This document supports a complete article on the building, by GMT Composites of Bristol, Rhode Island, of a mast for the sailing vessel *Morgan's Cloud*. It should be read in conjunction with the article, available at:

http://www.morganscloud.com/gear_failures_fixes/gfmast.htm

To learn more about *Morgan's Cloud* and her owners, Phyllis Nickel and John Harries, go to:

www.morganscloud.com

Mast Analysis
For Sailing Yacht “Morgan’s Cloud”

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SDK Structures LLC was asked by the owner of the McCurdy-Rhodes sloop “Morgan’s Cloud” to analyze the scantlings of the current carbon fiber mast to determine its structural adequacy in comparison to other known standard mast scantling guidelines. The current mast was built by GMT in Bristol, RI. This investigation was instigated due to the owner having some structural problems with the mast. These problems included some local failure and cracking around some of the fittings. In addition the mast exhibits a twist of approximately 10 degrees between butt & masthead. These issues alarmed the owner who then discussed the alternatives for a new mast with other spar manufacturers and questions were raised regarding the current mast laminate and whether the laminate thickness was too thin given the mast tube section size and if the laminate fiber orientation was appropriate for mast construction.

Without a full survey of the mast, inspection of all the attachment details, and knowledge of the construction details it would be difficult to make a full assessment of the mast construction. Thus, the analysis work SDK Structure performed was focused only on the global mast structure, .i.e. an analysis of the base tube inertias as well as the potential of buckling failure in the mast wall.

The first step of the analysis was to calculate the yacht’s current stability characteristics. Based on a 1996 vintage IMS certificate, the owner’s description of changes to the yacht that had occurred since 1996, as well as the weights and centers of both the original and current mast, a righting moment curve was produced to quantify the increase in the yacht’s stability. Due to removal of teak decking, increased tankage in the keel, and the lighter weight of the carbon mast the yacht’s stability has increased nearly 50%. Figure 1 shows the stability curves for both the current and the 1996 IMS condition.

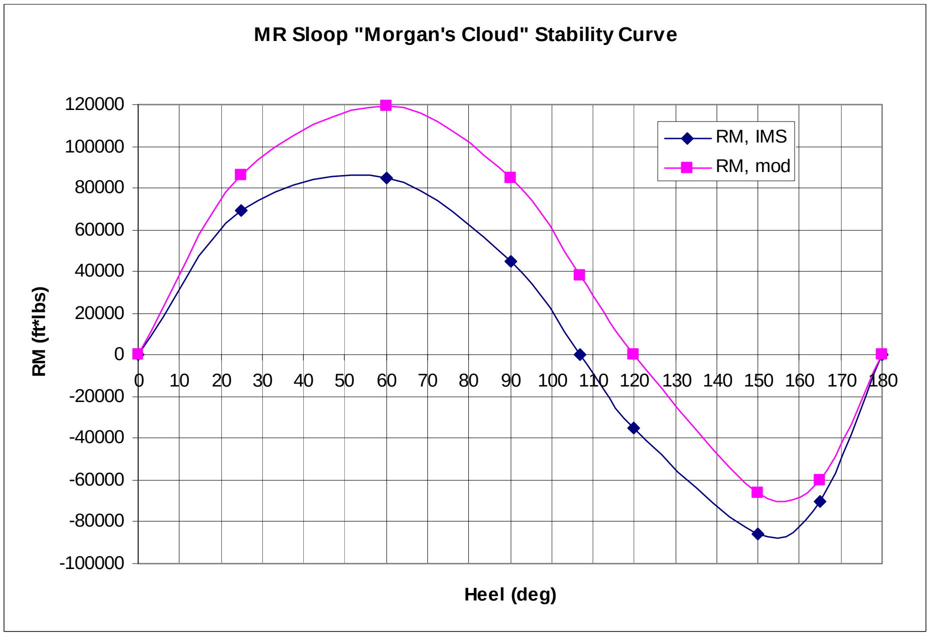

Figure 1, Righting Moment Curve

The mast layout information was pulled from designer’s original spar plan. This plan was also used to configure the new current carbon mast. Calculations of the required mast tube inertias were made using the SDK Structures standard mast analysis spreadsheet, with the calculations run for both the original measured stability and the calculated current stability.   As part of our analysis the loads in the shrouds were also calculated and compared to the rod breaking strength. For the shrouds the strength margins are still sufficient despite the large increase in stability; the original rigging sizes were well over-sized in comparison to standard practice. Figure 2 is a summary of our mast calculations.

SDK Structures: **Morgan's Cloud** Rig Analysis Output 6/8/06

Geometry input data: **McCurdy & Rhodes Design no. 43/55 Sailplan**

	Measurement stability data[1] (lb. ft.)		Estimated increased stability data[3] (lb. ft.)	
RM_U	**68946**	upwind sailing stability (25° heel)	**86446**	upwind sailing stability (25° heel)
RM_X	**86000**	ultimate stability[2]	**119353**	ultimate stability[2]

1 From 1997 measurement sheet
2 Estimated stability at 53° heel.
3 Based on owner's estimate 2000 lb. removed 5' above CG, 4530 lb. Added below CG after measurement, lighter mast

		Spreader, Jumper, and Mast data – Measurement stability				Spreader, Jumper, and Mast data – Increased stability			
Panel below/fitting:		boom	S1	S2	D3 tang		S1	S2	D3 tang
spreader lengths	in.		60.0	46.5			60.0	46.5	
spreader heights	in.		318.0	571.5			318.0	571.5	
top tang height	in.				798.0				798.0
top tang height/IM					0.978				0.978
Heeling force at top tang	lb.				1037				1300
Spreader sheeting angles	deg.		20.3	29.7			20.3	29.7	
Spreader deflection angles	deg.		2.7	8.8			2.7	8.8	
Spreader compression	lb.		995	774			1247	971	
Mast compression (P1 to P3)	lb.		51823	46601	42249		57164	50617	45433
Required EI_{TT}	mip in.^{2}	669	572	454	383	738	631	493	412
Required EI_{LL}	mip in.^{2}	1058	944	849	716	1167	1042	922	770

		Shroud loads – Measurement stability					Shroud loads – Increased stability				
Shroud		V1	V2	D1	D2	D3	V1	V2	D1	D2	D3
Size		- 40	- 22	- 22	- 17	- 22	- 40	- 22	- 22	- 17	- 22
Shroud angle from vertical	deg.	0.3	3.0	10.9	13.6	11.8	0.3	3.0	10.9	13.6	11.8
Shroud load RM_U (lb.)	lb.	8349	5066	5204	3269	5065	10468	6351	6525	4099	6350
Load as % BL at RM_U		21%	23%	23%	19%	23%	29%	28%	29%	23%	28%
Shroud load RM_X (lb.)	lb.	10414	6319	6492	4078	6317	14453	8769	9009	5659	8768
Load as % BL at RMx		26%	28%	29%	23%	28%	39%	39%	40%	32%	39%

Section properties for uniform wall exclusive of tracks/backing plates

			wall thickness 0.250"	wall thickness 0.177"
	I_{TT}	in.^{4}	81.5	56.9
	I_{LL}	in.^{4}	200.0	140.5
estimated	EI_{TT}	mip in.^{2}	1083	756
estimated	EI_{LL}	mip in.^{2}	2660	1869

Figure 2, SDK Mast Analysis Summary

We have run the GMT laminate stack through our laminate analysis program and calculated a laminate elastic modulus (E) of 13 msi, which is in line with other standard carbon mast laminates. The inertias of the base mast tube section were calculated for a variety of wall thicknesses. Based on the thickness that GMT reported for the actual laminate as well as what would be normally calculated based on the fiber weight and ply count, a thickness of 0.16" appears to be a reasonable assumed wall thickness. In addition to the theoretical calculated tube stiffness, GMT has reported stiffness values for the finished tube based on their bending tests of the finished mast. These reported stiffness values are in good agreement with the theoretical values.

As an additional check on the required mast stiffness, we have run the mast configuration through the Nordic Boat Standard (NBS) scantling rule, which is applicable for 2 spreader rigs. Figure 3 is a summary of the results of our required tube stiffness values, the NBS required values, and the GMT reported as-built values.

SDK Structures LLC
Morgan's Cloud: Mast Tube Requirement Comparison 6/5/06

	SDK/DKI Standard	GMT Achieved Comp'd to Required	Nordic Boat Standard Scantling Rule	GMT Achieved Comp'd to Required	GMT Achieved (per bend test of spar)	Calculated from tube, t = 0.25"	Calculated from tube, t = 0.177"	Calculated from tube, t = 0.168"	Calculated from tube, t = 0.158"
Req'd EI,TT (mip*in^2)	630.5	1.06	421.2	1.59	669.5	1059.5	739.7	702.0	660.4
Req'd EI,LL (mip*in^2)	1040.0	1.63	1086.8	1.56	1690.0	2600.0	1826.5	1734.2	1630.2
Req'd I,TT (in^4)	48.5	1.06	32.4	1.59	51.5	81.5	56.9	54	50.8
Req'd I,LL (in^4)	80	1.63	83.6	1.56	130	200	140.5	133.4	125.4

Assumed Tube Modulus (msi) = 13.0 << Based on MicMac analysis of +60 deg, - 60 deg, 0 deg x5 laminate of T700 fiber @ 36% rbw
Calculated Wall thickness (in) = 0.158 << Based on ply thickness
Reported Wall by GMT (in) = 0.168

Note Req'd stiffnesses reported above apply to the lower section of the mast. SDK/DKI and NSB req't's would decrease towards the top of the mas
GMT mast is constant laminate thickness to top of mast.

Figure 3, Summary of Required Tube Stiffness

The tube inertias that have been achieved with the GMT mast are in excess of what SDK would typically specify for a standard rig by a factor of 1.06 longitudinally and 1.63 transversely. In comparison to the Nordic Boat Standard, the GMT mast is in excess of the requirements by factors of 1.56 longitudinally and 1.59 transversely. The longitudinal stiffness requirements for a mast are somewhat subjective and are driven not only by the requirement to avoid mast column buckling, but also by performance requirements based on past experience and this subjectivity is likely the reason for the large difference between the SDK and the NBS required longitudinal stiffness.

In looking at the current mast tube section a feature that stands out is that the overall section shape is relatively large while the walls are relatively thin. This approach results in a mast tube that meets the required stiffness targets with a relatively light weight but is potentially subject to other failure modes. The thin walls do not have as much material to absorb local loads from hardware attachments (unless otherwise reinforced with local patching). The strength (section modulus) of the tube is lower for a given stiffness, so that the mast is somewhat less resilient in absorbing bending loads. An additional failure mode of thin walls is local buckling, where the mast tube walls deform locally in a bulging pattern and are unable to absorb the compression loads that the gross sectional area and compressive strength of the laminate would otherwise indicate. This local buckling failure is best analyzed with a finite element analysis (FEA) of a section of the mast tube that is loaded with the calculated mast compression. The owner of the yacht expressed concern with the thin tube wall and asked us to go ahead with an FEA buckling analysis.

The FEA model was made using shell elements with the cross section shape taken from a tube drawing provided by the owner. [The details of the GMT laminate have been removed from this report]. The resulting wall thickness was just over 4mm. The compression loading was taken from our rig calculation, based on the maximum expected compression. This compression load is likely to be relatively conservative (on the high side) as compared to other calculation methods. This is because the calculation takes into account the headstay/back stay load (headstay loaded to 50% of breaking strength) as well as the halyard & sheet induced compression loads assuming full racing trim.

Plots of the FEA model and results are shown in figures 4-7. Figure 4 shows the base tube model with the compression loaded nodes indicated by green arrows. Figure 5 shows the tube cross section shape & thickness. Figures 6 & 7 show the wall buckling mode along with the load multiplier that was needed to induce the wall buckling. For the load case run the multiplier was just over 4 times the assumed maximum compression load in the mast, indicating a factor of safety of 4. This factor of safety is higher than would typically be found in the standing rigging and is at a level we would be comfortable with having in a mast that we were designing. The FEA results indicate that the mast is not likely to fail due to local buckling of the side walls.

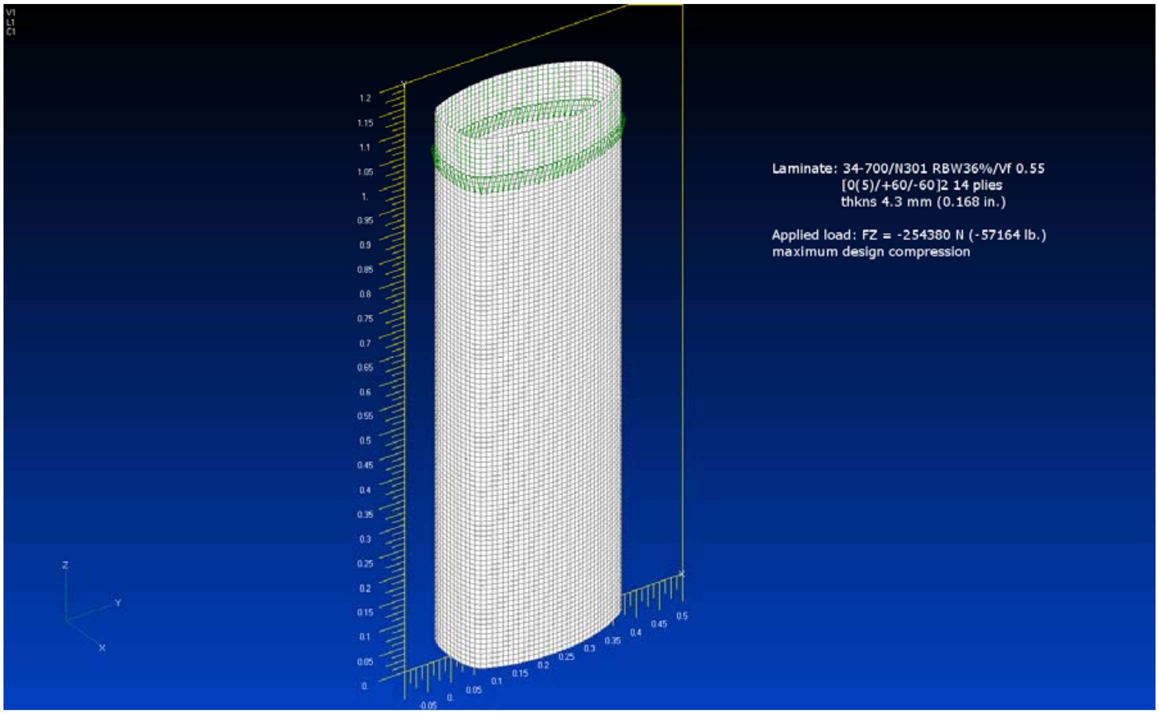

Figure 4, Base FEA Model

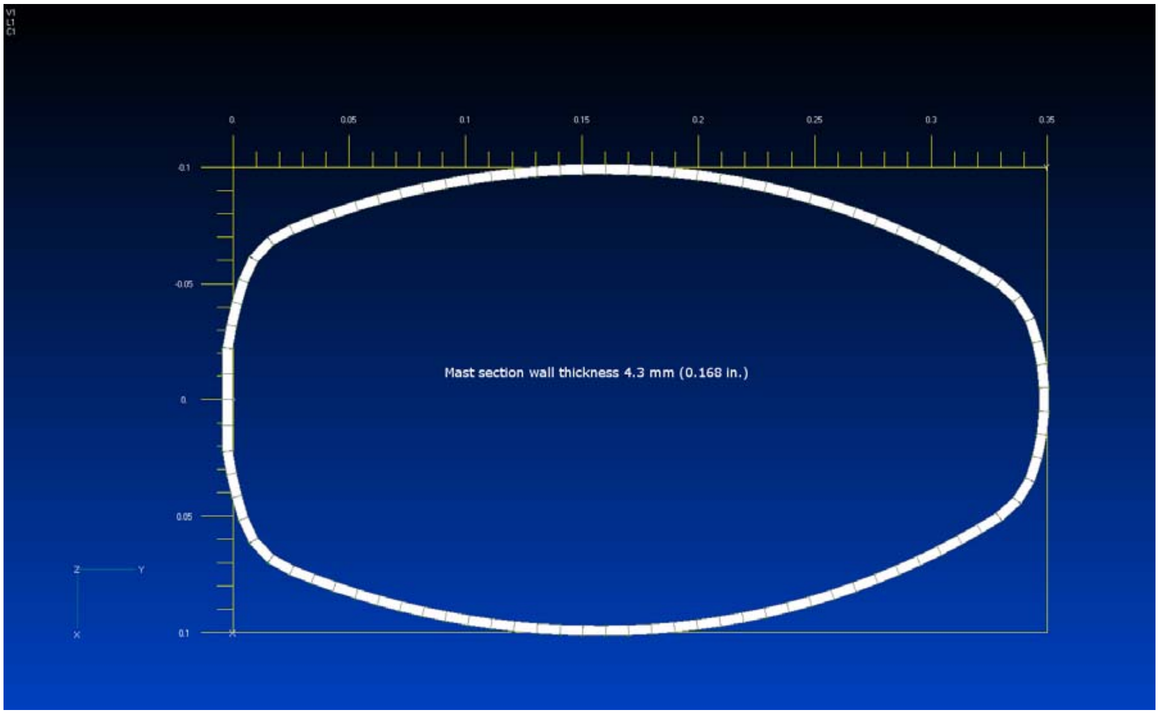

Figure 5, Section through FEA Model

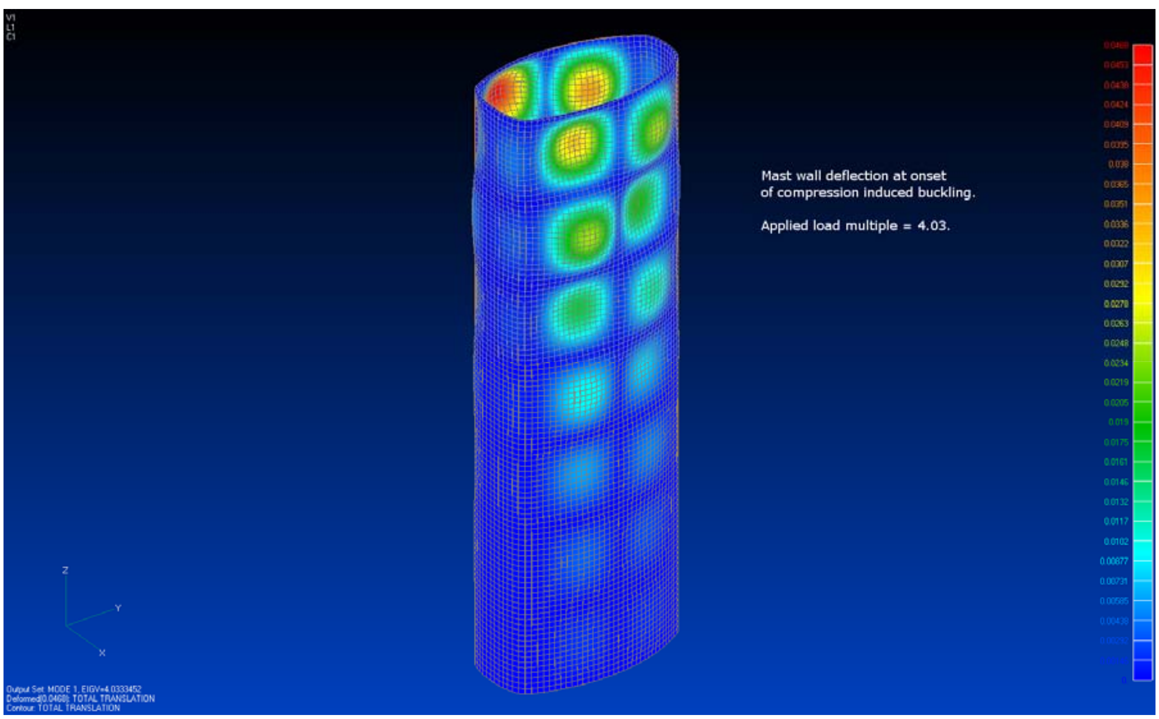

Figure 6, View of onset of wall buckling & associated load multiplier

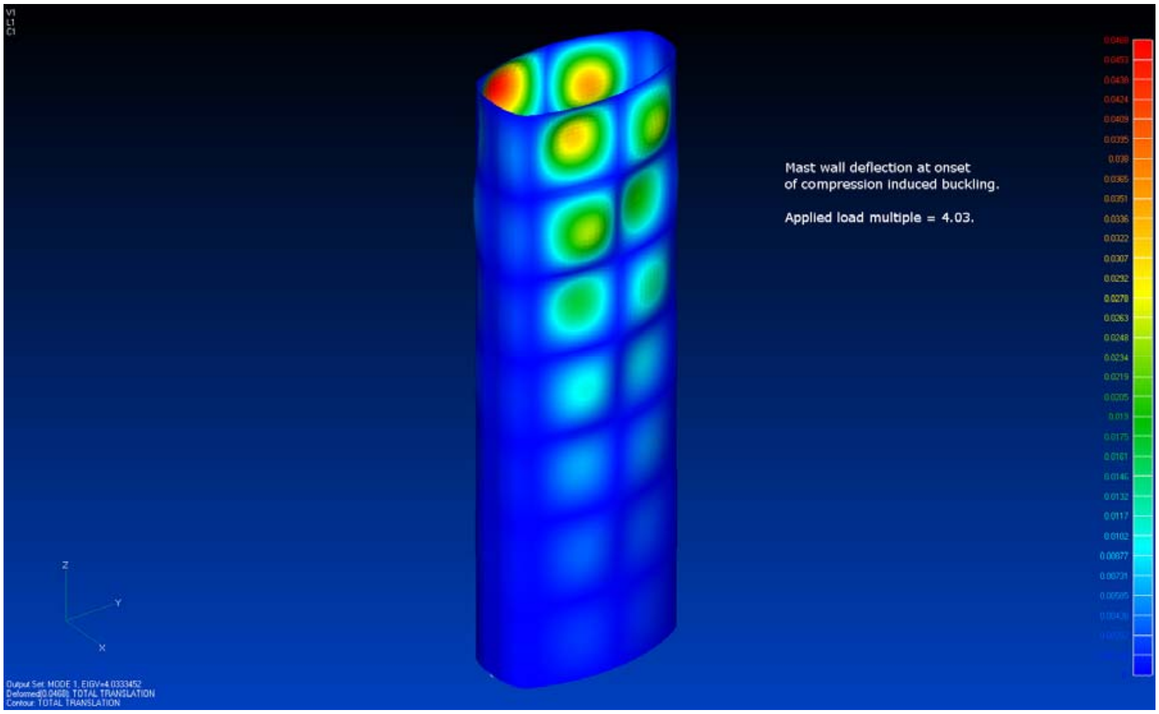

Figure 7, View of onset of wall buckling & associated load multiplier

An additional feature of this mast that stands out is the laminate fiber stack. [The details of the GMT laminate have been
While this arrangement provides the required longitudinal stiffness and the ratio of 0 degree to off axis fiber is in line with what is used by other manufacturers, the thick stack of 0 degree material without interleaved plies of off-axis fiber is not typically seen. A more common arrangement would be to have the off-axis plies of a somewhat lighter fiber weight which would allow them to be more interspersed within the laminate stack. Also, the +-60 degree fiber orientation is un-common, with 90 deg & +-45 deg fibers being used for the off axis plies by most other manufacturers. The advantage of a more even distribution of the off-axis fibers is that it better reinforces the laminate against the interlaminate splitting that could potentially occur with the 0 deg stack. Most spar laminates we see have stacks of only 3 or 4 plies of 0 deg fiber before an off-axis ply is introduced. It is difficult to quantify the effect that this un-common approach to the laminate may have but a greater dispersion of the off-axis plies is considered better practice.

Another somewhat unusual feature of the spar laminate is that it is constant from top to bottom. The compression loads as well a secondary loading (boom, spinnaker pole, and trysail) increase in the lower section of the mast and is it common practice to tailor the mast laminate so that more fiber is concentrated in the lower section of the mast with thinner walls in the upper portion. This optimizes the weight and vertical center of gravity of the mast and allows the safety factors to be more evenly distributed over the length of the tube.

Regarding the built-in 10 degree twist in the mast tube, there is no doubt that this defect is undesirable. It will always complicate tuning and it casts a shadow of doubt on the mast in the eye of any potential buyer. However, from a structural point of view, the twist can probably be dealt with by proper set-up of the rigging, spreaders, etc. and it is not likely that the twist in the base tube would lead to a catastrophic failure of the mast. For a top notch racing mast, this twist would most likely be considered unacceptable and the mast would be rejected on the basis of “tune-ability” issues.

Having not inspected the mast, we cannot comment on any local attachment problems that have arose, nor are we in a position to comment on the local hardware patching and fastening details. It is worth noting that the relatively thin walls of this mast are less resistant at withstanding local point loads from hardware fasteners; it is imperative that proper local reinforcing in the form of local laminate patching and/or backing plates are utilized in way of all highly loaded hardware fasteners.

In conclusion, our analysis indicates that the mast meets the tube stiffness requirements that we would use for engineering the mast for use in a modern sailing yacht. The longitudinal stiffness is somewhat higher than we would specify as a minimum and the transverse stiffness is well in excess of what we would specify. In comparison to the NBS standards, the tube stiffness has an even higher margin on longitudinal stiffness. Considering wall buckling, while the wall thickness appears to be relatively thin, it has a margin of safety that indicates that wall buckling failure is unlikely.

This mast gets its required inertias with a combination of large section shape and relatively thin walls. This approach gives a theoretically lighter solution but results in a somewhat less robust mast. We would not normally specify a tube with the proportions of section size to wall thickness that this mast features, but more extreme examples have certainly been built. The tube laminate does not exhibit the interleaving of off-axis fiber that is commonly found in masts and that we would specify in our designs. In addition, the laminates are constant from top to bottom so are not optimized weight-wise to the expected stresses in the mast. The twist in the tube is a clearly visible defect in the mast, but not likely to cause it to fail. The items mentioned in this paragraph are subjective and different spar manufacturers and designs will end up with different solutions.

There is nothing in our analysis that indicates that this mast will not serve its intended purpose so far as the overall global structure is concerned, with this statement predicated on the tube laminate being properly applied, consolidated, and cured. There are features that could clearly be improved upon and optimized, but it is likely that the mast will provide acceptable service once the issues of local hardware attachments and rigging details are properly attended to.