The Shock of the Old

Part 3: Choosing What To Use

Don't do dogma, says Moray MacPhail as he continues his series

The story so far. In W142, it was about bending of planks and buckling of columns; in W143, a quick review of the characteristics of the materials – wood, composites and metals – that are available. This time it is about putting those two aspects together to give an idea of why materials are chosen for particular jobs.

Here is the first of a few tables with key figures to help us. For each material I have listed the Young's Modulus (E – the higher the number the stiffer it is); the density (water is 1000 kg/m3 for comparison); and the maximum tensile and compressive stresses which the material can withstand.

For almost all of these materials, I have had to make assumptions: on the state of temper of the bronze; the type of the GRP layup; the moisture content of the wood etc., which may not be appropriate for all cases but should do for our purposes here.

Table 1 Material Properties

Material	E	density	σ max (tension)	σ max (comp)	Assumption
	Mpa x 1000	kg/m3	MPa	MPa	
Spruce	9.9	360	60	38	12% Moisture
Teak	10.7	630	118	58	12% Moisture
Marine Ply	9.0	525	30	25	Douglas Fir Ply
Glassfibre	14.0	2000	300	250	General layup
Carbon	110.0	1580	700	500	Woven tubes
Stainless steel	193.0	8000	580	580	316 or A4 grade
Aluminium	70.0	2800	240	240	Medium strength alloy
Bronze	116.0	8850	480	480	Phosphor bronze half hard

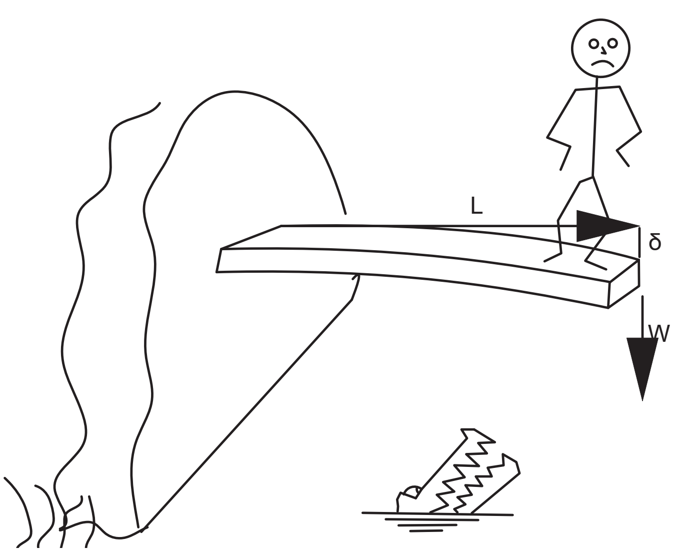
Bending

Many of the components in a boat are subject to bending, including unstayed masts, other spars, the planking, even the keel.... For illustration, we'll return to our plank in the wall first seen in W142.

Let's say it is 10" wide and 6' (0.25 x 1.8m) long. It is fixed into a wall at one end and I – at my pre-lockdown weight – am standing on the free end. Two ways of looking at this plank come to mind. The first is to fix the thickness – at 2" (50mm) – and look at the deflection. The second is to specify the deflection and work back to the thickness. What happens to planks made from each material listed?

The good news is that nothing breaks, the maximum percentage stress being 43%. So if the aim was to stop me falling, then all the

Figure 1 Walking the Plank (again!)



materials work in this application with a good margin of safety.

The left hand set of figures applies to a case where the actual size of the plank is important – it is constrained to be 2" (50mm) and you can see that there is a trade-off of weight versus deflection. If it is minimum weight you want, then wood is the answer, carrying 5-10 times its own weight. If the aim is to minimise the deflection, steel is the clear winner but the plank weighs twice as much as the load. If on the other hand you wanted large deflections without much chance of breaking, then glass fibre is a good choice; ideal for fishing rods, tent hoops and sail battens.

As I mentioned a couple of articles back, most things are designed for – and often judged by – stiffness rather than strength: "This feels strong!"

The figures on the right hand side apply to the case where stiffness is the aim. Of course, if you are going to specify deflection, there is no point in using a material which deflects a lot like glassfibre. So why is it widely used for hulls in all kinds of craft where it is subject to both local and overall bending? Because other considerations come into play. Glass fibre has the great advantage of being cheap to form into complex shapes in low volume production. The trick then is to mitigate any weaknesses by cunning design – rather than a homogeneous plank using fibres in all directions, a directional layup on a lightweight core could be much more effective. So even though glass fibre is not very good at resisting bending, it is a useful material for making hulls or other complex shapes.

At a cost in weight, steel could do the same job using a third of the thickness and indeed where weight is less critical and/or cost predominates – for example: narrowboats, larger cruising yachts, oil tankers – it is widely used. It would clearly be inefficient to use in thin-shelled structures like cars. It is, though, because with sophisticated tooling, steel allows the cheap production of high quality, high consistency components which are easily joined and finished. So steel is not particularly weight efficient at resisting bending but a great material to mass-produce car bodies from. The fact that people like me spend time grovelling about chasing the rust around doesn't, I'm afraid, feature very highly at the design stage.

While we are on the subject of car bodies, you can see from the table why racing cars used to be built from aluminium, and are now built from carbon fibre, and why both these materials find increasing use in both cars and boats.

But why not wood? Both spruce and elm make for the lightest result, and with their massive resources, Formula 1 teams could easily afford the cost of construction. Mainly because in a complex structure – not a simple plank – wood needs to be laminated or otherwise combined to provide resistance to forces from a variety of directions, so the performance along any single direction is reduced, as we can see with plywood.

Where you do want a simple plank, as in scaffolding boards or the planking of a boat, solid wood is a very good material and is still a good choice in both modern and traditional construction. So why not use spruce for planking? Because

Table 2 Bending – Plank 0.25m x 0.05 m, 1.8m long fixed one end, 750N (75 kg) load

Case 1 – 50 mm thick				Case 2 – 40 mm deflection		
Material	deflection (mm)	Stress (Mpa)	Weight (kg)	Thickness (mm)	Weight (kg)	stress (% max)
Spruce	56.6	22%	8	56.1	9.1	17%
Teak	52.3	11%	14	54.7	15.5	9%
Marine Ply	62.2	43%	12	57.9	13.7	32%
Glassfibre	40.0	4%	45	50.0	45.0	4%
Carbon	5.1	2%	36	25.1	17.9	7%
Stainless steel	2.9	2%	180	20.9	75.1	13%
Aluminium	8.0	5%	63	29.2	36.8	16%
Bronze	4.8	3%	199	24.7	98.4	11%

Table 3 Tension – Rod 6m long, load 5000N (500kg)						
	Case 1 – 6mm diameter			Case 2 – max stress 30%		
Material	Extension (mm)	Stress % max	Weight (kg)	Diameter (mm)	Extension (mm)	Weight (kg)
Spruce	107.2	295%	0.06	18.8	10.9	0.60
Teak	99.2	150%	0.11	13.4	19.9	0.53
Marine Ply	117.9	589%	0.09	26.6	6.0	1.75
Glassfibre	75.8	59%	0.34	8.4	38.6	0.67
Carbon	9.6	25%	0.27	5.5	11.5	0.23
Stainless	5.5	30%	1.36	6.0	5.4	1.38
Aluminium	15.2	74%	0.48	9.4	6.2	1.17
Bronze	9.1	37%	1.50	6.6	7.4	1.84

considerations of soakage, robustness and longevity come into play. You can build a boat from balsa wood but don't expect to pass it on to your grandchildren.

Despite the generalities resulting from over-simplified assumptions, this trivial example shows that the choice of materials comes from constraints on the one hand – cost, weight, size, skills available, length of production run – and objectives on the other – strength, stiffness, longevity and so on. The constraints and objectives will interact in a different way to create a different solution. That's sound engineering. There is never an all-encompassing solution correct in all situations.

Tension

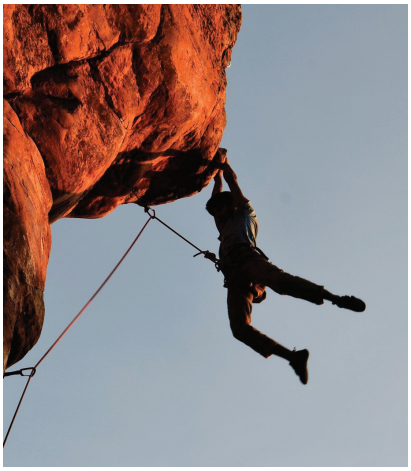
What about tension members like standing rigging? Let us assume a round bar 6m (20') long with the load of 5,000 Newtons (about 1/2 ton). In the first case the diameter is constrained to 6mm (1/4"); in the second the maximum allowable stress is specified at 30%, giving a factor of safety of just over 3.

In the first case, it would seem that wood isn't even in the game, the 6mm (1/4") rod having broken at less than a half of the applied load. But in the second case, weight for weight, solid wood compares very well in tension with metal. The snag is that it is hard to make use of this property in practice because it is very difficult to design a joint which transfers a tensile load evenly across a piece of wood. But close relations of wood – grass and cotton – were, as natural fibre ropes, used for centuries as the best option for standing and running rigging.

Turning to the metals, you can see that at the cost of some weight, steel is the way to go if you want low deflections. Please bear in mind that a solid rod of stainless steel – as listed here – is likely to behave rather differently from a wire made from multiple strands but given that, steel is clearly favourite of the metals for bits of a structure in tension like rigging.

The impressive results come from the fibres, particularly since in a slim tension element you could tailor the layup to suit, rather than use the general properties I have assumed here. So the outcome would be likely to be considerably lighter, smaller and stiffer. It is not surprising that, despite the expense, the yacht racing fraternity use advanced fibres such as Kevlar and carbon in ropes and rigging.

There are still issues of longevity and joining/terminals, but I have no doubt that these materials will find their way onto traditional craft just like the



In some situations, stretch in a rope can be very advantageous..

adoption of polyester ropes and sailcloth over the past 40 years. Better to have less stretch on the bobstay tackle than to have to steeve the bowsprit down when not under load.

Talking of stretch, remember that sometimes it is a requirement. Climbers, for example use ropes which stretch to avoid the possibility of being stopped – literally – dead should they fall.

Compression

Now to slim columns in compression, also known as stayed masts, bowsprits and sometimes booms. I have assumed a 6m (20') long pole, pinned at both ends. The first case shows results for a solid spar of 100mm (4") diameter; the second a tubular spar able to withstand a buckling load of 15000N (about 1½ tons).

In the first case, the table below shows the answer in terms of the load the spar can withstand, its weight, and the relationship between the two. Carbon is the clear winner, with spruce, steel and aluminium grouped closely in second place. As a comparative exercise this is valid but not terribly realistic since while you might use wood in the solid form, it would be strange to use solid billets of steel, aluminium, carbon or indeed plywood!

So for the second case I have assumed a given design load – and wall thickness typical for the material – and worked backwards from that to get the required diameter and weight. Again carbon is the winner, with spruce and aluminium a close second if you are worried about cost and don't mind the windage. If on the other hand weight doesn't matter but space does – as in the interior of a boat – then steel would be a good choice for, say, a mast support pillar.

Glass fibre with its high strength and low stiffness may be a great choice for sailboard rigs where you want the rig to dump load quickly in a gust. I can tell you that it is not a great choice for a mast in compression, resulting in a rig which is either too whippy, too heavy or an unhappy combination of both – I did tell him but he wouldn't listen!

So you can see how the materials for

This modern bicycle frame combines bamboo and carbon fibre!
Photo: www.bamboocycleclub.org

spars select themselves, namely carbon, spruce and aluminium in that order. Sometimes nature does the hard work for you by creating bamboo – a traditional choice for small boat spars, and still used today for scaffolding and bicycles. The final choice of course combines with other considerations like cost, aesthetics, availability, ease of repair and so on.

Finally, what about bronze? In all cases,it is either heavier, weaker orcostlier than the alternatives, so why use it? Because it is usably strong, it doesn't corrode and is not susceptible to fatigue. So for long-lasting fittings, it can be good value. I'll leave the aesthetics to your individual taste.

That's quite enough of this rather abstruse stuff but we will need to refer to it in future articles as we deal with actual rigs. Next time, we'll look at how to design unstayed masts.

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Table 4 Compression – 6m long column pinned both ends

	Case 1 – 100 mm diameter			Case 2 – 15000N (1500 kg) critical load			
Material	Buckling load (N)	Weight (kg)	Buckling Load per kg	Diameter (mm)	Weight (kg)	Wall thickness (mm)	Buckling Load per kg
Spruce	13323	17	785	108	11.5	19	1307
Teak	14400	30	485	105	19.4	19	773
Marine Ply	12112	25	490	110	17.1	19	877
Glassfibre	18841	94	200	125	26.9	6	557
Carbon	148033	74	1988	70	7.9	4	1908
Stainless steel	259731	377	689	65	28.0	3	535
Aluminium	94203	132	714	90	13.8	3	1089
Bronze	156108	417	374	77	37.0	3	405