Department of Naval Architecture and Ocean Engineering
Independent Research in Naval Engineering Final Report

Development of a Four-Pound Human-Powered Vessel

by

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May 4, 2007

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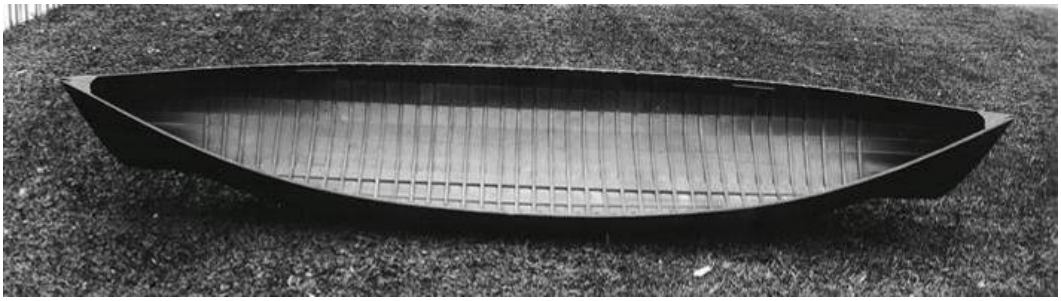
In 1882, John Henry Rushton built the Sairy Gamp; a nine foot long, twenty-four inch beam, double-paddle canoe weighing in at ten and a half pounds[1]. To minimize weight, Rushton built the Sairy Gamp using a combination of thin wood planking for the hull and numerous transverse ribs for structural support.

Over a century has passed since Rushton built the Sairy Gamp, yet little improvement has been made to design and build a canoe that weighs less then ten pounds. Therefore, the purpose of my independent research is to use modern ship building software in union with a structural analysis program to design a five-pound double paddle canoe from lightweight composite materials.



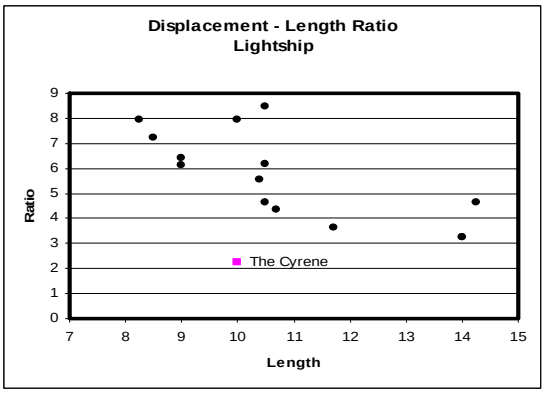
The *Sairy Gamp*[2]

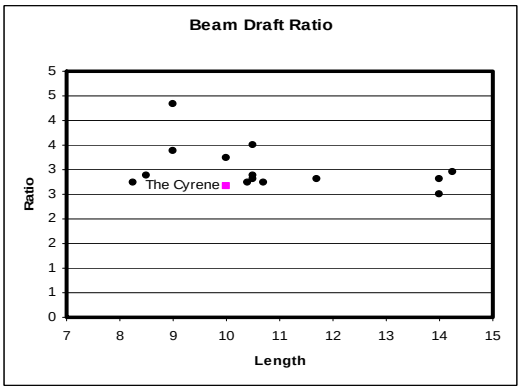
To begin the project, the general dimension of the canoe are estimated and compared to other lightweight canoe designs. With this data, a canoe of similar dimensions is chosen as the design basis. Using ship design software, a faired hull is created and exported to a structural analysis program. Using the analysis program, modifications are made to the hull structure, namely the core thickness, in attempt to reduce the weight while maintaining acceptable factors of safety. The results are drawn and the thicknesses are noted for the final design.

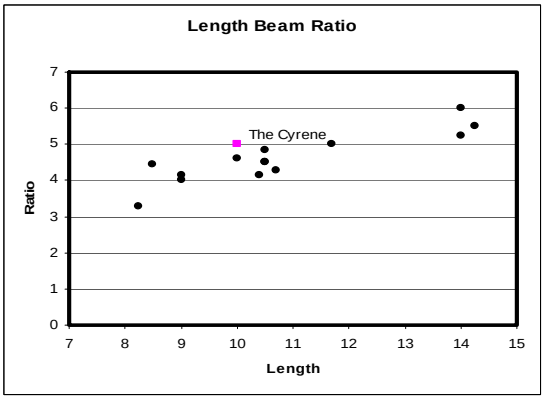
The initial research of Rushton's canoe designs and other lightweight designs was necessary to build sufficient data for comparative analysis of the preliminary hull

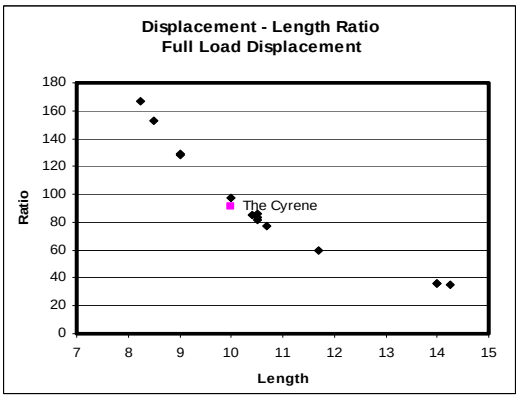
dimensions. The length, beam, center rise, and displacement information is used to calculate the full-weight displacement to length ratio, beam to draft ratio, length to beam ratio, and light-ship displacement to length ratio.

Comparative Analysis Data [3 4 5 6]						
Design #	Name	Length [ft]	Beam [in]	Center Rise [in]	Weight [lb]	Disp [lb]
1	Nessmuk	10	26	8	17.8125	217.8
2	Susan Nipper	10.5	28	8	16	216
3	Sairy Gamp	9	26	6	10.5	210.5
4	Bucktail	10.5	26	9	22	222
5	Nessmuk 2	8.5	23	8	9.9375	209.9
6	Grants Ultralight	14.25	31	10.5	30	230
7	Sairy Gamp Carbon	9	27	8	10	210
8	Hornbeck boats	10.4	30	11	14	214
9	black Jack	10.7	30	11	12	212
10	Arrow 14	14	28	10	20	220
11	Snowshoe 12	11.7	28	10	13	213
12	Snowshoe 14	14	32	12.75	20	220
13	Snowshoe lassie	10.5	28	10	12	212
14	Sweet Peak Mk 2	8.25	30	11	10	210
15	The Cyrene	10	24	9	5	205



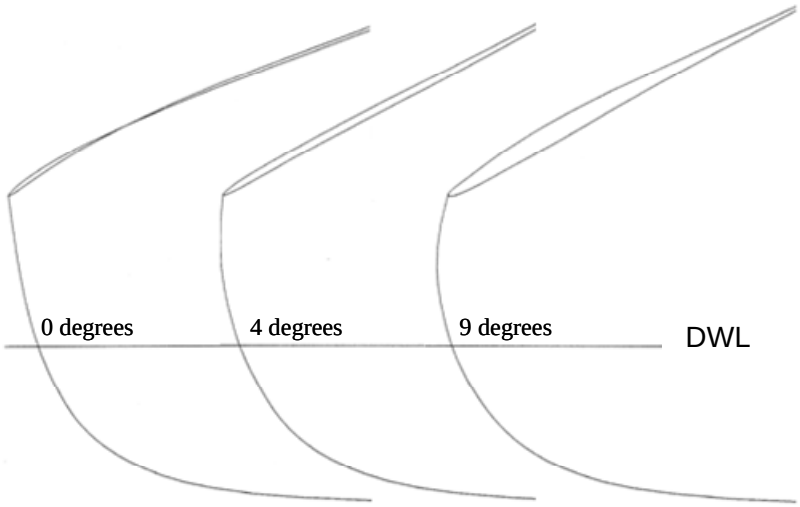






Analyzing the plots of the different ratios, the initial design estimations for length beam and draft are reasonable, falling within the trends of actual designs. The only exception is the lightship displacement to length ratio; however, this non-conformity is desired because the project's goal is to build a canoe lighter than all the previous designs.

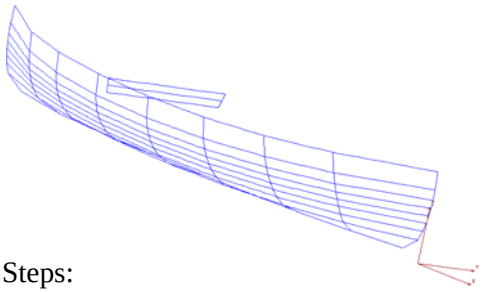
Taking these initial dimensions into consideration, the hull design of the "SnowShoe Lassie" was chosen because of its similarity. The hull is part of a collection of ultra-light designs know as Geodesic Airolites, by designer Platt Monfort[6]. Using the lines drawings provided on the website, a collection of "markers" are recorded. These markers are entered into the ship design software, Maxsurf. Maxsurf is software specifically used for modeling three dimensional surfaces for marine design. After inserting the markers, a surface is created to model the canoe's hull. In its initial state, the surface looks nothing like the desired hull shape. Thus, the control point locations are modified to warp and bow the surface to match the general shape outlined by the markers. The surface is then faired by making small alterations to the control points and modifying the surface stiffness in the longitudinal and transverse directions. In order to view the effect of tumblehome on design strength, three initial designs with varying amounts of tumblehome are created from the base design of the "SnowShoe Lassie".

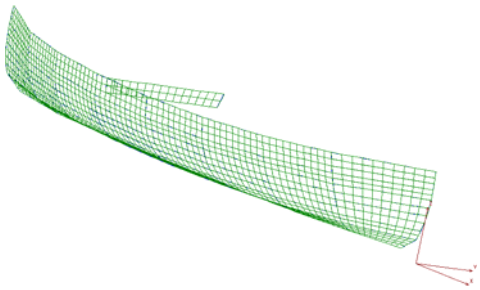


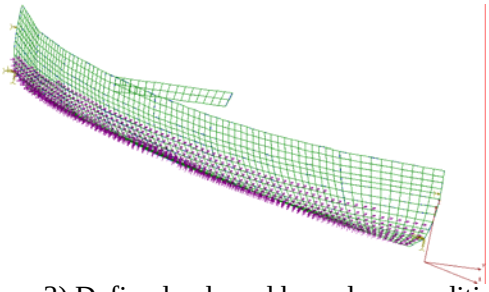
Tumblehome Comparison for Amidships Cross-section

Using the finished designs in Maxsurf, data files are exported for all three designs. The exported files are loaded into COSMOS, the structural analysis program. The refinement and modification of the hull structure is accomplished using COSMOS. COSMOS will is also used in the analysis process to determine the resulting deflections, weight, and factors of safety (FOS). COSMOS is a finite element analysis (FEA) program that operates by subdividing a large complex structure into small parts, know as elements. Each element is modeled as a spring, governed by the equation F=k*u (F is the applied force, k is the stiffness, and u is the displacement). Specifically, COSMOS uses the Tsai-Wu method to analyze the FOS of stress in composite materials, which calculates the percentage of failure in each laminate of the composite. The composition of all the elements creates a large system of springs that are connected at adjoining sides. When forces and constraints are applied; the resultant forces, moments, and displacements between adjoining elements must be balanced to provide continuity throughout the entire system. COSMOS and other FEA programs use matrix math to simultaneously solve the multiple equations, which balance out the reactions between the elements.

The three models show the stepwise progression of modeling the canoe in FEA





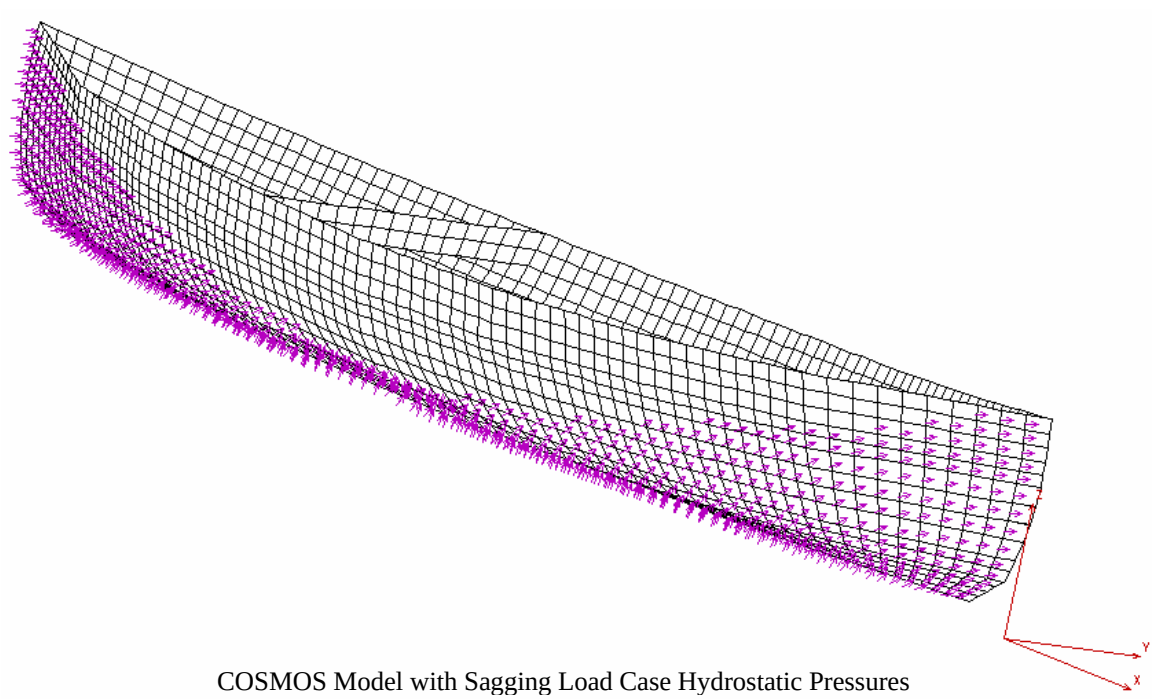


Steps:
1) Create hull's structural surfaces 2) Divide surfaces into multiple elements 3) Define loads and boundary conditions

Once the hulls' structures are properly created in COSMOS, to include the addition of the crossbeam back support, the material properties of the composite materials must be entered before any analysis can be performed. The initial design iteration is performed with 2oz glass cloth t = 0.0022", 2.9 oz 1k carbon cloth t = 0.0045", and aluminum honeycomb of varying thicknesses. The laminate lay-up consists of five layers: 1) fiberglass 2) carbon fiber 3) aluminum honeycomb 4) carbon fiber 5) fiberglass. In the design iterations, the thickness of the core material is reduced to less than a quarter of an inch. With such a small thickness, the honeycomb core would fill with resin during the lamination process, causing a dramatic increasing the overall canoe weight. Therefore, in later iterations, the aluminum honeycomb core is replaced with ROHACELL 51, a low-density ridged foam material.

In addition to the material properties, the load cases must also be entered into COSMOS before analysis may be performed. For the project, four load cases are designed to: working load, gunwale supporting load, seat load, and sagging wave load. The first load case, the working load, is the scenario that the canoe is expected to experience during normal operating conditions. In this instance, a portion of the passenger weight is applied on the seat area while the remaining vertical forces are applied at the location of the feet. Horizontal forces are applied to the cross beam to simulate the forces of the passenger's back leaning on the beam. Furthermore, horizontal reaction forces of equal magnitude are applied at the feet to maintain balanced forces on the canoe. For this load case, the assumption of calm water is made and hydrostatic pressures are applied, normal to hull surface, on all the elements below the designed waterline.

The remaining load cases are expected to occur, but for short periods of time. These scenarios, however, still require the canoe to be built to the same FOS that is expected for the working load case. The second load case is representing the scenario in which all the passenger's weight is placed on the gunwales forward of the cross beam. This would occur when the passenger is attempting to raise or lower himself into the seat. The seat load, modeling the entire passenger weight in the center seat area, is designed to represent the loading that would be caused by the passenger stepping into the canoe. Like the working load, both the gunwale load case and the seat load case have hydrostatic forces applied uniformly beneath the designed water line. The final load case is the sagging wave load case, which represents the worst wave condition. For this load case, a wave of equal length to the canoe crosses the canoe such that the bow and the stern are lined up with the wave peaks, and the midship section is above the wave trough. This creates a situation in which the middle of the canoe sags down because the buoyancy force up is being applied at the edges while all the weight of the passenger is being applied at the seat area in the center.



COSMOS Model with Sagging Load Case Hydrostatic Pressures

Using these four load cases and several displacement definitions, locking nodes from movement in certain degrees of freedom, the analysis on the structural integrity of the canoe design may be performed. The displacement definitions are used to accurately model the circumstances of the real canoe, and they are also used in order to allow COSMOS to run properly. Without certain displacement definitions, COSMOS is unable to analyze the model, or the produced analysis results are unrealistic. Therefore, with a completely built model in COSMOS, analysis and design iterations may now be performed. Using the program, the core thickness is modified in order to strengthen areas of high stress. Therefore, while the thickness of the core material in the canoe's frame, consisting of the ribbing, gunwales, and seat area is increased; the core thickness of the remaining areas of the canoe is reduced. This process creates an overall decrease in weight without decreasing the FOS. With multiple iterations, a final structural layout is determined that is applied to the three tumblehome variations.

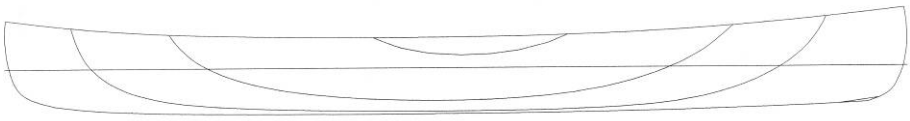
To further reduce weight, the shear at the bow and the stern is lowered to decrease the hull area. In order to reduce the amount of time spent revising all three models in Maxsurf, the three tumblehome designs are compared, taking into consideration deflection, weight, and FOS in buckling and in stress to determine the best tumblehome variation. The analysis between the three tumblehome variations yields:

Tumblehome Variation	Stress FOS	Buckling FOS	Weight (lbs)	Max Displacement (inches)
Zero	4.66	-1.60	4.01	0.795
Four	4.61	-1.55	4.02	0.711
Nine	4.54	-1.51	4.04	0.641

Using the above data table, the zero tumblehome variation is determined to have the greatest FOS in stress, the greatest FOS in buckling, and the weighed the least. At this point, modifications to the zero tumblehome hull design are made in Maxsurf to reduce the shear. The new hull design is then imported into COSMOS and the new model is created. Subsequent design iterations are performed in order to reach the acceptable FOS in buckling of three and the acceptable FOS in stress of two.

Profile view showing the reduction of shear at the bow and stern

Initial Design



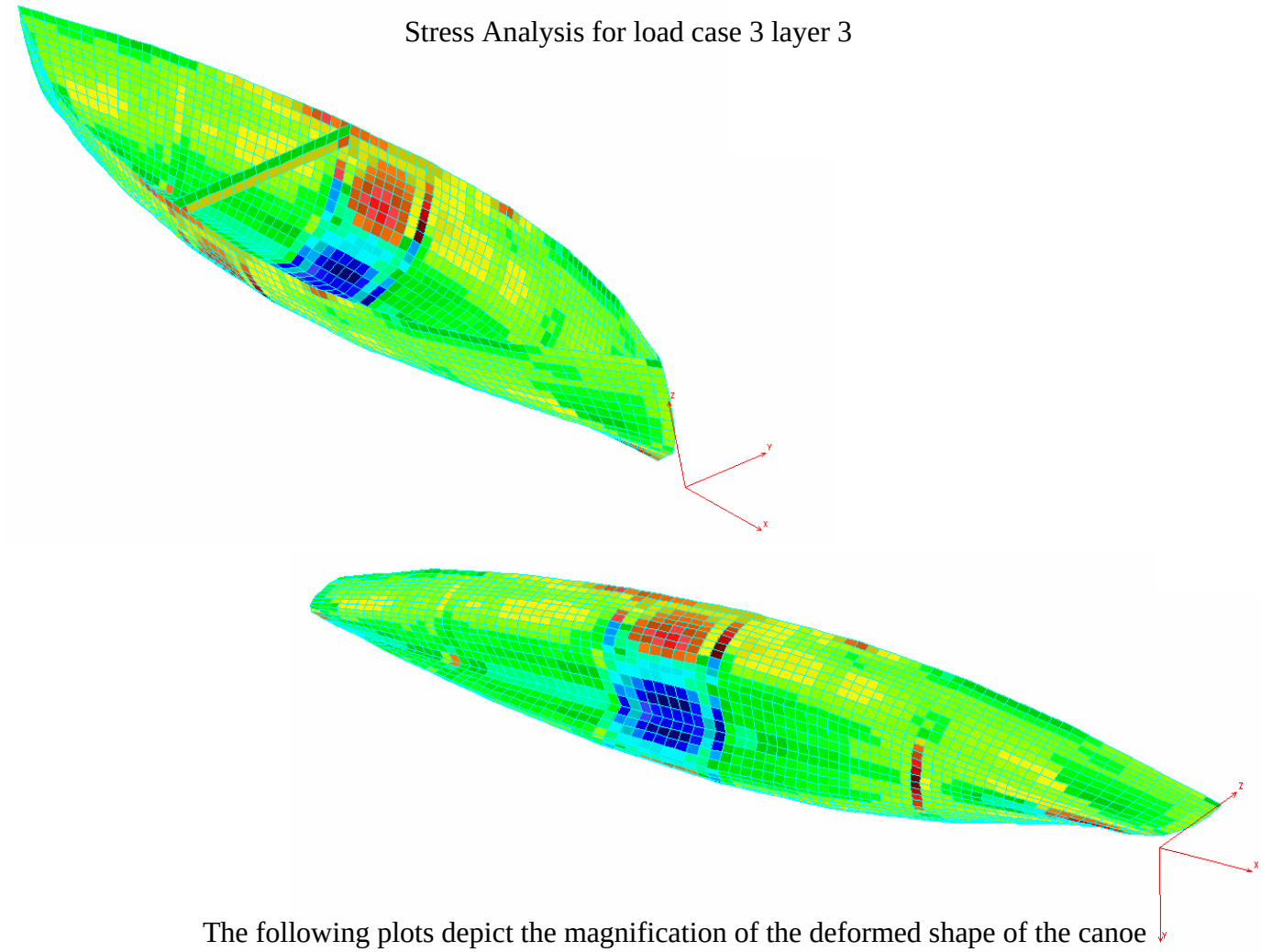
Post – Cut Design

Design Area Difference

The finial design iteration produced a canoe weighing 3.5 pounds, having a minimum FOS of 3.14 in buckling and a minimum FOS of 5.25 in stress for all four load cases. The maximum displacement of 0.47 inches occurs during the sagging load case. The core thicknesses vary from 1mm thick to 12 mm thick.

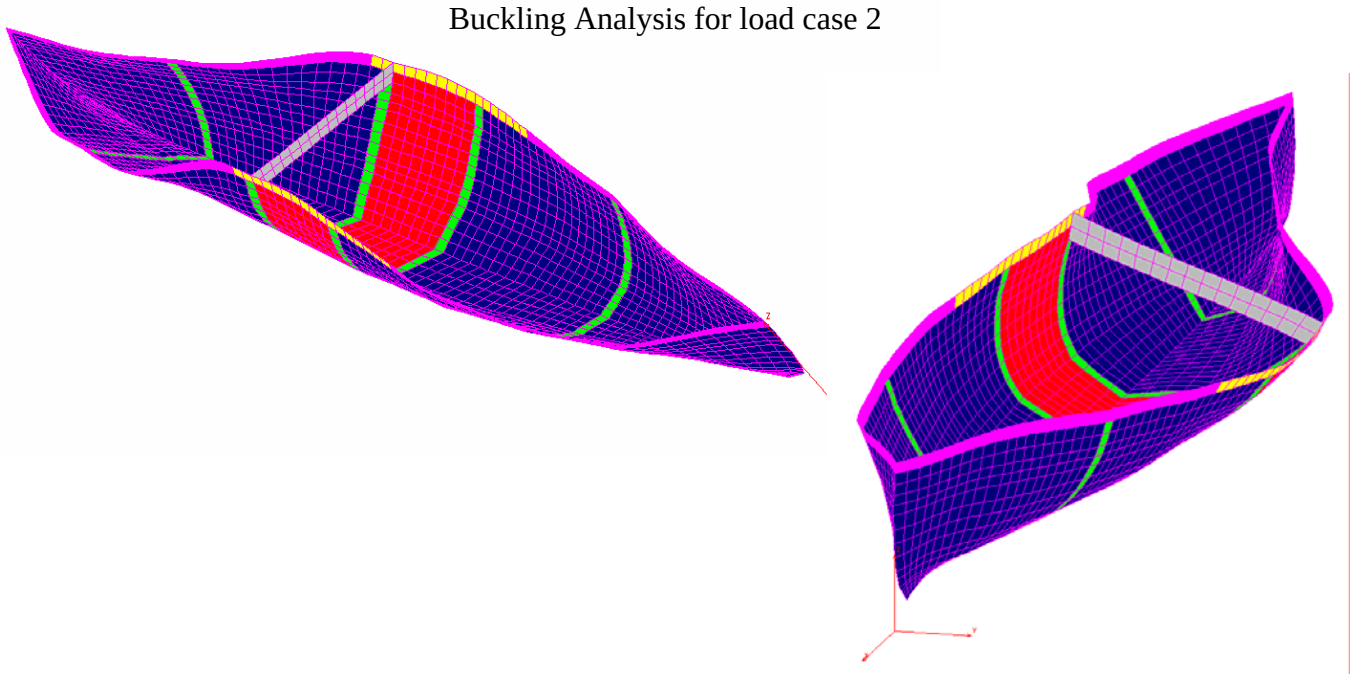
The following two plots show the Tsai-Wu stress analysis of load case 3 for the third laminate. The dark red areas and dark blue areas denote regions of high stress.

Stress Analysis for load case 3 layer 3

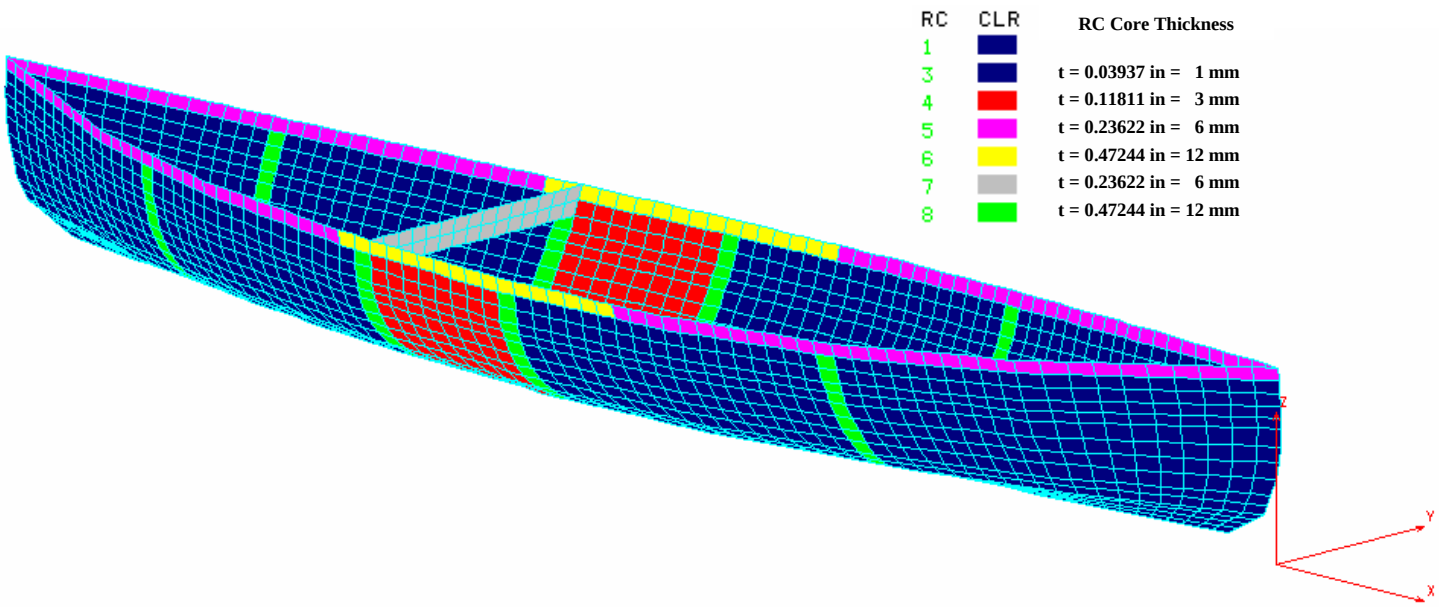


The following plots depict the magnification of the deformed shape of the canoe when load case 2 is applied. The shape represents the deformation due to buckling. The different colors in these plots represent the different core thicknesses.

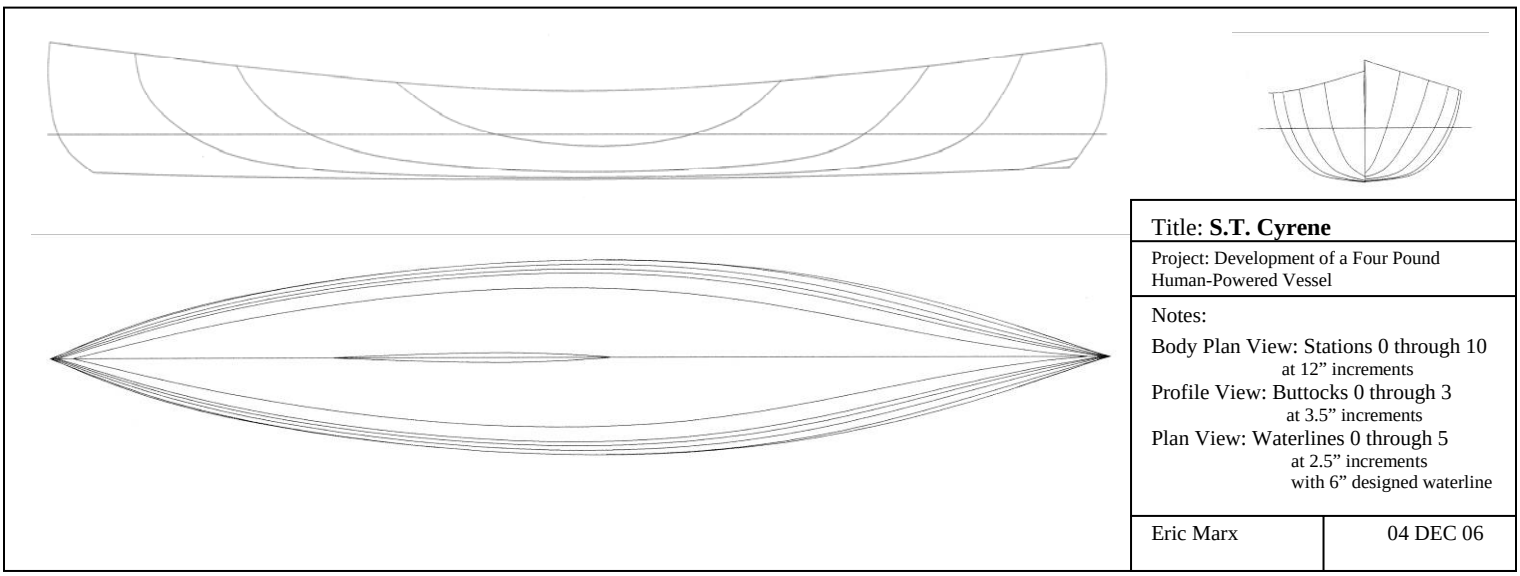
Buckling Analysis for load case 2



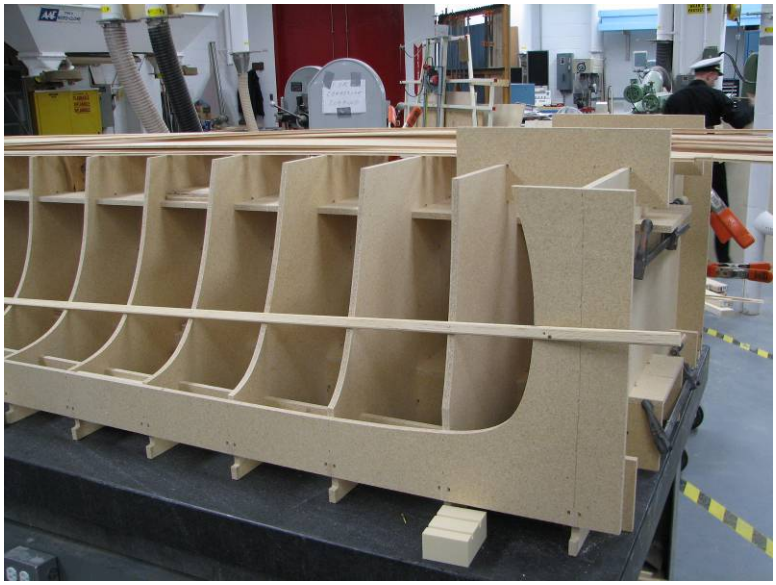
The following plot outlines the areas of different core thickness, denoted by the different colors. The entire canoe will be layered with the same amount of fiberglass and carbon fiber.



The following is the finished lines plan for the canoe design.



Once the computer model's predicted weight is reduced sufficiently, and sufficient FOS for stress and buckling forces are present, the three-dimensional lines plans are exported. From the exported model, two centerline profile lines are cut along with station ribs. The ribs and centerline profiles are placed together forming the skeleton of what will be the female mold.



Ribs are equally spaced along the length of centerline profile piece

The process of strip-planking is then performed, laying thin long strips of sugerpine wood across the ribs like a spline. The strip is nailed down to each rib and glued to its adjacent strips. The strips are cove and bead to allow the strips to overlap, minimizing gaps between adjacent strips.

Wood strips nailed and glued down to rib frames (uncompleted)

Once all of the strips have been laid across the ribs and secured, the excess planking is cut away. The rough edges are sanded and a mixture of epoxy and microlight is smoothed into the gaps and allowed to cure. The inside of the mold is smoothed using a series of sandpaper roughnesses ranging from 60-grit to 400-grit. The sanded surface is then coated with Duratek paint. Once dried, the surface is again sanded using up to 400-grit paper.

Mold surface is coated with Duratek paint and sanded

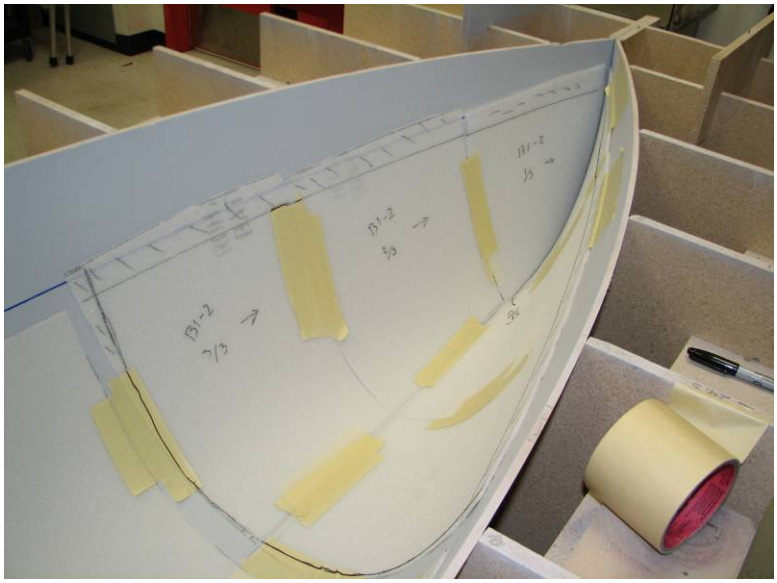
The sheer line on one half of the mold is scribed into the paint cutting a groove along the length. Depth offsets are taken from the top of each station down to the shear line and transferred as a tick mark on the other half of the mold. Thus a shear line of equal height on both sides of the mold is created. The two mold halves are then rotated such that they face towards each other. After aligning the two halves, clamps are used to pull the molds together along the baseline and bolts are used to secure the bow and stern.

Bow secured by bolts and baseline secured by c-clamps

At this point in the building process, the focus is transferred to the preparation of the cloth and core materials. The cloth is laid down in the dry mold and cut to size. The fiberglass is cut such that one piece runs the length of the mold. The carbon fiber is cut such that three pieces run transversely across the hull. Once the material is cut, the sheer line on both sides of the hull is redrawn with blue permanent marker for increased visibility. Using the dimensions recorded from the FEA model, templates are cut for the core material using sheets of brown paper.

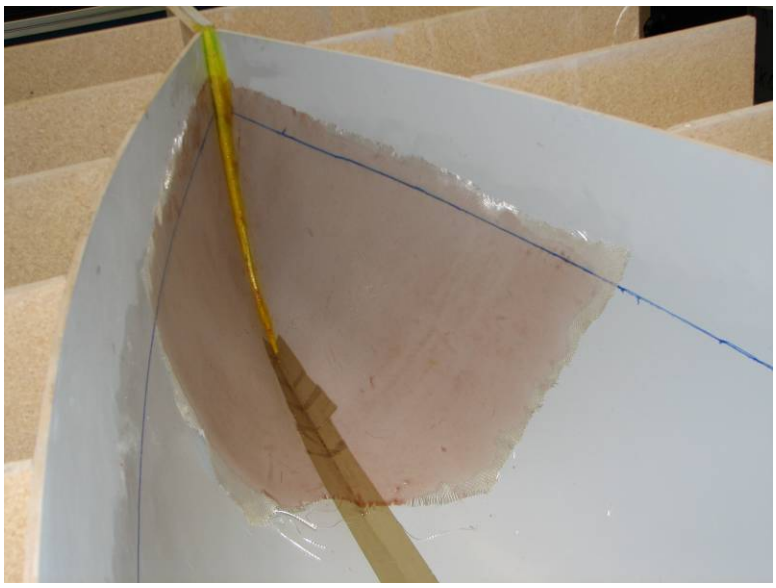
Templates used to cut core are fitted in mold

After inventory of the core material is done, the best orientation of the material and templates is determined such that the core pieces located at the bow and the stern will have their transverse cuts align. This must be done because the core material is not flexible enough to allow one piece to run transversely across the hull.



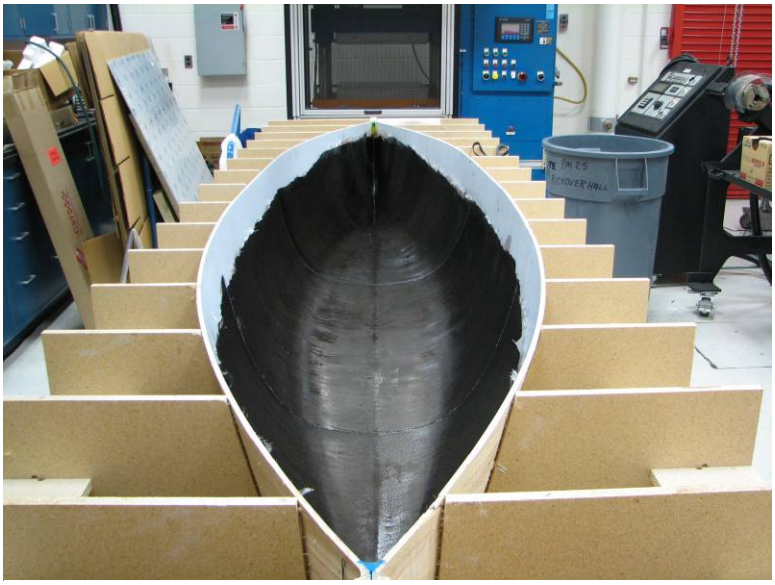
Six individually cut core pieces are used for bow section

The remainder of the main core pieces are cut and trimmed to size. Tape is then placed along the baseline, creating an airtight seal which will be necessary for the vacuum bag process. In the bow and the stern, clay is pushed into the knife-edge point, creating an airtight seal and a workable radius of curvature for the cloth to form around. The mold is then waxed so that the resin will not bond with the mold, allowing the cloth lay-up to release. At this stage, a test mold is created using boat cloth. The purpose was to test the mold release wax and the viability of working a single sheet of cloth into the stern area.



Test piece is laid-up in stern using boat cloth

Upon verification of the test piece, several more layers of mold release wax are applied. The 2.2oz fiberglass is dry fitted into the waxed hull, and pro-set 125 resin and pro-set 226 hardener are used to wet out the cloth. After working the glass into the mold, the 2.9oz carbon fiber is then laid-up on top of the glass and wetted out with the resin. These two layers are then allowed to cure.

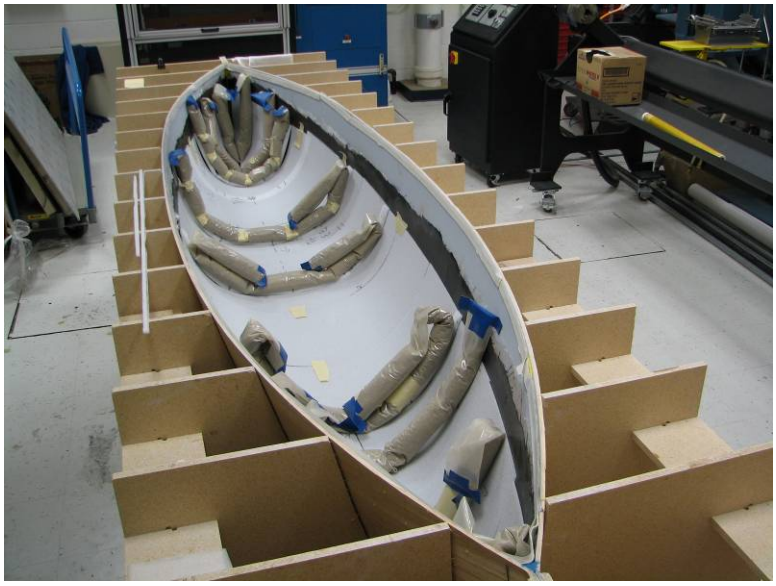


Fiberglass and carbon fiber are wetted out in mold

After the first two layers of cloth have fully cured, the inside is wiped out to remove the blush, created by the curing process. The surface is also scuffed such that a proper secondary bond is created when resin is applied. The core is again dry fitted to the mold to ensure proper fitting. The structural hoops are cut and layered. Because of their stiffness, the hoops had to be broken into three pieces or more, to allow them to properly bend down to the mold surface. Once all the pieces are fitted, the thicker core material must be tapered to allow smooth transitions between the varying thicknesses. Along the length, the gunwales are tapered with a 1:5 ratio. All other transitions are cut at 45 degree angles.

Structural hoops and gunwales are fitted around main body pieces

In order to prevent the core pieces from moving once the resin applied and the vacuum bag has yet to apply full pressure, tubular bags are filled with sand and placed across each of the main body pieces as well as each structural hoop. Hinges are then inserted into the sand bags to allow them to bend properly and apply enough force on the pieces to keep them in place.



Sandbags are used to secure pieces

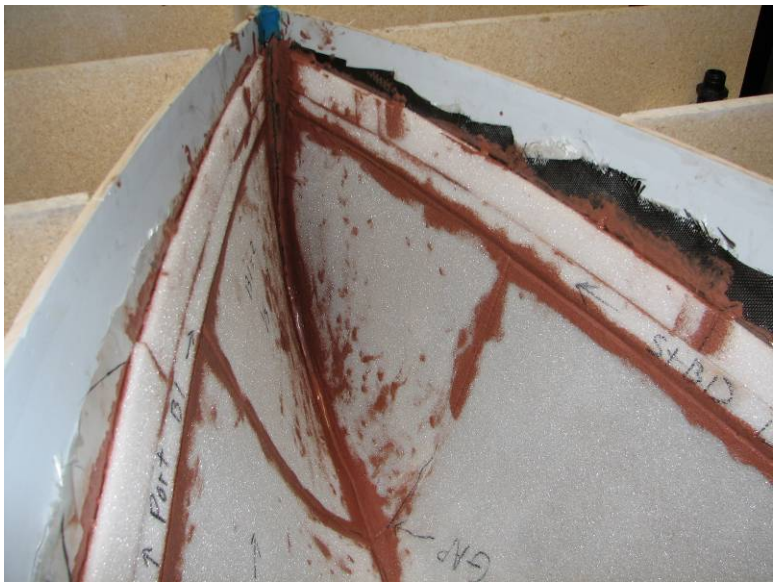
The vacuum bag tape is laid just below the top edge of the mold and the bag is placed in the mold, attaching it to the tape. Creases are made by extending tape off the main tape strip. A dry run of the vacuum bag is done to ensure that the bag is large enough. The bag was too small, so a new bag is cut and refitted and tested. During the test, the pressure is monitored and leaks in the bag are found and sealed. After testing, the bag is removed, and the resin is mixed with microbubbles to create a thick paste. The past is applied to the cured carbon fiber and the sheets of core material are placed. The pieces are aligned, and the sandbags are placed. Then the vacuum bag is reapplied to the mold. The newly applied resign is allowed to cure.

Large creases are inserted to allow the vacuum bag to sit properly

Perforated tube runs length of hull to allow suction to reach all parts of the vacuum bag

The vacuum bag is connected to a suction pump that maintains a pressure over 20 psi

After the resin cures, fixing the core material to the outside layer of cloth, the vacuum bag is removed. The gaps between the pieces of core are filled with a combination of microbubbles and pro-set resin. The resin - microbubble combination is further added to assist in the tapering between adjacent pieces of core that are of different thickness.



Resin-microbubble combination is used to provide fillets

Because of the inconsistencies, in the first lamination of the core, additional pieces of core are applied to the mold in order to increase the depth of the gunwale. This additional thickness will later be shaved off, providing a smooth sheer line. The same resin – microbubble combination is used for the application of the supplementary gunwale.

The additional pieces of core are inserted above the gunwale pieces

After the addition core pieces and fillets cure into place, the smooth surfaces are scratched, to allow proper secondary bonding. The core is then painted with resin as the carbon-fiber cloth is laid down. Addition resign is applied to ensure that all the carbon is wetted out. The carbon is allowed to cure, and the process of removing the blush and scratching the surface is done.

Inside carbon layer is applied around structural hoops

The final layer of cloth is dropped into the mold dry and wetted out on top of the scratched carbon fiber. The delicate nature of the fiberglass creates a difficulty when forming it around the structural hoops. Extreme care must be taken to prevent it from bridging or creating air pockets. Because of the difficult nature of the fiberglass, it was laid-up along the majority of the length; however, it is not in the area around the bow or stern.

The ending point of the fiberglass before it reaches the bow

Once the layer of fiberglass cures, the bolts and clamps are removed allowing the mold halves to be pulled apart slightly. Using wedges, the molds are slowly separated at the bow and stern, while long scrapers are used to pop the hull off the mold. Once out of the mold, the excess material on top of the gunwale is trimmed off. Using power cutters, the sheer line is cut with approximately 1/8 inch excess which will be sanded off, creating a smooth gunwale.

Hull out of mold with trimmed but un-sanded gunwales

The gunwales will be sanded down, and the exposed cloth will be scratched to allow proper secondary bonding for the carbon fiber caps that will be placed on the sheer line. The carbon will be cut to size, and laid down onto the gunwale dry. Using the pro-set resin, the carbon will be wetted out and allowed to cure.

Holding the S.T. Cyrene canoe, weighing 8.9 lbs

During this process of building the canoe mold, several independent steps are taken. The first step is to lay-up test samples, cored and a coreless section. Before laminating the material into the hull mold, one test sheet is laid-up with two layers of 6mm core and a layer of carbon fiber and fiberglass on each outer surface. This will then be cut into 1.5 in wide by 10 in long segments. These pieces are then subjected to 3 point bending in order to determine the functional strength in comparison to the FEA model predictions. Similarly, a sheet consisting of coreless laminate is also made in order to compare the functional tensile strength in comparison to the FEA predictions. The pieces are cut into strips 1 in wide by 11 inches long. The tensile test samples are broken recording the max elongation and load. Using the recorded data, stress vs. strain is determined for each test piece. For the 3-pt bending test pieces, load and deflection vs. time is recorded. The tensile test is proves the resilience of the laminate because the FEA model predicted the pieces would fail under a load 90% of the actual failure load. The 3pt bending test was not conclusive because the cylinder that was used to load the test sample created a high concentration of force along a single line. This concentrated force exceeded the crushing strength of the core material which caused a localized depression, cracking the carbon fiber. Therefore, information pertaining to the resistance to bending is unknown.

Tensile and 3-pt bending test sample pieces

Tensile Test		
Sample	Length (in)	Max stress (lb/in^2)
1	9.5	61503
2	9.2	54466
3	8.6	55193
4	9.6	50039
5	9.5	55539
Average	9.28	55348

3-pt Bending		
Sample	length (in)	max load (lbs)
1	8	-47.29
2	8	-44.29
3	8	-41.99
4	8	-49.31
5	8	-50.61
6	8	-48.50
Average	8	-47.00

Values recorded from the test samples, the averages are the FEA models' input

Before the gunwale caps are placed and the crossbeam's secondary bonding are accounted for, the canoe weighs 8.9 lbs. This is 5.4 lbs over the FEA predicted weight. The difference between the weight of the FEA model and the actual hull is due to the addition of unaccounted for resin. The first area that the resin was not properly accounted for was the core material. The weight in FEA is determined by multiplying the density of each component by its total volume in the hull. The number entered for the core material did not properly account for the amount of resin that it would soak up in the lamination process. The incorrect weight can even be seen in the 3-pt bending test pieces. The FEA model predicted the weight of a piece to be 0.026 lbs while the actual test pieces weighed 0.5 lbs. Therefore, further testing of simple plates should be done in order to accurately determine the proper factor to increase the density of ROHACELL 51 so that it accounts for the additional resin. A second area that resin was not accounted for in the FEA model was the resin – microbubble filets that are placed at each thickness transition. Because of the numerous transition covering the length of the canoe, a substantial amount of resin was used, adding addition weight. Another area of uncounted for resin is the multiple curing stages in the hull construction. Because the hull was not laid up in one step, excess resin was allowed to build up after each stage of curing. The process of laying up one layer, letting it cure, and then laying up the next added additional weight that was not accounted for in the FEA model. Lastly, the nature of the materials used did not lend itself to maintaining a proper weight to resin ratio. The fiberglass's weave was so light that it was difficult to scrap the excess resin out of the cloth. As a result, more than the predicted weight of resin remained in the cloth as it cured. Therefore, further analysis should be done in order to account for the resin in the core, and once accounted for, methods to further reduce the weight may be made.

Despite the large increase in weight from the predicted weight, the canoe is still lighter than any known canoe, beating the Carbon Sairy Gamp by one pound even with the competitions hull being a foot shorter in length than the S.T. Cyrene.

In the final stages of construction, the gunwale caps and crossbeam support must be installed to complete the structure. Initially, the gunwale caps were to be constructed from the carbon fiber; however, due to the rigidity of the carbon, the glass cloth is used to insure proper wrapping around the surface. Long pieces of glass cloth and peal-ply are cut to run the length of the gunwale. The area to be bonded is wiped down with alcohol to remove the remnant mold release wax from hull mold. The epoxy is thickened with microbubbles and cabasil. For aesthetic purposes, graphite shavings are also added to the epoxy to blacken the mixture. This thickened epoxy is beaded along the length of the gunwale, creating a continuous rounded surface for the glass cap to rest upon, instead of the porous core material. Once the thickened epoxy is down, and the glass has been run along the length, unthickened epoxy is used to saturate the glass cloth and the peal-ply.

The preconstructed crossbeam support is positioned in the hull, and in a similar manner, thickened black resin is applied to the top edge of crossbeam and the glass cloth is laid across with peal-ply. At each end of the crossbeam, where it buts up against the hull, thickened epoxy is applied to create a fillet joint. To further increase the strength of the joint, two layers of carbon cloth are laid over the thickened epoxy and wetted out with unthickened epoxy. Once cured, the structural construction of the canoe is finished.

Before the first testing, voids in the hull must be filled. Due to knife-edge bow and stern sections, the cloth did not sit properly during the laminating procedure, creating gaps and voids. These voids must be filled with thickened resin to ensure proper strength uniformity. The gaps and voids must be exposed and sanded so that the newly applied epoxy properly bonds to the existing surface. Once these gaps and voids are sanded and filled, the hardened epoxy must be sanded down to match the form of the hull.

Voids are filled with black thickened epoxy

During testing, the canoe's transverse stability was extremely low making the canoe's handling difficult. While seated on a 2 inch pad, I was unable to maintain the canoe in the upright position, rolling from sided to side and taking on water. Once the pad removed and I was seated directly on the hull, the stability improved drastically, allowing me to maintain the canoe in the upright position.

After the testing, a layer of polyurethane was added to increase durability and protect the composite material from sun damage. To prepare the canoe for the coat of polyurethane, the hull was sanded with 220 grit paper and wiped with alcohol to remove any excess mold release wax, which would prevent the polyurethane from properly bonding to the surface. Once cleaned, the polyurethane is brushed on to ensure a gloss finish. The finished canoe weighs 9.35 pounds.

The polyurethane gives a high gloss finish to the canoe

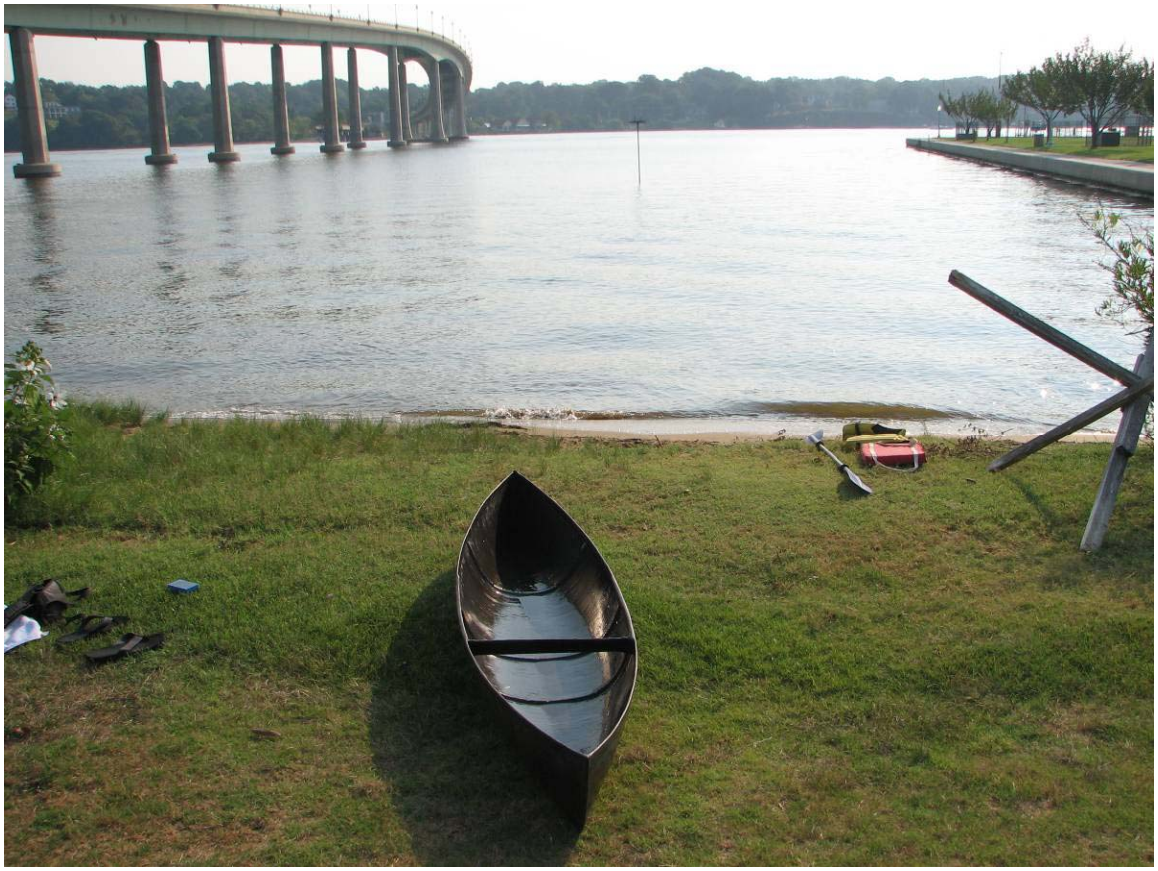
S.T. Cyrene testing

If a second iteration of this project was undertaken, the tumblehome in the canoe design should be increased and the hull should be less rounded. During the design process three tumblehome variations where all modified, and the zero tumblehome variation was selected for its larger factors of safety. However, after the construction phase had already begun, the design with nine degrees of tumblehome was found to be stronger in buckling than the design with zero degrees of tumblehome. Because the weight of the structure is driven by the FOS in buckling, a lighter canoe may have been achieved by using the nine degrees tumblehome design. In addition to the change in tumblehome, the hull should be less rounded to improve stability. During the testing, the

stability proved to be extremely low and flatting the hull would increase the handing of the canoe.

Changes in the construction phase could have also been done to improve the overall quality of the project. The canoe was laminated with the two halves together; however, quality could have been improved if lamination was done on the two halves separately. Because of the small radius of the bow and stern, it was difficult to fit the cloth and ensure that it laminated properly. Therefore, laying up the hull in two halves would allow for better control of the lamination at the bow and stern, preventing voids and gaps. To further improve the quality of the lay-up and reduce weight, the ribs construction should be changed. Instead of making breaks in the core material's normal thickness of 2 mm to insert the ribs, the core thickness changes should be minimized and the ribs added using secondary bonds after the inside laminate is laid. This would ease the cutting and fitting of the hulls core material, reducing the amount of resin required to fill the gaps, and it would simplify the lamination of the inside layers of cloth. The method used was difficult because the various pieces had to be formed to the hull surface and the ribs, requiring extra resin to prevent possible voids. If the ribs were added after the main hull construction, the amount of resin used could be controlled more readily.

Therefore, if the canoe was built with the noted changes, the final design could be more stabile, easier to build, and most importantly, the S.T. Cyrene would be lighter.



S.T. Cyrene

Special thanks to:
Prof. Paul Miller and Mr. Tom Price for guiding me through the construction process and for all the hours they were down in the lab, helping me build the mold and hull.

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