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A NEW WOOD-BASED LIGHTWEIGHT COMPOSITE FOR BOATBUILDING

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ABSTRACT

Wood-based lightweight composites are widely used and appreciated in marine craft, being suitable for meeting the requirements of such a high-challenging application, due to their high strength to density ratio. While marine plywood represents a consolidated product for skins formation, the research is today focused on new high-performing composites with special cores.

In this context, the paper reports the development and testing of an innovative wood-based composite. This is in the form of a sandwich panel made of okoumé (*Aucoumea klaineana* Pierre) plywood skins bonded to an innovative honeycomb core constituted by lozenge-shaped, okoumé plywood cells. A physical-mechanical characterization was performed, aimed to obtain an overview of the performances achieved by the panel; moreover, a preliminary investigation of the sound absorption properties was carried out. On the whole the results promote further developments, in particular regarding the optimization of the sound absorption properties in the low frequency range.

KEYWORDS: Lightweight wood-based composites, boatbuilding, mechanical properties.

INTRODUCTION

Boatbuilding represents a challenging application for structural and high-performing materials. These must provide at the same time lightness, adequate durability in marine environment and fit for mechanical and other purposes.

Wood-based lightweight composites are suitable for meeting the requirements of marine applications, in particular for their high strength to density ratio (Zenkert 1995). Sustainability, recyclability and valuable look are further characteristics making these panels appreciated by boat designers. Hence, today they find wide use as components of decking, suspended ceilings, floor structures, interior furnishing, bridge deck consoles, accommodation cabin units, light partition structures and, more rarely, the construction of the hull. The application of these materials is also frequent for the repair and refitting of historic boats (Cremonini et al. 2008).

Wood-based lightweight composites belong to the family of sandwich panels, made of two thin skins bonded to an inner thick core. While marine plywood is a consolidated product for skins formation, the research is today focused on new and high-performing materials for the core, particularly in terms of lightness and mechanical properties. In fact, developing high-performing composites represents a relevant innovation opportunity for the forest products industry, which is facing hard challenges to remain competitive nowadays (Crespell and Hansen 2008).

In this context, the present work is focused on the development of a new lightweight composite intended for boatbuilding. The composite is made of two okoumé (*Aucoumea klaineana* Pierre) plywood skins bonded to an innovative, okoumé honeycomb core constituted by plywood cells. These provide lightness, form a central rib giving strength to the panel and can be exploited for conferring sound absorption properties. The composite is also particularly interesting in terms of recyclability, being entirely made of okoumé plywood. Okoumé wood was chosen since today it is widely used for marine applications, due to its lightness, durability and valuable look (Brunck et al. 1990).

Subsequent to the description of the production process, the paper reports the physical-mechanical properties of the composite, in order to give an overview of its performances. Moreover, also a preliminary investigation on the sound absorption properties achieved by the composite with a drilled skin was performed. Aim was to assess if sizing of the honeycomb cells is able to activate a relevant Helmholtz resonance effect (Fasold and Veres 1998) in the low frequency range.

MATERIAL AND METHODS

Composite manufacturing process

The composite was manufactured through a process based on four different steps (Fig. 1a-d). The first operation consisted in the production of a three-layer melamine-urea-formaldehyde (MUF) plywood, made with 0.8 mm thick okoumé (*Aucoumea klaineana* Pierre) veneers.

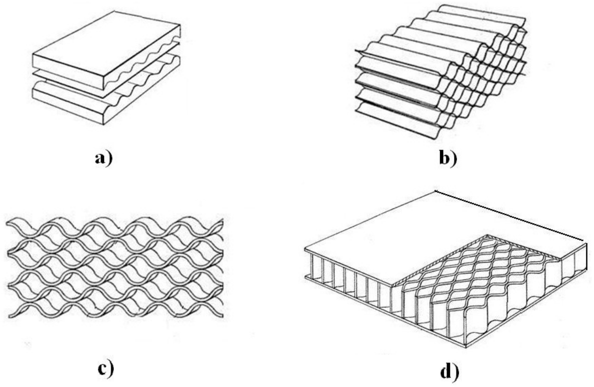

Fig. 1: Scheme of the production process of the lightweight panel

These were laid in a press with upper and lower wavy plates (Fig. 1a), so that the grain of two external layers was parallel to the waves direction. The adopted MUF resin system is able to satisfy the bonding quality Class 3 according to EN 314-1. By hot pressing mode at 105 °C with pressure of 5 kg.cm^{-2} applied for 15', wavy plywood panels with dimension of 960 x 750 mm and thickness of 2.5 mm were produced. In the second step, the above panels were overlapped and cold bonded together by means of the above-mentioned MUF glue system. In this way a honeycomb block with dimensions 960 x 750 x 260 mm was produced (Fig. 1b).

As third step, the block was cut perpendicularly to the honeycomb cells in order to obtain sheets with dimensions 960 x 260 x 15 mm (Fig. 1c). Each sheet, later used as a core, was made of lozenge-shaped (for reading ease, the plywood cells are referred to as lozenge-shaped. Actually, each cell is formed by two sinusoidal waves bonded along a transversal symmetry axis.) cells 45 mm wide and 95 mm long. The lightweight composite was finally assembled by laying side by side the honeycomb sheets and bonding to them two skins made of 4 mm thick, 3-layer okoumé marine plywood. The sandwich was pressed at the temperature of 105 °C with pressure of 1.5 kg.cm^{-2} for 15'. The final thickness was 23 mm (Fig. 1d), which represents a value commonly used for many marine applications. By means of the above described process, 20 sandwich panels with dimensions 850 x 600 x 23 mm were produced.

Physical-mechanical characterization

Different physical-mechanical properties were determined, aimed to obtain an overview of the performances achieved by the panel. Tests were carried out according to EN standards specifically developed for the wood based panels sector. These are recalled in European standards, such as BS1088 or RINA, which fix the specific requirements for marine plywood.

Prior to testing, all samples were stored in climate chamber at 20 °C and 65 % relative humidity (RH) until achieving the equilibrium moisture content (EMC). The physical-mechanical properties were determined using an universal testing machine type Zwick/Roell Z050 with maximum load 50 kN. Each property was determined by testing at least 10 test pieces cut from different panels.

In this context, three-points bending test was performed according to EN 310 on test pieces having dimensions 510 x 110 x 23 mm (Fig. 2). 10 test pieces were oriented in longitudinal and 10 in transversal direction.

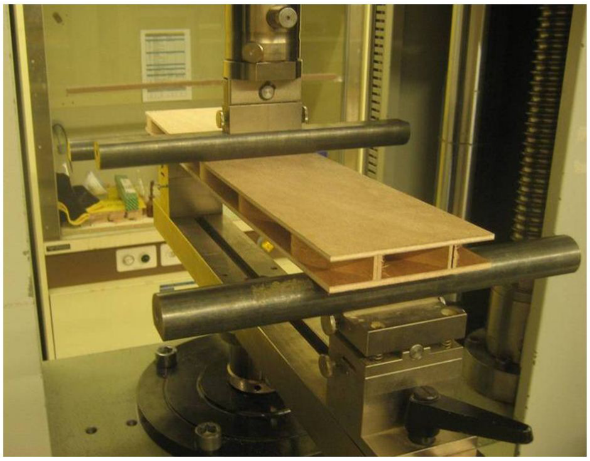

Fig. 2: Bending strength test performed on the wood-based composite

Panel density was calculated in accordance with EN 323 on test pieces with dimensions 110 x 110 x 23 mm. Weight was measured through a scale having accuracy 0.01 g, while dimensions were determined with a digital caliber having accuracy 0.01 mm.

Dimensional variations associated with changes in relative humidity were evaluated for an absorption and a desorption cycle complying with EN 318. The first cycle consisted in storing the test pieces in a climatic chamber at 20 °C with 3 subsequent levels of RH (30 %, 65 % and 85 %) until they achieved the EMC. Desorption cycle followed the reverse path in terms of RH. Once concluded the cycles, thickness variations were measured on three points marked on the test pieces, while length variations were evaluated by measuring the distance between two metallic buttons formerly glued over their faces through a bi-component epoxy resin. The dimensions of the test pieces were 300 x 50 x 23 mm. 10 of them were oriented in longitudinal and 10 in transversal direction.

To determinate the resistance to traction perpendicular to panel faces, internal bonding test was performed according to EN 319. Test pieces dimensions were 50 x 50 x 23 mm.

The moisture resistance was determined according with EN 321. In this case, test pieces with dimensions 50 x 50 x 23 mm were subjected to 3 aging cycles, at the end of which glue lines conditions were evaluated. Each cycle consisted in storing the test pieces for 3 days in cold water (20 °C), 1 day in freezer (-20 °C), 3 days in oven (70 °C) and finally 4 h in climatic chamber (20 °C, 65 % RH).

Shear strength parallel to panel surface was determined according to EN 789. Specimens were 225 mm long and 110 mm, with 10 or them oriented in longitudinal and 10 in transversal direction.

The preliminary investigation on the sound absorption properties was carried out by means of the impedance tube (Kundt's tube) method, according to EN 10534-2. Five test pieces were tested with different drilling percentages: A= 0.8 %, B= 1.4 %, C= 1.8 %, D= 2.1 %, E= 4.0 %; reported results are the average of 3 test repetitions as recommended by EN 10534-2.

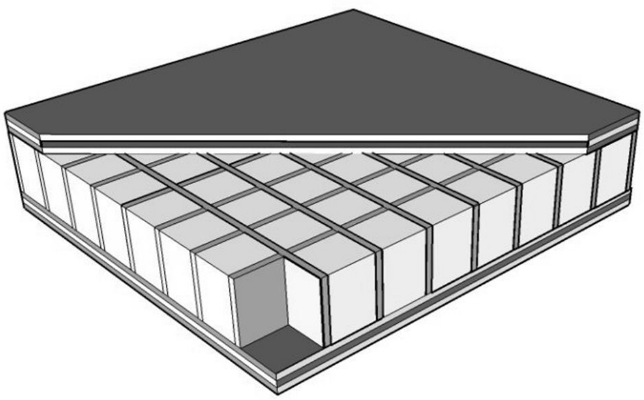

Fig. 3 : Illustration of the commercial sandwich panel

The physical-mechanical properties were also tested for a lightweight wooden composite intended for boatbuilding and already available on the market, which was chosen as a benchmark for its wide diffusion in boatbuilding. (other typologies of lightweight composites are available on the boatbuilding market, still they are not made of a wood-based honeycomb core.) The selected product is made of two MUF okoumé plywood skins (4 mm/3-ply) bonded to a honeycomb-like core (Fig. 3). The latter is manufactured in form of a square structure of vertical ribs on okoumé veneers including a low-density polystyrene foam (60 kg.m^{-3}). Squares are 5 cm long and 15 cm high, while veneers thickness is 0.2 mm. Bonding between core and faces is realized by means of a MUF adhesive system.

RESULTS

The results obtained by the experimental composite in test for determination of bending strength, modulus of elasticity and planar shear strength are illustrated in Tab. 1; t-test was performed setting the confidence level for statistical significance at 95% (α = 0.05).

Tab. 1: Longitudinal and transversal mechanical properties determined for the experimental panel and t-test results for evaluating the differences

Mechanical properties	Long. mean (N.mm^{-2})	Transv. mean (N.mm^{-2})	t-test[a] p-value
Bending strength (MOR)	17.89	12.75	0.000*
Modulus of elasticity (MOE)	2860	2015	0.000*
Planar shear strength	0.65	0.28	0.000*

a * = significant difference at 0.05 level

The results of the physical-mechanical properties determined for the experimental composite and the commercial product used as a reference; are sumarized in Tab. 2; for evaluating the differences between the panels, t-test was performed with the confidence level for statistical significance set at 95 % (α = 0.05).

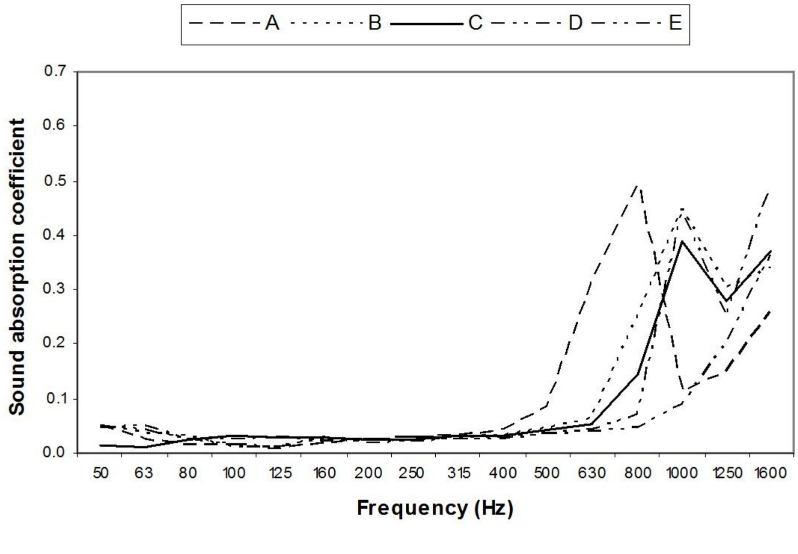

Fig. 4: Sound absorption properties determined for different surface drilling percentages: A= 0.8 %; B= 1.4 %; C= 1.8 %; D= 2.1 %; E= 4.0 %

Tab. 2: Mechanical properties determined for the experimental sandwich and a commercial product and t-test between the experimental and the commercial panel

Property	Standard	Unit	Experimental panel		Commercial product		t-test[a]
			mean	std. dev	mean	std. dev.	p-value
Density	EN 323	kg.m^{-3}	205	11.7	215	3.3	-
Longitudinal bending strength (MOR)	EN 310	N.mm^{-2}	17.89	1.1	17.25	1.8	0.475
Transversal bending strength (MOR)	EN 310	N.mm^{-2}	12.75	1.6	16.12	0.4	0.000*
Longitudinal modulus of elasticity (MOE)	EN 310	N.mm^{-2}	2860	186	2458	123	0.001*
Transversal modulus of elasticity (MOE)	EN 310	N.mm^{-2}	2015	82.2	2464	57.7	0.000*
Longitudinal planar shear strength	EN 789	N.mm^{-2}	0.65	0.1	0.43	0.02	0.000*
Transversal planar shear strength	EN 789	N.mm^{-2}	0.28	0.03	0.36	0.02	0.001*
Traction perpendicular to faces	EN 319	N.mm^{-2}	0.38	0.08	0.45	0.09	0.061
Thickness change after desorption	EN 318	%	-0.39	0.1	-0.44	0.1	0.449
Thickness change after absorption	EN 318	%	0.41	0.1	0.36	0.1	0.419
Length change after desorption	EN 318	mm.m^{-1}	-0.85	0.3	-1.21	0.4	0.140
Length change after absorption	EN 318	mm.m^{-1}	0.35	0.1	0.25	0.1	0.073

a * = significant difference at 0.05 level

The sound absorption values obtained in the low frequency range through different surface drilling are illustrated in Fig. 4. Low drilling percentages (from 0.8 to 4.0 %) were chosen for not compromising the mechanical properties of the panel.

DISCUSSION

Density of both sandwiches turned out within the range of lightweight materials. In fact, even if a general definition for this class is still lacking, wood-based panels with density below 500 kg.m^{-3} can be classified in this category (Theomen 2008).

Longitudinal vs. transversal mechanical properties of the experimental composite were compared through t-test (Tab. 1), which showed a significant difference ($p < 0.05$) for bending strength, modulus of elasticity and planar shear strength. In detail, the longitudinal properties resulted significantly higher. This plane-oriented behaviour reflects the composition of the honeycomb core waves, which in longitudinal direction support the loads working for their entire length. This can constitute an advantage if adequately considered by boats designers. For the same properties, the commercial product showed more homogeneous values, which can be explained through the regular pattern of its squared core and the contribution of the synthetic foam filling.

In bending test, failures of the experimental composite occurred for cracking of the tense plywood skin, indicating that the honeycomb core adequately supported the test loads. In planar shear test, failures occurred for splitting between the core and the plywood skins. Fibre release was over 90 % in correspondence of the glue lines between faces and core, indicating an adequate resistance of their MUF bonding. Previous studies report a mean shear panel strength of about 1.6 $N.mm^{-2}$, in both plane directions, for 24 mm poplar plywood (Baldassino et al. 1997) and of 2.0 $N.mm^{-2}$ for 20.5 mm birch and Norway spruce plywood (Sretenovic et al. 2005). In this context, the behaviour of the experimental composite is appreciable and also suggests that the bonding between core and faces is satisfactory.

Using t-test, significant differences ($p < 0.05$) between the experimental and the commercial panel were seen in transversal bending strength, longitudinal and transversal modulus of elasticity, longitudinal and transversal planar shear strength (Tab. 2). Differences in longitudinal bending strength resulted not significant ($p < 0.05$). On the whole, the experimental panel performs better in longitudinal direction thanks to the plywood waves forming the honeycomb core, while the squared structure of the commercial panel is able to provide higher values in transversal direction.

Moisture resistance and traction perpendicular to faces tests indicated that the bonding quality of the experimental panel can be considered as well-adequate. After three-week cycle according to EN 321, any test piece showed delamination. With respect to the traction perpendicular to faces test, fibre release was over 80 % in correspondence of the glue lines between faces and core. Moreover, no significant differences ($p < 0.05$) were found between the experimental and the commercial panel. These positive indications are reinforced by the above mentioned mechanical tests, where the glue lines showed an efficient behaviour.

Results of dimensional variations linked with changes in relative humidity indicate a good behaviour of the experimental panel. In particular, no significant differences ($p < 0.05$) were found between the experimental and the commercial panel. This suggests that, for dimensional stability, the main role is played by the skins, which present the same composition in the two panels. It is worth to note that dimensional stability represents a fundamental requirement for wood-based panels intended for boatbuilding. In this application, in fact, the combined action of heat, high relative humidity due to proximity to sea water and use of air conditioning system can highly challenge wood based panels.

Finally, results of the preliminary acoustic testing (Fig. 4) suggest that the panel is suitable for achieving interesting sound absorption properties in the low frequency range. In fact, the surface drilling turned out able to activate the Helmholtz resonance effect, acting like a mass-spring system in conjunction with the air included in the honeycomb cells. In particular, sound absorption coefficients higher than 0.4 were achieved around 800 and 1000 Hz. This is particularly interesting considering that recent studies (Goujard et al. 2005) pointed out that, on board ships, passengers evaluate acoustics comfort as criterion of prominent importance.

CONCLUSIONS

The present work reports the development of a wood-based lightweight composite, realized in order to meet different requirements for marine applications. The composite is a sandwich panel characterized by an innovative honeycomb core, designed for achieving lightness and mechanical performances at the same time. Furthermore, it is particularly interesting in terms of recyclability, being entirely made of okoumé plywood.

On the basis of the performed tests, the composite turned out extremely light, with a density of 205 kg.m^{-3}. Regarding the physical-mechanical properties, it resulted to be suitable for meeting boatbuilding requirements, in terms of bending strength, modulus of elasticity, shear strength, traction perpendicular to faces and dimensional stability. In particular, performances turned out in the same order of magnitude of another wood-based lightweight composite available on the market and currently used for its physical-mechanical properties.

Taking this paper as a starting point, other researches will be carried out. In particular, the optimization of the sound absorption properties will be further investigated by studying the effect of different surface drilling. In fact, the performed preliminary tests indicated that the drilled panel is able to activate the Helmholtz resonance thanks to the air included in the void cells. Optimization of the acoustic properties could provide relevant sound absorption amounts in the low frequency range, in particular for absorbing the noise coming from marine engines rumbles.

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