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EXECUTIVE SUMMARY

Circuses are known to be majestic and unbelievable acts that travel around the world to entertain by demonstrations of great talent or unusual skills. Moving from city to city, they attract masses and in a glimpse, they are gone, leaving fantastic memories to those who had the chance to witness their beauty. Aiming to impress and to be remembered, Laval presents its most fascinating act, *Maximus*.

Located in historic Québec City, Université Laval is the oldest institution of higher learning in Canada. Throughout the years, its civil engineering department has become a leader in shotcrete, and its renowned research center in concrete and infrastructure makes it a choice place to achieve technical development and groundbreaking research projects.

Université Laval’s concrete canoe team was formed in 1996, setting the team’s high standards that same year by winning its first of ten Canadian titles. Those results allowed Laval to perform amongst the best at the National Concrete Canoe Competition (NCCC), ranking second three consecutive times with *Apogée* (2002), *Phoenix* (2003) and *Iceberg* (2004).

The team joined the New England conference in 2007 and qualified four times to compete at the national level. With the recent successes of *Voltage* (3rd place, 2011) and *Borealis* (2nd place, 2012), Laval demonstrated its skills in terms of optimization and hard work. Although ranking second at the NECCC with *Éphémère* (2013), the team decided to make the most of the gained experience. With this in mind, this year’s team worked on a hull optimized for straight line speed without compromising Laval’s signature lightweight concrete, and is now aiming for the first place at the NCCC.

*Maximus*’ team worked on improving upon past successes to produce Laval’s most optimized and sustainable canoe to date. The hull was designed for a fast straight line speed, taking into account paddlers’ comfort in order to ensure the efficiency of each stroke. By collaborating with the school’s forestry department, the team had the mold milled by a Computer Numerical Control (CNC) machine. The use of this new technique allowed an important reduction in time and material spent on construction, all the while improving quality control. Many innovations such as modifications to the moist room, new thickness control measures and better training prior to canoe projection also helped making *Maximus*’ construction more efficient and eco-responsible.

Cracking in the gunwales being an important concern, this year’s team decided to push further its understanding of the concrete’s behavior in these structural elements. By simulating the maximal tensile stresses induced to the concrete by paddling strokes, the study of the apparition of cracks was made possible. Through its innovative researches, the team improved its understanding of structural elements’ design. Furthermore, separate mixes for the hull and structural elements were developed, as both parts are solicited differently. This combination allowed weight optimization, leading to a remarkable 110 lbs canoe.

Great care was taken in enforcing the use of appropriate safety gear and safe behaviors. Additional trainings and the establishment of a new health and safety program improved team members’ safety throughout the project.

Superior quality control, knowledge transfer and great teamwork are essential for Laval’s legacy. Seven chiefs and a captain ensured the achievement of these goals by keeping the team motivated and closely supervising activities, resulting in an outstanding product. Laval is now ready to reveal the amazing *Maximus*, a showstopper that will fill everyone with wonder.
The team’s objectives for this year’s project management were to optimize time by building an efficient and cohesive team, in order to produce a national-class canoe.

In early June, seven chiefs and a captain were elected among the most experienced and dedicated members. The chiefs’ responsibilities were concrete mix design, academics, aesthetics, paddling, construction, analysis and treasury.

Maximus’ team is composed of 22 newcomers and 23 veterans, making it a large team to steer. To ensure great quality control and continuous involvement, members were encouraged to join subgroups supervised by chiefs. Communication flowed between participants through weekly meetings, activities and specialized mailing lists. Great care was taken in involving, teaching, and transferring concrete canoe passion and knowledge. Veterans oversaw the new members on their tasks, assuring quality control and perpetuation of Laval’s high standard techniques.

Since health and safety is one of the team’s foremost priorities, this year’s team captain and construction chief were in charge of ensuring safe behaviors, work environment and equipment by supervising all activities. By collaborating with the school’s head of health and safety, a new safety plan was elaborated and established. Moreover, team members attended a training concerning respiratory equipment and workplace safety meetings were performed prior to every workday.

Efficient time management skills were essential as the team had the objective of constructing the concrete canoe in late December, allowing the curing to take place during Christmas break. To reach this goal, Laval decided to have the mold built using a CNC machine. By cooperating with the school’s forestry research center, the team was able to cut construction time by 300 hours. A total of 5800 man-hours were spent to complete the project. This represents a reduction of 11% compared to Éphémère (2013). Figure 1 illustrates the man-hour distribution.

Maximus’ financial plan was based on past experience. Some local companies encountering difficulties, sponsorship was greatly affected. The team turned to an extensive fundraising period to cover project expenses. This led to generous monetary and material donations from industries, individuals and university sponsors. The overall savings due to fundraising and donations were estimated at $14,000. The budget was fixed at $33,000 and was divided as shown on Figure 2.

A detailed project schedule with major milestone activities was drafted in late July, setting important deadlines. The team established the critical path by determining the codependent activities which took the most time in the project. It included mix selection, analysis, canoe construction and finishing. One buffer week was added to take into account delays and uncertainties. Major milestone activities are listed in Table 3.

Through efficient time management and great teamwork, Laval was able to reach its objectives in terms of time optimization, leaving more time for finishing and aesthetics. This allowed the team to achieve an astonishing final product.
ORGANIZATION CHART

2014

Team Captain

Éric Normand-Gagnon
Project management, tasks delegation, quality control and health and safety

Academics
Ann-Frédérique Laroche
Design paper, oral presentation, video, engineer’s notebook

Élodie Labonté
Product display, canoe graphics, cutaway section

Alexandra Beaulieu
Hull and structural elements design, 2-D structural analysis

Pierre-Luc Théberge
Mold and canoe construction, shotcrete gun

Mathieu D.-Jéqueul
Concrete mix development

Gabriel S.-Gannond
Paddling technique instructor, muscular and cardio program

Alex E.-Tremblay
Fundraising, material procurement, logistics, promotional products

Aesthetics
Véronique Chabot
Claudia D.-Leclerc
Josée Drapeau
Audrey G.-Thibaut
Maxime Ouellet
Stacy Paté
Camille Rivet
Flavie St-Pierre

Analysis
Frédéric Bédard
David Cusson
Cédric G.-Trudel
Nicolas Naud
Sarah Sinard

Éric Bard
Amélie Vézina

All members
Vincent B.
Dominic Caisse
Boroo Chénard
Pascale D.Dudal
Claudia D.-Leclerc
Helin Dor
Manon Gaboriau
Serge Lamothe
Maxime Ouellet
Flavie St-Pierre
Diane Svebo

All members
Frédéric Bédard
Hieranni Bottari
Félix Demers
Boroo D.Dudal
Félix Fortin
Julie Gagnon
Nicolas Naud
Arnaud Plante
Sarah Sinard
Vicky T.-Mallette
Julien Vérette
HULL DESIGN & STRUCTURAL ANALYSIS

The canoe’s hull shape considerably affects its performance on the water. With this in mind, Laval decided to use the best of its expertise to design the fastest, lightest and most stable canoe.

Maximus’ hull was designed using Orca3D®, a watercraft conception software. Since Éphémère’s (2013) hull demonstrated great stability and straight line speed, the team decided to reuse its shape as a basis. Aiming to optimize its speed and maneuverability, the team observed the impacts of varying physical characteristics as they directly affect the canoe’s behavior. To obtain parameters suited to all the races, a total water displacement of 510 lbs was used taking into account 400 lbs for paddlers and 110 lbs for the canoe.

Shape performance was evaluated using 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, calculated using Equation 1 (Brewer, 1993).

\[
\frac{D}{L} = \frac{1}{35.88 \left(0.01 \cdot LWL\right)^3}
\]  
Eq.1

In this previous equation, the parameter \(D_t\) is the displacement of the boat in the water in long tons and LWL is the load waterline length in feet. This ratio was minimized, as it reduces wavemaking resistance and improves top speed. The B/T ratio is the maximum width at the waterline divided by the draft. It provides information about the drag constituents of the wavemaking resistance and the wetted surface friction. In this case, the ratio was kept as low as possible by diminishing the total wetted area. A comparison of these ratios is presented in Table 4.

Table 4: Ratios for a Water Displacement of 510 lbs

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam-Draft (B/T)</td>
<td>4.3</td>
<td>5.8</td>
<td>5.9</td>
</tr>
<tr>
<td>Disp.-Length (D/L)</td>
<td>27.2</td>
<td>28.8</td>
<td>27.2</td>
</tr>
</tbody>
</table>

Last years’ team encountered very low pressure under the front paddler during the race involving two women. This was due to an especially low waterline causing high shear-bending stresses under the front paddler. In order to eliminate this problem, the maximum beam width was moved backwards. This modification moved the boat’s center of flotation and therefore ensured a more even waterline. Moreover, this adjustment allowed the narrowing of the bow which improved straight line speed by lowering the D/L ratio. The freeboard’s height is an important parameter as it directly affects the weight of the canoe. Although the team aimed to minimize this value, Éphémère’s freeboard height was kept as it proved to be the optimal choice in terms of paddlers’ comfort and light weight. Values for rockers and maximum beam-width were also kept as these values proved to be the best compromise in terms of maneuverability, stability and paddlers’ comfort. Studied characteristics are compared in Table 5.

Table 5: Hull Shape Characteristics for Borealis, Éphémère and Maximus for a Water Displacement of 510 lbs

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Waterline Length</td>
<td>236.0</td>
<td>234.4</td>
<td>233.9</td>
</tr>
<tr>
<td>Maximum Beam-Width</td>
<td>27.0</td>
<td>30.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Beam-Width at Waterline</td>
<td>24.1</td>
<td>27.3</td>
<td>27.3</td>
</tr>
<tr>
<td>Freeboard</td>
<td>8.1</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Bow Rocker</td>
<td>5.7</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Stern Rocker</td>
<td>8.7</td>
<td>3.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Once the hull was designed, the team established two failure modes for a predetermined thickness of 0.25 in: (1) the topmost of the hull cracking due to the longitudinal negative bending moment and (2) the hull cracking under paddlers due to the shear-bending (S-B) phenomenon. A critical loading case was determined for each failure mode, allowing the team to dimension the gunwales and to choose the reinforcement under the paddlers.

Six loading cases were studied: (1) two men paddlers, (2) two women paddlers, (3) four paddlers, (4) vehicle transportation, (5) being on its display stand, and (6) carrying. Vehicle transportation was not considered critical, as the canoe carrier supports it entirely, significantly reducing vibrations and stresses during transport.

For the first failure mode, each loading case was studied using arbitrary fixed gunwales’ height (h) and width (w). The mesh was considered as a precaution, for the canoe was designed to limit maximum stresses under the concrete yield tensile strength. Properties such as second moment of area and center of gravity of the hull and gunwales were calculated separately.
dividing the canoe in 5 sections. Values for the second moment of area for the hull (H) and gunwales (G) were then summed on each section using the parallel axis theorem, as shown in Equation 2.

\[ I_{(h,w)} = I_k + A_k d_k^2 + 2[I_k, (h,w) + A_k (h,w)d_k (h)^2] G \]  

Eq.2

For each case involving water, the load applied on each section of the canoe was calculated using Archimedes’ principle and the waterline found with Orca3D®. Using beam theory, the bending moment around the y-axis was obtained by integrating twice the distributed load. With the values for second moment of area and the bending moment, it was possible to find maximal stresses in the canoe using Equation 3, where "x" is the longitudinal position in the canoe if the axis system is placed as shown on Figure 3 and finds its origin at the bow.

\[ \sigma(x,h,w) = \frac{M(x) k(x) h}{I(x) (h,w)} \]  

Eq.3

Results showed that the canoe undergoes maximum stresses under the two men paddlers loading case due to the longitudinal negative bending moment.

Once the final mixes were found, gunwales’ dimensions were chosen using a custom-made Maple® program, an analytical computing environment. Width and height were varied until the maximum stresses were below the 28-day cyclical structural elements concrete strength. The maximum stresses calculated in the analysis were magnified by 1.25 (Paradis, 2004) to consider the dynamic nature of the races. Final dimensions for the gunwales were 2 in by 0.5 in.

The closing/opening displacement is a phenomenon that found to be maximized during the coed races. To minimize it, the team used four ribs. Their positions were chosen according to paddlers’ location and structural effectiveness. Each rib was assigned a tributary area on which the applied water pressure for the coed scenario was calculated. The section with the maximum water pressure was considered critical and was used to dimension the ribs. Considering the symmetry, half of the cross-section used was split up in 50 straight lines as shown on Figure 4, on which a water pressure was applied.

Starting at the center of the canoe, a deformation was calculated for each straight line by considering the perpendicular water pressure. Since this pressure also creates a displacement on previous lines, its effect was also calculated. The total displacement was calculated by summing these values. With an iterative process using Maple®, the final ribs’ dimensions were found when the total displacement at the topmost of the hull was inferior to 0.25 in (Paradis, 2004). The corresponding dimensions were 2 in by 0.25 in. The factored maximum stresses of the analysis are compared to the concrete properties in Table 6.

<table>
<thead>
<tr>
<th>Critical Stress</th>
<th>2-D Analysis Factor Stress (psi)</th>
<th>28-Day Cylindrical Structural Concrete Mechanical Properties (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Tensile Stress</td>
<td>265</td>
<td>373</td>
</tr>
<tr>
<td>Max. Comp. Stress</td>
<td>370</td>
<td>2,278</td>
</tr>
</tbody>
</table>

For the second failure mode, each paddler was studied individually using its own waterline. It was determined that the critical loading case was the two men paddlers. Previous experience demonstrated that a second layer of carbon-fiber mesh located under the paddlers’ knees diminished cracking by stress distribution (Borealis, 2012). It was also proven that the use of a third layer of carbon-fiber mesh located under the paddlers nearly eliminates cracking (Éphémère, 2013). However, the team decided to accept the damage caused to the concrete by the shear-bending phenomenon and use only two layers in order to comply with the Canadian competition’s rules and regulations. Past experience demonstrated that the use of two layers of carbon-fiber mesh under the paddlers’ knees ensures the canoe’s structural integrity and its capacity to take part in the races.
Laval had two major goals for this year’s development and testing: (1) produce a light and strong canoe through the development of two mixes and (2) better understand the strain-hardening behavior of the concrete and provide data to demonstrate the efficiency of the reinforcement used in the gunwales.

In order to create the best canoe possible, the team established a design process consisting of several iterative processes allowing the selection of the optimal hull shape, concrete mixes and structural elements’ dimension. The design process is shown on Figure 5.

Éphémère’s hull mix design was used as a baseline, as its cementitious paste had interesting lightweight properties. This mixture’s mechanical properties were 2,079 psi for compressive strength, 315 psi for tensile strength and 451 ksi for Young’s Modulus. This concrete included Type I white Portland cement, class F fly ash, silica fume, K25©, K37©, K46© hollow microspheres, Poraver© 0.1-0.3, and 0.25 in PolyVinyl Alcohol (PVA) fibers. In order to ensure deformational compatibility, Maximus’ concrete mixes were designed using the same cement matrix and Young’s moduli were compared during testing. The use of an iterative mix design process and previous experience allowed the team to develop both mixes within only 30 batches.

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 for the mix design and 28 days for the final mix. Hull mix batches were shot and structural elements mix batches were hand placed, ensuring representative specimens.

Laval used shotcrete for the hull as high velocity enables compaction and provides microfiber orientation. The 2-D alignment nearly doubles fibers’ efficiency compared to 3-D random orientation (Bentur & Mindess, 2007). Moreover, shotcrete allows the placement of an extremely thin layer of about 1/16 in. Wanting to make Maximus a more sustainable canoe, the team decided to keep the cement matrix used for Borealis (2012) and Éphémère (2013), as previous experience and data proved its efficiency. It included 44% v/v Type I white Portland cement, 26% v/v class F fly ash and 30% v/v silica fume. A w/cm ratio of 0.7 was also used as it allows proper workability and reduces unit weight.

In order to achieve the perfect hull mix, the team tried various combinations by adjusting the cementitious paste (35.5%-41.8% v/v) and 0.25 PVA micro-fibers (1.20%-1.80% v/v). Lightweight was an important parameter as the hull mix represents 80% of the concrete used for the canoe. Different aggregates such as Poraver© (0.25-0.5 and 0.1-0.3) and K1©, K15©, K25©, K37©, and K46© were also tested in various proportions. The mix offering the optimal mechanical properties, workability and low unit weight was found at a cementitious paste proportion of 36.0% v/v and a PVA micro-fibers proportion of 1.65% v/v. The aggregates were 9% Poraver© 0.1-0.3, 65% K15© and 26% K37©. The usage of recycled materials and industrial residues such as Poraver©, silica fume and fly ash, reduced Maximus’ ecological footprint.

Since shotcrete is not appropriate for closed narrow spaces, the team had to develop a hand-placed mix for the structural elements. Strength was the foremost priority for this mix’s design as the structural elements encounter major stress concentration. Workability was also an important factor as it facilitates placement and helps avoiding air voids. Considering the same cement matrix, combinations of the cementitious paste (36.5%-39.0% v/v), 0.25 PVA micro-fibers (1.65%-2.00% v/v) and aggregates were tested.
while seeking different properties for the mix. The chosen mix’s aggregates were 9% Poraver© 0.1-0.3, 72% K15© and 19% K37© with a cementitious paste proportion of 38.0% v/v and a PVA microfibers proportion of 1.90% v/v. Admixtures were used in both final mixes to obtain suitable concrete properties. Deviation between the recommended and the actual dosage as seen in Table 7, was attributed to the use of a non-standard concrete.

Table 7: Recommended and Actual Admixture Dosage

<table>
<thead>
<tr>
<th>Admixtures</th>
<th>Recommended Dosage (fl oz/cwt)</th>
<th>Actual Dosage (fl oz/cwt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glenium® 7700</td>
<td>4.0-15.0</td>
<td>18.51</td>
</tr>
<tr>
<td>Pozzolith® 100 XR</td>
<td>2.0-4.0</td>
<td>6.73</td>
</tr>
<tr>
<td>Rheomac® VMA 362</td>
<td>2.0-14.0</td>
<td>99.86</td>
</tr>
</tbody>
</table>

Tensile and compressive strengths of the material do not consider the cyclical stresses induced in the canoe during the races. To take this effect into account, a cyclical third-point bending test and compression test were used, representing paddle strokes during the canoe’s service life. By submitting specimens to 4500 load/unload cycles at different maximum stresses, the team was able to determine final mix’s mechanical properties. Acceptable damage, defined as no visible cracking after testing, was found at 85% (373 psi) of the yield tensile strength and 90% (2,278 psi) of the yield compressive strength. Residual Young’s moduli of 539 ksi for the structural elements and 439 ksi for the hull were used in the analysis. Final mixes mechanical properties for cyclical loading exceeded design values.

In order to optimize structural elements’ efficiency, this year’s team decided to push further its understanding of concrete behavior and energy absorption. Since the gunwales are submitted to important tensile stresses during the races and often undergo wide cracking, the team decided to test reinforced and non-reinforced structural concrete samples using a third-point loading test (ASTM C1609).

Three non-reinforced specimens were submitted to third-point loading and demonstrated impressive strain-hardening capacities. As the strain-deflection curves demonstrate in Figure 6, the concrete can undergo greater stresses once the first crack appears. Represented by the area under the curve, the absorbed energy needed for the apparition of the second crack is inferior to the energy causing the opening of the first crack. The concrete is therefore subjected to great deflections before rupturing. This behavior is mostly due to the addition of PVA fibers in the concrete mixture. Although the concrete shows very interesting features, the sample displays wide cracking which is not the desired behavior.

Figure 6 : Load-Def. Curve for Non-Reinforced Specimens

Three specimens were reinforced using seven carbon-fiber mesh strands equally distanced, placed at a 0.5 in depth from the bottom. This position ensured the strands were working in traction, simulating the stresses induced in the gunwales. The tests proved the efficiency of the addition of carbon fiber mesh strands in concrete submitted to tensile stresses. The strain-deflection graphic shown on Figure 7 demonstrates a 40% augmentation in the absorbed energy compared to the non-reinforced specimens. This increase is adequate for the gunwales as the cyclical stresses induced by paddling generate an important amount of energy. Moreover, the samples showed microcracking, proving its capacity to distribute stresses. This type of cracking allows the occurring of even greater deflections before rupturing.

Figure 7 : Load-Deflection Curve for Reinforced Specimens

The use of excess material from previous years, the reduction of laboratory time required for testing and the overall reduction of concrete usage allowed the team to meet its objectives in terms of sustainable development.
Laval’s ambitious objectives for the construction division were to improve upon established techniques in order to optimize time and enhance quality control. This resulted in an outstanding canoe, exceeding the team’s expectations.

Maximus was built using a male mold as it is the most suitable form for shotcrete placement and a flawless inner hull. Mold construction first started by digitally splitting the inner hull shape into 12 blocks using AutoCAD. Each element was milled into polystyrene foam using a CNC machine and carefully assembled on a wooden base. The first row of polystyrene blocks were secured to the wooden base using twenty-four 8 in long screws. The second row was glued to the first one using insulation panel adhesive. Block joints and flaws were corrected using drywall compound. The decrease in the number of pieces used to build the mold allowed a reduction of 60% of the adhesive usage and of 50% of the drywall compound usage. It also diminished time and team members’ exposition to chemical products. Female molds were built at each end of the mold to create oversized caps, allowing them to be sanded to the perfect shape. Mold construction is shown on Figure 8.

In order to reduce Maximus’ ecological footprint and cost, the team decided to reuse Éphémère’s fiberglass practice canoe for paddling training as the new hull shape showed only minor modifications. This decision also affected time and expenses as the team did not have to repair the mold for the concrete canoe construction.

To ensure a monolithic structure, ribs and gunwales were carved directly into each block of the foam mold with the CNC machine. This new precision greatly affected sanding time as their dimensions were more accurate. Structural elements’ location and dimensions were determined by the preliminary 2-D analysis and past experience. They were carved larger than required so that they could withstand the mold’s removal. Once the mold was completely refined, a plastic membrane was applied to its surface, providing Maximus with a stunning and flawless interior finish and allowing an easier form removal.

Throughout over a decade, Laval has developed extensive knowledge in wet shotcrete technology. This technique was adjusted to the team’s needs by the construction of a custom shotcrete gun, displayed on Figure 9.

The shotcrete gun was built to provide adapted concrete velocity and good maneuverability considering the narrow space available in the moist room. It consisted in a 4 in diameter ABS pipe connected to two 120 psi pressurized air entries. The first air tube was attached to the top cap, constantly pushing concrete downward toward the flexible lance. The second air tube directed the concrete through the lance and nozzle. Valves and pressure regulators were used to ensure a sufficient output. Two specimens were built to optimize the shooting process and avoid cold joints by guaranteeing a continuous supply of fresh concrete.

In late December, these shotcrete guns were used for Maximus’ construction, which took place in a custom-built moist chamber. In preparation for the shooting day, a total of 16 batches of 0.25 ft³ 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.

Since the hull and structural elements were placed using different methods, the shooting day had to be perfectly managed. In order to ensure...
quality control, tasks were given to each member prior to the work day including shooting, thickness control, mixing, structural elements’ placement as well as carbon-fiber mesh placement. One week prior to the concrete canoe shooting, newcomers attended a special training on their specific tasks. Under veterans’ supervision, they then put their new knowledge to action by working on the cutaway section. Based on past experience, Laval opted for the multiple layering of concrete as it has proved to be the most efficient since it helps avoid cold joints by ensuring continuous fresh concrete placement. The first layer was shot from bow to stern following the structural elements’ concrete placement. The carbon fiber mesh was unrolled on the mold as the first layer reached the half of the canoe. The second layer of concrete was started simultaneously. The second mesh was added under the paddlers’ knee and slightly oversized to consider the uncertainty of their location.

Aiming to reduce its concrete usage, the team developed a new thickness control technique as shown on Figure 10. Five laser-cut cross-section gages designed for a 0.4 in thickness were fixed to the mold as the last layer of concrete was shot. These landmarks avoided excessive concrete placement and sanding. Furthermore, 10 screws were placed at non-critical locations to ensure uniform thickness and allow measurements during the sanding process.

![Figure 10: Cross-Section Guides and Landmarks Left on the Hull](image)

In an effort to reduce Maximus’ water usage, a new moist chamber was designed. By reducing its size and improving airtightness, the team was able to considerably reduce its water usage. Moreover, the team used an automated system to cut water waste during the curing process, diminishing the average water flow. The system, consists in an automated floating valve that guarantees a sufficient amount of water to keep the room at a humidity level of 95%.

The mold was removed after 21 days of curing to avoid shrinkage cracking and ensure the canoe would withstand the effort related to this activity. Polystyrene sections were removed manually from the center to the ends of the canoe. The cure was continued for an additional 7 days in order to obtain proper concrete resistance.

To ensure a perfectly smooth finish, the canoe was hand sanded using sandpaper ranging from 120 to 1000-grades. The reduction of excessive amounts of concrete shot on the mold enabled the team to avoid using 36 to 80-grades, therefore minimizing sandpaper usage and sanding time. Moreover, the team was able to use surplus from previous years, diminishing material purchase. The sanding process was controlled using 27 laser-cut gages, ensuring the achievement of the perfect outer hull shape. Structural elements were accurately sanded down to their required dimensions determined by the analysis.

Once the sanding was completed, Maximus was stained using a water-based stain. A sealer was then applied to the surface and sanded from 400 to 2000-grades, providing Laval’s signature smooth finish while allowing the canoe’s true vibrant colors and preventing its graphics from being damaged. From a technical standpoint, the sealer also prevents the concrete from absorbing water during races as it significantly decreases concrete permeability.

As respiratory risks are a major concern with concrete sanding, the team followed a training course on the proper usage of respirators. A respirator fit test was also performed by a health and safety professional on all team members. Safety meetings took place prior to every construction day and appropriate safety gear and equipment were mandatory.

Throughout the entire project, the team was able to meet its objectives in terms of sustainable development through innovations and improved quality control. Indeed, the team reduced the amount of materials and resources used which directly diminished the project’s costs and work time required. Efficient training and supervision of new members helped avoiding rookie mistakes and enhanced knowledge transfer.
APPENDIX A - REFERENCES


ASTM (2013). “Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete”, C138/138M-13a, West Conshohocken, PA.


Université Laval Concrete Canoe Team (ULCCT) (2011). “Voltage Design Paper”, Québec, Qc.

Université Laval Concrete Canoe Team (ULCCT) (2012). “Borealis Design Paper”, Québec, Qc.

Université Laval Concrete Canoe Team (ULCCT) (2013). “Éphémère Design Paper”, Québec, Qc.

Victor C Li (2002). “Advances in ECC Research” ACI Special Publication on 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

<table>
<thead>
<tr>
<th>Hull Mix</th>
<th>Design Batch Size (ft³)</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cementitious Materials</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CM1</td>
<td>Type I White Portland Cement</td>
<td>3.03</td>
</tr>
<tr>
<td>CM2</td>
<td>Silica Fume</td>
<td>2.22</td>
</tr>
<tr>
<td>CM3</td>
<td>Class F Fly Ash</td>
<td>2.53</td>
</tr>
<tr>
<td><strong>Total cementitious Materials</strong></td>
<td></td>
<td>563.70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fibers</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>PVA fiber 6.35 mm.</td>
</tr>
<tr>
<td><strong>Total fibers</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aggregates</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Poraver® 0.1 - 0.2</td>
</tr>
<tr>
<td>A2</td>
<td>K15®</td>
</tr>
<tr>
<td>A3</td>
<td>K37®</td>
</tr>
<tr>
<td><strong>Total aggregates</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>Water for CM Hydration (W1a + W1b)</td>
</tr>
<tr>
<td>W1a</td>
<td>Water from Admixtures</td>
</tr>
<tr>
<td>W1b</td>
<td>Additional Water</td>
</tr>
<tr>
<td>W2</td>
<td>Water for Aggregates. SSD</td>
</tr>
<tr>
<td><strong>Total Water (W1 + W2)</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Admixtures (including Pigments in Liquid Form)</th>
<th>% Solids</th>
<th>Dosage (fl oz/cw t)</th>
<th>Water in Admixture (lb/yd³)</th>
<th>Amount (fl oz)</th>
<th>Water in Admixture (lb)</th>
<th>Dosage (fl oz/cw t)</th>
<th>Water in Admixture (lb/yd³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ad1</td>
<td>Rheomac © VMA 362</td>
<td>8.4</td>
<td>20</td>
<td>34.65</td>
<td>96.52</td>
<td>28.436</td>
<td>20.15</td>
</tr>
<tr>
<td>Ad2</td>
<td>Glenium © 7700</td>
<td>8.9</td>
<td>34</td>
<td>17.89</td>
<td>4.636</td>
<td>3.74</td>
<td>0.172</td>
</tr>
<tr>
<td>Ad3</td>
<td>Pozzolith © 100 XR</td>
<td>10.2</td>
<td>46</td>
<td>6.51</td>
<td>1.575</td>
<td>1.36</td>
<td>0.058</td>
</tr>
</tbody>
</table>

| Water from Admixtures (W1a) | 34.65 | 12.8 | 35.85 |

### Notes:
- **Cement-Cementitious Materials Ratio** | 0.50 | 0.50 | 0.50 |
- **Water-Cementitious Materials Ratio** | 0.70 | 0.70 | 0.70 |
- **Slump, Slump Flow in.** | 2 ± 1 | 1 | 1 |
- **M Mass of Concrete. Lbs** | 1281.07 | 47.45 | 1325.35 |
- **V Absolute Volume of Concrete. ft³** | 25.380 | 0.940 | 26.257 |
- **T Theoretical Density. lb/ft³ = (M / V)** | 50.48 | 50.48 | 50.48 |
- **D Design Density. lb/ft³ = (M / V)** | 47.45 |  |
- **D Measured Density. lb/ft³** | 49.09 | 49.09 |
- **A Air Content. % = [(T - D) / T x 100%]** | 6.00 | 2.75 | 2.75 |
- **Y Yield. ft³ = (M / D)** | 27 | 0.967 | 27 |
- **Ry Relative Yield = (Y / Y₀)** | 0.967 |

Note: numbers shown in the table may be off due to the use of rounding in the Excel spreadsheet.
## APPENDIX C – BILL OF MATERIALS

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity</th>
<th>Unit</th>
<th>Unit Cost</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concrete Constituents</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type I White Portland Cement</td>
<td>33.83</td>
<td>lbs</td>
<td>$0.25</td>
<td>$8.46</td>
</tr>
<tr>
<td>Silica Fume</td>
<td>16.92</td>
<td>lbs</td>
<td>$0.07</td>
<td>$1.18</td>
</tr>
<tr>
<td>Class F Fly Ash</td>
<td>16.92</td>
<td>lbs</td>
<td>$2.08</td>
<td>$35.19</td>
</tr>
<tr>
<td>PVA Fibers 1/4 in</td>
<td>4.41</td>
<td>lbs</td>
<td>$6.60</td>
<td>$29.11</td>
</tr>
<tr>
<td>Poraver© 0.1 – 0.3</td>
<td>9.23</td>
<td>lbs</td>
<td>$0.70</td>
<td>$6.46</td>
</tr>
<tr>
<td>K15© Glass Bubbles</td>
<td>11.07</td>
<td>lbs</td>
<td>$18.50</td>
<td>$204.80</td>
</tr>
<tr>
<td>K37© Glass Bubbles</td>
<td>10.46</td>
<td>lbs</td>
<td>$8.23</td>
<td>$86.09</td>
</tr>
<tr>
<td>Viscosity modifying agent (Rheomac® VMA 362)</td>
<td>1.403</td>
<td>gal</td>
<td>$20.00</td>
<td>$28.06</td>
</tr>
<tr>
<td>Set retarding agent (Pozzolith® 100 XR)</td>
<td>0.095</td>
<td>gal</td>
<td>$10.00</td>
<td>$0.95</td>
</tr>
<tr>
<td>High-range water reducing agent (Glenium® 7700)</td>
<td>0.260</td>
<td>gal</td>
<td>$25.00</td>
<td>$6.50</td>
</tr>
<tr>
<td>Carbon fiber mesh</td>
<td>72.33</td>
<td>ft²</td>
<td>$5.95</td>
<td>$430.36</td>
</tr>
<tr>
<td>Sandpaper</td>
<td>---</td>
<td>Lump sum</td>
<td>---</td>
<td>$300.00</td>
</tr>
<tr>
<td>Water based stain (INTERSTAR® NSTAR series)</td>
<td>0.35</td>
<td>gal</td>
<td>$66.24</td>
<td>$23.18</td>
</tr>
<tr>
<td>Sealer (Kure-N-Seal™ 30 ES)</td>
<td>0.5</td>
<td>gal</td>
<td>$25.00</td>
<td>$12.50</td>
</tr>
<tr>
<td>Stencils</td>
<td>---</td>
<td>Lump sum</td>
<td>---</td>
<td>$100.00</td>
</tr>
<tr>
<td>Vinyl lettering</td>
<td>---</td>
<td>Lump sum</td>
<td>---</td>
<td>$50.00</td>
</tr>
<tr>
<td><strong>Mold</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Styrofoam mold, complete</td>
<td>12</td>
<td>blocks</td>
<td>$36.40</td>
<td>$436.80</td>
</tr>
</tbody>
</table>

**Total Production Cost:** $1,759.64

*A total of 11 batches for the hull and 2 batches for the structural elements of 0.25 ft³ were considered to construct the canoe before sanding*