Engineering the Sailboat—Safety in Numbers

By Eric W. Sponberg, Naval Architect

Author's note: *This article was first published in SAIL magazine in June, 1985. Since then, a few improvements or changes in yacht design and engineering have occurred. Therefore, I have modified the article where necessary to bring it up to date. EWS.*

How do you design a rig strong enough to stay up in the worst weather, but not so oversized that it creates excess windage and diminishes stability? How is a hull engineered to hold together in adverse conditions but not built so heavily that it sails like a bathtub? Where is the line between safety and performance?

Engineering a sailboat can take several forms. A naval architect could begin by analyzing or estimating the loads on the structure and then calculating as closely as practical the stresses (pounds per square inch of cross-sectional area) and deflections (amount of bend, elongation, compression, or twist) in each of the boat's parts. Or, the naval architect may extrapolate from the results of past practices. Every part is then either drawn or specified from equipment catalogues so that the expected stresses and deflections are well below the breaking levels of the materials from which the parts are made. Let's look at this process more closely.

Analyzing the loads. The wind and the sea are in continuous motion, and the loads they create on a sailboat are complex and unsteady. The naval architect, therefore, must make some simplifying assumptions about the loads so that they can be comprehended and studied easily. To compensate for the simplifications, and for fatigue that degrades structures over time but cannot be positively quantified, safety factors are included at certain stages in the engineering to insure that the structure, in reality, will stay in one piece.

Safety factors usually vary between 1.5 and 4.0 times the estimated maximum load, but on occasion can be 10.0 or more, depending on the structure. On a racing sailboat, which will receive continuous care and where excess weight and windage in the rig are undesirable, the smaller safety factors are used. On an offshore cruising boat, where safety and durability are of prime importance, the larger safety factors are in order.

In general, analysis of loads is not a cut-and-dried process. Because of this, the line between safety and performance is a crooked one.

Stress, deflections, and design. Determining shapes and sizes of hull structure and fabricated parts can be handled by three different means:

First engineering principles—that is, using engineering equations and methods of analysis in their most fundamental forms;

Rulebooks, most notably the American Bureau of *Shipping's Guide for Building and Classing Offshore Racing Yachts* and Lloyd's Register of Shipping *Rules and Regulations for the*

Classification of Yachts and Small Craft. These books contain equations, methods of analysis, and construction standards that are based on first engineering principles as well as shipbuilding experience accumulated over 150 years. Other rule books include the *Standards and Recommended Practices for Small Craft* by the American Boat and Yacht Council (ABYC) and various Coast Guard regulations;

(Readers should note that in 1997, ABS decided to no longer administer their own structural Guides and Rules for any yacht under 79' Loa because of the impending implementation of the new ISO structural standards that are being adopted worldwide. The ISO standards are still being written. The ABS sailboat Guide, nevertheless, provides some engineering guidance for designing sailboat structures. EWS)

Personal experience, using one's past successes and failures to improve on the design at hand, or using estimates based on scientifically sound rules of thumb. Frequently, all three methods of engineering are tried on one particular problem with the most reasonable one becoming the basis for design.

Now that we understand the general engineering process, the naval architect arms himself with a fresh supply of pencils and calculator batteries and goes to work. *(We use computers a lot now, too, but the calculator is still an essential tool. EWS)*

Rig. The engineering of a sailboat rig generally occurs early in the yacht design because this is where the loads first begin to act. We want to look at the boat when it is working the hardest, which usually occurs on a close reach with all the sails up just before they need to be reefed, in about a 15- to 20-knot wind.

Assume here that the wind pressure is acting at 1 pound per square foot, evenly distributed over both the main and jib. The load from the main is spread uniformly along the full height of the mast, and the load from the jib acts on the mast were the head stay is attached (Fig. 1). Once this assumed loading is drawn, the reactions within the shrouds and their associated components in the rig can be calculated, and the shrouds, stays, turnbuckles, mast, boom, chain plates, and other gear can be specified from equipment catalogues or else designed directly.

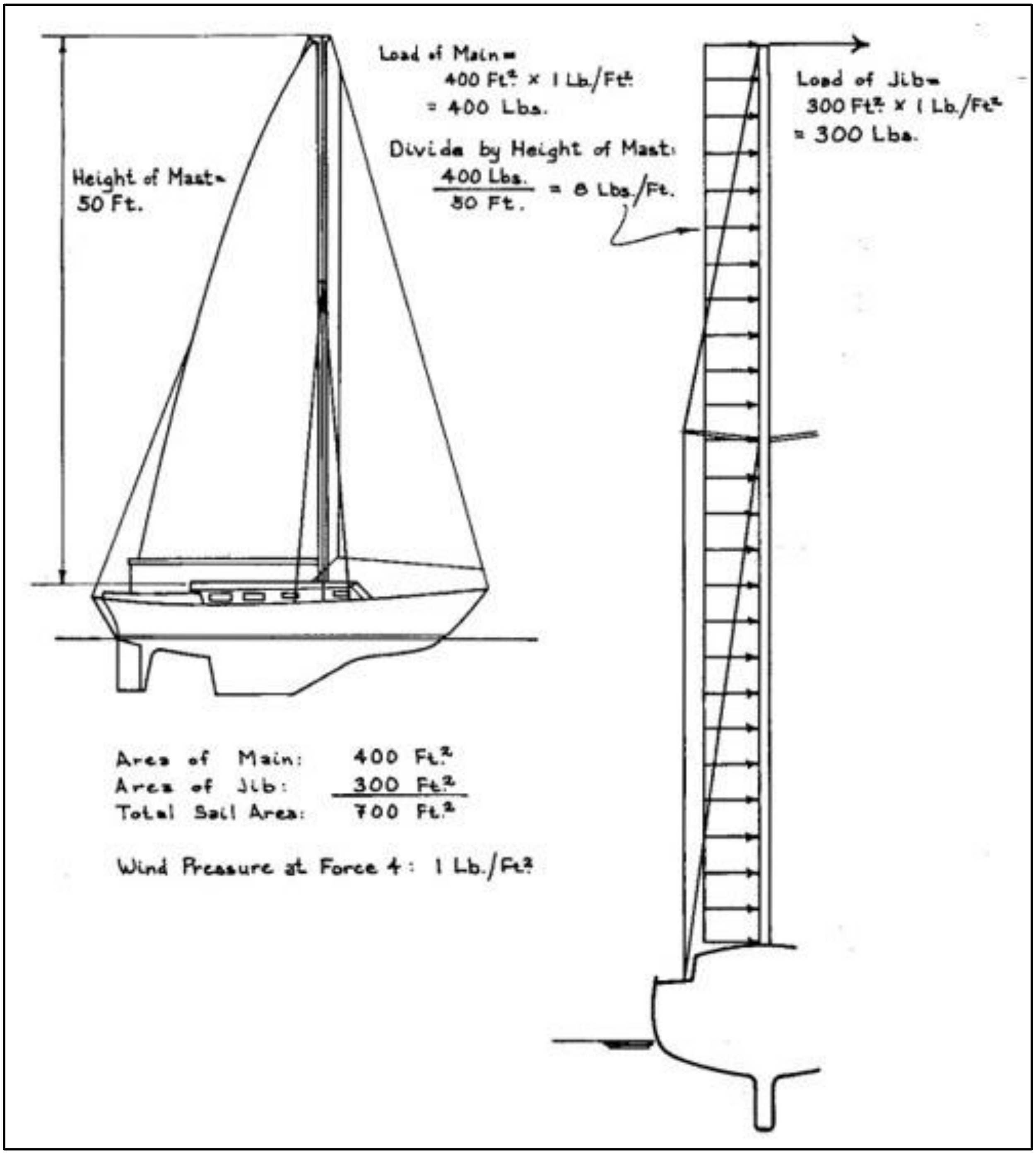

Fig. 1. *The basic loading on a mast.*

We can check our calculations by adding together all the tensions in the shrouds on one side of the boat and comparing the result to the compression in the mast. They should be equal and opposite, as this is the case in reality (Fig 2). Also, since these reactions are separated by the distance between the chain plates and the mast step, they form a couple, or moment, which, in fact, is the heeling moment of the boat in the assumed wind condition. This heeling moment should be equal and opposite to the boat's righting moment, which can be calculated from the lines plan and weight estimate or from an inclining experiment. In fact, some designers take rig loads form the boat's righting moment, using 30 degrees of heel as the condition of greatest loading. *(With computers now, we can calculate the actual maximum righting moment of the boat, which typically occurs between 45º and 60º of heel. EWS)*

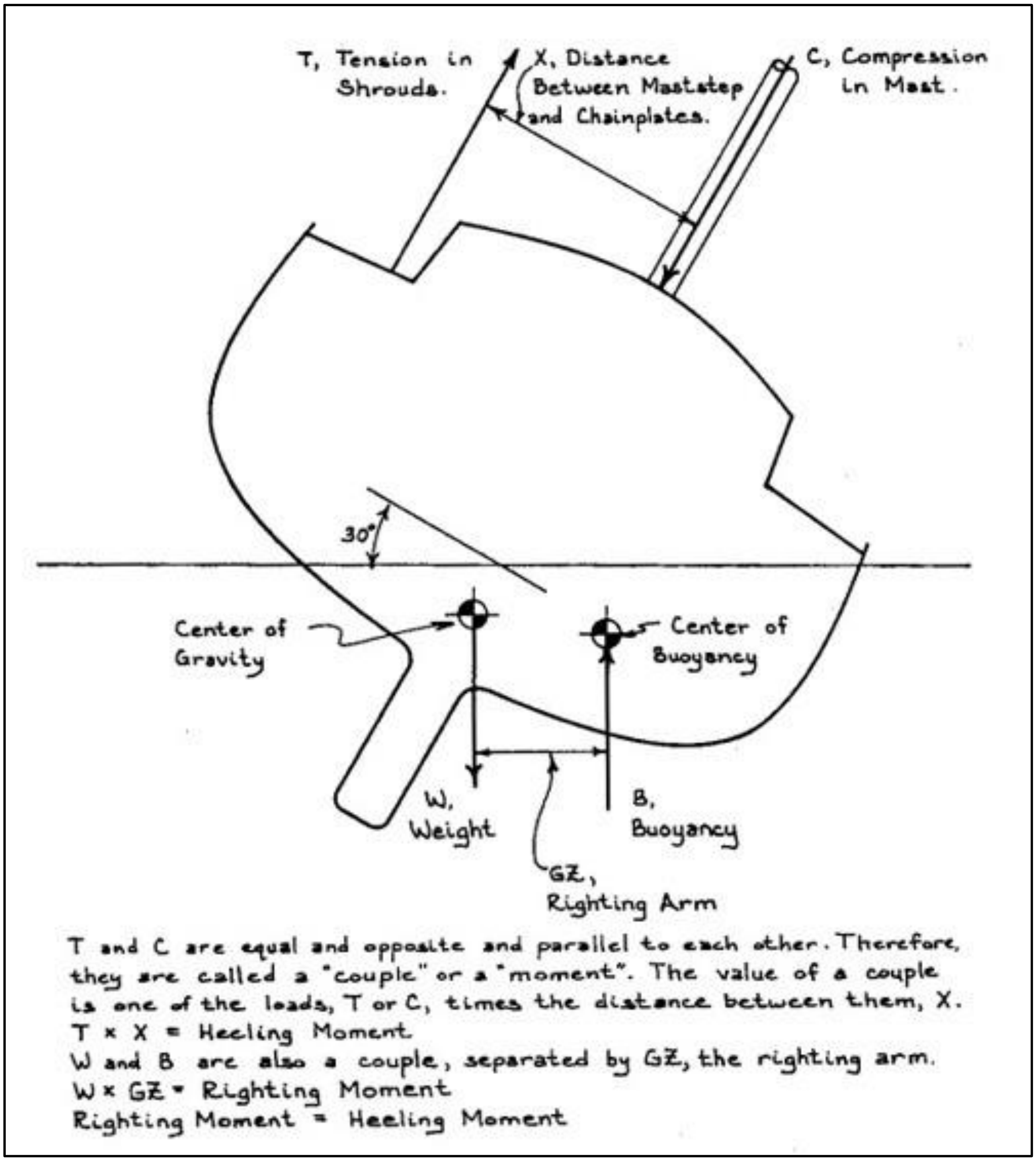

Fig. 2. *Mast compression and shroud tension form a couple that is equal to the couple created between the boat's weight and buoyancy. In fact, to engineer a sailboat rig, you can ignore the heeling moment created by the loading by the wind on the sails and start with the boat's righting moment. By definition, righting moment and heeling moment are equal and opposite.*

It has been possible to measure rigging loads under actual sailing conditions to determine the accuracy of the above design procedure. But, because of the cost and complexity required to obtain meaningful data, we have never been able to take measurements in very adverse, stormy conditions to determine the absolute maximum rigging loads. In addition, we have never been able to measure long-term loading frequency for judging fatigue life of various rig components. Therefore, we cannot say, based on any test or measurement, just how long a component will last before it breaks. In these areas, we must rely on past experience for engineering guidance. *(New load cell equipment is available now to continuously monitor rigging loads and store the data on a notebook computer. EWS)*

We can see that the naval architect has traced the loads on the rig down through its various parts and into the hull. We want to combine these loads on the hull and proceed with the hull engineering. The naval architect pulls out some clean paper and continues.

Hull. The hull and deck are considered to be a box girder in which the skin is the main structural member, stiffened and strengthened locally where necessary. This has been the general approach to shipbuilding for over a hundred years, but for a time in the early to mid-1970s, some yacht designers and naval architects took a different approach. An aluminum and stainless steel tube frame was designed as the main structural member and bonded into a very lightweight composite hull. The tube frame was to withstand all the rigging and hull bending loads, while the hull and deck skins were only to keep the water out. The goal was to make the boat lighter than would otherwise be possible, but still keep it stiff and strong.

The efforts were not entirely successful. The tube frame was difficult to engineer and the boat not necessarily lighter once it was bonded into the hull; the frames were unsightly and difficult for the crew to maneuver around; and the hull and deck skins were so thin that they punctured easily when hit by buoys, boats, docks, and floating debris. The practice finally lost general favor, and designers and naval architects returned to the reasoning that the hull has to be there anyway, so make it do all the work.

The many different loads on a hull can be combined into four major categories and analyzed accordingly:

> **Primary load pattern:** tensions from the standing and running rigging and compression from the mast; bending of the hull because of large waves;
>
> **Secondary load pattern:** hydrostatic pressure from the sea;
>
> **Areas of local loading:** weight of the ballast keel; forces on the rudder; forces on miscellaneous rigging and deck hardware;
>
> **Indeterminate loads:** impact from waves and hard objects.

Primary load pattern. The boat is imagined sailing in smooth water, but the standing rigging wires are all assumed to be tensioned to their breaking strengths, pulling up on the ends and sides of the boat and causing the mast to push down in the fiddle (Fig. 3). It is easy to see how the boat will tend to fold upwards.

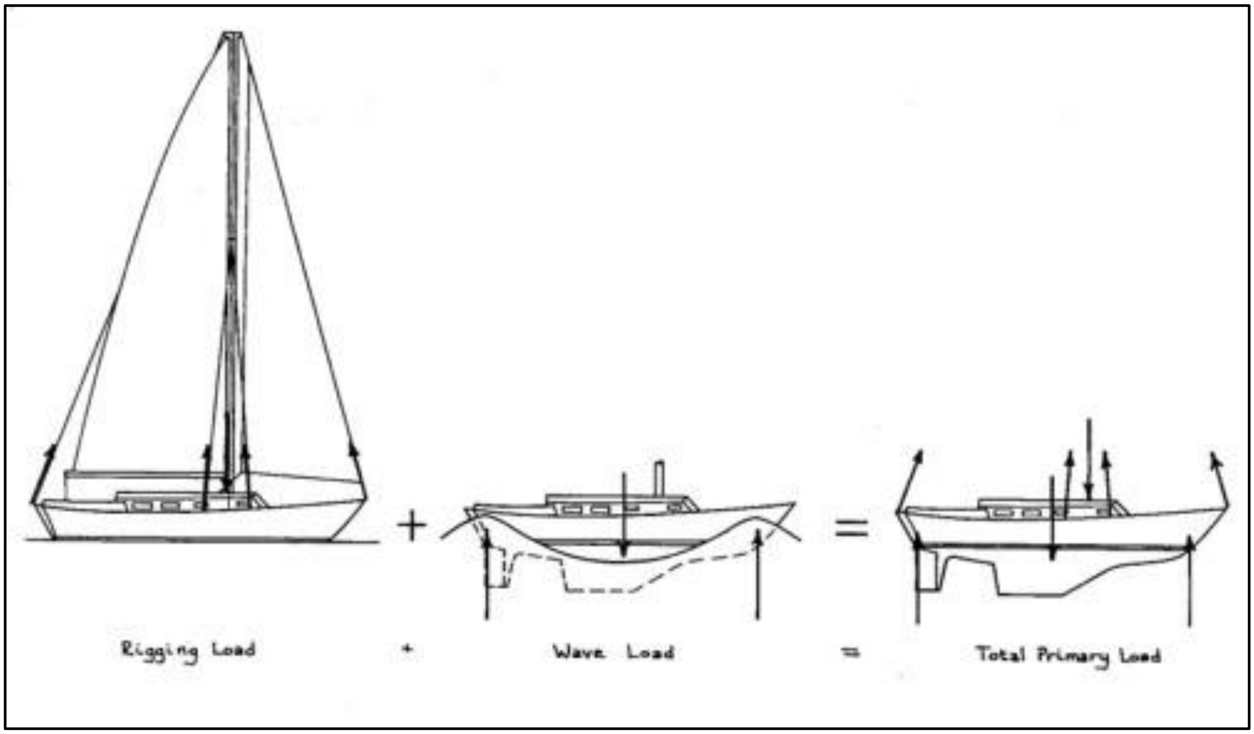

Fig. 3. *Primary loading on the hull of the combined rigging and wave loads*

Many naval architects consider this loading alone to be the worst condition on a sailboat hull, but some naval architects add something more when designing very large sailing yachts. Classical naval architecture has long practiced that the worst loading for a ship is to be fully laden and sitting in a wave trough that is as long as the ship itself. So, rather than sailing in smooth water, the sailboat is imagined riding between two waves with the crests at the bow and stern and the trough in the middle. While the water pushes up on the ends of the hull, most of the boat's weight pushes down in the middle, adding to the bending of the hull caused by the rigging.

Other than the idea that the rigging wires act at full strength all at once, this image of a hard-driving sailboat in large waves is a very real situation. The loads caused by the waves are considerable, accounting for 25 percent to 30 percent of the total longitudinal bending load on a boat.

Under this load arrangement, the boat bends with the deck in compression, the bottom of the hull in tension, and the sides of the hull in shear. The magnitude of the forces within the deck and hull can be calculated and the required laminate or plating thick nesses determined according to the strength of the materials used and with appropriate safety factors.

Secondary load pattern. As a sailboat moves through large waves, whole sections of the hull can get buried under water (Fig. 4). The depth, or head, of water from the top of the wave next to the hull to any submerged point on the hull imparts a hydrostatic pressure at that point. (The wave is assumed to be stopped in place, or static, hence the term *hydrostatic*.)

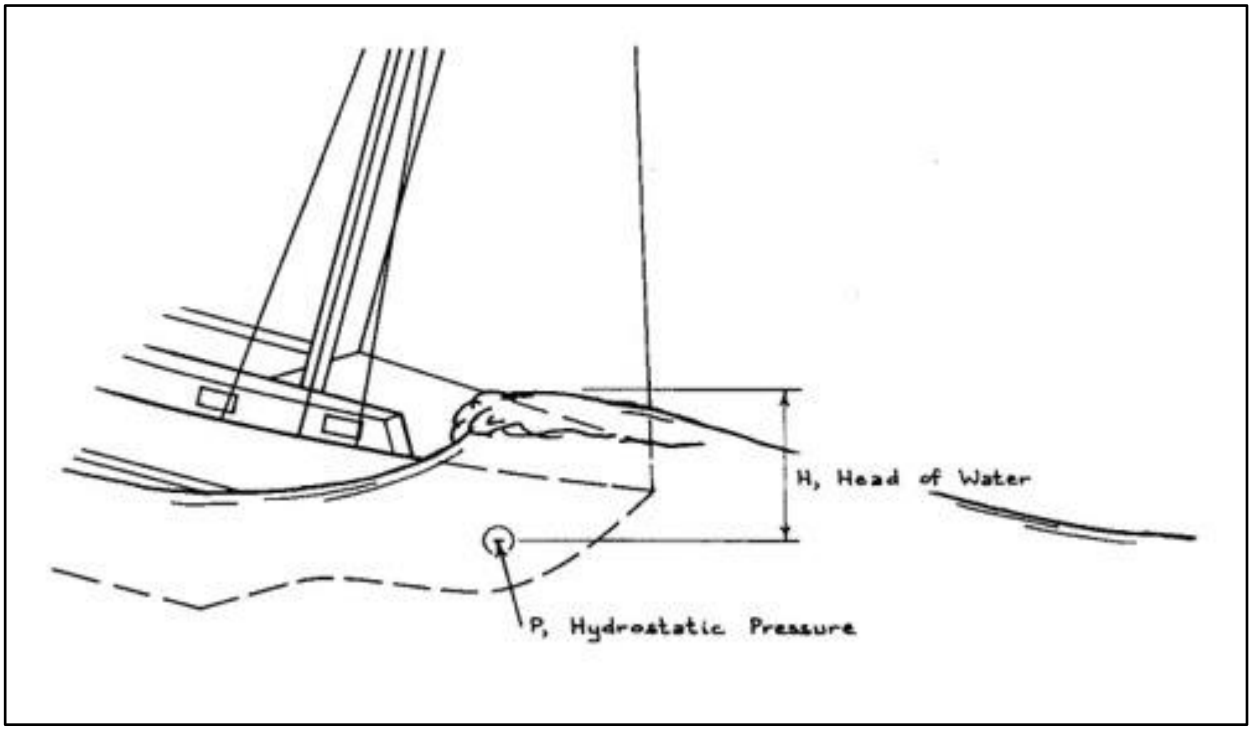

Fig. 4. *Hydrostatic wave loads on the hull.*

Sections of the hull and deck can be viewed as being comprised of panels, each panel bordered by some interior structure, such as a bulkhead, deck edge, stringer, or frame. Beginning with the panel thickness derived from the primary load pattern and an assumed head of water pressing against it, the panel is checked for strength and stiffness. If necessary, the panel thickness is increased, or stiffeners, partial bulkheads, or frames are added to help the panel withstand the load.

What is the correct head of water to assume? After all, waves come in all different sizes. There are various industry standards that try to establish something closed to reality. The most commonly used are contained in the ABS and Lloyd's rules which have tables of water heads based on the size of the boat and the location of the panel on the hull and deck. Larger boats experience greater water pressures than smaller boats, and the forward sections of a boat greater pressures than the after sections.

Interestingly, this secondary load pattern for hydrostatic pressure is the only method of hull and deck loading considered by ABS and Lloyd's. So, if a boat is "built to the rules" alone but equipped with a very powerful rig, there is a likelihood the hull could be overstressed by the rigging loads and suffer some serious damage. Admittedly, such a boat is probably quite rare; nevertheless, ABS and Lloyd's scantlings are limited.

Areas of local reinforcing. We find that our well-worn and much annotated copies of the rules offer engineering guidance in two other areas: keel bolts and their surrounding hull structure, and rudder stocks.

For a ballast keel, the worst loading that can be imagined is a 90º knockdown. The bending moment on the keel bolts in this likely situation is shown in Figure 5. Generally, keel bolts are not located on the keel centerline because they would bend too easily. A stronger arrangement is to locate them as far off the centerline as possible. Dividing the keel bending moment by the distance between the two rows of bolts gives the total load in all the bolts. The number and size of bolts can then be selected accordingly. Usually, a significant safety factor is added to counteract corrosion or flaws. The boat's bottom structure is stiffened with heavy transverse webs to spread the keel bolt loads over the bottom hull surface.

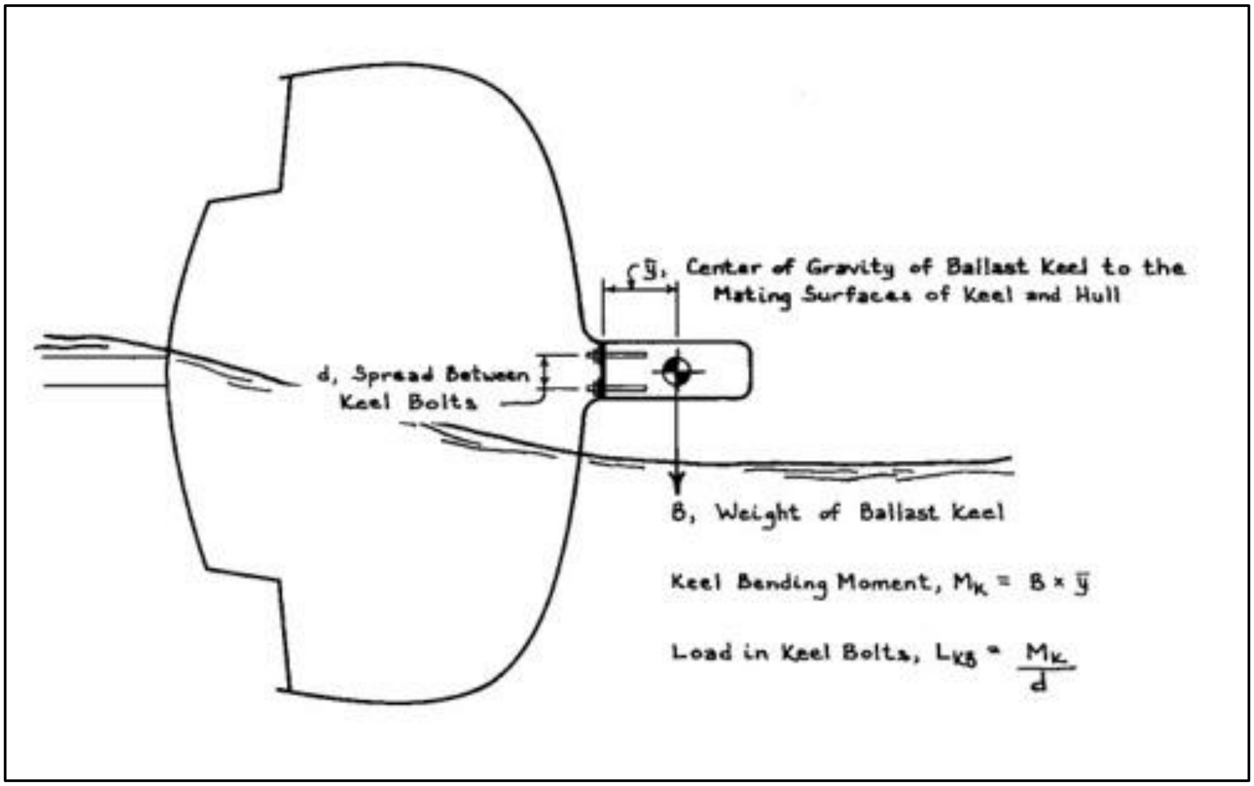

Fig. 5. *Basic keel loading, worst-case scenario.*

The rudder stock diameter can be calculated directly from formulas in ABS and Lloyd's, both of which consider that the stock undergoes simultaneous bending and torsion (Fig. 6). If a skeg is used to help support the rudder, it too must be engineered for the bending load. Lloyd's formula is probably a bit nearer reality because it considers vessel speed. The higher the speed, the bigger the rudder stock.

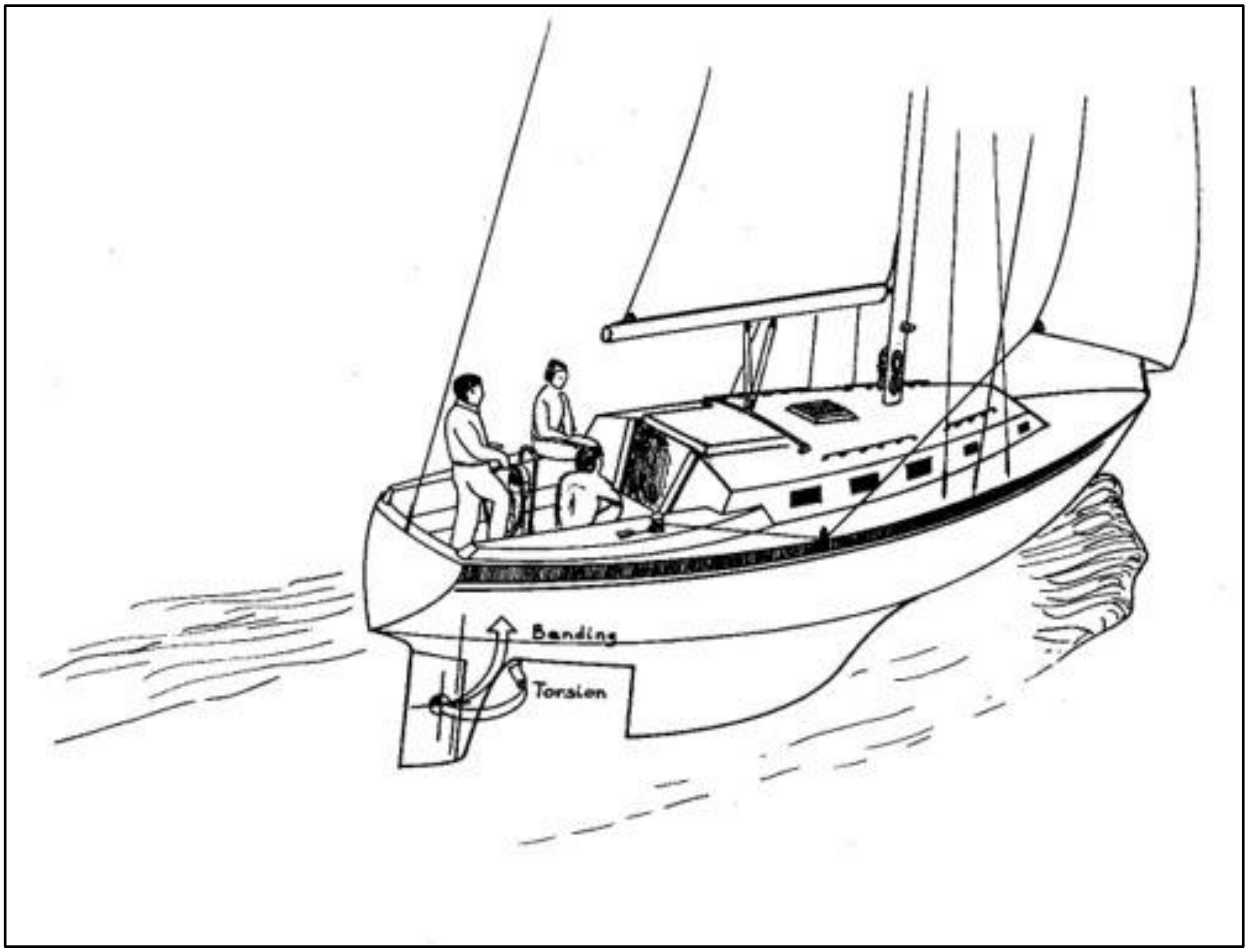

Fig. 6. *The bending and torsion loads on a rudder.*

ABS, on the other hand, bases its rudder load only on the rudder area and the waterline length of the boat, thereby assuming that the boat will never travel faster than hull speed. This is not necessarily true for some light-displacement racing boats that can plane or surf on occasion. On such boats, it may be necessary to engineer the rudder stock and the whole steering system from first engineering principles. If that is the case, other factors to include besides rudder area and boat speed are the rudder lift and drag coefficients and angle of attack.

How the rudder stock is fixed within the rudder blade and supported inside the hull also must be engineered. These details are not covered by ABS or Lloyd's, so the method of construction is left to the naval architect.

After keels and rudders, standing and running rigging attachments to the hull and deck are the remaining local areas that must be engineered. The loads are simply the breaking strengths of the wires or lines.

To engineer a chain plate (Fig. 7), the naval architect must check the shear strength of the turnbuckle clevis pins, the bearing stress in the upper half of the clevis pin hole, the tension stress in the material either side of the pin hole, the shear stress in the material above the pin hole, and the number and size of the mounting bolts required. Interestingly, the length of the chain plate is not determined by the stress in the metal. Rather it is the shear stress in the bulkhead or bracket where the chain plate is attached that is the critical factor. The longer the chain plate, the lower the shear stresses in the bulkhead or bracket.

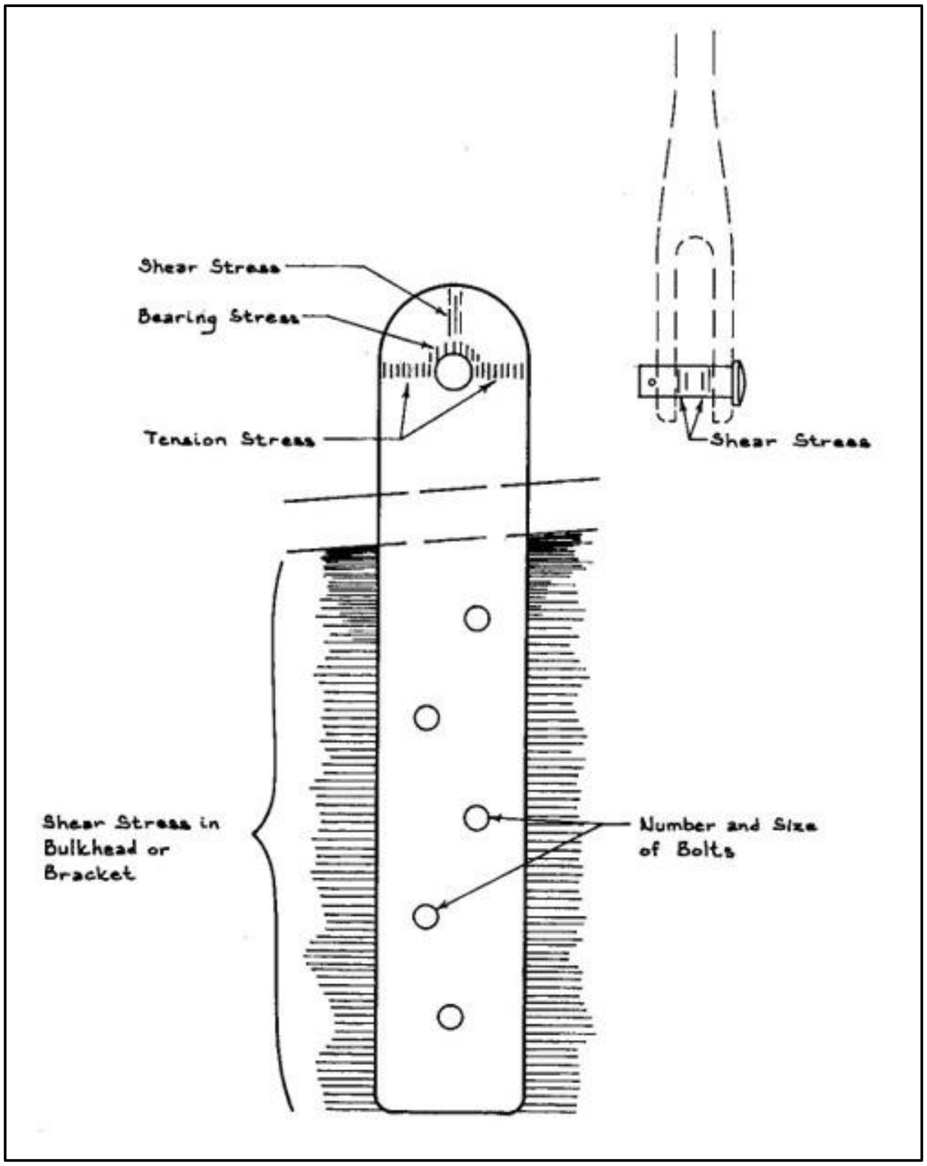

Fig. 7. *These are the areas to engineer in a chainplate.*

For sheet winches, presumably the manufacturer has engineered the number and size of mounting bolts, but the naval architect may want to check the immediate boat structure for shear and tear-out strength. This also applies to any highly loaded turning blocks, tracks, travelers, and cleats.

Indeterminate loads. There is one area of sailboat engineering that is unaccounted for, but about which we cannot accurately anticipate: impacts. How do you design a boat to withstand hitting a whale or vice-versa? How big is a rogue wave, what is the force behind it, and where will it hit? These questions are nearly impossible to answer, and if we cannot assess what the loads will be, how can we scientifically engineer a structure strong enough to withstand them? We can't. We must apply safety factors proven over years of practice—as determined by ABS or Lloyd's or by our own experiences as designers and sailors.

Technology is enabling us to learn ever more about sailboat loads. As the accuracy of our assumptions and calculations increases, the need for large safety factors and excess weight in the structure decreases. Thus, as engineering becomes more and more refined, so the line between safety and performance runs a little straighter.

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