
UNIVERSITÉ
LAVAL
BOREALIS
DESIGN PAPER 2012

Table of Contents

List of Figures

List of Tables

List of Appendices

Table 1: BOREALIS Specifications

BOREALIS' Specifications	
Weight	75 lbs
Length	237.0 in
Width	26.0 in
Depth	13.4 in
Thickness	0.25 in
Concrete color	Grey
Stain Color	White and blue
Reinforcement	Carbon fiber mesh

Table 2: BOREALIS Concrete Properties

Concrete Properties	
Unit Weight (23 ℃/50% R.H)	48.0 lbs/ft^3
28-day Comp. Strength	1,787 psi
28-day Cyclical Comp. Strength	1,608 psi
28-day Tensile Strength	377 psi
28-day Cyclical Tensile Strength	302 psi
Young's Modulus	420 ksi

Executive Summary

Université Laval sits on the outskirts of historic Québec city and is the oldest institution of higher learning in Canada. Throughout the years, this renowned school has become a leader in accomplishing technological development and groundbreaking research projects.

Université Laval's Concrete Canoe team was founded in 1996. That year, Laval won its first of nine Canadian National titles setting the team's high standards of excellence. Those victories have enabled Laval to participate at the National Concrete Canoe Competition (NCCC) and rank second for three consecutive years with ***Apogée*** (2002), ***Phoenix*** (2003) and ***Iceberg*** (2004).

Since 2007, Laval has been a member of the New England conference and in five years of participation, has qualified four consecutive times to compete at the national level. Last year VOLTAGE's 3rd place finish at the *NCCC* proved the importance of lightweight concrete and the use of structural elements, resulting in the lightest canoe of the competition. Laval also dominated on the water, as paddlers won every single race. In the midst of these great achievements, the team continued its traditions of excellence for its latest canoe.

Auroras are phenomena that occur primarily in high latitude. This majestic dance of the spirit is caused by the clash between the solar wind and the atoms of the frozen atmosphere. Auroras borealis are created from the energy of an ancient source, the sun. As for the sun, Université Laval's Concrete Canoe Team is a long-standing star that shines upon its new entry, BOREALIS. With its new canoe, Laval has only one objective in mind: the highest honors at the *NCCC*.

This year, the team has designed a new hull shape that is faster than its predecessor. This has enabled Laval to produce a new canoe focused on speed and lightness. Another new feature was to enhance the finite element analysis (FEA) model, by using a complete two-dimensional mesh, increasing result accuracy. In addition, the team deepened its understanding of a major phenomenon – Shear-Bending (S-B) under paddlers' knees. An experimental program has been developed to reproduce and accurately determine the behavior of a thin hull when submitted to both a hydrostatic pressure and a punching load. Through its innovative research program, the team has increased its understanding of concrete canoe design. This resulted in a canoe with a remarkable weight of 75 lbs.

This year's project has significantly reduced its ecological footprint by diminishing the amount of concrete needed for both development and testing and BOREALIS' construction. The latter reduction was possible through lowering the thickness of the concrete placed on the mold without compromising the canoe's finish. Moreover, this reduction enabled the team to complete the sanding faster, allowing more time for aesthetics.

The transfer of knowledge, superior quality control, and concrete canoe passion are essential for Laval's legacy. A captain and eight chiefs assured these objectives by entrusting and motivating newcomers from the beginning. Combining this new energy with experience consolidated members' strength, resulting in major advancements. Hence, Université Laval's Concrete Canoe Team has become a star that produces grandiose phenomenon. The outcome BOREALIS' shimmering lights embody energetic elegance and splendor that stay frozen in people's thought.

Hull Design

The canoe's hull shape considerably affects the behavior of the canoe during races. With this in mind, the team designed a new hull shape in order to improve its performance on water. The major goal was to enhance a previous shape based on four criteria: (1) top speed, (2) maneuverability, (3) stability, and (4) weight.

In early 2000, Laval developed a great expertise in concrete canoe hull design. For the past three years, this know-how has not been required, as the concrete canoes' shape was imposed by rules and regulations. Consequently, the team looked back on past expertise. BOREALIS' hull was designed using Prolines©, a watercraft conception software. BOREALIS' shape was based on *Stadacona* (2007), as it was the best and the most esteemed by paddlers.

Physical characteristics of a boat such as length, beam width, rocker heights, and chine radii directly affect its behavior. This year's study investigated the impact of these characteristics by varying them one at a time. Several shapes were produced in an iterative process and then compared to identify the impact of the hull characteristics on the canoe performance with respect to the four objectives listed above.

Shape performance was compared based on two important parameters in boat design engineering: the Displacement-Length (D/L) ratio and the Beam-Draft (B/T) ratio. The D/L ratio is an indicator of the wave generation of the hull passing through water. This nondimensional value is calculated using equation 1 (Brewer, 1993).

$$D/L = \frac{D_t}{(0.01 \cdot LWL)^3} \qquad eq.1$$

"D_t" is the displacement of the boat in water in long tons and *LWL* is the load waterline length in feet. The B/T ratio is the maximum width at the waterline divided by the draft. This value provides information about the drag constituents of the wavemaking resistance and the wetted surface friction. For BOREALIS' design, the B/T ratio was used as an indicator to minimize resistance. To obtain parameters suited to all the races, a water displacement of 480 lbs was calculated using equation 2, where W_i is the carried weight and D_i is the travel distance of each specific race.

$$\overline{W} = \frac{\sum W_i \cdot D_i}{D_{tot}} \qquad eq.2$$

To optimize the canoe's top speed, the D/L ratio was kept as low as possible, as this reduces wavemaking resistance. This in turn decreased the drag force, increasing top speed. The B/T ratio was also minimized to reduce friction drag by diminishing the total wetted area. Table 3 emphasizes the importance of designing a new shape as BOREALIS has better theoretical results than its basis (*Stadacona,* 2007) and the 2009-2011 imposed shape.

Table 3: Ratios for a Water Displacement of 480 lbs

Ratio	2009-2011 Imposed Shape	Stadacona	BOREALIS
Beam-Draft (B/T)	6.2	4.5	4.3
Disp-Length (D/L)	28.9	27.3	27.2

The rocker heights were increased as they significantly improve maneuverability. The overall chine radii were increased as they improved stability and decrease the draft. Table 4 shows the canoes characteristics.

Table 4: Hull Shape Characteristics for BOREALIS, Stadacona, and the 2009-2011 Imposed Shape for a Displacement of 480 lbs

Characteristic	2009-2011 Imposed Shape	Stadacona	BOREALIS
Length at the Waterline (in)	234.0	238.5	236.0
Beam Width at the Waterline (in)	28.3	27.9	24.1
Freeboard (in)	11.4	7.2	8.1
Bow Rocker (in)	4.0	3.5	5.7
Stern Rocker (in)	2.5	4.7	8.7

The freeboard height is also an important parameter considered in the analysis. This value was restricted to a minimum of 6.3 in, as previous experience showed that water enters in the canoe for lower values. In order to reduce the weight of the canoe, the freeboard height was maintained as low as possible. The estimated critical height occurs during the coed race and was estimated as 6.4 in for a carried weight of 700 lbs.

This year's new challenge enabled BOREALIS' team to produce a new hull shape that surpassed previous canoes by optimizing the hull for top speed, maneuverability, stability, and weight.

Structural Analysis

The main goals of the analysis were to obtain maximum stress values under the most critical loading scenario using a *FEA* and to determine the maximum stress value caused by the S-B phenomenon with an experimental program. The team also had to determine the optimal placement and dimensions of structural elements for a predetermined hull thickness of 0.25 in.

The first step was to establish the most critical loading case. Five scenarios were studied: (1) two paddlers, (2) four paddlers, (3) vehicle transportation, (4) being on its display stand, and (5) carrying. Vehicle transportation was not considered critical, as the team uses a canoe carrier that supports the entire canoe, significantly reducing vibrations and stresses during transport.

To create the 3-D model, the hull coordinates were downloaded from Prolines© into Rhinoceros©, a 3-D modeling software. The resulting 3-D model was brought to NX7.5© for finite element analysis. The mesh was made of 34,000 elements of mainly 0.25 in^2 each. To obtain a more representative model, the team upgraded its structural elements from a 1-D to a 2-D mesh shell. Ribs and gunwales were used as they reduce strain and tensile stresses in the canoe for they attract most of the stresses. Without these elements, the canoe would have a thickness of 0.5 in and a weight of 123 lbs. Primary structural element dimensions were the same as VOLTAGE (2011). Their positions were determined according to paddlers' positions and structural effectiveness.

For each loading case involving water, the waterline was determined using Prolines©. The load used for the preliminary analysis was 75 lbs for the canoe and the actual weight for paddlers (115-200 lbs). Reactions under the paddlers were simulated as six fixed nodes acting as a bearing surface, which had been locked in all translations. A hydrostatic pressure was applied to the hull.

Maximum stresses determined by the preliminary *FEA* were magnified by 1.25 (Paradis, 2004) to take into account the dynamic nature of the races. Results showed that the canoe undergoes maximum stresses under the two paddlers loading case due to the longitudinal negative bending moment.

The second step was to define final structural elements' dimensions. The team chose to compromise strength for lighter concrete, structural elements had to be dimensioned accordingly. Acceptable maximum stresses were found for the gunwales and 4 ribs of 2 in x 0.5 in each. Results based on *FEA* suggested that the use of structural elements reduced stresses by 150% and the transverse strain by 300%. *FEA* results as well as BOREALIS' concrete mechanical properties are noted in Table 5. A Young's Modulus of 420 ksi and a Poisson's ratio of 0.2 were used in the analysis. The mesh was not considered in the *FEA*, for the canoe was designed to limit maximum stresses under the concrete yield strength to avoid fissure. It was considered as a precaution.

Table 5: Final Critical Stress with the 28-day Yield Concrete Mechanical Properties

Critical Stress	*FEA* Factored Stress (psi)	28-day Cyclical Concrete Mechanical Properties (psi)
Max. Tensile Stress	272	302
Max. Comp. Stress	174	1,608

The first failure mode was the topmost hull fissuring due to the longitudinal negative bending moment. As displayed on Figure 1, *FEA* results showed the maximum tensile stresses at the topmost hull section and the maximum compressive stresses at the two rear ribs.

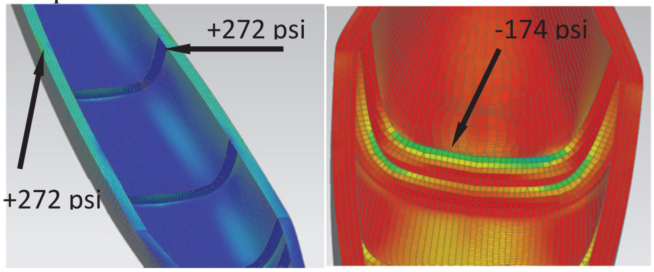


Figure 1: Location of Critical Stresses

The second failure mode was the hull fissuring under paddlers due to the S-B phenomenon. This was experimentally studied through a new test. It considered partial-interaction in composite and showed that the maximum tensile stress under a paddler's knee was 325 psi for two layers of mesh. The experimental program showed that the yield tensile strength is increased by 12% when reinforced with 2 layers of mesh (338 psi).

Development & Testing

The team had two major goals for development and testing: (1) produce a concrete as light as possible with both appropriate workability and mechanical properties and (2) develop a test to determine stress distribution in the hull under a paddler's knee.

The team implemented several iterative processes in order to determine the optimal hull shape, concrete mix, and structural elements' dimensions. The design process is shown on Figure 2.

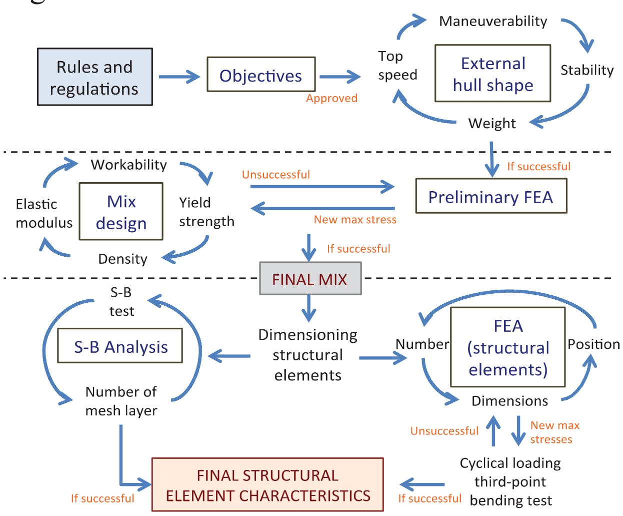


Figure 2: Design Process

VOLTAGE's mix design was used as a baseline, as this mix mechanical properties were 2350 psi for compressive strength, 480 psi for tensile strength and 800 ksi for Young's Modulus. This concrete included type GU white Portland cement, class F fly ash, silica fume, K25© and K37© hollow microspheres, Poraver© 0.25-0.5, crushed glass, and 0.25 inch polyvinyl alcohol (PVA) micro-fibers. A good combination of all these materials enabled Laval to use shotcrete.

Shotcrete was used as high velocity enables compaction and provides micro-fiber orientation. The 2-D alignment nearly doubles micro-fibers efficiency compared to 3-D random orientation (Bentur, 1990). Different configurations were tested and confirmed the increase of the concrete tensile strength for the 2-D alignment. Moreover, shotcrete enables the placement of an extremely thin layer of about 1/16 in, as the concrete is sprayed during the shooting process.

Mechanical properties were evaluated experimentally using ASTM standards. The team used ASTM C78 for flexural strength, ASTM C39 for compressive strength, ASTM C469 for Young's Modulus, and ASTM C138 for density and gravimetric air content. Each batch tested was prepared in laboratory conditions and moist cured for 7 days or 28 days.

Within 55 different batches the team designed an optimized lightweight concrete mix by changing one parameter at a time. Various combinations were tested adjusting w/cm ratio (0.6-0.8), cementitious paste (36%-42% v/v), and 0.25 inch PVA micro-fibers (0.9%-1.7% v/v). Different aggregate proportions were tested: Poraver© (0.25-0.5 and 0.1-0.3) and K1©, K25©, K37©, and K46©. The mix that gave the optimal combination of mechanical properties, workability, and a low unit weight was chosen. The final cementitious paste proportion was 36% v/v and cementitious material proportions were 44% v/v type GU white Portland cement, 26% v/v class F fly ash and 30% v/v silica fume. The team used 1.5% v/v PVA micro-fibers as this proportion gave the best tensile strength results. Optimal mechanical properties and workability were found with these volumetric proportions: 12% Poraver© 0.1-0.3, 61% K25© and 27% K37©. BOREALIS' mix w/cm ratio was fixed at 0.7, for it reduced concrete unit weight and improved workability.

The team had to consider damage in concrete induced by cyclical stresses induce by races to determine final mix mechanical properties. Different concrete specimens submitted to 6500 load/unload cycles at different maximum stresses were tested through a cyclical third-point bending test and a compression test. These cyclical tests would represent the number of paddle strokes during the canoe's service life. Acceptable damage – defined as no visible fissure and non-excessive permanent deflection after testing – were found at 80% (302 psi) of the yield tensile strength and 90% (1,608 psi) of the yield compressive strength. These tests allowed the team to determine the maximum stresses in order to avoid visible damage in the canoe after races. A residual Young's Modulus of 420 ksi was used in the analysis. Final mix mechanical properties for cyclical loading exceeded design values, which were 272 psi and 174 psi for tensile and compression stresses respectively.

Admixtures were used in the final mix to obtain suitable concrete properties. Deviation between recommended and the actual dosage shown in Table 6 was attributed to the use of a non-standard concrete. A high-range water-reducing agent (Glenium® 7700) was used to get proper mix fluidity. A dosage of 18.9 fl oz/cwt provided a mix with proper workability. A amount of 6.8 fl oz/cwt of Pozzolith®, a set-retarding agent, was added to avoid cold joints. Finally, 103.3 fl oz/cwt of Rheomac®, a viscosity-modifying agent, was incorporated in the mix to avoid segregation and to assure fiber dispersion during the mixing process.

Table 6: Recommended and Actual Admixture Dosage

Admixtures	Recommanded Dosage (fl oz/cwt)	Actual Dosage (fl oz /cwt)
Glenium® 7700	4.0 - 15.0	18.9
Pozzolith® 100 XR	2.0 - 4.0	6.8
Rheomac® VMA 362	2.0 - 14.0	103.3

Last year, Laval observed fissures under the paddlers' knees after races due to the Shear-Bending (S-B) phenomenon. As shown on Figure 3, the team developed a test to determine stress distribution in the hull under their knee to avoid fissuring and produce a safer canoe for them. The experimental program was based on the *African Water Bed Test* (Morgan and al., 1999), which is used for quantifying shotcrete resistance to uniform earth-pressure in mining industry. To simulate the concrete canoe hull, a concrete plate of 23 in x 23 in x 0.25 in was attached on every edge in a rigid wooden box. Water was introduced underneath the specimen to simulate hydrostatic pressure acting on the canoe. Knowing that the water pressure reduced the stress in the hull caused by the paddler's knee, the pressure had to be minimized. A 2.5 in water head was determined by Prolines©, and adjusted through a graduated cylinder. This value represents the pressure under the front paddler during the men's sprint race. Afterward, a critical load of 80 lbs was applied at the center of the plate to act as a paddler knee. This force was calculated using a paddler's weight of 200 lbs divided by 2 (two knees per paddler). This was reduced by 20% to take into account the load applied along the leg.

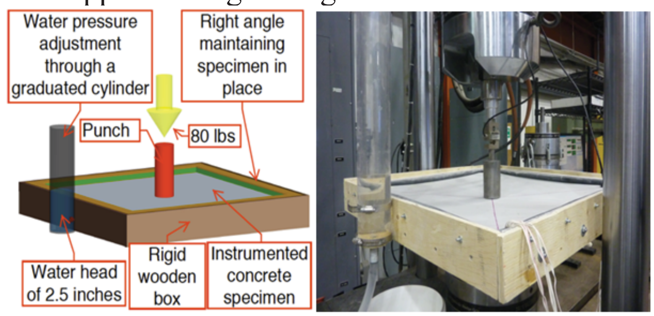


Figure 3: Shear-Bending Apparatus

Ten strain gages were placed at different specific distances from the center of the plate for each concrete specimen. These gauges allowed the team to evaluate the stress distribution in the thin plate when both the punching load and the water pressure were applied.

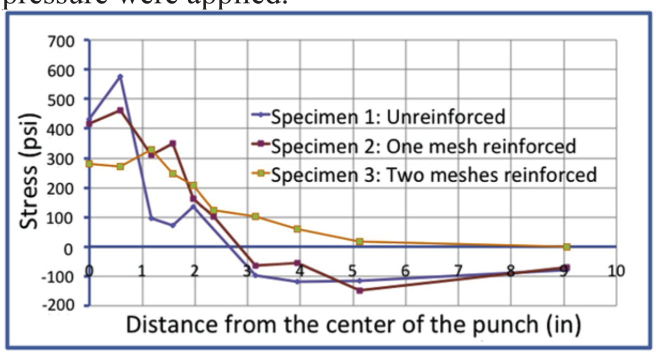


Figure 4: Stress Distribution in Specimens for the Shear-Bending Test

Three samples were tested: specimen 1 was unreinforced, specimens 2 and 3 were reinforced with one and two layers of carbon fiber mesh respectively. As shown on Figure 4, specimens behave differently according to the number of mesh layers. Stress distribution is improved with the addition of a second mesh. According to experimental results, the hull was reinforced using one mesh layer for the entire canoe and an extra one under the paddlers. The overall Percentage of Open Area (POA) was 48% for both meshes. This test led the team to design a – 0.25 in thick hull – canoe that withstands paddlers without significantly increasing material and labor.

Construction

The construction division's ambitious goals were to improve upon established techniques and enhance quality control procedures. This resulted in the production of an outstanding canoe that matched the team's expectations.

For BOREALIS, the team opted for a male mold, as it was the most suited form for shotcrete placement and to produce the desired inner hull shape. Mold construction first started by digitally splitting the new inner hull shape into 120 two inches thick cross-sections using AutoCAD©. Each element was cut into Styrofoam® with a band saw, then carefully assembled and glued on a wooden base. This material allowed the team to easily achieve the required hull dimensions with sandpaper ranging from 60 to 220-grade. The mold shape was corrected using drywall compound when necessary. As shown on Figure 5, accurate dimensions were achieved through 15 laser-cut gauges. An external form was built at both ends to ensure that the proper amount of concrete was placed.

Figure 5: Mold Construction

Considering significant changes in the hull shape over recent years, the team chose to build a practice canoe for paddling training. In November, a fiberglass canoe was built using BOREALIS' mold. Once set, the practice canoe was carefully removed from the mold and then sanded, strengthened, and painted; ready for intense training. Following the team's sustainability policy, the form was repaired and sanded so as to receive BOREALIS. This allowed Laval to significantly reduce material usage; therefore lowering the overall construction cost. To ensure a monolithic structure, ribs and gunwales were carved into the mold using a rotary tool. Structural elements' locations and dimensions were determined following the *FEA*. They were carved larger than required so that they could easily withstand the mold's removal. This also allowed the team to sand them down to their required dimensions. Once it was completely refined, a plastic membrane was applied onto the exposed surface, providing the BOREALIS smooth and stunning interior finish. This film also made the form's removal easier. Twenty screws were placed on the mold at non-critical locations to ensure the appropriate uniform thickness throughout the projection.

The team has developed an extensive knowledge in shotcrete technology, as Laval has been using it for over a decade. This technology was adjusted to the team's needs by the development of a custom shotcrete gun. This gun was built to provide adapted concrete velocity and good maneuverability in a tight environment. It was made from a 4 in diameter PVC pipe, which is connected to two 120 psi pressurized air tubes. As shown on Figure 6, a pressurized air tube is connected to the removal cap, ensuring a constant downward concrete flow. The other tube is connected to the lance, enabling high concrete velocity.

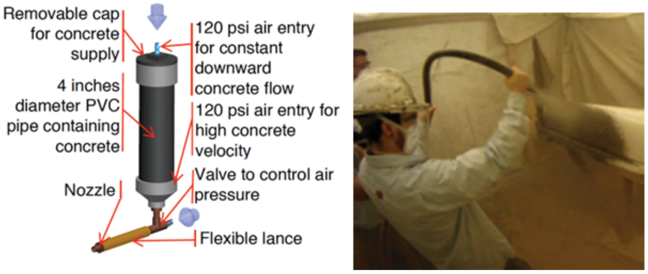


Figure 6: Custom Shotcrete Gun

In late January, this gun was used for BOREALIS' construction, which took place in a custom-built moist room. In preparation for the shooting day, 30 batches of 0.25 ft^3 each were pre-weighed in which all cementitious materials were hand sieved. This prevented material agglomeration from weakening the canoe's integrity as well as avoiding flaws on the final product.

Based on past years' experience, Laval opted for the proven efficiency of the laminated concrete placement method. This technique ensured continuous fresh concrete placement to avoid cold joints. Different tasks were assigned to team members for BOREALIS' construction, including concrete placement, thickness control, trowelling, mixing, rib and gunwale reinforcement placement, as well as carbon-fiber mesh placement. The first layer of concrete was applied from the bow to the stern while gunwales and ribs were being poured. Once the first layer reached the half of the canoe, a carbon fiber mesh was unrolled to allow the placement of the second layer of concrete. Following this experimental program, the team added a second layer of carbon fiber mesh under the paddlers in order to prevent concrete from being damaged during races. This additional reinforcement was slightly larger than necessary to take into account uncertainties of the paddlers' positions during races. Afterward, concrete was applied onto the mold until an overall thickness of 0.75 in was reached. The team applied more concrete than needed to achieve Laval's signature smooth finish by sanding down the outer hull to the design shape.

The mold was removed after 14 days of curing to ensure that the canoe would withstand the effort related to this activity. Styrofoam® sections were manually removed from the center to the ends of the canoe. Figure 7 shows BOREALIS during the removal of the mold.

Figure 7: Mold Removal

The canoe was kept in moist conditions for an additional period of 14 days in order to obtain proper concrete resistance. To ensure a perfectly smooth finish, the canoe was hand sanded with sandpaper ranging from 36 to 1000-grade. The sanding process was controlled using 20 laser-cut gauges in order to achieve a perfect outer hull shape. Screw holes left from the shooting day were used to measure local hull thickness via a digital caliper. Structural elements were accurately sanded down to the required dimensions determined by the final *FEA*.

Once sanded, BOREALIS was stained with an airbrush, stencils, and paintbrushes. A sealant was applied to the canoe's surface, providing a stunning glossy finish; thus, allowing its true vibrant colors as well as preventing its graphics from being damaged during transportation. From a technical standpoint, it also prevents the concrete from gaining weight in water, as it decreased permeability. This sealant was sanded up to 2000-grade.

Maintaining exceptional quality control was a forefront aspect of this year's project. To ensure this, all newcomers were supervised by veterans in their specific tasks. This also guaranteed direct involvement of every member, enabled the transfer of knowledge for the upcoming years, and allowed the team to avoid learning curve errors. Mistakes resulting from poor quality control would have affected cost by increasing the amount of required materials. Furthermore, great quality control contributed to decrease the necessary labor to complete the project.

This year, the team significantly reduced the number of batches required for the canoe construction by reducing the thickness of concrete shot onto the mold. This new feature saved half the man-hours required for sanding. Indeed, BOREALIS required the use of only 30 pre-weighed concrete batches, which corresponds to 55% of the amount of concrete needed for VOLTAGE (2011). Moreover, material usage and equipment were decreased, which significantly reduced the expenses. Risks related to thin-particle exposure were minimized by this reduction in sanding time combined with the use of appropriate masks and safety glasses. Throughout the project, the team worked in collaboration with Université Laval's health and safety department in order to assure an adequate and safe workplace. Prior to major construction activities, a professional approved the procedures by inspecting safety gear and equipment.

Project Management

This year's high objectives for project management were to build a cohesive team that would produce a national-class champion.

In late July, eight chiefs and a captain were elected among the most experienced and skilled members. The chief's responsibilities included concrete mix design, academics, aesthetics, construction/health & safety, paddling, analysis, treasurer, and multimedia. BOREALIS' team is composed of 20 newcomers and 14 veterans, making it a large team to steer. To ensure great quality control and continuous involvement, chiefs built their own subgroup according to each member's interest. Communication flowed between participants through weekly meetings and specialized mailing lists. Great care was taken in involving, teaching, and transferring concrete canoe passion to allow knowledge transmission.

Efficient time management skills were essential, as over 9,000 man-hours have been spent to complete the project. Figure 8 illustrates the man-hour distribution.

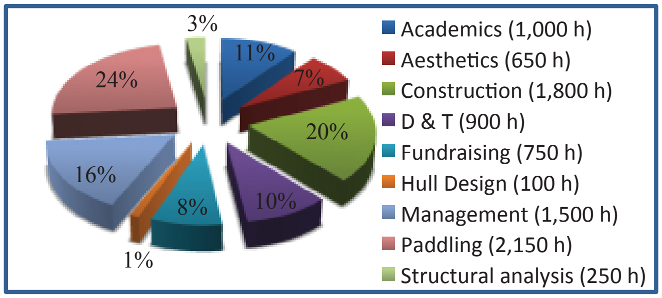


Figure 8: Man-hours Distribution

Ensuring great quality control was taken seriously, as it considerably affects material usage and the required man-hours to complete the project. To ensure this, all new members were put under the supervision of a veteran in their task. Compared to the VOLTAGE (2011) experience, this year's project has reduced labor by 700 hours. This decrease is greatly due to the team's sustainability policy during construction activities and by reducing the number of batches to achieve the final mix. BOREALIS' development and testing team reduced the amount of concrete in comparison to last year's project. This was achievable through improved analysis of the experimental data and more experienced members.

BOREALIS' financial plan was based on previous experience. An extensive fundraising period was implemented to cover project expenses including unexpected costs. This led to generous donations from over thirty industries, individuals and university sponsors. The team also obtained material donations, cutting construction spending. The overall savings due to donated materials were estimated as $2,700. The budget was fixed at $55,000 and was distributed as shown on Figure 9.

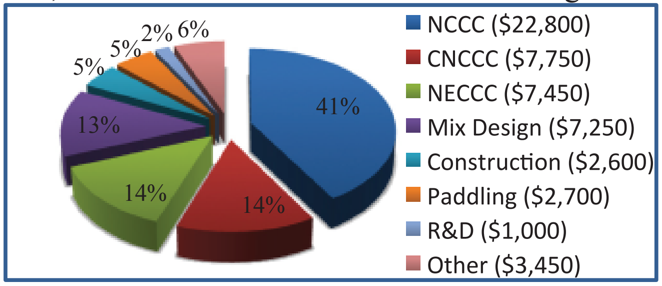


Figure 9: Allocation of Expenses

A project schedule with major milestone activities was drafted in late July. Based on previous years, its critical path phases were established with the activities that had the most impact in accomplishing the project on time. One month's worth of buffering was added to take into account uncertainties and risks related to project management. Major milestones and principal critical path activities are listed in Table 7.

Table 7: Project Milestones

Major Milestone & Principal Critical Path Activities	Delays	Reason
Fiberglass Canoe Construction	None	Proper scheduling
Mold Completion	2 weeks	Improved quality control
Mix Selection	2 weeks	Additional testing
Concrete Canoe Construction	2 weeks	Additional S-B data analysis required
Sanding Completion	None	Proper scheduling

The construction manager was also in charge of promoting and ensuring safe behaviors during all construction activities and tests. Workplace safety meetings were performed prior to every workday. Safety issues and risks regarding proper equipment use and adequate protective gear were then discussed.

Sustainability

For BOREALIS' project, sustainability was introduced through the Cradle-to-Cradle concept. Although the team strived to enhance sustainability throughout the project, Laval weighed up the merit of building a concrete canoe.

This project requires considerable materials, equipment, and energy, and only produces a canoe with an expected service life of three competitions before becoming a wall decoration. For Laval, the merit of building a concrete canoe comes from a long-term vision. The impact this project can have on developing the sustainable thinking and behavior of Laval's future engineers; however, is worth the initial ecological cost. Laval realized that this project not only tried to reduce its own ecological impact, but also provides a moral incentive for participants. This ensures that future generations have access to the same environmental, social, and economic conditions. Spread over 34 engineering careers, the application of these notions will have an impact, which far outweighs the resources spent on this project. Laval therefore took great care to apply sustainable practices wherever and whenever possible.

This year, sustainability was oriented towards the Cradle-to-Cradle (C2C) approach. This concept incorporates the intentional reuse and recycling of materials and resources directly into the initial design. Simply put, it suggests that industries must protect and enrich ecosystems by integrating environmental, economic, and social dimensions. Implementing this concept in Laval's Concrete Canoe project contributed to complete BOREALIS with a low negative environmental impact.

The team's construction and aesthetics divisions joined to design the mold, which is usually the source of the most wasted materials. It was built in such a way that it could be used for both the initial practice canoe and the final canoe as well as the display, which was made from the salvaged parts. This gave the polystyrene foam and wood used three complete life cycles, all incorporated in the initial design.

Economic sustainability was also part of Laval's design process. The C2C design proved its financial relevance by considerably reducing expenses. Manufacturer location and policies, as well as the team's own sustainability policies allowed the BOREALIS project to favor the surrounding economy by using 63% local materials. Laval also increased the proportion of its suppliers that have sustainable policies to 75%.

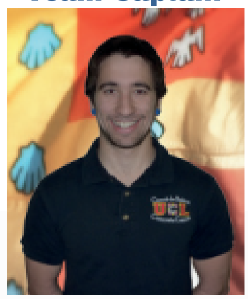
The mix design, aesthetics, and construction processes were developed to minimize the team's ecological footprint. BOREALIS reduced test batches from 82 (from VOLTAGE 2011) to 55 without compromising final mix quality. This 33% drop was possible through the implementation of an improved iterative design. It incorporated better testing analysis processes over previous trial-and-error methods. Unrealistic aesthetic goals were changed in favor of more ecological choices. For many years, Laval aimed to obtain a perfect unpatched hull finish, causing the team to initially use much more concrete on the hull. This caused a considerable amount of concrete removal and waste, and ultimately patches were always necessary. This year, Laval chose to end this wasteful practice and accept the possible need to aesthetic patching (which has no notable impact on the canoe's performance), reducing the concrete used in BOREALIS' construction by 47%.

Finally, sustainability is also a social challenge. Laval's concrete canoe team has traditionally been entirely made up of civil engineering majors, but this year Laval opened its project to students in mining, water, and software engineering. This brought many new skill sets and ideas from other engineering fields.

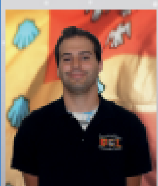
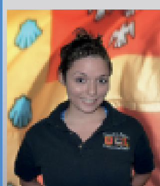
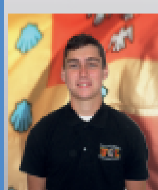
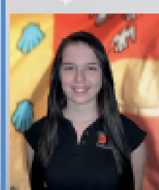
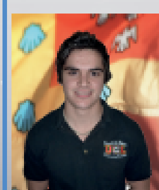
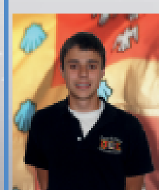
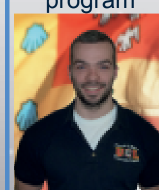
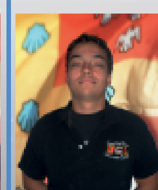
Laval concedes that building a concrete canoe consumes a considerable amount of resources and energy. However, the team hopes that with the experience building BOREALIS, each team member will be better prepared to apply sustainable development to their future projects over their entire careers.

Organization Chart

Team Captain



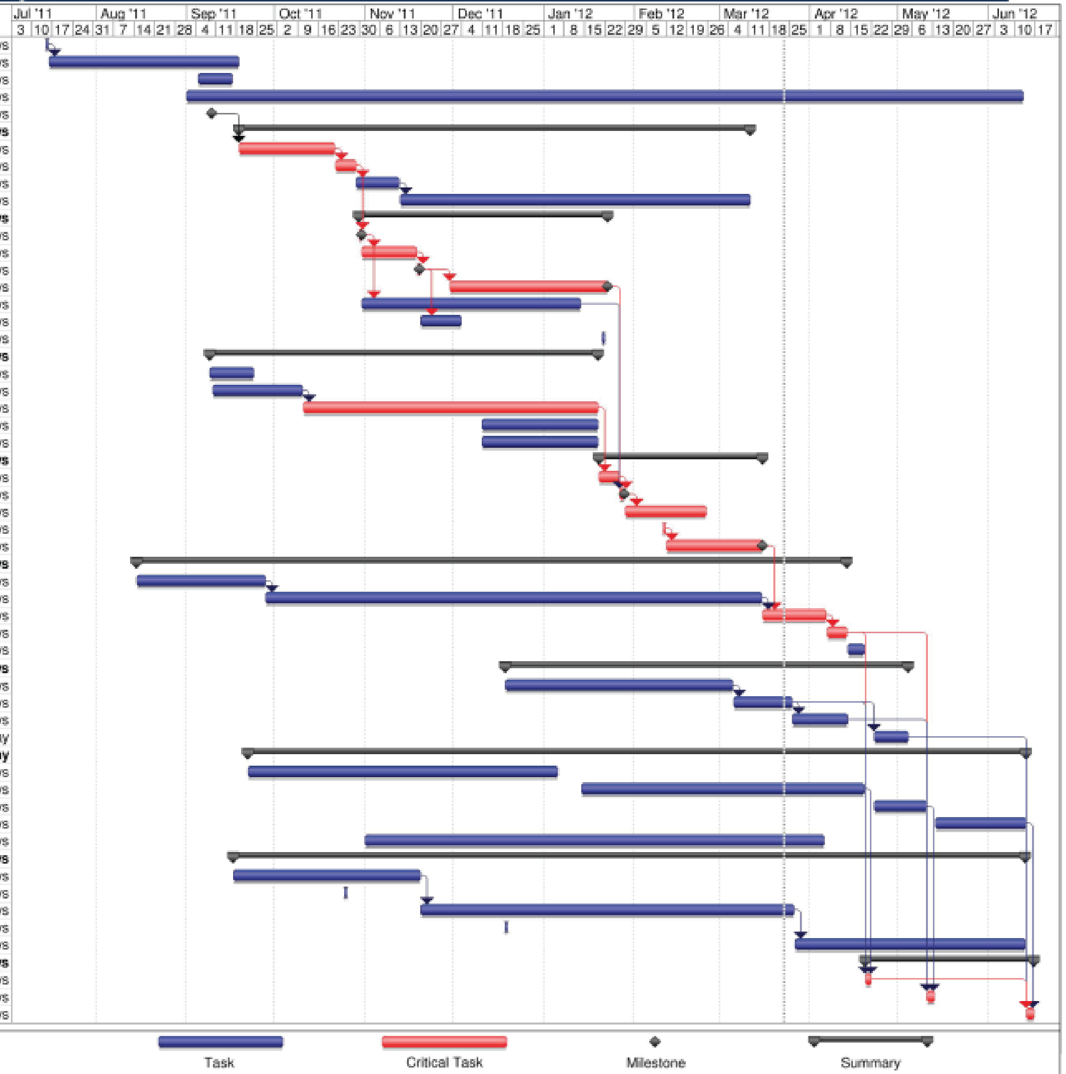
Kevin Gagnon

Treasurer	Aesthetics	Mix Design	Academics	Construction, Health & Safety	Analysis	Paddling	Multimedia
Fundraising, material procurement, logistics, promotional products	Product display, canoe graphics, cutaway section	Develop the concrete mix, trial bathes, mix testing	Technical report, oral presentation, engineer's notebook	Mold and canoe construction, shotcrete gun, safety officer	Hull and structural elements design, FEA	Teach paddling technique, elaborate muscular and cardio program	Oral presentation video, web site
							
Jean-Sébastien Fortin	**Christina Bélanger**	**Éric Normandeau-Gagnon**	**Ann-Frédérique Laroche**	**Nicolas Lambert**	**Éric Bard**	**Sébastien Girard**	**Cédric Gélinas-Trudel**
A. Maltais	A.-F. Laroche A. Maltais A. Pelletier	P.-L. Théberge M.-A. Thibault L. Lévesque M. Paquette A. G-Bhérer M. J-Durand V. Gosselin P.-G. Morel L. Roy S. Genest	S. Girard K. Gagnon	All members	F. Dion	E. Mercier N. Lambert E. Lavoie K. Gagnon K. Lavoie S. Simard J. Simard E. Paquet	J-S. Fortin S. Deschambault

BOREALIS

Project Schedule

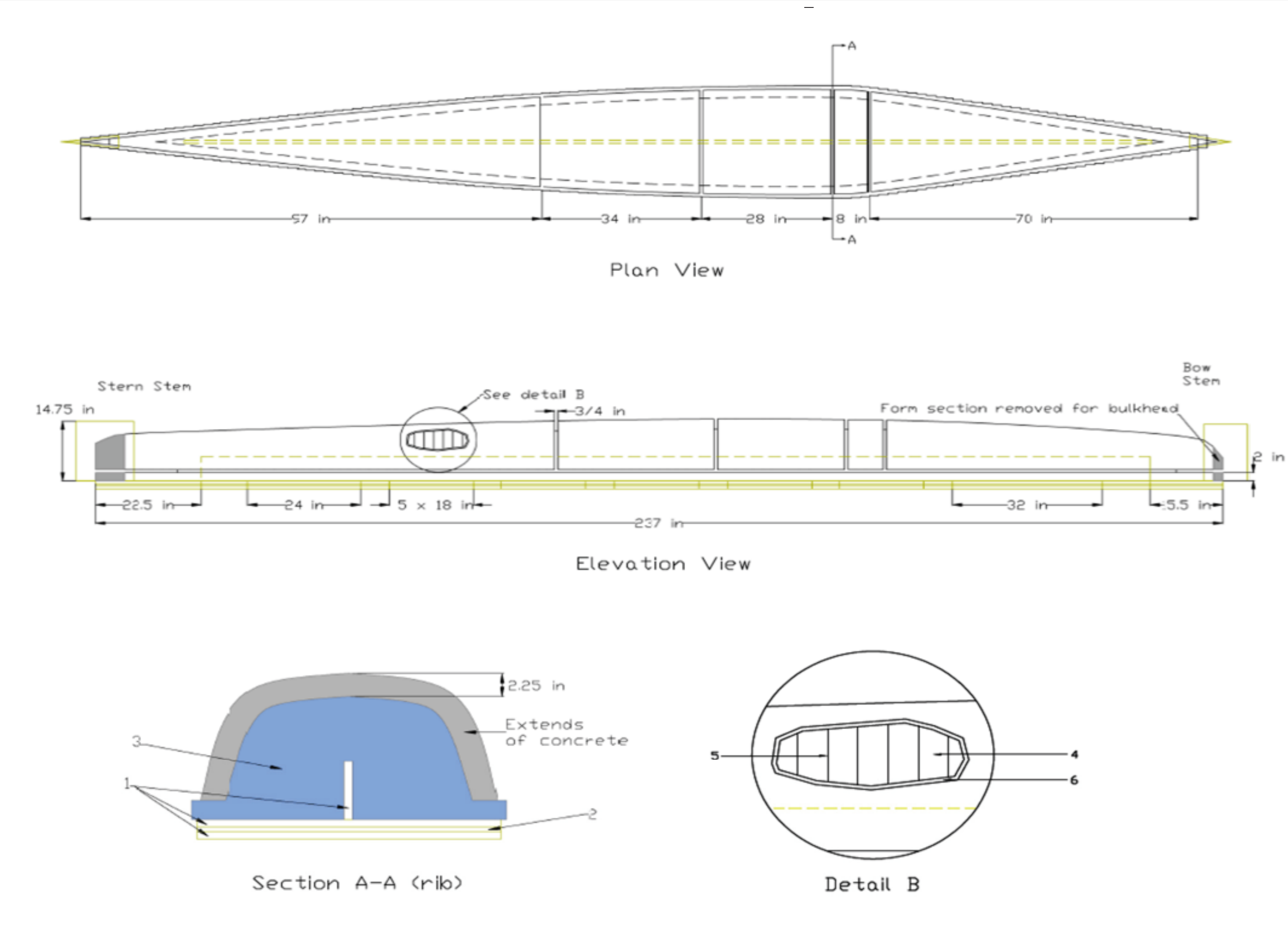
ID	Task Name	Duration	Start	Finish	Baseline Start	Baseline Finish	Finish Variance
1	First Meeting	1 day	Fri 7/15/11	Fri 7/15/11	Fri 7/15/11	Fri 7/15/11	0 days
2	Transfer of Knowledge	65 days	Sat 7/16/11	Sun 9/18/11	Sat 7/16/11	Sun 9/18/11	0 days
3	Recruitement	12 days	Mon 9/5/11	Fri 9/16/11	Mon 9/5/11	Fri 9/16/11	0 days
4	Fundraising	286 days	Thu 9/1/11	Tue 6/12/12	Thu 9/1/11	Tue 6/12/12	0 days
5	2012 Rules and Regulations Publication	1 day	Fri 9/9/11	Fri 9/9/11	Fri 9/9/11	Fri 9/9/11	0 days
6	**Conception**	**175 days**	**Mon 9/19/11**	**Sun 3/11/12**	**Sat 11/19/11**	**Sat 3/17/12**	**-6 days**
7	Hull Design	33 days	Mon 9/19/11	Fri 10/21/11	Mon 9/19/11	Fri 10/21/11	0 days
8	Mold Design	7 days	Sat 10/22/11	Fri 10/28/11	Sat 10/22/11	Fri 10/28/11	0 days
9	3D Modeling	15 days	Sat 10/29/11	Sat 11/12/11	Sat 10/29/11	Sat 11/12/11	0 days
10	Finite Element Analysis	120 days	Sun 11/13/11	Sun 3/11/12	Sun 11/13/11	Sat 3/17/12	-6 days
11	**Construction**	**85 days**	**Sun 10/30/11**	**Sun 1/22/12**	**Sun 10/30/11**	**Thu 1/12/12**	**10 days**
12	Mold and Cross-Section Construction	1 day	Sun 10/30/11	Sun 10/30/11	Sun 10/30/11	Sun 10/30/11	0 days
13	Mold Sanding for Practice Canoe	19 days	Mon 10/31/11	Fri 11/18/11	Mon 10/31/11	Fri 11/18/11	0 days
14	Practice Canoe Construction	1 day	Sat 11/19/11	Sat 11/19/11	Sat 11/19/11	Sat 11/19/11	0 days
15	Mold Repair and Finishing	54 days	Wed 11/30/11	Sun 1/22/12	Mon 11/21/11	Sun 1/8/12	14 days
16	Cross-Section Finishing	75 days	Mon 10/31/11	Fri 1/13/12	Sun 10/30/11	Sun 1/8/12	5 days
17	Fiberglass Canoe Finishing	14 days	Sun 11/20/11	Sat 12/3/11	Sun 11/20/11	Sat 12/3/11	0 days
18	Moist Room Construction	1 day	Sat 1/21/12	Sat 1/21/12	Thu 1/12/12	Thu 1/12/12	9 days
19	**Mix Design**	**133 days**	**Fri 9/9/11**	**Thu 1/19/12**	**Mon 9/19/11**	**Thu 1/19/12**	**0 days**
20	Adaptation of the Design Sheet	15 days	Fri 9/9/11	Fri 9/23/11	Mon 9/19/11	Mon 9/26/11	-3 days
21	New Product Testing	31 days	Sat 9/10/11	Mon 10/10/11	Mon 9/19/11	Mon 10/10/11	0 days
22	Conception and Optimisation of the Final Mix	101 days	Tue 10/11/11	Thu 1/19/12	Mon 9/19/11	Thu 1/5/12	14 days
23	Cyclical Test	40 days	Sun 12/11/11	Thu 1/19/12	Sun 12/11/11	Thu 1/5/12	14 days
24	Shear-Bending Test	40 days	Sun 12/11/11	Thu 1/19/12	Sun 12/11/11	Thu 1/5/12	14 days
25	**Concrete Canoe**	**56 days**	**Fri 1/20/12**	**Thu 3/15/12**	**Fri 1/6/12**	**Thu 3/22/12**	**-7 days**
26	Batch Preparation	7 days	Fri 1/20/12	Thu 1/26/12	Fri 1/6/12	Fri 1/13/12	13 days
27	Projection Day	2 days	Fri 1/27/12	Sat 1/28/12	Fri 1/13/12	Sat 1/14/12	14 days
28	Curing	28 days	Sun 1/29/12	Sat 2/25/12	Sat 1/14/12	Sat 2/11/12	14 days
29	Mold Removal	1 day	Sat 2/11/12	Sat 2/11/12	Sat 2/11/12	Sat 2/11/12	0 days
30	Sanding	33 days	Sun 2/12/12	Thu 3/15/12	Sun 2/12/12	Thu 3/15/12	0 days
31	**Aesthetic**	**243 days**	**Mon 8/15/11**	**Fri 4/13/12**	**Mon 8/15/11**	**Wed 4/18/12**	**-5 days**
32	Theme Proposition	44 days	Mon 8/15/11	Tue 9/27/11	Mon 8/15/11	Tue 9/27/11	0 days
33	Theme Development	170 days	Wed 9/28/11	Thu 3/15/12	Wed 9/28/11	Thu 3/15/12	0 days
34	Canoe Staining	22 days	Fri 3/16/12	Fri 4/6/12	Fri 3/16/12	Fri 4/6/12	0 days
35	Sealent Application	7 days	Sat 4/7/12	Fri 4/13/12	Sat 4/7/12	Fri 4/13/12	0 days
36	**Safety Week**	6 days	Sat 4/14/12	Thu 4/19/12	Sat 4/14/12	Thu 4/19/12	0 days
37	**Design Paper**	**138 days**	**Mon 12/19/11**	**Fri 5/4/12**	**Sun 1/1/12**	**Fri 5/4/12**	**0 days**
38	Premilinary Version	78 days	Mon 12/19/11	Mon 3/5/12	Sun 1/1/12	Sat 2/18/12	16 days
39	NECCC Version	20 days	Tue 3/6/12	Sun 3/25/12	Sun 2/19/12	Sun 3/4/12	21 days
40	CNCCC Version	19 days	Mon 3/26/12	Fri 4/13/12	Mon 3/5/12	Wed 4/4/12	9 days
41	NCCC Version	12 days	Mon 4/23/12	Fri 5/4/12	Sun 4/22/12	Thu 5/3/12	1 day
42	**Oral Presentation**	**266 days**	**Thu 9/22/11**	**Wed 6/13/12**	**Thu 9/22/11**	**Thu 6/14/12**	**-1 day**
43	Presenters Selection	106 days	Thu 9/22/11	Thu 1/5/12	Thu 9/22/11	Sat 12/10/11	26 days
44	NECCC Script	97 days	Sat 1/14/12	Thu 4/19/12	Sat 2/18/12	Thu 4/19/12	0 days
45	CNCCC Revision	18 days	Mon 4/23/12	Thu 5/10/12	Mon 4/23/12	Thu 5/10/12	0 days
46	NCCC Revision	31 days	Mon 5/14/12	Wed 6/13/12	Mon 5/14/12	Wed 6/13/12	0 days
47	Video	157 days	Tue 11/1/11	Thu 4/5/12	Tue 11/1/11	Thu 4/5/12	0 days
48	**Paddling**	**271 days**	**Sat 9/17/11**	**Wed 6/13/12**	**Sat 9/17/11**	**Wed 6/13/12**	**0 days**
49	Outside Practices	64 days	Sat 9/17/11	Sat 11/19/11	Sat 9/17/11	Sat 12/3/11	-14 days
50	First Selection	1 day	Tue 10/25/11	Tue 10/25/11	Fri 11/4/11	Fri 11/4/11	-10 days
51	Inside Practices	128 days	Sun 11/20/11	Mon 3/26/12	Sat 12/3/11	Sun 4/15/12	-20 days
52	Final Selection	1 day	Mon 12/19/11	Mon 12/19/11	Sat 1/7/12	Sat 1/7/12	-19 days
53	Outside Practices	79 days	Tue 3/27/12	Wed 6/13/12	Mon 4/16/12	Wed 6/13/12	0 days
54	**Competitions**	**58 days**	**Fri 4/20/12**	**Sat 6/16/12**	**Fri 4/20/12**	**Sat 6/16/12**	**0 days**
55	NECCC University of New Hampshire	2 days	Fri 4/20/12	Sat 4/21/12	Fri 4/20/12	Sat 4/21/12	0 days
56	CNCCC University of Moncton	3 days	Fri 5/11/12	Sun 5/13/12	Fri 5/11/12	Sun 5/13/12	0 days
57	NCCC University of Nevada, Reno	3 days	Thu 6/14/12	Sat 6/16/12	Thu 6/14/12	Sat 6/16/12	0 days



BOREALIS- Project Schedule

UNIVERSITE LAVAL

Design Drawing



Université Laval

Canoë de Béton UL Concrete Canoe

No.	Qty.	Description
1	6	3/4" Plywood Sheet
2	3	1/2" Plywood Sheet
3	20 ft	Plastic Wrap
4	25	4'x8'x2" Polystyrene sheet
5	1 gal.	Insulation Panel Adhesive
6	3 gal.	Drywall Compound

BOREALIS
Mold Design Drawing

General notes:
1. Design drawing not to scale
2. All ribs have the same dimensions
3. Both forms for bulkhead are made of plywood

Drawn by: Eric Bard

Project number: 01-Borealis

Date: 03-10-2012

Checked by: Sébastien Girard

Sheet number: 11

Appendix A - References

ASTM (1999). "Standard Specification for Portland Cement", C 150-98, West Conshohocken, PA.

ASTM (2005). "Standard Specification for Chemical Admixtures for Concrete", C494-05, West Conshohocken, PA.

ASTM (2005). "Standard Specification for Silica Fume Used in Cementitious Mixtures", C1240-05, West Conshohocken, PA.

ASTM (2006). "Standard Specification for Fiber-Reinforced Concrete", C 1116-06, West Conshohocken, PA.

ASTM (2006). "Standard Test Method for Slump of Hydraulic-Cement Concrete", C143-10, West Conshohocken, PA.

ASTM (2008). "Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle", C807-08, West Conshohocken, PA.

ASTM (2010). "Standard Specification for Hydraulic Cement", C 1157-10, West Conshohocken, PA.

ASTM. (2003). "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete", C 618-03, West Conshohocken, PA.

ASTM. (2003). "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)", C 78-02, West Conshohocken, PA.

ASTM (2004). "Compressive Strength of Cylindrical Concrete Specimens", C 39/C 39M-01, West Conshohocken, PA.

ASTM. (2003). "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression", C 469 03, West Conshohocken, PA.

ASTM. (2004). "Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete", C 138-01, West Conshohocken, PA.

Bentur, A. (1990). "Mechanical Behaviour of Fibre Reinforced Cementitious Materials", Fibre Reinforced Cementitious Composites, 15-87, National Building Research Institute, Haifa, Israel

Dudley R. Morgan and Dallas N. Mowat (1984). "A Comparative Evaluation of Plain, Mesh and Steel Fiber Reinforced Concrete", American Concrete Institute, SP 81-15, 307-324

Brewer, T. (1993). "Understanding Boat Design 4TH Edition", International Marine Publishing, Crawfordsville, IN, USA

Jolin, M. and Paradis, F. (2003). "High Tensile Strength Lightweight Concrete: Ideal for a Concrete Canoe", Quebec, Qc.

Laval University Concrete Canoe Team (2010). "The Norseman Design Paper", Quebec, Qc.

Laval University Concrete Canoe Team (2011). "Voltage Design Paper", Quebec, Qc.

McDonough W. and Braungart M., (2002) "Cradle to Cradle: Remaking the Way we Make Things", North Point Press

Meyer, M. and Mu, B. (2003). "Bending and Punching Shear of Fiber-Reinforced Glass Concrete Slabs", ACI Materials Journal, 127-132.

Morency, M. and Paradis, F. (2007). “Designing a Concrete Canoe with Regard to Fatigue Damage”, Concrete Canoe Magazine, 23-30.

Morency, M. and Paradis, F. (Fall 2001). “Lightweight Shotcrete Canoe”, Shotcrete Magazine, 10-14.

Morgan and al. (1999). “Comparative Evaluation of System Ductility of Mesh and Fibre Reinforced Shotcretes”, Burnaby, British Columbia, Canada

Neville, A.M. (2011). “Properties of Concrete” Fifth Edition, Essex, England.

Paradis, F. (2004). “Analyse du comportement structural d’un composite mince de béton: Analyse du comportement structural du canoë de béton”, Université Laval Québec, Qc, 98. (French)

Perez F., (2005). Contribution à l’étude du comportement Mécanique des Éléments Bicouches sous Sollicitations Statiques et Cycliques (in french), Ph.D. Thesis, Université Laval 240p.

Saito M. (1987). “Characteristics of microcracking in concrete under static and repeated tensile loading” Kanasawa Institute of technology, Nonoichi, Ishikawa 921, Japan

Victor C Li (2002). “Advances in ECC Research” ACI SP 206-23, Concrete Material Science to Applications

Zhang, J. (1999). “Fatigue life prediction of fiber reinforced concrete under flexural load”, University of Michigan, Ann Arbor, USA

Appendix B - Mixture Proportions

Mixture ID: Structural Mix					Design Proportions (Non SSD)		Actual Batched Proportions		Yielded Proportions	
Y_D	Design Batch Size (ft^3):		27							
Cementitious Materials				SG	Amount (lb/yd^3)	Volume (ft^3)	Amount (lb)	Volume (ft^3)	Amount (lb/yd^3)	Volume (ft^3)
CM1	Type 1 White Portland Cement			3.03	281.75	1.49	10.44	0.06	285.22	1.51
CM2	Class F Fly Ash			2.53	140.88	0.89	5.22	0.03	142.61	0.90
CM3	Silica Fume			2.22	140.88	1.02	5.22	0.04	142.61	1.03
Total Cementitious Materials:					563.51	3.40	20.88	0.13	570.44	3.44
Fibers										
F1	PVA fiber ¼ in.			1.30	32.83	0.41	1.22	0.02	33.24	0.41
Total Fibers:					32.83	0.41	1.22	0.02	33.24	0.41
Aggregates										
A1	Poraver© 0,1-0,3	Abs:	30.0%	0.90	103.17	1.84	3.82	0.07	104.44	1.86
A2	K25©	Abs:	0.0%	0.25	144.44	9.26	5.35	0.34	146.21	9.37
A3	K37©	Abs:	0.0%	0.37	96.29	4.17	3.57	0.15	97.48	4.22
Total Aggregates:					343.90	15.26	12.74	0.57	348.13	15.45
Water										
W1	Water for CM Hydration (W1a + W1b)			1.00	394.45	6.32	14.61	0.23	399.31	6.40
	W1a. Water from Admixtures				36.99		1.37		37.44	
	W1b. Additional Water				357.48		13.24		361.89	
W2	Water for Aggregates, SSD			1.00	30.95		1.15		31.33	
Total Water *(W1 + W2)*:					425.40	6.32	15.76	0.23	430.64	6.40
Admixtures				% Solids	Dosage (fl oz/cwt)	Water in Admixture (lb/yd^3)	Amount (fl oz)	Water in Admixture (lb)	Dosage (fl oz/cwt)	Water in Admixture (lb/yd^3)
Ad1	Glenium© 7700	*8.9178*	*lb/gal*	34%	18.93	4.90	3.95	0.18	19.16	4.96
Ad2	Pozzolith© 100 XR	*10.187*	*lb/gal*	46%	6.88	1.67	1.44	0.06	6.97	1.69
Ad3	Rheomac© VMA 362	*8.3667*	*lb/gal*	20%	103.23	30.42	21.54	1.13	104.50	30.79
Water from Admixtures *(W1a)*:						36.99		1.37		37.44
Cement-Cementitious Materials Ratio					0.50		0.50		0.50	
Water-Cementitious Materials Ratio					0.70		0.70		0.70	
Slump, Slump Flow, *in*.					1" ± 1/2"		1/4"		1/4"	
M	Mass of Concrete. *lbs*				1365.64		50.58		1382.45	
V	Absolute Volume of Concrete, ft^3				25.38		0.94		25.69	
T	Theorectical Density, lb/ft^3 = *(M / V)*				53.81		53.81		53.81	
D	Design Density, lb/ft^3 = *(M / 27)*				50.58					
D	Measured Density, lb/ft^3						51.20		51.20	
A	Air Content, *%* = *[(T - D) / T x 100%]*				6.00%		4.84%		4.84%	
Y	Yield, ft^3 = *(M / D)*				**27.00**		0.988		**27.00**	
Ry	Relative Yield = *(Y / Y_D)*						0.988			

Abs. = Absorption, SG. = Specific Gravity

Appendix C - Bill of Materials

Material	Quantity	Unit	Unit Cost	Total Price
Concrete Constituents*				
Type I White Portland Cement	16.09	lbs	$0.25	$4.02
Silica Fume	8.04	lbs	$0.07	$0.56
Class F Fly Ash	8.04	lbs	$2.08	$16.72
PVA Fibers 1/4 in	1.87	lbs	$6.60	$12.34
Poraver © 0.1 – 0.3	5.89	lbs	$0.70	$4.12
K25 © Glass Bubbles	8.25	lbs	$9.69	$79.94
K37 © Glass Bubbles	5.5	lbs	$8.23	$45.27
Viscosity modifying agent (Rheomac® VMA 362)	0.259	gal	$20.00	$5.18
Set retarding agent (Pozzolith® 100 XR)	0.017	gal	$10.00	$0.17
High-range water reducing agent (Glenium® 7700)	0.048	gal	$25.00	$1.20
Reinforcement				
Carbon fiber mesh	60	sq. ft.	$5.95	$357.00
Finishing				
Sandpaper	---	Lump sum	---	$500.00
Water based stain (sold as a concentrate)	0.3	gal	$177.80	$53.34
Sealer (Kure-N-Seal™ 30 ES)	0.5	gal	$25.00	$12.50
Stencils	---	Lump sum	---	$100.00
Vinyl lettering	---	Lump sum	---	$50.00
Mold				
Styrofoam mold, complete	24	sheet	$19.28	$462.72
			Total Production Cost:	**$1,705.08**

* A total of 7 batches of 0.25 ft^3 were used for canoe construction