The Shock of the Old

Part 4: Unstayed Masts

If you like the idea of the stick without all the stays, crunch the numbers first, says Moray MacPhail.

To keep things really simple, why bother with shrouds or stays at all? As we saw in previous episodes, if you are limited to low strength, low stiffness materials like wood, then unstayed masts tend to be confined to small craft. These don't have to be simple lugsail dinghies; many international racing classes – Finns and OKs for example – have used unstayed wooden masts to great effect, though in both cases other materials are now chosen.

Indeed, the availability of relatively light, higher stiffness or higher strength materials, such as aluminium and carbon fibre, has meant that unstayed rigs could be more widely considered. Still popular for racing classes – over 200,000 Laser sailors can't be wrong – unstayed rigs began to reappear in cruising designs, notably in Garry Hoyt's Freedom yachts and Nigel Irens' Roxane and Romilly luggers.

There also exist a few examples where the halyard is set to windward and aft of the mast to act as a stay. These include Yorkshire cobles and Scottish fishing boats with dipping lug rigs; I have a sense though, that if you have one of these craft you'll not need me to tell you how they work.

Design loads

One of the few sources to mention design loads for an unstayed mast is Norman J Skene's *Elements of Yacht Design* of 1927. The mast is reckoned to be a cantilever beam - just like all that standing on a plank stuff in W144 – where the maximum bending moment and stress will occur at deck level. Simple beam theory is by no means a complete descriptor of real life but it is OK as a model.

The relevant sum is:

$$\sigma_{max} = \frac{M \cdot y}{I}$$

where:

- σ max is maximum stress, compressive for wood. This is a known factor.
- M is the bending moment at the deck
- Y is the distance of the surface of the spar from the neutral axis, which is the radius for circular sections.
- I is the moment of inertia which is also known for a given configuration

So we know everything except the bending moment at the deck, M. That is going to depend on the sail area, the length of the mast and decisions on design loads to use. What should we assume for the force on the sails?

Skene presents wind pressures based on Martin's formula which gives $p=0.004 \times V^2$ – p being pressure in pounds per square foot and V being wind speed in miles per hour. He uses 1 p/s/f as a design load which equates to a windspeed of about 16 mph.

Except it doesn't, but Skene was well aware of the limitations of this approach: "The pressure of the wind on sails for a good whole-sail breeze is generally considered to be a little over one pound per square foot of area, say 1.15 pounds. This is not the absolute pressure of the wind such as mechanical engineers use in designing structures but a sort of constant. The assumptions made here are that the sails are perfectly flat surfaces, lying in the central plane of the boat and that the wind blows in a direction perpendicular to the longitudinal axis of the boat. These conditions are, of course, not realized, and for this reason p must be considered a factor for wind pressure."

This is a really important point which we will come across a number of times. In this case. it is that a "good whole sail breeze" of 15 knots (17mph) will yield – using Martin's formula – a value of 1.15 as a design load. There is nothing wrong with using a given number as a design point, but we need to be wary of spurious validation which comes from linking simple assumptions to complicated real life. This issue will recur when it comes to righting moments later on.

Anyway, whatever the real life value of p, clearly the sail area is a direct factor in the loading assumptions. Since Mr Skene was clearly an intelligent and conscientious man, I'm happy to assume 1.15 multiplied by the sail area in square feet to give the design force – in pounds force – for the time being. I'll metricate things later.

But how and where does the total sail force P act? Skene assumed that it acted as though a distributed load on a cantilever beam – to continue the 'me on my plank' analogy, I am now lying along the plank rather than standing on it, so spreading the load.

Let's look at that assumption by seeing how the bending moment at the deck varies with different assumptions on loading. Moving from left to right:

- The diagram on the left shows all the load from the sail acting as if at the top of the mast. In practice this does not happen; the lower corner of the sail will take some portion of the force even if is not attached to the mast, as in luggers where the tack is attached to a thwart or gunwale. This case may be relevant if you release both the spinnaker guy and the sheet at the same time!
- So the next one applies the sail force as two point loads; half at the mast head and a half near the deck. This could be a balanced lug or a gaff where the main loads are at the jaws or saddle at the top and the gooseneck at the bottom. Though the total load from the sail stays the same P, the moment at the deck is halved.
- The next shows the assumption made by Skene. It could represent a gaff sail laced to a mast. Whether or not it is realisable in practice, the moment is still halved at the deck.
- Next a triangular distribution which looks 'realistic' for small craft. In this case because the Centre of Effort is lower, the moment is reduced from PL/2 to PL/3.
- But most sails don't sweep the deck, so what happens if you move them up 20% of the length of the mast? In this case the moment is roughly halved rather than divided by three.

To cut to the chase, whatever the total sail load P is, a fair estimate of the moment under practically achievable assumptions is PL/2, where L is the mast length.

Now everything is reasonably nailed down apart from the fact we still don't really know what the design load should be. So we need a factor of ignorance – often referred to as a factor of safety. Why don't we know what is going on?

- We don't know how accurate the wind loading factor of 1.15 lb per sq ft actually is.
- We have made no allowance for the loading on the mast from halyards, sheets or other running rigging.
- There is no accounting for dynamic effects – falling off a wave, a sudden gust, unscheduled contact with terra firma; all the real life stuff which this simple model doesn't cover.
- And we assume a mast rigidly fixed when in practice a boat is not fixed in space but will heel or pitch in response to loads on the mast.

So I'm going to fall back on Skene and his successor Francis S Kinney's revised edition of *Elements*. In the only worked example Skene gives, he uses a wind factor of 1 pound per square foot and a safety factor of 4. Kinney proposes wind factors between 1.15 and 1.5 p/s/f. The implication is you can make the mast lighter if the boat is small. That makes sense, given:

- The relative ease with which a smaller boat will heel over to reduce the effect of a gust.
- The likelihood that a small boat sail will be eased more quickly.
- The lighter winds assumed in designing small boat rigs.

Kinney then proposes safety factors between 1.5 for small boats and 3.5 "for large catboats with gaff rigs". It is likely that larger boats are less compliant. Combined with the consequences both practical and financial of losing a larger boat's rig,

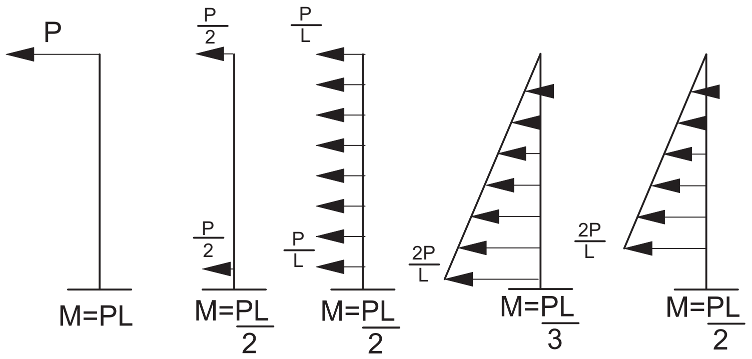

Figure 1 Bending Moments on an Unstayed Mast

you can see why bigger numbers might be used for larger boats.

So after all that and a bit of juggling of the equation, we end up with:

$$d=\sqrt[3]{\frac{16\cdot SA\cdot p\cdot L\cdot sf}{\pi\cdot\sigma_{max}}}$$

for a solid mast of circular section. This is the same as the one in Skene.

You may be wondering why we have spent so long getting back to sums first proposed in 1927. The point is to understand how they came about, and so be reasonably confident about extending them to include materials and configurations other than solid spruce. A given sailplan will exert the same forces on a mast whatever it is made of and a given hullform will have the same compliance to the loads imposed by the rig.

And the answer is...

Converting to metric and extending the idea to hollow masts made from any material you like, we get the following formula for solid spars:

$$d=17.2\cdot\sqrt[3]{\frac{SA\cdot p\cdot L\cdot sf}{\sigma_{max}}}$$

and for tubular spars with wall thickness less than 5% of the diameter, we get this:

$$d=t+\left(25.22\cdot\sqrt{\frac{SA\cdot p\cdot L\cdot sf}{\sigma_{max}\cdot t}}\right)$$

where:
d = diameter in millimetres
SA = sail area in square metres
p = sail loading (which varies between 50 and 75 Newtons per sq metre)
L = the length of the mast in metres
sf = factor of safety between 1.5 and 3.5 for small to large boats respectively
σ max = Maximum tensile or compressive stress in MPa
t = the wall thickness in millimetres of a thin walled composite or metal tube

If you have a thick-walled tube such as a hollow wooden spar, where the wall is thicker than 5% of the diameter, then you are best to do sums based on the maximum stress, using:

$$\sigma_{max}=\frac{\left(16000\cdot D\cdot SA\cdot p\cdot L\cdot sf\right)}{\pi\left(D^4-d^4\right)}$$

Here, D is the outer diameter and d the inner diameter, both in millimetres. You may find that you have to do some trial and error to get to the answer, though this is a better approach for any hollow section.

But does it work in practice?

Well, I looked at examples ranging from traditional lugsail dinghies to gaff-rigged catboats using wooden spars via modern carbon-sparred luggers, and it worked out pretty well.

In one case I know, the unstayed mast was marginally strong: it worked for an experienced helm but snapped for someone less skilled. The formula predicted the need for a mast of 80 mm (about 3 1/8") although the original mast fitted was 70 mm (2¾") diameter. The replacement mast – and now specified on the plans – is indeed 80 mm.

How do other materials compare? I'm going to start by looking at the very popular Laser dinghy to see how this formula works in real life, and to see what would happen if we re-rigged using different materials. The normal Laser mast is a 64mm (2½") diameter aluminium spar with a 3 mm (1/8") wall thickness. Assuming sail loadings at the low end of the scale and also the safety factor at the bottom of the range – I know from personal experience that it pays to release the sheet promptly in a Laser! – and the values for aluminium listed in the previous article. It produces sensible results. The maximum stress at the deck is calculated to be around 200 MPa, where a typical value of maximum tensile stress for

Alternative Masts for a Laser Dinghy

Material	Aluminium	Wood	Wood	Carbon	Glass	Steel
Wall thickness (mm)	3	Solid	19	2.5	4	3
Diameter (mm) (1)	64	77	80	46 (2)	50 (2)	43
Deflection (3)	1	1.08	1.02	2.1	8.7	1.23
Weight kg (4)	9.5	9.9	7.7	3.1	6.8	17.1
In this table:	1: Assumes a constant section for comparison only.					
	2: Could be woven more directionally to improve performance.					
	3: This is the amount it bends relative to the aluminium tube.					
	4: Again assuming a constant section, so comparative only.					

aluminium is around 240 MPa.

Now let's try to re-rig a Laser with different types of spars. The results are as in the table.

Compared with the aluminium mast, the wooden spar is larger and about the same stiffness and weight, while the carbon version is smaller, lighter and more flexible. The GRP mast is also smaller and lighter but very bendy indeed! The steel option is small and stiff but heavy just where you don't want the weight to be.

This confirms that if the primary issue is bending – which it is here –then it is strength you need. That's why classes like the OK and Finn moved away from wooden masts and are now using either aluminium or more recently carbon – and wisely avoiding steel on the way!

To quote from the class association: "Although the Finn hull has changed little since 1949, there have been developments to the rig. The original spars were made of wood until the late 1960s and early 1970s when there was a slow change to aluminum masts. Aluminum is significantly more flexible and gives more control over sail shape. It became commonplace after the 1972 Summer Olympics in Munich when they were first supplied to Olympic sailors. Recently, carbon fibre masts have become commonplace in competitive Finn fleets."

Carbon spars on Romilly, a modern lugger designed by Nigel Irens. Photo: Kathy Mansfield

And for the OK: "This involves combining a mast with suitable bend characteristics with a matching sail. The secret is to find a mast which will provide maximum power in a moderate breeze but which can be bent further to flatten the sail for stronger winds".

The point for both of these classes – and the Laser – is that bend in the mast, particularly at the top, is the way of managing stronger winds by flattening the sail. I remember OK sailors at my sailing club gently adjusting the bend characteristics by shaving their wooden spars down, while fervently hoping they didn't go so far as to have them break. That flexibility can now also be achieved by using metal or fibre spars of various sections to match the sail and/or the sailor's weight.

But I thought you were going to talk about traditional rigs; what is all this about Finns, OKs and Lasers? Because their experience can be usefully transferred to lugsails and gaffs in a quest for improvement in many ways, as we'll see in future articles. Next time we'll complicate things by adding stays.

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