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.

\[ d_k = \sqrt{\frac{2.55 \cdot W_k \cdot Y_k}{\sigma_y \sum \varepsilon_k}} \]

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
- \( \sigma_y \) = the minimum yield strength of the keelbolt material, in psi, kgf/mm², or N/mm²
- \( \sum \varepsilon_k \) = 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 "\( \sum \varepsilon_k \)" 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 "\( \varepsilon_k \)" is calculated for each...
bolt, and these numbers are added together (hence the "\( \Sigma \)" 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 \( \Sigma d_i \) 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

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**ABS Method of Summing Keelbolt Transverse Offsets**

\[
\Sigma d_i = 2\frac{3}{8}'' + 4\frac{3}{4}'' + 6\frac{1}{4}'' + 10\frac{1}{2}'' + 15\frac{7}{8}'' + 15\frac{5}{6}'' + 11\frac{3}{4}'' + 5\frac{3}{4}'' = 87.0625''
\]

*Figure 2*
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 scannlings 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 no 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, 1/8" 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 $LWL \geq 20m$ (66'), grounding load

$$F_A = 3F_A$$

For $LWL \leq 10m$ (33'), grounding load

$$F_A = 1.5F_A$$

Where:

$F_A$ = the maximum displacement (weight) of the yacht

The vertical load acting upward on the bottom of the keel = $1.5F_A$.

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
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 boat-building wood in the world!"). The keelbolts are 18mm-diameter (5/8") 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 light bulb like amount of lead into a beaver tail bulb (photo, facing page). In this modification, we used four 5/8"-diameter (18mm) silicon-bronze threaded rods to fasten the bulb onto the keel. The engineering required that the sheet 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 scuttling 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...
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

![Fabric and glue](image)

**Fabric and glue**

*As a matter of fact, it is rocket science.*

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**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).
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% GAW (geometric airfoil width) 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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First, the extra width made the section stronger and stiffer, so it could be made out of ½"-thick (12mm) aluminum plate. Second, the fat width also made it easier to fasten in a substantial trim tab without hard knuckle on the low-pressure side at the trim-tab axis (Figure 9). This idea was derived from earlier America's Cup designs, and, in Project Amazon's case, worked well. In fact, the owner and skipper, Sebastian Reidl, proved to the Around Alone Race Committee by a demonstration in Charleston Harbor a week before the 1998 race start that the trim tab alone could reliably steer the boat, and thereby satisfy the rule requirement for an emergency rudder.

A third advantage of the thick keel was that the empty space inside the blade was perfect for holding almost a ton of fuel—enough to power generators, as well as to cook and heat the boat, on a trip nearly twice around the world. It also kept the fuel weight well below the waterline, which measurably enhanced Project Amazon's stability. A fourth advantage was that, despite profile drag being marginally higher than that of a thinner airfoil section, in the ocean's turbulent seas the large section made it easier for the keel to hold its lift—that is, it would not stall nearly as easily.

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as a thinner section.

Project Amazon's bulb and keel were designed in an E configuration: the nose of the bulb is in line with the leading edge of the blade, so the keel's profile shape looks like a backward E (Figure 8). In a T configuration, the nose of the bulb extends forward of the blade leading edge, and the tail of the bulb extends aft of the trailing edge, thereby resembling an upside-down T.) The planform shape of the bulb, as is typical of many of my designs, I call a "beavertail-swallowtail bulb," or BS bulb for short (pun intended). Despite the nickname, this bulb design has low drag and low weight. The swallowtail shape at the aft end of the bulb helps to bleed off the bulb's own wake.

The bulb-bolting arrangement on Project Amazon is horizontal through the tip of the aluminum keel structure, which is recessed into the top of the bulb. Again, the number and size of the bulb bolts—in this case stainless steel, to minimize corrosion due to dissimilar metals—are engineered to hold the bulb weight with an appropriate factor of safety.

Kevin Mihle, president of Mars Metal Company (Burlington, Ontario, Canada), was a speaker in the IBEX seminar on which this article is based. Mars has been building custom and production lead keels for 25 years; it has the capability to cast keels from 100 lbs up to 200,000 lbs (45.4 kg to 90,718.5 kg).

Scheherazade’s keel, pictured on page 73, is one of Mars’ larger projects. Here are a few more examples of the company’s work.

Right—An example of Integrated Cast Bulb technology, developed and registered by Mars Metal Company. ICB allows for the marriage of two dissimilar metals by directly casting one to the other, eliminating the need for bolts and internal attachment structures. The process saves time and cost, and reduces the amount of fairing required when the bulb is bolted to the fin. Here, a J/125 nickel-aluminum-bronze fin is set up in the mold half incorporating a MarsKeel-designed armature, ready to accept the lead bulb integrally cast onto it. Once the fin is cast to the lead bulb, the recessed junction of the two dissimilar metals is caulked, then wrapped in fiberglass to seal the joint and isolate the two metals against dissimilar expansion.
Right—A MarsKeel stainless steel fin with lead bulb weighing over 11 tons (9,980 kg) is inverted and in the process of being milled to a tolerance of 0.01" (0.25mm). To achieve such fine tolerances, Mars worked from a surface-lofting IGES file, supplied by the designer, to program the six-axis CNC mill. Solid cast-lead keels can be milled along with most dissimilar-metal keels.

Far right—A custom stainless steel fin and integrally cast lead bulb. The 90/10 ratio of lead to fin makes for an extremely low vertical center of gravity. The vertical fin is fabricated by forming a 316L stainless steel skin 3/16" to 1/8" thick (4.8mm to 7.9mm); the addition of vertical and horizontal stiffeners results in a seam-welded watertight foil section. In this particular keel, high-strength Aquamet 22 bolts maximize shear strength and are incorporated into the top foil by means of an internal superstructure welded from within for attachment to the hull. In cases such as the DS42 lifting keel, which Mars produces for The Hinckley Company (Southwest Harbor, Maine), these fabricated fins can be built as lifting keels with internal structures to implement the hydraulics for vertical movement of the fin. In certain keels, the fabricated hollow fins are used for fuel or fresh water storage, or for optional water ballast.

—Eric Sponberg
Left—The yard that built Project Amazon modified the author's original design—without consulting him; the redesigned keel/bulb connection had eight bolts, oriented vertically. Right—When it was discovered that the bulb was too heavy by about a ton, some serious surgery took place. The yard faired the bulb to an acceptable shape, but before the 1998 Around Alone Race, the author designed a new bulb, cast by Mars Metal Company.

While this is how I designed the bulb attachment, it is not how it was built. When the owner first approached the builder in South Africa, the builder advocated orienting the bulb bolts vertically, and showed the owner some examples. The owner liked what he saw and agreed to the change. It also meant, however, that the blade would come down to the top of the bulb—not be recessed into it—and the bolting arrangement was redesigned by the yard (photo above, left). The bulb, of course, ended up being about a ton too heavy when the lead filled in the volume that was to have been taken up by the recessed blade. The yard did not take that into account, nor did they consult with me on what they were doing. So the boat was then about 5% too heavy on account of their error.

After a curious exchange of faxes about the bulb problem, the owner
sent me the photograph to the right on the facing page. Armed with heavy-duty electric saws, the crew had cut sections out of the bulb, making it look like the inside leftovers of a great white shark. They reinforced the bulb casting with a makeshift stainless steel cage, and filled the voids with putty and filler. Once faired and painted, it didn’t look too bad, but to my mind it certainly was not structurally reliable. Ultimately, the owner had SYDI design a smaller, lighter bulb, which was built by Mars Metal Company and installed a month or so before the race.

- **Lifting keel.** My lightweight 44’ (13.4m) wood-epoxy sailboat design, Bagatelle, has a carbon fiber and wood-epoxy lifting keel. For an in-depth discussion of Bagatelle’s design, including the keel arrangement, see “Case Study in Lightweight Engineering,” PBB No. 79, page 48—Ed. The keel blade section is narrow, with a 10% airfoil section for low profile drag. Such a thin section made engineering more difficult, and

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**Figure 11**

Bagatelle, another of the author’s designs, is a 44’ (13.4m) wood-epoxy sailboat with a carbon fiber and wood-epoxy lifting keel. The three keel sections here show how the carbon fiber skin wraps around the solid wood core. The section that remains in the keel box is square, and the stainless steel armature at the bottom fits just inside. The bulb was cast by Mars Metal Company directly onto the stainless steel armature provided by the owner.
that’s why we had to rely on a carbon fiber skin for strength and stiffness. The keel section was built up with solid timber, over which was laid a thick carbon fiber and epoxy skin (Figure 11). The engineering involved treating the keel as a cantilever beam with a heavy weight at the end—the bulb—just as the ABS Guide assumes. Given the section shape, we determined the skin thickness for the necessary strength and stiffness; about ⅛” (8mm). A stainless steel armature was built into and bolted through the solid wood core, and the carbon fiber laminate over that extended down over the top rabbet in the bulb casting.

The lifting keel rides in a slot. Bagatelle’s slot is a balsa-cored fiberglass box that is fiberglassed at the hull (through the longitudinal keel structure) and at the overhead, and opens through the top of the doghouse roof. A keel in a slot is always supported at two discrete points—at the top of the keel and at the exit through the hull. The reaction loads in the box are equal and opposite; and the farther apart the support points, the lower the loads. These loads are easily identified in terms of the cantilever beam model, so engineering and design are relatively simple. In the lowered position on Bagatelle, the upper end of the keel swings against the inside of the box at the level of the galley countertop. The other reaction is against the keel structure at the hull opening. It’s a simple matter to reinforce these areas to handle the loads. The keel is pinned through the keel box, well above the waterline, by a single ¼”-diameter (18mm) stainless steel pin. The stainless steel lifting cable is attached directly over the keel’s center of gravity so that the keel comes up through the slot perfectly straight.

The photos on the facing page show how Bagatelle’s keel went together. Engineering the keel blade skin as we did satisfied the basic bending load, as ABS assumes; but what about the grounding load? We made the keel box long enough so the owner could install crush boxes in front of and behind the keel. Our thinking was that if the boat hit hard ground, as Bagatelle did early in her maiden season, the keel could rotate aft and crush the box before crushing either itself or the hull structure. The crush box performed as designed. When opportunity permits, a replacement crush box can be installed.

**Rudder Engineering**

Rudders are much more difficult than keels to engineer because their loads are more complicated. Rudders must withstand both a bending moment and a torsional moment simultaneously, as illustrated in Figure 12. If the rudder is mounted on a skeg, the engineering is especially complex because the skeg carries some of the load and must be correspondingly engineered along with the rudder.

The ABS Guide covers rudder engineering in Section 9, “Rudders, Rudders, Rudders, and Rudders.” The first calculation in the scantling rule is for the diameter of a solid rudder:

\[
d = \sqrt[3]{\frac{32}{0.5M + 0.5\sqrt{M^2 + 4T^2}}}\]
Bagatelle’s keel at various stages. **Upper left**—Builder Rick Waters with the 10’ tall (3m) wood keel blade. The blade’s thin section meant that a carbon fiber skin would be needed for strength and stiffness. **Left**—The carbon fiber skin, after sanding but before fairing. A stainless steel armature was built into and bolted through the solid wood core; and the carbon fiber laminate over that extended down over the rabbet in the bulb casting. **Lower left**—A close-up of the crush boxes at each end of the keel blade. If the boat hit hard ground, as she did early in her maiden season, the keel could rotate aft and crush the box before crushing either itself or the hull structure.
Where:
\( \sigma_c \) = the allowable stress in the rudderstock, based on either the ultimate strength of the material or the yield strength
\( M \) = the bending moment of the rudder on the rudderstock
\( T \) = the torsional moment of the rudder on the rudderstock.

All these factors are fairly straightforward to calculate according to the equations in the Guide and the geometry of the rudder. The above equation is called a “combined load” calculation, wherein the bending moment and the torque are combined into a single load to determine the rudderstock diameter. Both \( M \) and \( T \) are moment loads, which mean they are force \( x \) distance. The force, \( P \), is the resultant lift force on the rudder, following hydrodynamic principles:

\[ P = k C L W A N \]  

Where:
\( k = 984 \) in metric units or 6.25 in imperial units. This keeps the units consistent, includes the density of sea water, and incorporates a factor of one-half, which is used in all basic hydrodynamic load calculations
\( C = \) the load coefficient = 1.5
\( L = \) length on the boat’s waterline, in meters or feet
\( W = \) the profile area of the rudder, in square meters or square feet
\( A = \) a factor based on displacement-to-length ratio of the boat; relatively simple equations are given for this in the Guide.

For the bending moment, \( M \), distance is the vertical distance between the center of rudder area and the center of the neck bearing (the bearing at the hull opening). For the torque, \( T \), distance is the horizontal distance between the center of the rudder area and the axis of the rudder stock.

If the rudder stock is a tube or pipe rather than solid, you can determine a suitable inside and outside diameter that is equivalent to the solid stock diameter, with the equation:

\[ d = \sqrt[3]{d^3 - d_1^3} \]

Where:
\( d_0 = \) the outside diameter of the rudderstock tube or pipe
\( d_1 = \) the inside diameter of the rudderstock tube or pipe.

You have to solve this by trial and error—pick a pipe or tube size, plug the values of \( d_0 \) and \( d_1 \) into the equation, and see if it calculates \( d \) that is equal to or greater than the \( d \) calculated in the combined-load equation.

The equations up to this point also assume that you are designing a metal, rather than a composite, rudder stock. The allowable strength, \( \sigma_c \), is assumed to be the same in all directions (isotropic); but composite stocks are not isotropic—the strength and stiffness are different in all directions, and they vary from design to design and builder to builder. A designer can use the ABS Guide for composite stock engineering but must justify his or her calculations with background data collected from other composite engineering sources.

These rudderstock diameters are calculated at the neck bearing and the upper part of the rudder. Allowances are made for reduced diameters at the
carrier bearing, which is the bearing near the top of the rudderstock. For a spade rudder, which does not have any lower bearing, the rudderstock may taper somewhat as it descends into the rudder. If the rudder has a lower bearing, or pintle, such as at the lower end of a skeg, the Guide includes rules for the stock diameter at the pintle. The Guide also gives rules for sizing the bearings themselves, so you can determine their type and height consistent with allowable loads pressing against the inside surfaces of the bearings.

The Guide has very little to say about the skin of the rudder blade. It appears you can design whatever you think makes sense; so, prudence plays a big role here. In fact, most rudder failures are in the stock, and very few involve the rudder skin. You are probably on safe ground if you emulate proven designs and follow established boatbuilding practices.

While all of this may look complicated, it gets worse. If the rudder is mounted on a skeg, the ABS Guide assumes, rightly so, that the skeg

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**Figure 12**

Rudders are relatively small structures compared to keels, and experience a more complex loading of combined bending and torsion. As a result, their engineering is more difficult than that for keels. If the rudder is mounted on a skeg, the engineering is especially challenging because the skeg carries some of the load and must be engineered accordingly.
Figure 13—Corroboree has a traditional fiberglass rudder filed with foam and built over a stainless steel pipe rudderstock. The skeg is solid wood with stainless steel straps rabbeted into the sides.

Figure 14—This cross-section of Corroboree’s rudder shows how the stock fits into the blade and the stainless steel strengthens the skeg.

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you have to work the equations by trial and error, see if your chosen inputs work out reasonably, and if not, start all over again. Maybe this is why we no longer see many rudder skegs in sailing yacht design. Just be aware that the engineering is not simple, and it requires a good bit of study to understand.

That said, it’s helpful to look at some design examples. **Corroboree’s** rudder blade is fairly traditional construction—fiberglass skins filled with foam around a stainless steel pipe stock (Figures 13 and 14). The larger-diameter upper stock fits over, and is pinned and welded to, a smaller-diameter lower stock that fits into a pintle at the bottom of the skeg. Stainless steel flatbars are welded to the stock in a narrow V shape to hold on the fiberglass blade.

The skeg is solid wood laminations glued together with epoxy. The grains of the different laminations extend vertically up into the hull’s keel timber and change their orientation to go parallel to the keel, so that the grain is always following the load. Since I was concerned about the stiffness of a totally wood skeg, in this design I included two stainless steel straps rabbetted into the skeg sides to provide extra strength and stiffness. These 50mm x 3mm (2” x ¾”) flatbars are locked into and bolted through the hull/keel structure and also fastened through the bronze shoe at the bottom. The finished rudder is exceedingly strong.

**Bagatelle’s** rudder (Figures 15–17) is all carbon fiber. The rudderstock was built by Composite Engineering (Concord, Massachusetts), and the owner built the blade over the stock. I followed the ABS Guide to determine the combined moment and torque all along the rudderstock. I also calculated a reasonable strength and stiffness for the carbon fiber laminate, calculated the required wall thicknesses for the shape I proposed, and worked out the carbon fiber laminate schedule. That left calculating the section shape properties and the rudder blade wall thickness so everything would match up (Figures 16 and 17). The end result is a well-built rudder that
**Figure 15**—The rudder on Bagatelle is a traditional form but is all carbon fiber, including the rudder stock. **Figure 16**—The cross-sections of Bagatelle’s rudder stock were determined at various heights, and the carbon fiber unidirectional strips and fabrics were laid out to give the correct thickness at the desired shape, as determined by the engineering.
Figure 17

Steers the boat like a sports car.

Project Amazon's rudders were engineered in a similar way, except that they were rudders-in-a-drum and, as such, did not have rudderstocks—at least in the traditional sense (Figures 18 and 19). The construction was a hollow carbon fiber skin for a 15% airfoil shape, with an all-carbon fiber central spar. The rudders had five locking-pin holes in them so they could be fixed at different depths 300mm (12") apart. The carbon fiber central spars were a little easier to engineer because their cross-sectional shapes could be made perfectly rectangular, rather than trapezoidally shaped, as on Bagatelle's rudderstock.

Each rudder was offset to one side, so that at heel, one of them stuck more or less straight down into the water and was out of the way of the wash from the keel. The high rudder could be totally lifted out of the water to eliminate drag. These rudders were huge: 3.695m (12.1') tall, and 600mm (23.6") on the chord, yet they weighed only about 140 lbs (63.5 kg). At least, that's what they were supposed to weigh. The shipyard subcontracted their construction to a shop that did not follow my construction plans, and the rudders initially came out at over
**Figure 18**—Project Amazon's two rudders are hollow, built of carbon fiber, over 12' (3.7m) tall, and weigh about 140 lbs (63.5 kg) each. The author terms them "rudders in a drum," and, as such, they have no conventional rudderstocks.

**Figure 19**—This cross-section through Project Amazon's hull shows how the rudder and drum are oriented.

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The author next to one of the rudders on Project Amazon. Note the locking pin through the rudder and the tiller arms at the top of the steering drum. Two hydraulic steering rams—one main, one backup—control the rudders. If those fail for any reason, wire cables are immediately handy and permanently attached so that they can be quickly engaged onto the steering wheel.

400 lbs (181 kg) apiece. After much discussion by phone and fax to the builder in South Africa, the rudders were finally split open, refabricated, and put back together to remove most of the excess weight.

One advantage of the construction method I specified is that if a rudder hits something in the water, it would shear clean off. The drums are watertight, so no water enters the boat. Project Amazon was sold to a new owner, and on her delivery up to New England for a refit, she actually did hit something that sheared off one of the rudders. It was rebuilt, this time following the construction plans closely, and the weight came out as expected—about 140 lbs.

The ABS Guide sets good standards for designing traditional keel and rudder structures, closely following first principles of engineering. For non-traditional designs such as lifting keels and rudders, the basic principles of loading are the same, and it’s possible to figure out the structures by similar principles so that they work properly and are relatively easy to build.

Designing keels and rudders is both an art and a science. A successful structure depends on the designer’s ability to apply basic engineering principles—sometimes in ingenious ways.

About the Author: After 24 years in Newport, Rhode Island, Eric Sponberg, naval architect and professional engineer, moved home and business to St. Augustine, Florida, in 2003. He can be reached at ewsonberg@se.rr.com, or 904-460-9494.

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