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Parameter of thermal resistance of bamboo multilayer wall

Показатели теплотехнического сопротивления бамбуковой стены

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Ключевые слова: бамбук; гуадуа; тепловое сопротивление; коэффициент теплопередачи (U-Value)

Abstract. With the increasing of problems related to air pollution and rising of the mean temperature around the globe, new solutions must be investigated in order to diminish the magnitude of such environmental issues. Therefore, the appliance of bamboo in the construction can be one of the solutions. Even though, this grass does not present mechanical or thermal homogeneity, its high sustainability (CO_2 reducer, highness and fast speed of growth), strength and hollowed cylindrical morphology make it an option in the construction sector. As an energy-efficient material, this woody grass can have a positive thermal performance due to the presence of air cavities, however, its rounded nature influence to a non-homogeneous performances in the surface and interior. The literature about the thermal performance of this element as building envelopment is reduced. Thus, the aim of this research is to analyse the thermal performance of a one, two and three bamboo layers, placing them in a way to mitigate the heat leaking and improving the thermal resistance. It is analysed numerically and through a simulation developed in THERM 7.5 Finite Element Simulator. As a result, two line of bamboo is convenient as a material construction with U-Value of 1.4 W/m^2.K, but three layers is recommended to mitigate the presence of thermal bridges. The results obtained leads to a different approach and suggests further analysis for different parameters.

Аннотация. Ввиду роста проблем, связанных с загрязнением воздуха и повышением средней температуры на планете, необходимы альтернативные решения, которые смогут снизить вред, наносимый окружающей среде. Применение бамбука как строительного материала может стать одним из таких решений. Несмотря на то, что он механически или теплотехнический неоднороден, его высокая экологическая устойчивость (снижает уровень CO_2, обладает высокой скоростью роста), прочность и полая цилиндрическая структура позволяют рассматривать бамбук в одном ряду с другими строительными материалами. Бамбук имеет хорошие теплотехнические характеристики благодаря наличию пустот, однако его цилиндрическое строение становится причиной неоднородного поведения внешней и внутренней частей материала. Недостаточное количество литературы, описывающей теплотехнические свойства бамбука как ограждающей конструкции, стало причиной для проведения анализа одного, двух и трех слоев бамбука путем, размещенных способом, уменьшающим теплопотери и повышающим тепловое сопротивление. Анализ был проведен численно и с помощью симуляции, разработанной в THERM 7.5 Finite Element Simulator. Результаты исследования показали, что достаточно двух слоев бамбука, чтобы получить строительный материал с U-value 1,4 W/m^{2}K, но использование трех слоев рекомендуется для уменьшения мостиков холода. Полученные результаты позволяют рассматривать использование нового подхода и могут стать основой для дальнейшего исследования других параметров.

1. Introduction

The construction industry is one of the major source of pollution in the air -around 4% of particulate emission-, water, noise and soil [1]. Therefore, the use of sustainable materials in construction is a decisive factor to reduce this negative environmental impact. The bamboo is a renewable material, well known as

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a giant grass, belongs to the family Graminace (Poaceae) and is spread around the world according to Figure 1.

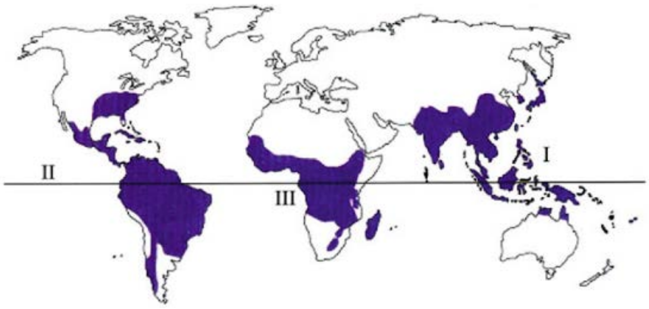

Figure 1. Distribution of Bamboo around the world. I – Asia-Pacific region, II – America region and III – African region (INBAR 2010 [2])

Some remarkable benefits of this vegetal are the capability of CO2 sequestration (Bamboo – Guadua fixing capacity of 76 t CO2/ha) [3], rapidly rate growth, 6 months to have its height and 4 – 6 years [4] and high mechanical performances along its fibres [5, 6]. International standardizations and codifications from China, Colombia, Ecuador, India, Peru and USA promote this sustainable material for construction of complex projects [7]. Moreover, it has high resistant in seismic events [8].

A cylindrical and hollowed shape governs the morphology of the bamboo stick. Normally, the separation of internodes varies between 10 cm and 40 cm (Figure 2). Depending on the specimens the culm can reach height upper 18m with diameters from 5 cm to 25 cm and wall thickness from 0.9 to 1.3 cm [9].

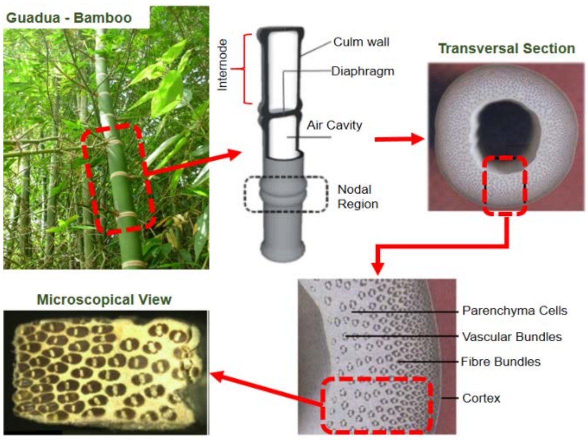

Figure 2. Morphology of Bamboo [9]

Regarding its thermal characteristic, it has a cavity filled with air entrapped, low thermal-conductor element, enveloped by a porous woody material with fibre and vascular bundles. However, the bamboo stick as an insulation material presents two noticeable withdraws: firstly, due to its vegetable nature, its physical, mechanical and geometrical properties change between species, moreover, [10, 11] demonstrated that in the wall of Guadua-Bamboo, after 15 % of its thickness measured from the cortex the aggrupation of vascular bundles are more separated (Figure 2), changing its properties. Thus, it is considered a heterogeneous material with physical, mechanical and thermal variations, making this raw product difficult for being industrialized in mass, like industrial woods panels or commercial wood elements [5, 12]. Because of this variability, many researches about bamboo are focused on making glued or pressed composites or mixing its fibres with another elements in order to improve the resistance of the bamboo and generate mechanical and thermal properties predictable for calculation [12, 13].

The second withdraw is related to its cylindrical geometry, Huang, P [10] researched the thermal properties of a stick (culm) of Asian family “Moso-Bamboo” (Phyllostachys edulis) and found that the thermo-diffusivity and thermo-resistance of this specimen vary in different transversal points, due to its rounded shape and heterogeneous density in its wall. He registered an average thermo-conductivity of 0.226 W/m*K. Mata, M [14] obtained values of 0.158 W/m*K for Bamboo-Guadua.

Even though the process of industrial lamination of bamboo is a feasible exportation technique, it demands unnecessary costs for infrastructures surrounded by this vegetal. The Colombian Standard NSR 10 [8] establishes parameters of constructability of raw bamboo walls for the specimen Bamboo-Guadua addressing suitable techniques for not losing its mechanical properties, however, a thermal performance section is not included in the chapter for bamboo. Construction of wall with this rounded material, as shown in Figure 3, creates joins which drive thermal bridges, giving the chance to of heat leaking due to the reduced contact area [15].

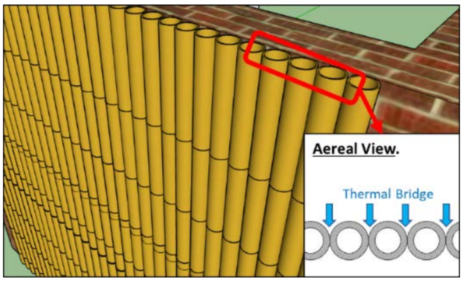

Figure 3. Thermal Bridges in Bamboo Wall

Nevertheless, the lack of studies related to Bamboo's thermal performance and its discrepancy of values still an issue, making unclear its properties, which leads for a reduced use of this material as insulation layer. Likewise, usually the studies linked to this material are about its mechanical characteristics. Due to this fact, this paper aims the study of bamboo as insulation material, and not, as a structural one.

Therefore, the objectives of this paper are:

- Numerical analysis of the thermal resistance of the non-homogenous surface of the Bamboo;
- Software thermal analysis by modelling in a finite element simulator THERM 7.5;
- Formulate a feasible solution to mitigate the presence of thermal bridges;
- Compare the result obtained both numerically and by Software Analysis.

The analysis is done in a residential house located in the city of Guayaquil, Ecuador.

2. Methods

This research include a numerical and a simulation method of thermal parameters of thermal resistance and heat lost through a theoretical wall, built of vertical sticks of bamboo in its natural state.

The bamboo model is located in Guayaquil, Ecuador with the adopted information:

- Outside Temperature: 37.2 ºC;
- Inside Design Temperature: 22.0 ºC;
- Relative Humidity: 79%;
- The wall length which underwent through thermal simulation has 1.00 m;
- The interior part of the bamboo was considered as a Frame Cavity – CEN Simplified;
- The thermal characteristics of the bamboo was set as Table 1.

Table 1. Thermal-physics Parameters: Thermal Conductivity (λ), Thermal Effusivity (e), Thermal Diffusivity (α), density (ρ) and Specific Heat (c) of Guadua According to Gordillo, F. [16].

λ $Wm^{-1}K^{-1}$	e $Ws^{1/2}m^{-2}K^{-1}$	α $10^{-6}m^2s^{-1}$	ρ 10^3kgm^{-3}	c $Jkg^{-1}K^{-1}$
0.157	1000 ± 20	0.11±0.01	0.6±0.07	1491

One of the facts of the thermodynamic law is the transference of the energy by the interaction (work and heat) of a system with its surrounding. The transfer used in this document is heat transfer, which is the thermal energy in transit due to a spatial temperature difference [17]. There are three modes of heat transfer: Conduction, Convection and Radiation.

This article pays more attention on the heat transfer that will occur through a medium (solid or stationary fluid), in this case, this medium is the bamboo layers. Therefore, it is necessary to calculate the capacity of the materials to conduct heat, in other words, the thermal resistance, which is estimated primarily by the Fourier Law.

$$q = \lambda * \frac{T1 - T2}{\delta} * A * t \quad (1)$$

where: λ – Coefficient of thermal conductivity (W/m K);

δ – Thickness of the material (m);

T1 and T2 – Indoor and outdoor temperature respectively (or outdoor if it is hotter that indoor);

A – Area of the surface of layer (m2);

t – Time (s).

In order to analyse the thermal resistance of the Bamboo layers, it will be calculated according to [18–21], which give the formulas (2) (3):

$$\mathrm{R} = \frac{1}{\propto_{\mathrm{int}}} + \sum_{i=1}^{j} \frac{\delta_i}{\lambda_i} + \frac{1}{\propto_{\mathrm{ext}}} \quad (2)$$

where: R – Thermal resistance (m^2 K/ W);

$\propto_{int}$ – inner surface heat transfer coefficient, 25 W/m2 K according to IRAM 11601;

$\propto_{ext}$ – outer surface heat transfer coefficient, 7.69 W/m2 K according to IRAM 11601.

A typical section of 2-layers bamboo wall was considered (Figure 4). The axis or sections 1, 2 and 3 represents different performances of the partial thermal-resistance located along each horizontal axis (A-O), moreover, the contact between sticks is studied as a perfect and constant contact along the elements and the air gaps formed, thanks to the union of each stick, is not considered, their small area is not representative for calculations.

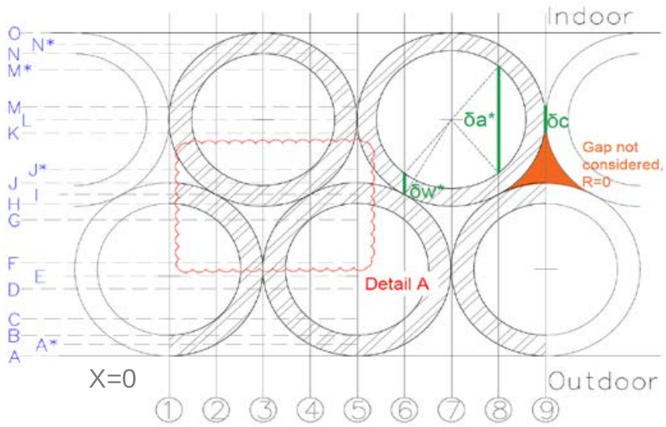

Figure 4. Cross-section of 2-layers bamboo wall

The one-dimensional tendency of the thermal resistances evaluated in the sections 1, 2 and 3 for "n" number of layers are described in the Table 2 and generalized in the equations 4 and 5 and 6.

Table 2. Thermal Resistance along the sections for n number of layers.

n Layers	Section 1	Section 2	Section 3
2	$\frac{\delta c}{\lambda b} + \frac{2\delta w}{\lambda b} + \frac{\delta a}{\lambda a}$	$\frac{4\delta w^*}{\lambda b} + \frac{2\delta a^*}{\lambda a}$	$\frac{\delta c}{\lambda b} + \frac{2\delta w}{\lambda b} + \frac{\delta a}{\lambda a}$
3	$\frac{\delta c}{\lambda b} + \frac{4\delta w}{\lambda b} + \frac{2\delta a}{\lambda a}$	$\frac{6\delta w^*}{\lambda b} + \frac{3\delta a^*}{\lambda a}$	$\frac{2\delta c}{\lambda b} + \frac{2\delta w}{\lambda b} + \frac{\delta a}{\lambda a}$
4	$\frac{2\delta c}{\lambda b} + \frac{4\delta w}{\lambda b} + \frac{2\delta a}{\lambda a}$	$\frac{8\delta w^*}{\lambda b} + \frac{4\delta a^*}{\lambda a}$	$\frac{2\delta c}{\lambda b} + \frac{4\delta w}{\lambda b} + \frac{2\delta a}{\lambda a}$
5	$\frac{2\delta c}{\lambda b} + \frac{6\delta w}{\lambda b} + \frac{3\delta a}{\lambda a}$	$\frac{10\delta w^*}{\lambda b} + \frac{5\delta a^*}{\lambda a}$	$\frac{3\delta c}{\lambda b} + \frac{4\delta w}{\lambda b} + \frac{2\delta a}{\lambda a}$

For the restriction.

$$\delta w < \frac{\delta a}{2}$$

Then,

$$R_1 = \frac{1}{\alpha in} + \left\lfloor\frac{n}{2}\right\rfloor\frac{\delta c}{\lambda b} + 2\left(n - \left\lfloor\frac{n}{2}\right\rfloor\right)\frac{\delta w}{\lambda b} + \left(n - \left\lfloor\frac{n}{2}\right\rfloor\right)\frac{\delta a}{\lambda a} + \frac{1}{\alpha ext} \quad (3)$$

$$R_2 = \frac{1}{\alpha in} + \frac{n}{2\lambda b}\left(\sqrt{3}\delta b - \sqrt{4\delta a^2 - \delta b^2}\right) + \frac{n}{2\lambda a}\sqrt{4\delta a^2 - \delta b^2} + \frac{1}{\alpha ext} \quad (4)$$

$$R_3 = \frac{1}{\alpha in} + \left\lceil\frac{n}{2}\right\rceil\frac{\delta c}{\lambda b} + 2\left(n - \left\lceil\frac{n}{2}\right\rceil\right)\frac{\delta w}{\lambda b} + \left(n - \left\lceil\frac{n}{2}\right\rceil\right)\frac{\delta a}{\lambda a} + \frac{1}{\alpha ext} \quad (5)$$

$$\delta a^* = \frac{\sqrt{4\delta a^2 - \delta b^2}}{2} \quad (6)$$

$$\delta w^* = \frac{\sqrt{3}}{4}\delta b - \frac{\sqrt{4\delta a^2 - \delta b^2}}{4} \quad (7)$$

where n = Number of bamboo layers in the wall;

δa = Diameter of the air cavity (δb- δw) (m);

δw = Thickness of the Bamboo (m);

δc = Distance of contact between bamboos –contact zone- (assumed as 0.15 δb) (m);

δb = External diameter of the bamboo stick (m);

λb = Conductivity of the bamboo woody material (W/mK);

λa = Conductivity of the air (W/mK).

Acknowledging the vertical Axis of the Figure 4 as the axis “X” of a Cartesian diagram and the result of every thermal resistance as the axis “Y”, it is possible to represent graphically the performance of every section for n number of layers, Figure 6. Nevertheless, in order to find an average performance of thermal resistance, it is assumed a hypothetical homogeneous wall, Figure 5, with similar tendency to the three sections aforementioned and following the next criteria:

Figure 5. Wall Equivalent for 2 layers bamboo wall. A, C and E is a hypothetical solid material with the same thermal properties as the Bamboo-Moso and B and D are air cavities

- Thickness of A and E are assumed similar.
- In the Figure 4 is observed that the proportion of air in the steam of bamboo from the sections 1-9 are similar between both layers. The air in the first layer section 1, 5 and 9 is δa, but in sections 2, 4 and 8 is δa*, as seen in the Figure. Thus, the average air in the first layer is measured as ¾ δa*, so it is assumed that B = D = ¾ δa*.
- For the first layer, it is shown in the Figure 4 that the section 1 and 3 show the minimum and maximum respectively in the first increase, so the first resistance purposed is by the means of section A and Section B, thus:

$$A = E = \frac{\delta w + 0.15\delta b}{2}\ (Thickness) \quad (8)$$

$$A = E = \frac{\delta w + 0.15\delta b}{2\lambda b} \; (Thermal\ Resistance) \tag{9}$$

- C is a variable and depends on A, B, D and E.
- The total resistance is leaded by the section 2 (Figure 4) and the section 1 and 3 have the minimum value, so (C is in function of δw):

$$A + B + C + D + E = \frac{R1 + R2}{2}$$
$$\left(\frac{\delta w + 0.15\delta b}{2\lambda b}\right) + \frac{3}{4\lambda a}\left(\sqrt{4\delta a^2 - \delta b^2}\right) + \frac{C(\delta w)}{\lambda b} = \frac{R1 + R2}{2} \tag{10}$$

After an interactive process, the value of C is defined as:

$$C = 1.787\delta w - 0.0016 \tag{11}$$

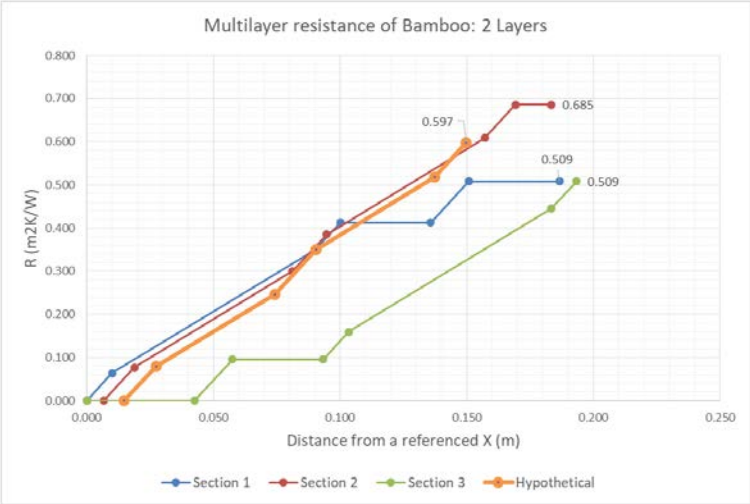

Figure 7. Thermal resistance in the axis 1, 2 and 3 and an equivalent wall, from a referenced x

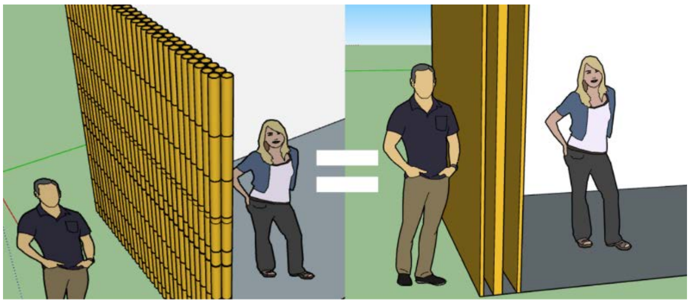

Figure 8. View of the hypothetical equivalent wall (right) and the bamboo wall (left)

The U-Value, which is a measure of the rate at which a building transmit heat [22, 23], is expressed in terms of thermal resistance. Therefore, it is given by (12).

$$U = \frac{1}{R}, \tag{12}$$

U – thermal transmittance (W/ m² K);

Consequently, the maximum value for the thermal transmittance for Guayaquil, referenced by the Argentina standard is 1.8 W/ m² K (IRAM 11.605).

According to World Meteorological Organization, Guayaquil has the following climate characteristics:

- Dew Point: 20.4 ºC;
- Hottest Month of the year: January 37.2 ºC.

For the simulations developed in this paper, the design temperature adopted will be 22.0 ºC.

The software simulation performed had the objective of analysing how the addition of more layers of Bamboo can improve the thermal characteristics of a wall and analyse the heat flux when using it as a single, double and triple insulation layer, as illustrated in Figure 8.

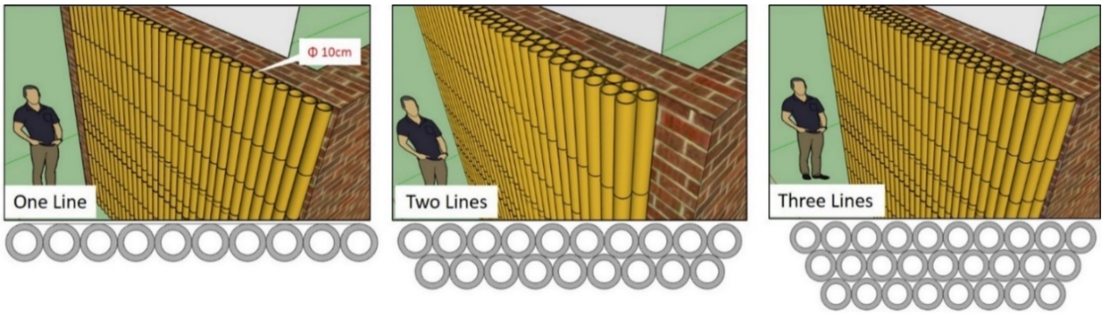

Figure 9. Proposed multi-layered bamboo façade: One layer, two layers and three layers, respectively. The first and second line for all cases are fixed at 10 cm

The specimen of Bamboo to use for calculation is Guadua - Angustifolia-Kunth. The diameter of the first line of bamboo is 10 cm, in accordance to the chapter E.7.6 of NSR 10 [24]. The elements of the second line was set at 10 cm also. According to [4] the thickness of the Guadua culms varies from 1,00 cm to 1.50 cm and regarding to the physical - thermal properties, it is adopted in accordance to the work of [10, 14, 16]. However, for this work the thickness adopted will be 10 cm.

For the simulation, it is used the software THERM 7.5, and whose initial parameters are similar to the previous numerical analysis, and the parameters expected are the heat flux, isotherms and temperature. Every extreme of the wall analysed corresponds to adiabatic sections. The air entrapped inside the every stick is considered as a Frame Cavity – CEN Simplified.

3. Results and Discussions

The results obtained in the software simulation are presented below (Figures 10–12). For all three simulations (single-layer, double-layer and triple-layer) it is displayed the temperature gradient through the bamboo and its heat flux.

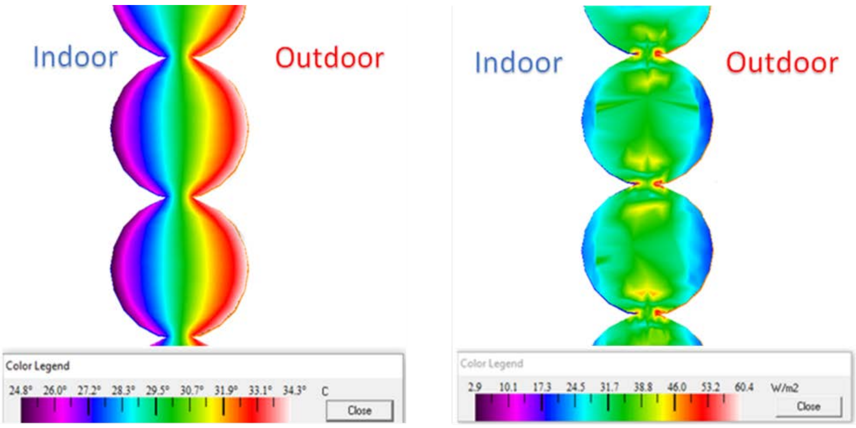

Figure 10. Temperature Gradient (OC) and Heat Flux Gradient (W/m²) for Single Layer Bamboo Wall

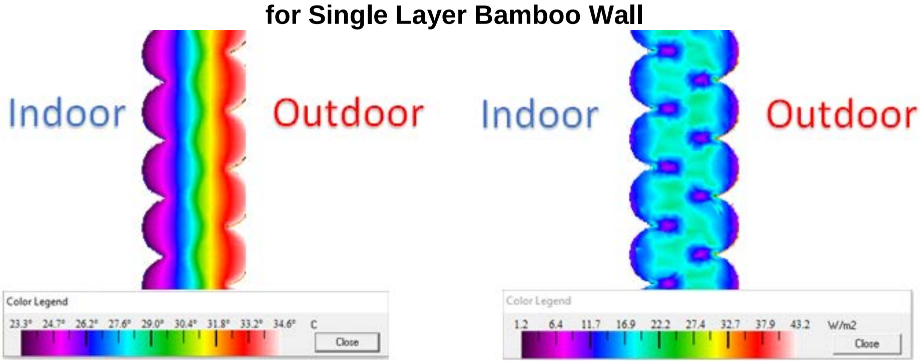

Figure 11. Temperature Gradient (OC) and Heat Flux Gradient (W/m²) for Double-Layer Bamboo Wall

Figure 12. Temperature Gradient (OC) and Heat Flux Gradient (W/m²) for Triple-Layer Bamboo Wall

When analysing the Temperature Gradient above, for all three simulations, a linear isotherm is obtained in the middle of the 2 and 3-layer wall, while the 1-layer wall illustrates a nonlinear patron. This is a result due to the rounded shape of the bamboo and as long as the walls with more layers get more stable, this variation tends to reduce. Furthermore, the heat flow gradient shows that adding a second and further a third layer of bamboo interspersed, the thermal bridges effect get reduced.

The Table 3 shows the values obtained after the Thermal Simulation. As expected, the U-Value decreased as the number of layers increased. In comparison with the standards (IRAM 11.605), both double and triple layer have a U-Value lower than the maximum recommended (1.8 W/m²K). Moreover, the amount of heat flow through the bamboos' layer decreased drastically when adding one layer as insulation material. It is important to point out that the thermal resistance shown in the Table 3 for a double layer bamboo converge with the value obtained by the hypothetical wall numerically calculated in the Figure 5.

Table 3. Results obtained for U-Value and Heat Flow

Layers	U-Value (W/m².K)	R (m².K/W)	Heat Flow (W) *
Single-Layer	2.07	0.48	34.20
Double-Layer	1.40	0.71	16.09
Triple-Layer	0.66	1.52	9.66

*Per meter

The values obtained in the Table above for simulated U-value for double layer have a close similarity with the theoretical calculated, oscillating between 1.34 and 1.67 W/m²K. Thus, the obtained result can be comparable with the research of [25], who investigated the thermal performance of many specimens of wood, for the structural softwood lumber (commonly used in construction) found a thermal conductivity between 0.1–0.4 W/mK (12 % of humidity); if a typical wood wall made of two panels of 13 cm thick from this wood and cavity air of 5 cm, have an approximate thermal resistance of 0.533 m²K/W (U = 1.87 W/m²K), it can be inferred that a bamboo wall layer, assuming complete contact between sticks, have similar thermal transmittance to a common system of wood panel with air cavity in-between.

Due to the non-homogeneity of bamboo and scarcity of literature about the thermal performance of bamboo walls, the values of thermal-resistance obtained is object of comparison with further studies.

4. Conclusion

A wall made of the renewable woody vegetal, bamboo, represents suitable values of thermal resistance for construction in regions with analogous climate characteristics, and energy-efficient regulations as the studied in this paper. Therefore, this paper concludes that:

- The results for U-Value obtained from the numerical evaluation and software simulation for double layer bamboo wall differ nearly 20 %, with values of 1.67 and 1.34 W/m²K respectively. Under the boundaries conditioned, it proofs a feasible use as construction material in building envelopments in hot regions;
- The more layers, the better the mitigation of heat leaking; it is proved that the use of three layers of bamboo, U=0.67 W/m².K, leads to an energy saving in the building;
- Therefore, it is important to mention that this investigation was carried out through computational simulation and numerical analysis and, as long as the bamboo is a heterogeneous material, it can lead to diverse results and additional measures of sealing.

Finally yet importantly, according to norms, it is necessary to submit the bamboo through some treatments in order to increase its waterproof, fire resistance and to avoid the presence of animals that can damage it. Future experimental studies will evaluate the influence of the orientation of the layers (horizontal and inclined – 45 %) and type of joins on the thermal behaviour of the bamboo. Furthermore, the analysis of relevant thermal parameters, as the thermal stability and the influence of the humidity in the conductivity, as the density changes radially.

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