

Structural analysis and design of a composite Portuguese 'Muleta' lateen mainsail yard

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ABSTRACT: Finite element analyses to refine an initial bending-only composite laminate design for the 16.5 m wooden mainsail yard (a spar) of a replica 'Muleta' are presented. The shear stiffness of off-axis fibres was found to be significant. Exploratory finite element modelling was then used to investigate the effects of (i) and increased proportion of longitudinally aligned carbon fibres, and (ii) reducing the extent of the extra reinforcement either side of the mast contact point. These findings were then used to redesign the composite laminate, giving a huge weight saving (55%) compared to the wooden yard. However, since this is a tourism craft, extra external layers of cheaper glass were added to give a more conservative final design, but with a 45% weight saving over the wooden yard. The tools developed will enable economically viable, longer life-cycle composite yard replacements for numerous other traditional sailing craft of the River Targus/Tejo, and further abroad.

Keywords: Traditional Sailing Vessels; Wooden Spars; Composite Materials, Finite Element Analysis (FEA).

INTRODUCTION

This paper documents the completion of the structural analysis and design of a fibre-reinforced polymer composite lateen mainsail yard (a spar crossing the mast from which a sail is set) for a 'Muleta' traditional fishing boat (Figure 1, Figure 2) initiated in (Viegas et al., 2024), and where further information on these vessels may also be found.

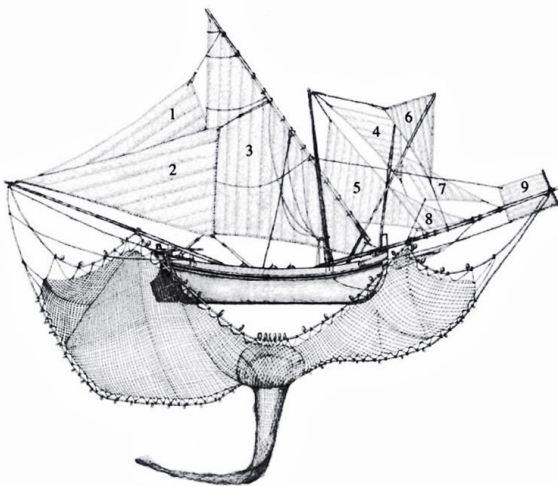


Figure 1: A 'Muleta' with trawled pelagic (mid-water) net (Duhamel du Monceau, 1772) Section III, Plate XXI, Fig. 4

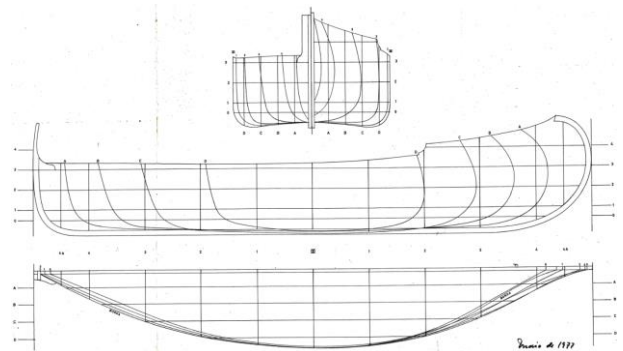


Figure 2: Typical 'Muleta' lines plan (Museu da Marinha, 1977)

The last working Muletas disappeared at the beginning of the last century, but in 2018 Jaime Ferreira da Costa & Irmão, Lda Construções e Reparações Navais constructed a replica - the 'Velho Álvaro', see (Viegas et al., 2024) for particulars, which is currently run as a tourist vessel by Nosso Tejo Lda (Figure 3). However, due to the breakage of the original wooden yard (the long diagonally orientated spar supporting the mainsail '3' in Figure 1 and shown without sail set in Figure 3), trips under sail are currently not possible, and the authors were commissioned to design a

replacement yard in fibre reinforced polymer (FRP) composites.



Figure 3: The replica Muleta ‘Álvaro Velho’ (Photograph by Mário Figueiredo, 2022)

As discussed in detail in (Viegas et al., 2024), this breakage was thought to be due environmental degradation of the wooden yard rather than any inherent deficiency in its design and dimensioning and hence this yard was used as the design baseline (in terms of stiffness and strength) for the proposed composite yard. However, to add some measure of extra security to the design (given its very novel nature), calculations were based on a Douglas Fir yard rather than Spruce as was used to construct the actual wooden yard.

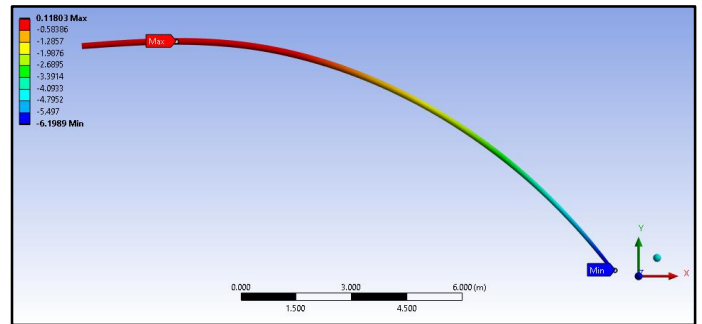
In terms of construction, resin infusion of epoxy / carbon and glass (Viegas et al., 2024) is to be used, with the existing wooden yard, repaired in so far as to restore its original geometry, serving as a male ‘mandrel’ mould to avoid the large time and financial costs of making a mandrel with different dimensions. This also simplifies the design process by fixing the geometry, leaving only the laminate materials and layup as parameters.

A simple bending only analytical approach as used to design and fabricate the 27 m long yards of the caravel ‘Vera Cruz’ in 2007 (Sutherland, 2024), which are still in constant use. Hence, this method was also used to design a composite replacement yard for the current Muleta (Viegas et al., 2024), resulting in a 40% weight saving over the original wooden yard weight of 158 kg (Viegas, 2024), and many-fold longer lifetime without any required maintenance.

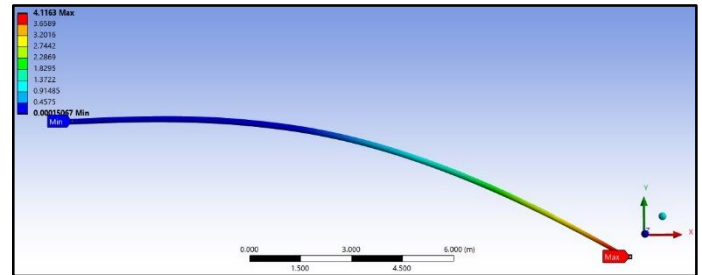
However, this was thought to be a significantly conservative design due to the presence of a significant amount of off-axis fibres contributing to shear stiffness and strength which were not accounted for by this bending only analysis. Hence, a Finite Element Analysis (FEA) model was developed to include these shear effects (Viegas et al., 2024), also allowing the estimation of expected deflections for a given loading.

Firstly, an FEA model of the wooden yard was completed (Viegas et al., 2024) to serve as the baseline for the composite laminate layup schedule design procedure to follow. The failure load applied at the tip

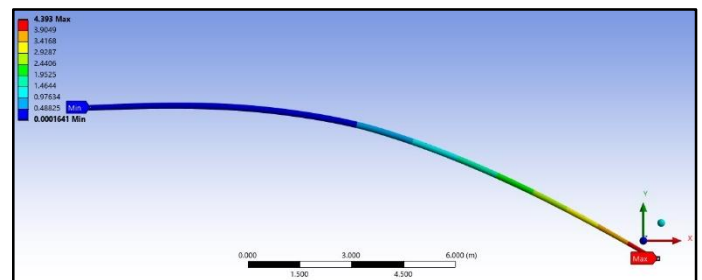
was seen to be 5.9 kN (on the tension side of the yard at the mast) and the corresponding failure bending moment predicted by this FEA model was extremely close to that predicted by the corresponding simple analytical bending-only model. This agreement could be expected as the wooden yard is effectively a natural UD composite material with fibres nominally aligned with the yard’s length and so the yard’s stiffness is likely predominantly due to bending stiffness. The FEA model of the wooden yard also predicted a failure very close to where the yard is supported at the mast (4.5 m from the foot) where the yard actually failed as was seen in reality. Further, the resulting deflection profile and tip deflection of approximately 6 m at the failure load (Figure 4(a)), are both very plausible solutions.



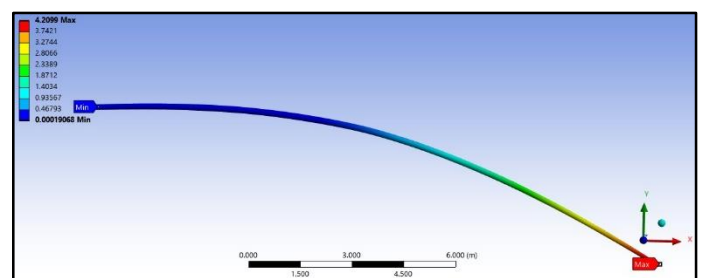
(a) Wooden yard, tip deflection 6.20 m



(b) Initial composite design yard, tip deflection 4.12 m



(c) 70% 0° UD carbon yard, tip deflection 4.39 m



(d) Shortened reinforced mast zone yard, tip deflection 4.21 m

Figure 4: Deflection of wooden and composite yards under 5.9 kN tip loads, real scale deflected shapes shown.

This paper now details the next phase of the project whereby an FEA model of the composite material yard designed using the simple bending-only analytical method is developed and then used to obtain a more refined (in the sense of reduced materials and hence raw material costs, manufacturing costs and time, and weight) design solution for the layup schedule.

1 FINITE ELEMENT ANALYSIS

FEA is a well-proven method for advanced analysis of marine structures (Miller, 2006) and for this project the ANSYS software package (ANSYS Inc. Cannersburg, PA, USA, 2022) was used. The yard is modelled horizontally here, with x defined as along the yard (longitudinal), y as up and down, and z as to port and to starboard. Given the slow response rate to loads, linear material properties and moderate deflections (although the deflections appeared large, the strains were moderate for the material), a linear static analysis was performed.

The same boundary conditions described in (Viegas et al., 2024) were applied here, as illustrated for the wooden yard in Figure 5. The yard is attached to the foredeck at its foot by two (one port and one starboard) short thick lines (which may be assumed to be effectively inelastic in the context of this case). This boundary condition is modelled as no translations in the y and z directions and no rotation about the x-axis and is applied to a 2.5 cm band around the yard circumference (corresponding to the notch in the yard in which these two lines are wrapped around the foot of the yard).

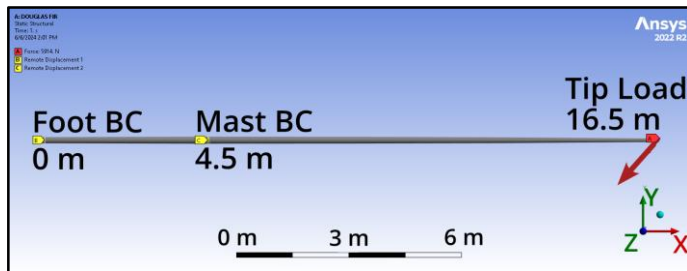


Figure 5: FEA boundary conditions and loading

The yard is also held to the mast by the main halyard which is assumed to be correctly and tightly hauled right up to the block, holding the yard snugly against the mast and hence eliminating displacements in all three axes. However, the yard is free to rotate about all three axes due to the elasticity of the halyard and especially of the protective rope padding between mast and yard. Here, this mast attachment boundary condition was taken to be at a distance of 4.5 m from the yard's foot after analyses of photographs of the vessel under sail with the wooden yard, and is applied

to a 5.08 cm band around the whole yard circumference to simulate two turns of a typical one-inch diameter rope halyard wrapped around the spar.

As justified in (Viegas et al., 2024) a worst case where all of the load (from the mainsail) is applied to the tip of the yard via the sail from the sheet (measured to be at a 40-degree angle to the yard – to the horizontal in the FEA axis system) was considered (Figure 5). This is not only a conservative approach but also a valid one since the objective of this analysis is not to predict the actual breaking loads but to ensure that future composite material solutions are at least as stiff and strong as the original wooden yard, and their respective responses will be compared using this same loading geometry. Further, to allow valid comparisons the failure load of the wooden yard of 5.9 kN is used for all cases. Finally, since this was also a comparison between analysis methods, for simplicity inertial effects were ignored.

The solid model of the wooden yard consisted of 39971 nodes and 24002 “SOLID187” elements. This element is a higher-order 3-D 10-Node (three degrees of freedom at each node: translations in the nodal x, y, and z directions) tetrahedral structural solid, with quadratic displacement behaviour selected for its robustness. The composite yard shell models consisted of 20694 nodes and 20685 “SHELL181” elements. This shell element is a four-node element with six degrees of freedom at each node. It can model anisotropic, orthotropic, or isotropic materials.

Full details of the design decisions behind the selection of the constituent fibre reinforcements and resin matrix for construction of the yard, together with the fabrication method, layup and material properties of the resultant composite laminate plies are given in full in (Viegas, 2024; Viegas et al., 2024). In summary, the laminate was to be infused with a Fibre Weight Fraction (FWF) of approximately 0.7, and consisting mainly of Unidirectional (UD) carbon reinforcements in orientations of 0°, 90°, 45°, -45° (with 0° defined as the longitudinal, x-direction of the yard), but also with small numbers of plies of woven E-glass - both infused against the mould for fairing purposes and hand laid up (FWF of 0.5) on the outer plies for improved resistance to impacts.

For these types of ‘non-standardised’ marine composites perhaps the most important and problematic part of the FEA is the procurement and estimation of the material properties. There is not space to describe the lengthy process required to obtain these multifarious properties here, but this is detailed in (Viegas, 2024) and the values used are given in Table 1.

2 INITIAL COMPOSITE YARD DESIGN

The objective here is to investigate the hypothesis that the initial composite yard design developed using the simplified bending-only analysis was actually stiffer

than calculated since the analysis did not include the shear stiffening effects of the off-axis UD carbon reinforcements.

The design decisions taken to arrive at this initial composite yard solution are detailed in (Viegas et al., 2024), and were envisaged as a conservative first design loop solution. The resulting lay-ups of the laminate are reproduced here in Table 2. The ‘base’ laminate extends over the whole yard, is approximately 5 mm thick, and has 50% of its UD plies at 0° with the remainder evenly distributed between 45, 90 and -45°.

However, in the zone where the yard will come into contact with the mast (the ‘mast zone’) this is further reinforced by the insertion of six quadri-axial infused layers (each of 4 plies) just under the exterior hand laid up glass layers to give an approximately quasi-isotropic (i.e. with equal amounts of 0, 45, 90 and -45° aligned UD carbon) laminate. This is to give extra protection during hoisting and lowering of the yard, during sailing manoeuvres such as tacking and gybing and to resist damage when rolling in light air and waves.

Table 1: Composite material properties

Material	C HS UD	C CQX*	HLU G W	Infused G W
Fibre volume fraction, V_f	0,6	0,6	0,44	0,55
Density, ρ , ((g/cm ³))	1,588	1,588	1,8288	1,9685
Young’s Modulus X, E_x (Pa)	1,37E+11	1,34E+11	1,74E+10	2,75E+10
Young’s Modulus Y, E_y (Pa)	9,20E+09	9,20E+09	1,74E+10	2,67E+10
Young’s Modulus Z, E_z (Pa)	9,20E+09	9,20E+09	4,30E+09	4,30E+09
Poisson’s ratio XY, ν_{xy}	0,27	0,27	0,094	0,14
Poisson’s ratio YZ, ν_{yz}	0,35	0,35	0,094	0,14
Poisson’s ratio XZ, ν_{xz}	0,27	0,27	0,094	0,14
Shear Modulus XY, G_{xy} (Pa)	7,17E+09	7,17E+09	2,94E+09	5,50E+09
Shear Modulus YZ, G_{yz} (Pa)	7,17E+09	7,17E+09	2,94E+09	5,50E+09
Shear Modulus XZ, G_{xz} (Pa)	7,17E+09	7,17E+09	2,94E+09	5,50E+09
Tensile Strength X, σ_{Tx} (Pa)	2,57E+09	2,86E+09	2,61E+08	4,35E+08
Tensile Strength Y, σ_{Ty} (Pa)	8,10E+07	8,10E+07	2,61E+08	3,86E+08
Tensile Strength Z, σ_{Tz} (Pa)	8,10E+07	8,10E+07	6,30E+07	6,30E+07
Compressive Strength X, σ_{Cx} (Pa)	-1,37E+09	-1,45E+09	-2,00E+08	-3,79E+08
Compressive Strength Y, σ_{Cy} (Pa)	-2,10E+08	-2,10E+08	-2,00E+08	-3,35E+08
Compressive Strength Z, σ_{Cz} (Pa)	-2,10E+08	-2,10E+08	-1,12E+08	-1,12E+08
Shear Strength XY, τ_{xy} (Pa)	9,70E+07	8,69E+07	3,20E+07	7,17E+07
Shear Strength YZ, τ_{yz} (Pa)	9,70E+07	8,69E+07	3,20E+07	7,17E+07
Shear Strength XZ, τ_{xz} (Pa)	9,70E+07	8,69E+07	4,70E+07	4,70E+07
Coefficient of Moisture expansion	1,00E-02	1,00E-02	6,00E-02	6,00E-02
Coefficient of Moisture expansion	2,00E-01	2,00E-01	6,00E-02	6,00E-02
Coefficient of Moisture expansion	2,00E-01	2,00E-01	6,00E-02	6,00E-02
Coefficient of Thermal expansion	-9,00E-07	-9,00E-07	1,44E-05	1,00E+07
Coefficient of Thermal expansion	2,70E-05	2,70E-05	1,44E-05	1,00E+07
Coefficient of Thermal expansion	2,70E-05	2,70E-05	1,44E-05	1,00E+07

C: Carbon; HS: High Strength; UD: Unidirectional; CQX: Quadri-axial (single ply); G: Glass; W: Woven; HLU: Hand layup. *CQX is a stitched layer of 4 single UD plies at 0, 90, 45 and -45°

The mast zone was defined as extending all the way from the foot of the yard to approximately 2 m past the mast contact point, i.e. to 6.5 m up the yard, and then this was then to be ‘tapered out’ by the successive stepwise removal of extra mast zone carbon plies for a further 4 m up the yard to avoid stress concentrations. However, this taper was modelled neither by the previous simple bending-only analysis in (Viegas et al., 2024) nor in the present FEA model due to time constraints.

The FEA y-direction deflection results for the wooden and initial composite design yards, both subjected to the same wooden yard failure tip load of 5.9 kN at 40° to the horizontal, are compared in Figure 4. Figure 4 makes it clear that the initial composite design yard (b) is significantly stiffer than the wooden yard (a), even though it was designed using the simplified bending-only analysis to be of comparable

stiffness to that of the wooden yard. The maximum (tip) deflections are 6.20 and 4.12 m for the wooden and initial composite design yards, respectively, corresponding to a stiffness underestimation of 34% by the simple bending-only analysis.

In terms of strength, it is necessary to select and specify the composite failure criteria to be used. Recapping from the introduction, this project used the FEA-predicted maximum capacity of the wooden spar, based on its dimensions, material properties and load direction, as the maximum load on the replacement composite spar. This meant that an equivalent factor of safety of one with the composites would provide an acceptable result. This assumption is somewhat conservative however, due to the differences in uncertainty of the wood and composite materials. As a biologic material, wood’s material properties have

larger coefficients of variation (COV) than most materials, including composites. This is reflected in the Factors of Safety required in design. For example, ABS requires a material reduction multiplier of 0.4 on wood's Modulus of Rupture (ABS, 2024). Composites can be less uncertain. That is reflected in that laminates made under controlled conditions and analysed using classical lamination theory are allowed a reduced reduction factor of 0.5 when using the ABS Rules. In both cases the material limits are stress-based, which makes the Hashin failure criteria (Hashin, 1980) appropriate for the composites analysis.

Table 2: Initial laminate layup, shaded layers in mast zone only

Base layer N°	Mast Zone layer N°	Material
	1	Infused G W 300g/m ²
	2	C HS UD 184 g/m ² (0°)
	3	C HS UD 184 g/m ² (0°)
	4	C HS UD 184 g/m ² (0°)
	5	C CQX 600 g/m ² (0, 90, 45, -45°)
	6	C CQX 600 g/m ² (0, 90, 45, -45°)
	7	C HS UD 184 g/m ² (0°)
	8	C HS UD 184 g/m ² (0°)
	9	C HS UD 184 g/m ² (0°)
	10	C CQX 600 g/m ² (0, 90, 45, -45°)
	11	C CQX 600 g/m ² (0, 90, 45, -45°)
	12	C CQX 600 g/m ² (0, 90, 45, -45°)
	13	C CQX 600 g/m ² (0, 90, 45, -45°)
	14	C CQX 600 g/m ² (0, 90, 45, -45°)
	15	C CQX 600 g/m ² (0, 90, 45, -45°)
	16	C CQX 600 g/m ² (0, 90, 45, -45°)
	17	C CQX 600 g/m ² (0, 90, 45, -45°)
12	18	HLU G WR 300g/m ²
13	19	HLU G WR 300g/m ²
14	20	HLU G WR 300g/m ²
15	21	HLU G WR 300g/m ²

G: Glass; W: Woven; C: Carbon; HS: High Strength.
UD: Unidirectional; CQX: Quadri-axial

Establishing a highly accurate limit value using the Hashin criteria is beyond the scope of this paper as it would require establishing statistically significant test data for both the wood and composites used (Miller, 1995). A first-order assumption can be made that the reduction factors required by ABS are a result of numerous tests of similar materials. That means that a ratio of the reduction factors, multiplied by the required factor of safety, in this case one, will provide an appropriate limit. With that approach, a laminate with a Hashin value of greater than 0.8 was deemed acceptable.

Here, some minimum Factor of Safety (FOS) values were indicated at the tip of the spar. This is not intuitive, and further investigation found these to be solely due to unrealistic stress concentrations due to

the modelling of the load application point. Instead of rectifying this by more complex modelling, since these FOS quickly increased to over 20 a very short distance from the tip, Saint-Venants principle could be assumed and these tip FOS minimum values ignored.

The minimum 'real' Hashin value for the initial composite design yard was 1.2, considerably higher than the 'failure' value of 0.8, on the tension face of the yard at approximately 1 m away from the tip end of the mast zone. Further, this minimum value was for matrix shear in a 45 ply, and this failure mode (matrix cracking) will not immediately precipitate structural failure of the yard. However, avoiding matrix failure will reduce moisture absorption, avoiding fatigue failure and promoting a long service life.

Hence, the initial composite design yard is significantly stronger than the wooden yard, and the hypothesis that the shear-stiffening effects due to off axis aligned UD fibres are significant has been confirmed, indicating that improvements in the composite yard design can now be developed with the aid of FEA modelling (which includes these shear effects).

The first stage of this redesign process was to see how two distinct strategies would impact the behaviour of the composite yard (sections 3 and 4). Finally, this information will be used to help completely redesign the composite yard laminate to give stiffness and strength behaviour comparable with that of the original yard with the aim of reducing materials, cost and weight (Section 5).

3 HIGHER RATIO 0° UD CARBON YARD

The initial composite design specified 50% of the UD carbon reinforcement aligned at 0° to the length of the yard. This was a conservative, first design loop decision since for such a tourist vessel high performance is not as important as durability and safety. However, Section 3 above has shown that the initial design is extremely conservative to the point of being over-engineered and hence there is possibly now scope to increase the proportion of 0° UD carbon.

The 27 m long composite yards for the caravel 'Vera Cruz' were designed and fabricated with 60% of the UD carbon aligned at 0° and are still in constant use over 15 years later. Hence, it was decided to increase the proportion of 0° UD carbon to 70% here, since it is an exploratory exercise to gauge the effects of increasing this proportion rather than to obtain a definitive design.

Substitution of quadri-axial four-ply layers with 0° UD carbon gave the base laminate shown in Table 3 with the required 70% 0° UD (in terms of mass).

The extent of the extra reinforced 'mast zone' remained as in section 2 (along a length of 6.5 m along

the yard from the foot), and six extra quadri-axial infused layers (each of 4 plies) were again inserted just under the exterior hand laid up glass layers.

To enable meaningful comparisons to be made, this '70% 0° UD' yard was also loaded at the tip at an angle of 40° to the horizontal with 5.9 kN. This resulted in the deflected shape shown in Figure 4 (c) with a tip deflection of 4.39 m, 4% more than for the initial composite design. This may appear to be counter-intuitive since as aligning more UD fibres along the length of the yard will generally increase tensile and compressive, and hence bending, stiffness. However, since only whole plies could be removed or added, in order to obtain an equivalent laminate, the overall number of plies, and hence weight of, carbon had to be slightly reduced here (by 8% and 5% for the base and mast zone laminates, respectively), explaining the very slight reduction in yard stiffness seen.

Table 3: 70% 0° UD base laminate layup

Layer	Material
1	Infused G WR 300g/m ²
2	C HS UD 184 g/m ² (0°)
3	C HS UD 184 g/m ² (0°)
4	C HS UD 184 g/m ² (0°)
5	C CQX 600 g/m ² (0, 90, 45,-45°)
6	C HS UD 184 g/m ² (0°)
7	C HS UD 184 g/m ² (0°)
8	C HS UD 184 g/m ² (0°)
9	C HS UD 184 g/m ² (0°)
10	C CQX 600 g/m ² (0, 90, 45,-45°)
11	C HS UD 184 g/m ² (0°)
12	C HS UD 184 g/m ² (0°)
13	C HS UD 184 g/m ² (0°)
14	HLU G WR 300g/m ²
15	HLU G WR 300g/m ²
16	HLU G WR 300g/m ²
17	HLU G WR 300g/m ²

In terms of strength, this 70% longitudinal carbon UD design returns a minimum Hashin value of 0.60 (again, on the tension face of the yard at approximately 1 m away from the tip end of the mast zone), significantly lower than the 0.8 'failure' value considered here. However, again this is in terms of matrix cracking (tension in a 0° ply, possibly due to a Poisson effect) and as such will again not result in immediate failure of the yard, only perhaps resulting in a shorter service life.

4 REDUCED EXTENT OF MAST ZONE

The second strategy to try to refine the composite yard design considered here was to reduce the extent of the thicker 'mast zone' laminate along the yard, from the initial range of from the foot to 6.5, down to

2.5 m either side of the mast contact point at 4.5 m, i.e. from 2 m to 7 m along the yard from the foot. The laminates here were kept unchanged from those detailed in section 2.

Comparing Figure 4(b) and (d) shows that thus reducing the extent of the mast zone does not change the global the yard stiffness, with just a 2% increase in tip deflection which is not at all significant given the expected level of accuracy of the model, nor in terms of practical sailing characteristics.

In terms of strength, a minimum Hashin value of 0.89 was calculated, again, on the tension face of the yard at approximately 1 m away from the tip end of the mast zone), significantly higher than the 0.8 'failure' value considered here, and is again in terms of matrix cracking (matrix tension in a 90 ply) thus indicating further strength in reserve until structural fibre failures would occur.

5 REDESIGN OF COMPOSITE YARD

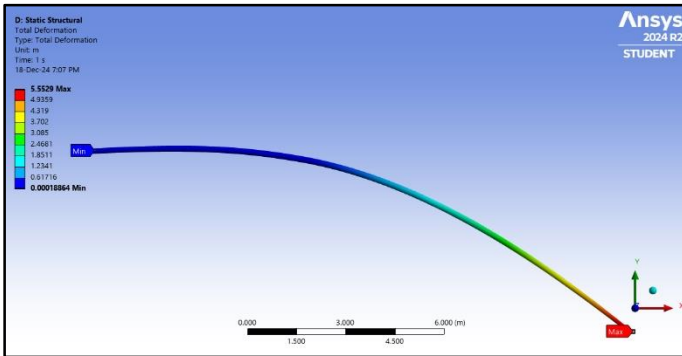
The final stage of this work was the development of a satisfactory composite yard design, using the initial design of section 2 as a starting point and the information gained from the designs of sections 3 and 4 as a guide. Since this consisted of the development of over 20 exploratory candidate FEA model solutions in order to arrive at the solutions presented below, as a design process the exact process is not detailed, but the main design criteria were for a Hashin value of 0.8 or above and similar tip displacement to that of the wooden yard under the latter's breaking load of 5.9 kN, as before. The resulting redesigned laminate layup is shown in Table 4.

Table 4: Redesigned laminate, shaded layers in mast zone only

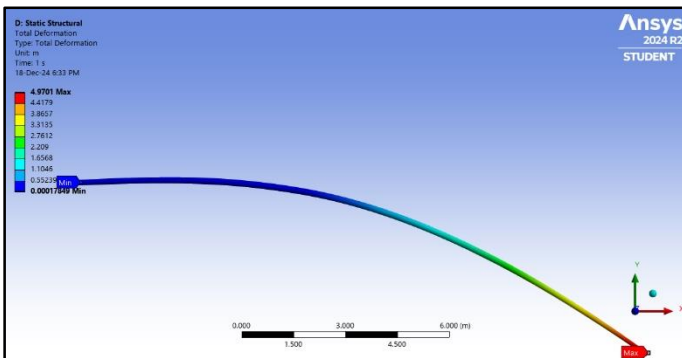
Base layer N°	Mast Zone layer N°	Material
	1	Infused G W 300g/m ²
	2	C HS UD 184 g/m ² (0°)
	3	C HS UD 184 g/m ² (0°)
	4	C CQX 600 g/m ² (0, 90, 45,-45°)
	5	C HS UD 184 g/m ² (0°)
	6	C CQX 600 g/m ² (0, 90, 45,-45°)
	7	C HS UD 184 g/m ² (0°)
	8	C HS UD 184 g/m ² (0°)
	9	C CQX 600 g/m ² (0, 90, 45,-45°)
	10	C CQX 600 g/m ² (0, 90, 45,-45°)
	11	C CQX 600 g/m ² (0, 90, 45,-45°)
	12	C CQX 600 g/m ² (0, 90, 45,-45°)
	13	C CQX 600 g/m ² (0, 90, 45,-45°)
	14	C CQX 600 g/m ² (0, 90, 45,-45°)
9	15	HLU G WR 300g/m ²
10	16	HLU G WR 300g/m ²
11	17	HLU G WR 300g/m ²
12	18	HLU G WR 300g/m ²

G: Glass; W: Woven; C: Carbon; HS: High Strength.
UD: Unidirectional; CQX: Quadri-axial

This solution gave a Hashin value of 0.85 for a load of 5.9 kN, with a failure point 7.7 meters from the foot of the yard, satisfying the strength requirement. With a tip displacement of 5.55 m (Figure 6) it is 10% stiffer than the original wooden yard (6.20 m), much closer than that of the initial composite design (4.12 m). The spar weight of 67 kg corresponds to a huge weight saving of over 55%, even greater than that (40%) of the initial composite design.



(i) Redesigned laminate yard, tip deflection 5.55 m



(ii) Final conservative laminate yard, tip deflection 4.97 m

Figure 6: Deflection of redesigned composite yard under a 5.9 kN tip load, real scale deflected shape shown.

However, the resulting laminate thickness for the lower ‘mast zone’ was 6 mm, and the ‘base’ laminate (extending from 6.5 m from the yard’s foot to its tip) was only 3.25 mm. Even with the rope padding that will protect the yard at the mast contact point (4.5 m from the foot) 6 mm was not thought to be a safely robust thickness since the lower section nearer to the foot is likely to come into contact with the stem and foredeck bulwarks. The 3.25 mm thickness of the upper part of the spar was definitely thought to be too fragile – both for a stable cylinder wall under load and definitely for accidental impacts that will occur when raising and lowering the spar or even when stowed.

These observations are based on the authors’ previous design and sailing experience rather than an extensive impact study since this would be very much outside the scope of the present work. However, for

comparison, the successful Vera Cruz 20 m long mizzen spar has mast zone and base laminates of 8.6 and 6.2 mm.

Hence, whilst the redesigned laminate of Table 4 would provide an excellent solution if the current design brief was for a craft taking part in the local (extremely competitive) traditional craft regattas, and satisfies the strength and stiffness requirements, in terms of everyday robustness it was not thought to be sufficiently sturdy for this tourist vessel.

Therefore, a further FEA design loop was completed to give a final, thicker, more robust composite yard layout as shown in Table 5. This was achieved via an increase in the thickness of the outer, protective hand laid up plies since strength and stiffness was not an issue, glass reinforcements are the least expensive, and resin rich hand laid up plies are a tough solution.

Table 5: Final laminate, shaded layers in mast zone only

Base layer N°	Mast Zone layer N°	Material
	1	Infused G W 300g/m ²
	2	C HS UD 184 g/m ² (0°)
	3	C HS UD 184 g/m ² (0°)
	4	C CQX 600 g/m ² (0, 90, 45,-45°)
	5	C HS UD 184 g/m ² (0°)
	6	C CQX 600 g/m ² (0, 90, 45,-45°)
	7	C HS UD 184 g/m ² (0°)
	8	C HS UD 184 g/m ² (0°)
	9	C CQX 600 g/m ² (0, 90, 45,-45°)
	10	C CQX 600 g/m ² (0, 90, 45,-45°)
	11	C CQX 600 g/m ² (0, 90, 45,-45°)
	12	C CQX 600 g/m ² (0, 90, 45,-45°)
	13	C CQX 600 g/m ² (0, 90, 45,-45°)
	14	C CQX 600 g/m ² (0, 90, 45,-45°)
9	15	HLU G WR 800g/m ²
10	16	HLU G WR 800g/m ²
	17	HLU G WR 800g/m ²

G: Glass; W: Woven; C: Carbon; HS: High Strength.
UD: Unidirectional; CQX: Quadri-axial

This resulted in mast zone and base laminate thicknesses of 6.82 and 5.82 mm, respectively, far more robust values, and as a consequence yard strength was increased, with a Hashin failure value of 1.21 (again at 7.7 m from the yard foot). Yard stiffness was reduced, with a 10% decrease in tip displacement to 4.97 m, corresponding to a 20% increase and decrease in yard stiffness from the wooden and initial composite designs, respectively. Of course, weight thus increased, by a third to 88 kg, but this still equated to a 45% reduction compared to the wooden yard.

6 CONCLUSIONS AND FURTHER WORK

Work to design a composite material replacement for a failed 16.5 m wooden lateen mainsail spar of a replica 'Muleta' (a traditional Portuguese fishing boat) has been continued.

Finite element analyses (FEA) to refine the previous, initial composite laminate design obtained using a simple bending-only analytical approach showed that the contribution via shear stiffness of the off-axis fibres was significant and that the tip deflection of this initial design would in fact be significantly less than predicted by the bending-only analysis.

FEA modelling enabled redesign of the composite laminate to give a huge weight saving of over 55% compared to the wooden yard, even greater than that (40%) of the initial composite design.

However, since this resulted in laminate thicknesses thought to be more suitable in a racing context, for added safety for this tourism craft, a thicker, more conservative final design was arrived at via the addition of exterior, economical, glass plies, but still resulting in a 45% weight saving over the wooden yard.

As detailed in (Viegas, 2024; Viegas et al., 2024), the material properties in Table 1 used in this analysis were based on standard values concerning equivalent materials. One area that appeared conservative was the ultimate elongation of the resin considered in the analysis, in this case just 0.8%. Un-post cured, rubber-toughened infusion resins are readily available with an ultimate elongation of 1.8%. A preliminary analysis using the latter, higher elongation value only for the unidirectional carbon transverse modulus, E_2 , resulted in a 12% higher Hashin safety factor (with just an insignificant 1% increase in tip displacement), indicating that further work to fully investigate the use of a more ductile resin throughout should be beneficial. Weight, laminate thickness and failure point were unaltered.

The optimised designs developed here also significantly reduce material costs, with the proportion of base (and mast zone) laminate reinforcement as carbon decreasing from 70% (and 85%) to 55% (and 70%), for the initial and final composite designs, respectively.

Hence, the tools developed here will enable economically viable and longer life-cycle composite yard replacements for both the Muleta and the numerous other traditional sailing craft of the River Targus/Tejo, as well as further abroad.

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