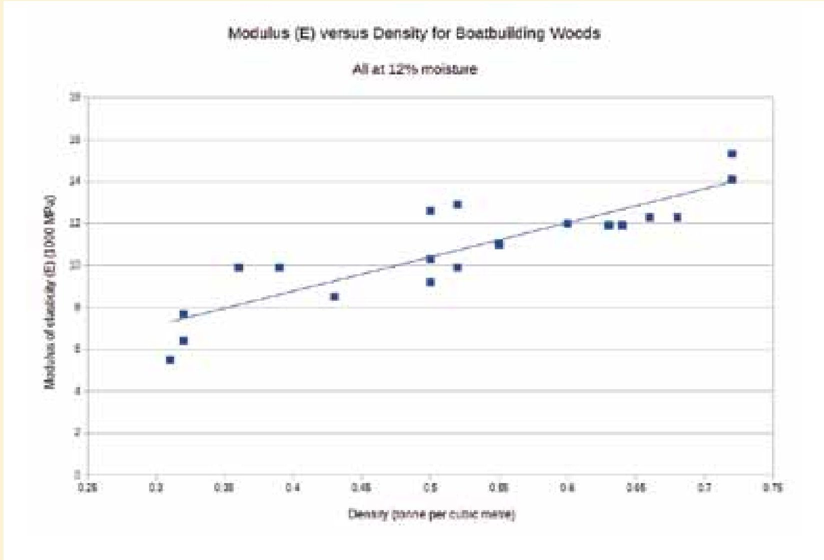
The Shock of the Old

Part 2: The Material World

Moray MacPhail continues his series on refining traditional boats by considering their materials from an engineering viewpoint



Left: *Seasoning Scottish larch 'in stick' at Black Dog Timber. Air drying softwood the traditional way typically takes one year for every 1" (25mm) of board thickness.*

Wood

A bundle of drinking straws is not a bad representation of wood. It is strong in tension, weak and easily crushed across the grain and the tubes are liable to buckle progressively in compression. If you cut one of the straws, the 'crack' which you have just introduced will not progress to the other straws, so wood is very tough across the grain.

With minor exceptions, wood is made from cellulose tubes, the main variation being the wall thickness of the tubes and their diameter. That means the modulus (E) is pretty much proportional to the density, for a given moisture content. So weight for weight, cedar is as stiff in tension as greenheart. If you need flexural stiffness, then for less weight and more inertia (I) – mostly related to size, so the lighter the bigger – you choose lighter woods. Hence spruce, fir and pine for elements in bending or compression like spars. But why not for frames, beams and planks?

Well, wood has its limitations. Firstly it tends to 'creep', which means that if a load is applied over a long period, the wood will permanently deform. So please don't leave a wooden boat on its mooring with high rigging loads. But more important than creep for us is the effect of moisture.

More moisture increases the size of the cell walls, less reduces them. This affects the size of the wood, mostly across the grain as you can see when the gaps between topside planks open up during a period of prolonged hot weather. Natural fibre ropes also change their dimensions as they get wet. Because of their helical construction, the effect of increased cell wall size is to shorten the rope.

In its freshly felled state, the moisture content in a tree may be over 100% of the weight of the dry wood. Of this, some 25% will be stored in the cell walls themselves, the remainder as liquid water inside the tubes. This moisture content needs to be reduced to that of the environment in which the wood is to be used. Outside this may be up to 22%, an unheated shed perhaps 15%, an air-conditioned heated building perhaps as low as 5%. The process of seasoning simply gets the wood to the right moisture content.

But the moisture can only escape by diffusion through the cell walls.

Modern wood construction: building a lightweight rowing skiff using cedar strip planks edge-glued together, often using epoxy... but not always. Photographs: www.cedar-strip.co.uk

So because of the effect of moisture content on the dimensions of the wood, combined with the weakness across the grain, the larger the piece of wood and the more dense the type of wood, the longer it takes to season. You can only create a limited 'moisture gradient' across the wood without it cracking.

Having seasoned the wood you can stabilise it to some extent by the use of paints and varnishes but until recently none of these was completely impermeable to water vapour. In the planking of a boat you inevitably have a moisture gradient between the sea on the outside and the air – ideally – on the inside. So if you wanted a ship or boat to last, it made sense to use denser timbers such as mahogany or teak for planking. Vessels built for a short and hard life like fishing boats would more often be built using lighter wood like larch. The same arguments apply to the frames, beams and keel, with the added requirement to minimise their encroachment on the space available within the hull. Hence the use of denser woods such as oak and elm in these applications.

With moisture comes rot. The fungal spores which create rot are always present in wood but become active at a moisture content above about 15% and then only in conditions of poor ventilation. A few species of wood contain toxins which resist rot, such as teak and iroko but most others are susceptible to some degree. The moisture content for rot is easily met when the wood is in contact with water and in conditions of poor ventilation. This applies as much to hollow spars as it does to the more inaccessible regions of a hull.

The development and adoption of epoxy coatings has done much to change the picture. Effectively impermeable to water vapour, if a piece of wood whose moisture content is less than 15% is coated with epoxy, it will remain both dimensionally stable and impervious to rot. It is now quite credible to make a long-lived boat using a softwood such as cedar for the planking, often skinned with a harder wood or glass fibre for robustness. In addition, the effectiveness of epoxy adhesives means that smaller pieces of wood – more controllable in terms of moisture content and defects – can be combined to make a structurally integral whole.

Nails and screws allied to cunningly designed joints – however well made – are woefully inefficient in transmitting loads compared with a glued structure. With wood-epoxy construction we effectively create cellulose reinforced plastics. What other reinforcements could we use?

Black carbon-fibre spars reduce weight aloft on this Francois Vivier-designed Jewell, a 22' (6m) trailable clinker plywood gaff yawl.

Composite materials

Composites in the form we know them now have only been in existence for about 50 years. Sure, the Egyptians made their bricks tougher by adding straw and Bakelite – plastic reinforced with wood pulp – made an early appearance in the gear knob of the 1906 Rolls-Royce Silver Ghost. But resins reinforced with long fibres started with canvas impregnated with phenolic resins to form Tufnol, still with us today as a material to make blocks and circuit boards. Further development has led through glass fibre to carbon and other high modulus fibres.

The fibres on their own are very strong and stiff but easily damaged, and don't do compression. So you add resin to protect the fibres and support them in compression. Because it is much weaker and less stiff than the fibres, the aim is to minimise the resin in the mix. For marine purposes a 50/50 mix is about as good as you can get using pre-impregnated fibres and a pressure or vacuum forming process. Some applications use less resi, but that can lead to problems with moisture; the old school 'bucket and brush' hand lay-up of a GRP hull will achieve nothing like 50/50.

If you don't vary the direction of the fibres you end up with something very strong along the grain but weak across it. But you can, in theory, construct the material to align with and matchthe forces acting on it. Snag is, you rarely know the forces to that degree of precision, if at all. So most composite structures – particularly in GRP – use a general lay up which maximises neither strength nor stiffness but does utilise its ability to form large complex shapes on simple tools.

Because of the expense of the material, the story is rather different for more exotic fibres such as carbon. Time was that carbon was considered a material adopted only for top-level racing craft where the performance gains outweighed the costs and technical risks.

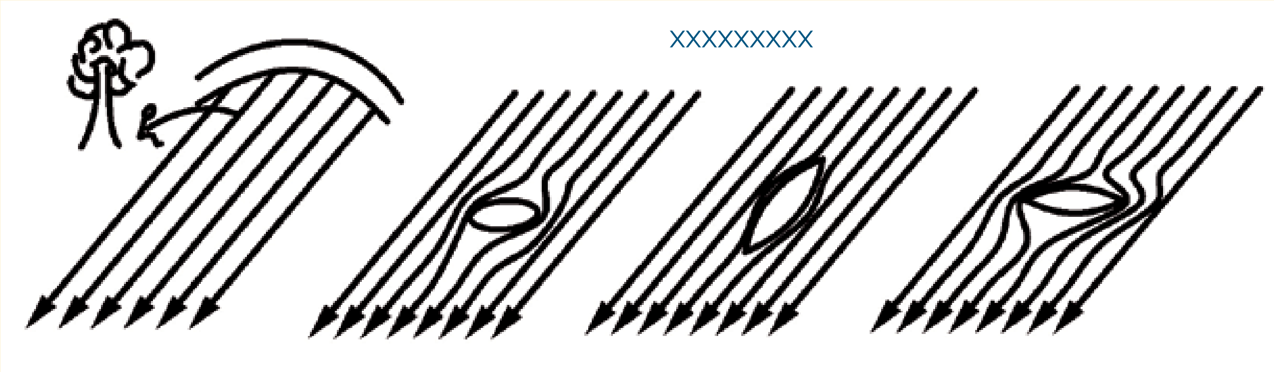
But now a number of firms have invested in machinery and tooling for spar making, typically involving a former which rotates while cloth and/or epoxy is wound on in successive layers. You then cook the laminate, get the former out and there is a carbon tube fairly close to the cost of the material. In turn that leads to more widespread adoption, hence lower material costs. Carbon spars are in the kind of cycle which saw transistors replace valves in radios and ball-points replace fountain pens. I will have more to say in a future episode on carbon fibre spars in traditional rigs.

Metals

Metals are very different in their nature from the fibrous materials we have addressed so far. They can be characterised by:

- An homogeneous structure, which means that whatever direction you pull them in they behave the same, so it matters less if the strength is not exactly aligned with the loads. Since you rarely know exactly how the loads are being applied, this is useful.
- Susceptibility to stress concentration. The downside of homogeneity is that cracks can run across the material. A small saw cut in a piece of wood or a surface scratch on a bundle of fibres does not usually cause failure. A crack in a metallic component can cause a whole structure to fail – as in the WW2 Liberty ships for example. This is worth a small digression.

Imagine stress in a plate as flow along a straight river. Without any disturbance, the stress is the same at any point (2.16 a). Now drop a circular rock into the river (2.16 b). To get past the rock the water has to divert either side of it and bunches together



A number of WW2 Liberty ships failed due to cracks being able to run through a welded structure, where before they would have been stopped in a riveted ship. So the stress concentration at a hatch corner caused complete failure.

near the rock; the 'stress' is increased, roughly doubling for a circular hole. What if instead of a circular rock, it is canoe-shaped and aligned with the flow (2.16 c)? The lines are again bunched but not so much, even if our new rock is as wide as the circular one. Drop it in across the flow (2.16 d), however and at the sharp ends the flow is very bunched up indeed.

In short the maximum stress to overall stress is inversely proportional sharpness of the defect. So a crack, sharply pointed at its tip, creates an 'infinite' stress concentration and so the crack grows. This is why an effective crack stopper is to drill a hole just beyond the crack. As the crack runs into the hole it will stop. Whether a crack grows a bit and then stops or races on to cause failure depends on many factors far beyond the scope of this article.

For our purposes, metals can be rated on a scale of 'brittle' to 'tough', noting that steels particularly can be both, even within one piece of metal. For example the very tip of a screwdriver is strong and hard but brittle, while its shank is relatively tough. I bet you have one with half a tip after heaving on something you shouldn't have.

End of digression.

- Another thing with metals is the possibility of metal fatigue. Under repeated loads, some metals can break at much lower stresses than you would normally expect. If you repeatedly bend a steel paper clip to and fro, after exactly 12 cycles – at least on the one I have just broken – it breaks. Below a certain level of stress it doesn't matter how many cycles you put it through, the metal is fine. Unless there is a stress concentration increasing the local stress, in which case you are in trouble. This was the issue with Comet airliners – cracks appearing at the corners of the square windows after a certain number of fuselage pressure cycles – and with the forestay rigging screws of some British Steel challengers 20 years ago – cracks starting at the root of threads during a prolonged thrash to windward. In very rough terms – and there are plenty of exceptions here – copper based alloys tend not to be affected by fatigue, most aluminium alloys do and some steels do, some steels don't.
- Metals tend to be heavier than their fibrous competitors and we will see the interplay of weight and other properties in the next article.
- Finally, all natural materials have a mechanism by which they break down. Wood contains the seeds – well, spores – of its own destruction. With very few exceptions, metals continually try to revert to the state in which they were found. To put it more simply, they corrode. I'm going to deal with that very important topic when we get to the practical aspects of fittings.

Next time I will explore how the nature of the materials we have looked at here combines with the structural aspects discussed in W142 to inform the choice of materials in practice.