The Vanderbilt Concrete Canoe Design Project:
The Little Engine that Canoed

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The Vanderbilt’s Concrete Canoe (VCC) Team has a competitive history at the Southeastern Regional ASCE Conference, placing in the top five schools throughout the past three years. The most recent concrete canoe project was named The Little Engine That Canoed in 2006 to honor Commodore Cornelius Vanderbilt’s origins in the railroad industry and as a reminder of the power of persistence. Developing The Little Engine was a small portion of the overall project objectives. The design team first compiled a significant body of literature that systematically outlined the steps for a successful concrete canoe project. The Little Engine boasts a fresh hull, three-dimensional finite element analysis, and an optimized concrete composite. The canoe construction efforts yielded a female mold, canoe carrier, and stands. Team members found the process of modeling the V-shaped bow and stern sections and a rounded stern stem to be the most challenging obstacles. Three-dimensional analysis was performed for the first time in school history and provided insight into graduate level coursework. Similarly, designing a concrete composite to withstand the rigors of competition required the use of a polymer to replace water in the concrete mix. To reach new heights, the team utilized a functional breakdown structure. Teamwork and communication, in the face of limited manpower, resulted in performing over 800 man-hours of concrete canoe related activities during a two-year period.

The 2006 Vanderbilt Concrete Canoe Hull Development (HD) Team envisioned The Little Engine that Canoed as the product of methodical research and design and creativity. Brainstorming sessions suggested remodeling Don’t Panic, the name of the previous year’s concrete canoe design project, to incorporate aesthetically pleasing Native American distinctions. The previous year’s team utilized an iterative design process, resulting in conservative geometric dimensions. Accordingly, optimization was desired. The HD Team assessed the advantages to be gained in all scoring divisions of the 19th Annual National Concrete Canoe Competition (NCCC), and proceeded to research and design an innovative hull for The Little Engine.

Canoe design is considered more an art than a science. Design evolution has grown from experience unlike naval research, which guides ship development. This difference in design strategy does not neglect the fact that designs are governed by their use. Ship theory literature, past experience, and interviews with a commercial canoe designer led the research effort.
Unfortunately, the sprint and slalom racecourses have contradicting requirements. The performance criteria of stability, maneuverability, and top speed are ranked in descending order by design teams. Before exploring the means for meeting these criteria, the alterable geometric dimensions were limited to the waterline length, waterline width, longitudinal curvature, freeboard, and draft.

Stability is the tendency of a hull form to return to its original position when inclined away from that position (Rawson and Tupper 1994). Lowering the center of gravity or providing excessive freeboard to counteract heeling, which is shown in rotation about the longitudinal axis, will reduce the risk of overturning. Excessive freeboard will hinder paddling technique. Therefore, lowering the center of gravity by increasing the waterline width is an effective method to increase stability.

Maneuverability is the ability to effectively carve a turn and track straight without losing momentum. Accomplished primarily by reducing lateral resistance, lateral surface area is a function of draft, waterline length, and longitudinal curvature. Turning was considered more important than tracking due to the numerous buoys encountered in the slalom course. Fortunately, there are means to track straight and are well: V-shaped cross sections have the ability to act as a keel. These were employed near the bow and stern to provide greater lateral stiffness.

Top speed is the product of the hydrodynamic hull form, paddling technique, and quality of wetted surface. The HD Team focused on the hull form and research indicated that longer waterline lengths and narrower waterline widths were beneficial to higher speeds. Furthermore, asymmetric shapes and sharp bow and stern tips were found to provide top speed advantages. Before proceeding to build The Little Engine, the HD Team contacted a commercial hull designer to confirm our research.

Nearly all previous nationally-recognized concrete canoes have featured waterline lengths over twenty feet that help in long courses. The short sprint and slalom courses limit length advantage dramatically (Scarsborough 2005). Thus, the designers reduced waterline length to improve weight, construction, maneuverability, and material cost. The team utilized Vacanti Prolines V7 R3.5 Pro® to

<table>
<thead>
<tr>
<th>TABLE 1 Hull Dimensions</th>
<th>FIGURE 1</th>
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<tr>
<td>Dimensions</td>
<td>Size</td>
</tr>
<tr>
<td>WL Length</td>
<td>17 feet</td>
</tr>
<tr>
<td>WL Width</td>
<td>31 inches</td>
</tr>
<tr>
<td>Freeboard</td>
<td>7 feet</td>
</tr>
<tr>
<td>Draft</td>
<td>6.5 inches</td>
</tr>
<tr>
<td>Asymmetry</td>
<td>126 inches</td>
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</tbody>
</table>

Rendered View of Hull Design
model and iteratively optimize *The Little Engine* for a four-person loading condition. Table 1 shows the concrete canoe dimensions and Figure 1 shows a rendered view of the hull design.

### Analysis

The next phase of analysis on *The Little Engine* began immediately after finalizing the hull design with all team members. Collaboration with the Mix Design Team was vital to gauge the material properties of the cementitious composite in tension, compression, and flexure.

In previous years, two-dimensional detailed analysis was employed as the only means of analyzing composite capacity. Distributed loads were made constant or linear to model shear and bending moment diagram calculations, and cross-sections were considered polygonal to calculate moments of inertia for bending stress equations. Compression and tension stress limit states were determined to be 282 pounds per square inch and 196 pounds per square inch, respectively.

Building upon these efforts, the analysis team decided to perform a two-dimensional precise analysis using the loading scenarios shown in Table 2. Men and women were assumed to be 180 pounds and 135 pounds, respectively. Extensive calculations were used to determine *The Little Engine* should weigh 175 pounds with concrete mixes designed at sixty-five pounds per cubic feet. The distribution of the buoyancy and gravity forces were determined by modeling submerged areas at every six inches along the length of the design model.

Vacanti Prolines Pro® provided the means to export dxf files for AutoCAD 2006® use. Submerged areas were assumed typical for 6 inch widths. The volume of water displaced for each section was determined and used to calculate a concentrated force. Spaced every 6 inches along the hull length, these concentrated forces formed the distributed buoyancy and gravity forces along the length of *The Little Engine*.

MATLAB Version 6.0.0.88 Release 12© was programmed to produce the shear and bending moment diagram shown in Figure 2. The two-man loading scenario was most critical for loading, producing

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**TABLE 2  Paddlers and Positions**

<table>
<thead>
<tr>
<th>Race</th>
<th>Paddlers and Position Aft Bow (Inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coed One</td>
<td>Male (36)  Male (104)  Female (138)  Female (174)</td>
</tr>
<tr>
<td>Coed Two</td>
<td>Male (36)  Female (76)  Female (138)  Male (174)</td>
</tr>
<tr>
<td>3 Males/Females</td>
<td>36     107    174   —</td>
</tr>
<tr>
<td>2 Males/Females</td>
<td>38     174   —     —</td>
</tr>
</tbody>
</table>

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**FIGURE 2  Two-Man Diagram**
maximum service shear and bending moment magnitudes of 160 pounds and 520 feet-pounds. The moments are not exactly zero at the ends due to computer rounding errors.

By examining the widest cross-section of *The Little Engine*, the moment arm between the tension and couple was estimated to be eight inches. Figure 3 shows a six-inch shell element modeled in SAP 2000® to aid this estimation. Using a safety factor of 2.0 and an ACI Building Code recommended dynamic load factor of 2.0, the required compression and tension capacities were computed to be 950 pounds per square inch and 145 pounds per square inch, respectively.

Since a three-dimensional analysis had never been performed on a concrete canoe at Vanderbilt University, performing further analysis required researching basic finite element systems defined as masses connected by springs. Similarly, an introduction to the commercial software available for analysis was necessary to gauge the difficulty in using their interfaces.

An IGES NURB, a high-level industry standard file defining the hull shape completely, was imported into ANSYS Release 7® and SAP 2000®. SAP 2000® was utilized for its ease in entering load data and applying end constraints. Restricting rotation and translation in all Cartesian directions, *The Little Engine* was treated as a beam, fixed at thirty-six inches from either end. Since tension and compression limit states were found from two-dimensional analysis, the goal of three-dimensional analysis was to determine a composite flexural capacity. Assuming a linear isotropic concrete composite, the flexural strength capacity, as computed by the effective stress, von Mises equation, was 425 pounds per square inch.

**Development and Testing**

The aim of the mixture design was to minimize concrete density while exceeding the minimum design strength. The primary concern for *The Little Engine* was its overall mass. While the buoyant design of the canoe could accommodate concrete as dense as ninety pounds per cubic foot, a heavier boat would be significantly harder to paddle than a less dense boat of comparable strength. The goal for *The Little Engine*’s seventeen foot long and one-half inch thick body was a maximum weight of 180 pounds according to the hull design team. Given a minimum compressive strength of 950 pounds
per square inch from analysis results, the concrete design required a density between sixty and seventy pounds per cubic foot to meet strength, weight, and workability requirements. Development of the concrete design began with material research and selection. Prior experience, constant research, and the knowledge gained from concrete experts were used to make judgments about the necessary set of component materials.

The Mix Design (MD) team considered cement, fly ash, ground granulated blast-furnace slag, and silica fume for cementitious materials. Over the years, the MD Team has learned that slag has poor workability while fly ash improves workability and decreases water demand. From past experience and research, silica fume greatly increases water demand. Therefore, the team decided to simplify the design and focus on testing with just cement and fly ash as binders. As a result, slag was omitted from the mix and the binders would be composed of at least seventy percent cement and at least fifteen percent fly ash. Additionally, the amount of fly ash would be maximized to thirty percent since it is the lighter material.

The composite aggregate must meet the ASTM C33 standard, which limits the particle size. Sand is a strong aggregate that can be graded to meet the standard. Because sand is a heavy material, the team incorporated glass microspheres to make the mix lightweight. According to the national competition standard, microspheres could only make up a maximum of ten percent of the aggregates, and the team decided to maximize the amount used.

Cylinders were tested for compressive strength at seven and twenty-eight days according to ASTM C39. Three main design areas were focused upon with controlled testing. First, the proportions of the main materials—cementitious materials, aggregate, and water—were varied. This was the primary focus since multiple parts of the mix depended on it. The minimum allowable amount of aggregate in the mix was proven unfavorable, as is shown in Table 3. Test results showed that the best design proportioning was at forty percent aggregate, forty percent cementitious materials, and twenty percent water, by weight.

<table>
<thead>
<tr>
<th>Ratios By Weight (cm/aggregate/water)</th>
<th>Concrete Density (Pounds Per Cubic Foot)</th>
<th>Compressive Strength (Pounds Per Square Inch)</th>
<th>Workability</th>
</tr>
</thead>
<tbody>
<tr>
<td>50/25/25</td>
<td>105.2</td>
<td>2462</td>
<td>Fair</td>
</tr>
<tr>
<td>40/40/20</td>
<td>92.2</td>
<td>2613</td>
<td>Easy</td>
</tr>
<tr>
<td>30/55/15</td>
<td>82.8</td>
<td>1388</td>
<td>Poor</td>
</tr>
</tbody>
</table>
Second, latex was varied to find the most workable and strongest mix. Test mixes ranged from containing no latex to all latex contributing to the amount of water in the design. A latex admixture was tested and utilized in order to provide more flexibility and workability than the water itself. Similar to past experience with the admixture, latex and water tend to separate and weaken the mixture. On the other hand, replacing all water content with latex nearly doubled the strength in a controlled test and also reduced the water-concrete ratio, as shown in Table 4.

Third, different amounts of carbon fibers were tested in the concrete mix. The Vanderbilt Canoe Team had yet to test the possibility of using fibers within the concrete, separate from reinforcement mesh within the composite concrete design. Using one-half percent to two percent fibers by weight, the average compressive strength increase was nearly 5.5%, but also the density increase was more than 2.4%. Combined with the longer mixing time and decreased workability, no carbon fibers were used in the final concrete design.

Additional admixtures of an air-entraining chemical and a water-reducing chemical were considered. Because the MD Team observed that air weakened the concrete, the minimal amount of air-entrainer was used. The water-reducing chemical was not necessary because the use of latex kept the water-concrete ratio under at less than 0.5. The chemical also made the concrete stick to one’s hands and not to the mold. Therefore, the only chemicals used in the final design were latex and air-entrainer. The final amounts of each material are shown in Figure 6, where latex contributes to a total of 15.7% of the water content by weight.

### Reinforcement

The static and dynamic loads under each paddler create the need for reinforcement to resist the tension forces from flexure. Types of reinforcement considered were carbon fiber, polypropylene, Kevlar, and fiberglass mesh. Carbon fiber mesh was tested and used because of its strength and relative ease of handling. The chosen carbon fiber mesh was a five-harness satin weave, with strands easy to pull in order to create an open weave where the concrete layers could bond to each other.

<table>
<thead>
<tr>
<th>Latex Proportioning (latex/water)</th>
<th>Density (Pounds Per Cubic Foot)</th>
<th>Compressive Strength (Pounds Per Square Inch)</th>
<th>Workability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/100</td>
<td>89.7</td>
<td>2540</td>
<td>Easy</td>
</tr>
<tr>
<td>50/50</td>
<td>90.5</td>
<td>1842</td>
<td>Fair</td>
</tr>
<tr>
<td>100/0</td>
<td>85.3</td>
<td>4982</td>
<td>Easy</td>
</tr>
</tbody>
</table>
Custom plates were tested for composite flexural strength, modified from ASTM C1018 for fiber-reinforced concrete. Representative of the bottom of the canoe, twelve inch by twelve inch by one-half inch plates were supported at their corners and loaded in the center until failure. Several reinforcement layouts were tested, but the baseline design of two mesh layers remained the best choice, with results shown in Table 5.

With a concrete density of sixty five pounds per cubic foot, The Little Engine weighs in at 175 pounds, under the design maximum of 180 pounds. The final concrete design produced a compressive strength of 1053 pounds per square inch, well over the target of 950 pounds per square inch. The composite concrete and reinforcement design yielded a flexural strength of 700 pounds per square inch, well above the target of 425 pounds per square inch.

**Project Management**

During the first project meeting, the four primary Vanderbilt Concrete Canoe team members decided upon a functional work breakdown structure (Oberlender 2000). Each member was given control of one of the following functional units: hull design and analysis, mix design and analysis, construction, and project organization. This structure was instituted to ensure accountability in each unit while facilitating communication among the team members.

**Estimating and Planning**

The scope of work in each unit was discussed at the project initiation, taking into account applicable rules and requirements. Past experience and consultation with engineering professionals were essential to estimating the amount of money and time required to complete each phase of the work. The five thousand dollar budget allocated traveling expenses to conference, construction materials, and paddling preparation. Utilizing surplus reinforcement from previous years saved a significant
amount of money, which was invested into new paddles and into the extra travel cost due to increased gasoline prices.

After the work was parceled into functional units, Primavera Project Planner was used to establish chronological relationships among each task. Tasks were assigned primarily using the same priority established in the first project meeting but were modified to accommodate situations in which resources were unavailable. The target project was primarily constrained by a twenty-eight day period needed for the concrete to achieve near maximum strength. Using a backward pass, late finish times were established for the project. Total float was then calculated by Primavera using a forward pass. Critical activities were defined as those activities with zero float and were those most significant to constructing the canoe early enough to allow it to completely cure. The critical path activities were lab preparation, mold construction and finalization, concrete placement, bow and stern cover construction, sanding and patching, and staining. Once the critical path had been determined, the team chose the project milestones of finalizing the hull design, mix design, mold, laying concrete, and finalizing construction. Four of the project milestones were delivered four days ahead of schedule due to accelerated productivity.

Project Execution

A regular weekly meeting time was established at the project initiation. The meeting served as both a way to quantify the amount of work being done as well as to direct impending work. At weekly meetings, project team leaders assumed tasks for the following week, reported the extent and nature of work completed in the previous week, and recorded the expense and total labor hours completed.

Underclassmen engineering students were recruited to assist the team leaders in the construction of the canoe. To promote involvement the Team campaigned in several undergraduate classes and at the biweekly chapter meeting of American Society for Chemical Engineers. In addition, advertisements were strategically placed within the primary engineering building. A total of approximately 820 hours

<table>
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<tr>
<th>Reinforcement Layout</th>
<th>Relative Flexural Strength</th>
<th>Ease of Placement</th>
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<tbody>
<tr>
<td>2 Layers, Normal Alignment</td>
<td>1.000</td>
<td>Fair</td>
</tr>
<tr>
<td>2 Layers, One Diagonal and One Normal</td>
<td>1.007</td>
<td>Difficult</td>
</tr>
<tr>
<td>2 Layers, One Concrete Layer with Mesh Fibers</td>
<td>0.814</td>
<td>Difficult</td>
</tr>
<tr>
<td>1 Layer, Normal Alignment</td>
<td>0.296</td>
<td>Easy</td>
</tr>
</tbody>
</table>
were spent by the team and additional students, distributed among design (250 hours), analysis (100 hours), testing (70 hours), canoe construction (300 hours), and paddling practice (100 hours).

**Construction**

The primary goal of the construction process was to ensure consistent concrete thickness and shape while efficiently utilizing resources. To effectively control concrete thickness and cracking while curing the canoe team elected to construct a new female mold from styrofoam. The choice of this foam was based on its low price, its ease of hotwiring, and its safety compared to other materials.

The three methods considered for mold construction were foam hotwiring, foam milling, and wood stripping. The past experience with hotwiring and unexpected delays with the software for milling the foam led to the decision to use hotwiring. Twenty-five transverse hull cross-sections, spaced six inches apart at the ends and twelve inches in the middle, were exported from Prolines to AutoCAD where they were formatted and uploaded into a computer numerically control machine. The small intervals, especially at the ends, were chosen to accurately capture to curvature of the hull because hotwiring only produces linear slopes between the cross-sections. Sheets of one-eighth inch Masonite were ideal for milling because of their lightweight and smooth cut edges. Each six inch by twenty inch by thirty-nine inch piece of styrofoam was fixed to a piece of level plywood, clamped between two consecutive Masonite templates, and shaped by dragging a hot copper wire along the Masonite. The tips of the bow and stern were hand-carved from soft floral foam to more accurately replicate the sharp points and dramatic slopes than hotwiring would have. Non-structural epoxy was used to connect the cut foam pieces. A thin layer was then spread over the foam to fill imperfections and joints, and to aid in releasing *The Little Engine*. Once the first layer had hardened the epoxy was sanded and the process was repeated until the desired smoothness was achieved.

The pre-construction process included portioning out materials for the mix and assigning the construction responsibilities of quality control, mixing, placing reinforcement, and constructing the immediate bow and stern. Before placing the concrete, WD40 was sprayed on the mold. Consideration of various releasing agents proved WD40 worked well and was the most cost effective and easiest to apply. Instructions and safety considerations, including wearing gloves and taking breaks, were explained to all workers prior to placing the concrete.

Quality control played a significant role throughout construction and finishing so the constructed canoe would be consistent with the designed hull. The hotwired cross-sections were measured to check the accuracy of the cuts and the epoxy was carefully applied and sanded to maintain the curvature of the hull. Several students monitored concrete quality and thickness by following those placing concrete and making adjustments where needed. The concrete was placed by hand to a depth of one-sixth inch, measured using thin steel rulers. The reinforcement was quickly placed on top of the completed concrete layer and pressed in before the placement of the second layer.
commenced. In all, the three layers of concrete and two layers of reinforcement comprised an overall thickness of one-half inch. A thick layer of plastic was placed over the mold to allow the concrete to cure and make it easily accessible for daily spraying of water.

Finishing

After the initial construction day, the inside layer was patched with concrete to repair air bubble ruptures and to improve the gunwale shape. Expanding spray foam was placed in the first two and a half feet of the bow and stern using a cutout cross-section to keep the spray foam in place until it dried. The top and side of the foam was covered with concrete to prepare the canoe for finishing. Once the concrete had cured for four weeks the canoe was removed from the form and placed upside down on a foam stand. Once the outside was patched and allowed to dry it was sanded using an electric sander with 100 to 3000 grit paper, upon recommendation of a professional knowledgeable about finishing and staining concrete. A stain recommended by the manufacturer for use on concrete was applied using an airbrush to get a consistent color with crisp edges between colors.

References


