A bio-composite racing sailboat: Materials selection, design, manufacturing and sailing

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1 Picture by Lorenza Menna

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Abstract

Bio-composites represent an interesting solution for replacing fiber-glass in yachts, with the aim of increasing the environmental sustainability of the nautical sector. This replacement is already occurring in several industrial sectors, from building to automotive. However, the nautical field seems reluctant in embracing this innovation; reasons might be found in the lack of technical references describing the bio-composite boat construction methods and the durability of the yacht within time.

The production of a 4.6 m flax-epoxy and balsa wood racing sailboat is here described. The final aim of the paper is providing boat designers and manufacturers with the methods to design and construct a bio-composite craft. Tensile tests were performed on several specimens to obtain the mechanical properties of different fiber batches. Resin absorption tests were conducted to select the natural core and surface treatment, to minimize the final weight of the sandwich laminate. Finally, a specific multi-step infusion technique was developed to manufacture the hull and deck, limiting the boat final weight to 65 kg. After four years from the launch, the boat neither shows structural failure nor damage. This is considered a good test and indicates interesting perspectives for the applicability of bio-composites into the nautical recreational field.

Keywords: Bio-composite boat, Biocomposites, Flax fibers, Sustainable design, Testing and Design, Multi-step infusion.

1. Introduction

Sixty years after the introduction of fiber-reinforced plastics into the nautical production field, the disposal of obsolete fiberglass hulls is becoming a pressing problem [1]. In the near future, steps toward a "greener" nautical production must be taken both from boat designers and manufacturers [2, 3]. Bio-composites (i.e., composite materials with natural components) can play a relevant part in this innovation process, replacing fiberglass in nautical applications. This replacement is already occurring in several industrial fields, from automotive to wind turbine blades, taking advantage of the significant work of research conducted world-wide on these materials in the last twenty years. In spite of this innovative trend, the nautical field still seems reluctant in embracing this type of materials. Among the motivations causing this resistance, there is a lack in the literature presenting: i) structural use of bio-composites for nautical applications; ii) the time-wise behavior and durability of bio-composite structures in the marine environment. With the aim of filling this gap, the construction (from materials selection to manufacturing) and sailing performance of a 4.6 m bio-composite skiff[1] are presented here. The boat was built in 2012 with a sandwich configuration of flax-epoxy and balsa wood. Tensile tests were performed to obtain the ply mechanical properties; resin absorption tests were conducted on the final sandwich layout to compare the behavior of different cores (balsa, cork and PVC) during the VARTM (Vacuum Resin Transfer Moulding, or infusion) technique. Finally, a dedicated multi-step infusion process was set up and applied to the boat manufacturing to limit the

[1]A skiff is a high performance racing sailing craft; see e.g., `http://www.international18skiff.org/`.

resin absorption of the laminate and to keep the boat weight as low as possible. The boat was built to compete in the 1001Vela Cup (a sailing university competition, see `http://www.1001velacup.eu/`) and since 2012 has been widely used both for training and regatta showing no failure nor damage. This gives indications on the applicability of bio-composites for nautical applications, at least for small crafts and dinghies.

In the nautical recreational industry fiberglass is the most employed material [4]. First composite prototype crafts appeared in the USA in the late 30's and after few years gave rise to large scale production, both in American and European shipyards. Nowadays part of these crafts are becoming obsolete and the disposal of fiberglass is a critical issue due to technical and economical problems [4]. In Italy, over 4,3% of the total number of crafts in 2008 (more than 618.000) was obsolete and close to be disposed of [3]; similar numbers were reported for France in 2014 [5]. As Europe counts over 6 millions recreational crafts [1], the quantity of craft disposal is clearly identified. To increase the environmental sustainability of the nautical production, the role of the designer is fundamental for a next generation of *greener* yachts [2, 3]. The European Directive 2008/98/EC [6] on waste management identifies the role of the designer for a more eco-sustainable product with the concept of *extended responsibility*.

In this context, bio-composites can represent a powerful tool, replacing glass fibers as reinforcement inside the composite structures. These materials (cf. [7] for a proper definition of bio-composites) employ traditional composite production techniques but combined with natural components, increasing the environmental sustainability of products. In general, the lower impact of a bio-composite product comes from two reasons: natural fibers production is less energy-consuming compared to glass [8]; secondly, if the product has to be incinerated at the end of the life cycle, incineration of natural fibers results in recovered energy and carbon credits while glass burning is difficult, expensive, and physically and environmentally dangerous [1, 8].

Starting from the 90s of past century there has been a growing industrial interest for composite materials deriving from natural constituents. An overview of last years bio-composite applications is reported in [9], where a comparison between glass and flax fibers is presented for a wind turbine blade case study. While bio-composite products appeared in almost every product category there are only few cases of nautical applications. Moreover, most of the information regarding these bio-composite boats are on-line publications and few technical data are reported. The first news on a bio-composite sailboat refer to the 9 meters *Tara Tari*, built in 2010 in Bangladesh, with a hybrid jute-glass laminate [10]. The boat sailed from Bangladesh to France and his builder won the *Moitesseir prix* [10, 11]. In the same year, the 50% carbon fiber and 50% flax fiber 6,5 m mini transat *Araldite* was launched to compete in the 2011 Mini Transat, a solo transatlantic race from France to Brazil [12, 13], where it gained the 15^{th} position [10]. However, carbon fibers are expected to carry the major part of the loads in this hybrid prototype. In 2013, Corentin de Chatelperron (the same builder of *Tara Tari*) built the 100% jute-polyester prototype *Gold of Bengal* [14]. The project received governmental support to sustain the economy of Bangladesh, which is one of world's main producer of jute. Further projects on future bigger bio-composite boats are reported in [10]. The lack of technical data is probably one of the reasons that prevents from a real introduction of bio-composites into the nautical production. As a matter of fact, some authors complain the lack of literature data on bio-composite structural constructions (e.g., [9]). Another important reason is related to the reliability of these materials in the marine environment. Natural fibers are subject to hygrothermal ageing (i.e., degradation of mechanical performance with time because of the water absorption), unless they are adequately protected [10, 15]. As investments for the construction of a boat are relatively high, manufacturers need to be aware of the expected life-time of the craft. Finally, a third reason is related to the mechanical properties of the natural fibers that are not as repeatable as those of the usual industrial fibers.

To provide designers and manufacturers with indications about the construction and durability of bio-composite boats, the realization process of the 4.6 m racing boat named *Aretè* (from Greek: *moral virtue*), produced with a sandwich of flax-epoxy and balsa wood, is presented. The design and manufacturing process required: i) tensile tests to obtain the mechanical characteristics of the flax reinforced plies; ii) resin absorption tests for the selection of the core for the sandwich structure, iii) a dedicated multi-step VARTM trchnique. As an indication of the durability of the manufacture, the sailing performance at four years from the launch of the boat are briefly reported.

In the next sections this process is presented: the selection of the materials based on the results of tensile and resin absorption tests is reported in Section 2; the structural design and the multi-step VARTM technique for the manufacturing of the hull and deck are described in Sections 3 and 4; finally, in the last Section 5, the sailing performance of the boat are briefly presented together with a discussion on the potential of bio-composites for future nautical applications. The final scope of the work is providing boat designers and manufacturers with all the necessary information to design and build a bio-composite craft.

2. Materials Selection

Three materials must be selected to obtain a composite sandwich structure: reinforcement fiber, core and resin. The sandwich structure solution was chosen for its high specific stiffness [16] and for its applicability to the VARTM process. The latter, in particular, represents the best trade-off between performance and costs for boat manufacturing [12]). Sandwich structures are the usual choice for medium-to-high performance boats [4], typically employing glass reinforced skins and PVC core.

2.1. Resin

The resins commonly used for nautical applications are of the thermo-set type. Among these, an epoxy matrix was selected for its high mechanical properties and the excellent adhesion. This last aspect is particularly important to obtain a strong interface between fibers and matrix, to overcome the typical low adhesion of natural fibers [7]. Other advantages of the epoxy resin are the limited shrinkage during the polymerization process and the limited water absorption.

The epoxy matrix used in this work was an epoxy system consisting of an EPIKOTE™MGS™RIMR 235 resin, with a RIMH 236 hardener, at a ratio of 25% parts by weight.

When the boat was built (in 2012), no reliable information were available on bio-matrices (resins with a natural component) which were, therefore, not taken into account. State-of-the art on bio-resin is briefly described in Section 5, together with recent developments at research level.

2.2. Natural Fibers

A research was conducted in the literature to identify the best natural fibers candidates. The main requirements for the fiber selection were: i) mechanical properties, ii) availability on the market and iii) good workability, to be easily employable in the VARTM technique. Among all natural fibers ((see e.g., [7, 17] for a complete overview)), the selection was reduced to the three candidates in Tab. 1. Jute fibers were soon discarded due to the high water absorption (see Tab. 1). The distance between the countries where jute is produced (e.g., Bangladesh [14]) and the boat production facility (Padova, Italy) played a minor role as well. Eventually, the selection was reduced between flax and hemp, which are both quite common in Europe [7]. Flax fibers feature the highest tensile strength σ_r (345 $\div$ 1500 MPa) and the lowest water absorption (7%) but Young's modulus E of hemp can be more than two times higher than the flax one (70 GPa against 27.6 GPa). In spite of this, flax was lastly selected for its greater availability.

Note that all natural fibers show lower mass densities compared to glass. Accordingly, specific properties (marked with superscript *) of bio-composite are usually comparable (or even superior) to glass reinforced composites [8, 9, 14].

2.2.1. Laminate tensile tests

Three different sets of tensile tests were performed on flax fiber laminates to verify the actual properties and compare them with data in the literature. For each set, three specimens were used to ensure a minimum repeatability. Firstly, unidirectional (UD) specimens (i.e., 0°) of nine plies of 180 g/m^2 flax were realized through infusion and tensile tested in the longitudinal direction (see curves of set A of fig. 1). Secondly, the same test was repeated on three specimens of four 180 g/m^2 UD layers coming from a different flax batch (B curves of Fig. 1). The aim of performing two sets of tensile tests in the longitudinal direction was evaluating the typical dispersion of the mechanical properties of natural fibers. Thirdly, tensile tests in the transversal direction were performed on three specimens of four 180 g/m^2 UD. Referring to Fig. 1, the following observations are reported:

- A marked difference in the longitudinal Young's modulus E_{11}, computed on the whole deformation range, is visible between the two set curves. E_{11} is $\simeq$ 19 GPa for the A set and $\simeq$ 11 GPa for the B one. This dispersion of mechanical properties is typical of natural fibers [7, 17] and is an important drawback both for designers and manufactures. It requires the adoption of significant safety factors and the testing of all the batches. A second index of this dispersion is visible in one of the A set specimens, which reaches the failure stress at lower values than the other two curves ($\simeq$ 150 MPa against $\simeq$ 230 MPa).

- The observed Young's modulus values are considerably lower than those reported in the literature for the flax fibers ($\simeq$ 27 GPa, see Tab. 1). On the other hand, a knee (i.e., a slope variation) is visible

	ρ [$\frac{g}{cm^3}$]	$\frac{\Delta l}{l}$ (%)	E [GPa]	E* [$\frac{GPa \cdot cm^3}{g}$]	σ_r [MPa]	σ_r^* [$\frac{MPa \cdot cm^3}{g}$]	water uptake (%)
E glass	2.5	2.5	70	28	2000÷3500	800÷1400	-
Flax	1.5	1.2÷3.2	27.6÷80	18.4÷53.3	345÷1500	230÷1000	7
Jute	1.3÷1.5	1.5÷1.8	10÷55	6.7÷42.3	393÷800	300÷610	12
Hemp	1.5	1.6	70	46.7	550÷900	370÷600	8

Table 1: Main natural fibers characteristics compared to glass, adapted from [17, 7]. Superscript * indicates specific properties with respect to mass density.

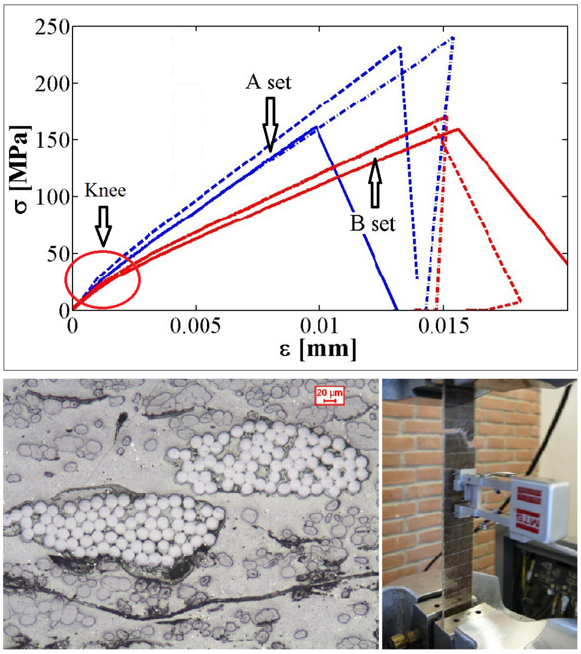


Figure 1: Tensile tests. *Top:* stress-strain curves for several unidirectional (0°) specimens; *Lower left:* microscope picture showing the fiber volume fraction; *Lower right:* tensile test after the braking load.

for the curves at small deformations ($\epsilon < 0.001$). Knees in stress-strain experimental results are usually due to slippage of the specimen or partial failure in multiple plies laminates. Accordingly, the elastic modulus at the beginning of the tensile curves is higher than the overall one. The local values of the elastic modulus before the knee are ≃24 *GPa* and ≃19 *GPa* for the A and B sets, respectively. Such results, which are closer to the magnitude reported for the flax fibers in Tab. 1, highlight again the large scatter of the properties typical of natural fibers.

As laminates are usually designed under the assumption of small displacements, the knee values of the elastic modulus are considered the most appropriate choice for the structural design, instead

E_{11} [GPa]	σ_{r11} [MPa]	E_{22} [GPa]	σ_{r22} [MPa]	ρ_{sup} [$\frac{g}{m^2}$]
19 ±1	165 ±6	4 <<	18 ±1	1700 ±25

Table 2: Laminate mean mechanical properties obtained from tensile tests and considered for the design process (B set). The longitudinal elastic modulus E_{11} refers to the left side of the curves before the knee.

of those associated with the entire tensile range.

- Between the two sets, the lower elastic modulus (the one pertaining to the B set) was considered for the boat design, for safety reasons. The corresponding mean value is reported in Tab. 2.
- Tests performed in the transverse direction showed elastic modulus values (E_{22}) close to that of the epoxy matrix, in accordance with the basic theory of laminates (the curves are not reported for brevity). The reinforcement contribution of the fibers is limited if these last are stressed in the transversal direction. The corresponding mean value is reported in Tab. 2.

2.3. *Core*

Among natural cores directly available and applicable in VARTM, balsa wood and cork were considered, being both commonly used in the composite manufacturing industry. The main properties of the cores used for the tests are reported in Table 3[2]. Superficial densities (i.e., mass for unitary surface [$\frac{g}{m^2}$]) are reported according to the nautical manufacturing practice. The thicknesses are reported as well, thus allowing the calculation of the mass densities (e.g. in $\frac{kg}{dm^3}$).

[2] Note that relevant specific weight variations were observed for the natural cores, depending on the relative humidity of the air. For instance, a decrease up to 300 g/m^2 was observed for a balsa specimen (6.5 mm thick), when inserted inside an environmentally controlled room with 0% of relative humidity.

Core	ρ_{sup} [$\frac{g}{m^2}$]	thickness [mm]
Cork	1240	7.0
Balsa	1140	6.5
PVC H200	2000	10

Table 3: Different cores used for the resin absorption tests.

A further requirement for the core was a low resin absorption during the VARTM process, to keep the final sandwich structure as light (and natural) as possible. This latter aspect turned out as a particular issue, due to the typical porosity of the cork and balsa. These materials normally absorb a large amount of resin during the infusion process because of their open-cell structure [18].

To overcome the problem of resin up-taking, two specific surface treatments were tested. The final aim was allowing the minimum resin quantity to wet the core surfaces (to obtain a strong bonding with the external skins) while, at the same time, avoiding the resin to penetrate the inner cavities of the core. This last event would only add extra-weight to the final laminate without increasing the mechanical properties. The surface treatments investigated were: i) hand painting of the core surfaces with resin to create a thin film of material; ii) vacuum bagging of the core between two layers of handed lay-up fiber-glass. For the sealing layers, the use of glass fibers instead of flax resulted necessary, being the latter quite difficult to hand-lay up. With the aim of selecting the core and the best surface treatment a specific resin absorption campaign was performed, which is described in the next section together with the major outcomes.

2.3.1. Resin Absorption test campaign

Several sandwich specimens of 500x500 mm (see Fig. 2) were manufactured employing the VARTM technique . The external skin sequence was the same for every laminate (a 106 g/m^2 glass ply and two 180 g/m^2 flax plies on each side). The following options were considered for the core and surface treatment (see Tab. 4): 1) balsa (without any surface treatment); 2) cork (without any surface treatment); 4) resin-painted balsa; 5) balsa sealed between two fiber-glass layers; 6) cork sealed between two fiber-glass layers. A PVC Divinycell®H200 core (specimen nr. 3) was included for the tests as well, to have a direct comparison with common cores for nautical applications. A 106 g/m^2 glass ply was used for balsa and cork sealing for the specimens nr. 5 and 6. No resin-painted cork specimen were tested, as this treatment resulted ineffective

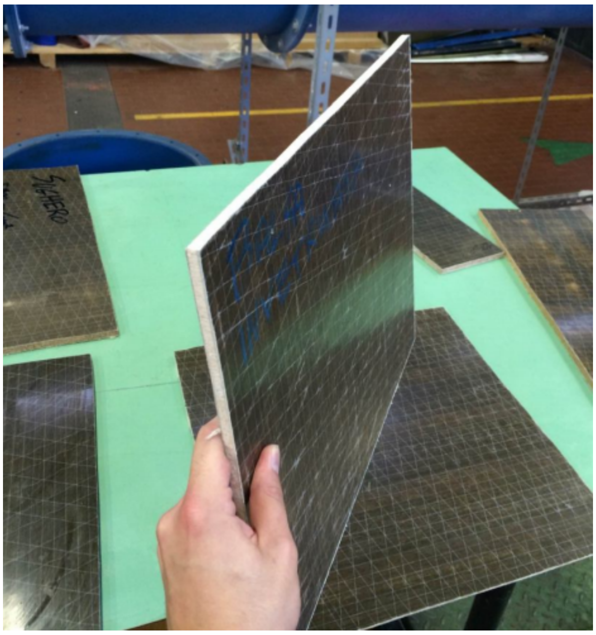


Figure 2: An example of the several specimens used for the resin absorption campaign.

in terms of resin-uptaking reduction from a preliminary test. Specimens nr. 4, 5, and 6 were drilled every 4 cm, to create channels that allow the resin to flow also on the mould side of the laminate. Each specimen was weighted to obtain the density and compute the resin absorption. Results are shown in Table 4 and the following observations can be done.

- As expected, balsa wood and cork (specimens 1 and 2) do absorb a large amount of resin during the VARTM process (62% and 56% of the overall weight, respectively). This excessive absorption is due to the material open-cell structure and is detrimental in terms of the final weight of the laminate.
- In spite of the highest specific weight of the core, the PVC specimen (nr. 3) shows the lowest superficial density ($\simeq$ 3.9 kg/m^2), due to the low resin absorption of the PVC closed-cell structure.
- The two surface treatments on the balsa wood (specimens nr. 4 and 5) give similar results in terms of superficial density. However, the specimen nr. 5 shows lower resin absorption (46% against 51%).
- Contrary to the balsa wood, no beneficial effects were obtained from fiber-glass sealing of the cork. Both the superficial density and resin absorption of specimen nr. 6 are similar to those of specimen nr. 2. This extra-absorption is caused by the

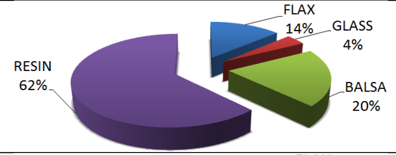
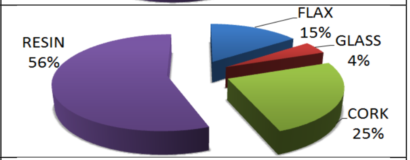
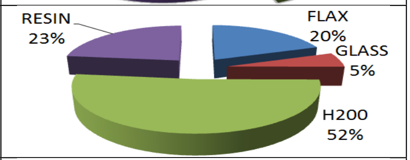
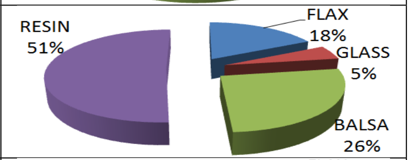
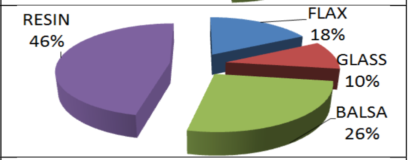
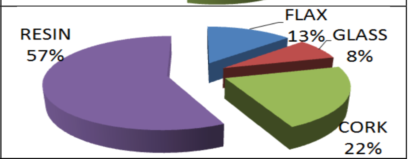
Spec.	core type	Resin Part	ρ_{sup} $[\frac{g}{m^2}]$	ρ $[\frac{kg}{dm^3}]$	Weight Distribution (%)
1	Balsa	62%	5640	0.687	
2	Cork	56%	5010	0.576	
3	PVC H200	23%	3870	0.331	
4	Resin-painted Balsa (*)	51%	4310	0.519	
5	Balsa + glass/epoxy skin (*)	46%	4350	0.483	
6	Cork + glass/epoxy skin (*)	57%	5660	0.596	

Table 4: Results of the resin absorption test campaign. The densities and resin absorption refer to the final laminate (i.e., skin layers included). (*) Specimens 4, 5, and 6 were drilled every 4 cm to create channels to allow the resin to flow on the mould side of the laminate. Resin part by weight.

drilled flowing channels: resin flows through the holes and penetrates transversally the whole core structure. The same behavior does not occur for the specimen nr. 5 (as verified sectioning the specimen) thanks to the balsa's intrinsic channel structure, which does not allow the resin to penetrate the core transversally.

According to the results of the test campaign, the balsa-glass/epoxy skin combination (nr. 5) was selected for the actual boat manufacturing. This solution allows for the minimum resin absorption and is more easily applicable to the curved shape of the hull. Moreover, a further laminate weight reduction can be reached using a lighter glass fiber tissue (e.g. 25 g/m^2) instead of the 106 g/m^2.

No flexural tests on the sandwich structures were conducted due to tight boat construction schedule. However, some references can be found in the literature (e.g., [19]).

3. Structural Design

The side view of the boat is shown in Fig. 3 with its maximum dimensions; LOA (Lenght Over All) was limited to 4.6 m by the competition rule [20], as well as the sail-plane (33 m^2) and mast height (7 m). Although waterline and structural design cannot be strictly separated in the design spiral [21], only the second one is presented. The design of the waterlines is a complex procedure (see e.g., [21, 22]) and is beyond the scope of this work.

3.1. Loads and Preliminary design

The structural design of the boat must ensure that the final structure will support the maximum loads assumed

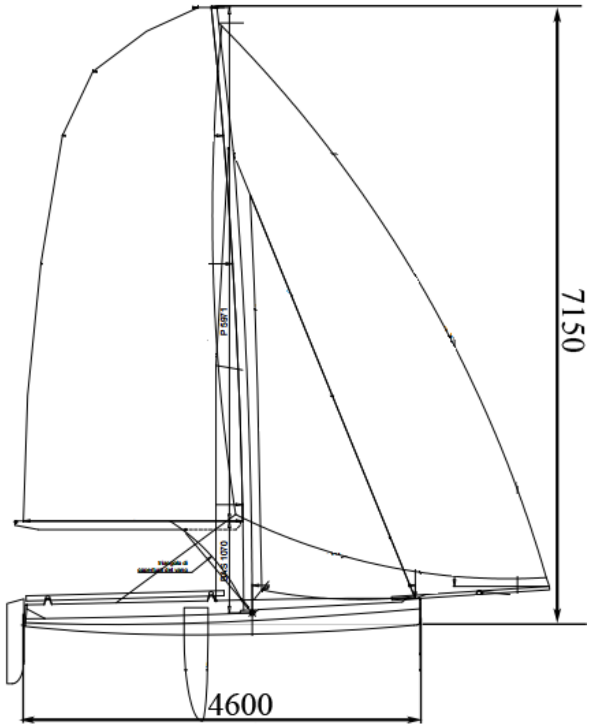


Figure 3: Areté side view; dimensions in [mm].

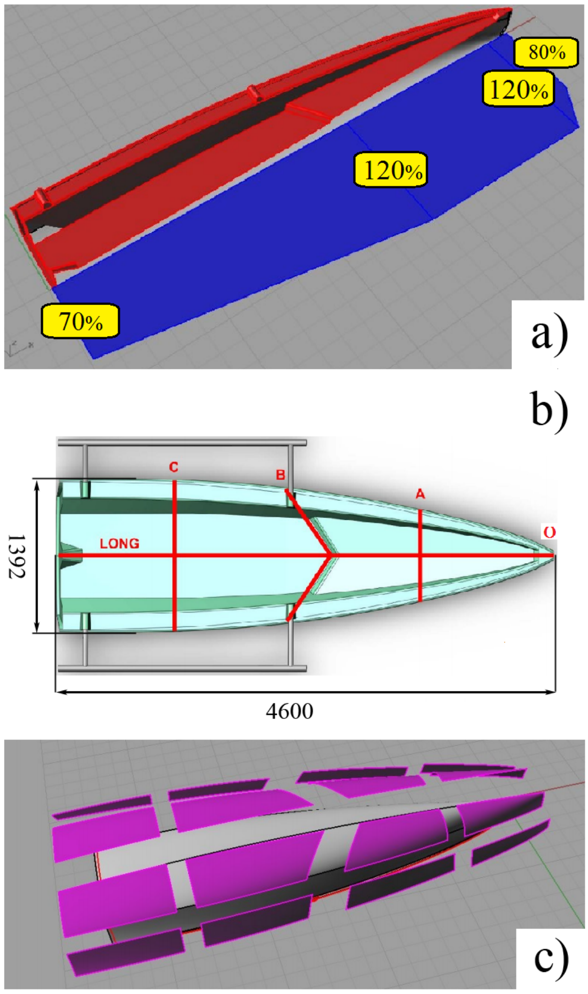


Figure 4: Structural Design of the boat: a) Load Curve (percentages refer to the Basic Head) BH_{hull}; b) Boat internal structures and consequent Panel subdivision c).

to be representative of the real navigation. According to authors' knowledge, racing dinghy design is not covered by any specific rule other than experience or specific class rules for monotype. In particular the 1001Vela Cup competition adopted a restriction-type class rules [20] rather than a monotype one. Accordingly, a well-known and industry-standard design criterion [23] was considered. Although the design indications contained in this reference are not strictly applicable to a 4.6 m skiff, the approach proposed in [23] to calculate and verify the structures of the hull and the wave-hull interactions remains valid for small crafts as well. In order to achieve a reasonable estimate of the hull weight and of the main structure arrangement, a preliminary hull scantling was defined. From hull dimensions it was possible to evaluate the load curve of Figure 4a) in which the numbers indicate percentages of the basic head BH (i.e., a pressure acting on the surface). For the hull, BH was computed as

$$BH_{hull} = 3 \cdot d + 0.14 \cdot L + 1.62 \quad (m_{H_2O}) \tag{1}$$

where d is the vertical distance of the specific panel from the waterline in meters and L is the scantling length (equal to LOA in this case). For Areté BH_{hull} is equal to 2.62 m_{H_2O} ($\simeq$ 26200 Pa).

The subsequent subdivision of the hull into panels through internal structure is mainly a matter of designer experience. In Figure 4b) the longitudinal and bulkheads are presented with the subsequent panel subdivision (4c)). The structural dimensioning of the deck follows a similar procedure but with a different basic head computation [23]:

$$BH_{deck} = 0.04 \cdot L + 1.83 \quad (m_{H_2O}) \tag{2}$$

In case of Areté BH_{deck} was equal to 2.01 m_{H_2O}.

From mechanical data on the flax laminate (see section 2.2.1) the sandwich structure for each panel can be specified. Note that the Guide [23] consider a safety factor equal to 2 (it was intended and tuned for racing yachts that would face open sea conditions and requiring an operating life longer than 20 years). Thus, the structure will likely be verified also for concentrated loads (resulting from crew steps, rigging, daggerboard, etc.). However, the whole boat structure has to be verified using a Finite Element Analysis (FEA).

3.2. Finite Element Analysis

The basis of the FE analysis are reported here. To verify the global behavior of the structure, the whole craft (hull + rigg + appendages) was modeled and analyzed using the commercial codes MSC® Patran and Nastran. Linear static analysis were performed with the aim of verifying a suitable safety margin on the resulting stress and strain distributions. The bio-composite parts (hull and appendages) were discretized with two-dimensional linear quadratic and triangular elements (QUAD4 and TRIA3, [24]). The shell property was applied with the laminate option (i.e., the mechanical properties are the result of the superposition of each layer, [24]). The aluminum rigging and the lateral wings were modeled using one-dimensional elements with the beam property. The wave pressure was applied as a distributed load, according to the *BH* distributions reported in Section 3.1. The loads resulting from the rigging, the daggerboard, the rudder and the crew were estimated using a traditional engineering approach (force and moment balance, aero-elasticity loads, hydrodynamic loads, CFD simulations, etc.) and were applied as concentrated forces (i.e., each load was applied on a limited number of nodes). The whole model was constrained to rotations and translations on the daggerboard center of mass. At the design loading condition, the model resulted perfectly balanced (i.e., the loads on the constraints were remarkably small). According to the results of the analysis in the worst-case scenario, only few reinforcements were added. This confirms that the preliminary design strategy adopted is a satisfactory compromise between strength and weight of the hull.

Finally, a global stiffness evaluation was performed on the bio-composite structure (without rigging, appendages and wings) with a modal analysis (see Fig. 5), to obtain the first flexural and torsional natural modes of the hull and compare them with the parameters of existing wooden racing skiff that previously showed a satisfactory response on the water. Results showed that the adoption of a flax composite material resulted in a significant weight reduction ($\simeq -20\%$) at equal stiffness. The entire structural design process was iterated until when the layout of the principal laminate was defined (see Table 5).

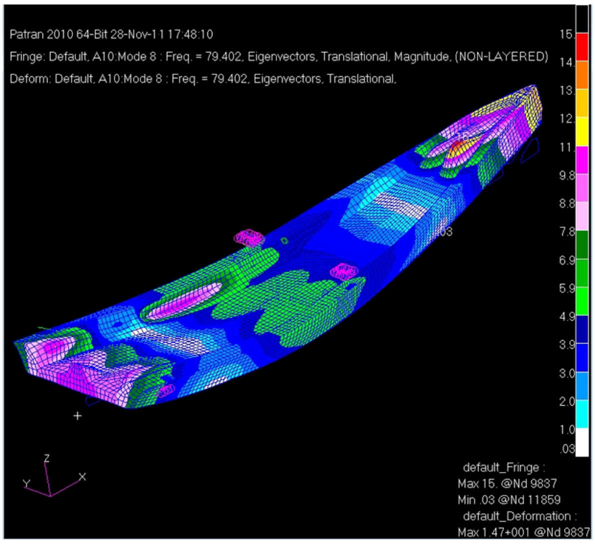


Figure 5: The results of the FE modal analysis performed on the hull.

	HULL	DECK	ρ_{sup} $[\frac{g}{m^2}]$
Flax	[0°/90°/0°/90°]	[±45°/±45°]	4 x 180
Balsa	6.5 mm	6.5 mm	1140
Flax	[0°/90°/0°/90°]	[±45°/±45°]	4 x 180

Table 5: Laminate sequence resulted from the design process; superficial density refer to the single flax ply (resin excluded).

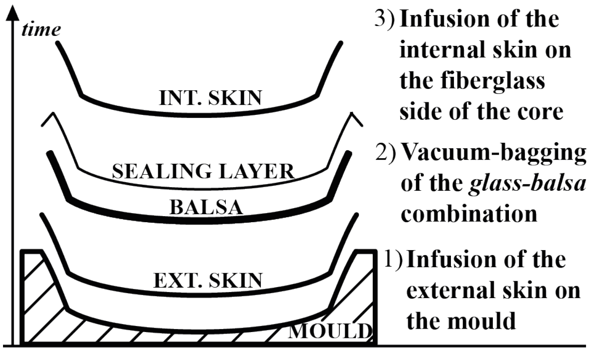


Figure 6: The multi-step infusion process used to manufacture the hull.

4. Multi-step infusion

In accordance with the decision of using the glass/epoxy-sealed-balsa core, multi-step infusion approaches were selected to build both the hull and deck (instead of a single infusion). Similar multi-step techniques are rarely employed, and only in case of high performance racing yachts (e.g. for America's Cup boats) due to the higher costs in terms of time and consumable materials. The process is different for the deck and the hull and, in particular, more complex for the latter. The hull is realized with two infusions (for the external and internal skins), while the core in between is vacuum-bagged. The process is sketched in Fig. 6, while some pictures of the boat construction are presented in Fig. 7.

The entire sequence is summarized in the following steps:

i) Resin infusion of the external skin (see Fig. 7 a) and b));

ii) Preparation and cleaning of the surface of the external skin for the core bonding (see Fig. 7 c));

iii) Vacuum bagging of the balsa core on the external skin and sealing with a handed-lay up glass ply on the upper surface (see Fig. 7 d));

iv) Preparation and cleaning of the upper surface of the glass-balsa core for bonding;

v) Resin infusion of the internal skin on the sealed core layer.

Practically, the entire hull structure was realized with two secondary bondings (i.e., bonding of the new laminate on an existing one). No specific curing process was considered for the secondary bonding of the two laminates. Accordingly, the state of curing was the simple post-infusion one. Although complex and expensive, the process ensures a full control of the resin that is necessary for bonding (and sealing) the core. However, great care must be taken. First of all, time is important: steps (ii) to (v) must be performed as soon as possible after the previous step (i). The strength of the secondary bonding is increased if the polymerization process of the previous step is not totally completed (i.e. the surface is still chemically active). Secondly, before proceeding both to the vacuum bagging and the infusion of the internal skin, it is important to scratch homogeneously the previous laminate to create a rugged surface (steps (ii) and (iv)). This expedient considerably increases the secondary bonding strength. Furthermore, surfaces must be clean and environmental conditions must be controlled to avoid dust deposition among the layers (see Fig. 7 c)).

In the boat construction, a lighter glass fabric was applied with respect to that used for the resin absorption campaign, to reduce the weight. Moreover, according to the sequence of operations used for the hull construction (see Fig. 6), there was no need to drill the core (to allow the resin flowing on both sides of the laminate) and this allowed a further weight reduction, with respect the data reported in Tab.4.

Instead, the deck was realized with a conventional one step infusion, after having previously sealed the balsa core between two glass/epoxy layers with the vacuum-bagging technique (and drilled it). This process (which is faster and need less consumable materials) was applicable to the deck only due to the planarity of surfaces. Accordingly, the manufacturing process continued as follows

vi) Vacuum bagging of the balsa core and the sealing glass layers directly on the mould, to realize a core-kit (see Fig. 7 e));

vii) Demoulding and superficial scratching treatment of the sealed glass-balsa core (on both sides) and drilling to allow resin flowing on both sides of the core;

viii) Single infusion of the whole laminate (external skin-sealed core-internal skin).

This same process was not employable for the hull because of the curved shape that would have not permitted the rigid sealed core of step (vi) to fit tightly the first infused layer, due to its added thickness. This would have resulted in consequent residual stresses in the laminate. No gel coat was used and only some regions of

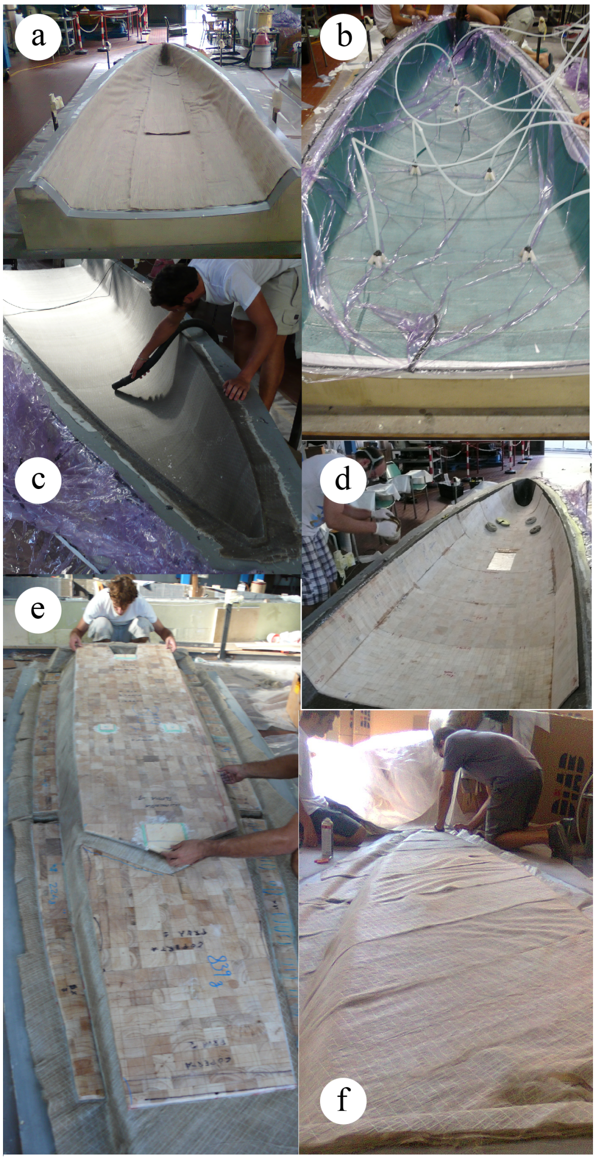


Figure 7: Some phases of the multi-step technique applied to realize the boat: a) Positioning of the flax fibers on the hull mould for the external skin; b) Infusion of the external skin; c) Preparation of the external skin before the vacuum bagging of the core; d) Handing-lay up of the core prior the vacuum bagging; e) - f) Preparation of the deck layers for the single infusion.

Figure 8: Areté during the last edition of the 1001Vela Cup regatta (2015), in Rimini, Italy; picture by Lorenza Menna.

the deck were painted to keep the weight as low as possible. During steps (i) and (viii), a single glass ply of 106 g/m^2 was applied externally on both the hull and deck to prevent eventual scratches on inner flax layers. The final weight of the boat (composed of hull, deck and plywood internal structures, rigging excluded) was ≃65 kg.

5. Boat performance and Discussion

The boat was launched in August 2012 and, since then, has been widely used for competitions and training, under several sailing conditions (from rough sea to windy lake). In Fig. 8 Areté is sailing downwind during the last edition of the 1001Vela Cup in Rimini (Italy). The boat demonstrated excellent performance: she took twice the 2^{nd} position and once the 3^{rd} in the last three editions (2013-1015) of the regatta. With the minimum maintenance, no structural failures were observed so far. This confirms the reliability of the multi-step process employed for the balsa sealing and boat construction. However, the boat spends most of its life-time outside the water (after sailing she is taken out of the water, parked on the shore and covered, while during winter is stored in a protected environment) but this is a common practice for dinghies and small crafts with dimensions up to 6-7 meters and weights up to 700 kg. However, in case of a serial production and to increase the fiber protection from hygrothermal ageing, the application of an external gel coat layer is adviced. Structural data will be collected in the next years to record the structural behavior of the boat, anyway.

The final weight (≃ 65 kg) is close to (or even lower than) the weight of glass/epoxy sailboats of similar dimensions. The multi-step process obviously requires more time and implies higher costs than the single step infusion. If a direct comparison in terms of construction time is performed with a conventional glass-epoxy-PVC craft of similar dimensions, the time required to perform an optimized bio-composite manufacturing technique is estimated to be ≃ 2 times higher than the conventional one, mainly due to the core-sealing operation. To authors' opinion, this aspect would not be critical for small craft production, while might be problematic for larger realizations (i.e., LOA > 8 m) in a capital-cost-conscious market. However, costs can be significantly reduced if a ready-to-use sealing surface treatment of the balsa core can be found. The tensile testing of the fiber batches represents a second additive cost. This cost could be avoided if the fiber suppliers were able to guarantee the minimum mechanical performance on the basis of reliable tests on their batches.

The process of balsa stagnation with vacuum-bagging demonstrated to be successful anyway. When a small section of the deck was cut to realize inspection tapping, the inner balsa core was found to be perfectly dry (i.e., no resin penetrated the thin fiberglass layer). For sure, the secondary bonding technique has some drawbacks in terms of fatigue strength [25, 26] but further analysis are required to evaluate the structural behavior over time.

At last, some considerations on the environmental sustainability of the boat are given. The resin part of the boat is not natural, but as reported by Mohanty et al [7]

> *"It is not necessary to produce 100% bio-based materials as substitutes for petroleum-based materials immediately. A viable solution is to combine petroleum and bio-resources to produce a useful product having the requisite cost-performance properties for real-world applications."*

The obvious step to further increase the natural percentage of the laminate will be the use of bio-based resins. After the construction of Areté, investigations have been taken on resins with natural components. Although an exhaustive treatment of the argument is beyond the scope of the work, some major insights are reported in the following. In Table 6 the principal characteristics of two commercial bio-resins currently available on the market are compared with the RIM 235 epoxy system used to build Areté. Compared to the 100% synthetic one, the mechanical properties of the SUPER SAP® resins decrease with the increase of the percentage of the natural component. In Table 6 the bio-resin BioE-HyRes with a natural component higher than 40% recently developed at the University of Padova has been included as well.

Resin	natural (%)	E [GPa]	σ_r [Mpa]	$\frac{\Delta l}{l}$ (%)
RIM 235	0	3.1	75	10
Super Sap®CLR[1]	17	3.03	65.5	5
Super Sap®ONE[1]	37	2.62	56.5	7
BioE-HyRes[2]	43	2.3	90	-

Table 6: Characteristics of Bio-resins. Natural component by weight. [1]Data reported in (https://entropyresins.com/product/super-sap-clr-clear-epoxy-resin/; [2]Mechanical results obtained from flexural tests.

Due to their recent appearance, the most important drawback of bio-resins is the lack of technical knowledge on actual applications. Furthermore, at present the cost is ≃ 1.5 times higher than that of a conventional epoxy.

Both the racing successes and time-wise overall behavior of the boat demonstrates that bio-composite materials can be structurally employed in the nautical field. On the basis of the experience gained from Areté, a second bio-composite boat is under construction with a similar but optimized technique. The launch is planned within September 2016.

6. Conclusions

The development of a 4.6 m flax-epoxy and balsa wood racing sailboat was presented, from the materials selection to the manufacturing technique. The goal was to provide useful information to boat designers and manufacturers who are interested in building a bio-composite craft. Tensile tests on the flax-epoxy laminates were performed to obtain the mechanical properties and showed the typical scatter of natural components. This latter aspect makes mandatory both the adoption of relevant safety factors during the design process and the testing of the different fiber batches. To limit the extra-weight caused by the high resin absorption of the balsa wood during the infusion process, a specific multi-step technique was developed and applied, according to the indications obtained by a specific resin absorption campaign. The overall final weight of the boat was limited to 65 kg. The craft demonstrated to sail with good performance, reaching the top score positions within the University competition 100Vela Cup (`http://www.1001velacup.eu/`). Moreover, after four years from the launch, no structural failure or damage were observed. We believe that the boat represents an important step in a wider applicability of biocomposites at structural level in the nautical recreational field.

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