Marine Applications of Natural Fibre-Reinforced Composites: A Manufacturing Case Study

Cristiano Fragassa

Abstract The rising concern about environmental issues and the need to find a realistic alternative to glass or carbon-reinforced composites have led to an increased interest in polymer composites filled with natural-organic fibers, derived from renewable and biodegradable sources. The scope of this article is to raise awareness regarding the current scientific and technological knowledge on these so-called green composite materials in order to support their larger application in a number of industry sectors. The general state-of-the-art in terms of green composites is proposed, together with some experimental evidence on the mechanical properties of various ecological materials. As a practical demonstration of this sustainable technology, the adoption of green composites as a valid replacement for fiberglass in sailing applications is also described. This article will, in fact, illustrate, step by step and in great detail, the Wet Lay-up Hand Laminating process used, together with Vacuum Bagging, to realize a yacht deck hatch out of ecological composite materials.

Keywords Boatbuilding · Green composites · Hybrid reinforcements · Manual stratification · Yacht desk hatch

1 Introduction

1.1 Composite Materials

Composite materials consist of two or more materials combined in such a way that the individual materials are easily distinguishable. The new material may be preferred for many reasons: common examples include materials which are stronger, lighter or less expensive when compared to traditional materials. The individual

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materials that make up composites are usually called *constituents*. Most composites have two constituent materials: matrix and reinforcement. The reinforcement is usually much stronger and stiffer than the matrix, and gives the composite its superior properties. The matrix holds the reinforcement in an ordered pattern. Because the reinforcement is usually discontinuous, the matrix also helps to transfer the load among the reinforcements. Considering the presence and the importance of fibers, these materials are also called *fiber-reinforced* composite materials. Most fundamental requirements for composites are directly related to the specificity of reinforcement. Reinforcements basically come in three forms: *particulate*, *discontinuous fiber*, and *continuous fiber*. Reinforcements are referred to as fibers when one dimension is at least one order of magnitude larger compared to others. Even if a large variety of reinforcement is possible, the most common are glass, carbon and aramid (commercially known as Kevlar). Matrix materials are usually some type of plastic, and these composites are often called *reinforced plastics*. The most common plastic matrices are epoxy and polyester and vinyl-ester resins.

1.2 Composites and Ecology

Fiber-reinforced composite materials have gained popularity, despite their generally elevated cost, in high-performance products that need to be lightweight, yet strong enough to withstand harsh loading conditions. At the same time, traditional composites do not represent a valid solution for the environment. One of the main limitations of the use of this large family of composites consists in the simultaneous presence of two different components. This makes reuse and recycling at the end of life quite difficult. Consequently, it is often preferable to engage in direct disposal into a dump or to incinerate the composite products. At the same time, plastic production requires remarkable consumption of oil-based resources, which are notoriously non-renewable. Polymer composites represent a great opportunity for a large range of applications, but the impact on the environment and the distance of these materials from a sustainable industry limits their level of diffusion (Pickering 2006).

With the boom in the nautical sector having started in the 1960s–70s, and given the expected lifetime of over 30 years of a recreational boat (Moreau 2009), the nautical industry expects that a number of boats will come to the end of their useful lives in the coming years. Even if these “dead” boats are not polluting in the sense that they are not releasing any harmful substances into the land or water, there is a risk that they will occupy valuable space in marinas and boatyards, or will be abandoned and dumped illegally, not to mention the derelict look it gives to the surroundings (ECDG 2011). Facing the reality of such risks, the recreational marine industry has recently launched several studies and pilot projects in Europe. However, a totally new approach to both product and production has to be proposed, including such modern tools for environmental evaluation as Risk Assessment and Life Cycle Assessment (Barberio et al. 2010).

1.3 Composites and Boats

As reported by Moreau (2009), in boat construction, the resins used in *fibre reinforced plastic* (FRP) structures are mainly thermosetting (polyester, epoxy, vinylester, etc.). Thermoplastic resins (polyamide, polypropylene, PET, PBT, etc.) have only recently started being used for boat-building or fittings. Recently, the composition of resins has evolved in two ways: both low emission and low styrene content resins are now available on the market. More recently, bio-based resins have started to appear, but their use is still very limited in the nautical sector. The environmental benefits of bio-based resins and adhesives lie in the elimination of toxins in general, the focus on human health and the environment, the reduction of hazardous and toxic materials and waste, the reduction of polluting air emissions, and their recycling capacities. Regarding fibres, natural fibres are also beginning to enter the composite market, but their use in structural elements is limited due to their relatively poor physical properties. Currently, they are used predominantly for filling functions. Glass fibres represent 89% of the worldwide volume of fibres used in composites, while only 10% are natural fibres (Moreau 2009). At the same time, numerous R&D studies for the use of natural fibres are under way and should allow for greater industrial applications in the midterm future

2 Green Composites

2.1 Environmentally-Friendly Materials

The rising concern about environmental issues and, on the other hand, the need for more versatile polymer-based materials have both led to an increase in the general interest in ecological composites. This need is leading scientific research to look for new alternatives, capable of replacing traditional polymer composites with substitutes that have a lower environmental impact, and which are thus often referred to as "*ecocomposites*" or "*green composites.*" These composites can be considered environmentally-friendly when the polymer matrix is biodegradable (e.g., if filled with natural-organic fillers), but also if it comes from renewable sources. The production and characterization of polymer composites based on recyclable polymers (e.g., polyolefins), filled with natural-organic fillers (e.g., fibers and particles extracted from plants) is an extremely interesting field of scientific research and industrial development. At the same time, in a recent period, investigations have also been focused on fibers. Instead of technological fibers such as glass, carbon and aramid, which are already widely used in marine and offshore industries (Camargo et al. 2016), more sustainable ones have been taken into consideration, such as flax, hemp, and cotton. Even if their level of performance is generally much lower compared to traditional composites, especially as far as mechanical resistance is concerned, it is notable that several applications could accept this degradation in requirements in the name of higher eco-sustainability (Sahari and Sapuan 2011).

2.2 Eco-Based Matrices

The availability of bio-based polymer matrices is relatively poor on the market nowadays, but it has been rapidly growing as a result of a large number of ongoing research and industrial investigations on the benefits introduced by these materials and their practical applicability in real cases. Preliminary information on the fundamental properties of composites realized through eco-based matrices is provided in De Paola et al. (2013), Hyseni et al. (2013).

Different kinds of bio-based polymer matrix are available. In particular, inside the families of:

– Thermoset matrices: polyols are compounds with multiple hydroxyl functional groups available for organic reactions, and they react with a large number of chemical species, called curatives or hardeners, to produce cross-linked thermoset matrices. The most important oil used in polyol production is soy bean oil, but cashew nut oil could also give the same results. In order to decrease the impact of their activity on global warming, polyols can also be combined with petroleum-based chemicals.
– Thermoplastic matrices: cellulose represents the most common commercial thermoplastic matrix among bio-based matrices, being 100% eco-sustainable and capable of providing high mechanical properties to the material. Starch-based polymers and Poly (lactic acid) PLA are both available: employment of the former depends on the ability to reduce their moisture absorption, while the latter has similar properties to polystyrene. Summing up, employment of these bio-based polymers depends on the possibility of modifying their properties in order to obtain an easier processing and improve toughness in the final biocomposite.

In addition to their environmental advantages at the end of life, bio-based resins reduce dependency on oil resources. For instance, propylene glycol, which is derived from bio-glycerine, a byproduct of bio-diesel production, can be used as a standard raw material in polyester resins. Vegetable oils from soya beans, castor trees or linseed can also constitute a base material for polyester. Many resin producers have launched R&D programs to obtain 100% bio-based resins, and a similar trend is currently evident in the development of bio-based adhesives.

2.3 Natural Fibers

Natural fibers are compounds combining cellulose, hemicellulose and lignin; they can be derived from leaves (e.g., sisal), bast (e.g., flax, hemp), seeds (e.g., cotton) or fruit (e.g., coir). The most important advantages of natural fibers relate to environmental issues: they are biodegradable and carbon positive, since they absorb more carbon dioxide than they produce (Bogoeva-Gaceva et al. 2007). In addition,

Table 1 Properties of natural and technological dried fibers

Fibers	Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Tensile strain (%)
Jute	1.3–1.45	342–672	43.8	1.7–1.8
Flax	1.50	300–900	24.0	2.7–3.2
Hemp	–	142–819	4.8–34.4	1.5–4.5
Basalt	2.80	4800	90	3.1
Sisal	1.45	444–552	9.4–22.0	2.0–2.5
E-glass	2.54	3200	70	4.0
Aramid	1.44	2400–3600	60–120	2.2–4.4
Carbon	1.81	5490	294	1.9

they are non-irritating and tend to be non-abrasive, with the latter property resulting in reduced wear on tooling and manufacturing equipment. Other important advantages are shown in terms of specific material properties: using natural fibers in place of synthetic ones, it is possible to reduce the weight of a composite material by up to 40%, and it is also possible to improve flexural strength, stiffness and ductility (De Paola et al. 2013). In addition, improved properties in the case of natural fiber thermoplastic composites can be provided by physical and chemical treatments (Zivkovic et al. 2016). However, in terms of overall properties of strength, synthetic fibers perform better than natural ones, even if there are some natural fibres that can approach the tensile modulus and tensile stress of glass (Table 1). These properties are reported in the technical datasheets of *Carbon Fibers America* and *Twaron* for, respectively, carbon (e.g., T800H) and aramid fibers, in Lopresto et al. (2011) for glass and basalt, in Sridhar et al. (1982) for sisal and flax, and in Duval et al. (2011) for jute.

2.4 Hybridization

According to Hall (2003), laminated composites can be classified as:

- composite laminates, obtained using a single type of fiber,
- hybrid composites, obtained from two types of fiber in the same array,

where this “hybridization” can offer a larger flexibility in searching for the proper material solution in respect to each specific application (Hardaker and Richardson 1980).

An interesting application of hybrid composites, including the use of natural fibers, for the fabrication of small boats can be observed, for instance, in Misri et al. (2010).

The hybrid system for improved material or structural performance is, in fact, a well-known concept in engineering design. Furthermore, it can be an extremely valid strategy in the specific case of green composites. Hybridization is a process of *incorporating* two or more types of fiber of varying properties, usually synthetic fibers with natural fibers, or exclusively natural (Bakkal and Savas 2013), or synthetic mixed (Mishra and Mohanty 2003), in order to yield better strength, better stiffness, a high strength-to-weight ratio and other mechanical properties Santulli (2007). According to this, hybridization of natural composites has been found to be an effective way to improve a composite's mechanical properties and dimensional stability (moisture, temperature, etc.). In particular, it permits solving the difficulties in the practical use of natural fibers related to their low stiffness, lower in respect to that of the synthetic ones. The stiffness of biocomposites can, thus, be improved through hybridization, with the aim of permitting the adoption of this class of composite for structural applications.

3 A Technology for Green Composite Production

3.1 Stratification

Composite materials are realized by adding layers, also called *plies* or *lamina*. A single ply consists of fibers oriented in a single direction (*unidirectional*) or in two directions (*bidirectional*, such as, e.g., a woven fabric). The thickness of the layers largely varies, depending on the characteristic of the fibers, resins, properties required, applications, etc. Thicknesses between 0.1 and 0.5 mm are frequently used in our researches on advanced composites, as in Ghelli and Minak (2011), Boria et al. (2016), Poodts et al. (2014), even if thicker layers are also common and may be especially used for low cost applications.

Composite properties are superior in the direction of the fibers, when oriented. If unidirectional, the composite materials have high strength and stiffness properties in the direction of the alignment of the fibers (Rohatgi 1988). Because most structures are not loaded in a single direction, even though one direction may dominate, it is convenient to orient fibers in multiple directions. This is accomplished by stacking multiple plies together, when each ply consists of unidirectional fabrics and fiber orientation may change from one layer to another, or using multidirectional fabrics. Such a stack is called a *laminate*, and the process is called *stratification*. The number of laminates depends on the properties of the layers so as to guarantee an adequate mechanical resistance and a reasonable weight. In general, these composites consist of 4–40 layers, even if there are well-known examples in naval ships of a larger number of layers being used (Mauritz et al. 2001).

Coming back to the characteristics of fibers, laminated composites can be obtained, in general, using long or short staple fibers. Short and discontinuous fiber composites, even if interesting and convenient in several aspects (such as cost, potentiality for process automation or material reuse), are characterized by mechanical properties significantly lower compared to materials with long and continuous fibers. However, in a large number of practical situations, short and discontinuous fibers are not totally randomly oriented. In this circumstance, the proper orientation of the different layers can lead to improvement of the mechanical properties of the composites, even in the case of short and discontinuous fibers.

3.2 Hand Lay-up Method

The Wet Lay-up Hand Laminating Method (also known as Hand Lay-up, for short) can be historically considered to be one of the earliest techniques used for the production of parts in composite materials. It can also be considered the simplest open moulding method of the composite fabrication processes. It consists in impregnating the fibers manually and then laying them on the mould. Nowadays, Hand Lay-up is still widely used in shipbuilding, especially with fiberglass. Since it is a low-volume, labour-intensive method, it is especially suited to large components, such as boat hulls. Glass or other reinforcing mat or woven fabric or roving is positioned manually in the open mould, and resin is poured, brushed, or sprayed over and into the glass plies. Entrapped air is removed manually with squeegees or rollers to complete the laminate structure. Room temperature-curing polyesters and epoxies are the most commonly used matrix resins. Curing is initiated by a catalyst in the resin system, which hardens the fiber-reinforced resin composite without external heat. For a high quality part surface, a pigmented gel coat is first applied to the mould surface.

This technique permits producing parts in composites of any size in a quite easy and inexpensive way, offering a practical answer to the limits encountered in other production technologies, such as in the case of woodworking (Fragassa 2017), even if attention has to be paid in respect to the environmental criteria on the emission of volatile compounds The technique can be used both for the realization of artefacts in "*solid laminate*," overlying layers of fiber up to the proper resistance, or in the "*sandwich*," consisting of external composite layers and a central core of a lightweight material. Inner and outer skins, beyond their primary function of sustaining loads, have additional purposes related to aesthetics and core protection.

3.3 Vacuum Bagging Method

Vacuum bagging is a technique used to create mechanical pressure on a laminate during its cure cycle. Pressurizing a composite lamination serves several functions. First, it removes air trapped between layers. Second, it compacts the fiber layers for efficient force transmission among fiber bundles and prevents shifting of fiber orientation during the cure. Third, it reduces humidity. Finally, and most importantly, the vacuum bagging technique optimizes the fiber-to-resin ratio in the composite part. These advantages maximize the physical properties of advanced composite materials.

It is noteworthy that in boatbuilding, production methods other than vacuum bagging are largely preferred, such as vacuum infusion. In Bank (2006), a complete overview of methods and processes is reported.

4 Materials and Hybrids

4.1 Mechanical Characteristics

As mentioned, in composites, the constituent materials, when combined, produce a material with characteristics different from those of the individual components. This is one of the reasons why composites offer a large range of chemical and physical properties. Furthermore, in the case of "green" constituents, there is an additional variability in properties intrinsically related to the high inconstancy of some parameters in the case of "living" elements (e.g., the percentage of water absorbed by flax).

A preliminary experimental testing of materials is necessary with the aim of reducing the high variability that used to distinguish green composites. The mechanical properties of several biocomposites, reinforced with natural fibers and moulded with a green matrix, have been tested in Pavlovic et al. (2013). All laminates have been realized through hand-up moulding. Three of them consist of natural fibers combined with an ecofriendly matrix (based on a specific vinylester). Two of them are hybrids, combined with two different fibers, both mixed up with a green thermoset resin (considering its low environmental impact). The first hybrid material is a compound of both synthetic and natural fibers (respectively, *carbon* and *flax*), and the second one is a compound with two different natural fibers (*basalt* and *flax*). The mechanical properties of these green materials have been compared with those of traditional fiberglass for nautical applications, obtained by combining fibers of glass with polyester resin.

4.2 Experimental Tests

In order to determine all mechanical properties of these laminates, four tests have been recently realized by the authors, according to the proper standards:

- A tensile test has been performed according to the ASTM D 3039 standard: a thin flat strip of material having a constant rectangular cross-section is mounted in the grips of a mechanical testing machine and monotonically loaded in tension while the load recorded. The ultimate strength of the material can be determined from the maximum load carried before failure.

– A flexural test has been performed according to the ASTM D 790 standard: a bar of rectangular cross-section rests on two supports and is loaded by means of a loading nose midway between the supports.
– A drop-weight impact test has been performed, according to the ASTM D-7136 standard, using a balanced, symmetric laminated plate. Damage is imparted through out-of-plane, concentrated impact (perpendicular to the plane of the laminated plate) using a drop weight with a hemispherical striker tip. The damage resistance is quantified in terms of the resulting size and type of damage in the specimen.
– An accelerated aging test uses aggravated conditions of heat and saline solution to speed up the normal aging processes of materials. It is used to determine the long term effects of expected levels of stress within a shorter time, usually in a laboratory according to controlled standard test methods.

Additional details on experiments and results are reported in Pavlovic et al. (2013), Hyseni et al. (2013), Fragassa (2016), or in the newest (Fragassa et al. 2017; Zivkovic et al. 2017). In particular, while the next-to-last (Fragassa et al. 2017), deals with the mechanical and impact characterisation of flax and basalt fibre vinylester composites, together with their hybrids, in the last one (Zivkovic et al. 2017), the influence of salt water absorption on these properties has also been investigated. These measures have now been considered in such a way as to enable selection of the proper combination of fibres and matrix, with the aim of providing an unconventional *green composite* to be used in the case study presented here.

4.3 Advantage of Hybridation

From these results, summarized in Table 2, it is already evident that green composites (e.g., basalt fiber and a vinylester green matrix) can represent a valid solution in terms of mechanical properties, at the level of other most common materials (e.g., fiberglass), but also adding the important property of eco-sustainability. They also confirm that the mechanical strength of basalt and hybrid laminates is greater than that of fiberglass. Adding their Young modulus, maximum strain becomes higher, as expected. Combining basalt with flax fibers proves to be a good method to reduce the stiffness and brittleness of basalt, demonstrated by plastic behaviour after yielding,

Table 2 Some mechanical properties of natural and hybrid composites (Fragassa et al. 2017)

Laminates	Tensile properties					Flexural properties		
	Σ (MPa)	ε (%)	E (MPa)	G (MPa)	ν (–)	σ (MPa)	ε (%)	E (MPa)
Flax	49.3	0.93	4854	2001	0.21	118.3	1.66	6930
Basalt	160.1	1.47	11,042	5368	0.03	265	1.84	14,481
Flax/basalt	86.5	1.12	8151	3879	0.13	144.8	1.69	8275

which provides greater flexibility to the material. The advantages of having a ductile material are multiple, as, for example, it can ensure greater security, because such a material shows, in general, large displacements before failure, when loaded statically. Thus, a ductile material is a good choice for structural elements, as we desire considerable warning to be provided before they fail. Similar behavior can be shown by multidirectional laminates subjected to progressive failure after the failure of the first ply.

5 Manufacturing

5.1 Case Study

In the case of the yacht desk hatch, this access door was realized as a sandwich, coupling two skins in green composite around a central core in light PVC. Each skin was realized by coupling four plies from two different green composites in an ecological hybrid composite. In particular, two plies of basalt fiber (Basaltex BAS 350 g/m^2, woven fabric) were used as an upper shell, creating a hard black surface. Two layers of flax (Lineo FlaxPly, 300 g/m^2, balanced fabric) were chosen to be the lower part, creating a brown and smooth internal surface. In both cases, green fibres were filled using a vinyl ester resin (Distitron VEef 220 STZ), obtained from bisphenol epoxy resin with low styrene content. All these constituents exhibit a high degree of environmental sustainability, particularly evident in comparison with the elevated impact of traditional materials such as fiberglass. As previously detailed, environmental sustainability is not only offered by the high fraction of natural elements used in the artefact (e.g., flax instead of glass; epoxy with low styrene), but also by the technological processes adopted for working the raw materials and made available on the market in the form of resins and fibers. At the same time, especially considering the substantial equivalence in terms of mechanical characteristics between basalt fibers and carbon fibers, both with a tensile strength higher than 4.000 MPa (Table 1), the hybrid material described here has been able to offer a level of resistance and lightness appropriate to the real application.

5.2 Mould Preparation

The manufacturing process started with the preparation of the mould (provided by the manufacturer), which had to be covered with a chemical agent to facilitate the release of the part when the lamination was finished and to avoid damage to the mould during the forming operation due to friction. In this case, a paste wax was used, specific for moulds in composite materials, as a release agent treatment. A *gel coat* was also laid out on the mould. The gel coat consisted of a resin filler which makes the mould smoother, allowing for a better surface as its finish.

5.3 "Skin Coat" Stratification

One of the most delicate phases was then ready to begin: the deposition of the first layer. Considering that this layer is the most external, and thus most in view, it is able to define the main properties of the artefact, including aesthetics and surface resistance. This so-called *skin coat* was realized by overlapping two plies of basalt and flax, rolled manually for the purpose of exalting the final finish of the product. With the aim of accurately cutting the fabric, a model in cardboard was realized, trimmed according to the geometry of the desk hatch (Fig. 1). Two basalt fabrics and two flax fabrics were trimmed to a size abundant enough to reach the edges of the template, so that the fabric would be sufficiently large and would fit easily onto the mould, covering it fully and comfortably in all its parts. The edges of the fabrics were trimmed from the wires coming out (Fig. 2). The preparation of the skin coat began with the impregnation by resin of the first fabric in basalt. The resin was prepared by mixing it with 2% (in weight) of catalyst, mixed well, for a total of 800 g of vinyl ester resin with low styrene content formulated (Fig. 3). The dry fabric (lying on the mould) was impregnated by pouring the resin on top and distributing it along the entire surface, using a spatula to carefully spread it to all its parts, from the centre to the edges (Fig. 4). The flax fabric was placed on top of that (Fig. 5), following which it was flattened, resin was poured on it, and that resin was spread until complete impregnation (Fig. 6).

The stratification of these two fabrics on the mould was particularly effortless thanks to their low weight, which permitted easy manipulation. In the cases of complex geometries, extreme care should be paid to the fastening of fabric that, once stretched, must be effectively retained in position to prevent shifting or folds (Fig. 7).

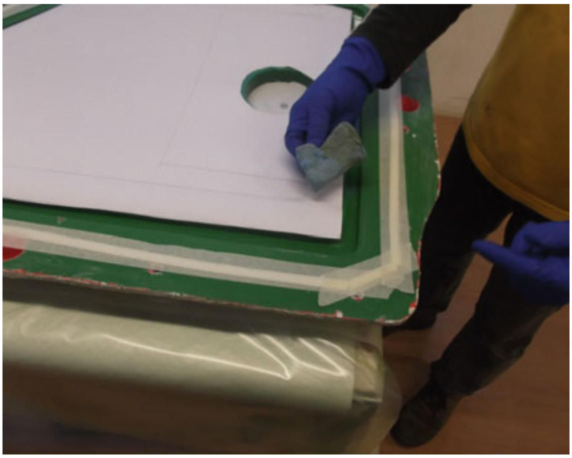


Fig. 1 A model in cardboard has been realized, and trimmed according to the geometry

Fig. 2 The edges of the fabrics have been trimmed from the wires coming out

Fig. 3 The resin has been prepared by mixing it with catalys in exact proportions

Fig. 4 The dry fabric has been impregnated by pouring the resin on top and distributing it along the entire surface, using a spatula

Fig. 5 The fabric made of flax has been placed on the previous one, flattening it

Fig. 6 The other resin has been poured and spread until complete impregnation

Fig. 7 Extreme care has been paid to the fastening of the fabric that, once stretched, has to be retained in position to prevent shifting or folds

5.4 Surface Finishing

After completing deposition of the skin coat, with a ply of basalt facing the mould cavity (as the first layer on the surface), all edges were trimmed with the aim of creating a precise overlapping between the mould and the vacuum bag. Additionally, a hole was drilled, creating an empty space where the handle would be allocated (Fig. 8), reinforcing the whole area with the remaining fabric scraps (Fig. 9).

As the next step, a micro-perforated film, which allows the excess resin and gaseous substances to escape from the laminate in a controlled manner, was stretched (Fig. 10), together with a fabric aerator (*bleeder*), which has the task of allowing the passage of air into the bag when it is subjected to depression, as well as sucking out the gases produced during polymerization (Fig. 11).

Fig. 8 A hole has been drilled, creating an empty space where the handle will be allocated

Fig. 9 The hole has been reinforced with the remaining fabric scraps

Fig. 10 A micro-perforated film, which allows the excess resin and gaseous substances to escape from the laminate in a controlled manner, has been stretched

Fig. 11 A fabric aerator (*bleeder*), which has the task of allowing the passage of air into the bag when it is subjected to depression, as well as to suck out the gases produced during polymerization, has been stretched

5.5 Vacuum Bag Preparation

Afterwards, it was necessary to prepare the vacuum bag that had been fixed to the mould (Fig. 12), all along its perimeter, by means of a double-sided high thickness tape, commonly called "tacky tape" (Fig. 13). This tape is adhesive on both sides and is protected by two layers that must be removed at the time of installation. The contact surface between the mould and the vacuum bag must be in good condition and perfectly clean. In this area, in fact, the vacuum bag must adhere perfectly to the mould, avoiding the passage of air from the outside. The vacuum bag is effectively fixed onto the mould, along the whole perimeter: one side of the tape adheres to the mould and the other to the vacuum bag, the high thickness of the tacky tape and its workability allowing for the creation of a barrier against the ingress of air from outside. The vacuum bag should also be applied with extreme care to avoid damage

Fig. 12 The vacuum bag has been applied with extreme care to avoid damage in positioning

Fig. 13 The vacuum bag has been fixed to the mould, all along its perimeter, by means of a double-sided high thickness tape

in positioning (Fig. 12). It is all too easy to create tiny holes that, while hardly visible, can frustrate the attempt to create the right depression. It is also recommended, if possible, to use a vacuum bag made from a single piece, avoiding the necessity of assembling multiple parties. The drafting of the vacuum bag must obviously encompass the mould perfectly, considering that, once the depression is created, the bag adheres strongly (Fig. 14). It is therefore necessary to provide a sheet large enough to allow for full adhesion without creating tensions that might tear it, defeating the process. In general, the surface of the vacuum bag must be slightly higher than the developed surface of the mould.

Fig. 14 The drafting of the vacuum bag obviously has to encompass the mould perfectly, considering that, once the depression is created, the bag will adhere strongly

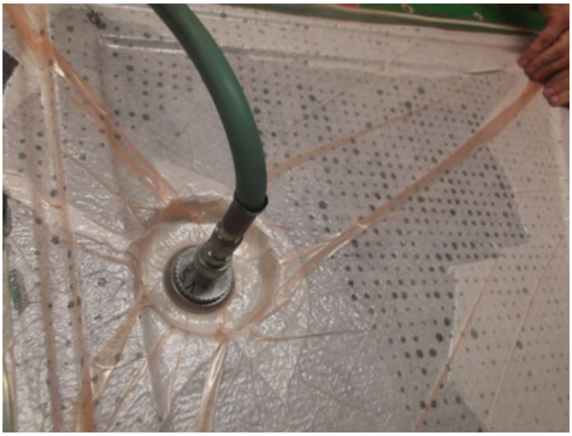


Fig. 15 When the vacuum pump is in operation, the air between the vacuum bag and the mould flows to the outside and the bag is pressed onto the mould

5.6 Vacuum Sealing

When the positioning operation of the vacuum bag is finished, it is possible to turn on the vacuum pump by connecting it to the intake valve, properly inserted. When the vacuum pump is in operation, the air between the vacuum bag and the mould flows to the outside and the bag is pressed onto the mould (Fig. 15). A depression is created in a very short time (a couple of minutes) and kept constant for a curing time of 12 h. Referring to the pressure of the pump, it is not possible to specify a value that will assure the validity of the process in all cases, but in this specific case, a value of 0.7 bar was preferred. At this stage, the first part of the process appears to be complete. However, it is important to remember that the resin is not fully cured, even if it is already in the solid state. An extra period of 24 h needs to be reserved before the vacuum bag is removed together with a micro-perforated film and the fabric aerator. The object, thus realized, has a perfectly glossy and reflective upper surface, corresponding to its side that is in contact with the mould (basalt fabric), while the opposite face is opaque and rough, because it was in contact with the peel-ply (flax).

5.7 Core Inclusion

The following day, after having consolidated the skin coat and removed the plastic bag (Fig. 16), the core in PVC was located, together with the last two plies as a final cover: a sandwich type construction was thus obtained (Fig. 17). The panel, which constitutes the core, was formed by a light material (PVC foam), squared, flexible,

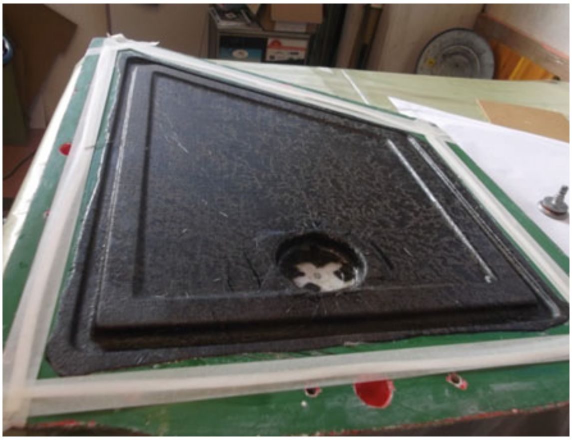


Fig. 16 After having consolidated the skin coat, the plastic bag has been removed

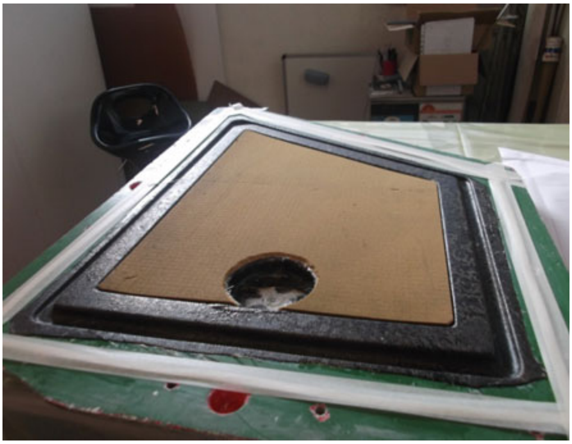


Fig. 17 The core in PVC has been located, just before the positioning of the last plies as a final cover

5 mm thick and generally serving to create space between the inner layers and the outer, increasing the stiffness of the artefact with respect to its weight. The panel was carefully contoured to avoid leaving empty spaces along the edges that would give rise to the accumulation of resin. The core had to be superficially impregnated with resin in such a way as to permit better skin adhesion. For this scope, a slight layer of resin was laid on the surface of the two stratifications (Fig. 18) and, after that, on the core (Fig. 19). A bioresin with 2% by weight of catalyst was also used in this phase.

Fig. 18 Resin has been laid on the surface of the stratifications

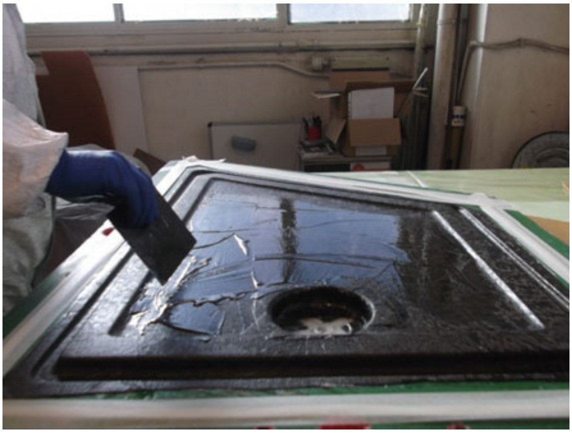
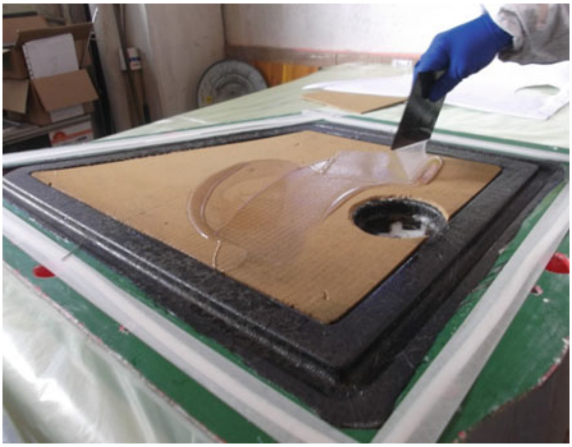


Fig. 19 The core has to be perfectly impregnated with resin through its entire thickness



5.8 Lower Surface

The second cover, used as lower part of the door, was manufactured through a similar procedure. It too was realized by overlapping plies of basalt and flax with resin stratification. But in this case, the basalt faced inward (with respect to the door) and the flax outside. In detail, the procedure included the following steps: impregnation by resin of two plies of basalt, deposition of two foils of flax, distribution of resin with a spatula, always with the foresight to perfectly distribute the resin and eliminate local excess (Fig. 20), provision of the laminate on the mould, edge finishing with a cutter, manual compaction of the layers so as to fit the shapes of the mould, deposition of the micro-perforated film, deposition of the fabric aerator, deposition of the plastic bag, connection of the valve to the vacuum pump, creation of the vacuum (Fig. 21).

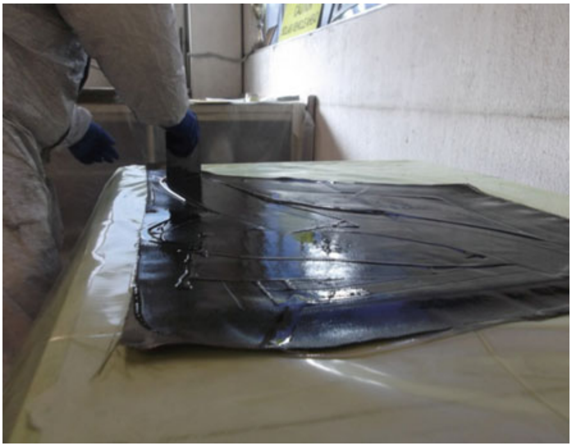


Fig. 20 Excesses of resin have been eliminated

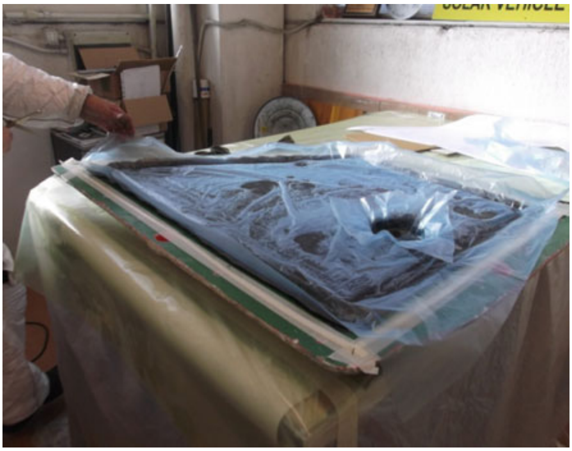


Fig. 21 Vacuum has been created

5.9 Final Finishing

After waiting 24 h, during which time the resin was allowed to cure at an ambient temperature, the artefact was released from the vacuum bag and removed from the mould. As usual, the extraction of the object from the mould was not trouble-free: specific attention had to be paid so as not to damage both factors (object and mould), also ascertaining that the resin had been completely cured. In this case, a plastic spatula, instead of a metal one, was used for the separation, minimizing the risk of scratches on the surfaces of the mould and the work piece.

5.10 An Ecofriendly Artefact

After sanding of the surfaces and finishing of the edges, the piece was ready for use. The access door, thus completed, presented a hard, intensely black, glossy and reflective upper surface, corresponding to the basalt skin coat (Fig. 22). It was considered to represent a valid solution as part of the upper deck on a luxury boat. The opposite face of the sandwich, made of flax, was opaque, naturally brown, smooth to the touch, and suitable as an internal part of the roof in compartments or cabins (Fig. 23). From a functional point of view, this door is characterized by its minimal thickness, lightness (only 1.8 kg) and, at the same time, high mechanical resistance, comparable to that of carbon fiber-reinforced components (Fragassa

Fig. 22 Upper surface in basalt (before finishing)

Fig. 23 Lower surface in flax (before finishing)

et al. 2017), even after prolonged immersion in salt water (Zivkovic et al. 2017). It is thereby evident that hybrid composites, such as the basalt-flax fiber-reinforced composite investigated here, could represent a valid material solution in boat-building, especially when eco-friendliness justifies an increase in cost.

6 Discussion and Conclusion

6.1 General Considerations

Recreational boating is sometimes considered a major source of pollution of the marine environment, due to its high visibility on lakes and along the coast. Even if this is far from the case, with boating actually accounting for less than 1% of overall pollution affecting the marine environment (Moreau 2009), the worldwide community has a different perception. This attention toward sustainability in processes and products can act to foster the adoption of uncommon materials, including, in the case of composites, the use of natural fibers and ecological resins.

The new ecological door is certainly more expensive than the original one. This is largely related to the adoption of more valuable raw materials such as fibers, flex and basalt instead of the cheap glass, able to redouble the material cost

(Santulli 2007). Even in the case of much wider utilization of green composites, as is quite reasonable to expect in the near future (Khalil et al. 2012), it is unlikely that the costs for these materials and their products will ever decrease in such a way as to be economically competitive with fiberglass. Thus, green composites will probably never represent a suitable material solution in the case of large-mass products, aimed at low-end markets (Bismark et al. 2006). Besides, eco-composites already appear to be a valid strategy for increased eco-sustainability, especially in respect to their mechanical properties. In Fiore et al. (2011), a direct comparison between the respective effects of glass and basalt, used as reinforcements in epoxy, is proposed and specifically addressed in regard to marine applications.

According to Artemenko (2003), for instance, basalt plastics have better physicomechanical properties than fibreglass plastics and are much less expensive than carbon-fibre-reinforced plastics. They also satisfy safety standards and environmental requirements. And even if other green reinforcements, such as flax, hemp, jute, etc., which offer lower performance than even basalt fibers (Table 1), are not able to provide the highest sort of performance offered by carbon fibers in the most exclusive applications, green hybrid composites can nevertheless demonstrate a specific resistance, acceptable in a large number of practical cases (Castegnaro 2017). Moreover, at least in anticipation, their final cost will soon be comparable with that of the carbon fiber-reinforced polymers. And in addition, they will guarantee a "*Thinking Green*" approach that several markets are already taking more and more into consideration, even renewing the level of competitiveness of composite products.

6.2 New Functionalities

Furthermore, fascinating evidence has been noted during the realization of the yacht deck hatch of the great potential interest in the case of other industrial applications. Ecological composites can offer products with a new aesthetic and a number of extremely refined functionalities. Basalt, for instance, is deeply black and intense in colour, much more homogeneous and aggressive than carbon, and often disrupted by the presence of fibers in evidence. Flax, its colour varying in shades of walnut and oak, looks warm and natural, perfect for enhancing its use for "human purposes." This is even more relevant in regards to contact. For example, it is impossible to handle fiberglass without adopting surface stabilization treatments that prevent glass fibers from escaping, polluting the environment or slipping into the skin. And it requires only minimum harm on surface, such as micro impacts or corrosion, to start this process. Contrastingly, with flax, it is immediately evident that this is, after all, simply another normal tissue, hardly different from the traditional garments and carpets that accompany us in life.

6.3 Green Composites and Environmental Sustainability

Currently, numerous research groups are dedicated to minimizing the environmental impact of polymer composite production, in which the polymer matrices are derived from renewable resources such as polylactide (PLA), thermoplastic starch (TPS) or thermoset matrices. Their high renewable content derives from vegetable oils and, combined with natural reinforced fibers (NF) to form environmentally-friendly and fully degradable composite laminates, they represent a potential substitute for petroleum-based resins. The complete characterization of the mechanical properties of ecological composites is an essential step for their common and widespread use. Several families of ecocomposite, consisting of a “green” matrix reinforced with natural fibers, have been produced and experimentally tested. These results have been compared with experimental data from “traditional” composites. The characterization of these materials’ mechanical properties is an important factor for their application in real cases. In fact, mechanical properties such as flexural and tensile resistance can largely limit the use of green composites in industrial applications. The use of hybrid laminates, together with sandwich solutions, can offer an interesting practical solution. In this investigation, use of fibers of mineral (basalt) and plant (flax) origin as the reinforcing fibers are assembled in a *green* thermoset matrix in sailing applications, offering low environmental impact. It can be concluded that natural fiber-reinforced biodegradable polymer composites can offer a valid response to the desire for sustainability over a wide range of applications, including sailing applications.

Acknowledgements The artefact was built at in Metal Tig Srl of Castel San Pietro Terme, Italy. The hatch was designed by Ferretti Yachts, and has already been produced and installed on several luxury yachts. This research is part of a larger international investigation regarding the use of natural materials, including wood and cellulose-based reinforcements, in market-oriented applications (as detailed in Savoia et al. 2016).

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