Engineered to stand alone

Eric Sponberg explains design and construction techniques for carbon-fiber spars

The modern freestanding mast may be one of the most promising and exciting sailing developments of recent years. By using advanced composite materials and technology to make it strong, stiff, and light, a freestanding rig eliminates much of the drag associated with a conventional stayed rig. For the same amount of lift, less drag means that more thrust is available to make the boat go faster.

The advanced composite materials (or composites, for short) used in the building of freestanding masts comprise both fibers and resins. Carbon fiber is the basic ingredient of composite freestanding masts. It is a tremendously strong and stiff fiber that is 91 to 95 percent pure carbon (as opposed to graphite fiber, which is better than 99 percent pure carbon and is much more expensive). The biggest producer of carbon fiber for the marine industry is the Celanese Corporation (Celon carbon fiber).

Any of three other fibers is used in conjunction with carbon fiber. E-glass is the standard glass reinforcement, including the woven products and unidirectional fabrics used to build fiberglass boats. In masts it is used for circumferential (or hoop) strength and stiffness and as a protective layer against abrasion and impact.

S-2 glass, which is twice as strong as E-glass, was originally developed for the military as S-glass. S-2 glass is similar in makeup to S-glass, but it has less stringent manufacturing specifications. In masts, S-2 glass replaces E-glass at a slightly higher cost.

Kevlar 49, an aramid fiber that is lighter than glass and carbon fiber, is halfway between glass and carbon fiber in stiffness and has very good impact resistance (it is the

Kriter Lady II on sea trials shortly after her launching in 1981. She carries the largest freestanding carbon-fiber masts to date

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Strong and stiff for its weight, carbon fiber is well suited to freestanding masts

The mechanical properties of spar materials

<table>
<thead>
<tr>
<th>prop.</th>
<th>mat'l</th>
<th>E-glass</th>
<th>S-2 glass</th>
<th>Kevlar 49</th>
<th>carbon fiber</th>
<th>6061-T6</th>
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<tbody>
<tr>
<td>tensile strength × 10^6 PSI</td>
<td>180</td>
<td>298</td>
<td>220</td>
<td>220</td>
<td>45</td>
<td></td>
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<tr>
<td>yield strength × 10^3 PSI</td>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>40</td>
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<tr>
<td>tensile modulus × 10^6 PSI</td>
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<td>12.5</td>
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<td>7.7</td>
<td>12.0</td>
<td>20.0</td>
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<td>97</td>
<td>287</td>
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<tr>
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<td>7.0</td>
<td>12.0</td>
<td>19.3</td>
<td>—</td>
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<tr>
<td>density lbs./in^3</td>
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<td>0.069</td>
<td>0.050</td>
<td>0.057</td>
<td>0.098</td>
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</tbody>
</table>

Figures for laminates are at 60 to 65 percent fiber content by volume.

It is used as a replacement for E-glass and S-2 glass in masts, but its advantages must be weighed against its relatively poor compressive strength and its higher cost. All Kevlar yarn is made by Du Pont.

There are several choices of resin for bonding the fibers together. Vinyl-ester resin has proven to be a very good resin to use in carbon-fiber laminates because of its high strength and an elongation high enough that it won’t crack when the fiber stretches. It also has good adhesion to fiber reinforcements and does not shrink on curing. It handles much the way polyester resin does.

Epoxy resin, the strongest of the resins, is somewhat toxic and much more difficult to handle without fairly sophisticated equipment as it cures on a production line. It is often used for custom mast construction.

Polyester resin, as used in boatbuilding, is not extensively used in composite masts because it has poorer physical properties compared to the other resins and also because it has shrinkage problems when it cures.

The accompanying table shows the mechanical properties of carbon, and of typical unidirectional laminates made with these fibers and epoxy resin. Figure 1 shows specific strength versus specific modulus of elasticity, or stiffness, of each laminate in the table. The specific strength and specific modulus of a material are found by dividing its measured strength and stiffness by its density. Looking at the graphs, it is easy to see why carbon fiber is so well suited for the building of freestanding masts; for its weight, it is the strongest and stiffest material available.

The engineering of freestanding masts requires an entirely different approach from that of stayed masts. Stayed masts undergo almost pure compression, whereas freestanding masts undergo almost pure bending. The engineering equations for designing freestanding masts, therefore, entail standard beam theory, where the spar is a beam supported at one end (maststep) and at a point along its length (partners). The equations were developed primarily for engineering with metals that are both homogeneous (a continuous mixture of metallic alloy) and isotropic (having the same mechanical properties in all directions). Composite materials are neither homogeneous nor isotropic, and the engineering equations must be adapted to take account of these features. The mechanical properties of composites depend on: choice of fiber, type and quality of fabric, orientation of the fabric in relation to the load, choice and quality of the resin, weight ratio of resin to fiber, curing agents used, and the method of fabrication.

With so many variables, testing of a completed mast or a portion of its laminate is an important engineering function. Full-scale loading of a mast to destruction is not usually done because of high equipment and expense costs. However, nondestructive tests using strain gauges and laboratory test equipment are often used.

How are composite masts made? Basically, there are three methods of manufacturing, each of which can be varied considerably to suit particular building situations. One of them is the male mandrel technique (Fig. 2).

Figure 1: Graphing the properties of spar materials (see table). When a freestanding mast bends, one side is in tension; the other, in compression. Compressive strength in composites is usually less than tensile strength, so it is used for the design stress...
winds glass, Kevlar, and carbon fiber in predetermined lengths and orientations onto a rotating and traversing aluminum mandrel. Wetting out is done by automatic impregnator, and curing is usually done by heat. Extraction of the mandrel, sanding, finishing, and attaching hardware follow as before.

Because there is less handling by human hands, this technique usually produces better quality masts. Filament winding equipment is much more expensive than that used in the male mandrel technique, but it is the most sophisticated process and lends itself easily to computer control.

In the female mold/inflatable bladder (Fig. 4) method, all the fiber is wetted out (by hand or impregnator) and laid into a two-part female mold. A deflated bladder of neoprene or silicone rubber is placed onto the laminate, and the mold is clamped shut. The bladder is inflated to 7 to 10 pounds per square inch, which squeezes the resin through the fiber while it cures at room temperature. After cure, the mold is opened, the bladder is extracted and cleaned for reuse, and the mast is removed for finishing and hardware.

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The equipment for this process is less costly than that for either of the other methods, and sanding and finishing of the mast is less involved. Both factors make this process very attractive to small builders. However, the big disadvantage of this process is that if anything goes wrong once the mold is closed, it is usually not discovered until after the part has cured, and then nothing can be done to correct the defect.

The key to engineering composite masts is to get the fibers to lie in the right locations and best orientation to carry the load. For example, on masts with wraparound sails, there is no torque, or twisting, load on the mast. Therefore, most of the carbon fiber should run axially (lengthwise) to carry the pure bending load. Some fiber in the hoop direction is also necessary to maintain the round shape of the mast section. Poor hoop stiffness and strength will lead to buckling of the mast section and premature mast failure. This type of mast is most easily built by the male mandrel technique where axial plies and hoop wraps are easily applied.

The largest carbon-fiber masts ever built were done by this technique for Kriter Lady II [see photo], a 70-footer designed for the 1981–82 Whitbread Round-the-World Race. She has three carbon-fiber freestanding masts, 12 inches in diameter at the base, 65 feet tall, and weighing 1,000 pounds each. An aluminum mast capable of carrying the same load would have to be at least 15 inches in diameter at the base and would weigh 2,200 pounds.

On masts with single-ply sails mounted on a track, the mast undergoes some twisting in addition to bending. Therefore, the laminate needs some fiber placed at about 45 degrees to the mast axis to carry the torque. This type of laminate is best done on a filament winder, which is easily adapted for bias plies at almost any angle.

Interestingly, not all filament winders can lay fiber down at zero degrees; 5 to 10 degrees is usually about the lowest angle obtainable because the

OCTOBER 1983 SAIL
The composite freestanding mast may soon be as generic a type as the stayed.

Carbon fiber conducts electricity and is an extremely noble material. Most metals other than gold and platinum will corrode if in contact with carbon fiber in a marine environment.

Stainless steel tracks and rivets are acceptable on carbon-fiber masts if generous amounts of caulking are used to insulate them. Aluminum tracks and rivets are completely unsuitable. The rivets used should have inside ends that spread out far so as to grip the laminate better. Self-tapping screws must not be used because carbon-fiber laminates, like fiberglass laminates, do not hold screw threads well.

All this engineering and technology is fine, but what about cost? How much does a carbon-fiber freestanding rig cost compared to a conventional stayed rig? Such a comparison is difficult to make because the amount of running rigging, winches, and other hardware can vary considerably from one conventional stayed rig to another. Freestanding composite masts can also differ widely, not only in their outfitting but also, as mentioned earlier, in the lay-up method used. Lacking equivalent examples for a cost comparison, one can only observe general trends.

Carbon-fiber laminates usually have a better cost (and weight) advantage in ever larger structures. In boat designs of roughly equivalent rig layout, the cost crossover point between stayed rigs and freestanding rigs seems to occur for boats between 30 and 35 feet length overall (LOA). Below about 30 feet LOA, a conventional rig is probably less expensive, whereas above 35 feet LOA the carbon-fiber rig would be less costly.

Development of the freestanding mast has been very dynamic in the last few years—and also very disjointed. Numerous companies are doing their best to produce a better mast, but not everyone has learned everyone else's lessons.

If present trends hold, we will probably see the two-ply, wraparound sail gradually give way to the single-ply sail (half the area of fabric, so less weight and cost). The wishbone boom may lose favor to the conventional boom (again, less weight, less cost, and now better attachment to the mast). Finally, the round mast may succumb to the rotating wingmast, which has better aerodynamic characteristics at the leading edge. It may take a few more years of refinement, but soon the composite freestanding mast will be as generic a type as the stayed mast—and possibly its replacement.

A Newport, Rhode Island, naval architect, Eric Sponberg has been engineering composite and freestanding spars for several years.

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Designing politics
The Cup’s gone, and gone to a demonstrably quicker boat. If there is a lesson to be learned and applied to our efforts to bring the Cup home, it is to keep politics out of designing our challengers. Last summer’s selections showed that Courageous was very nearly as quick as Liberty; and for those of us with a bit of a memory, in 1974 Courageous herself was little, if any, faster than Intrepid. Intrepid’s first win was in 1970, fully 13 years ago, which says little for design progress in the meantime.

The time-honored political workings of Newport have effectively barred all but a very limited number of designers from having input in our Cup efforts. This is not the best way to obtain the best boat. Who in the United States is qualified? The first place to look is in the ranks of designers active in the only current international development rule: the International Offshore Rule (IOR). Among the most significant competitions held under that rule are the World Level-Rating Championships, or the Ton cups. They are the only international events that are straightforward boat-for-boat races, without the distortions of handicapping and, from a designer’s point of view, are indisputably the most competitive events in the world.

Six U.S. designers—Dick Carter, Doug Peterson, Gary Mull, Bruce King, Brit Chance, and Bruce Kelley—have Ton cup wins in the last decade to their credit, while none of the current U.S. 12-Meter designers has any. Of the six, Doug Peterson stands out as the most successful, and his designs have taken a healthy string of SORC victories to underscore the point. Only the politics of the Newport clique can have passed over Peterson as the American designer of choice to defend the America's Cup. Must we repeat our errors, and is the hold of the Newport politics an ingrained prerogative to prevail?

Bruce Kelley, Naval Architect
St. Petersburg, Florida

Sour grapes?
In the aftermath of the America’s Cup, the greatest disappointment was not the loss of the Cup, but the unbelievably poor sportsmanship displayed by the Liberty syndicate and, in particular, Dennis Conner: from the decision to reballast Liberty, to the deliberate attempts to draw a foul, to his failure to appear at the President’s reception. Once Liberty lost her momentum, the bombast and hubris turned to sour grapes and recriminations. It seems that Conner has won so often that he does not know how to lose with grace. It is not surprising that by the last race many Americans, including myself, were rooting for the opposition.

Lewis M. Overton, Jr.
Houston, Texas

CORRECTIONS
In the article “Engineered to Stand Alone” by Eric Sponberg (October 1983), in the graph on page 132 showing tensile strength versus tensile modulus, the labels for Kevlar 49 and aluminum 6061-T6 were transposed.

In the news story “Replica Schooner under Construction in Charlestown” (November 1983), Melbourne Smith is credited with the design of Pride of Baltimore; her designer is naval architect Thomas C. Gillmer.