Ocean Engineering 133 (2017) 142–150

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

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

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ARTICLE INFO

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

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.

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 (Marsh, 2013). In the near future, steps toward a "greener" nautical production must be taken both from boat designers and manufacturers (Abrami, 2008, 2010). 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 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.

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

http://dx.doi.org/10.1016/j.oceaneng.2017.01.017
Received 7 April 2016; Received in revised form 14 July 2016; Accepted 18 January 2017

In the nautical recreational industry fiberglass is the most employed material (Marsh, 2006). 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 (Marsh, 2006). 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 (Abrami, 2010); similar numbers were reported for France in 2014 (Le Duigou et al., 2014). As Europe counts over 6 millions recreational crafts (Marsh, 2013), 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 (Abrami, 2008, 2010). The European Directive 2008/98/EC (2008) 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. Mohanty et al. (2005) 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 (Joshi et al., 2004); 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 (Marsh, 2013; Joshi et al., 2004).

Starting from the 90s of the 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 Shah et al. (2013), 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 m *Tara Tari*, built in 2010 in Bangladesh, with a hybrid jute-glass laminate (Brunazzi, 2014). The boat sailed from Bangladesh to France and his builder won the *Moitesseir prix* (Brunazzi, 2014). In the same year, the 50% carbon fiber and 50% flax fiber 6.5 m mini transat *Araldite* was launched (Stewart, 2011; Lineo website, 2010) to compete in the 2011 Mini Transat, a solo transatlantic race from France to Brazil, where it gained the 15th position (Brunazzi, 2014). 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* (de Mony-Pajol et al., 2014). 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 Brunazzi (2014). 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., Shah et al. (2013)). 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 (Brunazzi, 2014; Scida et al., 2013). 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 *Areté* (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 technique. 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 (Gibson, 2011) and for its applicability to the VARTM process. The latter, in particular, represents the best trade-off between performance and costs for boat manufacturing (Stewart, 2011). Sandwich structures are the usual choice for medium-to-high performance boats (Marsh, 2006), typically employing glass reinforced skins and PVC core.

2.1. Resin

The resins commonly used for nautical applications are of the thermoset 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 (Mohanty et al., 2005). 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., Mohanty et al., 2005, Zini and Scandola, 2011 for a complete overview), the selection was reduced to the three candidates in Table 1. Jute fibers were soon discarded due to the high water absorption (see Table 1). The distance between the countries where jute is produced (e.g., Bangladesh (de Mony-Pajol et al., 2014)) 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 (Mohanty et al., 2005). Flax fibers feature the highest tensile strength σ_r (345 ÷ 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