



THE 16th CHESAPEAKE SAILING YACHT SYMPOSIUM

ANNAPOLIS, MARYLAND, MARCH 2003

Student Research Projects for the New Navy 44 Sail Training Craft

Paul H. Miller, Naval Architecture and Ocean Engineering Department, United States Naval Academy, Annapolis, Maryland



ABSTRACT

Offshore-capable sail training craft (STC) specifically designed and built for the United States Naval Academy (USNA) have been a cornerstone of its seamanship training program since 1939. Currently the fourth generation of these craft is under development and this paper summarizes research projects performed by eight midshipmen in the areas of parametric design criteria, structures, appendage development and analytical tool evaluation. While the results are oriented toward the new sail training craft, they are general enough to apply to any medium-sized offshore sailing vessel.

NOTATION

ABS	American Bureau of Shipping
CFD	Computational Fluid Dynamics
CLT	Classical Laminated Plate Theory
CSNTS	Command, Seamanship, and Navigation Training Squadron
CSYS	Chesapeake Sailing Yacht Symposium
ENA	Naval Architecture Major
EOE	Ocean Engineering Major
IMS	International Measurement System
LCF	Longitudinal Center of Flotation
M&R	McCurdy and Rhodes, Inc.

NAOE	Naval Architecture and Ocean Engineering Department
NSWC-CD	Naval Surface Warfare Center, Carderock Division
STC	Sail Training Craft
USNA	United States Naval Academy
VOST	Varsity Offshore Sailing Team
VPP	Velocity Prediction Program

INTRODUCTION

The United States Naval Academy has as its Mission Statement, “to develop midshipmen morally, mentally and physically and to imbue them with the highest ideals of duty, honor and loyalty in order to provide graduates who are dedicated to a career of naval service and have potential for future development in mind and character to assume the highest responsibilities of command, citizenship and government.” (USNA Catalog) Seamanship training helps prepare the midshipmen by providing them the skills for command at sea. The math and science-dominated academic curriculum helps prepare them mentally for a technology-driven workplace and battlefield. In the engineering departments “real world” research projects are often used to allow the midshipmen to apply their new skills. Often these projects are selected by the midshipmen in areas of their interest. This paper

presents results from eight research projects performed by eight midshipmen in the Naval Architecture and Ocean Engineering Department (NAOE). The first project began in the spring of 2000 and the latest project is on-going. The effort to-date by the midshipmen exceeds an estimated 1500 man-hours. The author was asked by the midshipmen to serve as their advisor due to his background in offshore sailing and sailing craft research and design.

In addition to a background section, the paper is organized by general functional categories of general design criteria, structures, appendages and analytical tool development. Each section is headed by the project's main topic and the student researcher(s) involved. A section at the end briefly describes the students' biographies. The goal of this paper is twofold. First, it presents results that might be of interest or use to those in the sail craft research field, and second, it illustrates the type of projects currently pursued by undergraduate students. The projects ranged in size from a two-week summer internship to a full-year, twenty one-credit Trident Project.

The projects included:

- Incline experiment, full-scale resistance and VPP study by Aaron DeMeyer
- Capstone design project by Mark Arvidson, Peter Firenze and Cecily Taylor
- Fiberglass laminate upgrade by Mark Arvidson
- Alternate wood laminate by Kent Simodynes
- Keel section and shape by Aaron DeMeyer
- Grounding analysis by Adam Driessen
- Rudder design and tank testing by Ted Huebner
- VPP, CFD and tank testing by Jon Silverberg

BACKGROUND TO THE 44-FOOT STC

The need for a dedicated offshore sail training craft for the Naval Academy's seamanship and navigation program was first proposed by CDR Conolly in the late 1930's. The first design, a 44-foot mahogany yawl designed by Bill Luders resulted in three boats delivered in 1939 and nine more in 1942. After a lengthy service life these were replaced by similar fiberglass versions between 1966 and 1968 (McNitt, 1996). The major changes in the second generation were the addition of an engine and chart table and the change in hull materials from wood to fiberglass and the rigs from spruce to aluminum (McCurdy and Bonds, 1989).

The third generation was developed in the early-80's due to the yawl's excessive maintenance demands and the dissatisfaction with the yawl's performance and comfort compared to modern vessels. The new vessels were developed in response to criteria developed by the Navy Sailing staff and members of the Fales Committee. The

mission statement and dimensions for the new boat were similar to the Luders yawls, but advances in rig design, construction, hull and appendage shapes and accommodation layout led to an all-new design by McCurdy and Rhodes (M&R). The broad mission criteria for every generation of the 44-foot STC's include (McCurdy and Bonds, 1989):

- Safe for novices
- Low maintenance
- Offshore capability for trips to Bermuda with a crew of ten
- Favorable treatment under existing rating rules

Specific requirements and specifications for all three designs were many pages in length. As with the earlier boats, the current 44's were heavily used, and by early 1996 discussions were taking place about possible replacements. In particular, dissatisfaction with the reliability of the engines and other systems prompted a review. By 1999 it became apparent that procuring new vessels rather than performing significant overhauls of the existing vessels was warranted. Table 1 shows the principal dimensions of the three 44-foot STCs and the "target" values for the next generation vessels based on current IMS measurement certificates and a 1939 Rudder Magazine article.

	Luders	Luders	M&R	"Mk 2"
	wood	glass		preliminary
LOA (ft)	44.0	44.2	43.9	44.0
LWL (ft)	30.0	30.1	34.2	36.8
Beam (ft)	10.6	11.1	12.4	12.4
Draft (ft)	6.00	6.17	7.25	7.42
Disp (lb)	23,400	24,800	28,600	27,700
Sail Area (sq ft)	980	1050	1017	1080
Disp-Length ratio	386.9	406.0	320.3	249.1
SA-Disp ratio	19.1	19.7	17.4	18.8
LPS (deg)	unknown	130	129	130

Table 1: Principal Dimensions of 44-foot STCs

With talk of a new 44 "in the works", midshipmen in the naval architecture and ocean engineering majors began requesting potential research projects that would combine technical course topics and would assist with the development of the next generation 44-foot STC. Depending on the students' time, the course configuration and the support available from the USNA Technical Services Department, projects were selected to support the students' educational objectives. To make the projects as practical as possible, the students were restricted to projects where the results would fit the STC mission.

PARAMETRIC DESIGN CRITERIA

Incline Experiment, Full-Scale Resistance and VPP–Aaron DeMeyer (DeMeyer, 2000a,b,c)

During his last semester Midn DeMeyer requested to remain at the USNA for a month during the summer to participate in offshore racing and to perform preliminary studies for the new STC. As many of the follow-on projects would need a solid baseline he selected as his first two projects full-scale incline and resistance experiments. From those results he explored design changes using a Velocity Prediction Program (VPP) and developed a preliminary keel design. The keel will be discussed in a later section.

The goal of the incline experiment was to validate the IMS measurement and to determine the impact of typical loading in Command, Seamanship and Navigation Training Squadron (CSNTS) configuration. As these missions stress seamanship and navigation in a non-race setting more equipment is carried than during races, resulting in a higher center of gravity.

NA-14 Intrepid was used as the test model for this experiment. Scheduled for departure at 1200 that day for a three-week cruise, the boat was in the typical full-load condition for a CSNTS cruise, minus the fuel jugs often carried on deck and the rigged sails.

To generate the heeling moment, the spinnaker pole was rigged and led outboard to be even with the upright longitudinal center of flotation (LCF). The outboard end of the pole was held in place with the port jib halyard rigged to the downhaul eye of the pole. The port spinnaker halyard was then passed through the jaw of the pole at the outboard end to serve as the hoist for 50-pound heeling weights. Both halyards were secured to deck winches. To hold the pole in place longitudinally, two spinnaker guys were attached to the outboard end of the pole. The after guy led outside the lifelines to a turning block aft of the cockpit and to the secondary winch in the cockpit. The fore guy was led to the mooring chock portside and aft to the starboard spinnaker winch. For additional weight, several locations on the deck were marked off with tape in order to place weight evenly and as near as possible to the LCF while allowing for the greatest possible heeling moment. Four 32-gallon trash cans were previously filled with fresh water and weighed.

In order to properly measure the heel angle of the boat, two digital inclinometers were used. They were set in position on horizontal Dorade covers roughly seven feet apart and secured with double stick tape. Finally, the recorder's position was marked off along the centerline of the vessel with a piece of small line. Figure 1 shows the general set-up.



Figure 1: Incline Experiment Set-Up

Weights were added consecutively and the angle of heel from each inclinometer was noted. Data collected during the experiment was analyzed using linear regression to produce a righting moment curve for small angles (up to eight degrees) and a metacentric height was determined. Data from the offset drawings was then used to find the vertical center of gravity location for the full-load for comparison to data generated for IMS ratings certification in the half-load condition for a similar boat.

The data gathered in the experiment agreed with predictions. IMS half-load incline righting moment for low angles was given as 1815.6 ft-lb/deg. The inclining experiment conducted in Santee Basin at the full-load condition gave a righting moment of 1794.5 ft-lb/deg, about 1.2% lower. Figure 2 shows the raw inclination experiment data prior to the correction for the added weight.

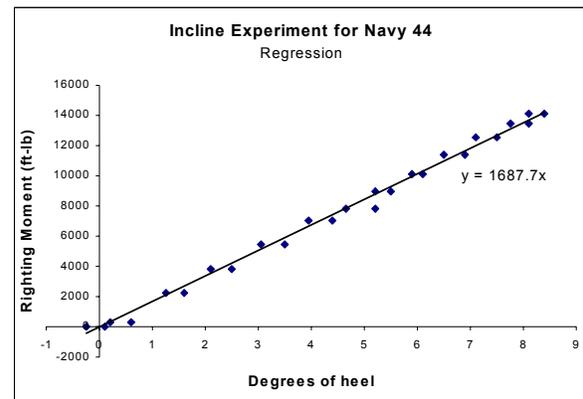


Figure 2: M&R Incline Experiment Data

The second experiment involved full-scale resistance tests. Resistance testing is used to determine the powering requirements for a given vessel and is normally conducted in a towing tank with scale models. In calm weather, resistance testing of full-size vessels is possible, and is perhaps more accurate. The goal of this study was to generate resistance data for comparison with later

velocity prediction program (VPP) results.

A 500-lb load cell was attached to the forward mooring cleats with the other end attached to a long Spectra™ towline. The towline was then connected to a powerboat in the Naval Station fleet. Power for the load cell was provided by the 12-volt outlet aboard the STC, connected to a 300-watt inverter. A 40-foot 12-volt extension cable was needed so that the instruments could safely be set up on the foredeck of the boat. A laptop computer was then also plugged into the inverter for recording and analyzing data. Two handheld VHF radios provided communications, and a hand-held GPS receiver was used for speed information (a result of the ending of selective availability).

After rigging the towline, the GPS was turned on and allowed to track on the satellites. After zeroing the load cell, the vessel was towed up the river (against the weak current) at varying speeds. At each speed, the measured resistance was recorded. After gathering upstream data, the boat was again towed, this time, downriver. Again, resistance was recorded at various speeds. A graph of the raw data was processed on the laptop computer so that any unrefined points in the curve could be retested. For the first two runs, the tests were conducted with the prop aligned vertically so as to minimize resistance. For the third and fourth, the prop was freely rotating as it would for a typical cruise with CSNTS.

The VPP used as a check in this project was loaned by Chris Todter of Keppel Consulting. The particular VPP was designed for lightweight day racing vessels however and no attempt was made to account for propeller, strut, roughness or biofouling resistance. As expected, the initial VPP results were optimistic! After the VPP was updated however to take into account the additional resistances, the results were reasonably consistent with the data. Figure 3 shows the results.

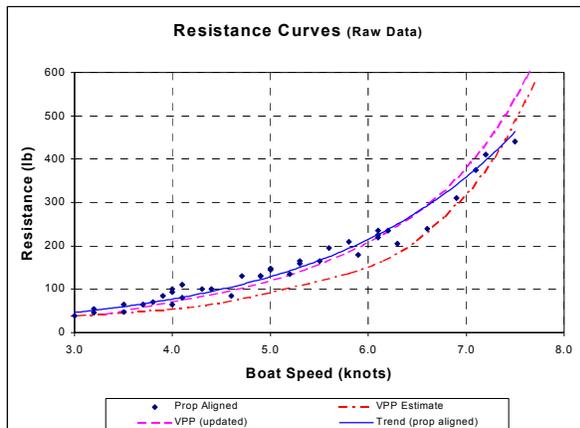


Figure 3: Full-Scale Resistance Data and VPP Estimate

The next step was to use the VPP to determine possible performance increases. Recognizing that the easiest way to increase performance was to make the design longer, lighter, and with more stability and sail area, Mr. DeMeyer was restricted to the same dimensional limitations as those specified for the generation that resulted in the M&R 44 (the M&R 44 is slightly shorter and shallower than allowed by the design criteria).

After consulting with two yacht designers, two design proposals were developed and compared to the existing design. One was a vessel similar to those type-formed by the IMS Rule. Although satisfying the desires of the offshore racing team the increased wetness from the plumb stem and the high speed potential was viewed as too risky for the CSNTS users and a more moderate design was proposed as a compromise. The major changes were to increase the waterline length, decrease the displacement, increase stability and lower the transom. The last was due to a belief that the top of the rudder was ventilating, adding to drag and reduced control, and also indicating that the full sailing length was not being used. Figure 4 shows the current design at high speed on smooth water. The top of the rudder is clearly visible.



Figure 4: M&R 44 Showing Rudder Exposure

Figure 5 shows the three design concepts. The top is the current M&R design. The second is the mid-level proposal and the third is the high-performance proposal. The bottom drawing is an overlay.

Mr. DeMeyer finished his TAD assignment by updating his keel design from a spring semester study to achieve the stability required for the mid-level performance design. The mid-level proposal became the baseline for the next student project.

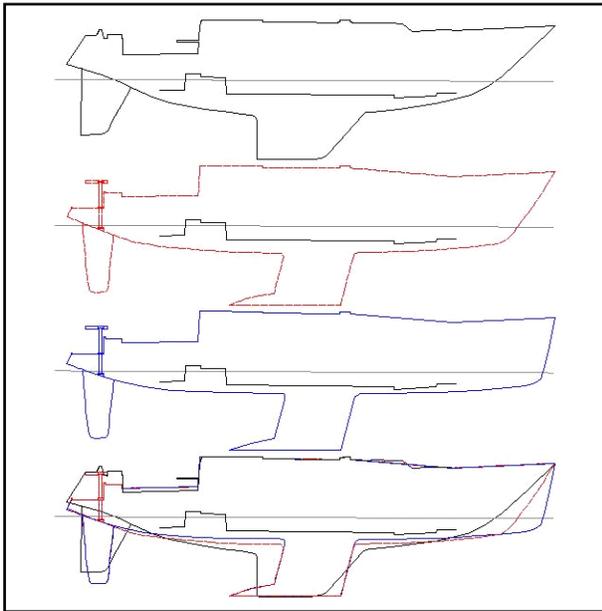


Figure 5: Proposals Based on Initial VPP Studies

Capstone Design Project – Mark Arvidson, Peter Firenze, Cecily Taylor (Arvidson, et. al., 2001)

Seniors in the naval architecture major are required to take two three-credit capstone design courses. The first has each member of the class perform a conceptual design of a vessel to a set of fixed criteria. The second allows groups of midshipman to design a vessel to their criteria.

The three midshipmen listed above designed and tank tested a potential STC design (“Defiance 44”) during the spring semester of 2001. The goal in this project was to use current technology and first-hand sailing experience to improve a good existing design. Their design study began with a parametric analysis of the existing design compared with current offshore cruiser/racers using the displacement-length and sail area-displacement ratios. Figures 6 and 7 show the results. The midshipmen identified reduced displacement (through improved materials), increased stability and increased sailing length as the major areas for improvement to achieve their target values. Rig height remained the same to allow for bridge clearance on the intracoastal waterway.

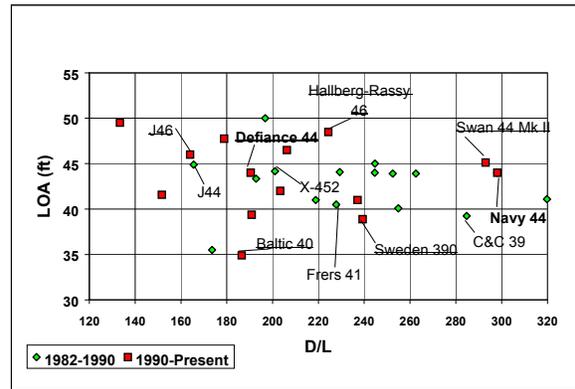


Figure 6: Comparative Displacement-Length Ratios

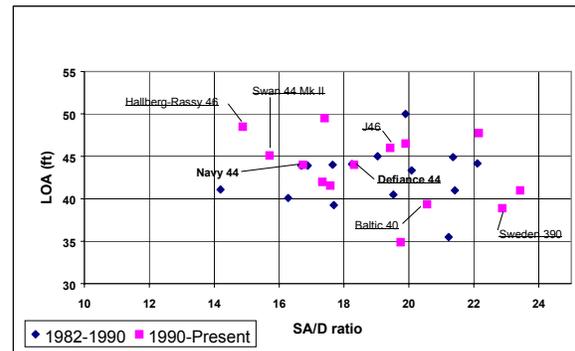


Figure 7: Comparative Sail Area – Displacement Ratios

Beginning with the mid-line proposal developed by Midn DeMeyer the students developed lines, sail plan, preliminary midship construction section, deck layout and interior accommodations plans. Figures 8 and 9 show the sail plans and deck layouts of the current and midshipmen designs.

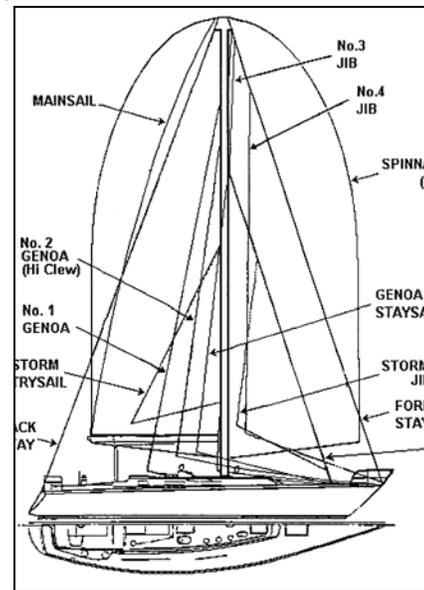


Figure 8: M&R 44 Sail and Deck Plans

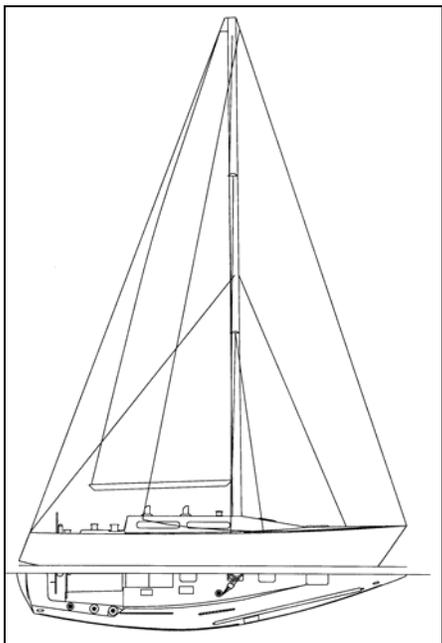


Figure 9: Midshipmen 44 Sail and Deck Plans

The new deck plan was developed after discussions with VOST and CSNTS staff and sailors and tours of similar local boats given by riggers. In particular their recommendations included:

- Replace the bow and the stern cleats with “pull-up flush cleats”. Presently, lines get snagged in the cleats while underway, leading to potential safety issues. Also, midshipmen are known to injure themselves by tripping on the present cleats. The new type of cleat recesses flush to the deck when not in use, eliminating the hazard. Attwood manufactures this type of cleat and has proven the recessed cleats have equal strength to the existing cleats.
- Eliminate forward hatch breakage problems caused by the hatch opening on to the cabin. The new design opens so that the hatch cover rests on the deck. In order to do this, the hatch was moved forward and the deck and cabin faired so the hatch is fully supported when open.
- Replace the current extruded hole toe rail design with a 5/8-inch T-track installed in the middle section of the boat. This will give more flexibility in outboard leads and will significantly increase comfort while hiking.
- To make the anchors more easily accessible, the anchors should be housed in watertight compartments on the deck near the shrouds.
- Removal of the Dorades forward of the mast.

Experience showed the best way to ventilate the boats is by using wind scoops through the open forward hatches while moored. While underway the forward Dorades leak in even moderate weather. Dorades will be added to the starboard side of the companionway to increase ventilation of the cabin.

- Remove two winches from the starboard side at the mast. The jib and spinnaker are usually set using the port halyards. The starboard halyards are used more as alternates for a spinnaker peel or mishap. The spinnaker halyard should remain on a winch so that time is not wasted applying pressure to release a rope clutch in the event of a broach.
- Recess the companionway entrance back into the cabin housing in an attempt to stop the shower of water that flows into the coach’s rack (the starboard quarterberth).
- Move the primary and secondary winches forward six inches and move the traveler aft to just in front of the helm. Use 3-speed Lewmar racing winches for the primary and secondaries to better fit the wide range of midshipmen strengths.
- Move the wheel aft and increase its diameter. The present wheel is slightly small if the helmsman is trying to steer by the telltales. By increasing the beam at stern and increasing the wheel diameter, the helmsman can position themselves further outboard thus improving the visibility for the helmsman. To increase forward visibility for the helmsman, the steering platform aft of the wheel is raised four inches.
- Connect the emergency tiller just forward of the main traveler. The emergency tiller will be the full length of the cockpit which will allow for excellent leverage and protection for the helmsman.
- Modify the seats to be three inches narrower and somewhat longer and make the cockpit floor two inches shallower. Since the cockpit will be wider with the increased beam at stern, there will be more cockpit room. Add a foot chock on centerline for bracing while the boat is heeled.
- Create a semi-open transom with a step down in the back. The cockpit coaming will arch in a continuous smooth curve around the stern as a helmsman seat. Under the seat the deck floor will drop below the cockpit floor to provide storage for the life raft. This design will make the life raft more accessible in case of emergency and improve cockpit drainage.

With the deck profile set the midshipmen moved to

Beaver in the USNA TSD Model Shop for testing in the 120-foot tow tank at the USNA Hydromechanics Lab. Resistance testing for upright EHP expansion was completed on the two models in two days of testing. The models were fully appended and Hama strips were attached to each model to trip the laminar flow to turbulent flow. The data collected from these tests was expanded into an EHP plot comparing the two designs. Figure 12 shows views of the two designs in simulated upwind conditions based on VPP predictions. Full-scale equivalent speed is 7 knots. The upper picture is of the M&R design and the middle is the midshipmen's. Although difficult to see, the top of the M&R rudder is ventilating. The lower picture is an upright test of the Luders yawl model at 6.7 knots with downwind trim.



Figure 12: Comparison of M&R and Midshipman Models Upwind at 7 Knots and the Luders Going Downwind at 6.7 Knots

Figure 13 presents the resistance versus speed for the three STC designs. The two newer designs have both upwind and downwind plots and the Luders has only the downwind plot. Using the VPP predictions for VMG, the upwind and downwind heel and trim were used. The results show the two newer designs have similar resistance for speeds less than 6.75 knots, but above that the midshipman design is less. From the VPP, 6.75 knots boat speed is achieved for upwind and downwind VMG in winds of 9 knots. Due to its less wetted surface area the Luders has less resistance at lower speeds, but with its shorter waterline the Luders has significantly more resistance at higher speeds. Even at nine knots the Luders did not use its entire length.

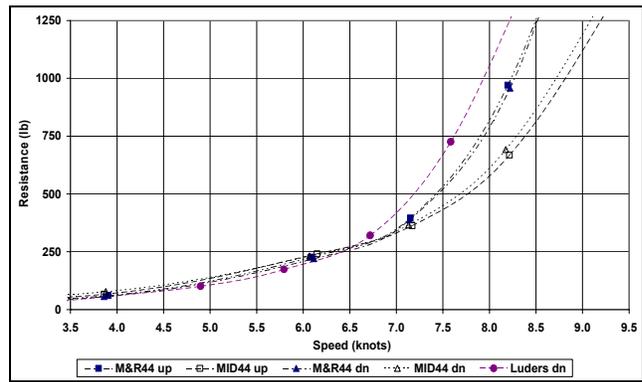


Figure 13: Resistance Measurements for Luders, M&R and MID44 Designs

In their conclusion the three midshipmen noted that they relied heavily on their experience as members of VOST and the guidance from others in the development of their design. Their hope was that aspects of their design would find application in the new boat and that the experience and desires of the midshipmen would be taken into account when future design decisions were made. In the capstone design class the design groups were judged by an outside group of practicing naval architects, which awarded this group the top grade of the seven teams.

Interestingly, many of the midshipmen's ideas were echoed in an earlier report by RADM McNitt, USN (ret) (McNitt, 1996), that was provided after they completed their project.

STRUCTURES

Fiberglass Laminate Upgrade – Mark Arvidson (Arvidson and Miller, 2001)

One of the earliest areas identified for possible improvement, and one of the most ambitious student projects, was the structural design of the hull, deck and internals. Two STC design criteria, safety and rating rules compatibility, drive the STC structural design through a required compliance with the IMS Regulations and the ABS Guide for Building and Classing Offshore Racing Yachts.

A review of all stakeholders indicated that the new boats should be at least as "rugged" as the current design, easily repairable, and must be able to maintain a high-quality surface finish. With the reduction in naval maintenance personnel, a material system that would localize damage and hence minimize repair costs was highly desirable. Like most vessels, a solution that reduced weight would be beneficial and cost was a factor.

The current topside hull laminate represents mid-80's technology for a tough fiberglass (E-glass) laminate. Two layers of 24 oz/yd² knitted fabrics combined with

1oz/ft² random-oriented mat sandwiched a 6 lb/ft³ Airex (linear PVC) core. A high-elongation vinyl ester resin served as the binding matrix and the outermost surface included a 1.5 oz/ft² mat cloth to provide a smooth surface. The in-house structural design criteria emphasized impact toughness.

Due to advances in material technology over the last twenty years the project began with a review of potential improved materials and discussions with material suppliers. Preliminary laminate analysis using classical laminated plate theory (CLT) was then performed. A test matrix of the major variables was developed and manufacturers were contacted for raw materials. Coupons and panels were fabricated in the Naval Academy's Model Shop and tested in the Academy's structures labs.

CLT analysis uses Hooke's Law to develop stress-strain relationships for multi-ply laminates. For most laminates a plane stress assumption is acceptable and requires three moduli (E_x , E_y and G_{xy}) and the inplane Poisson's Ratio (ν_{xy}). Failure analysis requires five strength parameters (σ_{xt} , σ_{xc} , σ_{yt} , σ_{yc} , σ_{xy}) and a failure criterion. The matrix math is relatively straight forward, but for ease of analysis, a share-ware program, "The Laminator" was used. Both in-plane and out-of-plane load conditions were analyzed with each laminate to obtain the highest factor of safety using the Tsai-Wu quadratic failure criterion.

Materials considered included the current materials as well as polyester and epoxy resins; S-glass and Kevlar reinforcements; and balsa, linear and cross-linked PVC cores. The CLT studies pointed out three trends and led to the selection of fifteen laminates for further study.

- Initial failure occurred early in the mat layers and removing the mat significantly increased the strength/weight ratio if delamination was not an issue.
- S-glass and Kevlar did not provide significant improvement in these overbuilt laminates in comparison to their higher cost.
- Core and resin comparisons were difficult to discern as impact loads and fabrication issues drive their relative performance.

As impact toughness was a significant driver the test matrix included an impact test as well as four-point bending tests. Panels representing the STC topside were fabricated using the manufacturers' recommended procedures and were painted by Naval Station personnel using the paint system from the current vessels. Panels ranged from the current laminate, to ones with the same weight of biaxial material but no mat, to ones of equivalent weight using only biaxial material, to variations in resins and cores.

The navy blue panels were then set outside in the

summer sun to determine "print through" and heat distortion properties. Set at the transom angle the surface temperatures peaked at 158° F in 95° air temperature. None of the laminates showed significant print through or heat related problems.

The panels were divided into coupons and a smaller panel. One hundred four-point bend tests were used to test the CLT-analysis accuracy. Although the actual failure values differed from predicted by up to 21%, the ranking remained the same. Unlike many marine composites that are brittle, most of the coupons showed extensive plastic deformation, which is desirable in impact situations. Figure 14 compares the load-elongation curve for the 8084 vinyl ester with the most brittle epoxy. The areas under the curve indicate the relative toughness of the two otherwise identical laminates. The toughened nature of the Airex and CoreCell linear PVC cores and the high elongation resins were the reason. The plastic region did make determining the yield point more difficult and "yield" was defined in this case as a 50% reduction in the flexural modulus. As the strength-to-weight ratio is important for this design, the normalized specific flexural yield strength was calculated for each laminate.

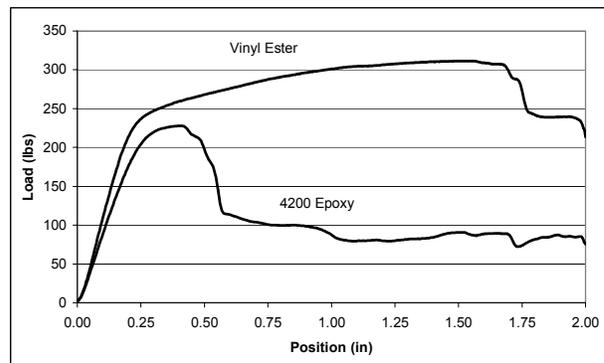


Figure 14: Load Elongation Curves For Two Potential Laminates Showing The Higher Toughness For The 8084 Vinyl Ester

Although the four-point bend tests gave an idea of stiffness and strength, edge effects were a concern due to the specimen geometry and ply orientation. Fibers oriented at 90° to the bending coupon primary axis would not contribute to hull panel stiffness as much as they would in a square panel with simply-supported edges. A better simulation of the in-service condition would have lateral pressure applied to composite panels. In this project square panels (24 in x 24 in) were placed on a 15 psi water-pressure bag and were held in place by an aluminum frame. Deflections were measured using string-pots at the panel center and on the frame. Results showed similar trends to the four-point tests, although the laminates with more bias and biaxial fibers performed relatively better. Although the lateral pressure was higher than that expected in-service due to waves, no panels failed.

To best simulate the in-service experience anticipated for these laminates, a steel replica of the first eight inches of the current Navy 44's bow was fabricated and attached to a six-foot swing arm assembly. Twenty panels were then subjected to an impact equivalent to a T-collision at 8.5 knots. Figure 15 shows the set-up before it was mounted to a more robust bracket and frame.



Figure 15: Panel Impactor

Damage was determined by visual inspection of the surfaces and by cutting through the impact area to inspect the inner laminate and core. Results of the impact test analysis agreed with some of the strengths seen in the four-point bend tests and disagreed with others. Not surprisingly, the laminate with the most reinforcement fiber fared the best. It substantially outperformed the equivalent weight existing laminate and showed little surface damage. The laminate constructed using the same amount of biaxial material as the current laminate, but without the mat performed nearly as well as the current laminate even though it was 35% lighter. The other interesting result was that the Kevlar/glass hybrid performed identically to the equal-weight all-glass laminate.

An important consideration for the Navy 44 is the ability to quickly and inexpensively repair the damage so as to return the vessel to service. The Naval Station provided repair estimates using a “shop rate” for each panel. An attempt was also made to determine “calendar” hours needed for each repair, but this proved to be too uncertain. Due to resin and paint curing and coating schedules, a minimum of three days was required for a

repair. Four of the laminates were too damaged to determine the cost of repairs while the best required little effort.

In the end a laminate using 60 oz/ft² of E-glass (18 oz woven roving, 24 oz double bias, 18 oz woven roving with a veil cloth on the outside) in 8084 vinyl ester on each side of a linear PVC core was recommended for the new topside laminate. This provided increases in stiffness, strength and toughness while decreasing weight and cost compared to the current laminate.

Using the “Defiance” design as the basis, a full structural design to the latest ABS Guide was performed. Recognizing that the ABS Guide does not cover every conceivable load case and that the current design has served well, the M&R 44 was reverse-engineered and the new design’s laminate was required to meet or exceed the M&R’s design safety margin for each laminate. As the ABS Guide became more stringent after the current vessels were built, this meant that some laminates became heavier. Nonetheless, the total projected weight savings using the new base laminate design was 900 pounds.

Alternative Wood Laminate – Kent Simodynes (Simodynes, 2001)

Although serious thought was never given to using wood in the construction of the new STC, interest existed among the students on the actual structural efficiency of modern wood construction. Midn Simodynes volunteered for a three-credit independent research project exploring the idea.

The ABS Guide for Offshore Yachts includes equations for determining required scantlings for both traditional carvel and modern cold-molded construction methods and also include material properties of the common boatbuilding woods to use in the equations. The midshipman’s project looked at both whether the material properties were accurate and whether the equations correctly predicted the traditional and modern construction methods.

The basic equations in the ABS Guide use Euler Beam Theory to predict the resulting stress in the wood. Although this was found to work for traditional carvel construction, questions existed whether the multi-directional characteristic of cold molding would allow for accurate strength prediction.

To check this, panels were made using various combinations of western red cedar, Honduras mahogany, balsa, pine and white oak. Plain coupons were tested in bending for comparison with the modulus of rupture and elasticity properties listed in the ABS Guide. All the base material properties agreed with the ABS Guide within 8%, with the ABS Guide always more conservative.

The combination laminates stressed using lighter weight interior woods with stronger outside laminates. An example was a three layer laminate of Honduras Mahogany with a cedar or balsa core. All the laminates were constructed with an epoxy recommended for wood construction. Over 150 coupons were fabricated by the midshipman and tested.

Using the ABS Guide as a basis the carvel equations yielded results within 10% of those predicted. The cold-molded laminates were as much as twice as strong as predicted however, indicating the ABS Guide could be quite conservative for that construction method. As a comparison the cold-molded laminates were also analyzed using CLT and the Tsai-Wu failure criterion. In this case the actual strengths varied from 77% to 120% of the predicted values. Although more accurate, the potential unconservativeness of the CLT approach indicates a higher factor of safety or material testing may be required if CLT was used.

The final step in the study was to determine what the weight difference would be between the fiberglass and wood STC's. From the testing, the three ply laminated Honduras mahogany coupons gave the highest specific flexural strength. The ABS Guide's factors of safety and loading methods were used with CLT and the Tsai-Wu criteria instead of beam theory. The results indicated the wood laminate would weigh roughly 400 pounds more than the equal strength glass sandwich laminate. Impact and cost considerations were not included in the analysis however.

APPENDAGES

Keel Shape – Aaron DeMeyer (DeMeyer, 2000)

The Luders 44 featured a full-keel, that although was imminently rugged for the inevitable grounding, was considered too low performance when the next generation STC was developed in the early 80's. Twenty years later as the new 44 develops, the question was again asked, "can we improve the keel design?"

The keel provides roll stability, directional stability and reduces leeway. It necessarily is very heavy and must withstand severe groundings. Many of these requirements are contradictory. Hydrodynamic efficiency leads to a high aspect ratio design, which increases bending moments when grounding. Similarly, narrow sections lead to reduced drag while increasing deflection and garboard stress.

Midn DeMeyer developed spreadsheets calculating lift and drag from lifting line theory and structural calculations based on the ABS Guide. The linked spreadsheets allowed the designer to vary parameters to find an "optimal" keel for a given stability goal. The resulting design featured a deep fiberglass bilge sump

with an IMS-style fin and bulb. With help from aerodynamicist Paul Bogataj, five sections were compared using computational fluid dynamics. A 14% J5013 section with a 5% area reduction was ultimately selected. The resulting keel was predicted to have a 15% lower VCG, and up to 8% lower drag than the current design. Although no keel failures have been reported on the current design, one additional limitation imposed by Midn DeMeyer in his analysis was an increase in the nominal grounding structural factor of safety by 25%.

At the end of his report Midn DeMeyer listed two items for further research. The first was a question of dynamic stability. The increased stability would certainly improve safety at the expense of a small decrease in comfort, but the question of the impact of the increased mass moment of inertia was beyond the scope of his project. Earlier capsizing studies performed in the Hydromechanics Lab indicated an increase in this quantity could increase capsizing resistance significantly (USYRU, 1985).

The second question dealt with a concern that a bulb keel would be more difficult to "unground" in the typical Chesapeake soft bottom conditions. This concern led to Midn Driessen's project.

Grounding Analysis – Adam Driessen (Driessen, 2001)

The concern over the bulb keel design's potential difficulty in ungrounding led to a literature review which unfortunately did not yield any useful information. During his last two weeks at the USNA, Mr. Driessen volunteered to run a study that might help answer the question.

The experiment used the two STC towing tank models in the USNA Coastal Lab's flume tank. Using a constant grounding force and measuring the force necessary to free the boat after it ran aground gave a qualitative idea of the keel designs' impact.

The models were ballasted to their design displacement and a constant-force gravity tow system was used to tow the models down the tank. Altering the weight attached to the pulley system varied the speed at which the groundings occurred. Two speeds were chosen for testing. The upper boundary speed range was 6 to 7.5 knots in order to provide data for normal operating speeds. The second speed was around three knots to analyze at low speed maneuvering. The "Defiance" model, due to its lower resistance characteristics hit the beach in each case with slightly greater speed.

To evaluate the impact that the beach slope has on the force required to free a vessel that has run aground, two different beach slopes were looked at: 1 on 8 and 1 on 12. The frontispiece shows a model in the tank.

A string potentiometer was used to determine the

speed the models attained, and a force sensor to determine the force necessary to free the model. Each speed and slope condition was repeated for 10 trials. The beach was raked after each trial to attempt to make the beach conditions similar for each trial. Figure 16 shows the different keel shapes embedded in the beach after the high speed run. The M&R design (on top) is embedded deeper in the sand compared to the bulb keel design of the MID44 model.



Figure 16: Model Keels Buried After High-Speed Grounding

The results were surprisingly consistent between runs although the slower speed towing cases showed more scatter. Typically after grounding the stern would kick out to one side and then return to close to its original position. The kick out distance varied from trial to trial and was not always present. More kick out lessened the pull-off force necessary to free the model because that extra movement provided some loosening from the sand for the keel. The magnitude of the kick out was greater in the MID44 model.

An interesting finding to note is the furrow or shape left in the sand by the keels. Each keel left a distinct and unique furrow. The M&R keel design embedded deeper in the sand than the proposed keel. The MID44's furrow shape was flatter and wider and did not appear to dig in

quite as deep. Minimal entrenchment is favorable because that should lessen the force required to free the vessel.

Table 3 summarizes the findings of the force data for both speed and beach slope conditions. In one case the required force was the same for the two models. In two cases the bulb keel required less force to unground and in one case the standard keel required less force. In the latter case the bulb keel was moving roughly 0.6 knots faster when it hit.

Slope = 1:8			
	Velocity (kts)	Avg Force (lbs)	COV
MR44	6.88	1.87	8.6%
MID44	7.43	2.01	8.2%
MR44	3.33	0.92	19.1%
MID44	3.4	0.56	18.0%
Slope = 1:12			
	Velocity (kts)	Avg Force (lbs)	COV
MR44	6.88	2.14	8.9%
MID44	7.43	2.14	16.1%
MR44	3.33	0.95	15.5%
MID44	3.4	0.91	21.5%

Table 3: Grounding Data Summary

Figures 17 and 18 show the different furrow shapes. Although the standard keel dug in much deeper the study seemed to indicate the difference between the keels in grounding was minimal.



Figure 17: M&R Keel Furrow

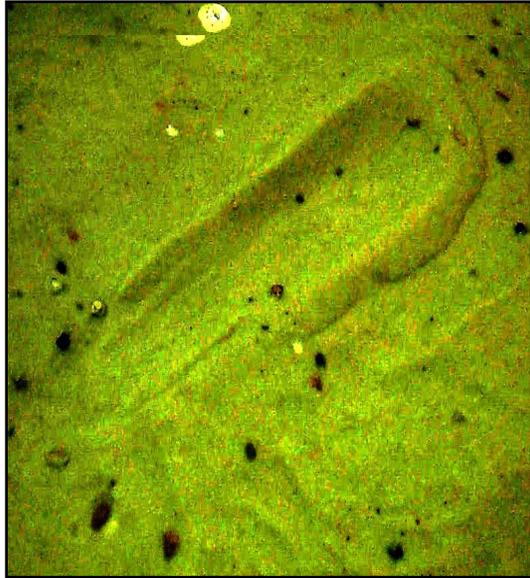


Figure 18: Bulb Keel Furrow

Rudder Design and Tank Testing – Ted Huebner (Huebner, 2001)

The capstone design team included a spade rudder in their design for the simple reason that the current skeg rudder design is rarely seen in recently-designed offshore sailing vessels. This led to a discussion on the actual trade-offs in performance as well as strength between the two designs, which led to a student pursuing a three-credit independent research project.

Rudder design is primarily a function of sideforce (lift) required, section shape, area and aspect ratio. These criteria affect how much sideforce and yaw moment the rudder can produce. In a well-tuned vessel the rudder is used to balance sideforce (leeway) and weatherhelm by setting the rudder at a small angle of attack (typically 0-3°). The vessel may sail in this condition for long periods of time, so the rudder should have low drag in this mode for the amount of lift produced. Additionally the rudder is required to produce large amounts of lift in turning situations, such as at marks, while docking, or while avoiding a collision.

These characteristics were tested on the two STC models using four different rudder designs. The models were tested on a rig that measured resistance, sideforce and yaw moment as functions of velocity, rudder angle and heel angle. Four conditions were tested; heeled at 10° and 20°, upright at speeds simulating motoring, and running in heavy air. Rudder angles were 0-10 degrees at two degree increments. These were compared to full-scale testing on an existing boat. To get an idea of the effect on maneuvering the models were towed and released with the rudder put over by a servo to determine the tactical

turning diameter.

The rudder on the existing design extends to 73% of the total draft and has an aspect ratio of 1.5. To compare design attributes the midshipman designed three more rudders. The first was a balanced spade rudder using the same planform of the existing rudder. The second was an elliptical planform of the same area and to 85% of the keel draft. This resulted in an aspect ratio of 2.6 for the elliptical rudders. The third was an elliptical skeg rudder sharing the same planform as the elliptical spade. Figure 19 shows the four rudder designs mounted on the model of the existing STC.



Figure 19: Midshipman Rudder Designs

To quantify the differences between the rudder designs the midshipman ran a matrix of 220 tank tests in the 120-foot tank and thirty free running tactical diameter tests in the 380-foot tank. He also determined the tactical diameter of the full-scale vessel by running tests in the Severn River.

Initial conditions were developed using a VPP. Although still useful, the Keppel VPP was replaced by the Martin (PCSail) VPP presented at the last CSYS. The main reasons for the switch were the easier to use input interface and the ability to easily update the resistance algorithms based on tank test data. In the upwind case the model was run at 10 and 20 degrees heel, simulating wind conditions of 8 and 20 knots. Velocity and yaw angle were set based on the VPP predictions of the optimum VMG.

Results for three of the eight test conditions were later found to be questionable due to an error in aligning the rudders. The 20 degree heel case provided interesting results however. Figure 20 shows the coefficients of drag versus lift for the range of 0-10 degrees rudder angle of attack using the “Defiance” model. The lower the line is

indicates higher lift for the amount of drag produced. In these tests the elliptical skeg gave the best results, followed by the elliptical spade, trapezoidal spade and trapezoidal skeg. This trend continued for the upright motoring and downwind conditions. Roughly one fourth of the data was checked for repeatability, which was generally acceptable. The existing STC model had much greater scatter, possibly due to the fact that in many conditions the upper portion of the rudder was exposed.

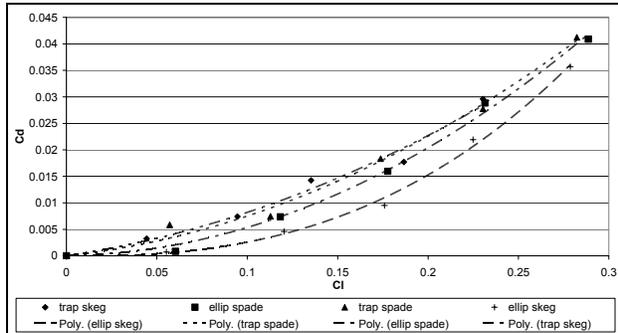


Figure 20: Coefficients of Lift Versus Drag For 20 Degree Heeled Condition On the MID44 Model

The tactical diameter tests were performed on the existing Navy 44 full scale and in all the model configurations with the rudder at 35°. Video was taken of the tests and tactical diameter was measured from the video. The results are shown in Table 4. One of the interesting points was that the full-scale vessel had a significantly higher tactical diameter than the model. This was primarily attributed to one factor. The models were not ballasted to match the full-scale vessel’s vertical mass distribution. In the videos it was clear that the full-scale vessel heeled more during the turn, reducing the rudder’s efficiency.

The tactical diameter data also indicates that the alternate rudder designs performed better than the existing rudder. The parameter not dealt with in this table is how much speed was carried through the turn, and in the testing there was no way to measure velocity as the models were free running and the velocity continually decreased for both model and full scale hulls. The midshipman noted that the existing rudder barely made it past 270° by the time it was stopped (in both the full-scale and model tests) and never completed a 360° turn. He attributed this to dragging the large skeg of the existing design through a relatively tight turn which created significant turbulence. He also noted the elliptical spade turned through 360° with little additional turbulence and carried significant speed throughout the turn.

Condition	Radius
Boat Lengths	
Full scale	1.63
Old Hull Existing Rudder	1.39
Old Hull Elliptical Spade	1.24
Old Hull Big Spade	1.22
Old Hull Elliptical Skeg	1.22
New Hull Existing Rudder	1.89
New Hull Elliptical Spade	1.35
New Hull Big Spade	1.22
New Hull Elliptical Skeg	1.22

Table 4: Tactical Diameters For Different Rudders

It is interesting to note that on the new hull the existing rudder did not produce the same tactical diameter as it did on the old hull. The increase of half a boatlength is due to the increased waterline of the new hull. To keep a new design performing to roughly the same standard as the existing boat some improvement will have to be made to the rudder. The elliptical spade rudder however generated a tactical diameter on the new hull that was slightly smaller than the tactical diameter of the existing configuration.

The conclusion from this project was that a well-designed skeg rudder might perform better in both upwind and maneuvering conditions than a spade rudder. At the same time, a skeg rudder could also perform worse. Structurally, all the candidate rudder designs were developed to exceed the ABS Guide. The short, high aspect ratio stock on the elliptical skeg rudder however required an expensive, heavy design compared to the spade rudders. The midshipman’s final recommendation reaffirmed the capstone team’s suggestion to use an elliptical spade rudder.

ANALYTICAL TOOL DEVELOPMENT

VPP, CFD and Tank Testing – Jon Silverberg (Silverberg, 2002)

From the project descriptions above it is clear that VPPs play a major role in sail craft design development. One important part of a VPP is the resistance determination of the hull in various trim, heel and yawed conditions. As no closed-form solution exists to predict resistance for an arbitrary shape, current VPPs use a best-fit parametric approximation equation based on a large series of tank tests. As mentioned in the previous student project description, the VPP could be updated with tank test data from a scale model of the actual vessel and the VPP accuracy would improve. Tank testing is beyond the reach of most projects however and best-fit equations are only as good as the data and model series. Extrapolation beyond the characteristics of the model series is risky.

An alternate resistance prediction method uses the basic governing equations of fluid dynamics to determine the pressure distribution around a numerically-represented shape. This process is called computational fluid dynamics (CFD). Well developed for fully-immersed flow, CFD has had accuracy issues when resolving flows at the water's surface, and the computational requirements to solve these problems require powerful computers. Nonetheless, with computer power improving rapidly and with improvements in the underlying theory, CFD offers potentially reduced costs and time compared to tank testing.

To accurately determine whether CFD can replace tank testing in sail craft design a large test matrix is required. Each CFD run must duplicate the tank test conditions for velocity, heel, yaw and rudder angle. A project of this size was beyond the allowable time for an internship or three-credit research course. The USNA offers seniors in the top 10% of their class the opportunity through the "Trident Program" to devote a majority of their last year performing independent research. Midshipman Jon Silverberg signed up in September 2002 to spend nine credits in the fall and 12 credits in the spring to explore the use of CFD as a potential design tool.

His ambitious project compares tank test results of the preliminary "Mk 2" STC to two CFD codes; FKS, a PC-based code developed at the Naval Surface Warfare Center at Carderock Divison (NSWC-CD), and SPLASH, a more powerful code developed by South Bay Simulations. Importantly, both groups loaned the codes and provided technical support at no charge. The initial conditions for the tank testing were again provided by the Martin VPP.

By December 2002 Midn Silverberg had completed a large tank test matrix (450+ runs) and compared the results with FKS. Although FKS is limited to upright conditions with zero yaw (ie no side force), Midn Silverberg needed to develop tank data for the full range of yaw, heel and rudder angle of attack for comparing SPLASH. Figure 21 shows the model setup. The carbon fiber stick connected to the stern controlled yaw and was used to calculate the yaw moment. Combined with a force block located just forward of the bulkhead, side force was also measured.



Figure 21: Model Setup in 120-Foot Tank

Due to the small model size, concerns over laminar flow issues led to the decision to test the model both with and without sand tripping strips.

FKS is a panel-based free-surface CFD code developed primarily from the theories of Dr. Noblesse from NSWC-CD. It calculates the Fourier-Kochin representation of farfield waves defining the wave spectrum of the Havelock formula. The Havelock formula is a continuum-based definition of the coefficient of wave resistance. Skin friction is estimated using the ITTC approximation method.

Figure 22 compares the predicted coefficient of wave making resistance from FKS to the tripped ("turbulent") and untripped ("laminar") tank test data. The line indicating "Vs=10 knots" shows the upper likely velocity for the STC and also indicates a practical limit to the code. At high speeds the wave slope of displacement craft becomes quite steep and will break or cause spray, violating a key assumption of continuum wave mechanics. FKS appears accurate for low Froude numbers, but in this case the Froude numbers below 0.1 also correspond to Reynold's numbers below 500,000. This is in the laminar region where model tests become uncertain. The tank test results also includes the drag associated with the sand strips.

During the spring semester of 2003 Midn Silverberg plans to continue analysis of towing tank data and complete the SPLASH comparison and use the programs to assist in the design development of the Mk2 STC rudder.

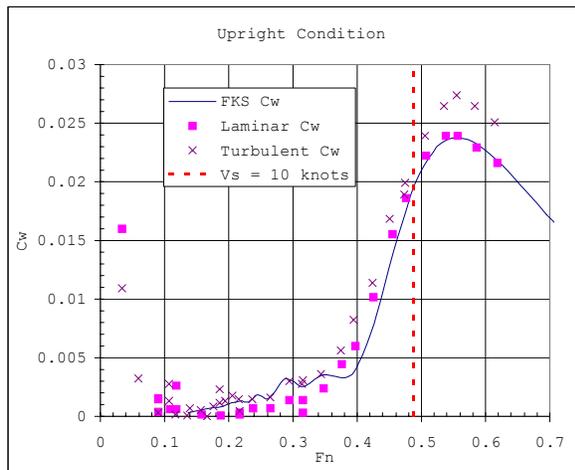


Figure 22: FKS Upright Prediction Compared to Tank Test Data of “Mk2” STC

CONCLUSIONS

Outside the America’s Cup and Round the World race arenas it is rare to find research of this magnitude performed for a single design. In many cases the midshipmen verified existing beliefs in yacht design and provided details useful to the design of the next generation STC. In other cases the midshipmen identified results that either questioned existing beliefs or advanced the current state of the art. No doubt their work will help provide an improved STC that will successfully train future generations of naval officers.

MIDSHIPMEN BIOGRAPHIES (as of Jan. 2003)

Mark Arvidson 2001, ENA, VOST, Sub school
 Aaron DeMeyer 2000, ENA, VOST, deployed aboard a DDG
 Adam Driessen 2001, EOE, Sub school
 Peter Firenze 2001, ENA, VOST, Helicopter Flight School
 Ted Huebner 2002, ENA, VOST, SWOS
 Jon Silverberg 2003, ENA, VOST, Selected Aviation
 Kent Simodynes 2002, ENA, Civil Engineering Corps, deployed
 Cecily Taylor 2001, ENA, VOST, P-3 NFO training

ACKNOWLEDGEMENTS

The midshipmen researchers on these projects should be thanked for their interest and motivation. I think all of them realized they could have earned the required “credits” performing much less demanding projects! In every case the desire to combine engineering with sailing motivated them to put in effort well above the amount expected. I thoroughly enjoyed working with each of them on their projects.

Each of their reports cite numerous people who contributed support to their projects and the space is not available in this summary to thank them all (over 80!). A few names were consistently seen and should be mentioned however:

- Tom Price and Bill Beaver of the USNA Model Shop
- John Hill and John Zselecsky of the USNA Hydromechanics Lab
- CAPT Harold Flammang, CDR Jack Eggleston, CDR Gerard Vandenberg and Ralph Naranjo of Navy Sailing
- Tom Carr of the Naval Station

REFERENCES

Arvidson, M., DeMeyer, A., Miller, P. Taylor, C. “Navy 44 Sail Training Vessel Design Improvement Projects”, Report EW-10-00, Division of Engineering and Weapons, United States Naval Academy, August 2000

Arvidson, M., Firenze, P., Taylor, C., “Defiance Class Sloop: A New Navy 44”, unpublished capstone design project report for EN476, 30 April 2001

Arvidson, Mark H., Midshipman 1/C, Miller, Paul H., Assistant Professor, “Hull Material Evaluation for Navy 44 Sail Training Vessel”, Naval Engineers Journal, Spring 2001

DeMeyer, A., “USNA 44-Foot Sloop Keel Re-Design Project”, unpublished independent research project report, 8 May 2000

DeMeyer, A., “Navy-44 Inclining Experiment Discussion and Results”, unpublished report, 7 August 2000a

DeMeyer, A., “VPP Performance Predictions for Current and Two Proposed Navy-44 Designs”, unpublished report, 14 August, 2000b

DeMeyer, A., “Navy-44 Full-Scale Resistance Test”, unpublished report, 21 August, 2000c

Driessen, Adam, “MR44 and MID44 Grounding Tests”, unpublished report, 11 July 2001

Huebner, T., “Performance Evaluation of Sailboat Rudders”, unpublished independent research project report, 14 December 2001

IMS Certificate (2001) for M&R Navy 44 STC

IMS Certificate (2002) for Luders 44 Yawl

McCurdy, I., Bonds, J., “The Planning, Design, and Construction of the 44-Foot Offshore Training Craft for

the U.S. Naval Academy”, The Ninth Chesapeake Sailing Yacht Symposium, 1989

McNitt, R., “Sailing at the U. S. Naval Academy”, Naval Institute Press, Annapolis, Maryland, 1996

McNitt, R., “The New Navy 44”, unpublished report, 13 September 1996

Miller, P., “Navy-44 Full-Scale Resistance Test- Update”, unpublished report, 8 December 2000

Silverberg, Jon, “Small Model Tank Testing Compared to Computational Fluid Dynamics with Respect to Performance Prediction and Design Optimization of the Mk II Navy 44 Sail Training Craft”, unpublished interim Trident Report, December 10, 2002

Simodynes, K., “Analytical and Experimental Evaluation of ABS Wood Construction Criteria”, unpublished independent research report, 12 December 2001

“The Naval Academy’s New Auxiliary Yawls,” Rudder Magazine, April 1939, pp 41

United States Naval Academy Catalog, 2002-2003

United States Yacht Racing Union and Society of Naval Architects and Marine Engineers, “Final Report to the Directors: Capsizing Report”, June 1985