Metals in a Marine Environment

To understand the use of metals - or indeed any other material - it is helpful to know a little about three properties; stress, strain and stiffness.

Stress is the amount of force acting over a particular area. If a 1 ton boat is suspended by a wire of a cross-sectional area of 1 inch, the stress in that wire is 1 ton per square inch. It doesn't matter what the wire is made of, the stress will be 1 ton per square inch. By using this concept, the strengths of different materials can be related. You can have a large piece of wood as strong as a smaller piece of steel but, because of their different cross-sectional areas, the stresses at which they break would be very different.

For metals, there are two useful values of stress to consider: the Ultimate Tensile Stress (UTS) which represents the breaking stress, and the Proof Stress (or for steels, Yield Stress) which represents the maximum useful static stress. The table shows sample stresses for a range of materials. These are guidelines only, and need to be modified to allow for certain further considerations:

- metal is subject to fatigue if put under repeated or cyclic loads.

- stress concentrates locally around holes, defects, sudden changes in cross-section and so on.

- the fact that even if you can accurately predict the strength of a fitting, it is rare to be quite so confident of the service loads it will be required to take. Ample factors of safety are needed.

The subject is further confused by the fact that different alloys, for instance the brasses or the steels, can have very different strengths. It tends to be that the stronger an alloy is, the more brittle it becomes.

Strengths	**Yield/Proof Stress (N/mm^2)**	**UTS (N/mm^2)**
Mild Steel	250	400
High Tensile Steel	1000	1500
Stainless Steel 316	325	575
Aluminium - cast - LM4	85	150
Aluminium - plate/bar	80-250	140-400
Copper - plate/wire - C101	200	300
Brass - cast - SCB4	90	280
Brass - plate/rod - common brass CZ108	340	470
Brass - plate/rod - naval brass CZ112	300	440
Brass - plate/rod - high tensile brass CZ114	285	510
Bronze - cast - gunmetal LG2	115	240
Bronze - cast - Phosphor bronze PB1	145	250
Bronze - cast - aluminium bronze AB2	275	680
Bronze - plate/rod - Phosphor bronze PB102	345	485
Bronze - plate/rod - Aluminium bronze CA104	385	720

All figures are for guidance only, and will vary widely depending on the heat treatment and/or work which the material has undergone

Strain is defined as the extension per unit length, usually expressed as a percentage. So if our wire was initially 100m long, and extended to 102m under load, the strain is said to be 2%. The amount of strain at fracture can give us a feel (but no more) of the brittleness of a material. Pottery breaks at about 0.5% strain, piano wire (steel) at 5%, mild steel at 30%, rubber at 2-300% and so on. Typical working stresses for metals induce strains of about 0.2 - 0.3%.

And finally, **stiffness**. Return to our 1 ton boat on the 1 inch wire. If the wire were steel, it would barely stretch at all. If it were wood it would stretch more, nylon more still, and rubber might simply keep extending to leave the boat on the ground! Each material under the same stress shows different strains. Divide stress by strain and you have a measure of stiffness - steel has a high value, rubber a low one. Stiffness - referred to as "Modulus of Elasticity" or "E" - stays fairly constant for a given base metal irrespective of the alloy. So wrought iron, mild steel, cast iron, stainless steel and high tensile steel all have virtually the same E. The table lists values for the usual metals found in boats.

Stiffnesses	**E (kN/ mm^2)**
Wood - along the grain	9-12
Aluminium & alloys	70
Copper, Brass, Bronze	120
Steel & Iron	210
Carbon fibre/Kevlar/ Boron fibre	300-800

Does any of this relate to the real world? To answer the question, let us look at one of the more "engineered" aspects of a boat: the rig. If you subscribe to the view that it is useful to stay the mast such that it remains roughly in the same place, you need to use a material that is both strong (to avoid large section areas and so reduce windage) and stiff (to maintain rig tension). Look at the strength and stiffness values and you can see that steel is as strong as most things, but considerably stiffer. Hence steel in various forms, is used for standing rigging - any other metal would be a nonsense. Only if you have a downwind rig such as square rig where the stresses are lower and the windage of less importance, is the use of traditional rope a feasible option. It is probably fair to say that the development of windward ability in boats owes as much to the availability of steel wire as it does to developments in rigs and sails.

Stiffness in rig adjusters is not so vital since, even at high strains, the length of the adjuster will be so small by comparison with the length of the stay that the overall extension is acceptable. So bronze rigging screws or deadeyes are feasible even though they are less stiff than steel screws - and from the point of corrosion rather better.

In practice, a large proportion of a boat's fittings and, indeed, most things we use in everyday life are designed for stiffness rather than strength, and in broad terms that outcome results from designing "by eye" or experience. For example, the pen I'm using now needs to be stiff, but the stresses in its casing must be trivial. Chairs and tables shouldn't wobble too much, but it is easy to work out that service stresses are very low. Deck fittings tend to pull out - often with a bit of deck or cabin top attached - rather than break.

All of which means that the selection of materials for general boat fittings tends to be based on considerations of usage, appearance, weight and workability rather than pure strength. For example a cleat will need to take so many turns of a particular size of rope, and that will pretty much determine its size. As long as the supporting structure and fasteners are adequate, the cleat could be made of almost anything. So in the areas where stiffness is more important to the function of an item than strength, what looks right usually is.

Fasteners

“If all else fails, use bloody great nails”

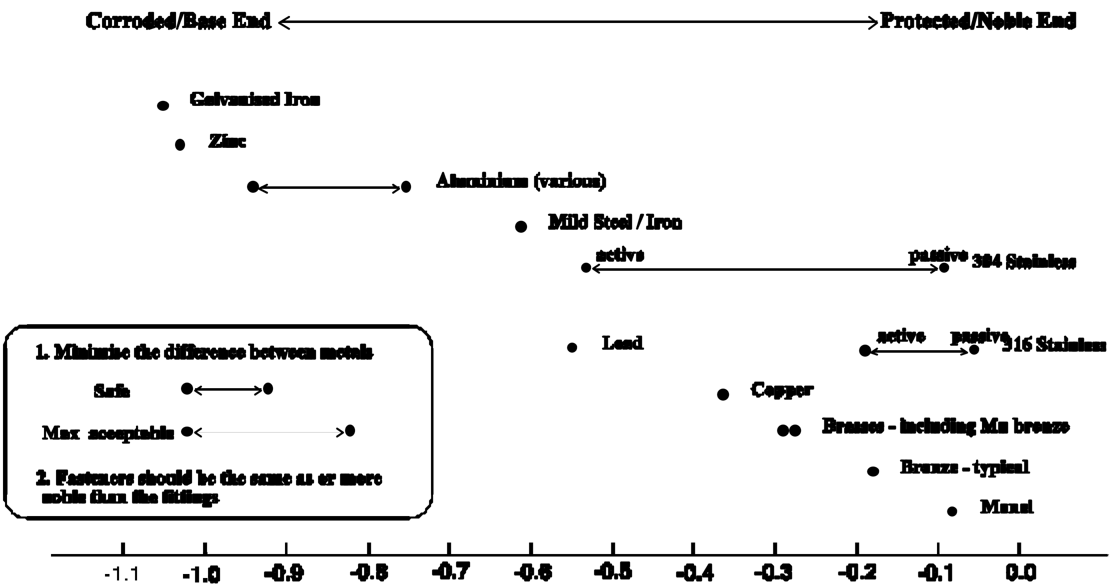
With fasteners, additional factors come into play. They need, of course, to be strong and, it’s a good idea if they are cheap, since you will use hundreds in even the smallest craft. But perhaps most important is that, once installed, they should neither corrode, nor be corroded by, the items being fastened - at least for a reasonable period of time. In this context there are two main types of corrosion to worry about.

Galvanic Corrosion

The first is galvanic corrosion, where two different metals are connected in the prescence of an electrolyte. Sea-water is, unfortunately, an excellent electrolyte and gets everywhere on a boat. The galvanic chart shown below shows the various electropotentials of commonly used metals in boats. I’ll not to get bogged down in too much chemistry, but here are three points which help to make the table useful:

- Where two metals are linked, the one to the left will corrode.
- An electropotential difference of 0.1 volt is usually safe and 0.2 volts usually acceptable, subject to the next proviso.
- The rate of corrosion depends, amongst other things, on the surface areas of the exposed metals. If the fastener is less noble than the fitting, it will corrode very quickly. If more noble you will get a useful working life.

Galvanic Chart



So is this of any practical use?

- It explains why most fasteners are at the noble end of the scale. Aluminium would be a nightmare, so make sure your pop rivets are monel (aluminium pop rivets are widely used the in the car industry).
- You can deduce which fasteners to use for which fittings (see table on the next page). Galvanised fasteners should of course be avoided on stainless or aluminium equipment. Less obvious is that brass screws are unsatisfactory, perhaps dangerous, for bronze fittings.
- There are some alloys which can create their own galvanic couple. The most significant is brass where (in the presence of an electrolyte) one ‘phase’ will corrode rather than the other. This is known as dezincification. A brass component that has been subject to dezincification is terrifying to behold - it has the appearance of, and not much more strength than, a ‘Crunchie’ bar.

It is also possible to induce a similar effect by working steel. For example, the heads and points of steel nails will corrode in preference to the shanks because they have been worked. This is not often significant in boats, but may help to explain why, when you are trying to remove old tacks or nails, the heads keep breaking off!

Fasteners for fittings

Fitting made of:	Fasteners: Acceptable	Fasteners: Avoid
Galvanised	Galvanised or Stainless	Brass or Bronze
Aluminium	Stainless	Galvanised, Brass or Bronze
Brass	Brass or Bronze	Stainless
Bronze	Bronze or Stainless	Brass
Stainless	Stainless or Monel	Galvanised or Brass

Chemical Corrosion

The second type of corrosion to give concern is attack from various chemicals. In general, metals form oxides to protect themselves, the crucial distinction being whether the oxide forms a hard self-repairing film, as in stainless, aluminium and yellow metals, or flakes off to expose fresh metal, as in steel. The effects can range from cosmetic if bronze or galvanised deck fittings become 'weathered', to dangerous if nail sickness occurs. The latter is primarily caused by the generation of acids as woods saturate and break down, oak being the worst offender. It's well known that steel can suffer - hence corroded keelbolts and hull fasteners. But is it less widely appreciated that stainless is also susceptible.

Stainless Steel

Because there are so many misconceptions about stainless steel (a misleading term in itself, though not as bad as 'inox') it's probably worth momentarily delving into the technicalities. As well as iron and carbon, stainless steels include a number of alloying elements. Of these the most important is chromium (Cr.). If there is more than 12% in the alloy, a complete layer of chromium oxide surrounds the metal. This layer, the 'passive' film, is resistant to most things and will self-repair in the presence of oxygen. Chromium-only stainless steels tend to be brittle, so about half as much nickel (Ni) is added to create a more usable material. 304 stainless (or A2) is one of the more commonly available and includes 18% Cr and 10% Ni. If you have a stainless sink or exhaust pipe it's likely to be 304 and, as anyone who's ever tried cleaning a sink or pulpit will know, is somewhat prone to attack from the organic acids generated by food, fingerprints and other pollutants.

The chemical and food industries alleviate these problems by adding a dash of Molybdenum (Mo). Thus 316 stainless (or A4) typically comprises 17% Cr, 11% NiI, 2 % Mo and is widely used to store and transport some very aggressive substances. So, you might think that this is the perfect stuff to use as a fastener in or through wood, and from the sole perspective of chemical attack you'd be right. But we need to reconsider the environment in which the fastener is doing its job. Imagine a bolt, nail or screw fastening a plank to a frame underwater. The head, at or near the surface, will be oxygenated enough to maintain its passive film. The shank, buried deep in the structure, is likely to be starved of oxygen but will be surrounded by various acids and chlorides. In these circumstances, the passive film may break such that the stainless becomes 'active'. This has two effects: firstly, look back at the galvanic series and you'll see that the difference between active and passive electropotentials in 304, and to a lesser extent in 316, is enough to cause galvanic corrosion. Like brass, stainless can form its own galvanic couple. Secondly, without the oxide layer, the stainless will corrode about as fast as steel. The upshot is that stainless fasteners below the water-line - irrespective of the grade - **may be no better than mild steel.** Above the water-line (more oxygen and less electrolyte) such fastenings are fine, but unless you value the extra lustre of 316, there's little point in paying for it.

While on the subject , I'd like to tackle the nonsense of shot-blasted stainless fittings which seek to ape the appearance of galvanised fittings. The ability of the passive film to self-repair is optimised if the surface of the stainless is highly polished. By forming millions of sharp peaks during shot-blasting, you significantly reduce this ability, which is why such fittings rust. If you want the appearance of galvanised fittings, try galvanised fittings.

Steel and Galvanising

Unprotected mild steel has no place on a boat because of its propensity to corrode, but it's a good material if suitably protected. This is usually achieved by adding a layer of zinc - "galvanising" - which has two benefits: firstly, zinc has good resistance to chemical corrosion and, secondly, it will corrode preferentially to the steel in the presence of an electrolyte. There are different types of galvanising, the key variable being simply the amount of zinc attached to the steel. For a useful life in a marine environment you need a covering of about 100 microns of zinc (1 micron is one thousandth of a millimetre). This can be provided by hot dip galvanising (up to 125 microns), painting (about 40 microns per coat) but not usually by electroplating, which tends to be limited to about 20 microns. So the BZP (Bright Zinc Plated) fastener available from your local hardware shop might be fine for the greenhouse, but won't last for any useful time on a boat. For marine fasteners you need hot dip (or spun) galvanising.

Unfortunately the cost of galvanised fasteners is increasing. In particular, galvanised nails are becoming increasingly rare and tend to come in large quantities. Apart from getting fasteners galvanised yourself - remembering that threaded components need to allow for the layer of zinc - options are restricted to paint coatings, which are only effective if unchipped, or the substitution of other materials.

Copper

Boat nails and roves widely used in the construction of traditional wooden boats are some of the few specialist boat fasteners still produced in copper. For these relatively flexible structures copper nails are perfect: easily worked, corrosion resistant and ductile enough to allow for movement. With the advent of glued construction methods and, of course, plastic hulls, it's quite surprising that copper boat nails are still available. The range, is however, reducing. For example, $^{3}/_{16}$" and $^{1}/_{4}$" roves (5mm & 6mm) are no longer made, so canoe builders will have to clench their nails. Also disappearing are the 'odd' sizes so useful on a re-fastening job where moving up one size can very effectively re-tighten the hull.

Brass

Brass is most commonly available as woodscrews - up to 14 gauge - and as machine screws/bolts. Remembering the problems of dezincification, brass screws should only be used in protected environments, for example in interior furniture, or in applications where your life will not depend on them.

Bronze

The usual alloy for fasteners is silicon bronze. As well as being used for bolts, coachbolts and ringshank nails, this is one of the few materials in which very large woodscrews (up to 30 gauge) can be obtained. It is sufficiently resistant to corrosion to have a very long working life (perhaps thirty to fifty years) so, in terms of value, bronze fasteners, though expensive, are competitive.

Copper-based Alloys - which is which?

	Name	Designation	Alloy Elements	Typical Uses
Brasses	Common Brass	CZ108	Zn 37%	Interior Fittings
	Naval Brass	CZ112	Zn 37% Sn1%	Pre-war boat fittings
	High Tensile Brass	CZ114	Zn 37% Mn 2% Al 1.5% Fe 1% Pb 1.5% Sn 0.8%	Snap shackles, Propellers, Winches
	De-zincification resistant (DZR) Brass	CZ132	Zn 36% Pb 2.8% As 0.1%	Hull valves and skin fittings
Bronzes	Aluminium Bronze	CA104	Al 10% Ni5% Fe5%	High strength fittings
	Phosphor Bronze	PB102	Sn 5% P 0.2%	Fabricated/wrought fittings
	Silicon Bronze	CS101	Si 3% Mn1%	Fasteners
	Gunmetal	LG2	Sn 5% Pb5% Zn5%	Cast hardware
	Aluminium Bronze - cast	AB2	Al 10% Ni5% Fe3%	Stanchions, some mast hardware

Al - Aluminium, As - Arsenic, Fe - Iron, Mn - Manganese, Ni - Nickel, P - Phosphorus, Pb - Lead, Si - Silicon, Sn - Tin, Zn - Zinc