Theme: Architecture, Engineering and Construction

Bamboo-based biocomposite: application for a sustainable naval architecture

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Abstract

A bamboo-based biocomposite, in the form of boards, has been developed and its suitability for boatbuilding has been studied. Bamboo species, resin and paints have been selected and tested, a process has been created, and mechanical as well as physical tests have been conducted on the new material, in laboratory conditions. A first prototype built in the *Bình Dương* province, in Vietnam, with a local carpenter experienced in wood boatbuilding, proved that the material could be used to build the small local river boats, with a little adaptation of the existing techniques. Additionally, a quick comparison with natural materials and composites shows that this solution can give outstanding property with a relatively low density. Finally, the evaluation of the building cost of a five meter long boat and the comparison with the current wood and composite techniques in the same environment was conducted. The study showed that this new biocomposite technology was promising, and the first success with a full scale prototype will pave the way to a development aiming to optimise our methods and truly compete with existing technologies.

1. Introduction

Traditional carpentry for boatbuilding, all over the world, is losing ground face to the new technologies which propose long lasting solutions with very little maintenance. The latter have already made their way in the northern hemisphere, to a point that harbours are now crowded with polymer and fibreglass boats. It results in a major environmental issue, as the fibreglass composite technology becomes more and more accessible but remains completely artificial and non-recyclable.

In the southern hemisphere, and particularly in Asia, the traditional way of building boats, with local wood essences, is still active and responding to a demand. However, its glory is fading and it may be living its last moments as modern composites become vastly accessible. In addition, the price of wood keeps increasing, due to a rarefication of the suitable essences and a globally challenging management of forestry resources. As a result, a concerning environmental issue is looming in southern countries where the boat fleet is counted in millions of units, especially in Asia. Moreover, a standardisation of moulding techniques is provoking a loss of the cultural specificities and traditional skills in areas strongly influenced by their proximity to the seas and rivers shores, like in Bangladesh or Vietnam.

Bamboo, as a fast growing plant with outstanding strength-over-density ratios, is becoming more and more appreciated for technical applications all over the world. The synthesis work done by B. Sharma et al. (two papers in 2015) emphasizes the importance of research conducted for the past decades in the field of engineered bamboo. These two papers show the variety of species and methods that have been successfully tested, and paved the way to a never-ending discovery of the potential of the plant in modern technology.

In the present paper we will expose how bamboo could potentially be used as a base material for a marine biocomposite with promising properties, able to compete with synthetic composites thanks to proper process and assembly. To our knowledge, a single work has been published in the field of engineered bamboo for marine use and boatbuilding (S. Corradi et al. 2009). The authors used bamboo strips laminated with epoxy to assemble a boat hull. The end result of the study appeared promising, but we decided to use different methods, for the assembly of the composite, as well as the assembly of the boat, in order to reach higher strengths with more accessible technics. We present here an overview of the project conducted for the past three years, focused on its key aspects, to develop this material that could preserve traditional boat carpentry and benefit to local populations by creating a sustainable naval architecture. First we will present the process and methods used to produce biocomposite boards, then we will present the mechanical and physical properties of the material tested in laboratory conditions, and finally we will present a practical application, achieved in Vietnam, along with a comparison with the existing technologies.

2. Process and methods: from poles to boards

The aim of the project started in Bangladesh and continued last year in Vietnam was to develop a strong bamboo-based material that could be used as boards to assemble boats using carpentry tools and techniques. Most authors who studied laminated bamboo composites used bamboo slats with rectangular sections (S. Corradi et al. 2009, Verma, C.S.et al. 2012, Lee, C. et al. 2012, Sulastiningsih, I.M. et al. 2009). A traditional way of flattening bamboo first learned in Bangladesh led us to choose long flattened strips instead of the latter to assemble boards. Compared to the regular slats, widely used for flooring and furniture, the flattened bamboo is straight-forward to produce and has the advantage to preserve the outermost and densest layers of the culms. Other authors previously used flattened strips (Nugroho, N et al. 2001, Lee, A. et al. 1998) with promising results. Mahdavi, M. et al. (2012) also proved that such strips could be obtained using only hand-tools, making it convenient to use anywhere in the world. C.N. Park, presented in 2015, at the World Bamboo Congress, a new method to flatten bamboo without any crack, using heat and pressure, making it a potentially very strong material with almost no inner defects. However this latter method appeared expensive to implement for our current project so it has not been considered yet.

The bamboo species used in the following process is a very common Vietnamese one whose vernacular name is *Luong* (according to a local specialist, it is believed to be *Dendrocalamus Barbatus*) coming from the *Thanh Hóa* province. Culms diameters are between 80 and 120 mm, lengths are 5 m and the wall thicknesses range from 5 mm to 15 mm, from top to bottom.

Prior to splitting, the bamboo poles are roughly sun dried and carefully sanded. This last step allows a good bonding with the glue (the bamboo skin cannot be properly wetted by most liquid materials) and is done using a belt sander. It can also be done by hand, with a sharp blade, but it is less clean and more tedious.

2.1. Preparation of the bamboo strips

2.1.1. Splitting and flattening

Culms are manually split in half, using a machete and following the natural curve of the bamboo so that roughly straight-edges pieces can be obtained, as showed in Fig.1. Then nodes' diaphragms are roughly broken and removed and the half bamboos are flattened by cracking along the length with a machine created by a local factory (from the *Bamboo Hardwoods Vietnam* Company, one of our local partner), as showed on Fig. 2 and Fig. 3. The flattening can also be done by hand, with a pointy machete, as it is commonly done in some parts of Asia (e.g. in the rural areas of Bangladesh).

Fig. 1 Fig. 2 Fig. 3

2.1.2. Calibration

The culms having different diameters, the flattened strips have different sizes and have to be calibrated before assembling the composite. This step will also allow to have cleaner and straighter edges, which will make the strips easier to process. Two widths are chosen, 15mm and 12mm, so that a minimum material is lost, and a double circular saw is used with a guiding rail to keep the strips straight.

Fig. 4

2.1.3. Planing

To assemble the strips together in order to form the composite, they must be planed down to a controlled thickness (the planer showed on Fig. 5 was used). This step also allows to have regular surfaces, improving the bonding quality with the glue. The thicknesses used depend on the final boards to be assembled and range from 2.5 mm to 4 mm. Below 2.5 mm it has been observed that too much strips got destroyed, due to the natural irregularity of a flattened bamboo pole, however using a bamboo species with more regular poles could allow to plane down to a lower thickness. This step can also be done by hand, thanks to the linear morphology of bamboo: in the Chittagong area (Bangladesh), it was common to find workers efficiently “delaminating” long flattened bamboos by hand, with a sharp machete. However using the machine makes it effortless, quicker and more accurate.

The strips are planed from the inside of the bamboo so that the densest and strongest part is preserved, then they are sun dried to approximately 15% moisture content, prior to gluing, as shown in Fig. 6 and 7.

Fig. 5 Fig. 6 Fig. 7

2.2. Assembly of the biocomposite

The biocomposite is laminated and consists of two elements: the bamboo strips and the resin. Research has been conducted on various resins to select the most suitable ones economically and environmentally. Unfortunately, for marine purpose, it is very challenging to find “green” solutions, especially at a low cost. After various tests and considerations, bisphenol A-based epoxy resin has been selected, as it offers an excellent bonding, with no need of treatment, and can be reticulated under ambient temperature. In addition, a laminated composite can be pressed with this resin applying a fairly low pressure, in comparison with formaldehyde-based glues traditionally used for marine plywood. D.E.R. 331 epoxy resin (Dow Chemical) has been selected, with an economical aliphatic polyamine hardener. The rate of resin used in the biocomposite depends on the thickness of the bamboo plies and number of layers, but it typically ranges from 15 to 25wt%. All the biocomposites exposed here are unidirectional: all the bamboo plies are in the same direction. Tests are on-going to process effective composites with angled plies, like 0°/90°/0°/90°/0°, but for the current project it has been considered sufficient to use only unidirectional boards.

With the idea to build a traditional boat, two types of element have been manufactured:

- Long and narrow boards for the broadsides of the boat, assembled on a single-curve mould with 4 or 5 layers of 5 m long, 150 mm wide and 3 mm thick bamboo strips, bonded with epoxy resin (Fig. 8);

- Short, wide and thick beams, from which the internal reinforcements are cut out, assembled under a simple flat press with 9 to 11 layers of 1.6 m long, 400 mm wide and 4 mm thick strips, also bonded with epoxy (Fig. 9).


a

b

Fig. 8

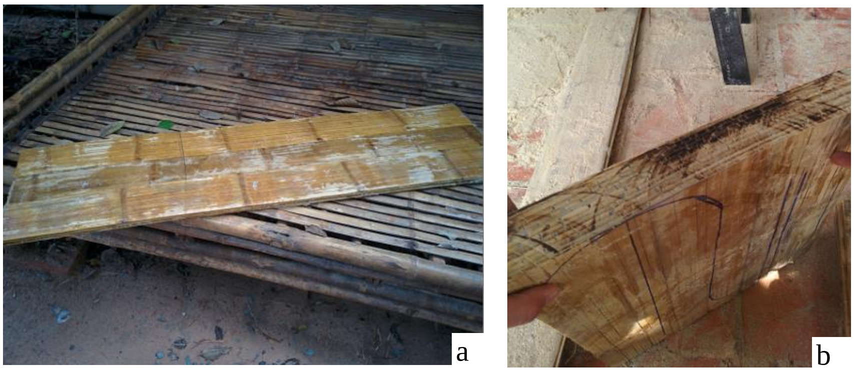


Fig. 9

Both of these elements are assembled using manual hydraulic jacks and clamps, hence the exact pressure used is not known, but it is believed to be between 2 and 5 kg/cm². This pressure is far enough to guarantee a good bonding between the bamboo and the epoxy while preventing the resin to be squeezed out. In addition, comparative tests conducted in laboratory conditions between composite pressed under 10 MPa and 2 MPa proved that using 2 MPa induced a bending strength about 25% higher and a bending modulus about 100% higher. We concluded that using higher pressures was unlikely to give better properties.

3. Mechanical and physical properties

All along the development of the project, various tests have been conducted in laboratories: most of them in collaboration with the Polymer and Composite Materials department of the Vietnam National University, in Ho-Chi-Minh City. In this part we will introduce some of the results we obtained, comforting the technical reliability of the material. Most of the time we observed the bending and shearing behaviours, as it is often done for such materials, being also representative of the use-phase. Some impact tests were also conducted on the composite.

No detailed analysis of the results will be conducted here, as this work aims to give an overview of the project. Additional details are likely to be described and analysed in other publication works.

3.1. Standards and methods

For bending tests, the ASTM D790 standard was used. When bamboo alone was tested, we used the same method, ensuring a length to thickness ratio equal or above 16:1, and the outer face of bamboo was kept intact (so the face was not perfectly flat due to the cylindrical shape of bamboo), facing down so that tensile stress is applied on it. For shearing tests on composites we used the short beam strength method, favouring shear stress: ASTM D2344. The shear tests on bamboo alone was done following the principle of the ASTM D5868 method, but carving the sample inside a 4 mm thick slat from the outer part of the culm (Fig.10): the lignin and the hemi-cellulose, bonding the fibre bundles together, is thus considered as the adhesive (the matrix in which the fibres run) and is directly the part under stress. This latter test on bamboo alone is considered very important as the failure in the composite has been very often observed to occur inside the lignin/hemi-cellulose, due to shear stress across the composite thickness. Finally, the impact tests were conducted following the ASTM D256 standard.

3.2. Tests on the *Luong*

The first thing tested was the bamboo itself, as it is interesting to compare the properties of the raw material with the properties of the assembled composite, the goal of a composite being to equal, and preferably surpass, the capacity of its components. In addition, during this project we used 5 m long strips, and when it comes to bamboo the question of the homogeneity of properties from bottom to top legitimately has to come out. Only 2 complete bamboo poles were tested, with a minimum of 5 samples, without nodes (nodes being chaotic fibrous areas often causing weakness), for every portion tested. More specimens should be tested to validate these results, however they have been considered sufficient for a rough evaluation and comparison purpose with the assembled composites. Here below are the results obtained with the stronger of the 2.

Portion of a 5m pole	MOR (MPa)	MOE (GPa)	Shear Strength (MPa)
Bottom	214,3	17,7	12,9
Middle	214,5	18,2	11,0
Top	167,3	15,2	10,2

Table 1. Mechanical properties of bottom, middle and top portions of a *Luong* culm

The exact ages of the bamboos we worked with were unknown, but the supplier ensured it was at least 3 years old: all of them were thus considered mature. All moisture contents were around 10% at the moment of testing, the average thickness of the bending samples was 3.2 mm, and the average thickness of the shearing samples was 4mm. Fig. 10 shows how the latter was conducted. Unfortunately, the densities of samples have not been measured precisely, due to a lack of tools, but it seemed to be very similar for all samples, around 0.8, this value being higher as the thickness of the sample decreased.

We observed that middle and top portions were very similar in regard of the bending strength and elasticity, and that the top portion is weaker (the results from the other pole led to the same observation). It has been observed by several authors, including Amada, S. et al. (1997), that the strength of bamboo relies on its fibres, which are distributed unevenly across the culm wall: a higher number of fibre bundles, smaller in size, are located at the periphery, ensuring the strength of the culm as a whole, and the distribution is shading in the radial direction until the soft inner periphery where fewer and bigger fibres are found.

The culm wall thickness varies from bottom to top, but extracting a 3mm thick peripheral sample is likely to give approximately the same fibre density all along the culm, and thus the same strength. The lower strength at the top is believed to be due to a lack of maturity of the upper portion at the time of cutting (insufficient lignification), but is also believed to cause very little inhomogeneity in the final biocomposite board. Regarding the shear strength, it is stronger from bottom to top, with this time a clear difference between bottom and middle portions. Here again the difference is considered acceptable to see the board as homogeneous, and alternating bottom and tops in the laminate stacking will further reduce the effect of these differences.

Fig. 10

Note: results obtained from studies on other bamboo species are comforting us in using the Luong, as the bending and shear strength were among the best ever obtained during our research on various Vietnamese species.

3.3. Mechanical testing of the biocomposite

We particularly studied the influence of the number of layers and their thicknesses on the mechanical properties of the long biocomposite boards. The targeted application (broadside pieces between 10 and 15 mm) and the limitation in the minimal thickness we can plane led us to consider three main configurations: a biocomposite board with 3 layers of 4 mm thick (called 3L4 further in the text), one of 4 layers of 3 mm thick (4L3) and one of 3 layers of 3 mm thick (3L3). Both of the two first configurations have a total thickness of around 12 mm, which makes the comparison interesting. The last one, thinner, has been considered with the idea to reduce the weight of the boat as we felt that 12 mm thick was oversized and unnecessary. All composites were around 0.9 in density.

All bamboo strips used to assemble the biocomposites are dried around 10% moisture content and are extracted from the middle portion of 5 m long culms. For each test, a minimum of 5 samples are used and no failed samples were used (if the result is much lower than the average, the sample is not taken into account).

Fig. 11

Fig. 12

Fig. 13

3.3.1. Results

Configurations	MOR (MPa)	MOE (GPa)	Short Beam Strength (MPa)	Impact strength (mj/mm^2)
3L4	195,46	5,83	16,53	50,22
4L3	269,91	8,25	24,98	50,32
3L3	261,37	20,73	15,98	55,43

Table 2. Mechanical properties of 3 biocomposite configurations

We firstly observed that the modulus of rupture seemed to be closely related to the thickness of the plies, considering the similar strength obtained with the 4L3 and 3L3. This could be explained by the fact that a thinner strip is denser, as density is higher when we approach the periphery of the culm, and thus stronger. However, increasing the number of layers from 3 to 4 did not seem to improve this property. For the modulus of elasticity, we obtained a surprisingly stiff composite using 3 layers of 3 mm, as the MOE reached was 20.73 GPa. This latter result is very unusual and may be due to a different length to thickness ratio used for the bending test of the 3L3, so no conclusion should be drawn. But if we consider only the 3L4 and the 4L3, increasing the number of layers and reducing their thicknesses seem to significantly improve this property. As for the short beam strength, which can be associated with the interlaminar shear strength (shear is favoured over bending), it seemed to be greatly affected by the number of layers: from 3 to 4 layers the strength is about 66% higher. This can be explained by the additional layer of resin within the composite, the bonding strength between the resin and the bamboo being higher than the inner bonding strength of the bamboo (which can be associated with the inner shear strength of the *Luong* studied above). Finally, the impact strength was very similar from one configuration to another and the thickness and number of layers were not proved to influence this property.

Compared to the bamboo alone from 3.2., we can observe that the modulus of rupture is improved. However, the strips in 3L4 are 4 mm thick, whereas they were only around 3 mm when the bamboo alone was tested, so it cannot be properly compared using this configuration. Even if the tests were different, we can also conclude that the shear strength has been improved, which is due to the addition of strong resin interfaces. On the other hand, the modulus of elasticity seemed to be reduced, except for the 3L3: similar length to thickness ratios were used to test the bamboo portions and the 3L3, so, considering only these, we could conclude that the modulus of elasticity is also improved by making the composite (more tests would be required to assert this theory).

3.3.2. Comparison with other studies

S. Corradi et al. (2009) developed a bamboo-based composite, using epoxy resin, for assembly of a boat hull. Slats extracted from the culm wall were 0.6 or 0.9 mm thick and assembled in 12 or 8 layers, alternating 0° and 90° oriented plies. Using the short beam strength method, a shear strength of 5.22 MPa has been obtained. They observed that using thicker plies induced higher resin rates and resulted in higher shear strengths. Even though the plies configuration was different, we can observe that the strength obtained in our study was much higher and may be due to the higher density of the plies used: the strips used by S. Corradi et al. were around 0.6-0.7, whereas the densities of our plies were around 0.8. *Phyllostachys Pubescens* bamboo species was used and may also explain the difference by a lower inner strength.

C.S. Verma et al. (2011) developed a layered laminate bamboo composite using 2 mm thick slats extracted from *Dendrocalamus strictus* species, glued with epoxy. Unidirectional composites made of 5 layers (total thickness was around 10 mm) of these slats were manufactured and flexural properties were observed. A mean modulus of rupture of 127 MPa and a mean modulus of elasticity of 13.3 GPa were obtained, with a length to thickness ratio of 20:1. This result can be compared to our tri-layer composite 3L3, tested with a ratio of 16:1 and from which we obtained 261.4 MPa and 20.7 GPa respectively. Here again we obtained stronger composite samples, probably due to the denser bamboo plies used.

Lee, C. et al. (2012) developed a laminated *Moso* bamboo flooring using 5 mm thick lamina glued with urea formaldehyde with different kinds of configurations (vertical glue-lines with 4 or 5 layers and horizontal glue-lines; various faces orientations; parallel and cross-layered). Flexural properties were observed, parallel and perpendicular to outside fibres. The best modulus of rupture and modulus of elasticity obtained parallel to fibres were 103,6 MPa, and 10 GPa respectively. Which could again be attributed to the low density of plies, but also to the weakness of urea formaldehyde glue.

Nugroho, N. et al. (2001) developed laminated bamboo composites using crushed bamboo mats and resorcinol-based adhesive. Mats were thick (average of 11 mm), but a hot pressing process followed by little planing reduced the thickness down to 5 mm of densified bamboo. Different faces orientations were tried, using 4 layers. Here again bending strength was tested and the best modulus of rupture and modulus of elasticity obtained were 86 MPa and 12 GPa respectively, with vertical glue-lines. The difference with our material can mainly be explained by a weak glue, as the density of the composite was as high as 0,94 (average).From our results and these studies, we can at the very least conclude that flattened bamboo strips are viable to assemble such composite. Cracks induced by the flattening process do not seem to create weakness, thanks to the spreading of the resin inside every ply.

3.3.3. Failure faces

Observing the failure faces is a great way to conclude on the quality of the bonding and thus on the quality of the composite. Most of the time the failure happened inside the bamboo and very rarely it happened at the interface between the bamboo and the resin. This latter case could be due to a defect or improper gluing on some spots.

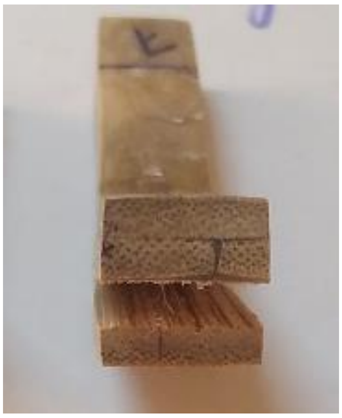


Fig. 14

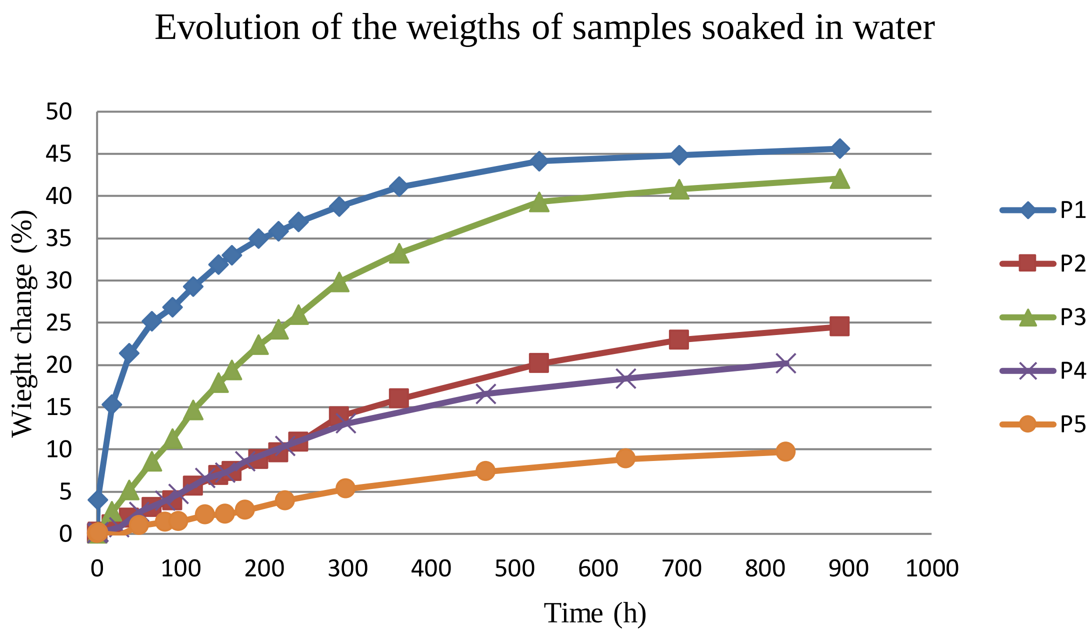
On Fig. 14, which show a typical face we observed after testing, we see that the failure happened close to the interface, but inside the bamboo: at the point where its inner strength is weaker due to a predominance of the lignin and hemi-cellulose. Hence, we concluded that selecting a bamboo with higher inner strength could potentially improve the properties of the composite.

3.4. Coating and aging of the biocomposite

3.4.1. Immersion in current water

Aging tests have been conducted, as the composite is to be used in an aquatic environment. Corrosion is not a problem using natural fibres and epoxy, and unsalted water has been proved to be more prone to be absorbed by bamboo than sea water by S. Corradi et al. (2009) and thus to be a more challenging environment for the biocomposite (absorption causing swelling and causing the ruin of the gluing).

Hence we soaked composite samples (3L4 type) inside a bath of current water and measured the absorption of water. Two kinds of paint have been tested as outer protection: Polyurethane (PU) paint and epoxy paint, the latter bheing commonly used as a strong first protection for all kinds of material, including wood, and the former being commonly used as a top coat to protect the epoxy against UV or even shocks (it also grants an effective additional water resistance). Different numbers of layers and combinations between the two have also been tested. The results are presented in the graph below.



Graph 1. 15

	P1	P2	P3	P4	P5
Description of the protection	Control sample, no protection	1 layer epoxy	1 layer PU	1 layer epoxy + 1 layer PU	2 layers epoxy

Table 3. Description of the different protections tested

Unsurprisingly, epoxy paint is the most effective barrier against water penetration: a single layer greatly reduces water absorption, from 45% to 25% after 900 hours inside water. Adding a second layer is again greatly improving the resistance: from 25% to about 10% after 900 hours. The second layer is covering the defects left by the first one, and is thus very effective. Adding a layer of PU on a single layer of epoxy adds a little resistance, on top of providing the suitable UV protection (this, however, has not been tested). The solution adopted for the application of the biocomposite was to apply 2 layers of epoxy paint and 1 layer of PU paint. More tests have to be conducted to optimize the coating. It is interesting to note that uncoated specimen show a Fickian-like law of absorption (shape of the absorption curve), and as the effectiveness of the coating improves it gradually tends to become linear.

3.4.2. Comparison with other studies

S. Corradi et al. soaked uncoated samples for 666 hours in distilled water and observed a weight gain of 58.6%. Here again, the difference with our results may be explained by the nature of the bamboo plies used: denser and less prone to absorption in our case.

Lee, C. et al. (2012), Nugroho, N. et al. (2001) and Lee, A. et al. (1998) obtained water absorptions ranging from 19,11 to 21,57% at best, without any coating, after 24h. We reached this point after approximately 50h, which could be explained by the difference in densities and bamboos, but also by the glues, urea formaldehyde and resorcinol-based adhesives, which can hardly be compared to epoxy when immersed in water.

4. Application: Assembly of a traditional Vietnamese boat

After two years of study in Bangladesh and one year in Vietnam, the technology developed was considered mature for a first full scale prototype embedding our latest research. According to the objectives of the project we collaborated with a local carpenter in Vietnam, in the *Bình Dương* province, to build a traditional boat using our biocomposite. The mutual adaptation has been fruitful and in one month of work our prototype was born, using boards and beams as introduced in part 2. One of our initial goals was to fully assemble the boards and build the boat with little equipment. As a result, every board was pressed with accessible tools and cut with electrical hand tools used for wood.

4.1. The construction

Nine 5 m long boards have been necessary to assemble the hull and three beams (1.6 m long and 400 mm wide) were used to cut out the reinforcements as well as the bow and the poop.

The raw material necessary for the construction was:

- 32 bamboo culms (5 m long)
- 27 kg epoxy
- 1.4 L epoxy paint
- 0.5 L PU paint

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

4.2. Feedback from the carpenter

During and after the construction, we discussed with the carpenter to know about his feelings with this new material. Overall, from his saying, working with the biocomposite was “70% like working wood”. All along our collaboration, he seemed enthusiastic and interested by the material. He underlined some key aspects and challenges, that we saw as opportunities to improve it in the future.

The main limit of such a material applied to naval architecture is the fact that it is a “dead” material: once the resin is cured, it cannot be bent (although it can undergo elastic deformation), unlike wood that can follow important curves and change shape when heated. As a result, prior measurement and calculation have to be very accurate because the margin of error is narrow. The key to the success of this work is that all broadside boards were bent to the same shape, during the pressing and curing of the resin. A flat board is impossible to bend this much.

Additionally, bamboo is very hard, much more than wood, due to the high amount of silica it contains. Adding epoxy inside makes it even harder and the resulting composite can be challenging to cut. For the construction of the boat we used wood tools, but blades had to be changed often. A better moulding technique could allow to limit the amount of shaping and cutting.

Finally, the sanding was a difficult part, due to the epoxy that is partly squeezed out during pressing. This part is necessary for the assembly, to make the boards more even and to prepare the surface for painting, but it also has been sanded further and finer to get a better appearance. Here again, limiting the squeezing of the resin during the process could save effort and time in the finishing steps.

As a conclusion, after building this first prototype, the technology appeared promising and adaptable. The collaboration with the carpenter has been very helpful in understanding the way we could further adapt and optimise the process to comply with this new biocomposite that cannot be used the exact same way wood is used.

5. Comparison with other major materials

5.1. Comparison of the mechanical properties

We used the software CES EduPack 2005 in order to compare some of the properties established in our studies with those of materials mainly used in boatbuilding. The easiest property to compare is the modulus of rupture (MOR), as the standard method to measure it is very common among all categories of materials. The appendix at the end of this paper presents a graph on which the ranges of MOR of several materials, among the natural materials and the composites universes, are plotted. The brown vertical bars are MOR ranges of the composites (fibreglass with epoxy or polyester resin) and the green ones are MOR ranges of natural materials (mainly woods, plywoods and raw bamboo). The red horizontal line represents the 260-270 MPa strength obtained with our best composites.

From this graph we can see that the only natural material above 200 MPa is the high density wood category, which can reach up to 240.9 MPa according to this data base, with densities between 0.85 and 1.43. But these woods are rarely used for boatbuilding. Among the composites, we can see that our material is only able to compete with polyester (glass fibre, preformed, chopped roving) and epoxy/E-glass fibre woven fabric QI (Quasi-Isotropic, with 90° and 45° oriented plies) laminate ("E"-glass stands for electrical, its initial application), both common in the boatbuilding industry. Additionally, the bottom of the strength range of the polyester with glass fibre woven fabrics composite has a MOR of 276 MPa, so it is comparable with our material. It is also interesting to note that densities of these composites are typically between 1.6 and 2.1, which is about twice the density of our biocomposite.

Despite these promising comparisons, it is important to remember that the biocomposite we have presented here is unidirectional, and that the strengths exposed in this paper have been measured longitudinally. Ideally, some parts of the boat should have oriented plies, to comply with stress in all directions, or the boat should be assembled in a way that safely allows unidirectional composites. In our case, the hull is constituted only of unidirectional long and narrow boards, but the structural work is carried by the reinforcement bars inside, which are perpendicular to the broadsides. These latter parts should have oriented plies to be more effective. For example the 9 layers beams should have a configuration like 0°/90°/0°/90°/0°/90°/0°/90°/0°. At the time this paper is written, we are still waiting for results on biocomposites with oriented plies. Also the beams and boards should be tested longitudinally and transversally. It is a study in progress.

Finally, it came to seem logical that having 10 mm thick boards with a MOR around 270 MPa is actually unnecessary: it is oversized. Strong woods among the medium density category are strong enough to make this kind of boat and some among them are rot-proof. Composites, that can be way stronger, are moulded and can form thinner and lighter structures. So our technique will be adapted in order to reduce thicknesses and further improve waterproofness (proper comparison with woods and composite is still to be studied), so that our biocomposite can really compete with the best boatbuilding materials.

5.2. Comparison of costs

Considering our current technology, we can draw a quick comparison of the fabrication costs between our biocomposite and other technologies. The same boat design is used for the comparison between the biocomposite and wood, and a similar design is considered to estimate the cost of the fibreglass solution.

5.2.1. Cost of the bamboo-based prototype

Even though it is a first prototype, a part of the process is half-industrialised and the following cost can be considered relevant to take into account. Prices have been paid in VND (Vietnamese dong) but are presented in USD, with a change rate of 22.000 VND for 1 USD.

	Bamboos	Resin	Paints	Work force	Total
Amount	32 pieces	27 kg of epoxy	2 L of epoxy paint + 1 L of PU paint	2 weeks work of a local carpenter (boat builder)	
Price per unit	1 x 5 m pole costs 5 USD (including transportation) and costs 4 USD to be transformed into 2 strips	1 kg of epoxy mixed with hardenner costs 5 USD	1 L of epoxy paint costs 9.5 USD and 1 L of PU paint costs 4 USD	230 USD	
Price (USD)	288	135	27	230	680

Note: the costs of the research and of the engineer and intern working on the field (mostly preparing the composite parts and managing the project) have not been taken into account.

It appears that the most expensive parts are the purchase of the bamboo, its transportation and its processing, as well as the assembly by a local carpenter. These 2 aspects could be optimised to drastically reduce the cost: for example by planting the bamboos around the production site, further industrializing the strip production process or by creating an optimised boat assembly process.

5.2.2. Cost of a wood boat in Vietnam

The carpenter who built the boat with us is originally building wooden boats and was able to give us the exact cost of such work and material at the time we met, in 2017.

The common wood used is called *Sao*, a strong and resistant to water local essence: the volume necessary costs around 275 USD for 1 boat, but prices keep increasing every year (in 2017 it is already about 30% more expensive than it was in 2012). It takes 6 days of work to the carpenter, at a cost of around 140 USD. And finally, the cost to apply a protective layer made of natural resin extracted from a local tree is around 45 USD. This construction and protection can grant a life span of more than 20 years, but only if the boat is well maintained and the natural resin layer renewed every year. The total cost is then 460 USD (selling price), one third cheaper than the low estimation of the cost using our biocomposite.

5.2.3. Cost of a fibreglass boat in Vietnam

This is the most common solution today in Vietnam, because it became very affordable along the years and grants a long lasting craft requiring little to no maintenance. An investigation in a shipyard of the Mekong Delta gave us the following information.

To produce a 5 m long, 0.26 m deep and 0.9 m wide boat (same design as the biocomposite and wood ones, as shown on Fig. 21), it takes 4 hours for 2 workers (considering that the mould is already done) and the selling price is around 136 USD. However this is the cheapest solution, with only 2 layers of fibreglass, and it is not considered strong enough, even potentially dangerous to use.

A safe solution for usage on rivers would require at least 3 layers, which costs around 240 USD in the same shipyard. Such a boat would be enough for a light use, and this price (which is the selling price) gives an idea about how competitive is the fibreglass technology today in this part of Asia.

Fig. 21

To conclude, for the same kind of boat, it would cost, today in Vietnam, only 240 USD to get a fibreglass boat, 460 USD to get a wooden boat and around 680 USD to get a boat made of our bamboo-based biocomposite. Further development of the project will allow us to optimise the technology and methods in order to compete with the existing solutions, but we consider positive to already obtain comparable prices.

6. Conclusion

The project conducted for the past three years in Bangladesh and Vietnam allowed us to develop a bamboo-based composite technology suitable for boatbuilding. A partly-industrialised process allowed us to efficiently produce flattened bamboo strips from *Luong* poles, a Vietnamese bamboo species, and to assemble them into biocomposite boards. This base material has been tested, mechanically and physically, in laboratory conditions, and even if some studies are still to be conducted, the obtained results and the comparison with previous studies as well as with other materials is promising: strong and light composite materials can be produced from bamboo to produce curved shapes and can compete with the existing technologies. Collaboration and mutual adaptation with a Vietnamese carpenter, experienced in the traditional building of southern river wooden boats, gave birth to a first prototype which proved the feasibility of the application and proved that such a boat could be produced with little equipment: only the sanding of the poles (to remove the outer skin) can be challenging by hand.

Today, if the technology has to compete with existing technologies, it seems clear that our techniques have to be improved in order to simplify the process, especially the manual steps, and reduce the global production cost. Particularly, the production of the flattened strips can be optimised through further industrialisation. This is part of the developments to come for the project, which is today an opportunity to create a sustainable naval architecture that will build viable, greener and local boats at interesting costs for the people of Vietnam, Bangladesh, and any other population around the world willing to associate shores and bamboos.

Figure captions

Fig. 1 Luong pole sanded and longitudinally split in 2
Fig. 2 Half bamboo after flattening
Fig. 3 Flattening process with a motorised machine
Fig. 4 Table used for calibration
Fig. 5 Wood planer used to reduce and control the thickness of the bamboo strips
Fig. 6 Inside view of a flattened and planed bamboo strip
Fig. 7 Sun-drying of the bamboo strips
Fig. 8 Bamboo-based shaped composite board (4 layers): a. Global view b. Cross-section view
Fig. 9 Bamboo-based composite beam (11 layers): a. Global view b. Cross-section view
Fig. 10 Shear test of a bamboo sample, carved in the wall
Fig. 11 Short beam samples, 3 layers of 4 mm (3L4) configuration
Fig. 12 Impact test samples, 4 layers of 3 mm (4L3) configuration
Fig. 13 Short beam test
Fig. 14 Side view of a sample after bending test, 3 layers of 4 mm (3L4) configuration
Fig. 15 Assembly of the hull of the boat: boards are nailed together and join at the bow and poop
Fig. 16 Fitting of the reinforcement bars cut out from the beams (9 layers)
Fig. 17 Caulking between 2 boards with a jute string
Fig. 18 Fully caulked hull: the jute strings are covered with natural tree oil
Fig. 19 Sanded and painted hull
Fig. 20 Final bamboo-based boat
Fig. 21 Fibreglass boat with a similar design and size to our bamboo boat

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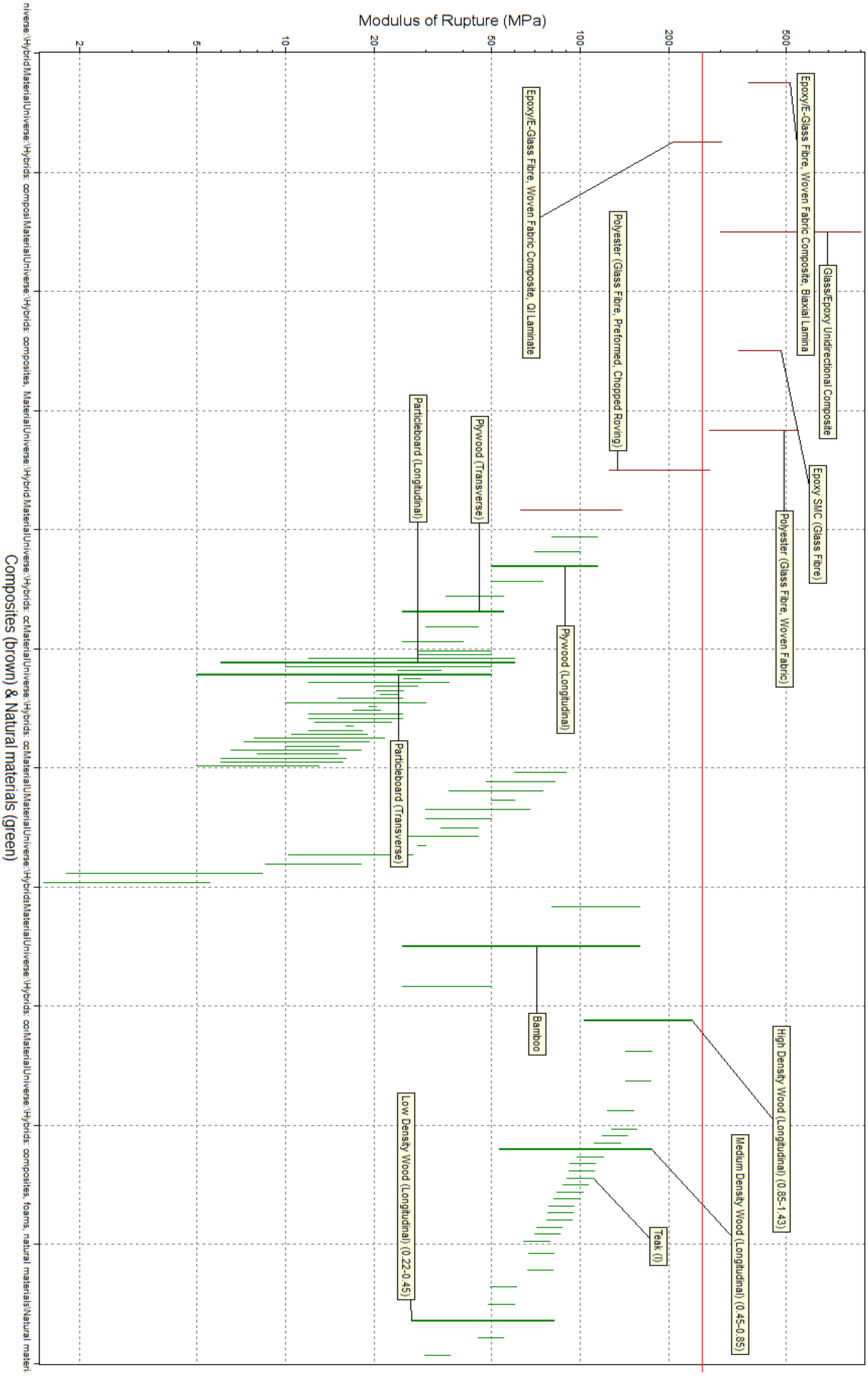
Appendix



Modulus of Rupture (MPa)
2
5
10
20
50
100
200
500
Epoxy/E-Glass Fibre, Woven Fabric Composite, Biaxial Lamina
Glass/Epoxy Unidirectional Composite
Epoxy/E-Glass Fibre, Woven Fabric Composite, QI Laminate
Polyester (Glass Fibre, Preformed, Chopped Roving)
Epoxy SMC (Glass Fibre)
Polyester (Glass Fibre, Woven Fabric)
Particleboard (Longitudinal)
Plywood (Transverse)
Plywood (Longitudinal)
Particleboard (Transverse)
Bamboo
High Density Wood (Longitudinal) (0.85-1.43)
Medium Density Wood (Longitudinal) (0.45-0.85)
Teak (l)
Low Density Wood (Longitudinal) (0.22-0.45)
Composites (brown) & Natural materials (green)