The Shock of the Old

In the first of a new series on refining traditional rigs, Moray MacPhail follows the science.

The most talented architect cannot do without tradition. He needs a knowledge of what was done in the past to know why certain things were done, for only then can a selective judgment be brought to bear on traditional characteristics, and those which are of value be separated from those due to be discarded", wrote Douglas Phillips-Birt in *An Eye For A Yacht*, Faber 1955.

That's going to be my approach to updating traditional rigs and continuing to develop them. Much is spouted in the name of tradition, the old ways of doing things valued just because they are old. And there's techno-babble with celebrity endorsement of gear indispensable because it is new. Steering between those two camps I'll try to show why traditional rigs are as they are – and how they could be developed, for I'm firmly of the opinion that they have much to offer for recreational boats today.

We'll start with a grounding in the materials available and how they work towards rigging a boat. Then to the geometry and arrangement of masts and standing rigging, and the loads to expect. Thus to the hardware needed to withstand those loads, together with the practical aspects of the fittings which make up the standing rigging. Finally, when we're all much older, to arrangements for the running rigging.

Above: *Gaffers, fairly ancient and very modern, race at la Semaine du Golfe Morbihan in 2008.*
Below: *Inspired by traditional Scottish workboats, designer Nigel Irens created the 22' (6.7m) modern lugger Romilly.*
Photographs: Kathy Mansfield.

Overcoming Inertia

Being in my prime of life, I think in feet and work in metres. For those not obliged to continually convert, a short explanation, using round number conversions where possible.

LENGTH: 1 foot = 12 inches = 0.3048 metres (m) = 304.8 millimetres (mm). 1 inch = 25.4 mm. 1 metre = 39¼ inches. The editor, who begrudges every unnecessary word, will inevitably want to complicate things by using the symbol ' for feet, so 1' is one foot and " for inches, thus 6" is six inches.

If that isn't confusing enough, the snag with units of length is that there are no ready round number conversions, so you need to be consistent.

AREA: This is a length multiplied by a length, so you get square inches, or mm^2 or something like that. For common shapes, Figure 2.1 illustrates how to get the areas. For odd shapes, you can trace onto graph paper or use a scanner! For sails, it's 11 square feet (11 $sq.ft^2$) to the square metre ($1m^2$).

MOMENT OF INERTIA: A bit more esoteric, but useful. The moment of inertia of a section is the sum of each little piece of area multiplied by the square of its distance from the neutral axis – for our purposes usually the centreline. It applies when we look at bending and buckling, so if you have ever had a centreboard break or a mast fall down, read on.

How to work it out? For simple sections see Figure 2.2, for more complex sections see Roark [Ref 2.1] The thing to bear in mind is that the moment of inertia (I) is always a length to the 4th power, for example mm^4 or in^4. Numbers to the 4th power mean that small changes make big differences. It's worth noting that having just 5% off its diameter to clean up an old spar Ifor re-varnishing to make it look newer will reduce its moment of inertia by nearly 20%.

MASS is the amount of matter in a thing, which will stay constant under all usual circumstances. 1 kg(mass) = 2.2 lb(mass), which rather happily means that 1 ton – the British 2240 lb type – is near enough 1 tonne – the metric 1000 kg type.

FORCE is different to mass, though the units used to express it often sound the same. In round numbers, 1 kg (mass) is about 10 Newtons (N), or 1 kg f. By a neat irony that the apple which fell on Isaac Newton probably weighed about 1 Newton. It matters whether you are talking kg or Newtons – or ton or ton f – so I'll try to explain as we go along.

PRESSURES or STRESSES are forces applied over an area, leading to ton f per square inch, Newtons per square metre – referred to as a Pascal(Pa) – or something like that.

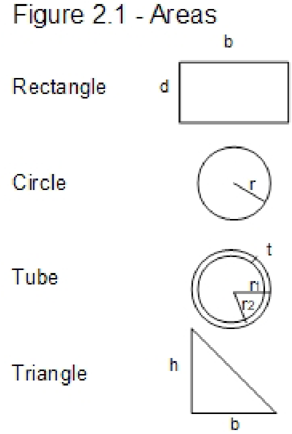
Because 10, 100 and 1000 are much easier numbers to use than 12, 32, 2240 and so on, I will use metric units throughout the series, with enough conversions to 'British' units to enable UK and US readers to follow the plot.

How does stuff behave?

To get a grasp of how materials behave when part of a structure, I'm going to share three more ideas with you.

STRESS, as mentioned above, is the amount of force acting over a particular area. If a 1 tonne (1ton) boat is suspended with a rod of a cross-sectional area of 645 mm^2 (1 square inch) the stress in that rod is 15.5 MPa or 1 ton per square inch. It doesn't matter what the rod is made of, or what shape it is, the stress will be the same. Different materials break at different stresses, though.

Figure 2.1 - Areas



Rectangle: $Area = b \cdot d$

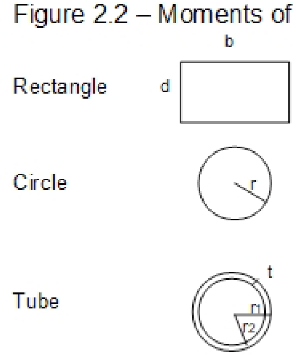
Circle: $Area = \pi \cdot r^2$

Tube: $Area = \pi (r1^2 - r2^2)$ for thick-walled tubes

$Area = 2 \cdot \pi \cdot r \cdot t$ for thin-walled tubes

Triangle: $Area = \frac{b \cdot h}{2}$

Figure 2.2 – Moments of Inertia



Rectangle: $I = b\frac{d^3}{12}$

Circle: $I = \frac{\pi \cdot r^4}{4}$

Tube: $I = \pi \frac{(r1^4 - r2^4)}{4}$ for thick-walled tubes

$I = 2 \cdot \pi \cdot r^3 \cdot t$ for thin-walled tubes

STRAIN is the extension per unit length, usually expressed as a percentage. So if the rod was initially 10m long, and extended to 10.2m under that load, the strain under that load 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 200 to 300% and so on.

STIFFNESS: Back to our 1 ton boat on the 1 inch square rod. If the rod 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 – the load per unit area – shows different strains – extension per unit length. Divide stress by strain and you have a measure of stiffness: steel has a high value, rubber a low one. Stiffness is usually referred to as Modulus of Elasticity or E.

Between them, strength and stiffness give you about as good a feel for the behaviour of a material as two numbers can, as illustrated in the following table:

Table 2.1 What Strength and Stiffness can describe – a few examples

	Strong	Weak
Stiff	Steel	Pottery
Flexible	Nylon	Cooked Spaghetti

How does this relate to boats? For standing rigging you need a material that is both strong – smaller section areas and less windage – and stiff – to maintain rig tension. Steel is as strong as most things but considerably stiffer. So it is often used for standing rigging

Stiffness in rig adjusters is not so vital since the length of the adjuster will be very small by comparison with the length of the stay. Even at high strains – a percentage of the length, remember – the overall extension is acceptable. So bronze rigging screws or traditional deadeyes with rope lanyards are feasible even though they are less stiff than steel rigging screws.

Most things we use everyday are designed for stiffness rather than strength, often designed '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. Deck fittings tend to pull out – perhaps with a bit of deck or cabin top attached – rather than break.

So the selection of materials for general boat fittings is often based on factors other than strength. For example a cleat will need to be large enough to take several turns of rope but could be made of almost anything; wood or plastic or metal. Where strength is not the main factor, what looks right often is. But that's not always true for the rig as we shall see.

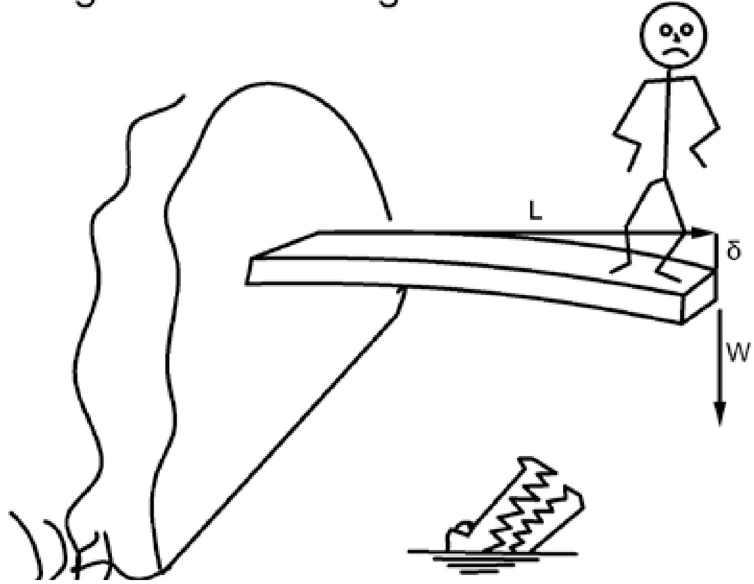
On beams, trees and – unstayed – masts

Imagine a plank stuck in a wall and you standing on the end. The plank will move at the point where you are standing; if you are too heavy or the plank too thin, it will break at the wall.

The plank must create an upwards force identical to your weight, and transmit that force into the wall, which ideally doesn't move. The plank shuffles your weight over to the wall by 'shear' stresses which it can resist because it is all in one piece. To see how this works, get a short piece of wood about 4-5 cm thick (say 1½- 2") and try to bend it. Nothing much happens. Now get hold of a thick softback book or a ream of paper. You can bend that, even though it is roughly the same amount of material. The pages of the book can slide easily over each other and can't pass on shear stresses like the piece of wood can.

The shear stresses create tension in the upper surface of the plank and compression in the lower surface. These stresses (forces) create strains (changes in length), so the top face gets a bit longer, the lower one a bit shorter and the plank bends downwards. These tensile and compressive stresses accumulate the further the distance from the load – you standing on the end – and quickly become significant compared with the strength of the material. Try holding a thin piece of wood and pulling it apart lengthways with your hands. Not much happens. Now break it by bending it. Easy and in doing so you have just created stresses too high for the wood to withstand.

Figure 2.3 Walking the Plank



So how might these stresses change? If you:

Double the.....	then the stress...
Load (W)	doubles
Length of plank (L)	doubles
Width of plank (b)	halves
Depth of plank (d)	divides by 4
Diameter (if a circular beam)	divides by 8 – because it is like doubling the width and doubling the depth

It doesn't matter what the material is. The stress in a plank of carbon fibre is the same as the stress in a plank of wood. Whether the material is strong enough is a separate issue. If you want to maintain the stresses on the outer surfaces of a plank at the same level, then you make it progressively thicker as it approaches the fixed point and you end up with the shape of the Eiffel Tower, the cantilevers of the Forth Rail Bridge and the trunks of trees.

So much for the stress, but what about the movement? Now if you

Double the.....	then the deflection...
Load (W)	doubles
Length of plank (L)	multiplies by 8
Stiffness of the material (E)	halves
Width of plank (b)	halves
Depth of plank (d)	divides by 8
Diameter (if a circular beam)	divides by 16 – because you are doubling both width and depth

So small changes in the dimensions – say 5% longer and 5% thinner – make for large changes, in this case about 33%, in the deflection. That's the effect of units to the 4th power.

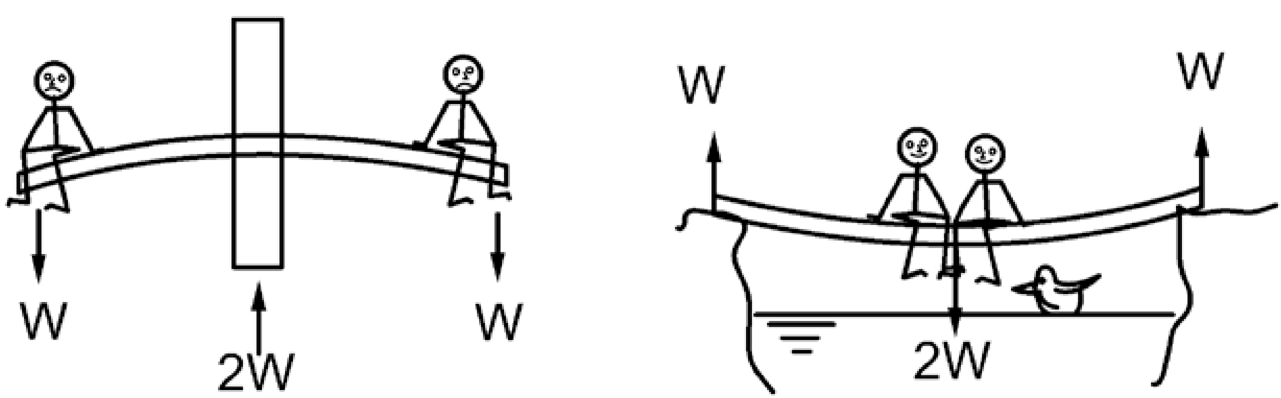
But lots of beams aren't fixed at one end but supported at both ends, like a boom or spinnaker pole for example. As the diagram shows, a beam between two supports is the same as two fixed beams upside down. But here maximum deflection and stress are in the same place. You know this already: if a plank is going to let you down, it is in the middle of a stream.

Let's rotate the wall-mounted plank to become a mast 6m(20') long with a sail loading of 500kg (1103 lbs) at the masthead. The maximum bending moment and hence stress is at deck level. Using data for Douglas fir (48 MPa max), the diameter needed for our 6m mast to avoid breaking under a side loading of 500 kg would be 180mm (about 7¼"). The equivalent carbon fibre (typically 500 MPa max) mast to do the same job could be about 84mm (3¼" or so) diameter. You can see why modern materials have found an application as unstayed masts.

Staying put – or how sweating up a halyard works

Imagine a jibsheet – fig 2.7a. The jib is pulling at one end with a force T, which the rope is transmitting back to a cleat, which resists with an exactly opposite force by loading up the fasteners in the deck which ... etc. But if the rope isn't

Figure 2.6 Bending in the Middle of a Plank



led correctly, you may want a block in the middle of the sheet. This pulls with a force P – fig 2.7b. If there is any load P, the sheet has to deflect sideways, however tight it is to start with. The sheet counteracts the pull of the block by diverting some part of its load T to deal with P. One way of reckoning this is to resolve the force T – fig 2.7c – in the direction of P.

If the angle of deflection is 0, the rope goes straight through the fairlead without touching it. At the other extreme, if the angle of deflection is 90˚ each side of the lead, sin 90˚ is 1 and P is 2T and the rope is turned through 180˚ as in a halyard. You can see that for small to medium deflections P is going to be a lot less than T.

Which is why:

a) However tight your foresail luff, it will never be straight while the sail is drawing.

b) The easiest way to break a bobstay or associated fittings is to have your anchor chain or mooring line pulling across it as the boat sheers about.

c) Sweating up a halyard by pulling sideways can be very effective: the small pull sideways creates a big pull lengthways.

Back to our plank in the wall, this time with you dangling from one end, and a wire going vertically to a skyhook – fig 2.8a. The wire takes your weight (W) and the plank does more or less nothing. But what if you can't find a skyhook and have to attach the wire to the wall?

In fig 2.8b the wire leads away from the end of the plank at an angle. The vertical component of the tension in the wire Tv must still equal your weight (W) otherwise you would either fly or fall down.

So, as the angle between the stay and the plank reduces, the load in the wire and the compression in the plank rise to become much bigger than the original load. Rotate this scheme to represent a mast and a shroud, and you can see why staying angles should be more than 10˚ to limit loads in the rig.

Adding a stay to our mast induces a corresponding compression in the mast. Staying our 6m mast on a boat with a 2m (6'6") beam, with 500kg at the masthead gives about 3 tonnes tension in the stay, and about 3 tonnes (or 30,000 N) compression in the mast.

Douglas Fir can stand a compressive stress of 48 N/mm², so all we need is 625 mm² of mast section to cope with the 30,000 N compression. That gives us a diameter of about 30mm (1¼"), as opposed to 180 mm (7¼") which we worked out earlier for the unstayed version. Wow! So that is why stayed masts are so widely used.

Sorry, it isn't quite like that.

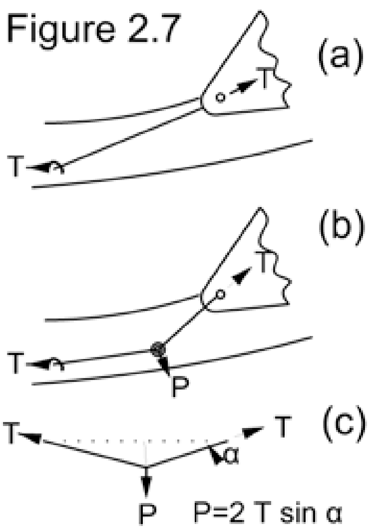
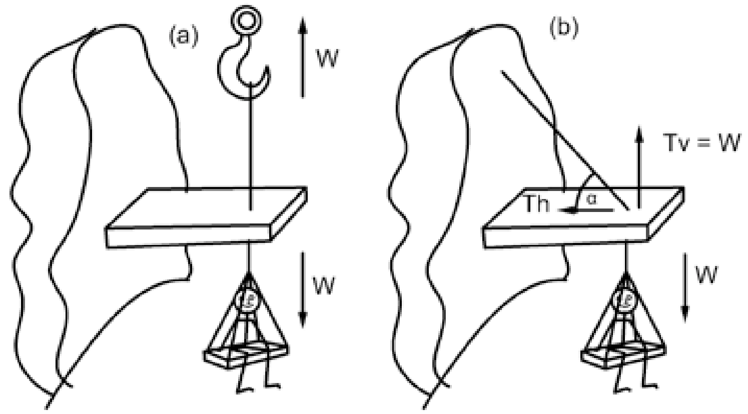


Figure 2.7

Figure 2.8 When a Skyhook isn't available


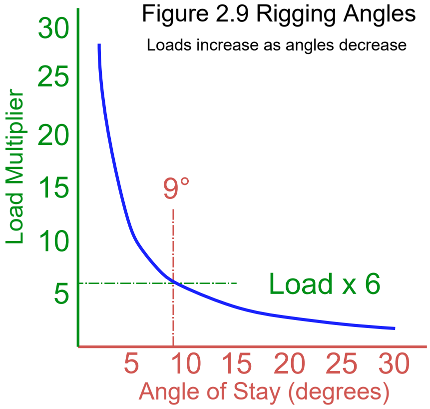
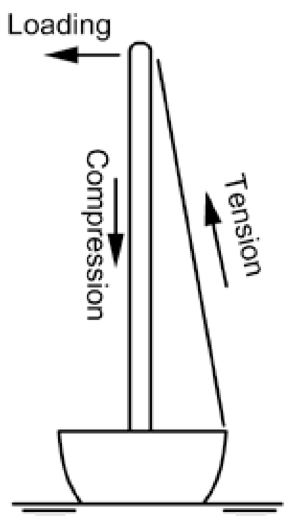


Figure 2.9 Rigging Angles
Loads increase as angles decrease

Figure 2.12 Adding a Stay


Buckling up

Things usually fail in compression by buckling. Push on something that is slender and it will bow out sideways at a fairly low load. Remove the load and it will spring back into its original shape none the worse for wear. This is buckling and it depends on stiffness (E) and inertia (I) as below:

Double the.....	**then the buckling load...**
Length	divides by 4
Stiffness of the material (E)	doubles
Diameter (d)	multiplies by 16
Strength of the material	stays the same

For a given section and material, the most important factor is the length of the item. But the load at which the column buckles is also influenced by whether the ends are fixed (like a keel-stepped mast), pinned (a deck-stepped mast) or free standing.

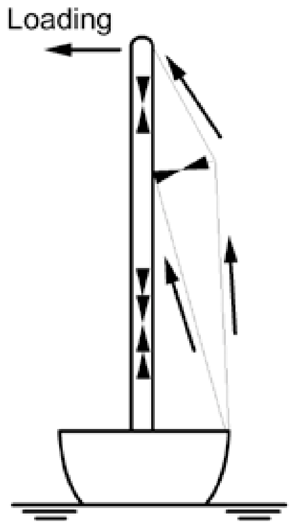
Plugging in the numbers revised to allow for buckling, the diameter needs to be 100mm (4") for a keel stepped mast, and 120mm (4¾") diameter for a deck stepped one. That is still a pretty useful saving over the original unstayed version of 180mm (7¼").

Spreading the load

Now suppose we add a set of spreaders 66% of the way up our mast, and 90% of the beam. They act like the jibsheet lead mentioned earlier, pushing the stay rather than pulling a sheet. This push goes into the middle of the mast, and is counteracted usually by the lower shrouds.

The angles have increased to 24° for the cap shrouds – the uppers – and 14° for the lowers, which is good. Shroud tensions are now 1.24 tonnes for the caps and 1.93 tonnes for the lowers. Topmast compression of 1.2 tonnes permits a 50mm (2") diameter. The shorter length of the lower mast allows the diameter to be reduced to 75-85mm (3-3½") even though the load is still 3 tonnes.

Figure 2.15 Spreaders



You can see the beginnings of a progressive trade-off involving weight, windage, complexity and cost which can be carried to the umpteenth degree by adding more and more sets of spreaders which we'll look at later.

Why wood is good for masts

To sum up, if something is subject to bending – an unstayed mast, for example – then the critical thing is the cross-sectional shape whose dimensions are determined by the material strength.

If subject to compression then the key factors are cross-section, length and stiffness, in that order. Strength is irrelevant, which is why a relatively low strength material like wood can be effectively used for spars. If subject to tension then strength is the only relevant factor.

In the September/October issue – out 27 August – I'll move a little closer to reality by looking at the actual properties of some of the materials we might use to rig a boat.