BAMBOO STRUCTURAL COMPOSITES FOR MARINE APPLICATIONS

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SUMMARY

Bamboo laminates are made from bamboo strips (slivers) milled out from the bamboo wall core. The use of natural bamboo fibre in composites is on the rise. In the present study, the overall mechanical characteristics of bamboo fibres reinforced composites and sandwich for general marine applications were analysed. An accurate analysis of processing possibilities and statements has been conducted, evaluating the relationship between composites performances and processing characteristics. The effectiveness of vacuum bagging and compression moulding processes were analysed. Accurate chemical – physical and mechanical characterizations of bamboo based reinforced resins (epoxy) were conducted, analyzing also the variation of these properties during the materials ageing. Accelerate ageing tests were conducted on bamboo composites and sandwich specimens, obtaining the relationship between materials characteristics and ageing time. Finally, absorption tests (in distillate and sea water) were performed to simulate the effective environment in which bamboo based composites have to be applied, denoting that bamboo composites exhibit excellent resistance to the marine environment and their applications could make good inroads in the marine sector worldwide. As application, a spinnaker pole have been realised and tested under axial compression load.

1. GENERALITIES

The use of natural fibres such as jute, sisal, banana, hemp, ramie, coir etc. as reinforcements in plastics is increasing tremendously. Wood flour and other fibres are primarily used as fillers in thermoplastic decking, building materials, furniture & automotive components. Long agricultural fibres such as flax, kenaf, bast, hemp and jute are used as structural reinforcements in thermoplastic/thermoset composites as a replacement of glass fibre.
Other authors have studied the mechanical properties of lignocellulosic/polyester composites with well-defined fiber orientation (unidirectional or bidirectional) [1,2,7,11]. The samples were produced either by wet layup or by press molding of MgO thickened prepregs (similar to sheet molding compound).
Bamboo [3,4] is one of the fastest renewable plants with a maturity cycle of 3-4 years, thus making it a highly attractive resource compared to forest hardwoods. Bamboo offers good potential for processing it into composites as a substitute of solid wood for structural uses [14,15,16].

The Bamboo is suitable as material for construction because it is sufficiently hard, strong and dimensionally stable. From a botanical point of view, bamboo is not wood but grass. Many Bamboo species exist, but the one used in technological applications is the *Phyllostachys Pubescens*, which can reach up to 20 meters of height and a diameter of 18 cm. The bamboo fiber cross-section is generally constituted by a near net of micro – openings which make it particularly sensitive to moisture absorption, but on the other hand the porous structure favours the wettability with matrices in composite applications.
The production of fibers unidirectional is sketched in fig. 1. Initially a primary process is done consisting in cross cutting, splitting and 2-D planning of the raw bamboo. Then management of thickness, sizing and sorting with a starch removal and moisture reduction are performed. Finally a light uniform spreading of resin and hot pressing are applied to ease dispatching and to control dimensional tolerance. This thermoplastic binder helps fiber preforms hold their shape and improves adhesion to the matrix.

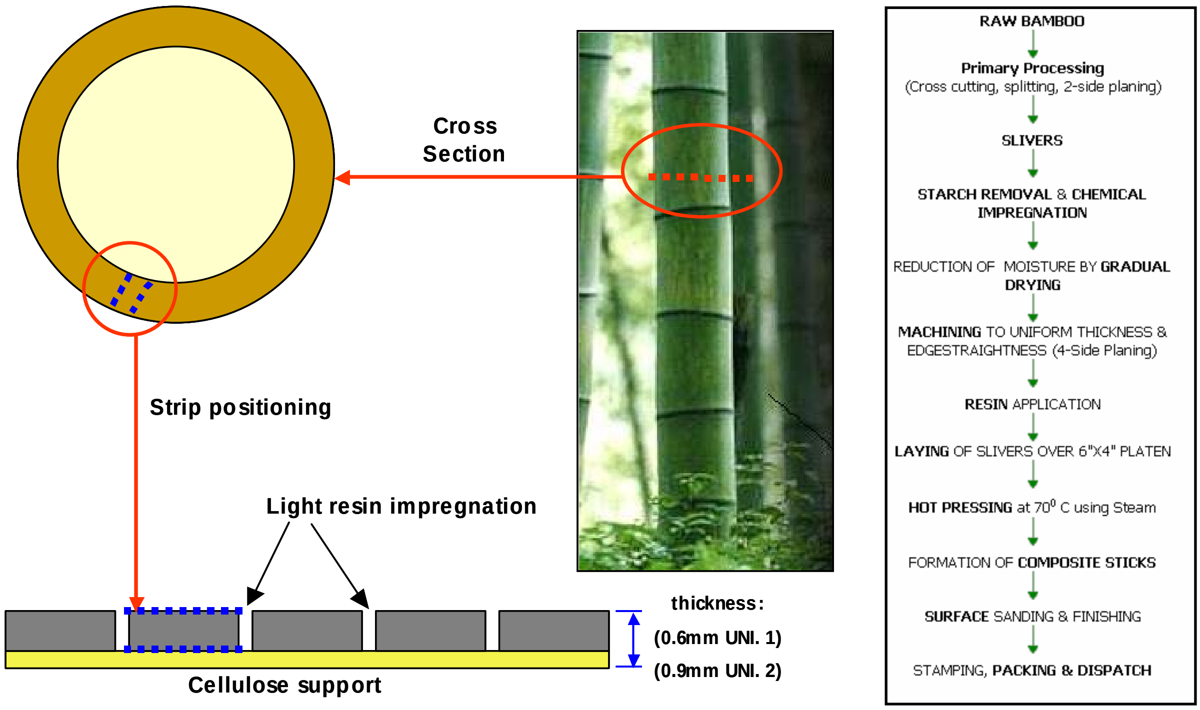


Fig. 1: Process fabrication of bamboo unidirectional

It has not been thought necessary, in this phase, to apply any chemical surface treatment neither physical treatment to bamboo fibers, considering that dry unidirectional fibers are already supplied with a light resin spreading that guarantees the necessary stability and the best adhesion to the used matrix.
Two standard thicknesses are available, according to bamboo plant thickness, “type 1” 0.6 mm. thickness and “type 2” 0.9 mm. thickness.
One of the objectives of this work was to identify, at least indicatively, all the process parameters that may influence the overall final mechanical characteristics of the composite: to such aim, together with vacuum bag technology, which appear suitable at least at this initial step, the hot pressing technology is then set up and utilised for comparison.

2. SPECIMENS FABRICATION AND EXPERIMENTAL RESULTS

Initially, raw bamboo unidirectionals have been tested on specimens measuring 20 by 200 mm under traction (fig. 2), whose results are reported in Tab. 1.

Fig. 2: Experimental tensile tests on raw bamboo unidirectional

	Mean Value	Standard Deviation	± [%]
Ultimate Tensile Strength [MPa]	58.34	1.58	2.70
Ultimate Strain [%]	1.74	0.12	6.90
Young Moduli E [MPa]	4517.17	634.36	14.04
Young Moduli $E_{1/3}$ [MPa]	5303.94	545.06	10.28

Fiber Type	Density (g/cm^3)	Elastic Modulus (GPa)	Specific modulus
E-glass	2.55	73	29
Hemp	1.48	70	47
Flax	1.4	60-80	43-57
Jute	1.46	10-30	7-21
Sisal	1.33	38	29
Coir	1.25	6	5
Cotton	1.51	12	8

Tab. 1: Raw bamboo unidirectional tensile tests results and some fibers characteristics

Compared to other natural fibers, bamboo unidirectional, whose density is 0.68 g/cm^3, denotes an elastic moduli of 4.5 GPa and a specific moduli of 6.61. Despite these non-top characteristics, the main advantage of bamboo unidirectional over the other natural fibers is the excellent raw configuration which allows good result reproducibility and constant mechanical properties.

Secondly, the quantitative measurement of fiber-matrix interfacial adhesion has been analysed. Both direct and indirect methods have been utilised, i.e. fiber pull-out test and short beam interlaminar shear test (ILSS).

In the case of fiber pull-out test, however, such typology of test couldn't be applied; the utilised bamboo fibers, in fact, are not fiber bundles, from which a single fiber can be extracted, but unidirectional sheets. The entire system therefore is constituted by fibers tied together with cellulose, emicellulosa and lignin. For this reason, the direct test realised only simulates the phenomenon of the pull-out. The specimens realised are the one depicted in Fig. 3. Epoxy resin CAMATTINI EC 130 with 30% in weight curing agent W 340 have been utilised. 14 hours curing time at 25° C and 10 hours post-curing at 60° C have been applied.

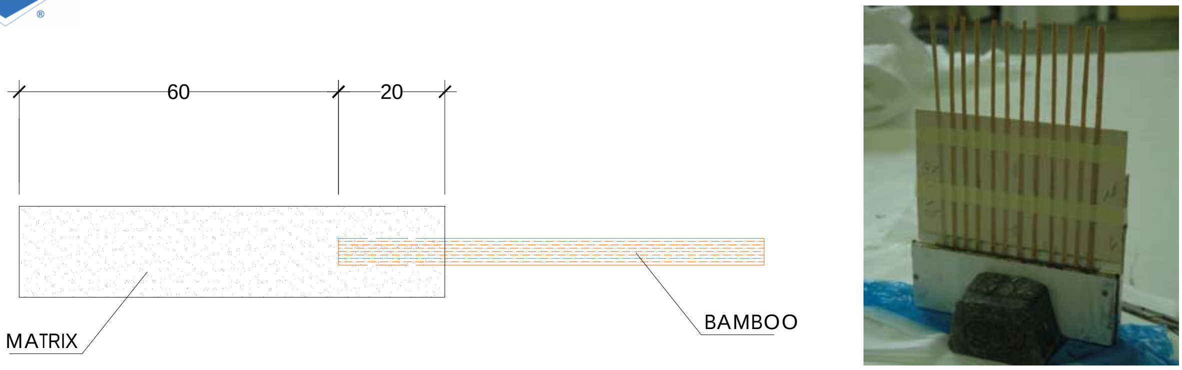


Fig. 3: Specimens for the pull-out test

The indirect method – the short beam interlaminar shear strength method – follows the ASTM D 2344–84. Two specimen configuration have been realised: 12 layers $[0^\circ/90^\circ/0^\circ/90^\circ/0^\circ/90^\circ]_S$ for type 1 unidirectional with dimensions of 70(L)x7.35(H)x11.3(S) mm. and 8 layers $[0^\circ/90^\circ/0^\circ/90^\circ]_S$ for type 2 unidirectional with dimensions of 70(L)x7.65(H)x10.0(S) mm. A crosshead speed of 1.5 mm/min. was used. Pull-out tests and short beam interlaminar shear strength test provided consistent results shown in Tab. 2.

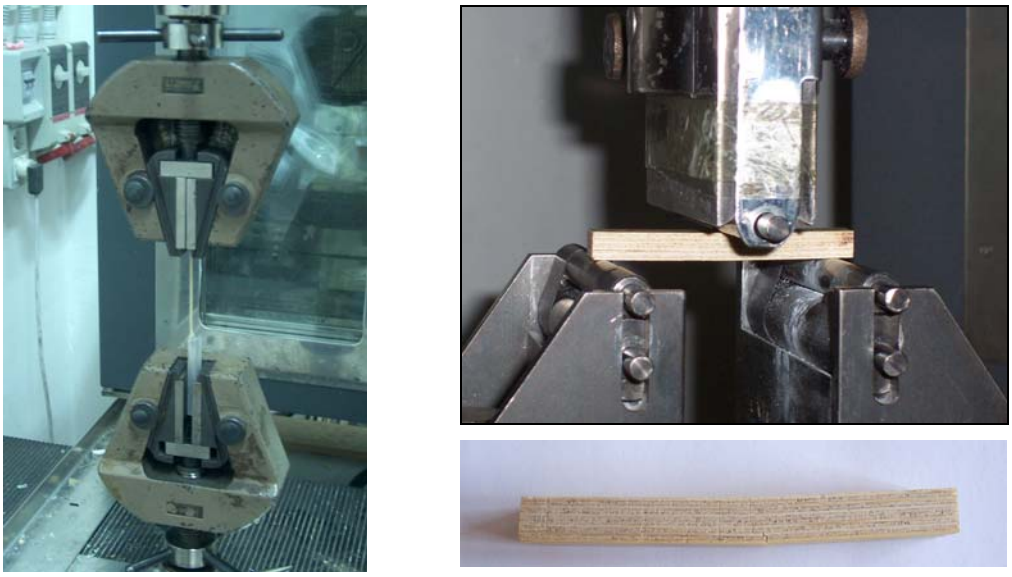


Fig. 4: Tests for the pull-out and for the ILSS analysis

As it can be seen from the following table, the ILSS increases as the reinforcement thickness increases, i.e. passing from type 1 to type 2 unidirectional, at constant pressure. This may be attributed to the greater fraction in weight of the matrix, which passes respectively from 23% to 38%.

SPECIMEN		L [mm]	W [mm]	h [mm]	P [N]	ILSS [MPa]
UNIDIRECTIONAL TYPE 1	1	70	7.35	11.30	407.62	3.69
	2	70	7.35	11.40	452.80	4.05
	3	70	7.20	11.35	383.35	3.52
	4	70	7.30	11.35	447.55	4.05
	5	70	7.30	11.40	373.49	3.37
	MEAN				412.96	**3.73**
	STANDARD DEVIATION				32.39	0.28
	STANDARD DEVIATION [%]				7.84	7.45
UNIDIRECTIONAL TYPE 2	1	70	7.65	9.90	506.67	5.02
	2	70	7.60	9.85	511.49	5.12
	3	70	7.60	10.00	536.15	5.30
	4	70	7.60	10.00	525.63	5.19
	5	70	7.60	9.60	533.68	5.49
	MEAN				522.72	**5.22**
	STANDARD DEVIATION				11.78	0.16
	STANDARD DEVIATION [%]				2.25	3.05

Tab. 2: Results for the ILSS

For the traction tests, two configurations have been prepared with both technologies, one for each type of unidirectional.

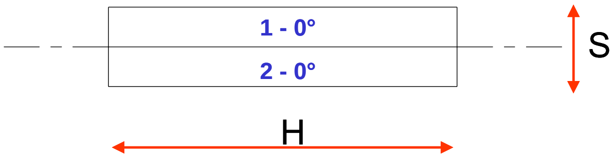


Fig. 5: Traction test specimen stacking sequence

For the hot pressing technology, two pressure levels have been selected: 3 bar and 50 bar.
This bunch of specimen - realised both with vacuum bag and with hot pressing at two pressure levels - allows to better understand process parameters - pressure, temperature and matrix content - influence on the final composite. All specimens for testing were cut from the flat section of the panel in such a way to ensure uniform fiber loading.

Fig. 6: Vacuum bag process for composite bamboo panels

Fig. 7: Hot pressing process for composite bamboo panels

Tensile tests on impregnated specimens measuring 20 by 200 mm were conducted according to ASTM D 3039–76 and flexural tests on sandwich specimens measuring 40 by 250 mm by ASTM C 393–88 at the Civil and Environmental Engineering Department of the University of Perugia with load applied perpendicular to the surface of the fiber unidirectional; corresponding thicknesses depending upon described lamination. A crosshead speed of 2 mm/min. was used. The stress-strain curves were analyzed using a three-parameter hyperbolic tangent model that has been shown to accurately represent the stress-strain behavior. The composite specimens were all tested to failure. Information collected in the tests included tensile strength at failure, tensile modulus, flexural strength, and flexural modulus. Tensile tests results are the following:

	Mean Value	**Standard Deviation**	**± [%]**
Type 1 – 3 bar			
Ultimate Tensile Strength [MPa]	72.46	1.01	1.39
Ultimate Strain [%]	1.31	0.07	5.02
Young Moduli E [MPa]	5535.80	266.0	4.80
Young Moduli $E_{1/3}$ [MPa]	5400.24	961.18	17.80
Type 2 – 3 bar			
Ultimate Tensile Strength [MPa]	100.00	5.83	5.83
Ultimate Strain [%]	1.87	0.21	11.23
Young Moduli E [MPa]	5425.00	796.00	14.70
Young Moduli $E_{1/3}$ [MPa]	5511.00	1269.00	23.10
Type 1 – 50 bar			
Ultimate Tensile Strength [MPa]	74.78	3.65	4.88
Ultimate Strain [%]	1.772	0.13	7.09
Young Moduli E [MPa]	4719.01	461.61	9.78
Young Moduli $E_{1/3}$ [MPa]	5121.77	484.79	9.46
Type 2 – 50 bar			
Ultimate Tensile Strength [MPa]	100.11	9.12	9.11

Ultimate Strain [%]	2.68	0.16	5.82
Young Moduli E [MPa]	3741.11	409.67	10.14
Young Moduli $E_{1/3}$ [MPa]	4406.43	457.41	10.38

Tab. 3: Hot pressing impregnated bamboo unidirectional: tensile tests results

Type 1 – Vacuum bag	**Mean Value**	**Standard Deviation**	**± [%]**
Ultimate Tensile Strength [MPa]	92.47	2.27	3.82
Ultimate Strain [%]	2.88	0.128	10.37
Young Moduli E [MPa]	5637	108.3	4.4
Young Moduli $E_{1/3}$ [MPa]	5689	98.3	3.4

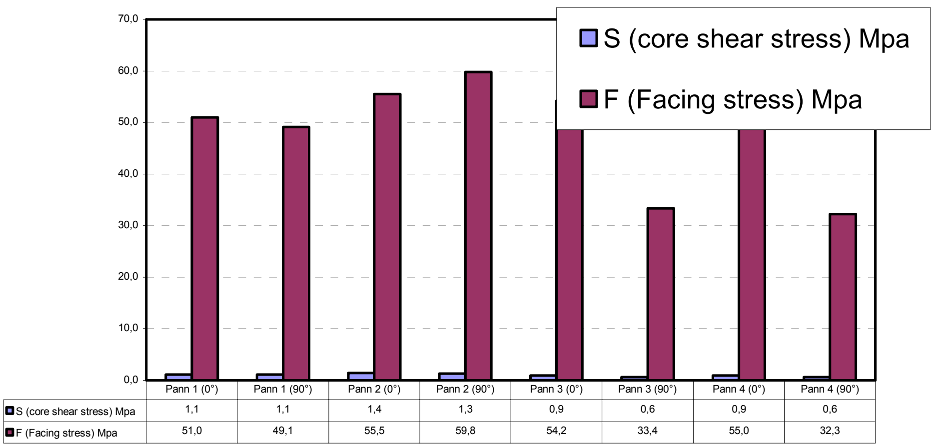
Tab. 4: Vacuum bag impregnated bamboo unidirectional: tensile tests results

From the above results, a remarkable effect is denoted: as the stamping pressure increases, the tensile strength remains constant but the elastic moduli decreases; this variation can be attributed to the fact that the bamboo fiber reinforcement and its cellulose support are characterised by a porous structure which tends to be more impregnated as the pressure increases. This is confirmed by the fact that the volumetric fraction in weight of the matrix increases from 23.5 % to 35.6 % passing respectively from 1 bar to 50 bar pressure. Therefore the Young moduli decreases since the matrix denotes an elastic moduli equal at the half of the one of the reinforcement.

For the flexural tests, only 0.6 mm. type 1 bamboo unidirectional has been utilised for sandwich realisation. Core material is a 6 mm. 150 Kg/mc balsa. The balsa comes in approximately 50 mm. square blocks which are glued onto a scrim. The balsa is quite flexible and lays around most compound curves without giving any unfair surface. All specimens for testing, realised by vacuum bag, were cut from the flat section of the panel in such a way to ensure uniform fiber loading.

The lamination of the sandwich panels is $[0°/90°/0°/90°]_S$ plus an intermediate core of balsa.

Results of the three-point bending tests on the realised sandwich are reported in Tab. 5. The experimental flexural strength – around 50 MPa - appear comparable to the tensile strength found with the traction tests.



Tab. 5: Stresses on sandwich subjected to three point bending test

3. PHYSICAL TESTING

Bamboo composites were exposed to the harsh marine environment. Two kind of tests have been performed. Through the moisture absorption test – conducted according to UNI EN 2489 both with sea and distillate water - the variation of weight and of tensile strength have been recorded. Weight gain as a percent of initial weight is reported in Fig. 9.

(a) (b) (c)

Fig. 8: Absorption test: specimens (a), immersion basin (b), digital balance (c)

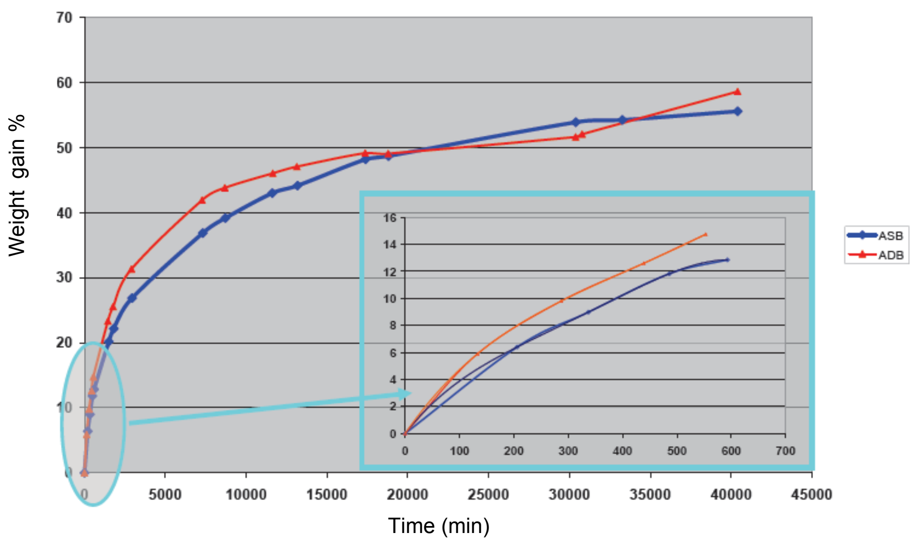


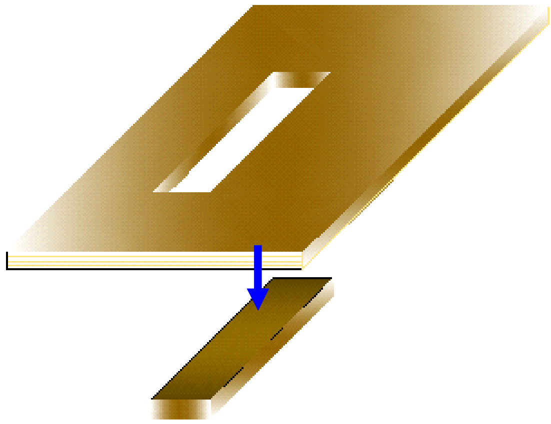
Fig. 9: Absorption test results on bamboo and epoxy resin specimen : (ASB: specimens in sea water; ADB: specimens in distillate water)

Even if the UNI EN 2489 does not specify the frequency at which the measurements should be taken, the first 12 hours (720 min.) may be particularly important, especially for the computation of the initial curve slope which leads to the computation of the water absorption speed (α) and then of the diffusion coefficient (D). At saturated condition, the bamboo and epoxy resin specimens have shown the following results:

	Absorbtion speed (1/√t)	Diffusion coefficient (mm^2/sec)	Weight gain (%)
In distillate water	-0.0044	0.92	58.6
In sea water	-0.0028	1.04	55.6

Tab. 6: Absorption characteristics for bamboo composites at saturated condition

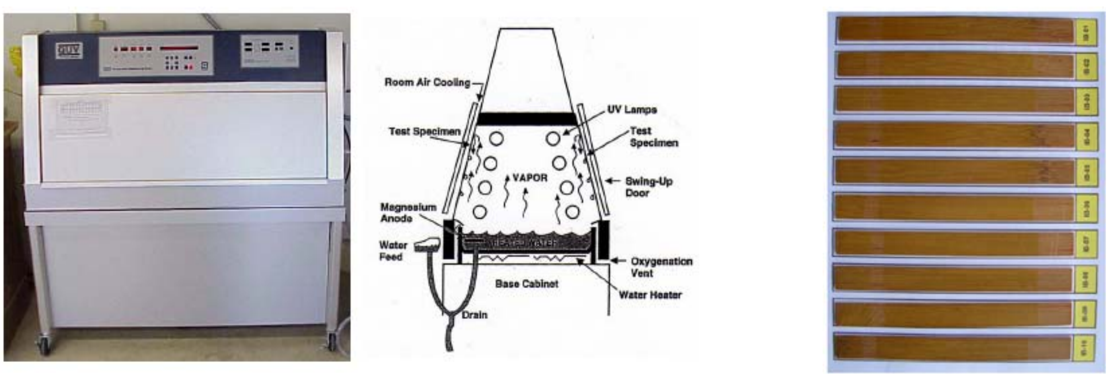
It should be noted that most absorption happens along the specimen edges, where no matrix is present. For this reason, the tested specimen are tailored from the inside of the whole aged specimen (Fig. 10).
The difference of the results may be due to the presence of salts in the cellulose support: in sea water the osmotic equilibrium is reached earlier, stopping or at least lowering the absorption phenomenon.
In the traction tests, constant results are obtained just after the first 120 hours and the total tensile strength decrease remains around -20 %.



Time (min)	Tensile Strength (Mpa)
0	92,47
7272	77,84
8683	75,74
16774	73,62
17364	72,94
18786	71,46
30377	72,57
30775	71,80
40395	71,97

Fig. 10: Tailoring of the specimen from the whole aged panel and tensile strengths for bamboo specimens subjected to absorption tests

The accelerated ageing tests have been performed in the QUV Accelerated Weathering machine of the Q-Panel Lab Products company, according with the ASTM D 4329-92.

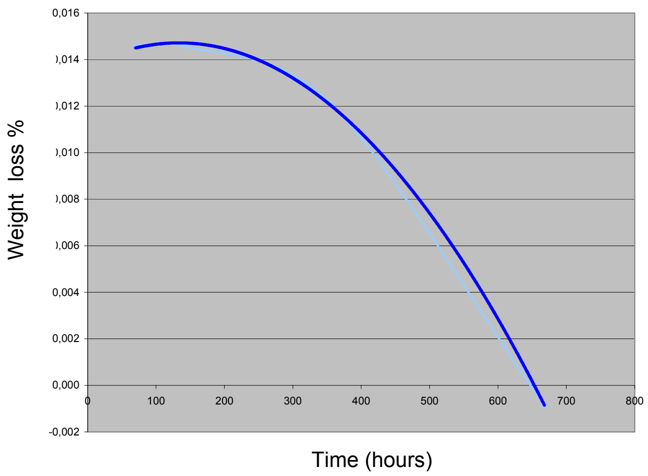


(a) *(b)* *(c)*

Fig. 11: View of the ageing machine (a); machine cross-section (b); bamboo specimens (c).

Three parameters have been strictly controlled: specimens temperature, flux density of the UVB fluorescent lamps and the moisture cycle. Each test lasted 720 hours (30 days) with the following cycle:

- 8 hours of irradiation with UVB-313 lamps (flux density = 0.8 W/m^2) at 140°F (60 ± 3°C) temperature;
- 4 hours of 100% humidity at 122°F (50 ± 3°C) temperature;



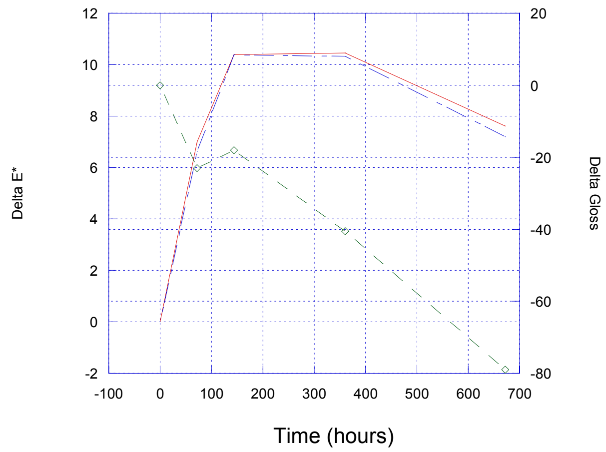


Fig. 12: Diffusion curve and colour- gloss specimens variation with time

The descending curve in Fig. 12, which represents the loss of weight with time, is exclusively due to the degradation and detachment of the superficial polymeric matrix. This behaviour is confirmed by the opacity surface appearance and by the measurements of the specimen colour and gloss, made with a sphere spectrometer with a D65 illuminating source and an angle of measure of 10°.
The specimen colour, after an abrupt initial variation, presents a stabilization in the range comprised between 140 and 400 hours, accompanied with a constant decrement of the gloss (Fig. 12). After 400 hours, a fast decay of the value of the gloss (all the specimen loose the superficial matrix layer and tend to be opaque) and an appearing recovery of the colour variation are recorded.
Traction tests provided similar results of the absorption tests, i.e. a strength decrease around -20 %.

4. EXAMPLE

In order to verify the machinability of the bamboo and the possibility to adapt it to special shapes and curvings, a 250 mm. diameter spinnaker pole laminated on a female mould – one half after another half - with a stacking sequence of $[0°/30°/90°/30°/0°/90°/30°]_s$ has been realised. Total thickness obtained is 1 cm. Successively several portions of 50 cm. length have been obtained for compression test. An ultimate compressive load of 550 KN, corresponding at a compressive stress of 70 Mpa, have been recorded. The numerical linear buckling analyses, with aforementioned mechanical bamboo characteristics, well confirmed both, critical compression values and mode shape.

Fig. 13: Compression test on a spinnaker pole section

5. CONCLUDING REMARKS

All the numerous experimental tests gathered important information about the bamboo composites and the best process formulations. Moreover such tests constitute fundamental confirmation of the reliability of the material and of its usage in marine applications. The tests of accelerated ageing and water absorption have evidenced the resistance of the material adopted to the aggressiveness of the marine atmosphere; in the realization of real prototypes it is previewed however the utilisation of waterproofing treatments on the exposed parts, to the aim to improve the mechanical property of the composite.
Adhesion tests proved optimal ILSS value even without any particular fiber treatment: a value over 3.5 Mpa allows the utilisation of such material in sandwich skins.
Future work could be directed to improve adhesion (using coating or fiber treatment) between the fiber and the matrix, to improve strength and impact resistance. Higher fiber volume fractions can be used to reduce resin usage, and properties of these higher fiber composites should be determined.

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