Building Carbon Masts

I never managed to get anyone to write this for me, so, as I was acting as an amateur journalist, I thought a journalists trick would do. I sat Simon Roberts and Dave Roe down with a pint each, turned a tape recorder on, and asked stupid questions. Some might also consider it characteristic that Simon ended up buying the pints because I didn't have enough cash on me.

Disclaimer

This document is compiled by an amateur, not a professional. It has been compiled in good faith, but almost certainly contains errors and inaccuracies. "Best practice" also changes frequently with changes in technology and materials. None of the procedures listed are guaranteed to work, and some or all of them may be hazardous. If you feel unable to take responsibility for your own actions and errors without resorting to the legal profession then you are advised not to read it, let alone build anything based on information here. In any case you are advised not to build a composite structure without someone experienced in the materials to contact for advice

Introduction

Mast building is probably the most challenging laminating job the amateur boat builder is likely to take on. It means handling a lot of material in a particularly tricky lay-up, and the consequences of getting it wrong are serious. If you build part of your boat with an unnecessarily strong lay-up then you've wasted a little bit of material and added a few grams of unnecessary weight, and if you make it too light then there'll be a small loss in stiffness and possibly the need to reinforce it. The kind of lay-ups described in other sections of these articles are very much on a "that will be plenty strong enough and adequately light" basis. Masts are more difficult. OK the possibility of making it badly and it ending up breaking is there, but that.s not the major issue. What's more serious is that the actual stiffness on the mast has - of course - a huge effect on the performance, and the actual difference between what we'd regard as a stiff mast and a bendy one is not really very much. This means that's its reasonably easy to end up with a telegraph pole or a fishing rod...
Don't take on a mast until you've done a good lot of laminating and can consider yourself reasonable skilled. You're also well advised to do a boom or a bowsprit first because the much smaller size makes the project easier, there's less of a worry about it ending up too stiff, and in any case its not such a big lump of cash in the bin if you get it very badly wrong.
This article is also rather less of a "how-to" than the others in the series, and rather more of a "how we did it". The folk who are building masts within the UK fleet are doing it with the benefit of some years experience and several boats behind them. There's no substitute for "getting your hands sticky". Its also well worth pointing out that there's no consensus as to the best way of building masts yet, and there are other methods that work just as well - maybe better.

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Designing the Section.

Its possible to start with a theoretical list of stiffness values and so on, and then go from there. This is what the companies who build big one off yacht masts and so on must do. All any of us have done is to start from a know alloy mast with published data as a basepoint, and then say -

well, a bit stiffer sideways, much the same fore and aft, bendier at the top and so on.
Working out the values for mast taper is mostly informed guesswork as the figures are not published, and although we have tried to measure one, we didn't really get any results that we had too much confidence in.
Designing the section isn't about the cross sectional shape itself, so much as identifying the dimensions and fibre lay-up that will give you the stiffness you want. The maths is roughly Mechanical Engineering graduate student level, which may not daunt you, but rather does me. If you have access to reliable information that other people have worked out then all well and good.
Basically a carbon mast tends to consist of a substantial layer of unidirectional fibres sandwiched between two layers of woven carbon which are primarily there to keep the unidirectional carbon in column and prevent buckling and peeling.
There are two ways of going about working out what this this lay-up should be.
One is to start with an existing mandrel or mould and then work out what lay-up is going to give you the stiffness you want.
The other alternative is to work out what lay-up you want to use, and then build a mandrel or mould to give you a section that will do the job you want. For instance Dave Roe's 1997 mast was based on 4 layers of unidirectional fibre. The actual mathematics required to design the lay-up is beyond the scope of an article like this - suffice to say if you haven't got either the mathematical skills or access to someone who has, or access to the technical information on the materials you propose to use, then probably you shouldn't be getting into mast building at the present state of the art
As an example one starts with the stiffness value of the particular carbon that you intend to use for the main structure of the mast, take off an allowance for the amount of resin that is likely to be in the lay-up, add allowances for internal and external skins (usually an order of magnitude smaller than the main unidirectional fibres), add an allowance for the mast track and then see what sort of figure you arrive at. This result may be unsatisfactory for one reason or another, in which case you have to repeat the exercise until you get something appropriate. A particular consideration here - especially with dinghy masts - is that they get bashed about a fair bit, what with beaches and trailers and roof racks and so on. Its probably fair to say that anything with a wall thickness of less than 1.5mm will be too prone too damage when not in use, no matter how appropriate the structure is for sailing with.
A couple of rules of thumb that can be of use are:-
Carbon rigs tend to be at least 20% stiffer than the equivalent section in alloy. This means that you can usually go one section size down when basing a carbon rig on an existing alloy one.
A 200g carbon cloth makes for about 0.2mm of section thickness in a lay-up.

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Material

You must be using a low viscosity resin with a very long cure time. It will take you hours to laminate up the tube. Resins from the Ampreg range are the conventional choice - Ampreg 26 is good. There are several reasons for using the Ampregs, which are, on the face of it, very expensive, but basically it boils down to "you get what you pay for" and in the case of the Ampregs you get an easy to handle lower toxicity resin with lots of desirable properties like low heat sensitivity, especially when cured. Don't economise on resin. Especially, whatever you do, don't consider using polyester resin!
There are all sorts of nasty small scale phenomena that can occur in carbon masts which just aren't an issue in a relatively low stressed hull construction that can cause all sorts of problems. One of the worst is "microcracking" which occurs if the resin takes up load before the carbon and cracks. Suddenly the carbon is unsupported and... I'm sure you can guess what happens next.
In the UK we tend to use fairly ordinary grades of carbon, which seem quite adequate. For the

woven cloth inside and out we use a single layer of 200gsm carbon, which is the most economical currently available. Two layers of 100gsm carbon, aligned in different directions would be superior, but four or five times the cost. Higher grades or carbon could certainly reduce the size and weight - Dave Roe has calculated that he could make a 1.5 inch diameter mast that would be around 70% of the weight of the current ones, but that the material cost would be something like three times greater...

Laying it Up

Release Agent

In the past we've used a lot of paraffin wax as a mould release agent that can be melted out. If you have appropriate facilities and are using an aluminium mandrel then laminating and curing at a relatively high temperature can help considerably as the thermal expansion of aluminium exceeds that of carbon lay-ups. Experience seems to indicate that ordinary mould release agents just won't guarantee you to be able to get the mast off the mandrel. This is an area that the commercial mast makers are looking at a lot, and will need to be solved before true mass production mast making can happen.

Consolidation

Lay-up consolidation is absolutely essential. The best bet seems to be vacuum bagging. There are people who use tape successfully, but there are a number of dangers in this, most especially that of dragging the lay-up round the mast in a spiral which will probably result in less stiffness than was planned. I don't propose to go into a full treatment of vacuum bagging for the amateur here, but there's space for a few pointers. Supposedly there are some good books on the subject, but we've all learnt from talking to people. There's a lot of people who use the techniques in one industry or another these days, at least in our part of the world.
Peel ply is essential. Perforated release film is good, but hopefully the peel ply will soak up the resin unless you've got far too much in the lay-up anyway. Breather cloth is quite cheap, and you may as well use the real thing, even though some people use Chopped strand mat instead (about all its good for!). Even old blankets from a car boot sale will do the job at a pinch though, and are much better than nothing. You can use virtually any airtight sheet plastic for bag film but proper bag film is very thin which leads to smaller wrinkles, a better finish and less extra work. You will need to smooth the bag down as the vacuum goes in to minimise the wrinkles. Where the vacuum goes in is important - in practice bags always leak, and so if you have a leak near the inlet you may not get much vacuum at the other end. A tube with holes in to distribute the vacuum is thus a very good idea to equalise things out. SP recommend no more than 0.5 bar for the vacuum but by the time you've spent 4 hours laminating it up so the first layer is half set, you're working maybe in 16 degrees instead of the specified 21 then you may need to go higher simply because the viscosity is higher and the mix has half gone off as well. In practice if all the bleed cloth is saturated in epoxy you won't get much more resin out of the mix, and if you've put 4 layers of unidirectional on that's about right. The danger with more tractable lay-ups is that you can actually suck so much resin out of the cloth that the strength is badly compromised
Having said that the lower the resin ratio the better (well almost) and carbon masts need to be as dry as you dare go. At a maximum you should be looking at a lay-up that is one gram of resin for every two grams of fibre. If you're not confident about achieving that then maybe you want to tackle another boat before you do a mast. Unidirectional cloth that has glass binder is useful for helping you see how well wetted out the lay-up is. Its also worth noting that the consolidation effect of the vacuum increases exponentially with the decrease in pressure, and at the far end small improvements can lead to big changes.

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Inner Layer

The technique we've used is to lay the mast up around a mandrel - effectively a male mould - and vacuum bag the mast onto that. Others have apparently made spars by making a female mould and using a bag on the inside to consolidate the lay-up. I guess that this would be more work on the mould, and more trouble to lay up, but be considerably easier to remove mast from mould.
The first (inmost) layer of lay-up is local reinforcement where fittings and so on will go. This is usually plain glass, and then a layer of light kevlar. This has two roles. The first is to add local strength where fittings and so on penetrate the mast, and the second is that the glass insulates the electrochemically active carbon from the fittings. Kevlar is chosen because its excellent for resisting crack propagation and so on, but has a tendency to go "furry at the edges", which glass doesn't suffer from.
The next layer should be Carbon cloth, 45/45 degree aligned for torsional strength. This is adequate for a dinghy mast, but something bigger will need to be designed more carefully. Its worth noting that, in contrast to a metal mast, fibre masts are not made out of a homogenous material, and can and will have significantly different properties according to the alignment of the fibres. It is not especially easy getting the fibres properly aligned and can be wasteful of cloth. None of this job is easy!

The Main Fibres

Once these layers have been cured and tidied up the main lay-up of uni-directional fibre can be commenced. This needs to be done as a single job, which will take several hours. Obviously it needs to be done carefully, making sure that all the fibre is properly wetted out (not always easy to tell with carbon,) and that there are no voids and that the fibres are correctly distributed round the spar.
Fair up this layer before you put the outer skin on. Here you've got to be careful with the (virtually inevitable) wrinkles. If you have longitudinal wrinkles of carbon sticking out then you can sand them down without too much worry. After all what they principally represent is fibres that have been squeezed out as the laminate compresses down, so you can take them out without compromising strength or lay-up thickness. Horizontal wrinkles are trouble because if you sand them off you are breaking into the carbon at a single point, making a spectacular weak point. This is mainly a matter for very careful vacuum bagging.

Mast Track

The track - provided you aren't making a trackless mast for a sleeve luff rig - should be made from half inch diameter pultruded tube from whatever your handiest source is. Glass is cheaper, heavier, and has less impact on the final bend characteristics. Carbon is more expensive, lighter, and contributes more to stiffness, especially fore and aft. Glue the track on with a reasonably strong filled epoxy mix, and then fair up the gap between tube and mast to your preferred shape with something a bit lighter.
Take a good look at the end of the mast track where the sail feeds in. Its very easy to let the luff rope get trapped across the groove. This puts a very big load on the track and has bee known to actually crack the track, after which the luff rope gets in the slot more and more often, rigging is a pain, and the luff rope can pull out of the groove whilst sailing.. Rainforce the last inch of the track so that this doesn't happen. Similarly be very careful about the end of the slot. If its too sharp a corner you may risk tearing the sail, but a very even taper means the luff rope getting caught for sure.

Outer skin

Lastly on goes an outside layer of 200gsm carbon, this time aligned 0/90 degrees to the mast, plus appropriate local reinforcement where needed. It goes round the mast track of course. Should you ever wish to modify the stiffness of the mast by adding (not always successful without great care) or removing fibre, you should sand off this entire layer and then replace it when you've made the changes. One has to be very careful about adding extra fibres later, because its very difficult to get really first class bonding between the original and added structure, which means that there's always the possibility that the load won't be distributed between the fibres that well. There is no especial constructional reason for having the 45/45 layer on the inside and the 0/90 layer on the outside other than it is easier to make a neat job of the 0/90 lay-up. As mentioned above the optimum would be a thinner layer of both each side of the uni-directionals.

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Getting it off and Putting the Fittings on.

A lot of people commercially are working on reliable release and easy lamination. It can be big trouble. Quite often its easier to simply cut the mast down one side and take it off like that. After you do that you'll need an outer layer of carbon again, but its not as disastrous as you might think because your cut is aligned with the majority of the fibres anyway. If you have an alloy mandrel you can make it as cool as possible to shrink it out from the lay-up, if you used wax then very hot water down the centre of an alloy mandrel gets it out a treat, or alternatively you can melt it out with a heat gun (don't get the lay-up too hot!).

Cut out the slot in the mast track. I suppose in theory the slot reduces the effect of the outer layer of fibres, but the track itself contributes plenty of strength in that area, and it doesn't seem to be a problem.

Fit out the mast out pretty much as normal - but be *very sure* that the fittings have been placed where the reinforcement for them was. Corrosion is a significant consideration - carbon is electrolytically active and there's a considerable potential between it and aluminium. Make sure there's no contact between aluminium and carbon - stainless rivets are definitely preferred. This applies to other fittings as well. Again glass can be used as an insulator, but resin coat the alloy fittings too and generally do your best to keep them isolated. In this context its worth noting that I've heard reports that RS600 mast bottom sections - which have an aluminium sleeve to shorten the mast to reduce sail area - have, in some circumstances, actually failed because of the expansion caused by corrosion of the aluminium. Be very careful with rivets and avoid them if you can. In particular make sure that the holes you drill for rivets are as tight as possible in order to avoid the rivet expanding in the hole and causing a local distortion in the structure. For similar reasons backing washers on rivets are nothing but a good thing if you can possibly get them on.

Jim Champ, 1998, with grateful thanks to Dave Roe, Simon Roberts & Tim Dean.