Keels and Rudders: Engineering and Construction

by Eric W. Sponberg

Editor's note: *This article is the second of a two-part series, based on an IBEX 2004 session titled "Practical Methods for Keel and Rudder Design," presented by David Vacanti, (Renton, Washington), naval architect Eric Sponberg (St. Augustine, Florida), and Kevin Milne, president of Mars Metal Company (Burlington, Ontario, Canada). In the last issue, Vacanti discussed the science of foil sections, planform shapes, lift and drag characteristics, and bulb and winglet keels. Here, Eric Sponberg looks at keel and rudder engineering and construction, including calculating keelbolt sizes and rudderstock diameters. And, Milne shows examples of his company's manufacturing processes.*

Engineering Fixed Keels

Keel engineering is relatively simple, and can be done with calculations and scantlings from the American Bureau of Shipping's *Guide for Building and Classing Offshore Racing Yachts*, last published in 1994. (When I mention the *Guide* in this article, it's to that publication that I'm referring.) ABS no longer classes recreational vessels below 79′ (24m) LOA, but still publishes the *Guide*. (To obtain a copy, see the contact information on page 95.) ABS's calculations for keels and rudders follow first-principles engineering quite closely, so be assured that if you meet these criteria, your structures will be sound. If you do engineer keels and rudders directly from first principles, it's wise to check your work against the *Guide* to make sure its requirements are satisfied.

- *Keelbolts.* Section 6 of the ABS *Guide*, "Details and Fastenings," focuses on two areas of concern for keels: the strength of the keelbolts to hold the ballast-keel casting onto the hull, and the strength of those bolts to resist grounding. The following equation calculates the diameter of the keelbolts for a given keel. It presumes all bolts to be the same diameter and material.

$$d_k = \sqrt{\frac{2.55\ W_k\ Y_k}{\sigma_y\ \Sigma \ell_i}}$$

inches, millimeters

Where:

W_k = the total weight of the ballast keel, in pounds, kilogram-force, or newtons

Y_k = is the vertical distance from the keel's center of gravity to the bearing surface of the bolt connection, in inches or millimeters

σ_y = the minimum yield strength of the keelbolt material, in psi, kgf/mm^2, or N/mm^2

$\Sigma\ell_i$= the summation of transverse distances at each bolt from the center of the bolt on one side of the keel to the edge of the keel on the other side, in inches or millimeters.

Figure 1 is a graphical representation of these variables in the load situation that ABS assumes. The greatest load on the keelbolts is when the sailboat is knocked down flat in the water—an occurrence that is rare but possible. The keel tries to bend off the hull, but is resisted by the keelbolts on the high side. The values of all the variables are easy to determine, and so the engineering is simple.

The term "$\Sigma\ell_i$" is illustrated in **Figure 2**. The keelbolts should be arranged in two to three rows along the top of the keel and as far outboard as practical, usually within 1" (25mm) of the keel's side surface. The distance "ℓ_i" is calculated for each

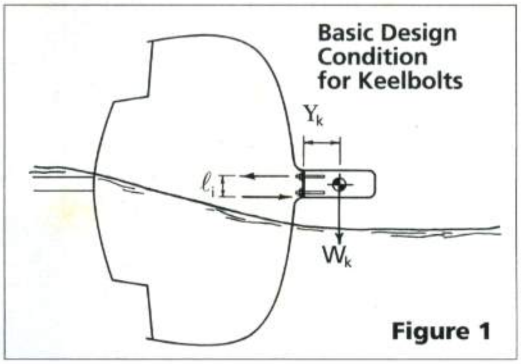

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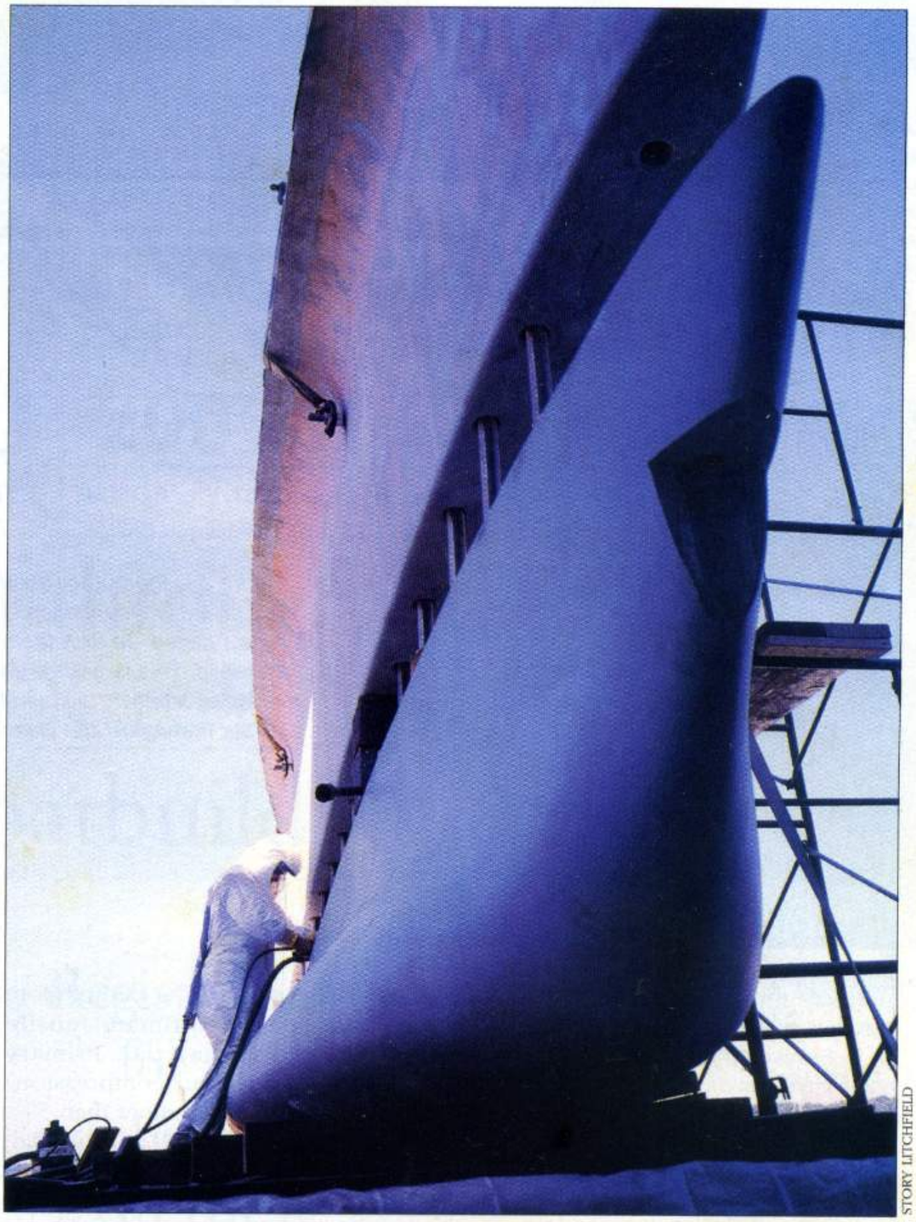
Figure 1*—The ABS* Guide for Building and Classing Offshore Racing Yachts *assumes that the largest load on a keel is in a knockdown situation. The keel can be seen as trying to bend off of the hull; that force is resisted by the pull of the keelbolts on the high side.*

Right*—At Hodgdon Yachts in East Boothbay, Maine, a crew member works on joining the keel of* Scheherazade*—a 155' (47.2m) cold-molded ketch designed by Bruce King and launched in 2003—to the hull extension. The 153,500-lb (69,626.4-kg) keel was cast by Mars Metal Company (Burlington, Ontario, Canada).* ***Figure 2*—The typical keelbolt arrangement pictured here illustrates that, when the boat is upright, all the bolts do the work, and they all do something to resist grounding loads. In a heeled condition, those on the centerline and the ones offset to one side do all the work. This schematic shows how* $\Sigma\ell_i$ *is calculated.*


STORY LITCHFIELD

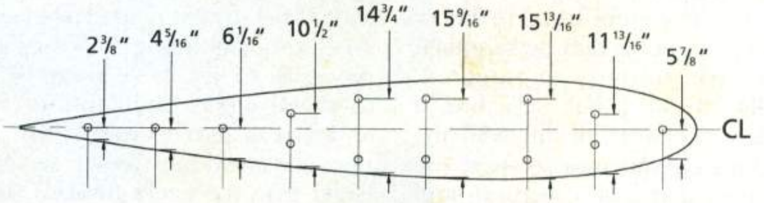
bolt, and these numbers are added together (hence the "Σ" symbol). The number 2.55 in the equation is a conversion factor to ensure that the units for diameter come out correctly, and it includes a safety factor. The resulting number is a minimum diameter, so the keelbolts should not be smaller than this. Of course, they can be larger, and the number can vary—the more there are, the smaller the diameter can be. It all depends on the prudence and expertise of the designer.

You can see that if the keel is very narrow, then the term $\Sigma\ell_i$ is much smaller, which makes the required diameter, d_k, much larger. So, narrower keels require thicker bolts, but as keels get narrower, it's harder to get the bolts into the keel—there just isn't room. For narrow keels, therefore, the solution might be to make the top of the keel fit into a socket built into the boat, and bolt the keel horizontally through the socket.

Interestingly, the ABS *Guide* says nothing about how far into the top of the lead casting the bolts should go. The usual practice is to make the bolts with a bent L shape at the lower end and cast them right into the ballast keel to lock them in place. Another method is to weld the lower ends of the bolts together to form a sort of cage structure to lock them inside the ballast casting. But how deep should they go?

In the classic book *Skene's Elements of Yacht Design*, by Francis Kinney, a designer who once worked at the New York City design firm Sparkman & Stephens, there is a complete copy of *Rules for Wooden Boats*, written by Captain Nathanael G. Herreshoff in 1927. His practice was to sink lag screws into the top of the ballast casting a depth of eight bolt diameters, with the threads sunk in seven bolt diameters. This can be construed as a practical minimum depth for lag screws, and the usual practice for cast-in-place bolts is to go somewhat deeper. Captain Nat also required that one or more keelbolts should pass all

ABS Method of Summing Keelbolt Transverse Offsets



$$\Sigma\ell_i = 2\tfrac{3}{8}'' + 4\tfrac{5}{16}'' + 6\tfrac{1}{16}'' + 10\tfrac{1}{2}'' + 14\tfrac{3}{4}'' + 15\tfrac{9}{16}'' + 15\tfrac{13}{16}'' + 11\tfrac{13}{16}'' + 5\tfrac{7}{8}'' = 87.0625''$$

Figure 2

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Figure 3

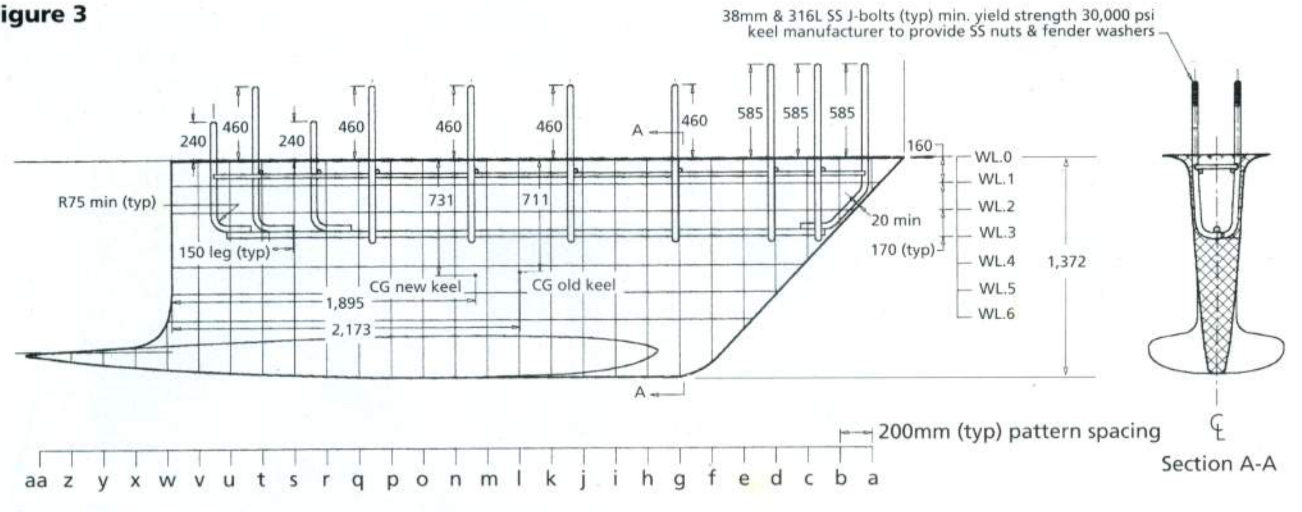

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Figure 3*—The author designed a new keel for* Zanabe*, a 25-year-old 72' (22m) wooden sloop. The keelbolts were L-shaped stainless steel rods, "caged" to lock them into the casting.* ***Left****—*Zanabe*'s keel installed. This is a fairly traditional low-aspect-ratio design, and includes a beavertail bulb that keeps weight low and reduces the tip vortex flowing off the lower end of the keel's trailing edge.*

the way through the ballast casting, but that is rarely done today.

- *Engineering the keel stub.* Section 9 of the *Guide*, "Rudders, Rudder Supports, and Keels," covers scantlings for the stub structure supporting the keel. Since many different designs could be conceived, this section of the *Guide* is quick to point out:

...this Guide is not intended as a substitute for the independent judgment of professional designers, which judgment covers various aspects not addressed in this Guide. This is particularly appropriate for those aspects of keels and their attachment not addressed in this subsection or elsewhere in this Guide for which the designers are solely responsible.

That is, designers have to know what they are doing and be sure their designs are properly engineered. Basically, the keel stub structure, if there is one, must line up with the boat's framing structure so there are continuous paths of structural support. Allowed shear stresses are to be not more than half the minimum shear yield strength of the material of which the structure is made, and this shear yield strength is to be not more than 40% of the ultimate tensile strength of the material. Primary stresses (tension and compression) are likewise to be not more than 50% of the yield strength of the material; and that yield strength must be less than 70% of its ultimate tensile strength. Similar requirements are listed for withstanding grounding loads, as well as for minimum plate thickness of the keel-stub sides, end, and bottom plating.

- *Casting the keel.* Casting keels is something of an art. Designers usually design the shape of the keel to the finished outside surface, and leave the details of actually casting it to the keel-casting company. The designer should be at least moderately familiar with the casting and fabricating processes so that the keel can be built to shape with a minimum of voids and errors. For example, the keel plug and mold must be made slightly larger than the keel's finished size to account for shrinkage of the lead when it cools. Generally, 1⁄16″ per foot (2mm per 300mm) in any direction is about the norm, but the keel caster will fine-tune that according to the shop's established practice. Kevin Milne discusses some of Mars Metal Company's casting and construction techniques in the sidebar on page 82.

- *Real-world examples.* How do all the above considerations play out in a typical keel? *Zanabe* was a 25-year-old 72′ (22m) wooden sloop for which Sponberg Yacht Design Inc. (SYDI) designed a new keel. (See **Figure 3**.) It was a low-aspect-ratio keel with a beavertail-like bulb. Its total weight is 17,450 kg (38,460 lbs), and was cast by I. Broomfield and Son (Providence, Rhode Island), who did a fine job of casting and finishwork. The keelbolts were 38mm-diameter (1.5″) L-shaped rods made of 316L stainless steel and caged to lock them into the casting. The **photo above** shows the boat with the new keel in place at Little Harbor Marine (now The Hinckley Company), in Portsmouth, Rhode Island. The wood structure above the keel inside this boat was massive, and the bolts went up through the transverse frames. The original keel was poorly made, and its keelbolts were not oriented vertically but were canted inward toward the boat's centerline, which made dropping the keel off the boat especially difficult. During the retrofit, all the original bolt holes in the structure were filled with long mahogany plugs, and new holes were bored.

Wooden boats lend themselves to a particularly clever structure to support the keel and withstand grounding loads, as shown in **Figure 4** (from *The Gougeon Brothers on Boat Construction*, published by Gougeon Brothers Inc., Bay City, Michigan). The keel flat, the centerline keel timber, and a keelson are joined in an I-beam structure that sandwiches the transverse frames. Should the boat hit hard ground, there is a tremendous uploading of the keel at the trailing edge as it rotates up and into the hull. This structure can absorb a great deal of energy before the keelson breaks in tension.

How much are grounding loads? This almost sounds like "How long is a piece of string?" The ABS *Guide* has an estimate, in pounds, kilogram-force, or newtons. At the toe of the keel leading edge, acting horizontally in the aft direction, the grounding load is:

For LWL ≥ 20m (66′), grounding load = $3F_\Delta$

For LWL ≤ 10m (33′), grounding load = $1.5F_\Delta$

Where:

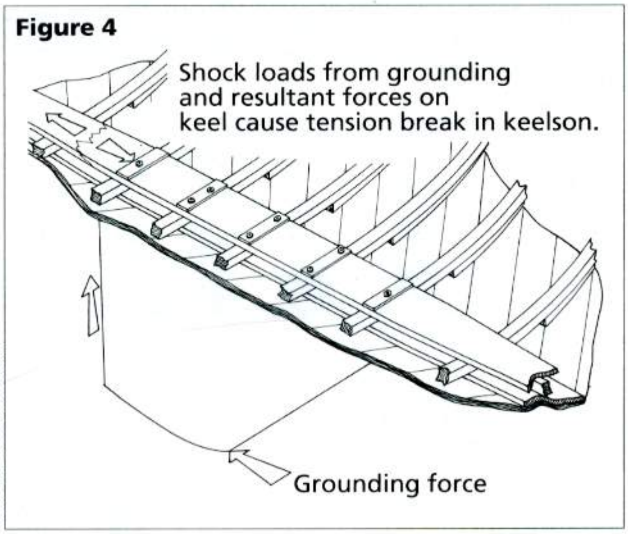
F_Δ = the maximum displacement (weight) of the yacht

The vertical load acting upward on the bottom of the keel = $1.5F_\Delta$.

Should the keelson break, it is easily repaired. This, in fact, once happened to the IOR racer *Golden Daisy*, built by the Gougeons, on her maiden voyage. She hit the reef at Port Austin Reef Light a few days before her first race, and the grounding broke the keelson, just as shown in **Figure 4**. According to Meade Gougeon, the boat was repaired in three days and nights—in time to make the starting line. This structure saved the boat from sinking; only a small amount of water came in through a minor crack in the hull.

I followed the same method of construction in *Corroboree* (**Figures 5** and **6**), a 35′ (10.7m) wooden sloop built for American owners by Lloyd Stevenson Boatbuilders in New Zealand. The transverse floors are

Figure 4



THE GOUGEON BROTHERS

***Figure 4**—An illustration from* The Gougeon Brothers on Boat Construction *showing a method for constructing a keelson in wooden boats. In a grounding, the structure can absorb a great deal of energy before the keelson breaks in tension, with relatively little damage to the hull. **Figures 5** and **6**—Cross-section and profile views of the keel structure on* Corroboree*—a 35′ (10.7m) sloop designed by the author—follow the Gougeon approach to keelson construction.*

Figure 5

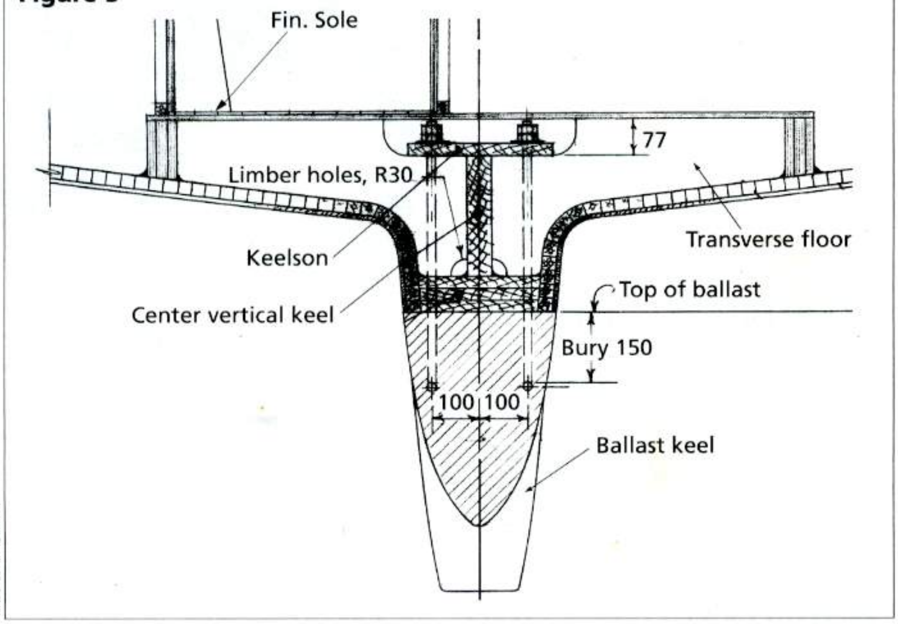


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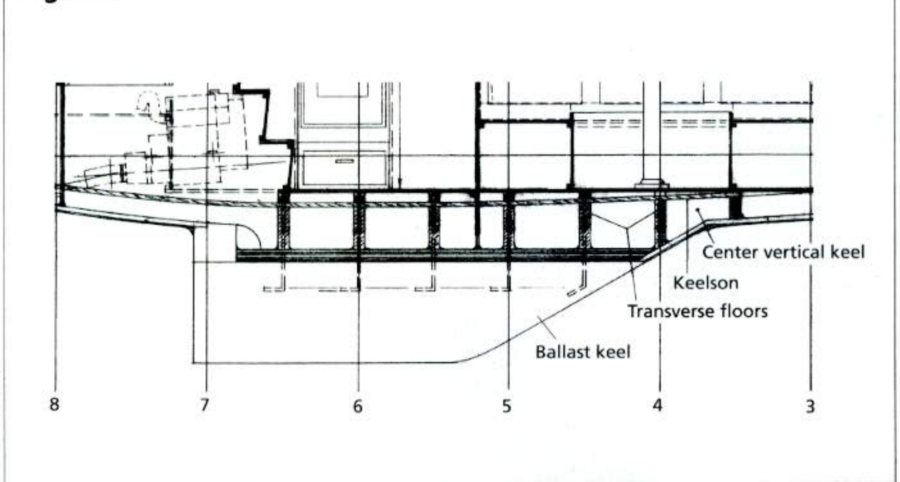
Figure 6



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mahogany plywood; the keel flat, the center vertical keel, and keelson were all specified as Honduras mahogany, but the Kiwis used kauri (as some of them would say, "the best damn boatbuilding wood in the world!"). The keelbolts are 18mm-diameter (¾″) silicon-bronze L-shaped rods cast into the ballast.

In wooden boats, it's preferable to run the keelbolts up through the transverse floors and the keelson, so they hold the entire structure together and the keel loads transfer directly into the boat framing. I once saw an elegant 38′ (11.6mm) wooden daysailer on which the keelbolts came up *between the floors and frames*, leaving only the cross-grain strength of the longitudinal keel timber and transverse floors to hold the keel on. The boat did not survive her maiden race. She left her keel at the bottom of the harbor and turned turtle in the waves. FRP boats, on the other hand, frequently have transverse floors built of fiberglass hat sections filled with relatively light-density core. The fiberglass at the bottom of the keel stub is usually very thick because the port and starboard hull laminates cross over the hull centerline through the keel stub. The keel stub is much more robust than the foam-cored floors. Therefore, the common practice is to bring the keelbolts up through the stub flat—not through the floors—but close enough to them so that floor structure can carry the load. If the keelbolts come up through the thinner fiberglass hat sections, there is a good chance that over time the foam could crush, and water could get into the foam along the keelbolts. The structure would not be easily repaired. I have used such bolting arrangements on all my keel designs for fiberglass boats—for example, the Cambria 44, built by David Walters Yachts (Portsmouth, Rhode Island).

Some years later, the second owner of *Magic*—Cambria 44 hull #2, a deep-keel version—hired SYDI to cut the draft of her keel by 12″ (305mm) and fashion a like amount of lead into a beavertail bulb (**photo, facing page**). In this modification, we used four ¾″-diameter (18mm) silicon-bronze threaded rods to fasten the bulb onto the keel. The engineering required that the shear area of the bolts be able to support the weight of the bulb plus a safety factor. The joint fit perfectly, and was filled with 3M 5200 adhesive-sealant. The owner swears the boat sailed a touch faster and a degree or two higher as a result. There are no scantling rules for this method of attaching bulbs to keels, so one has to use common sense and perhaps some first-principles engineering to come up with the design. I have done this type of design a few times, and it has always worked out well.

Movable Keels

Swinging and lifting keels present a different set of circumstances from the traditional fixed-keel designs discussed so far, because they have no bolts holding the keel to the hull. A designer's expertise is crucial to the success of a movable-keel design, since no engineering guidelines for it exist.

- *Swinging keels*. My Open-class 60 design for the 1998–99 Around Alone

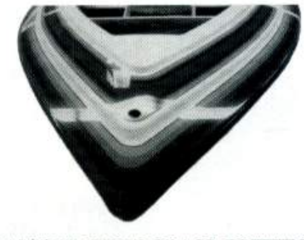
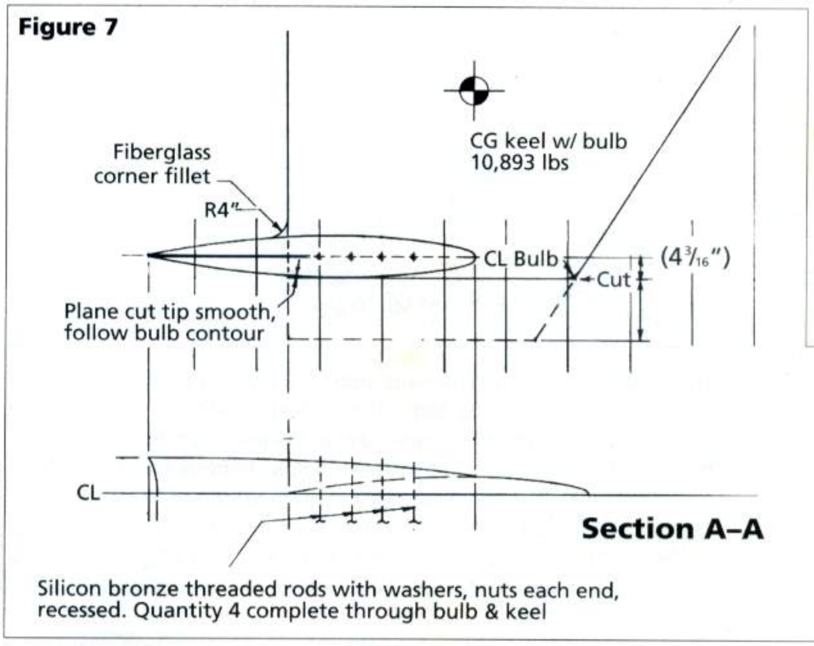
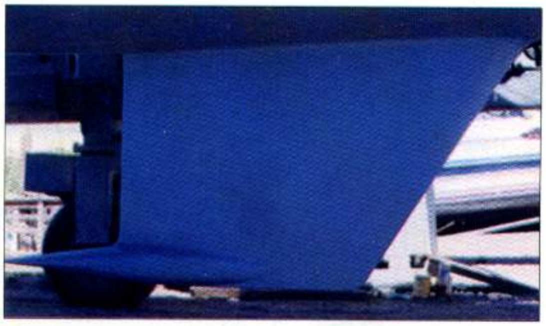


Figure 7





ERIC SPONBERG (BOTH)

Figure 7**—This drawing shows the modification to the keel on* Magic, *a deep-keel Cambria 44. The keel's draft was reduced by 12" (305mm), and a beavertail bulb added.* ***Above—Magic*'s bulb modification was done by Pilot's Point Marina (Westbrook, Connecticut).*

Race, *Project Amazon*, had an all-aluminum swinging keel with ballast bulb (**Figures 8, 9, and 10**). Her keel swings about 25° to either side, which shifts the heavy bulb out far enough to one side or the other to enhance her stability. The swing is done by two large hydraulic rams attached to the top of the keel blade and to the hull at the chines. The keel pivots on a 6″-diameter (150mm) solid aluminum shaft mounted inside

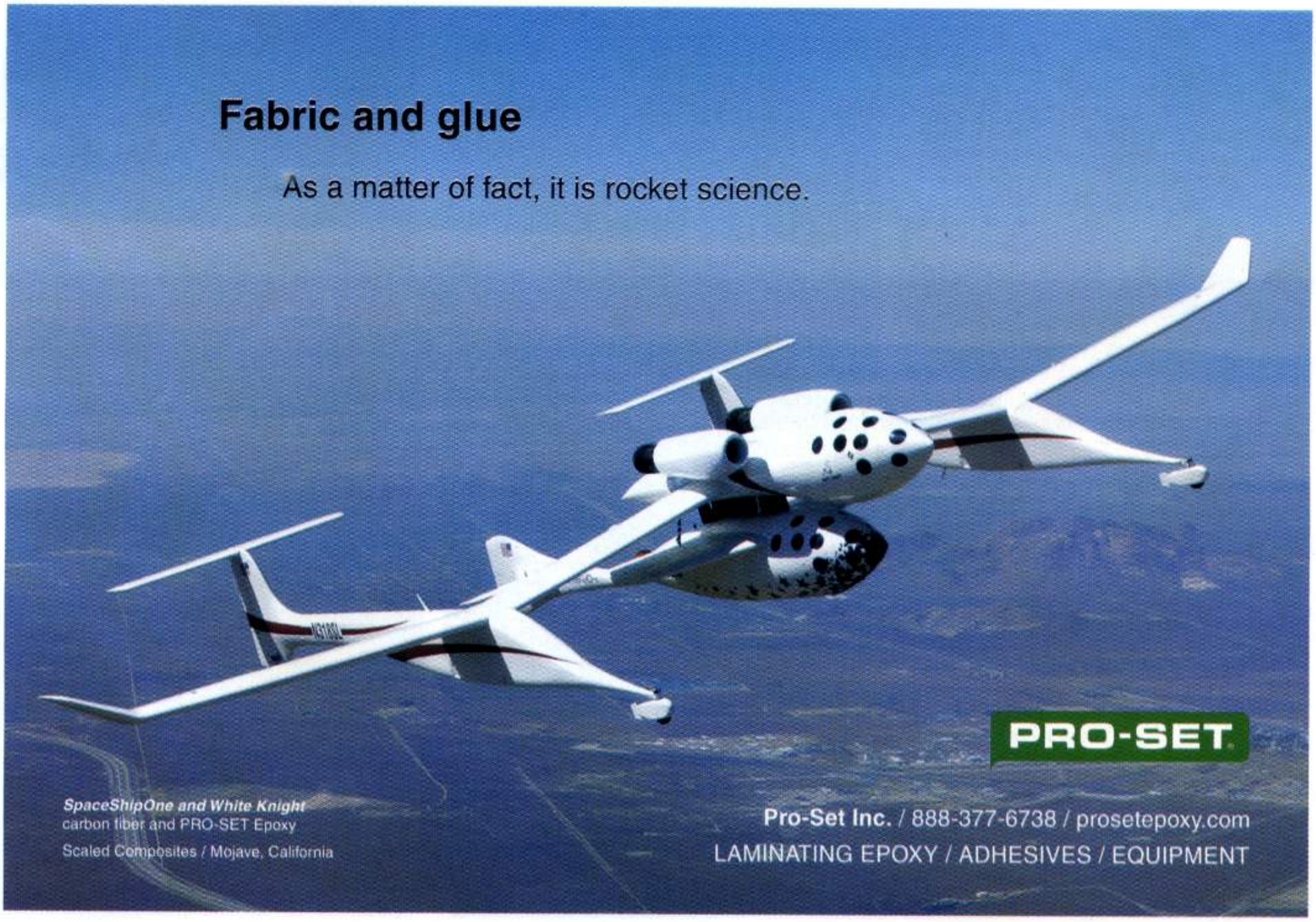


Figure 8

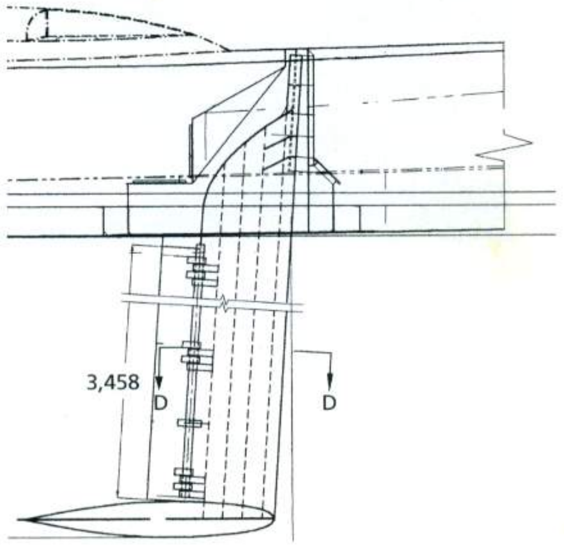
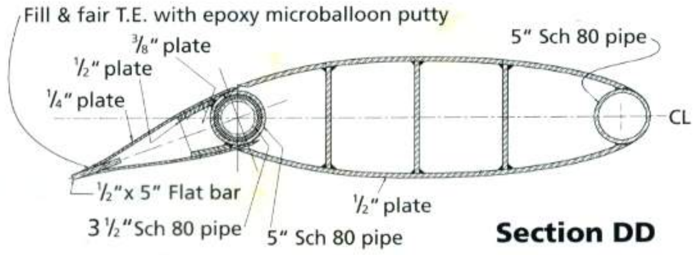


Figure 9



ERIC SPONBERG (BOTH)

Figure 8*—Project Amazon—the author's Open-class 60 design for the 1998–99 Around Alone Race—has a swinging keel in an L configuration built as a hollow airfoil section that includes a trim tab. The hollow part of the keel holds nearly a ton of diesel fuel.* ***Figure 9****—The relatively wide section shape of* Project Amazon*'s keel blade makes it possible for the low-pressure side of the surface to be completely fair when the trim tab is deflected. If it were narrower, there would be more of a knuckle at the trim tab axis.*

clamshell bearings. The shaft is engineered to support the weight of the keel in a knockdown and to withstand the ABS grounding load with a safety factor of two.

In order to make the keel-blade structure strong enough, the airfoil section had to be quite fat: a 21% GA(W) airfoil (meaning the width of the airfoil section is 21% of the chord length). Most keel designs are about 12%–15% or thinner, for low-profile drag consistent with the correct volume of lead ballast. The wide section had several advantages.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