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Sustainable Sandwich Panels Made of Aluminium Skins and Bamboo Rings

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This work investigates the mechanical behaviour of a sustainable sandwich panel, consisting of bamboo rings core, treated aluminium skins and epoxy adhesive. A Design of Experiment (DoE) is used to identify the effects of bamboo diameters (30 and 45 mm) and aluminium skin treatments (alkaline degreasing and application of primer) on the mechanical and physical properties of sandwich panels. The aluminium skins treated with the wash primer significantly increase adhesion to the polymer, resulting in greater maximum load, flexural strength, maximum skin stress and maximum core shear stress; while the skins treated with NaOH resulted in a greater flexural and core shear modulus. Relatively more rigid and resistant structures are obtained with Ø30 mm rings, due to the increased surface contact area and the number of constraints on the core. The samples fail due to the skin fracture, implying an efficient face-core bond that is attributed to the proper absorption of the polymer by bamboo and the treatment of the aluminium surface. The proposed panels present good mechanical performance, proving to be a feasible and promising alternative for secondary structural applications.

Keywords: *Bamboo rings, Sandwich panels, Design of Experiment, Aluminium surface treatment, Mechanical properties.*

1. Introduction

Lightweight structures have been widely used in high-performance applications such as aerospace, automotive, civil engineering and many other fields in recent decades[1]. Sandwich structures have also gained much attention due to their excellent mechanical performance and outstanding energy absorption properties[2-4]. Sandwich panels are lightweight structures, typically composed of two thin sheets of stiff and strong material, separated by a thick core of low-density material[5-7]. The optimal design of a sandwich panel has been a challenge since the designer can tailor the composite properties by adjusting its constituents and geometrical parameters[5,6,8]. Among the huge variety of parameters, the core and face constituents, core geometry and core/face adhesion are widely considered.

The skins are generally made of metal sheets (aluminium or steel), fibre-reinforced laminates, plywood and others, while the core is made of resin-impregnated paper, reinforced polymers, polymeric and metallic foams, perforated chipboard and lightweight concrete[1,9]. The core can have many different shapes[10], including honeycomb structures, foams, corrugated plates and new lattices[11], such as auxetic honeycomb structures[12,13], egg-box-like core[14] and truss core[15]. Hexagonal honeycombs are the most common cellular cores used in structural applications[16]. However, circular cell honeycombs, arranged in different packing geometries (cubic, hexagonal and orthotropic), have recently been proposed as a very promising core topology to improve the rigidity and strength of sandwich panels[17-19].

The skin-core bonding is critical for sandwich panels, as the adhesive layer must ensure an efficient skin-core load transfer. The improvement of structural stiffness can be achieved by controlling the amount of adhesive or applying surface treatments to the skins, especially when considering metallic surfaces[20]. Epoxy polymers are the most common type of structural adhesive, providing relatively high modulus and strength to the structure[21].

In the last decades, unbridled population growth has led to high production and consumption of materials, causing accumulation of waste and depletion of resources. Thus, another challenge for materials scientists and engineers is not only to develop efficient and cost-effective products, but also to keep evolving technologically without compromising the availability of resources for future generations[22]. More research is needed to reduce the environmental impact of disposing of materials that use natural and biodegradable resources in high-end quality sustainable industrial products.

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In this context, bamboo can be exploited for the design and development of composite materials due to its intrinsic characteristics, such as high renewability, biodegradability, versatility, rapid growth, low weight, low cost and, especially, for its physical and mechanical properties that already meet engineering requirements for use in civil construction[23-26].

Bamboos are giant grass-like plants, abundant in tropical and subtropical regions such as Latin America and south-eastern Asia. More than 1500 different species are available worldwide and their chemical composition varies widely from species to species[27,28]. For most woody species, the bamboo structure is composed of cylindrical shell culms with solid transverse diaphragms or “nodes” that separate hollow inter-nodal regions along with their height[29]. The circular cross-section is composed of unidirectional cellulosic fibres oriented parallel to the longitudinal axis of the culm embedded in a lignin matrix[29].

Bamboo can be an alternative material for the development of structural biocomposites for everyday use, such as prefabricated wall panels[30], sports equipment[31], lightweight car components[32] and others. Recently, the use of bamboo rings as a circular core in sandwich panels for structural applications has been investigated experimentally[33] and numerically[34]. Hartoni et al.[33] performed bending tests on sandwich composites made with bamboo core and plywood skins, varying the thickness of the skin and panel. Meanwhile, Darzi et al.[34] conducted numerical studies on the flexural capacity of ultralight composite sandwich panels made of plywood faces and bamboo core. Both studies revealed promising features for structural applications according to the properties of bamboo sandwich composites.

To the best of the author’s knowledge, this is the first attempt to investigate the flexural behaviour of sandwich panels made from bamboo rings core, treated aluminium skins and epoxy adhesive. A statistical design is carried out to identify the effects of the factors: aluminium treatment (alkaline degreasing and primer application) and bamboo diameter (30 and 40 mm), on the physical and mechanical properties of the panel. Failure analysis and a comparison study with another type of core are also evaluated to investigate the feasibility of the proposed panel for secondary structural applications.

Table 1. Full Factorial Design (2^2).

Experimental Condition	Aluminium Treatment	Bamboo Diameter
1	NaOH	30 mm
2	NaOH	45 mm
3	Wash Primer	30 mm
4	Wash Primer	45 mm

2. Materials and Methods

2.1. Materials

The sandwich panels consist of a pair of treated-aluminium sheets as skins, bamboo rings as a core and epoxy polymer as an adhesive. The brushed aluminium casting alloy sheets of 0.5 mm thickness are sourced from *Alumiaço* (Brazil). Sodium hydroxide (NaOH, 97.5%) from *Sulfal Química* (Brazil) and wash primer (bicomponent: 045 / 051) from *Sherwin Williams* are used to treat aluminium surfaces for better adhesion. The wash primer is a combination of vinyl, epoxy, phenolic resins, mineral fillers, anti-corrosive organic and inorganic pigments, hydrocarbons aromatics and acetates[35]. Bamboo culms belong to the *Bambusa tuldoides* species and are harvested at the Federal University of São João del-Rei (Brazil, 21°08’26.5”S 44°15’41.3”W). The epoxy resin Renlam M and the Aradur HY951 hardener, supplied by *Huntsman,* are used as a core-face adhesive.

2.2. Statistical analysis

A Full Factorial Design (2^2) is established to investigate the effect of the factors (levels), aluminium surface treatment (NaOH / Wash Primer) and the bamboo diameter (30 mm / 45 mm) on the mechanical and physical properties of sandwich panels, providing 4 experimental conditions as shown in Table 1. A constant cubic packing geometry of bamboo rings is considered for the core design. Three specimens are fabricated for each experimental condition with two replicates, running a total of 24 panels. Analysis of Variance (ANOVA) is used to assess the significance of each experimental factor and/or interaction within a 95% confidence interval. Minitab v.18 software is used to manipulate the data.

2.3. Aluminium treatment

Aluminium sheets are cut according to the sandwich panel dimensions, that is, 90×240 mm^2 and 90×225 mm^2, for Ø30 and Ø45 mm bamboo rings, respectively. The skins are degreased with an ordinary detergent and water-rinsed (Figure 1a), cleaned with acetone to remove remaining dirt

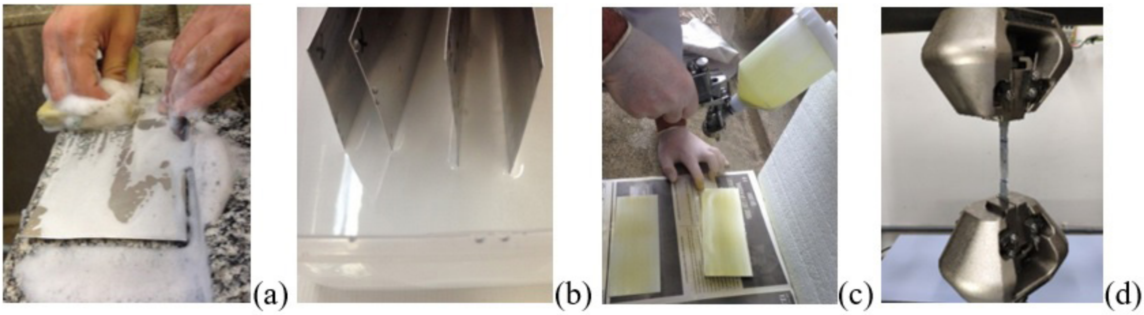


Figure 1. Aluminium treatment: (a) degreasing of the skins, (b) immersion in the NaOH solution, (c) pulverization with wash primer and (d) tensile test.

and dried with a gun dryer. Half of the clean aluminium skins are immersed in a 5 wt.% solution of sodium hydroxide (Figure 1b) at room temperature for 1 minute and then rinsed with water. The skins are dried and placed on a plastic film to prevent moisture absorption until the sandwich panels are manufactured. The pre-primer solution is prepared by adding two parts of Wash Primer 045 to one part of catalyst (051) and then spraying onto the other half of the skins (Figure 1c). After 20 minutes of pre-primer curing, the skins are immediately used in the manufacture of sandwich panels. Ten aluminium specimens without treatment are tested under tensile loads according to ASTM E8/E8M-16a[36] (Figure 1d) to better assess the properties of the sandwich panels. The tests are performed at 2 mm/min on a 100kN Shimadzu AG-X Plus test machine equipped with video extensometer.

2.4. Bamboo preparation

Bamboo culms approximately 3-years-old (Figure 2a) are harvested during the waning moon and left upright for three weeks to drain the starch present internally and to stabilize radial shrinkage. The bamboo rings are cut by a bandsaw at different heights, 13 mm (rings for sandwich panels, Figure 2b) and 60 or 90 mm (rings for compression test - height is twice the outer diameter, Figure 2c). Subsequently, the rings are oven-dried at 50°C for three days for complete drying and left 24 hours at room temperature (23°C and 55% of relative humidity) to reach the equilibrium moisture content. Fifteen dried bamboo rings of each diameter are characterised by compression (Figure 2d) and density tests following ISO 22157-1[37] and ISO 22157-2[38]. The tests are performed at 2 mm/min on a 100kN Shimadzu AG-X Plus test machine. Due to the curvature and surface of the bamboo, the tests are conducted without video extensometer; deformation was calculated based on the crosshead displacement. The strength is determined by the maximum load applied to the cross-sectional area of the hollow tube, i.e., considering the outer and inner diameter.

2.5. Manufacture and characterization of sandwich panel

The manufacture of the sandwich panel begins by inserting the treated aluminium skins into a wooden mould covered with an *Armalon®* release tape to prevent leakage (Figure 3a). The epoxy system (10:1 resin/hardener) is hand-mixed for 5 minutes and poured uniformly into the mould, considering approximately 1 mm thick. Bamboo rings, previously selected to avoid height variation (13 mm ± 0.05), are then placed on the skin according to the experimental condition, i.e. Ø30 or Ø45 mm (Figure 3b). The mould is closed with a wooden lid and compacted with a cold uniaxial pressure of 2.3 kPa for 24h at room temperature (Figure 3c). Subsequently, the material (Figure 3d) is demoulded and the second skin is bonded following the same process, resulting in a sandwich panel approximately 15 mm thick (Figure 3e). The panel is cured for 7 days at room temperature (22 ± 2°C) before testing.

The sandwich panels are characterised by three-point bending test (Figure 3f). A 100kN Shimadzu AG-X Plus test machine is used, considering a crosshead speed of 6 mm/min and a span length of 150 mm. The maximum load, flexural strength and modulus are determined based on ASTM D790[39], considering the panel as a solid and homogenous material. The skin stress is calculated based on ASTM C393[40], while the core shear stress and modulus responses are based on standard bending theory[9] and ASTM D7250[41]. The equivalent density of the sandwich panels is also assessed by measuring the dimensions and mass of the panels using a calliper (0.01 mm) and a precision scale (0.001 g).

3. Results and Discussion

3.1. Individual phases

Table 2 shows the mechanical and physical properties of the aluminium sheets and bamboo rings of both diameters

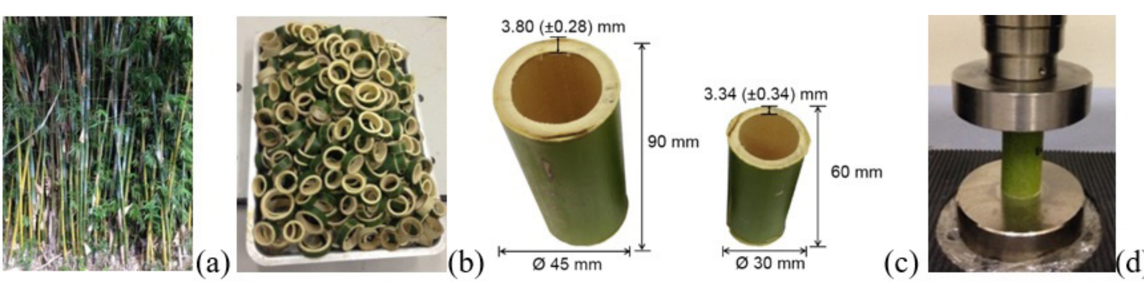


Figure 2. (a) Bamboo culms, (b) bamboo rings, (c) bamboo samples for (d) compression test.

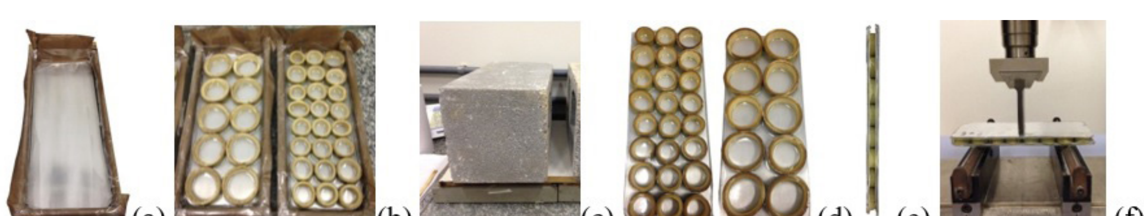


Figure 3. Manufacturing steps: (a) mould preparation, (b) bamboo ring insertion, (c) cold compaction, (d) second layer bonding, (e) sandwich panel and (f) bending test.

Table 2. Mechanical and physical results of the panel constituents.

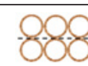
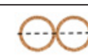
Material	Tensile		Compressive		Physical
	σ_{max} [MPa]	E_T [GPa]	σ_{max} [MPa]	E_C [GPa]	ρ [g/cm^3]
Brushed aluminium	103.5 (± 7.6)	35.3 (±4.9)	-	-	2.7*
Bamboo ring Ø30 mm	-	-	148.7 (±16.4)	12.1 (±0.7)	0.85 (±0.02)
Bamboo ring Ø45 mm	-	-	142.1 (±19.5)	12.1 (±0.6)	0.79 (±0.03)

*Obtained by the manufacturer.

Table 3. Mean and standard deviation values for DoE responses.

E.C.		Equivalent Density (g/cm^3)	Maximum Load (N)	Flexural Strength (MPa)	Flexural Modulus (MPa)	Skin Stress (MPa)	Core Shear Stress (MPa)	Core Shear Modulus (MPa)
R1	1	0.616 (± 0.012)	2835.7 (± 175.8)	29.92 (± 3.84)	6.41 (± 0.04)	160.43 (± 0.08)	2.74 (± 0.56)	93.67 (± 4.01)
	2	0.609 (± 0.009)	2610.7 (± 207.0)	28.36 (± 1.09)	6.56 (± 0.31)	153.96 (± 25.25)	2.47 (± 0.05)	77.70 (± 13.56)
	3	0.618 (± 0.018)	3172.0 (± 138.8)	33.85 (±1.11)	5.86 (± 0.06)	176.02 (± 5.50)	3.12 (± 0.10)	88.33 (± 10.00)
	4	0.601 (± 0.013)	2857.6 (± 336.1)	30.93 (± 1.01)	5.04 (± 0.08)	165.31 (± 18.40)	2.93 (± 0.33)	64.44 (± 5.93)
R2	1	0.613 (± 0.012)	2728.1 (± 152.1)	30.71 (± 2.41)	6.65 (± 0.25)	163.94 (± 18.44)	2.77 (± 0.16)	91.67 (± 7.17)
	2	0.610 (± 0.025)	2683.6 (± 289.9)	27.76 (± 13.03)	6.41 (± 0.15)	159.04 (± 27.43)	2.39 (± 0.38)	73.93 (± 13.99)
	3	0.623 (± 0.002)	3101.6 (± 159.8)	33.70 (± 0.66)	5.89 (± 0.33)	171.88 (± 1.68)	3.05 (± 0.03)	90.74 (± 6.34)
	4	0.608 (± 0.011)	2801.0 (± 301.1)	31.14 (± 3.08)	5.05 (± 0.03)	164.56 (± 19.29)	2.91 (± 0.34)	63.36 (± 2.16)

Table 4. Additional characteristics of sandwich panels.

Material type	Bamboo rings per panel	Surface contact area (mm^2)	Voids (%)	Core configuration (where force is applied)
Sandwich panel Ø30 mm	24	11745.35	45.62	
Sandwich panel Ø45 mm	10	8929.66	55.90	

investigated. The brushed aluminium sheet exhibits an ultimate tensile strength and modulus of 103.5 MPa and 35.3 GPa, respectively. Figure 4 shows a typical stress versus strain curve. This behaviour, also observed by[42,43], corresponds to an aluminium casting alloy with additions that lead to less mechanical strength and stiffness, but greater elongation. The compressive moduli of both diameters are similar. However, the compressive strength and equivalent density show higher results for bamboo rings of smaller diameter (Ø30 mm). According to Krause et al.[25], the increase in density occurs mainly due to a combination of fibre volume fraction increment and voids volume fraction decrement, and the relationship between the increase in strength and the variation in density is almost linear. Therefore, these smaller bamboo rings, located higher above the culm, show a reduction in the number and size of the vascular bundles with a consequent increase in the fibre volume fraction, resulting in superior properties[44].

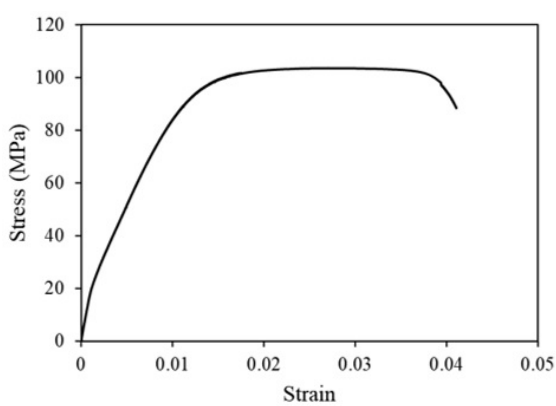


Figure 4. Stress-strain curve for the aluminium alloy.

3.2. Sandwich panel

Table 3 presents the mean values and standard deviation of each replicate for the sandwich panel responses, which are statistically interpreted in Section 3.3.

Table 4 shows the additional characteristics of the sandwich panels. Twenty-four (24) bamboo rings of Ø30 mm are used in E.C. 1 and 3, resulting in a cross-sectional area of 11745.35 mm^2 and a void percentage of 45.62. On the other hand, ten (10) bamboo rings of Ø45 mm are used in E.C. 2 and 4, resulting in a cross-sectional area of 8929.66 mm^2 and a void percentage of 55.90. The core configuration in the middle of the sandwich panel is different between conditions. In E.C. 1 and 3, the force is applied in the interface of six (6) Ø30 mm bamboo rings, while in E.C. 2 and 4, the force is applied in the middle of two (2) Ø45 mm bamboo rings. This fact leads to different moment of inertia of area in the middle of the panels, which can also affect the bending rigidity of the structure. This issue will be further discussed in section 3.4.

3.3. Statistical design

Table 5 presents the DoE/ANOVA analysis. The significant effects (P-value ≤ 0.05) are underlined and those in bold (superior order) will be interpreted via effect plots, illustrating

Table 5. Analysis of variance (ANOVA).

	P-value ≤ 0.05						
	Equivalent Density	Maximum Load	Flexural Strength	Flexural Modulus	Skin Stress	Core Shear Stress	Core Shear Modulus
Treatment (T)	0.905	**0.002**	**0.000**	0.000	**0.006**	0.000	0.000
Diameter (D)	**0.011**	**0.005**	**0.001**	0.004	**0.017**	0.001	0.004
T x D	0.100	0.094	0.393	**0.005**	0.422	**0.044**	**0.025**
R^2 - adj	75.57%	91.86%	97.31%	97.57%	85.87%	97.69%	97.93%
Anderson - Darling	0.990	0.082	0.898	0.686	0.435	0.288	0.640

the statistical design. The R^2_{adj} (adjusted) parameter varies from 75.57 to 97.93%, indicating good predictability of the statistical model used. Although the R^2_{adj} for the equivalent density is slightly lower, it still indicates a model of good predictability since 75.75% of the variability of this response is explained by the factor and the interactions. This reduction is attributed to the "Treatment" factor and "Treatment x Diameter" interaction, which are not significant (P-values < 0.05) and, therefore, contribute to the reduction of R^2_{adj}. The P-values for the Anderson-Darling normality test are greater than 0.05, which implies the data follow a normal distribution, validating ANOVA.

3.3.1. Equivalent density

Figure 5 shows the main effect plot for the mean equivalent density. The treatment of the aluminium surface does not affect the physical characteristics of the panels, since the gain or loss of mass is negligible. Thus, only the diameter factor has a significant effect on the response, exhibiting a significant (albeit small) increase of 2% for sandwich panels with Ø30 mm bamboo rings, which is attributed to the lower percentage of voids (higher structural weight) as shown in Table 4, and greater density of this ring when compared to the Ø45 mm (Table 2).

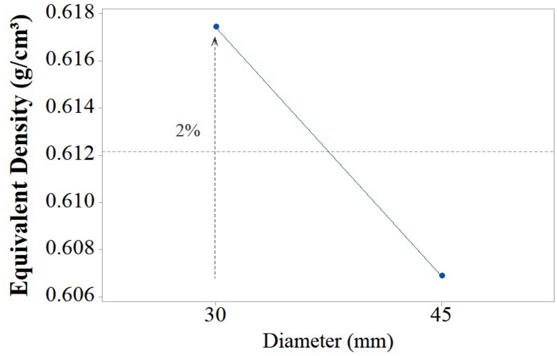


Figure 5. Main effect plot for the mean equivalent density.

3.3.2. Maximum load

Figure 6 exhibits the main effect plot for the mean maximum bending load. Wash primer treated aluminium skins lead to a 10% increase in the maximum load of the sandwich panels compared to those treated with sodium hydroxide (Figure 6a). According to Oliveira et al.[20] and Davies[45], the use of surface primers on metallic skins can provide protection against moisture and corrosion while enhancing the chemical bond between the skin surface and the polymeric adhesive. Therefore, the increase in this response implies an improvement in the skin-polymer interface adhesion, especially in the plastic region, when the primer is used.

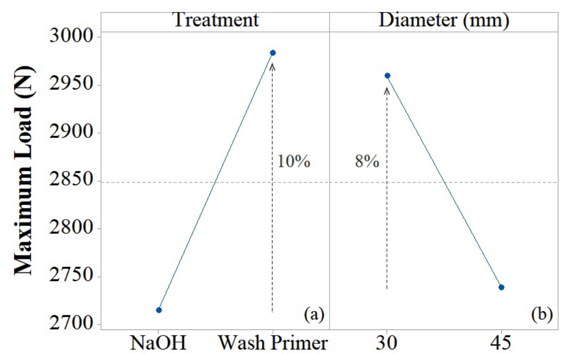


Figure 6. Main effect plots for the mean maximum load.

Sandwich panels with Ø30 mm bamboo rings exhibit an 8% increase in maximum load (Figure 6b). The bamboo rings have several vessels for transporting water and sap, oriented parallel to the longitudinal axis, which causes absorption of the polymer by capillarity[29]. Therefore, the greater surface contact area of these panels (11745.35 mm^2) compared to those with Ø45 mm (8929.66 mm^2) results in greater core-face adhesion and, consequently, greater efforts are required under bending loads.

3.3.3. Flexural properties

Figure 7 shows the main effect plot for the mean flexural strength, which shows similar results for the maximum bending load. Increases of 11% and 8% are observed for sandwich panels with wash primer and Ø30 mm bamboo rings, respectively, attributed to the efficient adhesion between the phases during the plastic regime and greater surface contact area. On the other hand, Ø45 mm sandwich panels have two bamboo rings located in the middle of the panel, where force is applied (see Table 4), which contributes to the reduction of flexural strength due to the lower properties of the bamboo in the transverse direction, taken the panel to a localised fracture, as shown in Figure 8.

Figure 9 shows the opposite behaviour in flexural modulus for NaOH treated sandwich panels, revealing increases of up to 28% when compared to the condition with the wash primer. While the treatment with sodium hydroxide consists of removing the unstable aluminium oxide/hydroxide film and cleaning the oils and greases from the bonding surfaces[46], the use of wash primer creates a thin layer on the aluminium surface, allowing a greater relative deformation between the phases, which increases the flexibility of the panel.

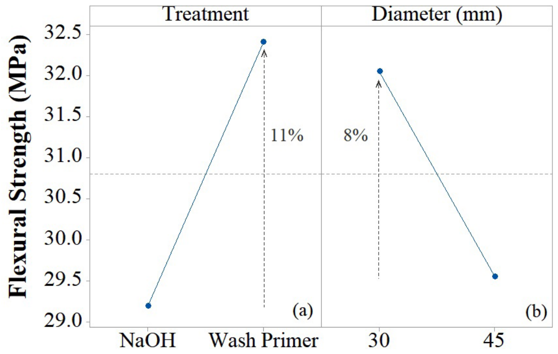


Figure 7. Main effect plots for the mean flexural strength.

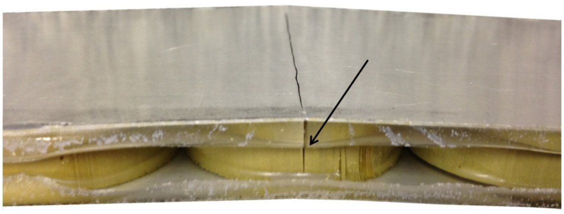


Figure 8. Bamboo fracture achieved for Ø45 mm panels.

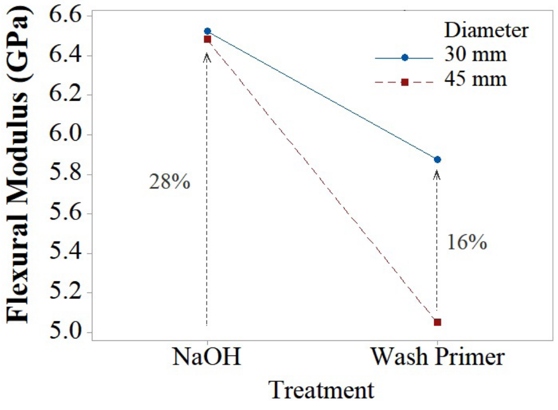


Figure 9. Second order interaction effect plot for the mean flexural modulus.

Panels made with Ø30 mm bamboo rings also result in a greater flexural modulus when considered a wash primer, being attributed to the greater amount of bamboo rings per area and, consequently, to the greater number of constraints on the core, requiring more efforts to bend the panel and displace the rings.

3.3.4. Skin stress

Figure 10 shows the main effect plots for the mean skin stress of the sandwich panels. The results are similar to that of the maximum load, since this response assumes that the facings withstand the full bending load[17]. Increases of 6% and 5% are noted in sandwich panels made with aluminium treated with wash primer (Figure 10a) and Ø30 mm bamboo rings (Figure 10b), respectively, attributed to the efficient adhesion between the phases and greater surface contact area.

The skin stresses are above the ultimate tensile strength of the aluminium sheet (103.5 MPa), resulting in a skin fracture for all experimental conditions, as will be shown

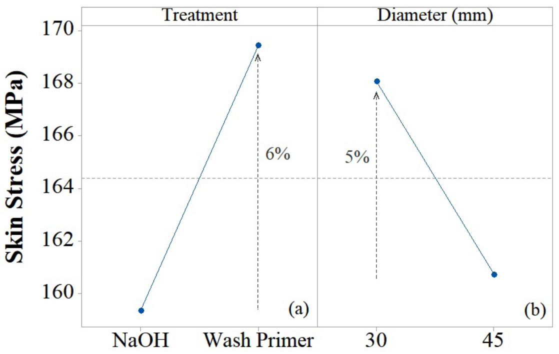


Figure 10. Main effect plot for the mean skin stress.

in Section 3.4. This fact implies a good core-adhesive and adhesive-face bond due to the high absorption of the polymer by the bamboo rings and the efficient surface treatment carried out on aluminium, respectively.

3.3.5. Core shear properties

Figures 11 and 12 show the second-order interaction effect plot for the mean core shear stress and modulus, respectively. The use of Ø30 mm bamboo rings shows superior results for both responses, exhibiting increases of up to 14% and 40% for core shear stress and modulus, respectively. Similar results are observed by Oliveira et al.[47], in which smaller bamboo diameters require more shearing efforts due to the greater number of bamboo rings per area and the lower percentage of voids, resulting in a greater number of in-plane constraints.

Sandwich panels with Ø45 mm bamboo rings and wash primer-treated aluminium skins exhibit a 20% increase in core shear stress (Figure 11), while those with sodium hydroxide exhibit a 19% increase in core shear modulus (Figure 12). The use of a wash primer provides a more flexible core-skin interface, which explains its improved behaviour for the core shear stress response. In contrast, the removal of a thin oxide/hydroxide layer from the aluminum surface with NaOH makes the interfacial adhesion more rigid, compromising the plastic shear strains of the core, leading to a greater core shear modulus.

3.4. Failure analysis

Figure 13 shows the typical force versus displacement curves for the experimental conditions obtained by the three-point bending test. All sandwich panels have a short elastic deformation followed by load reduction in the nonlinear region due to the beginning of cracks between the adhesive and the skins. Subsequently, the increase in displacement causes a progressive failure, resulting in a sudden drop with the rupture of the bottom skin due to tensile stresses (Figure 13). Wash primer sandwich panels (E.C. 3 and 4) lead to greater toughness attributed to more flexible interfacial adhesion compared to NaOH treatment.

The sandwich panels made with Ø45 mm bamboo reveal not only the skin, but also bamboo fractures located in the region of the applied force, as shown in Figure 14. This behaviour can be attributed to the greater displacement of the lower skin under tensile loads and the strong face-core bonding interface that radially stretches the bamboo ring.

In addition, the bending moment applied to the longitudinal cross-section of the bamboo also contributes to propagate the crack transversely. It is noteworthy that this fracture does not affect the sandwich toughness, as shown in Figure 13. This failure mode is not observed in sandwich panels with Ø30 mm bamboo rings, since the force is applied at the cell interface.

It is worth mentioning that the moment of inertia of area plays an important role in the bending rigidity and strength of the panels. As shown in Table 4, and previously mentioned, Ø30 mm bamboo rings lead to a cell interface in the middle of the panel, while Ø45 mm bamboo rings are positioned through the centre. It would be expected that the latter would lead to an increase in stiffness or strength; however, the opposite occurred (Figures 7 and 9), which demonstrates that the mechanical performance of the panel depends mainly on the adhesiveness of its components, that is, the greater contact area, the greater the strength and stiffness of the panels.

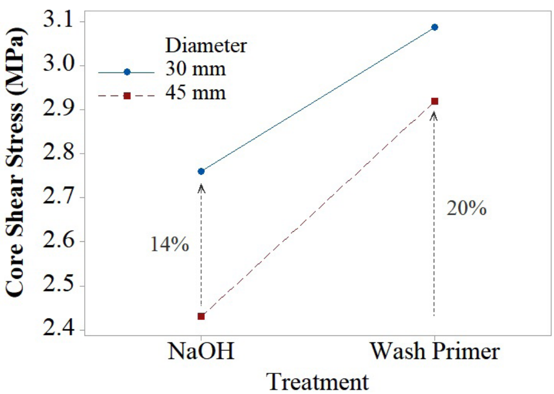


Figure 11. Second-order interaction effect plot for the core shear stress.

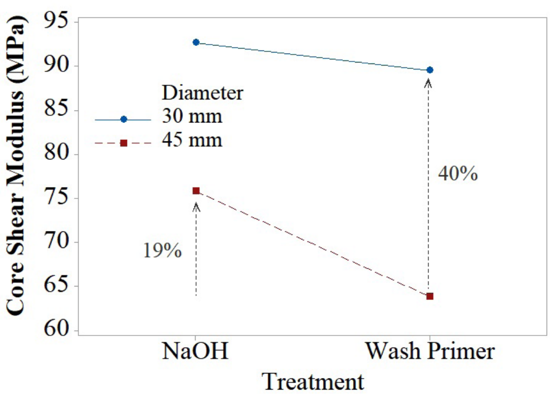


Figure 12. Second-order interaction effect plot for the core shear modulus.

3.5. Comparison to other core type

The properties of the proposed bamboo core panels are compared with sustainable sandwich structures made from bottle caps core and aluminium skins, developed by Oliveira et al.[20] for secondary structural applications. The comparison is made with the experimental condition C3 in both studies, since the similar configuration is considered, such as cell diameter (30 mm); aluminium type (brushed); polymer type (Renlam M/HY951 Hardener); cell packing (cubic) and skin treatment (wash primer). Both structures were manufactured in a similar way, using cold compaction pressure.

Table 6 shows the overall properties of the panels and their respective specific properties (absolute properties divided by density). All properties are superior for the sandwich

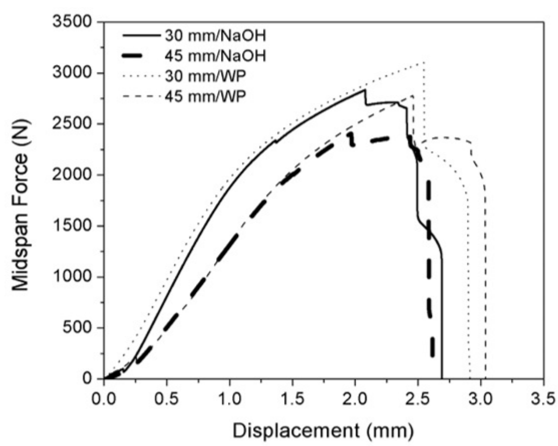


Figure 13. Typical bending behaviour for the sandwich panels.

Table 6. Comparison between the proposed sandwich panels and bottle caps panel.

Property	Core type		Percent increase (%)
	Bamboo	Bottle caps[20]	
Equivalent Density (g/cm^3)	0.62	0.59	5.1
Maximum Load (N)	3144	2111	48.9
Flexural Strength (MPa)	33.8	27.2	24.2
Specific Flexural Strength (N.m.g^{-1})	54.5	46.1	18.2
Flexural Modulus (GPa)	5.88	2.83	107.8
Specific Flexural Modulus (kN.m.g^{-1})	9.5	4.8	97.7
Skin Stress (MPa)	174.0	129.2	34.6
Specific Skin Stress (N.m.g^{-1})	280.6	219.0	28.1
Core Shear Stress (MPa)	3.08	0.86	258.1
Specific Core Shear Stress (N.m.g^{-1})	5.0	1.5	240.8
Core Shear Modulus (MPa)	90	30	198.5
Specific Core Shear Modulus (N.m.g^{-1})	144.4	50.8	184.0

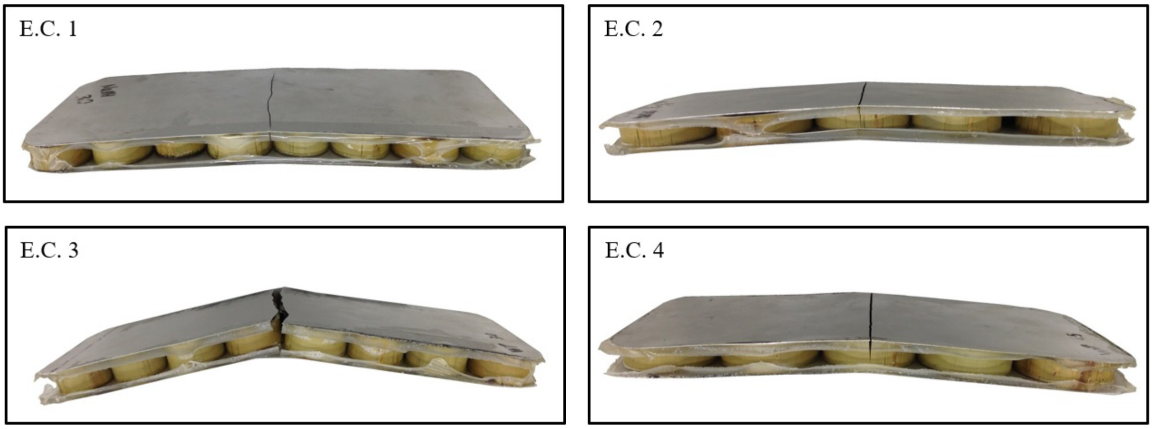


Figure 14. Failure mode of the sandwich panels for each experimental condition.

panel made with bamboo core, revealing increments of up to 258.14%. This increase is attributed to the high elastic modulus of the bamboo rings (12.1 against 1.01 GPa[10]) and their greater adhesion to the epoxy polymer, requiring more efforts to deform and fracture the panel.

Finally, the use of bamboo rings as a core material in sandwich panels, in addition to sustainable and economic issues, revealed good mechanical performance, resulting in a feasible and promising alternative in the replacement of secondary structural components in various fields, such as transportation facilities, civil infrastructure, cargo bays and others.

4. Conclusions

This work describes the mechanical behaviour of a sandwich panel composed of bamboo rings as a circular honeycomb core, treated aluminium skins and epoxy adhesive. The effect of the aluminium treatment and bamboo diameter on the equivalent density, flexural and shear properties of the panels is identified through a statistical design. The main conclusions from the present work are:

i. Primed-aluminium skins provide more flexible adhesion to the skin-core, leading to greater maximum load, flexural strength, skin stress and core shear stress. Otherwise, aluminium treated with NaOH leads to a more rigid skin-core adhesion, resulting in a greater flexural and core shear modulus.
ii. Relatively more rigid and resistant structures are obtained with Ø30 mm bamboo rings attributed to the increased surface contact area and the number of constraints in the core.
iii. All experimental conditions fail due to skin fracture, implying an efficient face-core bond, attributed to the proper absorption of the polymer by the bamboo rings and the superficial treatment of aluminium. Cracks along the bamboo rings are evident only for diameters of 45 mm.
iv. Bamboo panels achieve a substantial increase in all absolute and specific physical-mechanical properties when compared to panels made with a bottle cap core, being a sustainable and promising alternative for structural applications.

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