Computational Water, Energy, and Environmental Engineering, 2020, 9, 37-47
https://www.scirp.org/journal/cweee
ISSN Online: 2168-1570
ISSN Print: 2168-1562

Design Procedure for Reinforced Concrete Beams and Reinforcement Replacement by Bamboo

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How to cite this paper: Tokuda, E.N., de Toledo Viana, J., Amorim, G.A.N., Dias, R. and Bigotto, S. (2020) Design Procedure for Reinforced Concrete Beams and Reinforcement Replacement by Bamboo. *Computational Water, Energy, and Environmental Engineering*, **9**, 37-47.
https://doi.org/10.4236/cweee.2020.93004

Received: December 14, 2019
Accepted: May 9, 2020
Published: May 12, 2020

Abstract

The use of non-renewable resources by the construction industry has several environmental consequences, contributing to excessive energy consumption and loss of materials. So, the construction sector is always in search of improvement and methods that innovate the existing techniques, aiming at the use of alternative and sustainable materials. Bamboo is a perennial plant with fast growth rate and low cost that has great physical and mechanical characteristics that assure its performance in the building environment. The use of beams with total or partial replacement of steel by bamboo has been well studied, due to the possibility of using the same design methods used in reinforced concrete beams, since the bamboo-reinforced beams meet the Bernoulli-Kirchoff bending theory. The objective of the work was to adapt a design procedure into an electronic spreadsheet for bamboo reinforced concrete beams subjected to four-point bending, with rectangular section, according to Brazilian Standard NBR 6118 (2014). The spreadsheet was tested based on other authors taking into consideration a steel double reinforcement. The resulting values were equivalents to those obtained by the authors, validating the efficiency of the worksheet. This methodology aims to optimize the design process of beams and enable the substitution of steel by bamboo, highlighting the validation, from the structural point of view, obtained by the authors.

Keywords

Bamboo, Concrete Beam, Alternative Material

1. Introduction

The employment of non-renewable resources in the construction field results in environmental consequences, contributing to the excessive consumption of energy and substantial material losses. Thus, the construction sector is in an ongoing search for improvement and innovation in their techniques, aiming the utilization of sustainable and alternative materials.

According to [1], in response to the never-ending search for renewable materials, the bamboo is an alternative with physical and mechanical characteristics that ensure its performance as a building material, being a low cost, fast growing and perennial plant.

Reference [2] stated that, due to its heterogeneity, the absence of standardization restricts its utilization on the construction field; even though the great variability of species of bamboo exists on Brazil has low cost, self-sustainability and is extremely easy to handle [3].

Since the 70s, some bamboo species are being studied and analyzed as reinforcement and molds for structural elements [4]. Even though being a sustainable material that has been used in Asia since ancient times, the overall number of researches in this subject is scarce [5]. However, the use of bamboo as beams' reinforcements has received more attention due to the possibility of using the same structural design methods as reinforced concrete [1], making a pre-treatment.

According to [6], bamboo has a fast maturing cycle that could vary from three to five years, depending on local climate and soil. The bamboo's tensile strength accounts for between 50% and 75% of steel, being influenced by its absorption capability [7].

The bamboo's structural performance is impaired due to certain anatomy particularities, presenting low shear strength parallel to the fibers and irregular geometry. Besides that, the lignin present in its composition is a target to xylophagous insects [5]. The bamboo's anatomic constitution (**Figure 1**) is composed by culm and rhizome. The culm can be divided into nodes and internodes, based on its fiber's orientation.

On the internodes, the fibers are axially oriented to the growth direction, diverging from the axis and concentrating on the nodes, which enables the diaphragm formation, giving lateral stability to the culm [8].

In its natural state, being an organic material, bamboo is susceptible to organic decay. Nowadays, there are numerous treatments for bamboo's preservation. The durability of the material is ensured by protection against fungal rot, attack by insects and cracks with wood preservatives [9]. Besides its susceptibility to insect attacks, the treatment could influence on the final material strength and adherence on concrete [4].

The bamboo's largest utilization difficulty as reinforcement is its water absorption rate. When in contact with fresh concrete and during the curing process, the excess of water is absorbed by the bamboo, which swells. After the

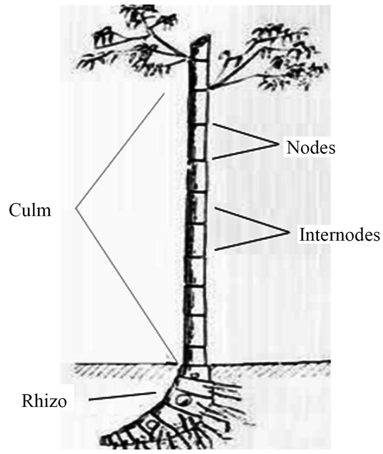

Figure 1. Bamboo's constitution. Source: HIDALGO-LÓPEZ (2003).

curing process, the bamboo loses the water and shrink, impairing the adherence with concrete.

Waterproofing treatments that do not damage the interface between concrete and bamboo, such as Asphalt paints, bituminous materials, and epoxy resins, are commonly used in this type of work [4]. Studies have shown [1] [7] that different treatments have a positive reflex in slippage strength.

According to [10], the performance of bamboo's reinforced beams is like the elastic behavior of regular concrete beams, according to the Bernoulli-Kirchoff bending theory. Studies [1] [11] have promising results on partial and total replacement of steel by bamboo reinforcement on concrete beams.

The ideal quantity of bamboo in a given cross-section varies between 1.25% and 8.33%, depending on various aspects [12]. Reference [13] studied the use of bamboo as shear reinforcement on concrete beams, founding that its behavior is inferior to steel.

In this context, the objective was to adapt a beam design system, using an electronic spreadsheet tool, to include and replace the bending reinforcement for bamboo.

2. Materials and Methods

The proposed design routine in the present study was based in the Brazilian standard [14] and the study realized by [15]. The final spreadsheet elaboration was realized in the Microsoft Office Excel software, including all the necessary equations and adaptations for the correct structural design for bamboo reinforced beams with rectangular section, submitted in a four-point bending moment, as shown in **Figure 2**. The electronic spreadsheet receives the input by the user, processes and gives instantaneous results as output.

2.1. Input Data

The input data are insert according to the project established values, basics for any structural design.

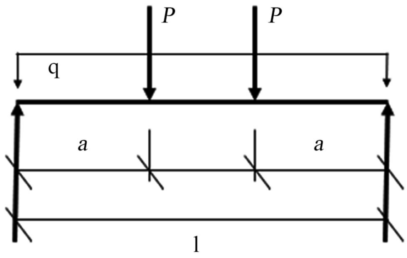

Figure 2. Four-point bending schematics.

2.1.1. Element Dimensions

The cross-section's height (h) and width (b_w), the element's length (l) are necessary measurements. Then, the spreadsheet can determine the loading points (a) and the working height (d), equivalent to the distance between the gravity center of the reinforcement and the compressed edge of the cross-section.

2.1.2. Concrete Types

The concrete used for beams should have a compressive strength of, at least, 15 MPa for non-structural applications. Generally, the compressive strength varies between 25 and 50 MPa for structural concrete in beams.

2.1.3. Steel Characteristics

The steel rebars used as reinforcement for concrete structural elements are classified by its characteristic yield stress (f_{yk}) divided into classes of 250 MPa (CA-25), 500 MPa (CA-50) and 600 MPa (CA-60), categorized by the Brazilian standard [16]. Usually, beams are reinforced with CA-50 steel.

Without any tests or the manufacturer's instructed values, the Young modulus (E_s) is admitted equal to 210 GPa, as stated by the [14].

2.1.4. Bamboo Characteristics

The tensile strength admitted for the bamboo ($\sigma_{\_bamboo}$) should be obtained by experimental tests, due to its variability, linked to species, maturity, and climatic conditions.

2.2. Output Data

The output data are generated based on the input cited on the previous section, by the equations shown in this section, initially obtaining the steel reinforcement area and its correspondent bamboo reinforcement area. **Figure 3(a)** and **Figure 3(b)** shows the cross-section of rectangular beam of conventional reinforced concrete and bamboo reinforced concrete, respectively.

The equations are obtained by constitutive law of materials (Materials Resistance) considering the internal balance of efforts. The external load (bending moment M_d) are balanced with internal binaries, represented by the representative strength of compressed concrete (R_{cc}) and the representative strength of tensile steel (R_{st}), distance to a length (z). **Figure 4** shows the internal equilibrium conditions

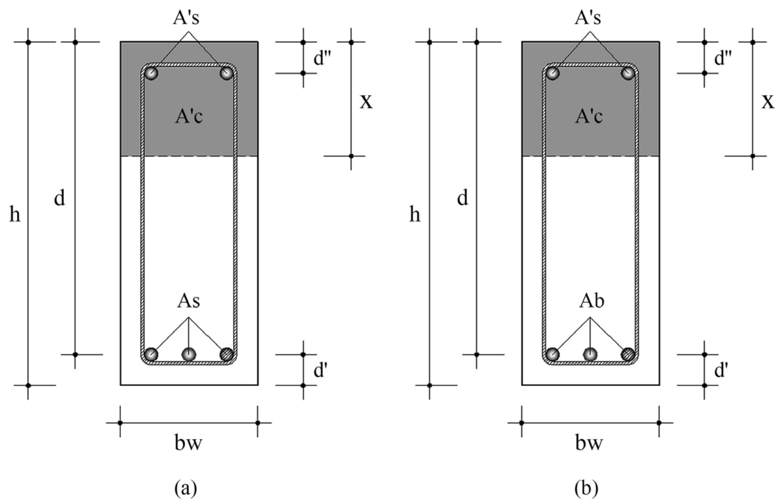

Figure 3. Cross-section of rectangular beam.

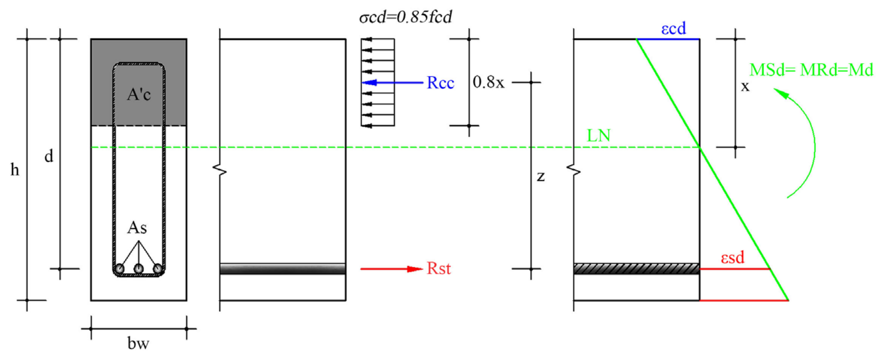

Figure 4. Internal equilibrium conditions.

2.2.1. Neutral Line (LN) Position

The neutral line position (x) was obtained by the Equation (1).

$$x = 1.25 \times d \times \left(1 - \sqrt{1 - \frac{M_d}{0.425 \times b_w \times d^2 \times f_{cd}}}\right) \quad (1)$$

Being:

M_d is the bending moment by a ponderation coefficient (kN.cm);

f_{cd} is Compressive strength (kN/cm^2);

b_w is the cross-section width (cm);

x is the distance between the compressed edge and the point without deformation and stress (cm);

d is the working height (cm).

2.2.2. Representative Strength of Compressed Concrete

The representative strength of compressed concrete (R_{cc}) was obtained by the Equation (2).

$$R_{cc} = 0.68 \times f_{cd} \times b_w \times x \quad (2)$$

Being:

f_{cd} is Compressive strength (kN/cm^2);

b_w is the cross-section width (cm);

x is the distance between the compressed edge and the point without deformation and stress (cm);

R_{cc} is the representative strength of compressed concrete (kN).

2.2.3. Representative Strength of Tensile Steel

The representative strength of tensile steel (R_{st}) was obtained by the Equation (3).

$$R_{st} = A_s \times f_{yk} \tag{3}$$

Being:

f_{yk} is the characteristic yield stress (kN/cm^2);

b_w is the cross-section width (cm);

x is the distance between the compressed edge and the point without deformation and stress (cm);

R_{st} is the representative strength of tensile steel (kN).

2.2.4. Bending Moment

The bending moment (M_d) was obtained by the Equation (4).

$$M_d = 0.68 \times f_{cd} \times b_w \times x \times (d - 0.4x) \tag{4}$$

Being:

M_d is the bending moment by a ponderation coefficient (kN.cm);

f_{cd} is Compressive strength (kN/cm^2);

b_w is the cross-section width (cm);

x is the distance between the compressed edge and the point without deformation and stress (cm);

d is the working height (cm).

2.2.5. Service Bending Moment

The Service bending moment (M_k) can be estimated in the Equation (5), dividing the bending moment by a ponderation coefficient.

$$M_k = \frac{M_d}{\gamma_f} \tag{5}$$

Being:

M_k is the bending moment (kN.cm);

M_d is the bending moment by a ponderation coefficient (kN.cm);

γ_f is the Load ponderation coefficient.

2.2.6. Acting Load

The acting load (P) was determined from the Equation (6) that links the load to the Service bending moment (M_k) and the element distributed weight (q).

$$M_k = P \times a + \frac{q \times l^2}{8} \tag{6}$$

Being:

M_k is the bending moment (kN.cm);

P is the acting load (kN);

a is the distance of acting load (P) from support (cm);

q is the element distributed weight (kN/cm);

l is the element length (cm).

2.2.7. Steel Reinforcement Area

The steel reinforcement area (A_s) was determined without the safety coefficients, according to Equation (7).

$$A_s = M_k / (d - 0.4x) \times f_{yk} \tag{7}$$

Being:

A_s is the steel reinforcement area (cm^2);

M_k is the bending moment (kN.cm);

d is the working height (cm);

x is the distance between the compressed edge and the point without deformation and stress (cm);

f_{yk} is the characteristic yield stress (MPa).

2.2.8. Reinforcement Area Equivalence between Bamboo and Steel

The corresponding bamboo reinforcement area was obtained by the equality of the needed force in the steel to resist the Service bending moment Equation (8) and the force admitted by a given bamboo area in Equation (9). It's very important to observe, the steel area can be partially or total replaced by bamboo. The combination with bamboo and steel could be made carefully, observing the total tensile strength R_{st}. This combination must be respecting the correlation shown in Equation (10).

$$\sigma_{\text{steel}} = F / A_s \tag{8}$$

Being:

σ_{steel} is the mean tensile stress of steel (kN/cm^2);

F = Acting force on the steel reinforcement (kN);

A_s is the steel reinforcement area (cm^2).

$$\sigma_{\text{bamboo}} = F / A_b \tag{9}$$

Being:

σ_{bamboo} is the mean tensile stress of bamboo (kN/cm^2);

F it the acting force on the bamboo reinforcement (kN);

A_b is the equivalent bamboo area (cm^2).

$$\frac{\sigma_{\text{bamboo}} \times A_b + \sigma_{\text{steel}} \times A_s}{R_{st}} \geq 1 \tag{10}$$

Being:

σ_{bamboo} is the mean tensile stress of bamboo (kN/cm^2);

σ_{steel} is the mean tensile stress of steel (kN/cm^2);

A_s is the steel reinforcement area (cm^2).

A_b is the bamboo area (cm^2).

2.2.9. Maximal Vertical Displacement

The vertical displacement ($D_{máx}$) limited by [14], was determined by the Equation (11).

$$D_{\max} = l/250 \tag{11}$$

Being:

$D_{máx}$ is the maximal vertical displacement allowed (cm);

l is the element length (cm).

2.3. Spreadsheet Validation

The validation was made by comparison with [15], adopting the same values utilized by the authors, and comparing the results shown in the spreadsheet and those from the paper.

In this study, the authors prepared 6 beams, three being reinforced with bamboo and the other three being reinforced with steel. The dimensions adopted were: 12 cm × 40 cm (width × height) for the cross-section and a total length of 300 cm, but an admitted length of 290 cm between supports. The concrete compressive strength was adopted as 25 MPa and the steel utilized was classified as CA-50.

The beams were designed to utilize the limit of both materials, disregarding all safety coefficients, facilitating the comparison between the results. The authors, through the use of the equations, determined the reinforcement needed to not get out of the situation of reinforcement failure. Then, the authors determined the equivalent bamboo reinforcement to compare the vertical displacements.

The bamboo's tensile strength was determined by tensile stress test and obtained a final value of 192.20 MPa.

3. Results and Discussion

A design procedure for bamboo reinforced concrete beams with rectangular cross-section was elaborated following based on the schematics presented section 2. The input data is entered in the electronic spreadsheet, highlighted by the blue color in **Table 1**. The spreadsheet systematically determines the output values highlighted in the color green.

As commented previously, all safety coefficients were disregarded, in order to enable comparison with [15]. However, the ponderation coefficients of steel (γ_s = 1.15) and concrete (γ_c = 1.4) can be manually inserted for consideration in the determination process, as stated by [14].

Table 2 shows a comparison between the values obtained by [15] and the values calculated by the electronic spreadsheet with the design procedure, proposed by this work.

A comparative analysis suggests an approximation between the results obtained by this study and those obtained during the study realized by [15], both determining a final area of 5.2 cm^2 of bamboo reinforcement.

Table 1. Electronic design spreadsheet.

Design spreadsheet for Reinforced concrete beams - Rectangular cross-section					
Simple bending					
		Input data		**Output data**	
General data		**Parameters**		**Single reinforcement**	
q (kN/cm)	1.2	P (kN)	31.09	βx (cm)	0.259
Steel	CA-50	Mk (kN.cm)	3131.70	As (cm^2)	3.12
Concrete	C25	Md (kN.cm)	4384.38	Domain	2
f_{yk} (Mpa)	500	fyd (kN/cm^2)	43.48	ρmin	0.0015
f_{ck} (Mpa)	25	fcd (kN/cm^2)	1.786	Asmin (cm^2)	0.74
b_w (cm)	12	d (cm)	36	**Double reinforcement**	
h (cm)	40	βx = 0.45	0.45	fyd' (kN/cm^2)	simple
l (cm)	290	μlim (βx = 0.45)	0.2509	As' (cm^2)	simple
d' (cm)	4	βx (Lim. Domain 2-3)	0.259	As (cm^2)	simple
d'' (cm)	4	μlim (Domain 2-3)	0.158		
a (cm)	96.67	βx (Lim. Domain 3-4)	0.628	**Solution**	
γ_s	1.15	μlim (Domain 3-4)	0.32	Single reinforcement	
γ_c	1.4	Mdlim (βx = 0.45) (kN.cm)	6967.85	As' (cm^2)	simple
γ_f	1.4	Mdlim (Dom. 3-4) (kN.cm)	8886.86	As (cm^2)	simple
E_s (Mpa)	210,000	x (cm)	9.324	As (cm^2)	3.20
Steel - bamboo equivalence					
σ_{steel} (kgf/cm^2)		5000	F (Kgf)	16,000	
σ_{bamboo} (kgf/cm^2)		1922	Ab (cm^2)	**8.32**	
			Dmáx. (cm)	1.16	

Table 2. Result comparison.

Data	Oliveira and Vito (2012) [15]	Design procedure (spreedshet)
M_d (kNcm)	4384.38	4384.38
M_k (kNcm)	3131.70	3131.70
P (kN)	31.09	31.09
A_s (cm^2)	1.94	1.94
F (kgf)	10,000.00	10,000.00
A_b (cm^2)	5.2	5.2

4. Conclusion

Comparison tests validate the electronic spreadsheet's procedure; thus, the design of reinforced concrete beams with rectangular cross-section in a four-point bending load can be realized in an optimized manner, obtaining a steel reinforcement area and an equivalent bamboo reinforcement area. Those results aim to support the diffusion of bamboo as a sustainable building material, capable of serving as reinforcement for concrete beams under bending efforts.

Acknowledgements

To the company Dias & Cardozo Engineering (D&C Engenharia) for partially financing the costs with the publication of this work, a very important private initiative for the promotion of research.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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