinforcement layers absorb most of the stress, and the middle layers act as secondary reinforcement. The concrete mix possesses the properties to achieve a thin, light and strong composite section. The hull section has a tensile strength of 5.1 MPa (740 psi) and an elastic modulus of 5900 MPa (860 ksi). The calculations for the reinforcement material thickness are presented in Appendix B-3.

Ribs were designed with a different concrete mix (RIBS), stronger and stiffer, reinforced by 15 carbon yarns on the outer surface (Appendix C-3). They have a square section of 20 mm, in accordance with 2002 rules, and the composite has a tensile strength of 12.2 MPa (1770 psi) and a modulus of 6200 MPa (900 ksi).

The final concrete mixes presented in Appendix B-4 are composed of Type I super-white cement, metakaolin, water and resin as binding materials, K46 glass bubbles as lightweight aggregate, superplasticizer and are reinforced by carbon micro-fibers. In both mixes the fiber dosage has been set at 1% (by volume of concrete) in order to optimize the gain in strength vs. the loss of workability and the density. Table 1 shows the mechanical properties of the HULL and the RIBS concrete mixes. The ribs mix is stronger because of its lower water to cement ratio and its higher binder content (Appendix B-1).

Table 1: Trial Mixtures *vs.* Final Mixtures

Properties at 7 days	2001 Mix	Mix #2	Mix #11	HULL	RIBS
Compressive Strength [MPa (psi)]	15.6 (2260)	13.6 (1972)	15.6 (2262)	18.6 (2697)	20.1 (2915)
Tensile Strength [MPa (psi)]	0.68 (99)	0.72 (104)	3.5 (508)	4.7 (682)	6.7 (972)
Modulus [MPa (ksi)]	3880 (562)	3710 (538)	4130 (599)	4950 (718)	6075 (880)
Dry Density [kg/m^3 (pcf)]	675 (42.2)	660 (41.3)	680 (42.5)	670 (41.9)	755 (47.2)

After 7 days of curing, the HULL concrete mix tensile strength is 4.7 MPa (682 psi) and it has a modulus of 4950 MPa (718 ksi) with a dry density of 670 kg/m^3 (41.9 pcf). The RIBS concrete has a modulus of 6075 MPa (880 ksi) and a tensile strength of 6.7 MPa (972 psi) with a dry density of 755 kg/m^3 (47.2 pcf). These tensile properties are a great improvement in comparison to previous years.

The finite elements analysis was used to assess the stress distribution and the strains and displacements of the hull under typical static load patterns. The most critical tensile stress (1.02 MPa) occurs in the ribs when the canoe is simply supported upside, and the biggest deflection is 4.56 mm. Under the races pattern, with 2 or 4 paddlers in the canoe, there are only small tensile stresses in the structure, except around the each paddler's knee. In these areas, the tensile stress reaches 2.98 MPa. The complete finite element results are shown in Appendix B-5 and animations can be seen on the CD-Rom in Appendix D. Following these analyses, the final hull structure complies with the concrete tensile stress limit and the displacement criteria determined in 3.3.

4. Construction

4.1. Mold

After having worked on the design and have decided which shape the canoe should have, full scale plans were generated with CAD software for the 122 sections of the male mold. Each expanded polystyrene sections were drawn, cut, and glued together and secured on a rigid wooden base, which was also used as the gunwale guide (Appendix C-1). The mold was sanded and a drywall compound was used to fill the cracks in order to get a smooth shape free of any discontinuities. A plastic sheet covered the mold to provide a good interior finish and to ensure easy removal of the canoe. Mold construction is shown in Appendix D.

4.2. Fiberglass Prototype

To ensure the soundness of the new design, a prototype was built out of fiberglass woven roving and mats and polyester resin. The first trials proved that the new design would have very good performances (Appendix D), so construction of the concrete canoe then commenced.

4.3. Concrete Canoe

As shown in Appendix C-2, the ribs were made prior to the canoe's construction. Carbon yarns were placed perpendicular to the ribs in order to anchor them to the hull. The hull construction was made as the cross section shown in Appendix C-3 and in pictures and video in Appendix D. The first fiberglass layer was placed over the mold, and then carbon meshes were impregnated with concrete applied by hand. After placing the fourth carbon layer, the exterior fiberglass mesh was placed and covered by a last coating of concrete. Gunwales were made with the edge extension of fiberglass and carbon meshes used in the hull (Appendix C-4). To prevent the concrete from drying during construction, the relative humidity in the construction area was increased to near 100%.

4.4. Curing and Finishing

The canoe was cured for 28 days under wetted burlap. The outer surface of the hull was sanded and corrected with the same concrete mix used for construction while the curing was going on. After mold removal, minor corrections were made to the gunwales, the ribs and the inner surface. The unfinished band location was strategically selected to include one of the ribs in order to show their perfection. The canoe was primed and painted, and a clear coat was applied on the

exterior unfinished band. Non-skid bands were painted on the inner surface of the canoe using a filler additive in the paint.

5. Project Management and Cost Assessment

5.1. Team

As the 2001 competition ended, the veteran teammates got reunited to evaluate the year 2001's performances, and to set goals for 2002. Meanwhile, two captains were chosen among the team's veterans, and a thorough accounts book was put together. Then, different committees were created; each lead by an officer in charge. One of the committees had to take care of *Fundraising*; hence a sponsorship folder was created. The *Paddling Team* started their training during summer, and convened with the *Hull Design* committee to help design the new shape. The *Concrete Mix and Reinforcement Design* committee began to think about new improvements in order to optimize the canoe structure further. Meanwhile, the *Academic* committee was put in charge of writing the technical report, preparing the oral presentation, and building the display. Everybody took part in the construction of the mould, the fiberglass prototype, and the concrete canoe.

5.2. Project Management

In September 2001, a general information meeting, open to every civil engineering student, was held to recruit new teammates. The students heard a short presentation, and watched a video that presented parts of last year's canoe construction and competitions. Each person was invited to become involved in one or more committees, according to their interests and abilities. Committee leaders had to teach the rookies the different tasks that needed to be accomplished. While learning from the veterans' previous failures and successes, the rookies also got to learn how to strive for excellence and the project continuity was thus assured for years to come. Weekly meetings were held in order to keep the different committees informed about their respective advances. Problems that occurred during the project were then exposed and solved. To facilitate information sharing in the team, every meeting report, results of development and any pertinent documents were stored on a web site with controlled access. Finally, each week's work schedule was displayed on the door of the concrete canoe workshop. Appendix E-1 shows the schedule that the team followed during year.

5.3. Cost Assessment

All year long, materials used were catalogued in a notebook kept in the team workshop. The notebook also included a time sheet so that everyone could write down how many hours they worked. Each week, a secretary compiled all the data. Hence, the costs associated with the *Apogee*'s development and construction are shown in Appendix E-2. All things considered, development costs totaled $67,040, which included $65,064 in labor cost. In addition, construction costs totaled $67,723, which included $65,579 in labor cost. The total project cost added up to $134,263.

6. Summary

After months of hard work and constant team-effort, the Apogee team achieved its objectives. Université Laval's Concrete Canoe Team is proud to present the result of their ingenuity, an amazing 6.48 m long canoe with a mass of only 34 kg. An improved hull design, a lighter canoe made out of a stronger carbon micro-fiber reinforced concrete and a new reinforcement design, strongly skilled paddlers, a unique oral presentation, and an outstanding display should lead the team to its *Apogee*!

Université Laval Concrete Canoe Team, 2000, *SC Minnow*, Design Paper, 10 p.

Université Laval Concrete Canoe Team, 2001, *Apocalypse*, Design Paper, 6 p.

Grandpierre Cyril, 1967, *Le tracé des carènes*, Loisirs Nautiques, 275 p.

CNCCC 2002, *2002 Rules and Regulations*, 45 p.

Vacanti Yacht Design, *Prolines 98 User Manual*, 73 p.

Craig, R.R Jr., 1996, **Mechanics of materials,** Wiley and Sons, 637 p.

APPENDIX A-1

S.C. Minnow 2000 & Apocalypse 2001
Specifications

SC MINNOW: 2000 CONCRETE CANOE

UNIVERSITÉ LAVAL

S.C. MINNOW

Overall Length	6.05 m	(19' 10")
Maximum Width	770 mm	(2' 6")
Maximum Height	280 mm	(11")
Rockers Height	50 mm	(2")
Length / Width Ratio	7.83	
Draft (2 paddlers)	108 mm	(4.25")
Wet Surface Area (2 paddlers)	2.90 m^2	(31.2 sf)
Lateral plane / Length Ratio	0.088	
Draft (4 paddlers)	152 mm	(6")
Wet Surface Area (4 paddlers)	3.485 m^2	(37.5 sf)
Lateral plane / Length Ratio	0.132	
Total Mass	40.5 kg	(89.3 lb)

APOCALYPSE: 2001 CONCRETE CANOE

Overall Length	6.40 m	(21')
Maximum Width	700 mm	(2' 3.5")
Maximum Height	290 mm	(11.4")
Rockers Height	55 mm	(2.2")
Length / Width Ratio	9.14	
Draft (2 paddlers)	116 mm	(4.6")
Wet Surface Area (2 paddlers)	2.84 m^2	(30.6 sf)
Lateral plane / Length Ratio	0.094	
Draft (4 paddlers)	163 mm	(6.4")
Wet Surface Area (4 paddlers)	3.488 m^2	(37.5 sf)
Lateral plane / Length Ratio	0.139	
Total Mass	39.5 kg	(87.1 lb)

APPENDIX A-2

Drag to Speed Analysis

Note: The following analysis comes from the wave and friction drag computation included in Prolines 98 DAO software. Due to the length to beam ratio exceeding 3:1, the following analysis is not accurate from an absolute basis, but design trends are valid. The results cannot be used to exactly predict nor speed or drag for these canoe designs.

Canoe Design Comparison
2 Men Paddlers

Slalom/Endurance 600 m race:

In 2001, men paddlers did 5:02 minutes with the *Apocalypse*, including 1:02 minutes to complete the slalom. Their average speed in the 500 m endurance race was 2.08 m/s (500m / 240s). The corresponding drag can be considered as the paddle stroke effort deployed by the paddlers to maintain their speed. In that case, the drag force is 5.5 kg.

Considering that the paddlers typically deploy the same effort in this kind of race, the *S.C. Minnow* was faster than the *Apocalypse* at a lower effort range. Some tests performed while training were in agreement with this analysis. *The Apogee* has almost the same properties as the *Apocalypse*.

Sprint 200m Race:

In 2001, men paddlers did 1:14 minutes with the *Apocalypse*, including 10 seconds to complete the U-turn. The average speed was 3.13 m/s in straight line (200m / 64s). The paddle stroke force in a sprint race could be considered equal to a drag force of 10.0 kg. It is clear that the *S.C. Minnow* is limited in speed capability when the paddlers are at their maximum effort rate. The *Apogee* should be faster than the *Apocalypse*.

2002 National Concrete Canoe Competition

Canoe Design Comparison
4 Paddlers (2 Men + 2 Women)

Sprint 200m Co-Ed Race:

In 2001, Co-Ed paddlers did 1:16 minutes with the *Apocalypse*, including 12 seconds to complete the U-turn. Their average speed was 3.13 m/s in straight line (200m / 64s). The paddle stroke effort deployed by 4 paddlers in a sprint race could be considered equal to a drag force of 16.8 kg. All the models behaviors are similar in this kind of loading condition. The *S.C. Minnow* was a little bit slower than the *Apocalypse*, but the *Apogee* should still have a little advantage in this race.

APPENDIX A-3

Maneuverability Analysis

Lateral Wetted Plane (LWP)

The Lateral Wetted Plane is defined as the lateral plane area under the waterline. The LWP decreases while raising the rockers. The LWP to length ratio could be used as a maneuverability factor to compare several hull shapes and to optimize the rockers. A higher ratio indicates that the rockers are low, and then the canoe is easy to track but has a poor tacking capability. A lower ratio means that the rockers are high, and the canoe has a good tacking capability but is more difficult to keep in straight line.

	S.C. Minnow	*Apocalypse*
Overall Length	6.05 m	6.40 m
Rockers Height	50 mm	55 mm
Lateral plane / Length Ratio (2 paddlers)	0.088	0.094
Lateral plane / Length Ratio (4 paddlers)	0.132	0.139

For the 2002 model, rockers are optimized to obtain ratios near those of the *S.C. Minnow*.

APPENDIX A-4

Apogee 2002
Specifications

APOGEE: 2002 CONCRETE CANOE

Overall Length	6.48 m	(21' 3'')
Maximum Width	700 mm	(2' 3.5")
Maximum Height	325 mm	(13")
Rockers Height	60 mm	(2.4")
Length / Width Ratio	9.26	
Draft (2 paddlers)	104 mm	(4.1")
Wet Surface Area (2 paddlers)	2.87 m^2	(30.9 sf)
Lateral plane / Length Ratio	0.085	
Draft (4 paddlers)	149 mm	(5.9")
Wet Surface Area (4 paddlers)	3.49 m^2	(37.6 sf)
Lateral plane / Length Ratio	0.129	
Total Weight	36.0 kg	(80 lb)

APPENDIX B-1

Comprehensive Concrete Testing Results

Flexural Testing and Mechanical Properties

Load to Deflection
Beam Flexural Test
2001 mix
(Normal Concrete)

Load to deflection
Beam Flexural Test
2002 Mix
(Micro-Fiber Reinforced Concrete)

Elastic Modulus (E)

This parameter is obtained with the following equation (ASTM-C1018):

$$E = \frac{23\,L}{1296\,I}\,\delta,$$

where L is the beam span, I is the beam's section inertia and δ is the slope of the linear part of the Load to Deflection relation.

Tensile Strength (T) vs. Flexural Strength (σ)

Tensile strength is considered as the stress value at the end of the linear behavior corresponding with micro-crack development in the matrix. In the case of normal concrete, the damage causes instant failure. Tensile and flexural strength are almost the same. But micro-fiber reinforced concrete is more ductile as seen on the preceding graph. Then, tensile (T) and flexural strength (σ) are two distinct parameters, and are obtained by the following equations (ASTM-C1018):

$$T = \frac{P_e\,L}{B\,H^2},$$

$$\sigma = \frac{P_{max}\,L}{B\,H^2},$$

where L is the beam span, P_e is the load at the elastic limit, P_{max} is the ultimate load, B is the beam width, and H is the beam height.

Concrete Mix Optimization

Concrete mixes are optimized by the variation of the binder content, the water to cement ratio, and the micro-fiber dosage (volume of concrete). Micro-fibers are mixed with the glass bubbles to measure the particles compactness that governs the minimum binder content required to embed particles.

	Particle compactness		
Glass Bubbles	Glass Bubbles + 1% fibers	Glass Bubbles + 1.5% fibers	Glass Bubbles + 2% fibers
60.7 %	52.0 %	51.2 %	50.3 %

Minimum Binder = 100 % − Compactness

Due to workability and strength requirements, the binder contents are higher than the minimum in the final mixes.

	DOSAGE (% VOLUME)	
	HULL mix	RIBS mix
Cement	11.0	16.3
Metakaolin	2.7	4.0
Resin	4.2	6.2
Water	34.3	33.7
Superplasticizer	0.3	0.5
Glass Bubbles	46.5	38.3
Carbon Micro-Fibers	1.0	1.0
Binder Content	52.5	60.7
Cement to Binder (% mass)	75	75
Water to Cement (% mass)	110	75

	MECHANICAL PROPERTIES	
	HULL mix	RIBS mix
Compressive Strength (MPa)	18.6	20.1
Compressive Modulus (MPa)	5020	5990
Tensile Strength (MPa)	4.7	6.7
Flexural Strength (MPa)	8.4	18.4
Flexural Modulus (MPa)	4950	6075

APPENDIX B-2

Composite Flexural Strength
Calculations & Experimental Results

Hull Composite Section

Theoretical Calculation

Carbon Scrim Mesh		Fibreglass Mesh	
Yarn Section Area	0.2 mm^2	Yarn Section Area	0.04 mm^2
Yarn / Layer	12	Yarn / Layer	37
E	220000 MPa	E	95000 MPa
n	46.4	n	20
Position from surface	1.7 mm / 2.9 mm	Position from surface	0.5 mm
Concrete		Composite Section	
B	75.0 mm	B	75 mm
H	7.0 mm	H	7 mm
E	4950 MPa	Unit Mr	0.110 kN*m/m
σ	8.4 MPa	σ	12.8 MPa

Test Result

Composite Section	
B	75 mm
H	7 mm
P_{max}	225.0 N
Unit Mr	0.105 kN*m/m
σ	12.2 MPa

Ribs Composite Section

Theoretical Calculation

Carbon Yarns		Carbon Scrim Mesh	
Yarn Section Area	0.15 mm^2	Yarn Section Area	0.2 mm^2
Yarn / Layer	5	Yarn / Layer	4
E	300000 MPa	E	220000 MPa
n	49.4	n	46.4
Position from bottom surface	1.5 mm 3.5 mm 5.5 mm	Position from top surface	2 mm 4 mm 6 mm 8 mm
Fibreglass Mesh		**Concrete**	
Yarn Section Area	0.04 mm^2	B	20 mm
Yarn / Layer	10	H	20 mm
E	95000 MPa	E	6075 MPa
n	15.6	σ	18.4 MPa
Position from bottom surface	0.5 mm		

Composite Section

B	20 mm
H	20 mm
Unit Mr	2.08 kN*m/m
σ	29.7 MPa

Test Result

Composite Section	
B	20 mm
H	21 mm
P$_{max}$	2130 N
Unit Mr	2.30 kN*m/m
σ	31.3 MPa

APPENDIX B-3

Reinforcement Thickness *vs.* Hull Thickness

Reinforcement Thickness vs. Hull Thickness

Reinforcement	
Thickness: 2 layers of fibertape	2 x 0,20mm
Thickness: 4 layers of carbon mesh	4 x 0,50mm
Primer thickness	2 x 0,12mm
Paint thickness	2 x 0,15mm
Total reinforcement thickness	**2,94mm**
Total hull thickness	**7.00 mm**
Reinforcement thickness percentage	**42.0 %**

Measured as described in 2002 rules and regulations II.C.6.d

APPENDIX B-4

Summary of Final Mixtures Proportions

TABLE II.C.6—SUMMARY OF MIXTURE PROPORTIONS
MIXTURE DESIGNATION: <u>HULL</u>

AIR AND CEMENTITIOUS MATERIALS			
Component	Quantity (whether base or batch)		Units
air content by volume of concrete		2.5	%
Super white cement (plain),	ASTM Type: 1	333	kg/m^3
other cementitious material 1*	Description: Metakaolin	67	kg/m^3
other cementitious material 2*	Description: Epoxy resin (67% solid)	45	kg/m^3
mass of all cementitious materials	cm: 445		kg/m^3 (1)
cement to cementitious materials ratio	c/cm: 0.75		

AGGREGATES			
	Base Quantity (SSD aggregates)	Batch Quantity (Aggregates at stock moisture content)	
mass of glass bubbles	$W_{SSD,1}$: 200	$W_{stk,1}$: 200	kg/m^3
mass of carbon micro-fiber	$W_{SSD,2}$: 18	$W_{stk,2}$: 18	kg/m^3
weight of combined aggregate	$W_{SSD,agg}$: 218	$W_{stk,agg}$: 218	kg/m^3 (2)

WATER			
water †	W: 368.00	w_{batch}: 343.25	kg/m^3
vol. of superplasticizer	x_1: 3333		ml/m^3
water from superplasticizer		$w_{admx,1}$: 2.75	kg/m^3
water from Epoxy Resin		$w_{admx,2}$: 22.00	kg/m^3
total of free (surplus) water from all aggregates		$\sum w_{free}$: 0	kg/m^3
total water	w: 368.00	w: ‡ 368.00	kg/m^3 (3)
concrete density §	1030.83	1030.83	kg/m^3
water to cement ratio	w/c: 1.10		
water to cementitious material	w/cm: 0.83		

* If the binder comes from the manufacturer mixed with water, include only the weight of the binder here.

† 1st column is used for the desired total water, the 2nd column is for water added directly to batch

‡ w in this column = $w_{batch} + w_{admx,1} + w_{admx,2} + w_{admx,3} + w_{admx,4}$. This value should match the value for W in the previous column.

§ The sum of items in rows (1), (2), and (3)

TABLE II.C.6—SUMMARY OF MIXTURE PROPORTIONS
MIXTURE DESIGNATION: RIBS

AIR AND CEMENTITIOUS MATERIALS			
Component	Quantity (whether base or batch)		Units
air content by volume of concrete		2.5	%
Super white cement (plain),	ASTM Type: 1	495	kg/m³
other cementitious material 1*	Description: Metakaolin	99	kg/m³
other cementitious material 2*	Description: Epoxy resin (67% solid)	67	kg/m³
mass of all cementitious materials	cm: 661		kg/m³ (1)
cement to cementitious materials ratio	c/cm: 0.75		

AGGREGATES			
	Base Quantity (SSD aggregates)	Batch Quantity (Aggregates at stock moisture content)	
mass of glass bubbles	$W_{SSD,1}$: 165	$W_{stk,1}$: 165	kg/m³
mass of carbon micro-fiber	$W_{SSD,2}$: 18	$W_{stk,2}$: 18	kg/m³
weight of combined aggregate	$W_{SSD,agg}$: 183	$W_{stk,agg}$: 183	kg/m³ (2)

WATER			
water †	W: 373.12	w_{batch}: 337	kg/m³
vol. of superplasticizer	x_1: 5000		ml/m³
water from superplasticizer		$w_{admx,1}$: 4.12	kg/m³
water from Epoxy Resin		$w_{admx,2}$: 32.00	kg/m³
total of free (surplus) water from all aggregates		$\sum w_{free}$: 0	kg/m³
total water	w: 373.12	w: ‡ 373.12	kg/m³ (3)
concrete density §	1217.12	1217.12	kg/m³
water to cement ratio	w/c: 0.75		
water to cementitious material	w/cm: 0.56		

* If the binder comes from the manufacturer mixed with water, include only the weight of the binder here.
† 1st column is used for the desired total water, the 2nd column is for water added directly to batch
‡ w in this column = $w_{batch} + w_{admx,1} + w_{admx,2} + w_{admx,3} + w_{admx,4}$. This value should match the value for W in the previous column.
§ The sum of items in rows (1), (2), and (3)

2002 National Concrete Canoe Competition

A = absorption of an aggregate, whether taken as a whole, the coarse, or the fine aggregate, %.

MC_{total} = total moisture content referenced to the oven-dried condition of the aggregate, %.

$MC_{free,}$ = free moisture content, referenced to the saturated, surface-dry condition, of the aggregate, %.

W_{SSD} = mass, in the saturated, surface-dry condition, of aggregate per unit volume of concrete, kg/m^3.

W_{stk} = mass, in the stock moisture condition, of the aggregate per unit volume of concrete, kg/m^3.

w_{batch} = the mass of water to be batched per unit volume of concrete when the aggregates are in a stock moisture condition, kg/m^3.

w_{free} = free water carried into the batch by a wet per unit volume of concrete, kg/m^3.

Each one of these formulas should be applied to each aggregate source:

$$A = \frac{W_{ssd} - W_{od}}{W_{od}} \times 100\%$$

$$MC_{total} = \frac{W_{stk} - W_{od}}{W_{od}} \times 100\%$$

$$MC_{free} = \frac{MC_{total} - A}{\left(1 + \frac{A}{100\%}\right)}$$

$$W_{SSD} = \left(1 + \frac{A}{100\%}\right) * W_{OD}$$

$$w_{free} = W_{SSD} \times \left(\frac{MC_{free}}{100\%}\right)$$

Note that w_{free} can be a negative number indicating a dry and absorptive aggregate.

$$W_{stk} = W_{SSD} + w_{free}$$

Then, for the mixture as a whole:

$$w_{batch} = w - \left(w_{free,agg} + \Sigma w_{admx}\right)$$

Aggregate:

- Glass bubbles: A = 0%, see Appendix G (data sheets) page 1, « no water absorption »

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APPENDIX B-5

Comprehensive Finite Elements Analysis Results

Upside Simply Supported


```
I-DEAS 8 m2:   Simulation
/users/fparadis/modelisation/fapogeebon.mf1
RESULTS: 3- B.C. 1,STRESS_3,LOAD GRAVITE
STRESS - MAX PRIN MIN:-4.00E+02 MAX: 1.02E+03
DEFORMATION: 1- B.C. 1,DISPLACEMENT_1,LOAD GRAVITE
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.37E+00          VALUE OPTION:ACTUAL
FRAME OF REF: PART                                      SHELL SURFACE: BOTTOM
                                                          1.02D+03
                                                          8.75D+02
                                                          7.33D+02
                                                          5.91D+02
                                                          4.50D+02
                                                          3.08D+02
                                                          1.67D+02
                                                          2.50D+01
                                                         -1.17D+02
                                                         -2.58D+02
                                                         -4.00D+02
```

Deflection	Lateral Displacement	Critical Tensile Stress	Location
4.56 mm	0.73 mm	1.02 MPa	Ribs

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Upside Down Simply Supported

```
I-DEAS 8 m2:   Simulation

                          /users/fparadis/modelisation/fapogeebon.mf1
RESULTS: 15- B.C. 4,STRESS_15,LOAD APPUIS INVERSE
STRESS - MAX PRIN MIN:-1.85E+02 MAX: 2.45E+02
DEFORMATION: 13- B.C. 4,DISPLACEMENT_13,LOAD APPUIS INVE
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 7.95E-01                VALUE OPTION:ACTUAL
FRAME OF REF: PART                                            SHELL SURFACE: BOTTOM

                                                                  2.45D+02

                                                                  2.02D+02

                                                                  1.59D+02

                                                                  1.16D+02

                                                                  7.29D+01

                                                                  2.99D+01

                                                                 -1.31D+01

                                                                 -5.61D+01

                                                                 -9.91D+01

                                                                 -1.42D+02

                                                                 -1.85D+02
```

Deflection	Lateral Displacement	Critical Tensile Stress	Location
0.81 mm	0.23 mm	0.245 MPa	Gunwale

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2 Paddlers


```
I-DEAS 8 m2:   Simulation
                                    /users/fparadis/modelisation/fapogeebon.mf1
RESULTS: 7- B.C. 2,STRESS_7,LOAD HYDRO2
STRESS - MAX PRIN MIN:-7.03E+02 MAX: 2.19E+03
DEFORMATION: 5- B.C. 2,DISPLACEMENT_5,LOAD HYDRO2
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.71E+00          VALUE OPTION:ACTUAL
FRAME OF REF: PART                                      SHELL SURFACE: BOTTOM
                                                             2.19D+03
                                                             1.90D+03
                                                             1.61D+03
                                                             1.32D+03
                                                             1.03D+03
                                                             7.45D+02
                                                             4.56D+02
                                                             1.66D+02
                                                            -1.24D+02
                                                            -4.14D+02
                                                            -7.03D+02
```

Deflection	Lateral Displacement	Critical Tensile Stress	Location
- 2.6 mm	-1.28 mm	1.03 MPa	Gunwale
		2.19 MPa	Paddler Knee

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4 Paddlers

Deflection	Lateral Displacement	Critical Tensile Stress	Location
- 1.65 mm	-0.97 mm	0.696 MPa	Gunwale
		2.98 MPa	Paddler Knee

APPENDIX C-1

Mold and Wooden Structure

Plastic sheet

Polystyrene section

Alignment railing
(wood)

Removable base
(wood)

Removable gunwale guide
(wood)

Longitudinal reinforcement (wood)

APPENDIX C-2

Typical Rib Section

Carbon fiber mesh

Fibertape (interior and exterior surfaces)

Hull

Strand carbon fiber

Transversal carbon anchored to the hull

Longitudinal carbon yarns

APPENDIX C-3

Typical Hull Cross Section

Paint

Primer

Micro-fiber
reinforced concrete

Fiberglass mesh

5th layer of concrete

Carbon scrim mesh

Micro-fiber
reinforced concrete

Carbon scrim mesh

Fiberglass mesh

APPENDIX C-4

Typical Gunwale Section

Polystyrene mold

Hull

Wooden base

Removable gunwale guide (wood)

Carbon fiber mesh

Gunwale

APPENDIX D

CD-ROM

APPENDIX E-1

2001-2002 Time Management Chart

Month Activity	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Fundraising		▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬									
Mix design			▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬								
Hull design	▬▬▬▬▬▬▬▬▬▬▬										
Mold construction				▬▬		▬▬					
Prototype construction				▬▬							
Section trials						▬▬▬▬					
Canoe construction							▬▬▬				
Finishing								▬▬▬▬▬			
Painting										▬▬▬	
Design paper									▬▬▬▬		
Oral presentation								▬▬▬▬▬▬▬▬▬▬▬			
Display									▬▬▬▬▬▬▬		
Training	▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬										

Canadian National Concrete Canoe Competition : May 11th and 12th

APPENDIX E-2

Cost Assessments

The cost assessments are broken into 2 phases: 1) Research and Development of Hull Design which includes all activities not directly related to the construction of the canoe and 2) Construction of Final Product which includes all activities associated with the fabrication of the canoe. Cost apportionment and working hours distribution diagrams are also presented at the end of this appendix.

a) Labor Costs : $DL = \left[\sum(RLR * HRS)\right] * (DEC + IEC) * (1 + P)$

Table of Billable Direct Labor rates

Raw Labor Rates (RLR)	1) Research and Development		2) Construction	
	Labor Hours	(RLR*HRS) ($)	Labor Hours	(RLR*HRS) ($)
Principal Engineer ($40/hour)	70	2800	25	1000
Project Manager ($30/hour)	80	2400	30	900
Project Engineer ($25/hour)	150	3750	35	875
Graduate Engineer ($18/hour)	180	3240	50	900
Technician/Drafter ($14/hour)	400	5600	680	9520
Word Processing ($12/hour)	150	1800	0	0
Foreman ($35/hour)	20	700	170	5950
Laborer ($25/hour)	160	1600	160	1600
Total	1210	21890	1150	20745

The Direct Employee Cost multiplier (DEC) is 1,4 and the Indirect Employee Cost multiplier (IEC) is 1.25. Furthermore, a profit multiplier (P) of 15% has been applied to labor. According to these numbers, the Total Billable Direct Labor (DL) is:

DL =[21 890]*(1,4+1,25)*(1+0,15)=66 710$ for Research and Development and DL =[20 745]*(1,4+1,25)*(1+0,15) = 62 320$ for construction.

b) Expenses : $E = \left(\sum MC + \sum DE\right) * (1 + M)$

Materials Costs (MC)

Material	Material rate($/unit)	1) Research and Development		2) Construction	
		Quantity		Quantity	Total cost ($)
Cement (kg)	0,085	13	1,11	15	1,28
Silica Fume (kg)	0,97	1	0,97	0	0,00
Superplasticizer (l)	2,32	0,2	0,46	0,2	0,46
Metakaolin (kg)	1,69	1	1,69	3	5,07
Glass bubbles (kg)	13,20	8	105,60	9	118,80
Carbon fiber (lb)	14,00	2	28,00	2	28,00
Carbon mesh (m^2)	68,00	2	136,00	24	1632,00
Fibertape (roll)	12,00	1	12,00	5	60,00
Epoxy Resin (l)	82,85	2,5	207,13	3	248,55
Polyester Resin (l)	3,75	20	75,00	-	0,00
Wood (panel)	32,00	6	192,00	-	0,00
Polystyrene (panel)	20,00	14	280,00	-	0,00
Fiberglass mesh (m_)	8,00	32	256,00	-	0,00
Others			500,00		50,00
Total material costs (MC)			1795,95		2144,16

Since they were no outside consultants and no other direct expenses related to Research and Development or Construction, Direct Expenses (DE)= $ 0. A markup (M) of 10% was applied to material costs.

Research and development : E = (1795,95 + 0) * (1 + 0,1) = $ 1976

Construction : E = (2144.16 + 0) * (1+ 0,1) =$ 2359

c) Total cost:

Research and Development = E + DL = 1 976 + 65 064 = $ 68 685

Construction = E + DL = 2 144 + 58664 = $ 65 579

Total cost of project

Phase and category	Cost ($)
Research and Development : labor	65 064
Research and Development : material	1 976
Construction : labor	65 579
Construction : material	2 144
Total	**134 263**

2002 National Concrete Canoe Competition

Working Hours Distribution

- Oral presentation 2%
- Display 5%
- Training 12%
- Design paper 4%
- Development 11%
- Mould construction 5%
- Financing 2%
- Prototype construction 4%
- Word processing 6%
- Painting 6%
- Finishing 28%
- Canoe construction 15%

Total = 2360 h

Cost Apportionment

- Development materials 1%
- Construction labor 47%
- Development labor 50%
- Construction materials 2%

Total = 134 264 $

APPENDIX G

Data sheets