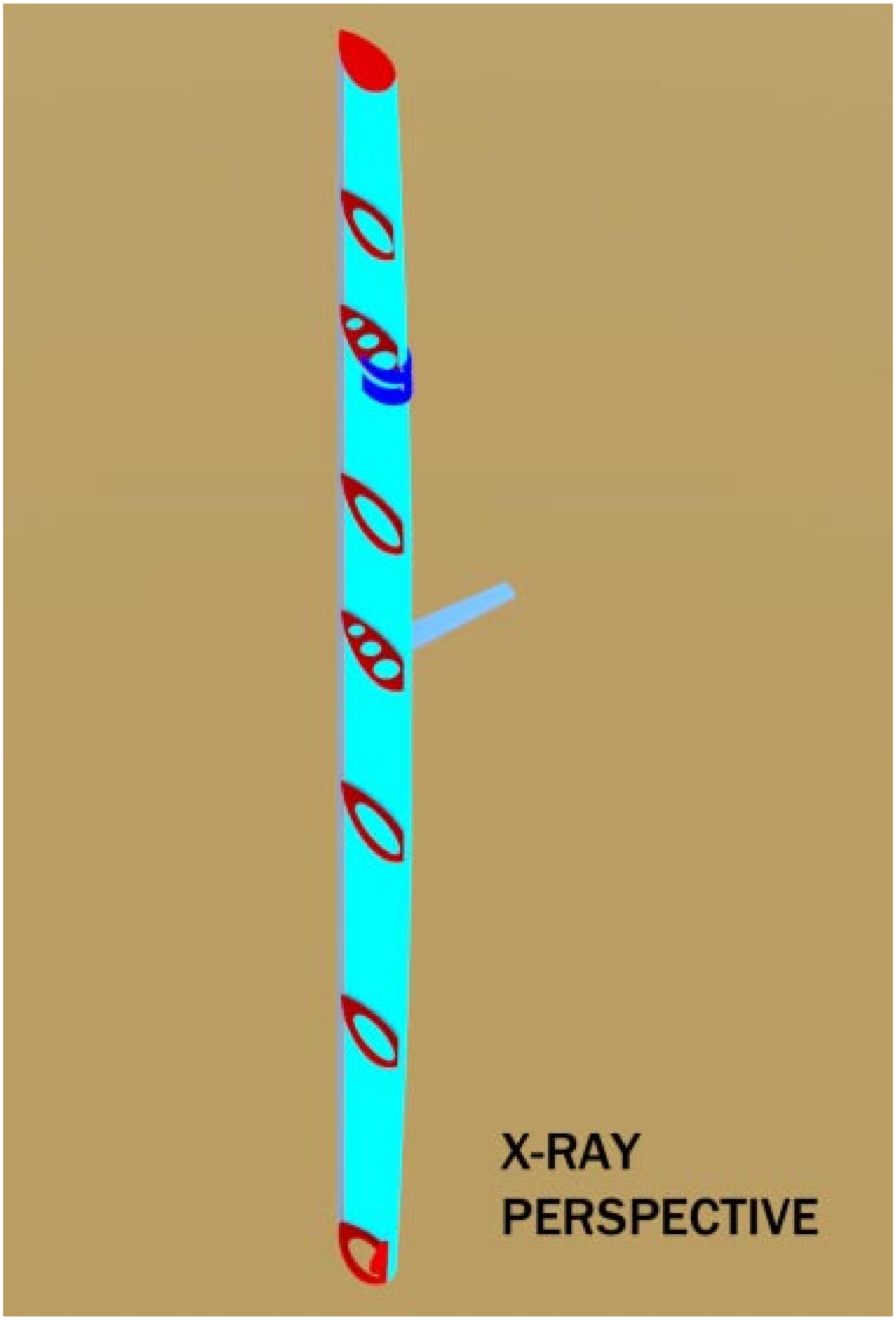
Wing Masts with Intermediate Bulkheads



Kurt Hughes Sailing Designs LLC

PREFACE

Back in 1994 I had an idea that if you took the shear web out of a wing mast, and added that material to the sides, you would have better section properties, and thus a stiffer wing mast, with no increase in weight. And the panel aspect ratios would be closer to 1:1 so stronger actually. Recall that a high aspect ratio panel behaves like it only has 2 fixed edges, not 4.
In fact few alum masts have shear webs, but everybody forgets that.

First of all, I built two nearly identical wing masts; one with shear web and the other with the half of each shear web glued to each side . Then I load tested them. The improvement was remarkable.

Next I had Paul Steinert Phd. run a finite element study of the idea. The results were so good that we wrote a technical paper together on it. The paper was given and published at the 1994 MACM marine composites conference.

The paper had some difficulty later getting online however. Word5 for DOS had a great equation writing feature. That part of the document would however completely lock up any later Windows version of Word. Also, the images used were actually from 35mm slides of the computer screen. Those took some work to get digital. Meanwhile I got busy and neglected that paper. Recently I have realized that nobody has any idea what I am talking about without this paper being able to be online. So, here it is.

I include an updated version of the slightly technical original paper so that science geeks can see how I looked at this idea.

WING MASTS WITH INTERMEDIATE BULKHEADS

KURT HUGHES, KURT HUGHES SAILING DESIGNS
PAUL STEINERT, COMPOSITE ANALYSIS

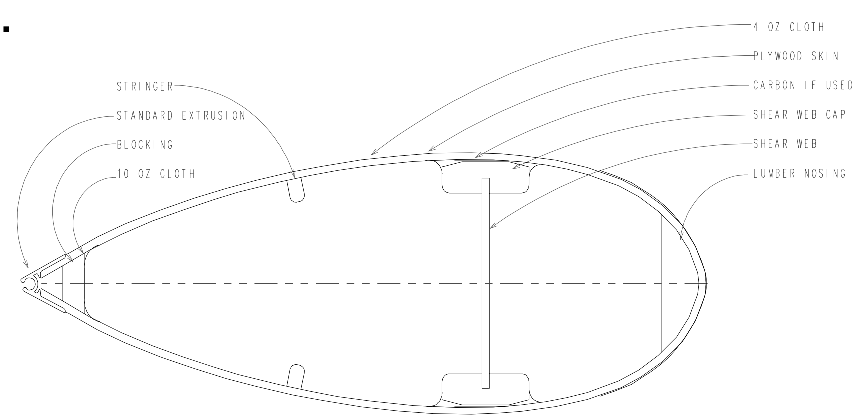
INTRODUCTION

Following a hunch that the use of intermediate bulkheads in a wing mast would result in a stronger, lighter mast, I needed to verify the validity of that hunch before the builders began construction. The use of finite elements and curved plate theory provided guidance
A mast/rigging structure can be analyzed as if it were a beam loaded in bending and compression. This paper investigates some aspects of the design of wing mast design using structural analysis.
We know that keeping the aspect ratio (how wide to how high) of a structure's unsupported panels as close to 1:1 as possible is important. A traditional wing mast with a central spine web results in unacceptably high aspect ratio panels. Those high aspect ratio panels are weaker than those with lower aspect ratios. They thus have to be too heavy to make up for that fault.
I also wanted to simultaneously explore ways to build big boat wing mastss without the excessive weight and time-to-build caused by strip plank wing masts or the moldbuilding time demanded by molded composite wings.

HISTORY

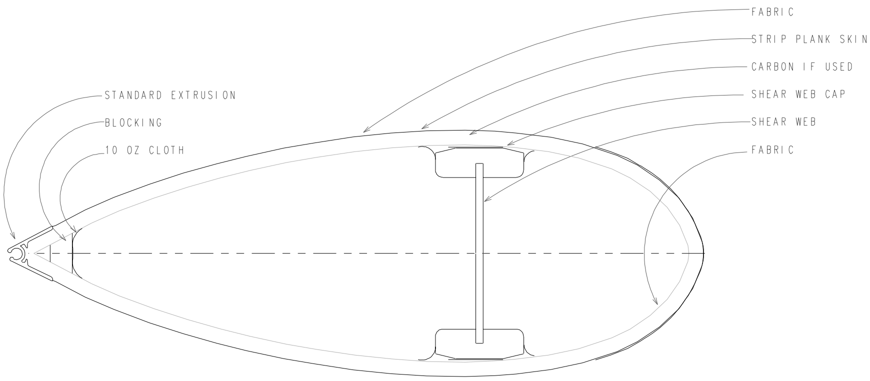
In the last few years more of my clients have been requesting wing masts for large multihulls. The advantages of wood/epoxy rotating wing masts for cruising multihulls are quite well known by now.
For multihulls of about 42' length or less I typically specify a Gougeon Brothers design. I compliment that design with a ten sheet upgrade design set from my office. Unfortunately the Gougeon sets are only for boats with 90,000 foot pounds righting moment or less. A 55' catamaran could have as much as 390,000 foot pounds of righting moment. Clearly an alternative is needed.

The two leading wing mast choices in wood/epoxy have been either a stitch and glue fold-up mast or a strip plank one.



CLASSICAL WING SECTION

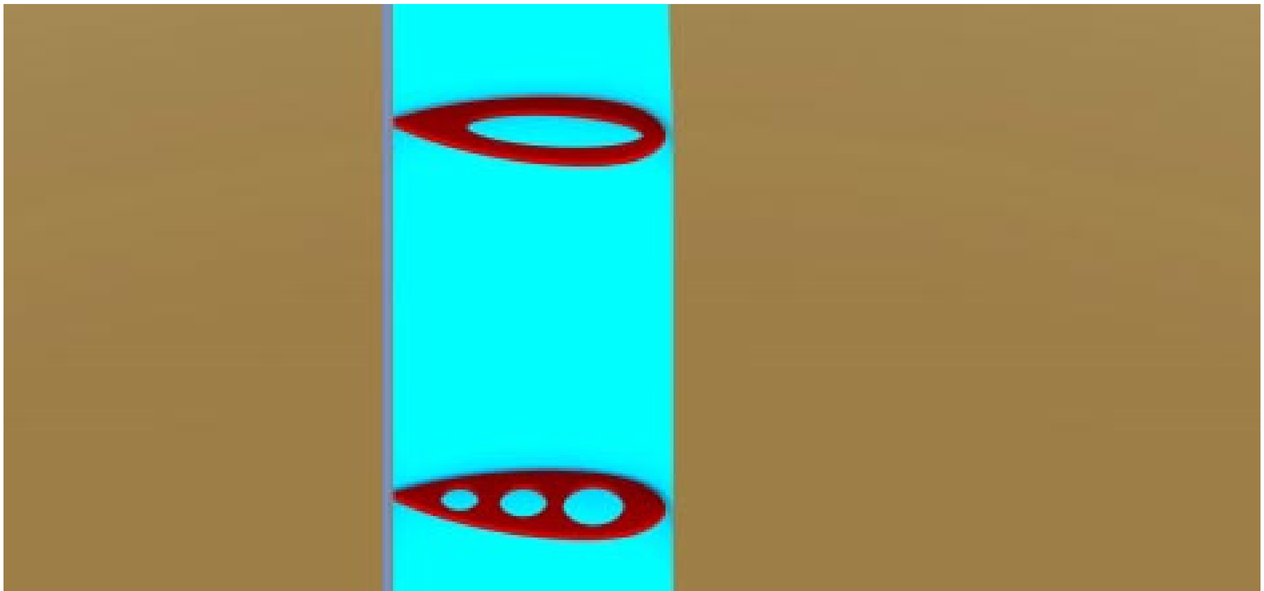
The stitch and glue mast must by definition have thin walls and usually a defining longitudinal spar or shear web that the walls are bent around. A wing mast with that longitudinal spar does have the disadvantage of creating extremely high aspect ratio panels. These panels are liable to fail sooner than lower aspect ratio ones. A stitch and glue mast is however built with the fewest number of pieces, which can speed construction time.



STRIP PLANK WING SECTION

The strip plank wing masts have ideal foil sections and can be of any size as the material is not forced to bend around any shape such as a shear web.
Excessive time to build and higher weight are the main objections to strip masts. These do have a large number of pieces to be joined together and additional fiber reinforcement is needed. Unfortunately that reinforcement must be oriented across the primary load direction and does not directly help resist those loads .

I realized that I actually knew very little about what the actual stresses on a wing mast were. The literature on wing mast stress and strain, or even simple rotating mast stress is practically nonexistent.
Probably Roger Hatfield of Gold Coast Yachts knows more about wing mast stresses than anyone. He not only has built and sailed dozens of them, sometimes with load cells installed, but he also does testing. He has never published any of his work on wing mast stresses however. I did send this mast design to Roger for his valuable comments.
To help me understand those stresses I contacted Paul Steinert at Structural Composites for a finite element study of a wing mast on a 53' catamaran. Based on earlier multihull beam design work by Reichard[1], intermediate bulkhead spacing were chosen as a possibly more efficient alternative to traditional wings with longitudinal shear webs.



Intermediate Bulkheads

As this study was done for a particular job rather than pure research many interesting questions were left alone. My biggest concern was that both of the existing alternatives all had longitudinal shear webs in them. I was proposing an alternative with apparently no history. I basically asked Paul to tell me if the thing would even work, as well as what I need to know to design this wing mast as light as possible and still have it not break.

Scale models were built of both the traditional longitudinal web structure arrangement and the intermediate bulkhead mast. The intermediate bulkhead mast proved to be both lighter and stiffer.

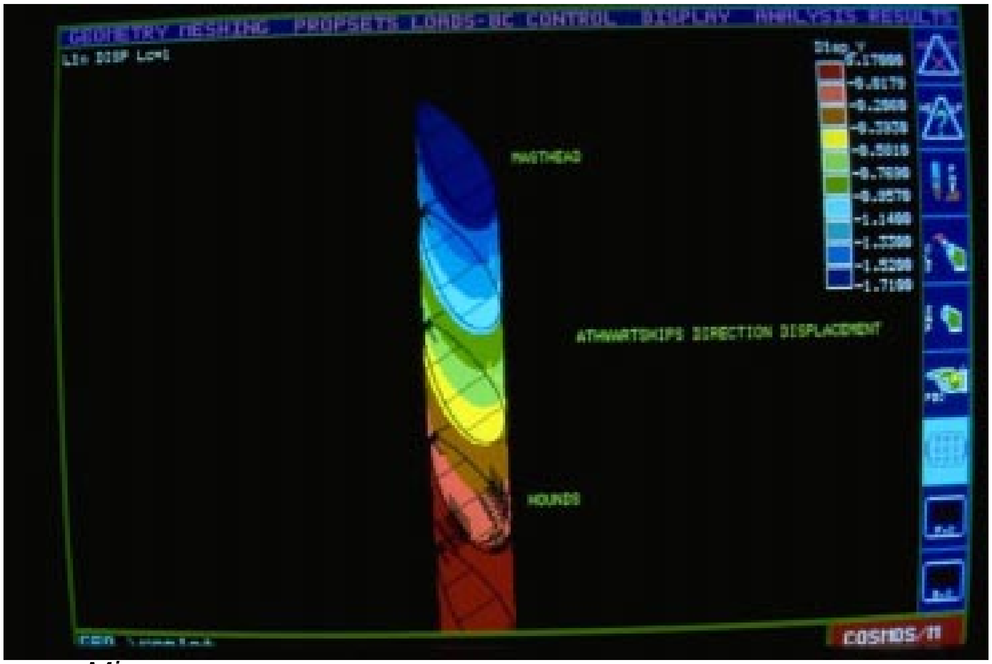
We intended to combine several areas of study at once, using both analysis and practical application. The combination included a new look at wing mast structural strategy, speed of construction considerations, and detailing based on improvements to previous projects.

STRUCTURAL ANALYSIS

A mast is a long thin tube which is essentially a beam loaded in bending and compression. The mast-rigging combination of a sailboat is a structural component which transmits the forces of the sails into the vessels structure.
In the study of the design of a mast, resisting buckling must be considered. Buckling must be viewed on two levels.

1. Global stresses & strains-the critical loads for overall mast loads must be evaluated.
2. Local buckling-mast wall tube sections must be evaluated to insure that local buckling modes do not occur.

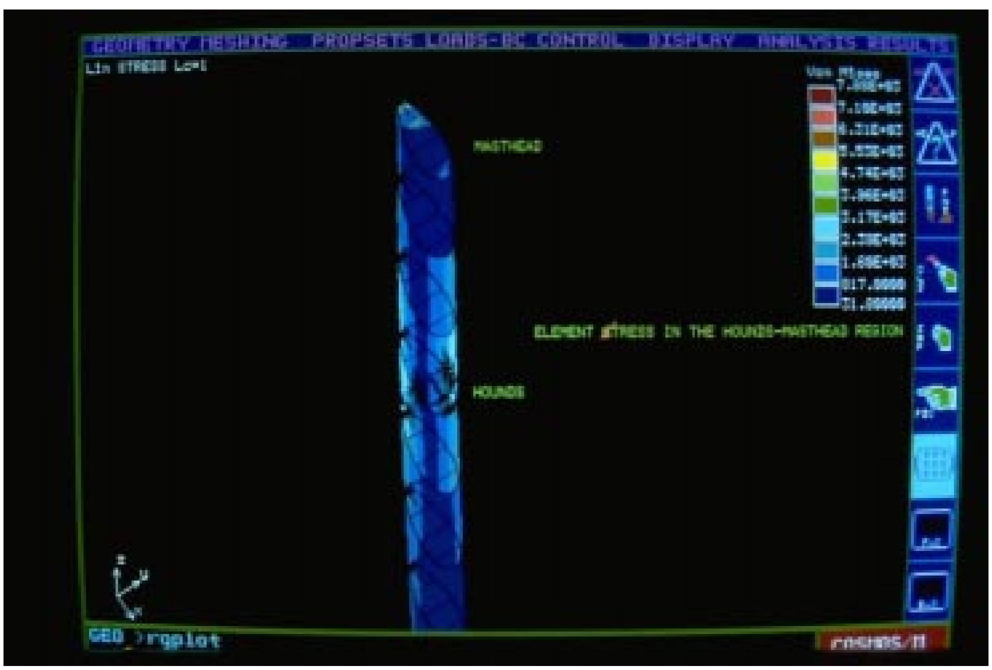
The global approach to the problem is to use a finite element study. Rigging is excluded from the model and loads are applied to the shroud attachment points on the mast
A uniform skin thickness is used with several trial section thicknesses. The plywood section is assumed to be quasi-isotropic in-plane (that means the for the



von Mises

purposes of this study the plywood was assumed to be equally strong in both directions) though it would actually have reduced properties in the transverse direction. As the transverse direction would not govern, it was ignored.

For plywood the compression modulus used is assumed to be the same as the tension modulus.



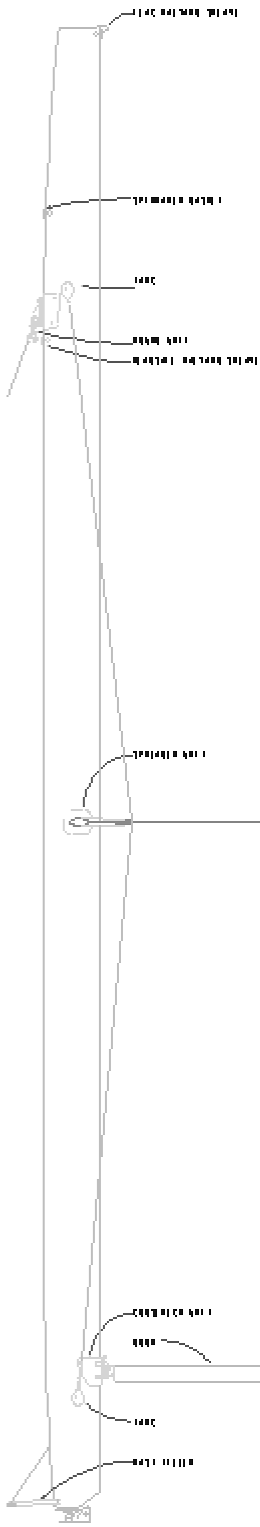
Athwartships direction displacement

Though this work was done with a plywood/epoxy wing mast, much of it would apply to a cored composite wing mast. The influence of the shear modulus would be more important if high modulus materials such as carbon fiber were used. For carbon fiber as an example, the compression modulus is significantly greater than that of plywood and would greatly influence the analysis.
The finite element mesh size needed to obtain the critical stresses for the tube wall makes the number of degrees of freedom very large, on the order of 10,000 for a 60 foot mast.

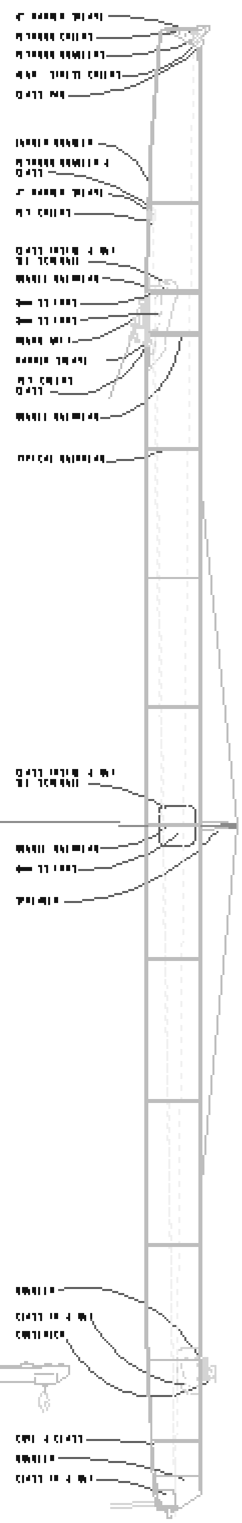
To show what we did, a little engineering nomenclature is needed. Engineers talking are funny. When the mast bends off at the top, an engineer says “delta transformation in the x axis.”
So here it goes
Loads on the mast were determined by geometry in static conditions.
These were assumed to be:
uniform load of 100# per foot in negative x & y directions.
masthead point load of 2000# in the negative x direction (aft) and 5000# in negative z (compression).
hound point load of 10,000# in negative z (compression)
The 30" chord mast section was assumed to be uniform. Young’s modulus of the mast skin was assumed to be 2 million. Stringers were not included in the study as they increased the complexity of the modeling.
The first iterations looked at the best skin and bulkhead thicknesses. Plywood skin thicknesses of .22" and .3" were examined. Bulkhead thicknesses of .005", .15", .22" and .3" were examined.

Areas of the most interest were y direction (side)deflection, skin stresses and bulkhead stresses. The highest stresses were located at the hound area both for the skin and the bulkhead. The highest stress area at the hound point load was ignored as the stainless steel hound plate would protect that area and diffuse those loads.
The significant bulkhead stress at the hound for the .15" thickness was 4.5E+03, a bit high so the .3" was chosen. In most of the other areas outside of the spreaders and base, the loads were lower than expected. That showed the spacing between bulkheads could be increased.
A .3" wall thickness gave a von Mises stress at the hound of 2300 psi, high but acceptable. Other areas of the mast are loaded as lightly as 800 psi. If this were a racing boat varying skin thickness would be used. As it is a cruising design, a uniform mast skin thickness is used for ease of construction. Safety factors to compensate for dynamic loads, fatigue, and other considerations are added as needed. For budget reasons a safety factor of one was chosen for the study. Areas of the rig that were known from past experience to be critical were given additional safety factors. These safety factors and the resulting additional reinforcements were determined by multiplying the stress indicated by the appropriate local safety factor.

The local approach to the mast tube is to consider the wall thickness of the mast based on analytical formula. These formula are found for isotropic cylindrical shapes. Minimum curvature or flat plate equations are used to produce conservative analysis results. The result is allowable stress in local buckling.
The allowable stress for a half section was determined. From that stress amount, bulkhead spacings are adjusted to allow the same or slightly less stress.



SIDE VIEW



MAST LONGITUDINAL SECTION

$$\sigma' = \frac{1}{6}\frac{E}{1-\nu^2}\left[\sqrt{12(1-\nu^2)\left(\frac{t}{r}\right)^2 + \left(\frac{\pi t}{b}\right)^4} + \left(\frac{\pi t}{b}\right)^2\right]$$

$$\sigma' = \frac{1}{6}\frac{2E6}{.91}\left[\sqrt{12(.91)\left(\frac{.3}{30}\right)^2 + \left(\frac{\pi.3}{26}\right)^4} + \left(\frac{\pi.3}{26}\right)^2\right]$$

$$\sigma' = 12{,}087\,psi$$

Curved plate equation

This showed a generous safety factor and in most parts of the mast below the hound the spacing was increased. This compression load is not as significant to the cantilevered mast area above the hound.

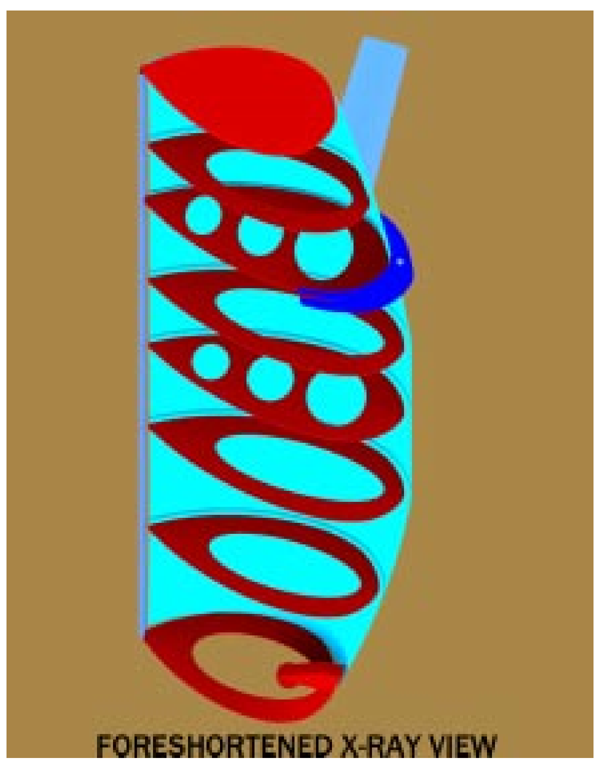
Intermediate bulkhead spacing is the critical factor to consider when sizing the mast wall thickness. Mast section is also an important factor, but that was already fixed by other constraints such as size and weight. A larger intermediate bulkhead spacing requires a thicker wall, a smaller bulkhead spacing, a thinner mast wall.

Success is when the mast wall thickness required by local buckling is nearly equal to that demanded by global loads. It would have been interesting to have tried a variety of bulkhead spacings. Unfortunately, for budget reasons only one finite element spacing iteration could be run. A spacing of 48" on centers seemed to be the most efficient average. Based on the results of this average spacing, and the curved plate equations, the actual bulkheads were located both farther apart where the stresses were lowest, and closer, as at the hound, where stresses were highest.

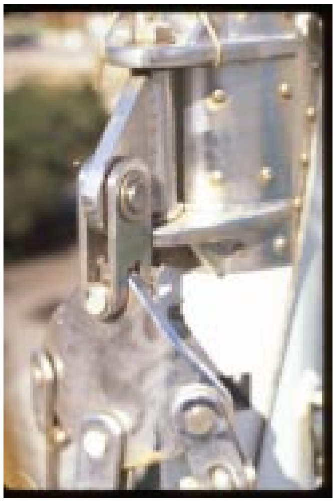
Deflection proved to be well within acceptable limits.

CONSTRUCTION

To facilitate ease of construction with as few pieces as possible, but without a central spar, the mast is made from multiple (2 or 3) thicknesses of thin plywood vacuum bagged together to form a pair of homogeneous curved mast sides. This is done in one step for each of two sides. They are identical but reflected. Internal intermediate bulkheads are added and the mast is closed up. Carbon laminate with or without core can be used. A fusion of thin plywood and carbon reinforcement is also a good option. They have similar stretch to failure, and the thin ply can be the live mold for the carbon. Local fiber reinforcement is added at high stress points, especially to add shear strength.



DETAILING

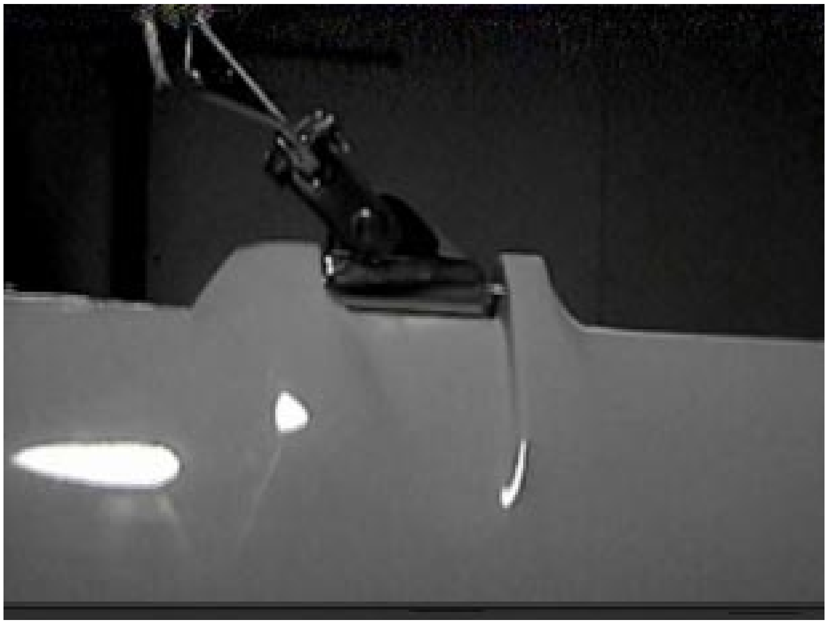


a stainless steel hound

The final step to ensure success of the actual product is the detailing. After over 30 years of detail refinement in trade winds charter catamaran design, very robust details can be and are incorporated into the design. One example is the massive pivoting hound. That allows the mast to rotate fully 90 degrees each direction from centerline and yet keep fatigue stress on the stays minimal.
Fixed beaks on big multis can tend to become unfixed after enough repeated side loadings.
To guard against crevice corrosion, these beaks and other metal fastenings should not be partly buried under composite materials.

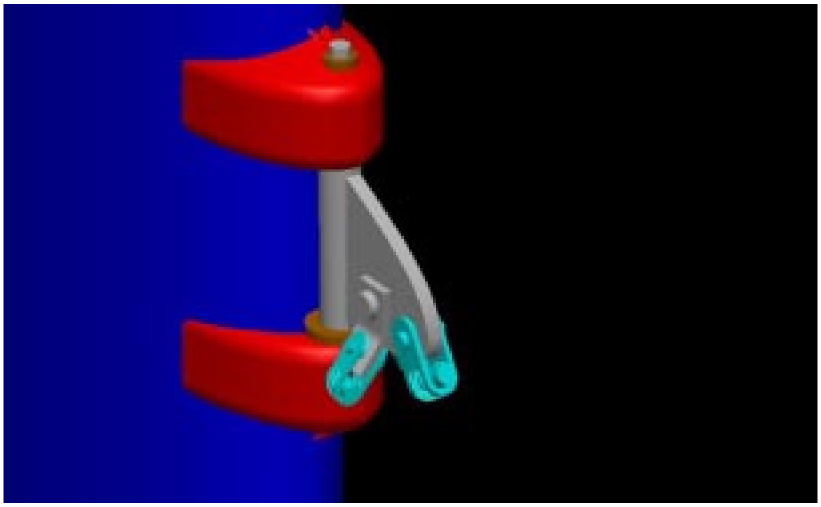
Another improvment is significantly reducing the chord length of the base so that the compression load can be transferred to the rotator pin with a minimum of bending load on the base plate.

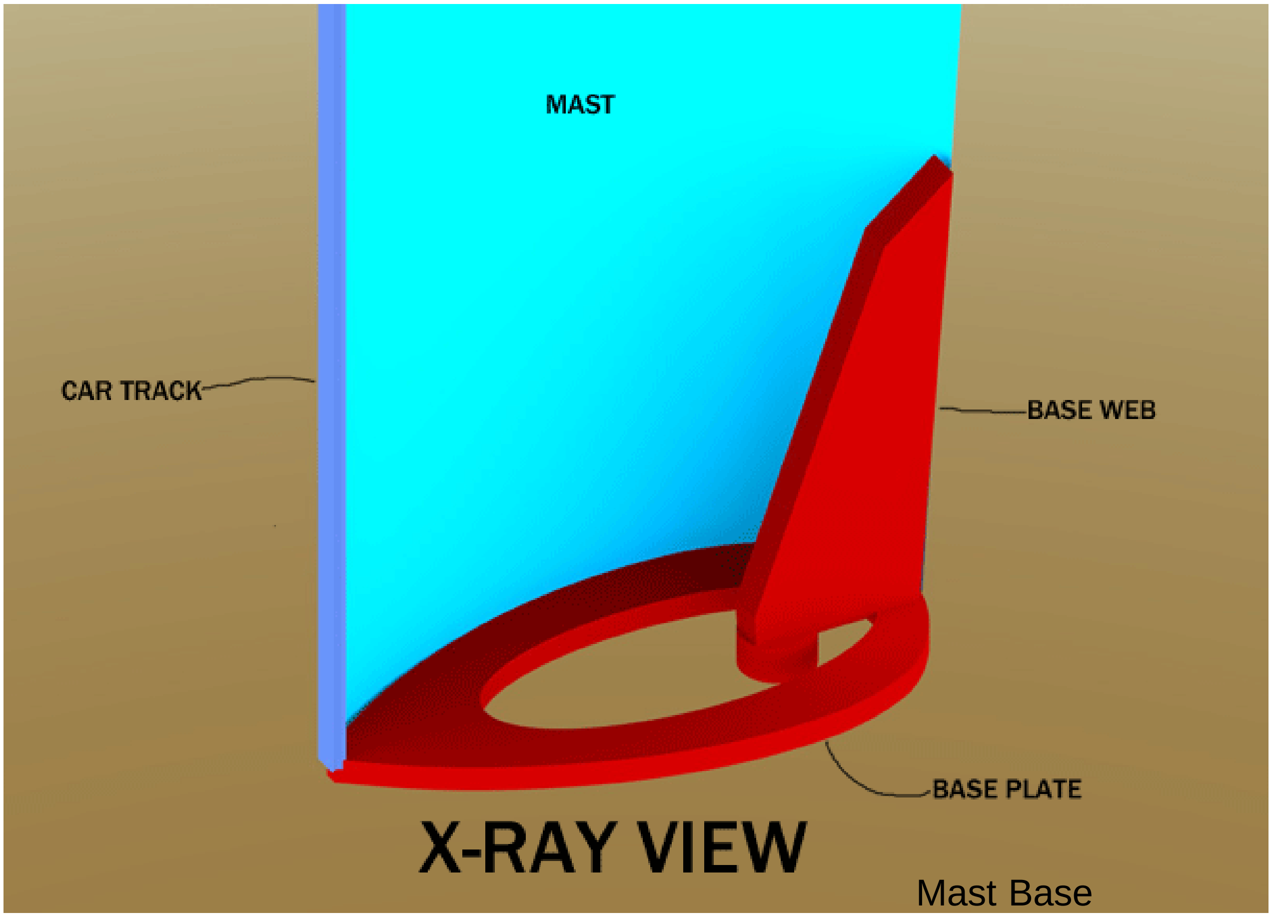
I see future hound assemblies being done in composite similar to the Navtec chainplates. Some composite hounds that I have seen use a big stainless steel ring glommed solidly to the mast by glass or Kevlar. The stays attach to this ring. As these are not free to rotate, I expect fibers holding them them to suffer relatively rapid fatigue damage. They also have a limited rotating range.
The composite hound assemblies that we will be specifying will allow the mast to rotate fully 90 degrees each direction from centerline and still keep fatigue stress on the both the composite parts and the stays minimal.
These hounds consist of a rotating stainless steel beak that is pinned by a stainless steel bolt. The bolt is secured by epoxy-glass ears that carry back onto the wing body. These laminates are engineered with the proper fiber orientation, the best stacking sequence and an ideal taper ratio to keep stresses, especially peel stresses, to a minimum.
I am also working with composite rigging guru John Fanta to see if we can come up with the best bases for all 3 stays.

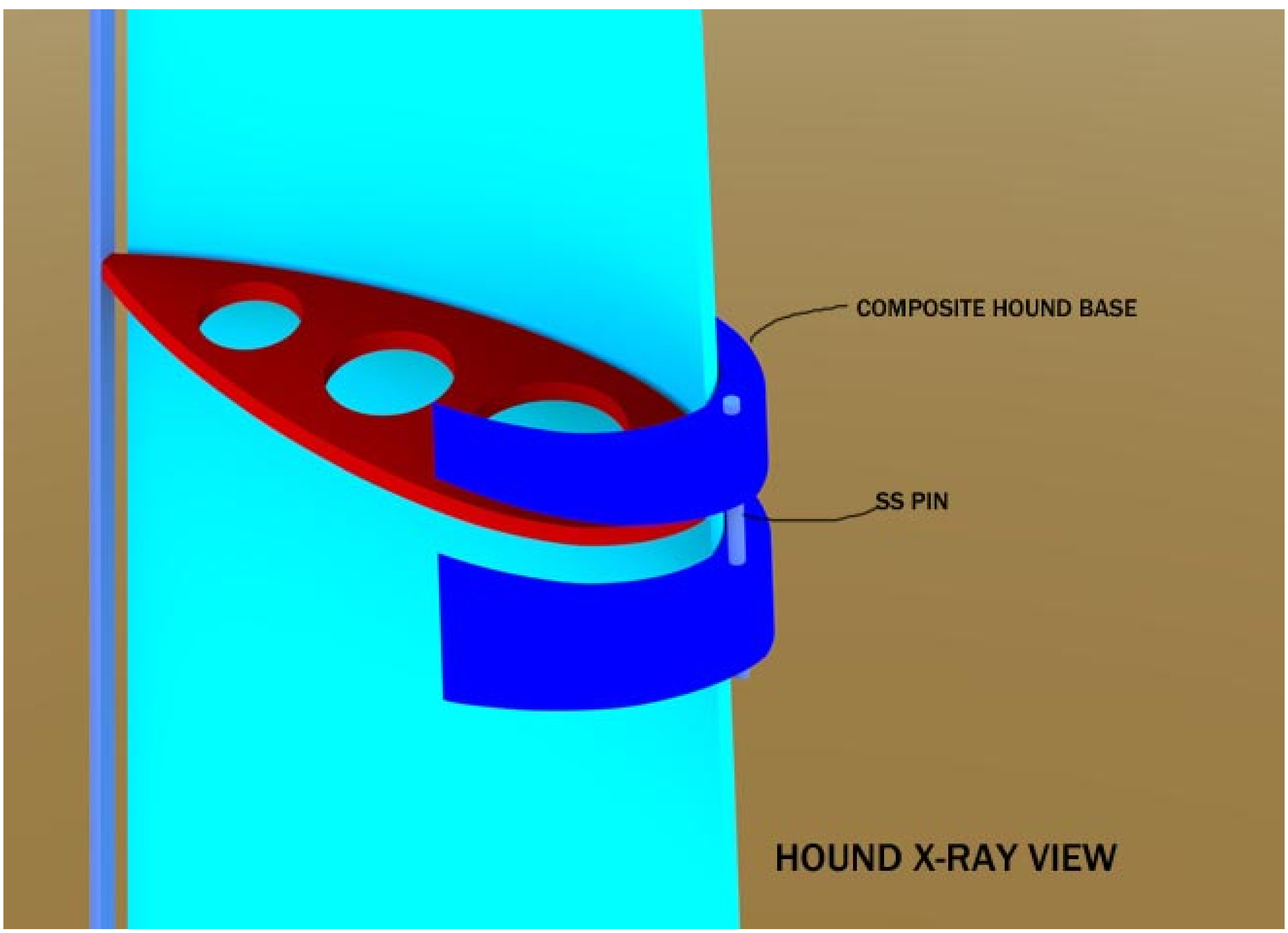


A composite hound

These masts are now being built all over the globe. Future work will include reducing the weight on higher performance masts, composite masts, and a finite element study of the composite hound and plate.




MAST
CAR TRACK
BASE WEB
BASE PLATE
X-RAY VIEW
Mast Base


COMPOSITE HOUND BASE
SS PIN
HOUND X-RAY VIEW