Innovative Bio-composite Sandwich Wall Panels made of Coconut Bidirectional External Veneers and Balsa Lightweight Core as Alternative for Eco-friendly and Structural Building Applications in High-risk Seismic Regions

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Abstract. The research that constitutes this paper is based on a series of publications that aimed at understanding, from an engineering perspective, the optimised mechanical efficiency of senile coconut palm stem-tissues as foundation for non-traditional building applications. Particularly, this study aims at determining, evaluating and analysing the mechanical properties of lightweight bidirectional sandwich-like structure wall panels made of balsa core material and coconut external veneers. To achieve these objectives, 10 test specimens cut from prototype panel 1 (1200 mm high, 600 mm wide and 124 mm total thick) and 10 test specimens cut from prototype panel 2 (1200 mm high, 600 mm wide and 74 mm total thick) were investigated under mechanical and seismic behaviours in accordance to the current American Society for Testing and Materials (ASTM) building standards. Preliminary results show that the proposed wall panels are up to two and three times more efficient, in terms of mechanical high-performance, than equivalent sections of solid wall bricks and concrete block walls, respectively. Therefore, the innovative panels constitute a feasible alternative to reduce/replace typical construction materials (e.g. steel, concrete and bricks) with a significant positive environmental impact that fully address current engineering requirements. These bio-panels are meant to be used as important non-traditional elements during the rebuilding process of low-rise and mid-rise residential buildings that were dramatically affected during the 2016 Ecuador earthquake.

Introduction

Building collapse or damage is one of the major causes for earthquake injuries and fatalities. The catastrophic Ecuador earthquake in April, 2016, left approximately 35,300 affected dwellings, out of which about 19,500 resulted totally destroyed or demolished. Tragic result of it, around 670 people died and 6,300 individuals were injured [1, 2]. Despite some advantages (e.g. fire resistance and durability) offered by traditional building structures made of typical materials (e.g. steel, concrete, bricks) [3], their partial failure or total collapse during extreme seismic events can lead to critical consequences as hereinabove mentioned. It has been estimated that during the 2016 Ecuador earthquake, many casualties occurred, not only by the structural framing collapse effect, but greatly by the overbalance masonry effect as shown in Fig. 1. Moreover, typical manufactured structural materials all involve very substantial use of energy during their production process, which in turn involves high generation of CO_2 to the atmosphere. Indeed, building with steel or concrete is 20 and 9 times, respectively, more CO_2 emissions intensive (i.e. compared on mass basis) than structural timber [4, 5].

Traditional masonry wall collapse or partial damage is one of the major causes for earthquake injuries and fatalities

Fig. 1. Overbalanced brick masonry recorded during the 2016 Ecuador earthquake occurred on April 16, with a moment magnitude of 7.8 and a maximum VIII severe Mercalli intensity. Adapted from [6]

Unfortunately, part of the Ecuadorian area affected by the earthquake is currently being rebuilt using the same traditional building methods and materials. The curious aspect of the rebuilding process is that huge amounts of concrete and steel are daily transported to the construction project sites whereas massive plantations of biomaterials surrounding the zone (e.g. coconut palms and balsa trees) are totally disregarded. These observations were the driven force behind the work in this investigation, which aims at addressing the hereinabove stated problems by proposing innovative bio-composite structural wall panels as alternative for masonry construction that makes the most of both fundamentals: (1) the enhanced performance of engineering wood products, cross laminated timbers, specifically, and (2) the optimal mechanical efficiency [7-9], in terms of mechanical performance (i.e. high strength versus moderate stiffness) per unit mass; the optimal mechanical efficiency that is best represented in biomaterials by either a sandwich-like structure (e.g. coconut stem tissues) or a tubular-like structure (e.g. bamboo culms) [10].

Materials and equipment

Two wall panel types were built in this study: prototype panel 1 (1200 mm high, 600 mm wide and 124 mm total thick) and prototype panel 2 (1200 mm high, 600 mm wide and 74 mm total thick). The prototype panels resemble a complex sandwich-like structure (see Fig. 2) that is made of two different biomaterials: (1) Ecuadorian balsa hardwood (*Ochroma pyramidale*) as core material [11], and (2) Ecuadorian coconut palmwood (*Cocos Nucifera L*) veneers as external boards. The balsawood core material was used in the form of the BALTEK® SB.100 product due to its high level of stiffness to weight ratio [i.e. Avg. Moduli of Elasticity (MOE) perpendicular to the plane of 2,526 MPa for an equivalent basic density of 148 kg/m^3 at an Avg.

moisture content of 12.6%). BALTEK® core material was acquired from the local supplier 3AComposites. Each external board (i.e. one board per external side of each panel as shown in Fig. 2) comprises three coconut veneers glued each other bidirectionally with acrylic vinyl resin following the same principle of cross laminated timbers (CLT) that are used for wall building purposes [12]. Coconut veneers were obtained by peeling process [13] of the peripheral section (Avg. MOE parallel to the fibers of 8,920 MPa for an equivalent basic density of 900 kg/m^3 at an Avg. moisture content of 12.6%) of three mature coconut palm stems. 2-component Polyurethane adhesive (Pur 2C) was used to glue the external coconut boards with the BALTEK® core material. Once fully assembled and glued, each prototype panel were hot-pressed at 400 psi and 100˚C for about 30 minutes.

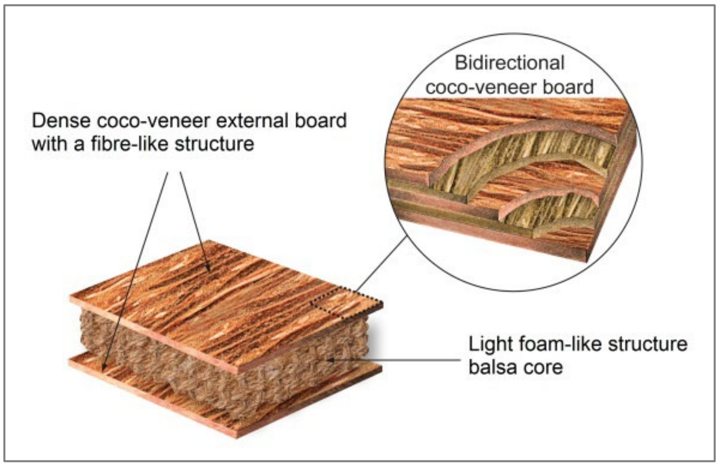


Fig. 2. Sandwich-like structure wall panel made of Ecuadorian balsa lightweight core and coconut bidirectional external veneers.

Methods

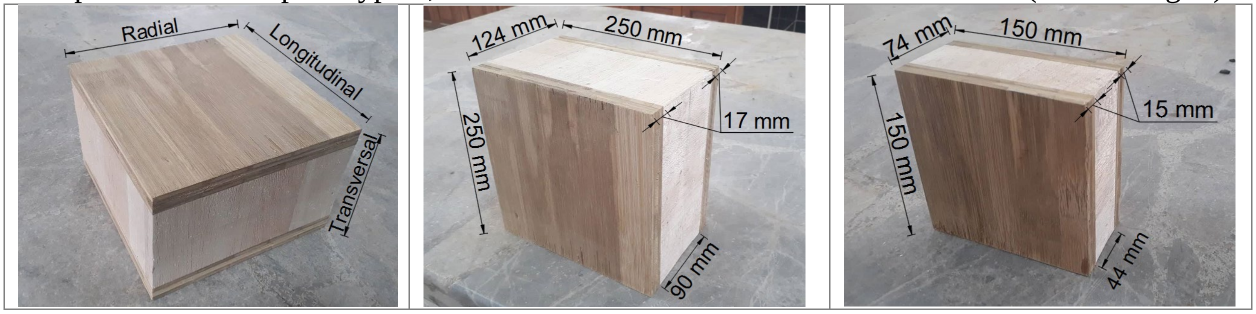
The research scope of the whole investigation includes the following tests: compression, bending, shear, tension, cyclic assessment, hardness, fire resistance, acoustic isolation, resistance to pathogens, glue and ply-delamination. Yet, only the first two mechanical modes with the corresponding determination of basic density and moisture content properties are included as part of the present paper. Specifically, this paper presents results from (1) axial stiffness and strength in compression and (2) bending strength in flat-wise four-point loading.

The mechanical tests were all carried out in an AGS-X Shimadzu universal testing machine (UTM) 300 kN capacity equipped with a non-contact digital video extensometer to measure deformations. Moreover, the acquired results for each mechanical mode were double-checked by pilot testing on selected samples using 5 mm long single-element strain gauges glued on the longitudinal-radial (L-R) external faces (refer to Fig. 3a) of each sample using adhesive cyanoacrylate ester and coated with instant repair epoxy resin/tertiary amine. The experimental equipment was complemented with Wheatstone bridge circuits to connect the strain gauges, a data logger (National Instruments NIcRIO-9074) and a computer for data processing.

Before testing and after sanding, each sample was labelled according to the mechanical mode to be investigated. Experimental tests were performed at room temperature and humidity.

Axial stiffness and strength in compression

According to the ASTM C364/C364M-16 Standard Test Method for Edgewise Compressive Strength of Sandwich Constructions, a total of 10 compressive tests were carried out on 5 small-clear panels cut from prototype 1, nominal size of 250 mm × 250 mm × 124 mm, and on 5 small-clear panels cut from prototype 2, nominal size of 150 mm × 150 mm × 74 mm (refer to Fig. 3).



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

Fig. 3 *Bio-composite sandwich panel-samples for compression tests, a) loading directions, b) nominal panel-sample from prototype 1, and c) nominal panel-sample from prototype 2.*

The UTM lower platen was fixed while the upper platen was mounted on a half sphere bearing which could rotate, so as to provide full contact between the platen and the panel-samples (see Fig. 4). Between the platens and the panel-specimens, 10 mm thick acrylic plates were inserted. To minimise friction, dry lubricant (graphite powder) was used between the panel-samples and the testing platens. Each panel-sample was then loaded in the longitudinal (L) direction (see Fig. 3a) up to failure at a cross-head speed of 0.5 mm/min to reach failure between 8 to 10 minutes.

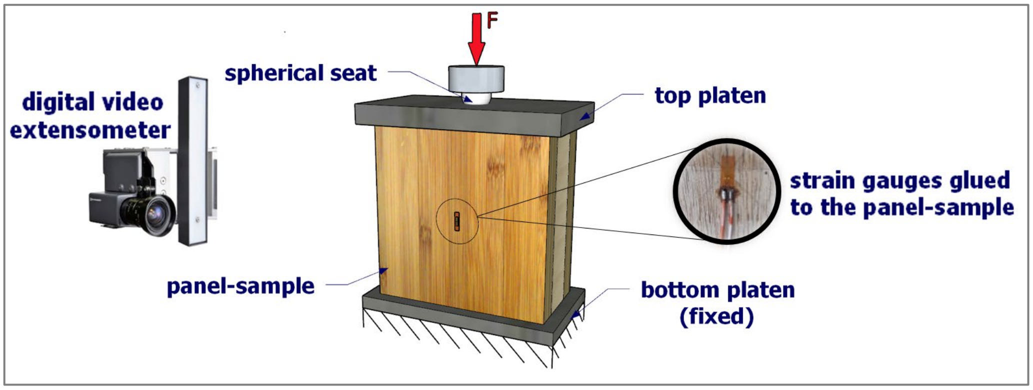


Fig. 4 *Compressive panel-sample test set-up.*

As friction was limited between the panel-samples and the platens, no stress developed in the plane perpendicular to the loading direction *i* and the Hooke's law [14] applied. The stress σ_i - strain ε_i relationship was therefore given as,

$$\sigma_i = MOE_i \cdot \varepsilon_i . \tag{1}$$

The elastic stiffness of the sandwich wall panel (i.e. the MOE) was then calculated for each test by performing a linear regression on the linear part (i.e. the proportional limit) of the stress-strain curves (please refer to the Results section).

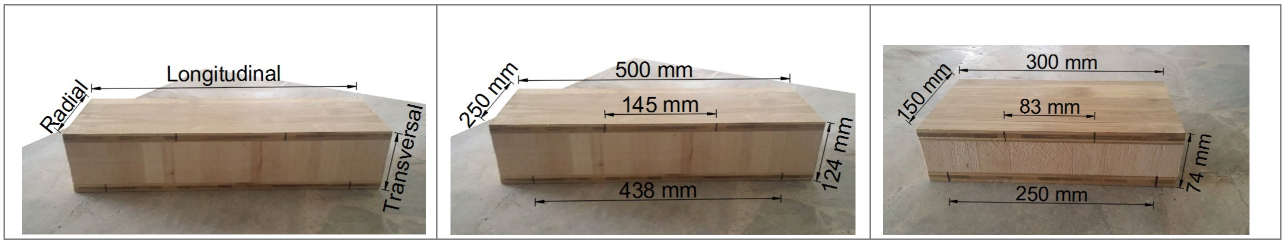
The ultimate edgewise compressive strength [i.e. the Moduli of Rupture (MOR)] that reflects the maximum load carrying capacity of the sandwich construction in the L direction of the applied load was also determined herein and calculated by applying Eq. 2 given in the ASTM C364/C364M-16 as,

$$MOR_L = F_{max} /(w \cdot t_{fs}), \tag{2}$$

where MOR_L is given in MPa, F_{max} is the ultimate force prior to failure (N), w is the width of the panel-sample (mm) and t_{fs} is the thickness of a single facesheet (mm).

Bending strength in flat-wise four-point loading

According to the ASTM C393/C393M Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure, a total of 10 flexural tests were carried out on 5 small-clear panels cut from prototype 1, nominal size of 500 mm × 250 mm × 124 mm, and on 5 small-clear panels cut from prototype 2, nominal size of 300 mm × 150 mm × 74 mm (please refer to Fig. 5).



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

Fig. 5 *Bio-composite sandwich panel-samples for bending tests, a) loading directions, b) nominal panel-sample from prototype 1, and c) nominal panel-sample from prototype 2.*

A 4-point loading configuration was carried out as shown in Fig. 6. The panel-sample was placed onto two lower supporting pins as set distance apart (S). The UTM top platen was mounted onto two loading pins placed equidistantly from the centre as set distance apart of 1/3 S. To minimise friction and prevent local damage between the panel-sample facings and set of upper/lower pins, 3 mm thick rubber pressure pads were used. Each panel-sample was then loaded in the transversal (T) direction (see Fig. 5a) up to failure at a cross-head speed of 6 mm/min to reach failure between 4 to 6 minutes.

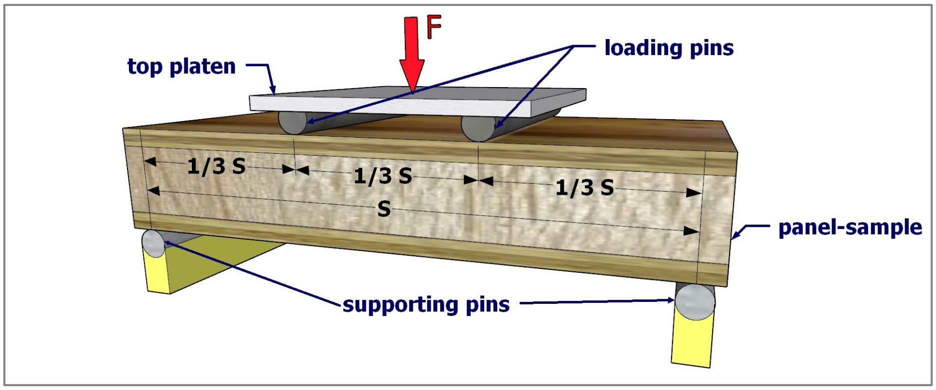


Fig. 6 *Bending panel-sample test set-up.*

The panel-sample facing bending maximum stress (σ_{max}) that reflects the maximum load carrying capacity of the sandwich construction in the direction parallel to the applied load was determined by applying Eq. 3 given in the ASTM C393/C393M -11 as,

$$\sigma_{max} = (F_{max} \cdot S)/[3t_{fs}(d+c)w], \tag{3}$$

where σ_{max} is given in MPa, F_{max} is the maximum force carried by test specimen before core-failure (N), S is the span length between lower supporting pins (mm), t_{fs} is the thickness of a single facesheet (mm), c is the thickness of the core material (mm), w is the width of the panel-sample (mm) and d is the sandwich panel-sample total thickness (mm).

The core shear ultimate strength (τ_{max}) that reflects the maximum load carrying capacity of the core sandwich construction in the longitudinal-transversal (LT) plane was calculated as (ASTM C393/C393M -11),

$$\tau_{max} = F_{max}/[(d+c)w], \tag{4}$$

where τ_{max} is given in MPa, F_{max} is the ultimate force prior to core failure (N), d is the total thickness of the panel-sample (mm), c is the core thickness (mm) and w is the panel-sample width (mm).

Results and Discussion

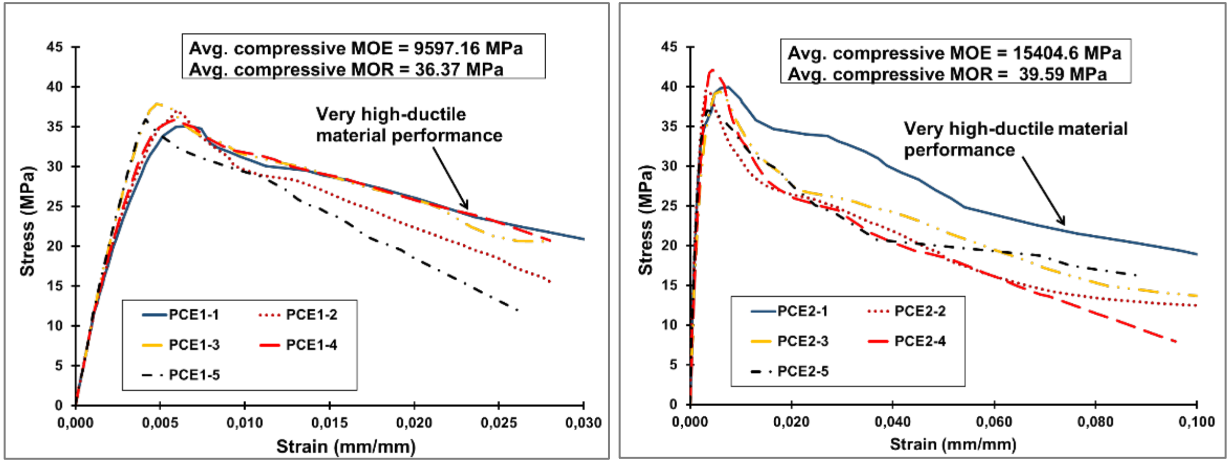
Axial stiffness and strength in compression

Detailed results of the complete set of tested panel-samples under compression are given in Table 1 and Fig. 7.

Table 1. Results from the compressive tests carried out on panel-samples cut from prototype panels 1 and 2.

PROTOTYPE PANEL 1					PROTOTYPE PANEL 2				
Panel-sample	Weight [kg]	Density at 11% of M.C. [kg/m³]	MOE_L [MPa]	MOR_L [MPa]	Panel-sample	Weight [kg]	Density at 11% of M.C. [kg/m³]	MOE_L [MPa]	MOR_L [MPa]
PCE1-1	2,31	300,86	8928,10	35,09	PCE2-1	0,62	405,23	15044,00	39,92
PCE1-2	2,39	308,47	9346,90	37,04	PCE2-2	0,70	422,16	15586,00	39,50
PCE1-3	2,40	313,35	10293,00	37,86	PCE2-3	0,69	411,58	15542,00	39,39
PCE1-4	2,35	303,13	9244,80	35,92	PCE2-4	0,68	414,11	15291,00	42,11
PCE1-5	2,41	311,37	10173,00	35,94	PCE2-5	0,69	416,79	15575,00	37,00
Avg.	2,37	307,43	9597,16	36,37	Avg.	0,68	413,97	15407,60	39,59
CoV	0,02	0,02	0,06	0,03	CoV	0,05	0,02	0,02	0,05

The results in Table 1 reflect a prototype panel 1 that is in average 1.6 times more elastically efficient (i.e. more deformable) than prototype panel 2 for similar range of densities (i.e. in between 307,43 and 413,97 kg/m^3) at 11% of moisture content. The higher elastic performance is likely produced by the greater amount of lightweight balsawood core material in prototype panel 1 (i.e. almost double compared with the core material of prototype panel 2). Thus, the MOE_L in the proposed bio-composite sandwich wall panels varies proportionally to the light foam-like structure balsa core. Yet, from the point of view of the mechanical performance per unit mass (i.e. mechanical efficiency) of both sandwich constructions, the results herein reveal highly efficient prototype panels 1 and 2 with average performance indexes (*PI*) equal to 10.07 GPa^{½} m^{3} Mg^{-1} and 9.48 GPa^{½} m^{3} Mg^{-1}, respectively. The performance index for this specific case denotes the material's performance for undergoing deformations when compressive stresses are acting over/on the panels.

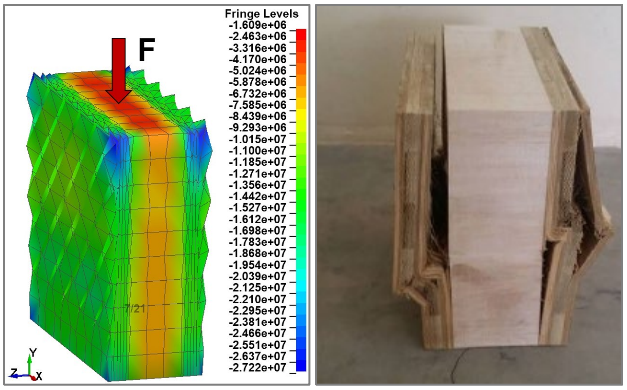


(a) *(b)*

Fig. 7. *Compressive stress – strain relationship for (a) five specimens cut from prototype panel 1, and (b) five specimens cut from prototype panel 2.*

As shown in Table 1 and Fig. 7, the ultimate edgewise compressive strength (MOR$_{\mathrm{L}}$) appears to be in the same order of magnitude (i.e. in between 36 MPa and 39 MPa) for both prototype panels. These compressive MOR$_{\mathrm{L}}$ results were expected as the thickness of the coconut external boards for both prototype panels varies by just 2 mm. The coco-veneer external boards with a fibre-like structure [15] are the denser part of the sandwich construction and, therefore, are meant to fully resist the progressive generation of compressive stresses. Accordingly, among the variables in Eq. 2 for the MOR$_{\mathrm{L}}$ calculations, it is not consider the total thickness of the panel-sample but only the thickness of a single facesheet (t_{fs}). It can also be inferred from Table 1 and Fig. 7 that the average compressive strengths of both prototype sandwich wall panels are up to three times more efficient, from the point of view of structural mechanics, than conventional concrete masonry units (CMU) with an average compressive strength of 12.5 MPa for the best CMU type according to the ASTM C-90/91 Standard Specifications for Load-Bearing Concrete Masonry Units. Similarly, the average compressive strengths of both prototype sandwich wall panels are up to two times more mechanically efficient than conventional solid wall bricks with an average compressive strength of 20 MPa for the best brick-type according to the ASTM C-55 Standard Specifications for Concrete Building Brick.

Fig. 7 also shows a very high-ductile material performance (i.e. the material's ability to undergo significant plastic deformation before failure) for both prototype panels, which makes them suitable to be used in eco-friendly and structural building applications located in high-risk seismic regions. It technically means the progression of compressive stresses within the bio-composite sandwich wall panels (see Fig. 8a) allows the whole building structure to gradually resist the cyclic and seismic forces before total collapse (see Fig. 8b).



(a) *(b)*

Fig. 8. *Experimental test post-analyses given by (a) the progression of normal stresses shown in a finite element panel model undergoing compression, and (b) the panel-sample facesheet compressive failure.*

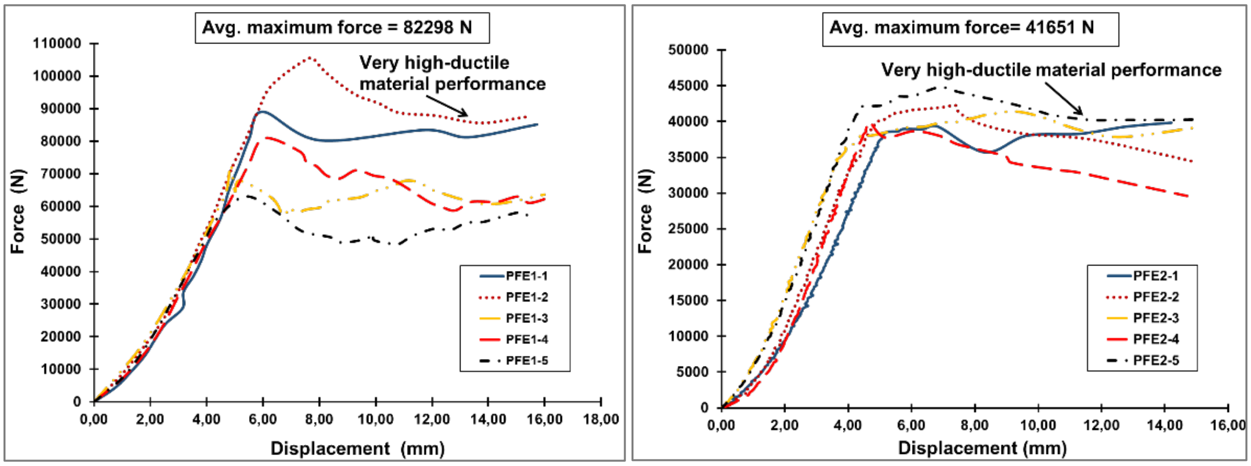
Bending strength in flat-wise four-point loading

MOE values are not calculated herein as, theoretically, this property would not significantly vary regardless the mechanical mode under investigation. What considerably varies is the material's capacity to resist progressive stresses (see Fig. 10b), which depends on the mode of loading, e.g. columns carry compressive axial loads, shafts carry torques, and beams carry predominantly bending moments. Therefore, this part of the paper focuses its analyses on both (1) the panel facing bending maximum stresses, and (2) the panel core shear strengths. Table 2 and Fig. 9 give the complete set of results for the bending tests carried out on panel-samples cut from prototype panels 1 and 2.

Table 2. *Results from the bending tests carried out on panel-samples cut from prototype panels 1 and 2*

PROTOTYPE PANEL 1					**PROTOTYPE PANEL 2**				
Panel-sample	Weight [kg]	Density at 11% of M.C. [kg/m³]	Facing bending max. stress σ_{max} [MPa]	Core shear strength τ_{max} [MPa]	Panel-sample	Weight [kg]	Density at 11% of M.C. [kg/m³]	Facing bending max. stress σ_{max} [MPa]	Core shear strength τ_{max} [MPa]
PFE1-1	4,77	312,37	14,43	1,70	PFE2-1	1,07	322,61	12,51	2,25
PFE1-2	5,04	328,79	17,00	2,00	PFE2-2	1,18	355,06	13,18	2,37
PFE1-3	4,69	306,09	11,72	1,38	PFE2-3	1,18	352,35	12,92	2,33
PFE1-4	4,88	321,57	13,06	1,53	PFE2-4	1,24	372,45	12,45	2,24
PFE1-5	4,69	305,60	10,15	1,19	PFE2-5	1,22	367,41	14,05	2,53
Avg.	4,81	314,88	13,27	1,56	Avg.	1,18	353,97	13,02	2,34
CoV	0,03	0,03	0,20	0.20	CoV	0,06	0,05	0,05	0,05

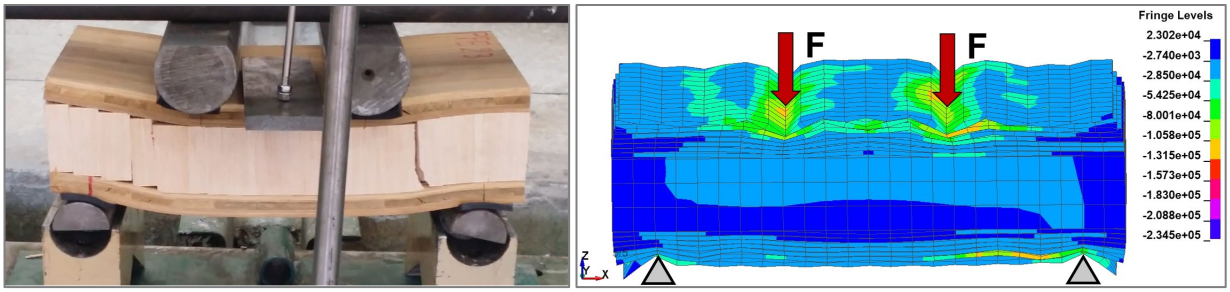
As shown in Table 2, the average facing bending maximum stress for both prototype panels are in the same order of magnitude (i.e. in between 13,02 MPa and 13,27 MPa) due to the similar thickness configuration of the coco-veneer external boards in both sandwich constructions. It is worth noting that the facing bending strength (i.e. the MOR_T) could not be calculated herein as, for this specific case, the light balsawood core shear failure always preceded bending failure of the dense coco-veneer external boards with a fibre-like structure (i.e. the panel-sample facings). Within this context, the core shear strength of prototype panel 2 is in average 1.5 times greater than prototype panel 1, which in theory is correct as the lighter core section of the sandwich prototype panel 1 is about 1.2 times greater in volume than prototype panel 2, and consequently, it makes the latter prototype less vulnerable to shear stresses. Moreover, it confirms one important finding in [8-10, 15-18] that states the mechanical properties in biomaterials are all quasi-linearly proportional to density. On the other hand, it is unfortunately not possible to establish any comparison between the resulting bending performances acquired in this study and conventional wall building elements (e.g. concrete masonry units and solid wall bricks) as they only mechanically perform under compression. Yet, the optimised bending performance of the proposed bio-composite sandwich wall panels clearly denotes herein a big plus over the limited capacity of conventional wall building systems (i.e. they do not hold the capacity to mechanically perform under bending stresses). It gives another reason to consider the proposed bio-composite wall panels as a feasible alternative to be used in eco-friendly and structural building applications in high-risk seismic regions.



(a) *(b)*

Fig. 9. *Bending force – displacement relationship for (a) five specimens cut from prototype panel 1, and (b) five specimens cut from prototype panel 2.*

Similar to the panel-sample's compressive performance shown in Fig. 7, the bending performance of both prototype panels (see Fig. 9) shows a remarkable ductility that allowed the core-panel reach failure only after having suffered a large plastic deformation (see Fig. 10). Moreover, it was also observed during the bending tests a high flexibility (i.e. the deflection due to a unit value of the applied load) of the panel-sample coco-facings with a high mechanical resilience (i.e. the material's capacity to spring back into shape). It simply reflects, from an engineering perspective, an optimal design of the bio-composite sandwich-like structure that efficiently performs its mechanical functions.



(a) *(b)*

Fig. 10. *Experimental test post-analyses based on (a) the balsawood core material shear failure, and (b) the progression of normal stresses shown in a finite element panel model undergoing bending.*

Conclusion

Significant findings have been achieved from this investigation that show the bio-composite structural wall panels fully address current engineering and environmental requirements like high structural performance, sustainability, design flexibility, low construction costs, short construction timelines, efficient and low embodied energy, durability, light weight, readily availability, easy transport and assembly, and minimum environmental impacts. The results thereof show that the proposed wall panels are up to two and three times more efficient, in terms of mechanical high-performance, than equivalent sections of solid wall bricks and concrete masonry blocks, respectively. More notably, the optimal cocowood mechanical efficiency [9] biomimicked into the innovative bio-composite sandwich wall panels, makes them suitable to be used in building projects located in high-risk seismic regions as its remarkable ductility, flexibility and resilience, could significantly reduce the overbalance masonry effect (typical for conventional construction wall materials) during high-intensity seismic events.

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