STRUCTURAL ENGINEERING

You may think that engineering is a scientific, easily quantifiable discipline. But with most engineering — and with yachts in particular — we learn by our past failures. Yes, there are principles by which you can interpolate. It is possible to say that if a certain structure works on a given vessel, we can scale the loads with smaller and larger yachts. However, if you venture far from the norm, you will either over- or under-build. To get it exactly right, you must first fail, then beef up. Still, some basic principles are universal and worth knowing.

HOW LOAD IS DEVELOPED

Sailing-yacht engineering is tricky with so many different types of load to be dealt with over time.

Righting Moment

In the end, however, the load factors are almost always in proportion to righting moment, or the stability of your yacht. As righting moment goes up, structural loads usually follow in tandem. This applies to rigs, keels, hardware, standing and running rigging, and to the structure to which all of this is attached.

Size

In many — but not all — areas, size plays a part. Size affects hull loads to some degree in large waves and also how loads are developed when your boat is hauled or aground.

On the other hand, it is possible to have a long, light boat with a more lightly loaded structure than on a shorter, heavier design.

Size usually only affects hull component loads on a direct basis.

Displacement

Other loads are based on the displacement (weight) of the boat. This is related to stability and to the speed-related forces the hull will encounter. You can have a heavy structure which does not see a lot of load and a light structure which is heavily loaded — or just the opposite. What is important is how the displacement interacts with speed and motion.

Speed

Speed, or forward velocity, is a powerful load-producing characteristic. Impact loads increase with the square of your speed. Therefore, if you hit something going 8 knots and generate a certain amount of force, you'll generate 1.56 as much impact force at 10 knots (8 squared is 64; 10 squared is 100; 100/64=1.56).

This is why high-speed vessels need such strong structures in their bows for wave impact.

Motion

Motion also contributes to load, as well as to material fatigue over time. The more motion there is in a given seaway, the more materials will fatigue. This reduces life span. Knowing that this is going to occur, factors of safety have to be increased. High polar moments (lots of weight aloft) in rigs and in the ends of the boat, combined with long overhangs, exacerbate the problem of motion.

G-Loading

G-loading occurs primarily while slamming into head seas, when hitting objects with the keel, and when being rolled or dropped off waves. It is very difficult to predict.

For a given set of circumstances, it is directly proportional to weight, as well as proportional to the square of boat speed.

G-loads are something designers learn about over time, as they are related to fatigue. What seems to be enough structure today may be a bit on the light side after several thousands of miles. A historical database on what works and what doesn't can come in handy.

SCALE FACTORS

If you've sailed on or designed a certain size of boat, and if you know how the loads worked out (for better or worse), it is relatively simple to interpolate these to other vessels by scaling.

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Dimensional Scaling

If you take a given design and blow it up, say, ten percent, all the dimensions increase — length, beam, and depth all go up in proportion. In this case, displacement typically increases with the cube of the dimensional change — i.e., by a factor of 1.33.

Sail area and surface area usually go up with the square of the increase (1.21).

Stability increases as a squared function, and polar moments go up with the fourth power (1.46).

Since sail-handling loads are typically related to stability, these increase with the square of the size increase. This affects deck hardware, running and standing rigging, spars, and how hard you have to work to trim sail.

Length Scaling

If all you do is increase the length of the vessel, keeping all other factors the same, then load, weights, and surface areas go up in direct proportion. A ten percent increase in just length only means a ten percent increase in all these other factors.

Displacement

How displacement actually scales on a cruising yacht is a little more complex than what we've just discussed. Basic structure is a function of the size-related functions. Payload, however, is typically an absolute number determined by the owner.

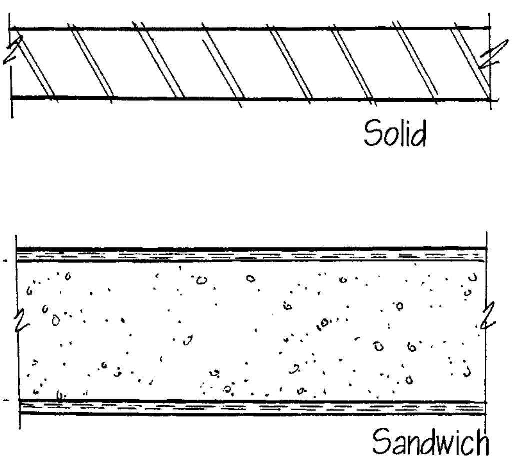
How much payload and where it is located affect stability (and, therefore, required structure).

If you simply increase payload in scale with size, then it goes up, as do the other elements in displacement (i.e.,with the cube of the size increase, if doing a three-dimensional scaling, and in proportion to the increase, if you are just scaling length).

However, what you typically find on shorthanded cruising boats is that the payload as a percentage of total displacement drops as boat size increases.

A couple setting out on a long cruise will have a certain amount of dinghy gear, safety equipment, electronics, pumps, fridge equipment, scuba, etc. — regardless of vessel size. Quantities tend to increase as boats get larger, but not nearly as fast as the load-carrying ability of the hull.

At the same time, some items do go up in scale, such as ground tackle or running rigging and sails.



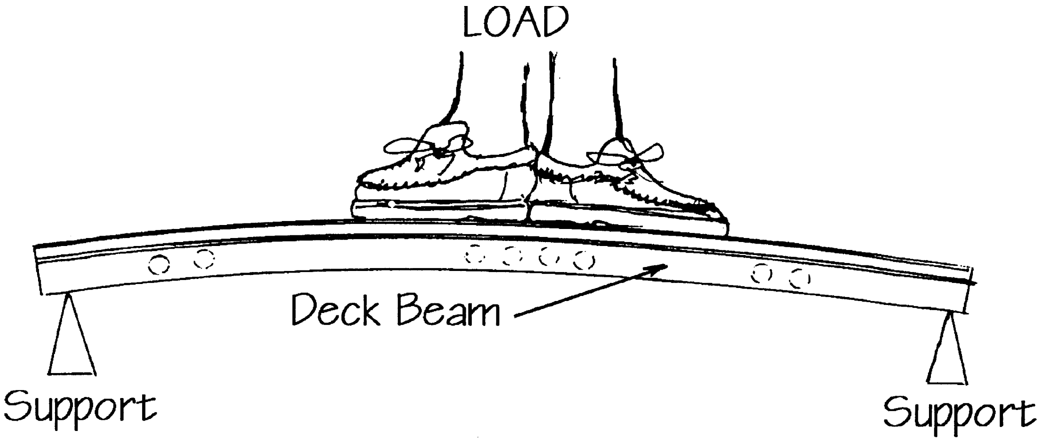
The stiffness of a solid section goes up with the cube of the increase in thickness. A half inch (12.6mm) of material would be almost eight times as stiff as one which is a quarter of an inch (6.3mm) thick.

A sandwich structure increases stiffness with the square of the change in thickness. Using the same comparison as above, except in a sandwich structure, the stiffness would increase by four times.

STRUCTURE

It's quite simple to understand the basic principles of how structures work. Even though you may never engineer anything on your own boat, understanding the basics will put you in a much better position to judge how different details have been executed. If you need to do some jury-rigging, your understanding will prove invaluable.

Almost all hull and deck engineering issues come down to stiffness of area in question. First, you have a skin of the hull, deck, or house. The member in question must be stiff enough to transfer the small load it carries to some form of supporting structure — perhaps a beam or structural floor. That supporting structure in turn picks up a percentage of all of the areas in which it has contact, called the tributary area. As this load is collected, it is transferred to some other point — perhaps the deck edge.



Span is measured as the distance between two support points, with the load applied between the supports either evenly or in concentrated form. The stress on the structure increases with the square of the span, so anything you can do to reduce the span increases the structural efficiency (and reduces the loads on the structure).

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Stiffness

Stiffness is an easy concept to understand. It is a function of the material being employed (or the modulus of the material, in engineering terms), and the thickness of the material (expressed as the moment of inertia).

Once you know the modulus of the material being used, you then look at the thickness. Stiffness increases with the cube of the thickness of a given solid structure and with the square of the distance between skins in a sandwich structure.

Span

Each structural element, whether a chunk of hull skin or a deck beam, has a span defined by the distance between the two supporting points. The load on the structural member increases with the square of the span, so anything you can do to reduce span pays big dividends in structural weight.

However, with stiffness going up by a cube factor with thickness, it sometimes is more efficient to simply increase beam size a bit (which nets an increase in load-carrying ability to the third power) and take the increased span penalty (just a second power function).

Tributary Areas

A tricky part of the engineering question is figuring out just how much load is going onto a given structural member. Typically, a series of different structural elements act together. If some of these are stiffer than others, they'll carry more of the load. The nearby members will not see any load until stronger member deflects enough for them to start picking up some tributary area.

This is a complex way of saying you need to look at all structural elements as a package — not just one by one.

The direction of load also needs to be considered. Loads that come in at an angle have to be treated differently than loads encountered straight on.

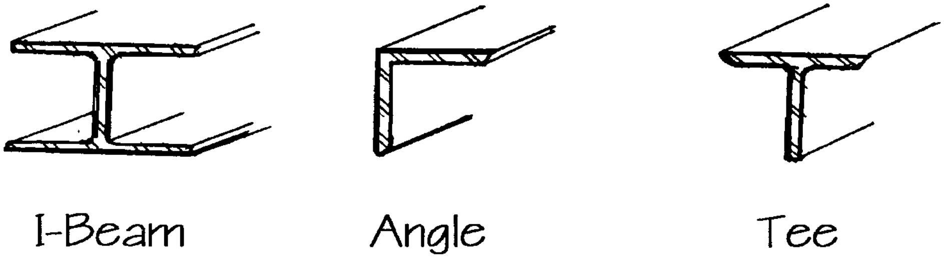
Any bending (moment) to the load must also be accounted for. Otherwise, the bending load tends to rotate or capsize the structural member.

Deflection

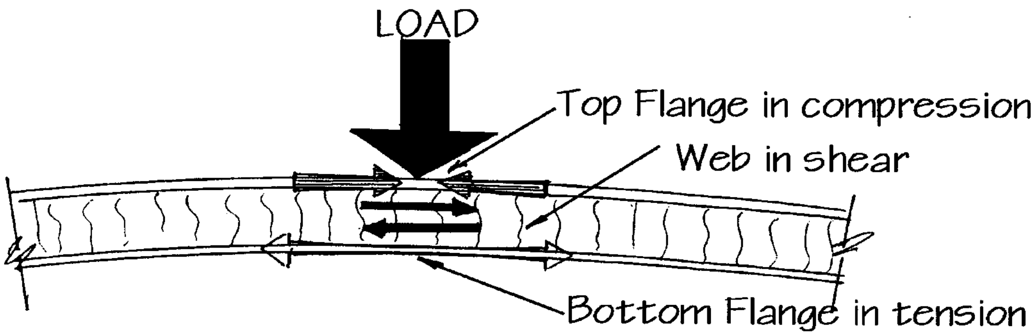
When you design a beam to carry a load, assume it will deflect a certain amount. The amount of deflection that is tolerable directly affects how much stiffness (and therefore weight) a structure will require.

Deflection is normally stated in terms of allowable deflection divided by the span. You might allow the mainsheet traveler to deflect up 1/4 inch (6 mm) in a 6 1/2-foot (2m) span.

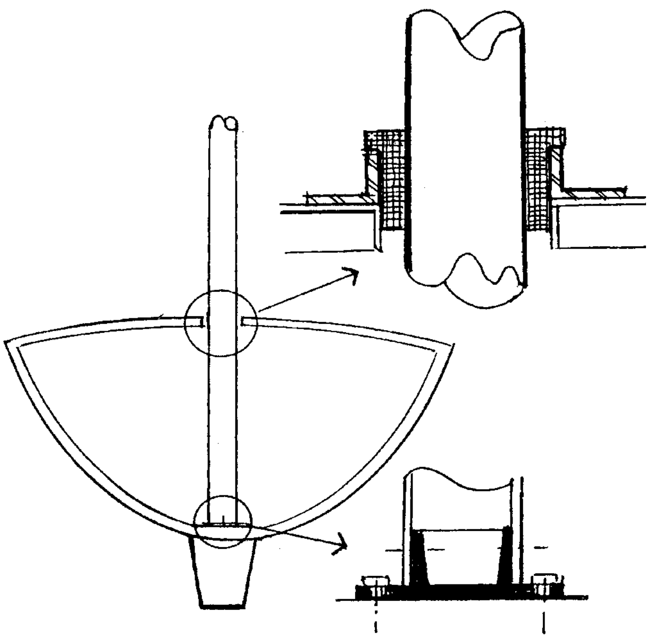
In most cases a certain amount of deflection is acceptable. However, the deflection causes flexing — some materials and structural connections are better than others.



Beams come in all sorts of shapes and sizes. The most efficient is a balanced or "I" shape (left). However, these are not always practical to work with in a boat. Angles are a form of beam, as are T's.



When a beam is loaded the top flange goes into compression while the bottom sees a tension load. The connection between the top and bottom, called the shear web, transfers the load between the two flanges. In fiberglass sandwich structures different materials are sometimes used in the top and bottom laminates to optimize them for the intended load. While the flanges are highly loaded the center or shear web does not carry much load at all. This is why sandwich structures work so well.



The keel-stepped mast is a good example of a bond beam. The bond is formed by connecting the beam (in this case the mast is the beam) in two places — at the deck and at the top of the keel. To work properly the mast has to be tightly held at the deck in the mast collar.

Structural Beams

A structural beam is more efficient at carrying load than a flat plate is. The beam is made up of either one or two flanges, with a web between the members. A cored fiberglass laminate is a beam structure, with the fiberglass acting as the flanges and the cores acting as the web.

In metal you can have H-, T- or angle-shaped beams. In the case of the H (sometimes called an I-beam), the top and bottom members are the flanges and the connecting member the web.

The stiffness of a beam is a function of its modulus and the distance between the "extreme" fibers. As already discussed, the distance is a cube function with solid structures, and a square function in sandwich structures. It is easy to see that small increases in depth make for big improvements in stiffness.

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A beam under load will have the top flange in compression, while the bottom flange is under tension.

The stiffness contributed by the connecting web is negligible. The loads carried by the web are also light, and it is not unusual to make cut-outs in the web to save weight.

Bond Beams

Bond beams are formed when one end of the beam is held tight. This stabilization increases the stiffness of the total structure. A keel-stepped mast is an example. The mast step and deck lock the mast in and form a bond beam in the lower panels of the spar, typically increasing the overall spar stiffness by around 20 percent, compared to a deck-stepped mast.

Load Path

The load path in a beam is a function of where and how load is applied and the span over which it is carried. In the center of the beam, the loads are the highest, while at the ends of the beam they are substantially reduced. As a result, beams are frequently tapered to match their loads where weight savings are critical.

Stress Concentration

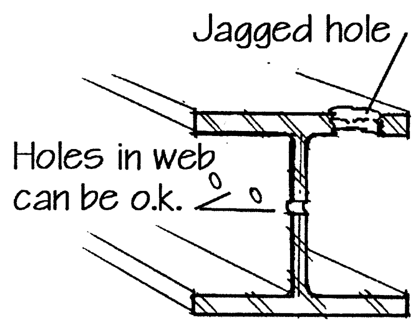
Stress tends to build up in the extreme fibers, at the ends of the beam, and in the edges of beam flanges. There isn't much you can do about extreme fibers, but you do need to be careful with how the load is transferred out of the end to another member.

For example, if you are fiberglassing a support knee in a chainplate area, you would want to taper the edges of the knee to avoid a hard spot (stress concentration) at the ends of the knee. If the knee wasn't tapered, the odds of a failure at the edges would increase over time.

Stress concentrations are also reduced by using gussets to taper a load away from an intersection point.

Stress Risers

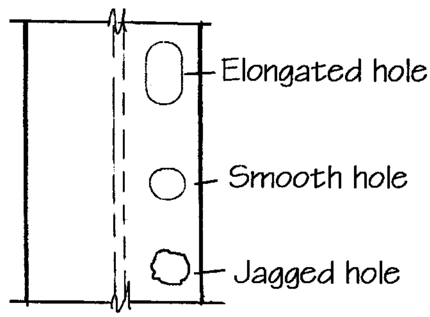
If you take a highly loaded member like a beam flange and drill a tiny, smooth hole in the flange, the stress around that hole will increase by a factor of three. If the hole is rough, the stress could increase by a factor of up to five. Thus, a beam designed to carry 3,000 pounds (1,333 kg) would only carry 1,000 pounds (444 kg) after you drilled that hole.



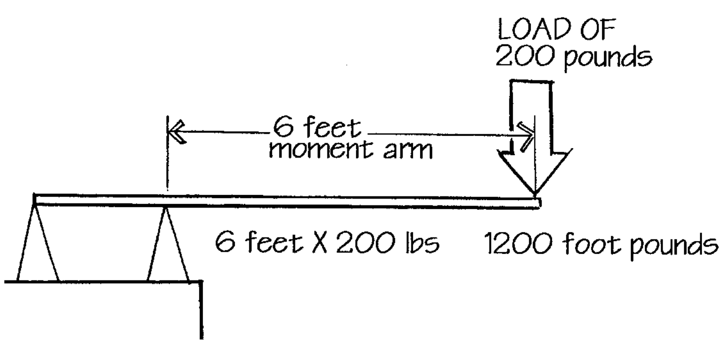
In most cases you can drill a hole through the center of a shear web in a beam without creating a problem. The one caveat here is that the hole must be on or near the "neutral axis" of the web (the neutral axis is where the loads are minimized between the two flanges of the beam).

On the other hand, a hole in the flange, especially one which is near the edge of the flange, will reduce the overall strength of the beam by as much as 66 percent.

If that hole is rough, perhaps with burrs left over from the drilling process, the strength in the beam can be reduced as much as 80 percent.



All holes form stress risers. A jagged hole or a crack typically concentrates stress by a factor of five. A smooth, round hole builds up stress by a factor of three. If the hole is elongated (ideally elliptically shaped) the stress concentration can be reduced to a factor of two.



Moment arms are important for everything from steering to winch handles to the way your boomvang works (or doesn't work!).

Take the load, times the distance, and you have the moment. It is really quite simple.

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Stress risers are also created with welding and bends. This means that if you want to maintain full strength in the beam and need to make an attachment, you must drill into the web or glue onto the beam to avoid the stress riser.

There are some occasions when because of access you must cut drill or cut into a beam. To keep strength at the designed levels, a doubler plate must then be attached to reinforce the area around the stress riser.

Moment Arms

If you put a load at the end of a lever arm, you have a moment arm. A simple example of this is a diving board. If the board is 6 feet (1.85 m) long and you put a weight of 200 pounds (90 kg) on the end, you have a load of 1,200 foot-pounds (168kgm). Increase the weight or the length of the arm, and the load goes up. Reduce either element, and it is reduced. These sorts of calculations are important in mid-boom sheeting arrangements and when looking at cabin or pilothouse structures in a knockdown.

Balance

It is necessary to balance all of the structural elements with each other. You don't want any weak links. At the same time, it doesn't make sense to have one element oversized, as this just throws away weight and cost.

What you want, ideally, is for everything to work together, in a balanced, harmonious manner.

FAILURE MODES

When you design a structure to go to sea, always look at the likely failure mode. Some are definitely more desirable than others.

Evaluate the various structural elements; see how the loads cascade from one to the next; and look for the weak point. You want the failure to occur in an non-catastrophic area. It is preferable to be able to use the failure as an early warning sign, allowing you to unload the boat and make temporary repairs until you can develop a permanent fix.

Cored Structures

In cored structures, for example, the typical failure mode is for the core to shear, allowing the extreme fibers (skins) to float. This keeps the hull shell intact and allows you to make repairs. If the skin were to fail, then you'd have a breach of watertight integrity.

Beam Failures

Beams typically fail in a buckling mode, where the flanges start to collapse. Once this process starts, the web between the flanges usually collapses or tears, and the entire structure falls down.

How the beam goes through this process is important. For example, with a balanced member like an H-beam, the failure will generally be parallel to the load — in other words, the beam will buckle directly under the load. Unbalanced members, like angle, however, tend to rotate out from under the load.

It is more difficult to temporarily repair a rotated failure than one that has failed in line with the load.

Fatigue

Fatigue is one of the most difficult factors to quantify. How much time, at what load, starts to age a given material? How do you even define fatigue — in terms of time under load, number of cycles, or just plain years?

We do know that some materials resist fatigue better than others. Metals that have been heat-treated or work-hardened are more subject to fatigue failure than those that are used in a weaker initial condition.

Fatigue failure is very much a function of the percentage of ultimate load that you work at. A structure might last indefinitely at loads of 30 percent — but bump that figure to 50 percent, and you might see a failure after a few thousand miles of sailing.

On a racing yacht the structure is engineered close to the limit. The designer and owner know that there is a limited useful life to the hull and related structure. On a cruising yacht, on the other hand, we expect the vessel to go on forever. Plenty of allowance for fatigue has to be made.

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Reverse-Cycle Loading

Equally degrading is reverse-cycle loading. This is where a load is off, then on again. An example of this is a boat at anchor in a rolly harbor. As the boat rocks from side to side, the shrouds are alternately loaded and then unloaded.

Another example would be a boom bail or mainsheet attachment point on the deck. On one tack the load is in to port. The next thing you know it is to starboard. That's why boom bails have such a high failure rate.

Reverse-cycle loading of this nature can be harder on a structure than a much higher but consistently applied load.

Exceeding the Elastic Limit

When a structure starts to deflect and/or fail, the material in the structure is stressed until it reaches its elastic limit. Once the elastic limit has been reached, you cannot bend it back into place.

If the failure occurs (and you catch it in time) and the elastic limit has not been exceeded, then you can usually shove, jack, or pull the deformed member back into position.

Stainless steel, for example, typically yields (starts to deform) at about 65 percent of its elastic limit. As a result, it can be brought back from the edge of disaster quite easily.

Aluminum, on the other had, only has about a 10-percent difference between its yield point and its elastic limit. If a failure starts to occur with aluminum, it must be caught much earlier in order to be able to reuse the materials involved.

These characteristics are known. Make allowances for them in the structure you are designing.

Section Modulus and Moments of Inertia

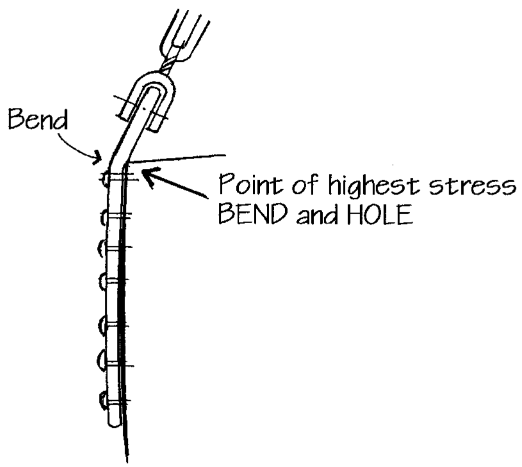
One way an engineer defines the stiffness of a given structure is with moments of inertia. Another way is with section modulus. There are important differences between the two methods, however.

If you think about the cube function and stiffness, you quickly realize that a very stiff, lightweight member can be made by pushing the extreme fibers (flanges) as far apart as possible. At the same time, you can make a beam of the same strength by having thicker materials closer together. Both will carry the same loads in bending or compression. The thicker, smaller beam will have a higher section modulus. The thinner, lighter, and deeper beam will have a lower section modulus. While both do the same work, the smaller, thicker beam has a higher resistance to damage when failure occurs. It may deflect a little too much, and then stop, more or less in good shape — whereas the low-modulus, lightweight beam buckles abruptly when its designed parameters are exceeded. One way to check this is with Euiler's formula. This predicts localized buckling due to excessively thin skins. (These factors are all considered in more detail in the chapter on mast engineering.)

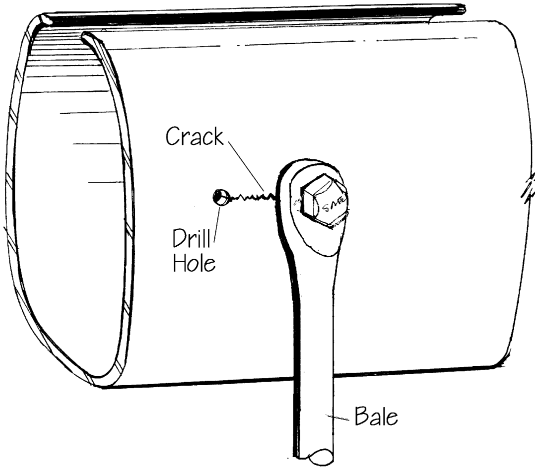
At Stress Risers

A stress riser is a hole, crack, bend, or perhaps weld in the loaded member. Anything that causes a discontinuity can cause a stress riser.

The stress riser concentrates the load around its edges. Depending on the type or shape of the stress riser, the localized loads can increase by anywhere from three to five times.



You often see chainplates bolted to the outside of the hull. Just above the last fastener they are bent to the angle of the shroud. Between the hole and the bend, you have a major concentration of stress. The only way to make this work is to increase the size of the chainplate by a factor of three or more over what would be required for one which could be bolted without the bend.



You can often stop a crack which is moving by drilling a small hole at the very end of the crack. By reducing the stress concentration at the end of the crack there is often enough material left to carry the load until you can properly repair the area in question.

This means that if a member is loaded to half its ultimate capacity, and if a stress riser is introduced, the load at the that point will be 1 1/2 to 3 times the ultimate capacity of the member — and it will fail.

If you have a stress riser in a highly-loaded member, failure will start at that stress riser. If it is a hole, failure will start as a tiny crack, across the direction of load. This is a sign that you've exceeded the yield point of the material where the crack has started (at the edge of the hole).

To reduce the chances of the crack continuing to move, drill a small hole at the end of the crack. This reduces the crack from a 5-to-1 to a 3-to-1 stress riser, affording time for corrective action.

Common examples of this type of problem occur in chainplate holes and in the slots sometimes cut into a boom for a mainsheet bail.

Factors of Safety

All structures have some factors of safety applied. These are to take care of fatigue loads, reverse-cycle loading, building mistakes, variations in quality of material, and changes in use by the operators (as compared to what was allowed for in the design).

The factors of safety reduce the everyday stress level of the structure, and in so doing substantially improve its ability to withstand usage over time.

It is usually the case that very small increases in structural weight can yield big increases in factors of safety. Sometimes adding as little as 10 percent to a total structure weight can double the factors of safety.

This makes a lot of sense in a cruising context. However, the increases have to be balanced throughout the structure. It makes no sense to build one element with such strength that the failure point is merely moved to the next weakest element.

It's also important to take hard spots into account. Don't abruptly terminate a load in a rigid structure — taper off instead.

MATERIALS

Each structural material, from wood to carbon fiber, has a series of quantifiable properties that are easily tested to ensure the values being used are correct. When you engineer a structure, consider how these properties react in the conditions being dealt with. Some materials may be stiff but brittle. Others may be strong and light, but subject to fatigue.

Modulus of Elasticity

Modulus of elasticity defines the stiffness of a material. The higher the modulus, the stiffer the material for a given amount of cross-sectional area. In a boat structure, where weight is always an issue, the designer looks at the modulus and weight of the material.

For example, stainless steel has a modulus of 27.6 (for 18-8 material), while aluminum's modules is down around 10. (Both numbers are in millions of pounds per square inch.) Since the density (or weight for a given area) of aluminum is slightly less than one-third of that for stainless, it is actually a hair stiffer for the weight.

Tensile and Compressive Strength

Compressive strength is how much you can compress a material before failure. This is important in column loads (like masts) and on the top side of beams (directly under the load).

Tensile strength relates to the capability of a material to handle linear loads where the ends are being pulled in opposite directions. With mast shrouds, we are concerned with tensile loading. The bottom side of a beam is also loaded in tension.

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Elasticity

Elasticity is an extremely important characteristic. The more elastic a material is, the more it will give and return to its shape before failure occurs. However, once the elastic limit has been exceeded, as we've already discussed, the material will not return to its former shape.

Generally speaking, the stiffer a material is (the higher the modulus), the less elasticity it has.

Heat-Treating

Many materials are heat-treated to improve their physical properties. This tends to harden the material and reduce the difference between the yield point and the load where ultimate failure occurs.

On the other hand, materials that have been heat-treated to improve their physicals will lose strength if heated improperly. Heat-treated aluminum extrusions, for example, will lose as much as 50 percent of their strength when welded. If this creates a structural problem, the welded item in question (perhaps a gooseneck or spreader base) can be re-heat-treated to bring it back to its original strength.

Work-Hardening

Materials work-harden when drilled, bent back-and-forth, or stressed under load on a long-term basis. Depending on the characteristics of the material (usually the difference between ultimate failure and where yield is exceeded), this may or may not create a problem.

With stainless steel, for example, as you drill a hole, you are hardening the area around the hole. This is why you need to get the hole punched through on the first go, before it has a chance to cool down. Once it cools, the surface of the hole you've started will be work-hardened — and the job of drilling will be a lot harder.

Work-hardening under load, with age, should be watched with care on lightly built, highly loaded structures.

Manufacturers' Factors of Safety

Physical properties of materials as published by manufacturers typically include a fudge factor of 10 to 15 percent. This is to cover them in litigation and allow for manufacturing tolerances.

If you are engineering to tight tolerances, and do not want to put your factors of safety on top of theirs, you can usually ask for physical property certification. If this is not easily available, testing labs can evaluate specimens, so that you may know exactly what you are dealing with.

BASIC CRUISING ENGINEERING

While you may not be an engineer, and while you may have slept through high school algebra, you should know a few simple calculations for checking things aboard your boat. Use a regular hand calculator and follow these directions to develop a feel for the safety factors at play in various parts of your vessel.

This may not be important right now, but one day you may be faced with jury-rigging a bit of gear in a faraway location, without an engineer to advise you.

Tension Calculations

In cruising, when engineering is required, chainplates are usually involved. You may have excessive wear, see a hole starting to elongate, or notice a crack. Since most chainplates are stainless steel the easiest thing to do is replace it with another of the same general design, just a hair larger — or weld a bearing washer around the perimeter to build up bearing surface.

However, stainless is hard to find in many parts of the world, and even harder to cut, drill, and especially weld.

If you are replacing one material with another you might just get away with using a stronger material and adopting the basic shape of the failed piece of gear. Substituting a chunk of high-carbon steel for stainless, for example, will give you a much stronger finished product (although there may be some rusting problems). But what if you can't find the same thickness, or what if only a piece of bronze or aluminum is available? Knowing the basic math that goes into the calculations may pay some dividends at some point — it has for us.

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Lets take a piece of 3/8-inch type-316 rigging wire, 1 x 19 construction, and see what we need for a tang.

The wire breaks at around 17,500 pounds. Let's use a factor of safety of 2 for the chainplate in this calculation (the wire already probably has a factor of safety for rigging loads of 2.5-to-1 or more).

So, our total load is 17,500 x 2 = 35,000 pounds. The standard pin size on a turnbuckle for this size wire is usually 0.625 of an inch. We want to solve for bearing strength of the chainplate. To find out the thickness of chainplate required for the pin to bear against, we take the load and divide it by the pin diameter multiplied by the bearing strength of the material being used at yield.

Let's assume we are going to use a piece of 5086 aluminum, H-34 grade. The bearing yield on this material is 66,000 psi. So, take 35,000 (load on wire with factor of safety), divide by 66,000 psi (bearing yield of the chainplate material) times 0.625 (the pin diameter at the bottom of the turnbuckle), and you get 0.848 inches. Since we can't ordinarily find aluminum this thick, we'd use the next size up, or 1-inch.

Minimum Metal Around a Hole

In the real world there are some generalized rules about metal around a hole. With aluminum, the norm is to allow at least one pin diameter on *each side* of the hole. One-and-a-half times is more conservative. For the example above, with a pin diameter of 0.625 inch and using a a single pin diameter on each side of the hole, you would have a total width to the chainplate of 0.625 + 0.625 + 0.625 or 1.875 inches.

With stainless steel, one usually leaves at least three-quarters of the pin diameter on the sides.

At the top of the tang *above* the pin, the norm is more like twice the pin diameter for aluminum and 1.5 times the pin diameter for stainless steel.

Material	Minimum Ultimate Tensile Unwelded Condition	Minimum Ultimate Tensile Welded Condition	Minimum Yield Strength Unwelded Condition	Minimum Yield Strength Welded Condition	Ultimate Bearing Strength	Bearing Yield
Aluminum 5086, H-34	44,000 psi	35,000 psi	34,000 psi	19,000 psi	101,000 psi	66,000 psi
Aluminum 5083, H-111 (extrusions)	44,000 psi	40,000 psi	24000 psi	21,000 psi	80,000 psi	56,000 psi
Aluminum 5083, H-32	44,000 psi	40,000 psi	28,000 psi	24,000 psi	80,000 psi	50,000 psi
Aluminim 6061, T-6	42,000 psi	22,000 psi	35,000 psi	15,000 psi	88,000 psi	58,000 psi
Steel, Grade A	58,000 psi		34,000 psi			
Steel, Grade AH 32	68,000 psi		45,000 psi			
Steel, Grade AH 36	71,000 psi		51,000 psi			
Stainless, Type 304	68,000 psi		37,000 psi		90,000 psi	
Stainless, Type 316	60,000 psi		32,000 psi		90,000 psi	
Bronze, Alloy 651	65,000 psi		32,000 psi		86,000 psi	

The chart above gives some very basic values for common metals. Note that for aluminum there is very little difference between ultimate strength and yield strength, whereas for the steels and bronze there's about a 2-to-1 factor. As mentioned earlier, if you see an aluminum structure starting to elongate (yield) you are very close to failure. Hence, you work with higher factors of safety relative to yield on aluminum. With the steels, and especially stainless steel, working the material (cutting, drilling, etc.) hardens and thereby increases the structural capability.

You will notice that the chart gives welded and unwelded values for the aluminum but not other materials. Aluminum tends to lose strength when welded; the others stay pretty much the same.

The data in this chart is assembled from a number of different sources. The data is close enough for rough approximations and where you are using high factors of safety. However, if factors of safety are cut down in the interest of saving weight, you would then want to check carefully with the supplier of the particular materials for certification of structural values. In the case where welds are part of the design, samples should be welded by those in the shop who will be doing the work, and then tested to failure, just to be sure.

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CONNECTIONS

Structural connections are the key to holding things together. And since the loads are usually quite high and stress risers are usually present, if a structural problem occurs, the odds are it will be at a connection. It may be a screw that shears or pulls out, a bolt that fails at its threads, or a weld that starts to crack or pulls out totally.

Welding

With metal structures, welding is the most efficient method of jointing structural members. If the welds are done correctly,the connection will be as strong as the surrounding area — unless the material has been heat-treated, in which case you'll need to re-heat-treat after welding.

The welding process is supposed to accomplish two things. The first one is to get the two pieces of metal hot enough to fuse together. The second is to deposit a fillet of weld rod or wire to help connect the structure.

There is a relationship between material thickness and the size of the weld bead. To some degree, the more weld bead you have, the better the load-carrying ability. However, there are definite limits.

Take care with how you end a weld, so as not to create a stress riser. In many situations, the norm is to stop the weld before a corner, or to pull a weld bead off at an angle rather than keeping it in line with the load, in order to avoid stress concentrations or risers.

Welds in Shear

Regardless of how strong a weld is, or how good the welder is, it's always better to take structural loads in shear, where the load is parallel to the weld bead. This means that the entire weld has to fail before any of the weld can begin to move. This is especially important where the loads are cyclical.

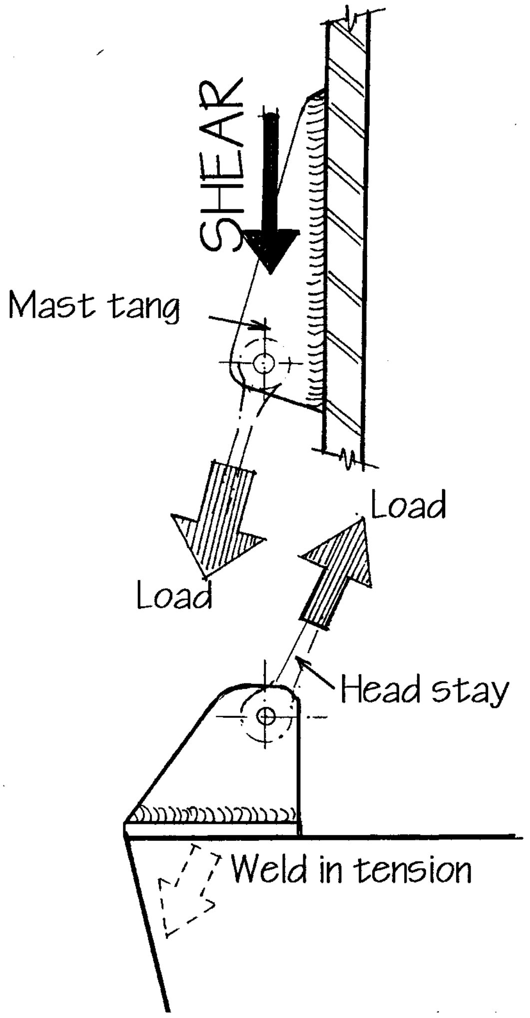
Welds in Tension

On the other hand, welds in tension should be avoided, as any quality problems could quickly lead to catastrophic failure.

A common example of tension welds can be found in headstay tang attachments. You will sometimes see a plate in line with the centerline which has been welded to a bow strap. These are a common point of rig failure. If you have such a condition on your own boat, keep a close eye on the weld edges — this is typically where welds in tension begin to fail.

Welds Subject to Bending

Also avoid welds that are subject to bending loads, especially if they are reversing. The flexing back and forth, even if the loads are moderate relative to the capacity of the weld, will lead to failure over time.



The right and wrong way to use a weld. The top drawing shows a mast tang, with the welds taking their load in shear. This means the entire weld has to fail all at once before any individual part can begin to fail.

The bottom drawing represents a weld working in tension. This is a typical headstay detail which is guaranteed to fail with age.

Because the load is pulling up against the weld, rather than along it (as in the top drawing) the ends of the welded tang can begin to lift before the center. This means that even a small weld fault will begin a tearing process all along the length of the weld.

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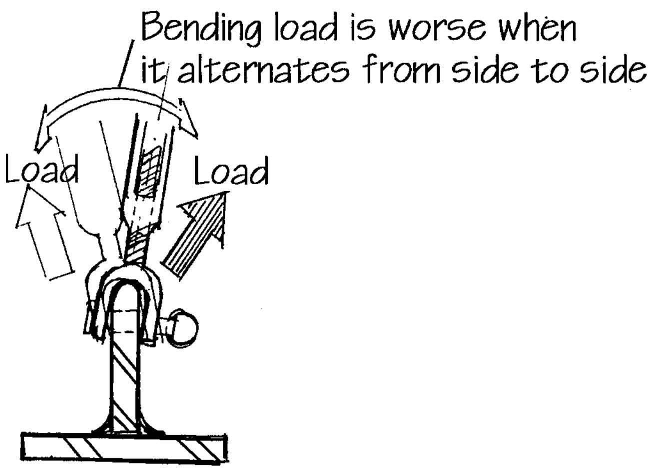

If there is a reversing bending load on a weld, the weld will eventually work, harden and then crack. Sometimes it is impossible to avoid these sorts of loads with running rigging. When this is the case, a reinforcing gusset which prevents the loaded member from moving can solve the problem. Or, you make the structural member much stronger than needed for day-to-day loads to account for the fatigue which comes with time.

Occasionally there is no way around bending loads on welded structure. If this is the case, working in a welded gusset will prevent the welded member from moving and will preserve your structural integrity over time.

Calculating Weld Properties

Some engineering calculations can be quite cumbersome, requiring lots of math and training. Welded connections, however, are actually pretty simple to work out.

To figure out how hard a weld is working or how much weld bead is required, you must first calculate the actual load, plus a safety factor. Let's say you want to weld a tang on your mast for a cutter-stay attachment. Start with the wire size and its breaking load. The wire will already have a factor of safety built into it from the rig designer's calculations — typically around 3-to-1. On top of this, you have an additional factor of safety from the wire manufacturer — wire is typically rated at around 85 to 90 percent of the actual break point. In addition, you might want to add some fudge factor on top of all of this for weld quality, aging, and unknown bending loads which might occur. The norm is around one-and-a-half times wire size.

In this example, the load for which you engineer the tang weld will be about five times the actual working load.

Say you have a piece of 3/8-inch (9.5mm) 1x19 stainless-steel wire rated at 17,500 pounds (7,900 kg). You would then multiply this by 1.5 for the extra factor of safety, giving you a figure of 26,250 pounds for the weld load.

The next step is to decide how long the weld will be. Assuming the tang is welded both sides, if it were 6 inches (150 mm) long, you'd have 12 inches (300 mm) of total weld length. Divide the total load by the weld length (26,250/12), and you get a figure of 2,180 pounds-per-inch of weld.

The next step is to look at the thickness of the mast to see how much load you can transfer to it per inch of weld bead.

Skip Chetelat, chief engineer at Forespar suggests a figure of 930 pounds (421 kgs) for each 1/16-inch (1.53 mm) of thickness of 6,000 series aluminum. So if the leading edge of your mast extrusion were 3/16-inch (4.5 mm) thick — a pretty normal number — it could handle 2,790 pounds (1,265 kgs) per inch (24.6 mm) of weld.

The next step is to look at the weld bead required to transfer this load between the cutter-stay tang and the mast extrusion. Generally speaking, to transfer load, the fillet weld should be three-quarters the

Al Ligget sent this photo of a piece of chain, the weld on which had failed in tension during a blow in Guam.

Welds in tension are generally not a good idea, but for chain there's not much else you can do.

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thickness per leg of the weld that the tang is, assuming that you can weld on both sides. If only one side of the plate can be welded, the weld bead should be doubled in size.

This situation becomes a little more complex when you get into really thick materials where welding heat is absorbed. In this case there are specific recommendations depending on material thickness and type for making sure the welds are properly done. These can range from a larger bead to preheating with a torch before laying in the weld bead.

Stainless is not a good material for structural connections that carry lots of load. Crevice corrosion can start where the bolt passes through a hole (due to a lack of air) — and you can't see the corrosion start. Finally, a small crack begins, and eventually catastrophic failure occurs. Where stainless fasteners are used for primary structure, they should be significantly oversized and checked on a periodic basis.

For different aluminum alloys, there are different welded properties. The same applies to steels, bronzes, etc. Heat-treated materials (like 6,000 series aluminum extrusions) have much lower physical properties after welding. However, if the welded part is re-heat-treated, the original properties can be attained after welding.

The main thing we are trying to convey here is a feel for the basics of the process — so if you need to have something welded, you'll have some idea of what is going on.

Secondary Bonds

With fiberglass laminates, structural connections are typically made by gluing bits and pieces together using resin and various types of reinforcements. How these secondary bonds are made is of course critical to the structure's ability to perform.

Proper surface preparation is critical, correct resins must be used, and the amount of time between basic laminate and secondary bond must be within the correct time frame.

Because these variables are difficult to consistently control, secondary bonds are designed very conservatively with high factors of safety. In areas of high stress, such as chainplates, we prefer to bolt the chainplates rather than depend on a secondary bond.

Tapped Connections

Along with bolting a connection, you can also tap into metal to make a connection where you don't have access to fit a nut. Tapped connections work fine in shear, but should not be used for tension loads. The load carried by a tapped connection is a function of the inherent strength of the metal, the thickness of the metal, the diameter of the bolt, and the number of threads engaging the metal. Note that in order to get good load-carrying ability, the threads must be well made with the bolt having a correct (not sloppy) fit.

The most common usage of tapped connections is fastening hardware to spars and toerails. Here are some values that Bruce Marek developed based on real-world tests for 316 grade stainless steel bolts in tension.

1/8 inch-thick (3 mm) material	
1/4-20	1,720 pounds
5/16-18	1,856 pounds
3/8-16	1,972 pounds
3/16 inch-thick (4.5 mm) material	
1/4-20	2,204 pounds
5/16-18	3,480 pounds
3/-16	4,176 pounds

It is surprising to note that just a 3/16-inch-thick (4.5 mm) aluminum plate is enough to create enough hold on a threaded connection to exceed the yield point on these bolts.

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Decimal Equivalents and Tap Drill Sizes

Frac./ Drill Size	Decimal Equiv.	Tap Size	Frac./ Drill Size	Decimal Equiv.	Tap Size	Frac./ Drill Size	Decimal Equiv.	Tap Size	Frac./ Drill Size	Decimal Equiv.	Tap Size
80	.0135		7/64	.1094		H	.2660		25/32	.7812	
79	.0145		35	.1100		I	.2720	5/16-24	51/64	.7969	
1/64	.0156		34	.1110		J	.2770		**13/16**	**.8125**	7/8-14
78	.0160		33	.1130		K	.2810		53/64	.8281	
77	.0180		32	.1160		9/32	.2812		27/32	.8438	
76	.0200		31	.1200		L	.2900		55/64	.8594	
75	.0210		**1/8**	**.1250**		M	.2950		**7/8**	**.8750**	1-8
74	.0225		30	.1285	6-40	19/64	.2969		57/64	.8906	
73	.0240		29	.1360		N	.3020		29/32	.9062	
72	.0250		28	.1405		**5/16**	**.3125**	3/8-16	59/64	.9219	1-12
71	.0260		9/64	.1406		O	.3160		**15/16**	**.9375**	
70	.0280		27	.1440		P	.3230		61/64	.9531	
69	.0292		26	.1470	8-32,36	21/64	.3281		31/32	.9688	
68	.0310		25	.1495		Q	.3320	3/8-24	63/64	.9844	1 1/8-7
1/32	.0312		24	.1520		R	.3390		**1**	**1.0000**	
67	.0320		23	.1540		11/32	.3438		1 3/64	1.0469	1 1/8-12
66	.0330		3/52	.1562	10-24	S	.3480		1 7/64	1.1094	1 1/4-7
65	.0350		22	.1570		T	.3580		**1 1/8**	**1.1250**	
64	.0360		21	.1590		23/64	.3594		1 11/64	1.1719	1 1/4-12
63	.0370		20	.1610		U	.3680	7/16-14	1 7/32	1.2188	1 3/8-6
62	.0380		19	.1660		**3/8**	**.3750**		**1 1/4**	**1.2500**	
61	.0390		18	.1695		V	.3770		1 19/64	1.2969	1 3/8-12
60	.0400		11/64	.1719	10-32	W	.3860		1 11/32	1.3438	1 1/2-6
59	.0410		17	.1730		25/64	.3906	7/16-20	**1 3/8**	**1.3750**	
58	.0420		16	.1770		X	.3970		1 27/64	1.4219	1 1/2-12
57	.0430		15	.1800		Y	.4040		**1 1/2**	**1.5000**	
56	.0465		14	.1820		13/32	.4062				
3/64	.0459	0-80	13	.1850		Z	.4130				
55	.0520		**3/16**	**.1875**	12-24	27/64	.4219	1/2-13			

The most important factor in getting a good tapped conection is having the proper sized hole for the tap. If it is too large, strength will be lost. If it is too small, the tap will bind and break. The table above gives the appropriate size hole for various taps. It also includes decimal equivalents, various number and fractional drills together with their decimal equivalents.

Bolted Connections

Bolted connections are easy to engineer and quite secure as long as the bolts are tightened (torqued) to the correct levels. If your bolted connection is in a working area — say, a rudder quadrant or shaft coupling — you will want to check that the bolts are properly tensioned on a periodic basis.

A variety of grades of bolts are on the market. These vary from mild steel (low strength) to specially heat-treated high-strength alloys. Bolts normally have the grade stamped on the head, so if you are replacing a failed bolt, take a look at the grade and go up a level.

Take care with stainless-steel bolts, as these are usually much weaker than even medium-grade steel bolts.

Bolts are typically marked on their heads to indicate strength level. Anything below grade 5 (the minimum commercial grade) should not be used for structural loads. Grades 6 and 7 are normally used for medium-load situations, while grade 8 is the strongest and is used when maximum strength is required. Note that for each grade and size of bolt, there is a correct torque.

However, don't overtighten — this can cause an internal failure in the bolt which you may not find out about until later. In situations where strength is critical, use a torque wrench.

In the following tables you will find various grades and sizes of bolts, in both coarse and fine threads. This will give you an idea of the structural capacity of different types of material. Note that each type has a stamped identification marking on the head.

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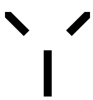
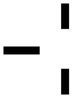
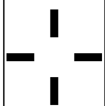
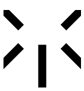
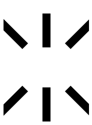
			Coarse Thread		Fine Thread	
Grade	**I.D.**	**Nominal Bolt Size**	**Proof Load, lb**	**Tensile Strength Min, lb**	**Proof Load, lb**	**Tensile Strength Min, lb**
1	none	1/4	*	1,750	*	2,000
		5/16	*	2,900	*	3,200
		3/8	*	4,250	*	4,850
		7/16	*	5,850	*	6,550
		1/2	*	7,800	*	8,800
		9/16	*	10,000	*	11,150
		5/8	*	12,450	*	14,100
		3/4	*	18,350	*	20,500
		7/8	*	25,400	*	28,000
		1	*	33,350	*	36,450
		1-1/8	*	41,950	*	47,100
		1-1/4	*	53,300	*	59,000
		1-3/8	*	63,550	*	72,350
		1-1/2	*	77,300	*	86,950
2	none	1/4	1,750	2,200	2,000	2,500
		5/16	2,900	3,600	3,200	4,000
		3/8	4,250	5,350	4,850	6,050
		7/16	5,850	7,350	6,550	8,200
		1/2	7,800	9,800	8,800	11,050
		9/16	9,450	11,650	10,550	13,000
		5/8	11,750	14,450	13,300	16,400
		3/4	17,350	21,400	19,400	23,850
		7/8	12,900	25,400	14,250	28,000
		1	16,950	33,350	18,550	36,450
		1-1/8	21,350	41,950	23,950	47,100
		1-1/4	27,100	53,300	29,950	59,000
		1-3/8	32,300	63,550	36,800	72,350
		1-1/2	39,300	77,300	44,000	86,950
3		1/4	2,700	3,500	3,100	4,000
		5/16	4,450	5,750	4,950	6,400
		3/8	6,600	8,550	7,450	9,650
		7/16	9,050	11,700	10,100	13,050
		1/2	12,050	15,600	13,550	17,550
		9/16	14,550	18,200	16,250	20,300
		5/8	18,100	22,600	20,500	25,600
5		1/4	2,700	3,800	3,100	4,350
		5/16	4,450	6,300	4,950	6,950
		3/8	6,600	9,300	7,450	10,550
		7/16	9,050	12,750	10,100	14,250
		1/2	12,050	17,050	13,600	19,200
		9/16	15,400	21,850	17,250	24,350
		5/8	19,200	27,100	21,750	30,700
		3/4	28,400	40,100	31,700	44,750
		7/8	36,050	53,150	39,700	58,550
		1	47,250	69,700	51,700	76,250
		1-1/8	56,450	80,100	63,350	89,900
		1-1/4	71,700	101,750	79,400	112,650
		1-3/8	85,450	121,300	97,300	138,100
		1-1/2	103,950	147,550	117,000	166,000

			Coarse Thread		Fine Thread	
Grade	**I.D.**	**Nominal Bolt Size**	**Proof Load, lb**	**Tensile Strength Min, lb**	**Proof Load, lb**	**Tensile Strength Min, lb**
5		6 8 10 12	770 1,190 1,490 2,060	1,090 1,680 2,100 2,900	860 1,250 1,700 2,190	1,220 1,770 2,400 3,100
6		1/4 5/16 3/8 7/16 1/2 9/16 5/8 3/4	3,500 5,750 8,550 11,700 15,600 20,000 24,850 35,050	4,450 7,350 10,850 14,900 19,850 25,500 31,650 44,400	4,000 6,400 9,650 13,050 17,600 22,350 28,150 39,150	5,100 8,100 12,300 16,600 22,400 28,400 35,850 49,600
7		1/4 5/16 3/8 7/16 1/2 9/16 5/8 3/4 7/8 1 1-1/8 1-1/4 1-3/8 1-1/2	3,400 5,500 8,150 11,150 14,900 19,100 23,750 35,050 48,500 63,600 80,100 101,750 121,300 147,550	4,250 6,950 10,300 14,150 18,850 24,200 30,050 44,400 61,450 80,600 101,500 128,900 153,600 186,850	3,800 6,100 9,200 12,450 16,800 21,300 26,900 39,150 53,450 69,600 89,900 112,650 138,100 166,000	4,850 7,700 11,700 15,800 21,250 27,000 34,050 49,600 67,730 88,200 113,850 142,700 174,900 210,250
8		1/4 5/16 3/8 7/16 1/2 9/16 5/8 3/4 7/8 1 1-1/8 1-1/4 1-3/8 1-1/2	3,800 6,300 9,300 12,750 17,050 21,850 27,100 40,100 55,450 72,700 91,550 116,300 138,600 168,600	4,750 7,850 11,650 15,950 21,300 27,300 33,900 50,100 69,300 90,900 114,450 145,350 173,250 210,750	4,350 6,950 10,550 14,250 19,200 24,350 30,700 44,750 61,100 79,550 102,700 128,750 157,800 189,700	5,450 8,700 13,150 17,800 24,000 30,450 38,400 55,950 76,350 99,450 128,400 160,950 197,250 237,150

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"STAINLESS" STEEL

If you've spent much time around salt water, you'll know that the term "stainless steel" is an oxymoron. It isn't stainless, nor is it a steal. The good stuff costs a lot of money to purchase and fabricate.

Nor is stainless always good in a saltwater environment. So why do we use it? Because it takes less maintenance than other choices and has good forming characteristics. Another factor is the ability to reform it after it has been bent out of shape.

Stainless Alloys

There are all sorts of stainless-steel alloys. The two that are typically used in the marine environment are 304 and 316. The 304 tends to rust more, but has about 15 percent higher physical properties. We used to specify 304 rigging because it is stronger. Today, 304 it is difficult to find, so we use 316, which contains more nickel and molybdenum. The molybdenum sharply increases corrosion resistance to chlorides and sulfates

Crevice Corrosion

Stainless steel depends on a super-thin layer of chromium oxide for its chemical resistance. This layer is formed by a combination of the chromium in the stainless steel and oxygen in the atmosphere. As long as oxygen is present, the layer will be quickly reformed any time the surface of the stainless is scratched.

However, if the stainless is encapsulated — or buried in a bedding compound or a laminate in an anaerobic state (no air) — then it becomes susceptible to corrosion. Toss salt water into the brew, add a bit of welding or scratching, and you are ripe for what is known as crevice corrosion.

If this occurs on a highly loaded member, such as a bolt making a structural connection, over time, it can lead to a failure.

Pitting Corrosion

Pitting corrosion develops from impurities in the alloy, weld splatter, or surface impurities imparted during the manufacturing process. An example of pitting corrosion is if your lifeline stanchions continually bleed, starting with a small dot of rust and then streaking.

Pitting indicates deep corrosion in localized areas. Dirt or grease may block oxygen from that surface, thus impeding the passive film that protects stainless from corrosion.

On an exposed surface, this is mostly a cosmetic issue (an annoying one at that!). However, in a bedded fitting, pitting corrosion can lead to more serious problems.

The outer wires from 1x19 rigging wire, from inside a Norseman terminal. This is most probably type 302 stainless steel. While the terminal did not fail, I'm not sure if I would trust my rig to something that looks like this!

Over time, corrosion would be bound to significantly weaken the wire.

Buffing

Any surface contamination or surface crevices eventually lead to rust stains. If the stainless steel is buffed after fabrication, it removes the surface contaminants and scratches. A good buff job is like an insurance policy against rust. However, buffing tends to be labor-intensive, so it is not always done as well as one might hope.

Passivating/Electropolishing

These are confusing terms, since the common usage has taken on a different meaning that the technical definition. Technically, passivating is not cleaning, but rather a process of dipping stainless into a nitric-acid solution to rapidly form chromium oxide on the surface of the material, creating a passive film that protects stainless from further oxidation. The purpose of passivating is to remove both grease left from manufacturing and traces of steel particles that may have rubbed off manufacturing tools onto the fastener.

In common commercial parlance — meaning nonmilitary and aerospace — passivating

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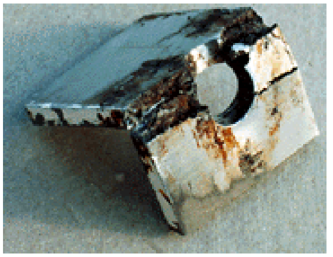
means cleaning , and the terms "passivating" and "cleaning" are used interchangeably. A wide range of cleaning methods using different mixtures containing nitric, phosphoric, and other acids, or simply exposing cleaned stainless fasteners to air for a period of time will result in a "passivated" condition. For fasteners that have been properly cleaned, it is impossible to determine the method of cleaning or passivation that was used.

Welding Issues

Stainless is easy to weld. However, welds should be carefully formed and buffed or electropolished after fabrication so they don't start a corrosion process, eventually weakening the weld.

Living with Corrosion

To some extent you just have to live with stainless-steel corrosion. Knowing it will be a problem, start out with oversized fasteners. It also helps to choose the best-grade alloys, especially in an anaerobic situation. If failure could cause a chain reaction of problems, the fasteners should be periodically removed and checked.



Four interesting photos from Al Ligget — the result of his recent re-rigging of 20-year-old *Sunflower.* All of these stainless-steel items, made in Taiwan from unknown types of "stainless," show severe forms of crevice corrosion. The toerail track (upper left and right) has a crack emanating from the fastener hole. The plunger holes, without fasteners, show no sign of corrosion. The shackle (middle left), with a small visual crack, could be broken by hand.

Most interesting is the pulpit photo (below). Note how there is lots of cracking in the tubing — but the tang and weld bead are fine (obviously a better stainless-steel alloy).

OTHER MATERIALS

A variety of other materials commonly used on cruising yachts are listed below.

Naval Bronze

This is basic brass, with a small addition of tin added for corrosion resistance against salt water. Naval bronze used to be used for castings for deck and spar hardware and plumbing fittings.

Monel

Composed basically of two-thirds nickel and one-third copper, monel is strong, has excellent corrosion resistance against salt water and in high temperatures, and is very expensive when compared to stainless. This is generally used for prop shafts and keelbolts.

Titanium

Titanium is a wonderfully strong, light material. It has been used extensively on racing boats, often to save weight on spars. It is very difficult to machine, due to its hardness. However, drilling and cutting — especially with laser cutters — is possible. On the other hand, welding titanium is very difficult — and if the welds are not done correctly, failure will eventually occur.

A number of people have been badly hurt by failing titanium welds. Our feeling is that if you plan to use this material, stay with designs that can be fabricated by drilling, cutting, and bending. Avoid welding.

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Brass

The most common alloy of copper, brass is basically two-thirds copper, one-third zinc. It is nonmagnetic with good strength and toughness, high electrical conductivity, and an attractive lustrous finish. It has good corrosion resistance against certain chemicals and acids, but weak resistance against other elements such as seawater.

SCANTLINGS

We should talk for a moment about what is an appropriate level of hull-construction scantlings.

For the yacht voyaging close to shore, where navigational dangers are modest and there's help close by, *conventional* scantlings are fine. But if you're going farther afield and insurance is an unpalatable financial burden, it makes sense to consider a little more beef in your hull structure.

Let's examine a few of the structural risks you have to think about.

That load of containers is the best reason I can think of for a strong hull and watertight bulkheads!

Unfortunately, when the insulated containers fall overboard, they float — especially when empty..

Grounding

There's no question that you're going to be aground if you do much cruising. If it's just a mud bank, the loads are not significant. But if the rocks or coral have a grip on your keel, and if seas are running, the loads on the hull — both impact and abrasions — will be significant. Situations vary, but over the years we've found that a multiple of four times the ABS rule requirements for keel and floor structure seems to work pretty well.

Logs (left) and deadheads (right) are an ever-present problem in the Pacific Northwest, Canada, and Alaska. Keep a careful watch when running, and avoid traveling at night.

Stout hull construction is necessary to deal with the occasional thump.

Abrasion Resistance

If you mess up and put your boat hard on the bricks, and if it sits on rocks or coral for awhile, abrasion resistance is going to have a lot to do with how well the boat does.

With metal, this is typically not as big an issue as with timber or fiberglass vessels. We've typically specified an abrasion patch around the waterlines of our fiberglass yachts, concentrated in the turn of the bilge between the forward and aft watertight bulkheads.

In the old days we'd typically add somewhere around one-half inch (12 mm) of woven roving and matt. Now,

What do a flock of birds standing on the water indicate? Either a log or a sand bar. In both cases, give the birds a wide berth.

Accidents happen. This powerboat (right) hit some debris, which started the outer fiberglass skin peeling back from the plywood hull. By the time they had made it back to shore, most of the fiberglass on the starboard side had pulled loose.

Intermezzo II had the misfortune of being "T-boned" by a Sunday-afternoon sailor in heavy traffic off Newport, Rhode Island. The other boat almost sank. We were a bit more fortunate. The toerail was "straightened" with a big sledge hammer. Then the damaged plate was cut away. Finally, new sections of plate were welded into place.

The entire process took about eight man-hours. When we got back to Florida, we re-finished the damaged area of paint.

If we had not been stoutly built, the damage would have been far more severe.

with GPS doing a better job of keeping people off the bricks, we go a little lighter. On the Sundeer production vessels we offered an option that was the equivalent of doubling the exterior laminate in the abrasion area. Almost all our owners went with this. It is cheap insurance!

Collision With Another Vessel

There are two forms of collision to be concerned with. The easiest to deal with is another vessel. Here, most of the loads are going to be concentrated in the hull-to-deck joint (sheer) or the bow, depending upon whether you're getting hit or doing the hitting.

Because collisions happen, we like to heavily reinforce our boats, and have a watertight collision bulkhead forward. Glass laminates will typically run three to four times as thick down the bow stem as on the hull itself.

In our aluminum yachts we add extra frames and/or longitudinal stringers in the bow to handle impact loads. The cutwater area and up at least half the topsides and sometimes all the way up frequently has a large plate stiffening this area running aft.

Deadheads and Containers

Collision with an underwater object — whether a large log (deadhead) or a refrigeration container barely awash — is more difficult to deal with. In this situation, the impact is lower in the hull, typically in the forward area.

It's hard to engineer for this problem, as it's impossible to anticipate speed, angle, the shape of what you are hitting, or how or even where on the hull the impact will occur.

That's why we like watertight bulkheads! An abrasion patch will help a lot in case you take that impact aft of the watertight bulkhead.

Head Seas

Pounding to windward over a long period of time puts substantial stress on the forward hull sections. They tend to flex as waves impact. As a result, yachts are typically built with heavier skins and closer framing in their bows than elsewhere.

The issue here is weight (trying to save as much as possible) as well as the size and shape of the seas, your angle to them, and how fast you are going.

The problems you've probably read about that some BOC and Whitbread race boats have had are nothing new. Twenty-five years ago aluminum race boats were bending their forward frames when slamming into big seas at speed.

There are two answers: One — put deeper, more closely spaced frames in the forward part of the boat. Or two — slow down and drive more carefully.

In our case, we build up the structure to multiples of the ABS rule, since the rule has been too light for slamming loads since its inception.

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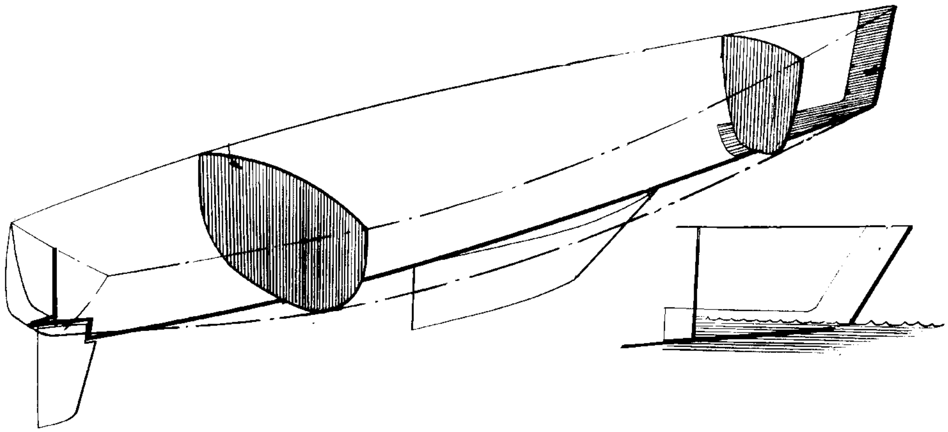

Starting with the very first boats we built for ourselves and others (back in the late 1970s), we've had fore-and-aft watertight bulkheads. The aft bulkhead cordons off the engine room. If we've used a center engine room, it blocks off the lazarrette, steering gear, and prop shaft support bracket.

The forward bulkhead isolates the forepeak. This has the extra advantage of keeping the smell of damp, grungy ground tackle and mildewed sails out of the living area.

The bow and forefoot areas always have lots of extra reinforcements in case of a collisions. This added reinforcement runs aft a short distance beyond the bulkhead, so as not to create a stress riser where the extra material ends.

Once past the bulkhead, the thicknesses are tapered, once again so as not to create a stress riser.

WATERTIGHT BULKHEADS

At some point, in spite of everything you do in terms of building a strong boat, you may end up with a collision that results in a breach of the hull. If you have a watertight bulkhead forward, this will be nothing more than an annoyance. If not, you will be probably looking around for your abandon-ship kit and getting the life raft ready to go over the side.

The bow is obviously the most vulnerable area. Another area that can lead to real problems is the stern of the boat. Rudder damage in a grounding is not that uncommon — nor is ripping the prop support bracket off, usually with a sheet wrapped around the prop with the engine in gear.

And aft watertight bulkhead contains the water in the back part of the boat.

We feel so strongly about this that every boat we've built since starting in this business has had watertight bulkheads at both ends.

New Construction Issues

Watertight bulkheads are quite easy to install when you are building from scratch, although there are some planning issues which should be taken into account before starting.

Structurally, the forward bulkhead can be subjected to high dynamic loads if water is surging back and forth. We've found that reinforcing the bulkhead with vertical stringers is an efficient way of obtaining the required strength. The ABS's rules for watertight bulkheads seem to work well.

Next, look at how you will deal with plumbing. There will be a requirement for separate bilge pumps and perhaps a deck wash in the watertight areas. If there's a damage-control pump, allow for that, too. There may be hydraulic lines from a steering system, perhaps a propane gas line, and maybe fresh water for an aft deck shower as well. We find the way to plumb all of this in a fiberglass boat is to glass a series of pipes through the bulkhead and then hose clamp on each end.

With metal construction, use the same approach, except the pipes are welded in place, rather than glassed. Or you can weld a coupling with a proper female pipe thread at each end, and connect through this.

With lines that must remain continuous, such as a propane line or a steering hydraulic — these can be run inside of tubes and then sealed in or run through watertight glands.

The same allowances must be made for wires. A number of single- and multi-cable waterproof glands are on the market. Or you can use a large pipe sealed with silicone.

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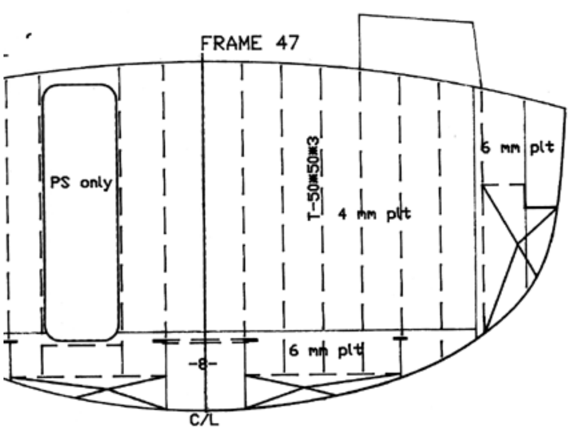
Here are three different approaches to taking plumbing through a watertight bulkhead. Above, left: A threaded pipe, welded to a metal flange. A composite fiberglass bulkhead has been bonded and bolted to the flange as well. Plumbing fittings are threaded to both sides of these pipes.

The upper right photo shows an extended pipe. With these, hoses will be clamped to both sides of the pipe, or will be run through the inside.

A sealing gland of some sort (lower right photo) will keep the connection watertight.



A typical watertight bulkhead detail from one of our boats. This one is for an engine-room bulkhead, so if there is a leak, the hydrostatic loads will be quite low. The bulkhead is made from 5/32-inch (4mm) plate with vertical stiffeners every foot (300 mm). The stiffeners are 2 inches by 2 inches by 1/8 inch (50 mm x 50 mm x 3 mm). A welded bulkhead like this will be quite unfair and will require quite a bit of "furring" to straighten it out enough for interior surfaces to look reasonable.

Retrofitting

Most cruising sailboats have a lazaret bulkhead at the aft end of the boat, forward of the rudder shaft and prop support bracket. By sealing all of the penetrations, and/or re-routing them to the top of the bulkhead, a watertight compartment can be easily made. You then need to add a small bilge pump, as this area will no longer drain to your sump.

At the bow, things may be a little more difficult, but not insurmountable.

There is almost always a bulkhead for stowage of sails and ground tackle. The base of this can be made watertight quite easily. You then need to deal with the doors. These always open aft, which means they naturally want to burst open from any hydraulic pressure.

If you work up a gasket around the edge of the doors, where they overlap the bulkhead, and then fashion a bar across them for locking — like an old-fashioned door brace — you will have something that is both strong and simple to execute. The hardware holding the bar should be through-bolted, and the bar needs to be very strong.

Full Compartmentalization

If you breach the hull between your watertight bulkheads, you will still sink. It is certainly possible to get around this with additional watertight bulkheads, but this solution is quite a bit more difficult — and really only practical with a new build.

The same construction issues apply in terms of bulkhead penetration — only now you need to add watertight doors through each bulkhead.

It generally takes five separate compartments to ensure that no single flooding will significantly affect stability and trim.

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Watertight Doors

If you have watertight bulkheads, you will need some way through or into the isolated sections of the hull.

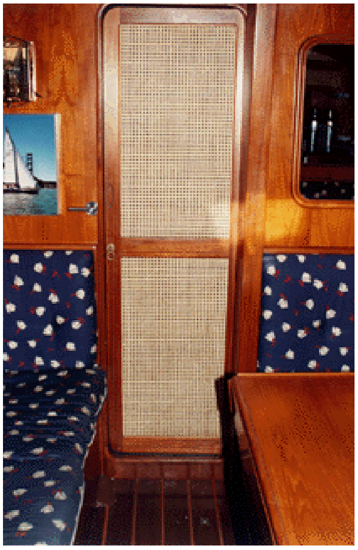
With forward areas, the easiest access is via a deck hatch. There are no leaks to worry about and the structural problems that come with hydrostatic pressures forward are never an issue as far as the door is concerned.

Our approach with watertight areas aft has always been to try to work with deck hatches too. However, eventually an aft engine room becomes large enough to allow access from the interior. At this point, a watertight door comes into play.

You have similar issues with which to deal when the central part of the boat has been bulkheaded.

Watertight doors are not easy to execute well. They need to be strong, watertight, fast acting, and blend with the interior. In general, they are hinged so that the expected water pressure will tend to keep them closed. In most cases metal frames are used for both the door frame and door support.

You can fabricate the doors on your own or buy them commercially made.

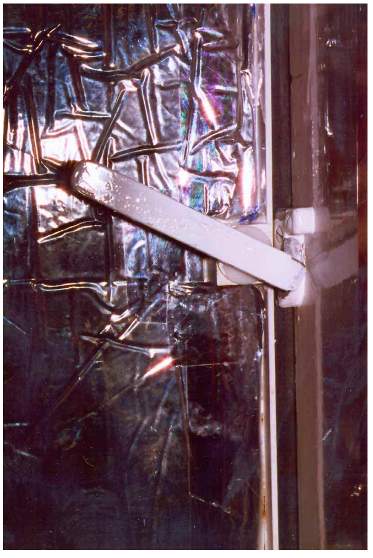


Interior watertight doors are difficult to execute and make look good. These two shots were taken aboard the Farr 46 *Beach Party*, a Kiwi-built yacht full of interesting details. A hollow rubber gasket surrounds the door and provides a seal. There are two doors. The forward door is the watertight unit, and is normally open. Aft, there is a second aesthetic door which also provides privacy.

The watertight door has a simple series of handles which engage a large stainless striker plate.

Dogging a watertight door should be fast, and should provide a secure clamping pressure so that gaskets are compressed. This detail is quite simple to execute. It is an aluminum handle which runs up an aluminum ramp, pulling the door tighter as the handle ascends the ramp. Four such handles are on this door — one at the top, one at the bottom, and two along the edge opposite the hinge.

Hinges are placed slightly off-axis, so that as the door closes, the hinge provides clamping pressure as well.



With moderate-to-light displacement designs, the head pressure that a watertight door has to withstand is not as great, since the hull is not as deeply immersed in the water. This allows the use of partial bulkheads. The upper left photo shows a system we worked out for *Wakaroa,* where a section of floorboard can be lifted in the middle of the main saloon to bulkhead off the middle of the boat.

A prefabricated cast watertight hatch for access to a lazaret or engine area.

Above: A crude but effective watertight door into the pilothouse of this rugged cruiser. This is really more of a hinged set of washboards than a door, since the height is low.

However, by grabbing the roof and swinging your legs in first, you soon become accustomed to entering.

Another round, watertight door, except this one opens into a pilot house. Note how all three dogs are connected to the center handle and are operated with one rotation.

If a watertight door is going to have a lot of traffic, as on a commercial vessel, linking the dogs makes sense.

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