XLIII
CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

Nonlinear modeling of a bamboo bio-concrete beam

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Abstract. Concrete is one of the most consumed materials in the world, so it is essential to promote the sustainable development of this material. For this, it is possible to obtain environmental benefits through the substitution of cementitious materials and/or aggregates. Bamboo is a material that has been used in several studies as an aggregate in the production of bio-concrete, through the pressing procedure or conventional techniques for manufacturing concrete. One way to evaluate the quality of this material is by analyzing its mechanical behavior, either by experimental procedures or numerical modeling. The objective of this study is to perform numerical simulations of a bamboo bio-concrete beam imposing different cracking models and tensile laws, and compare the numerical results to the experimental ones collected from the literature. The results indicated that the Rotating cracking model represented better the experimental load versus deflection curve than the Fixed crack model. Furthermore, all tensile laws showed consistent results by varying only their intrinsic characteristic of tensile softening.

Keywords: bio-concrete, mechanical behavior, numerical modeling.

1 Introduction

The use of concrete in civil construction is increasing every year. Therefore, it is very important to promote the sustainable development of this material, since it is also part of the list of materials that cause environmental impacts [1]. Currently, there is a growing concern of the scientific community focused on the production of low carbon concrete. This benefit becomes possible both by the substitution of cementitious materials and aggregates. With emphasis on the replacement of aggregates, it is worth mentioning the use of construction and industrial waste and vegetable biomass [2].

Among the plant materials, bamboo has been conveniently used as a raw material in several industrial sectors. Its use is widespread in the production of construction materials and structural elements [3]. However, there are few studies on bamboo bio-concretes produced without pressing, a procedure that requires significant energy expenditure to mold the material. Thus, a viable alternative consists of production using conventional concrete manufacturing techniques [2].

On the other hand, one way to evaluate the quality of concrete is by analyzing its mechanical behavior, whether performed experimentally or through numerical modeling. In the process of numerical simulation of conventional concrete, most studies are based on the Finite Element Method (FEM), which is one of the most applied computational methods currently in the solution of mechanical problems and representation of the behavior of materials in general [4].

This work aims to perform nonlinear numerical simulations of a bamboo bio-concrete beam subjected to three-point bending, being analyzed using different cracking models and tensile laws, and finally, to compare the numerical results to the experimental tests. For this, it was considered as experimental basis the studies developed by Andreola [2] and the numerical simulations were performed using the software DIANA® version 10.4.

2 Methodology

To verify the mechanical behavior of the bamboo bio-concrete, a numerical model was created using the educational software license DIANA® version 10.4, in order to reproduce an experimental three-point bending test of a beam performed by Andreola [2]. Initially, a calibration of the computational model is performed by varying the finite element dimensions and different cracking models. Next, the influence of increasing the modulus of elasticity is verified, considering the coefficient of variation presented in the experimental tests. Finally, with the refined model, the use of different tensile constitutive laws is simulated.

2.1 Characterization of the bamboo bio-concrete and the experimental beam

The bamboo bio-concrete used in the research is composed of Portland Cement CP V - ARI, bamboo fine aggregate, water and Rheomac UW 410 viscosity modifier additive. It is important to note that the fine aggregate is obtained through a process of crushing, sieving and homogenization.

Figure 1 shows the dimensions, length x width x thickness, used in the preparation of the numerical model, according to all the characteristics of the prototype beam tested in the laboratory by Andreola [2].

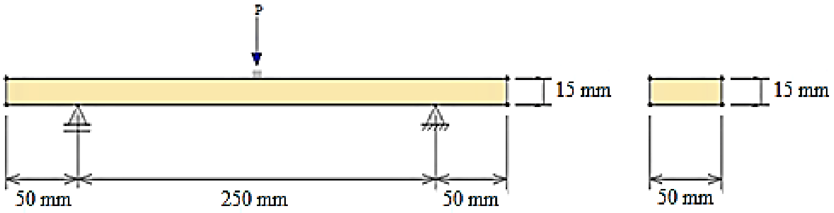


Figure 1. Beam dimensions
Adapted from Andreola [2]

The experimental results of Andreola [2] are used as input data in the software DIANA® version 10.4. Table 1 presents the values of the average modulus of elasticity (E_{cm}), Poisson's ratio (υ), ultimate tensile stress (f_t), ultimate compressive stress (f_c) and tensile fracture energy (G_f) used in the numerical model. The fracture energy is calculated as the area under the tensile test curve (stress - specific strain) multiplied by the length of the specimen.

Table 1. Material properties

E_{cm} (MPa)	υ	f_t (MPa)	f_c (MPa)	G_f (N/mm)
2350.00	0.20	0.72	4.70	0.20

Figures 2 and 3 show the constitutive relationship of bamboo bio-concrete to compression and tensile, respectively, obtained experimentally by Andreola [2].

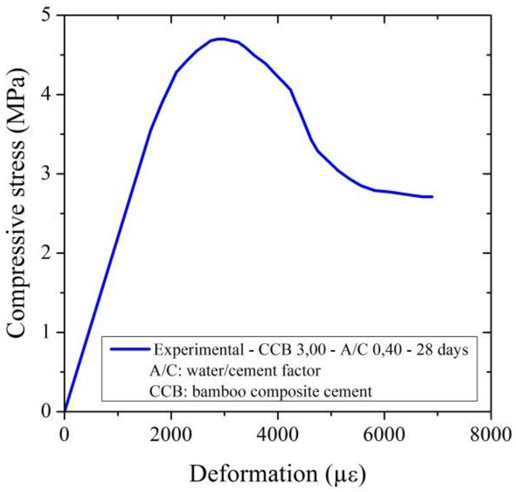


Figure 2. Stress-strain curve Figura
bamboo bio-concrete in compression
Adapted from Andreola [2]

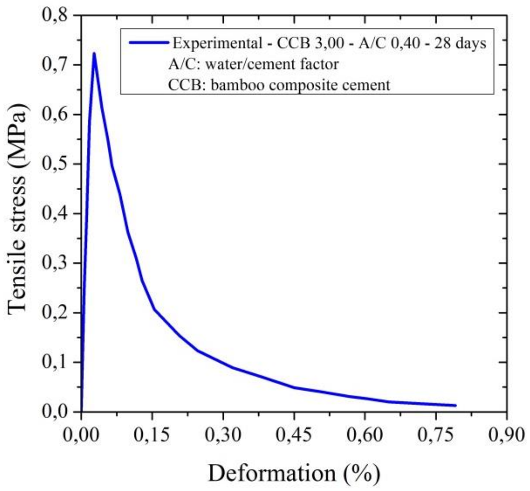


Figure 3. Stress-strain curve Figura
bamboo bio-concrete in tensile
Adapted from Andreola [2]

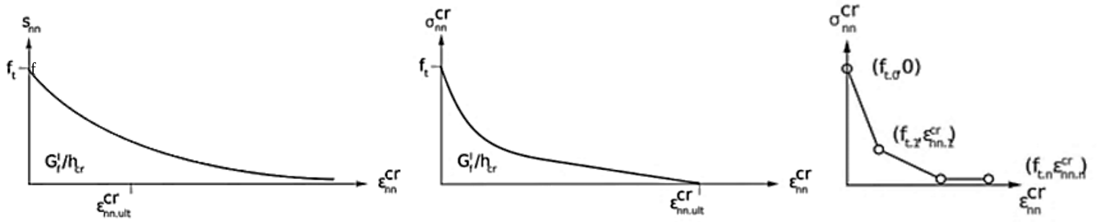
2.2 Numerical model

This topic presents the general aspects of the modeling strategy adopted to analyze the behavior of the bamboo bio-concrete beam subjected to bending. For this purpose, nine numerical models were generated that present the following characteristics in common: geometry, interface elements at the supports, constitutive model of the material in compression, applied loading, boundary conditions, type of finite element, convergence criteria and solution algorithms. The differences between them are due to the different cracking models, finite element dimensions, modulus of elasticity of the material and constitutive models of the material to tensile, using the same G_f and f_t in all of them.

2.3 Material constitutive models

The constitutive model assigned to the concrete was the distributed cracking model of the "Total Deformation" type. In the current numerical simulations the exponential, Hordijk and multilinear tensile softening models were used. And for the compression behavior the ideal model was used.

The exponential and Hordijk models depend on two parameters: the tensile strength (f_t) and the Mode I fracture energy (G_f^I). Moreover, they are based on energy criteria, in which the area of the graph is equal to the ratio G_f^I/h (energy required to open a crack in tensile), where h is the crack bandwidth. These two models are similar in that they are both based on exponential equations. The multilinear model is composed of multiple points that are entered as input data into the program by the user and can be based on experimental tests. This fact makes it possible to have a better fit of the numerical curve to the experimental response [5]. The models are illustrated in Fig. 4 a-c and Fig. 5.



a) Exponential b) Hordijk c) Multilinear

Figure 4. Tensile softening models
DIANA® theory manual [6]

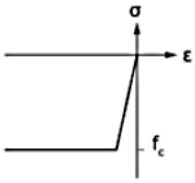


Figure 5. Optimal stress-strain relationship for concrete in compression
DIANA® theory manual [6]

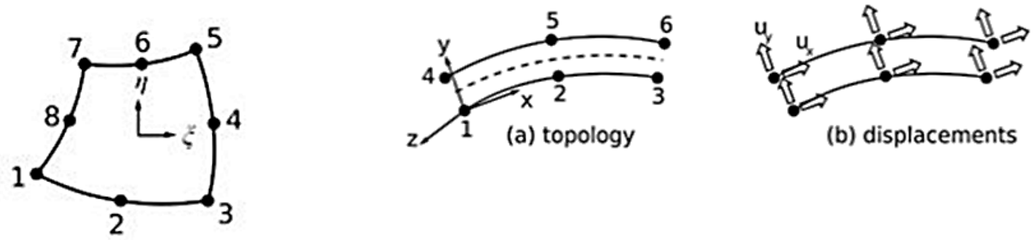
2.4 Boundary condition

In all computational models steel plates were added, with isotropic linear elastic properties, simulating the supports and the load application point, to avoid stress concentrations. On the right support, restrictions were added to translations in the x and y directions, and on the left support, translations in the y direction were prevented. Interface elements were also applied between the steel plate and bamboo bio-concrete, with linear elastic properties, so that it is possible to transmit orthogonal forces and make the forces parallel to the contact surface negligible.

The loading was applied as a prescribed displacement, and a total displacement of 2.35 mm was imposed on all nodes on the top face of the volume intended for loading. In all models the vertical displacement was applied in 1000 increments of 0.001 mm.

2.5 Finite elements and meshes

The bamboo bio-concrete and steel plates, the supports, were discretized into isoparametric elements CQ16M (Fig. 6-a) formed by eight nodes. To represent the interface between the steel plate and the bamboo frame, we used the CL12I element (Fig. 6-b), which consists of a two-layer interface, each with three nodes. Both elements use quadratic approximation function of their displacements and are part of the element library of DIANA® software version 10.4.



a) Finite element CQ16M b) Finite element CL12I

Figure 6. Finite elements used for modeling
DIANA® theory manual [6]

For the numerical evaluation of the bamboo bio-concrete, meshes with dimensions from 0.625 to 2.5 mm are used. It was decided to vary the mesh size by considering 0.3125 mm. However, due to the limitation of the student license of the software DIANA® version 10.4, regarding the number of elements and nodes, it was impossible to halve the mesh of 0.625 mm, being the last one used.

2.6 Crack Models

When a concrete element is subjected to bending that exceeds the value of the material limit stress, cracking occurs. To represent the behavior regarding distributed cracking, the software DIANA® version 10.4 presents the Fixed and Rotating models.

In the Rotating model stress-strain relationships are verified in the principal directions of the strain vector. This approach allows the orientation of the cracks to co-rotate with the principal strain axes, so that the crack direction coincides with the principal strain direction. It is worth noting that, in this case, shear transfer does not play a relevant role, excluding the need to specify a retention factor. On the other hand, in the Fixed model the stress-strain relationships are evaluated according to a fixed coordinate system, preserving the initial crack orientation in the following stages. Also, the principal stress vector does not coincide with the principal strain vector. And the material's behavior regarding shear is considered [7].

2.7 Solution method and convergence criteria

The system of equations generated by DIANA® version 10.4 was solved by the Secant (Quasi-Newton) equation solving method. The analyses were performed with displacement control, and the convergence criterion was satisfied when the energy norm reached values less than or equal to the 0.01% tolerance.

3 Results and discussions

3.1 Calibration of results

With possession of all the material data, present in Tab. 1, and using the exponential tensile law, the first analysis is performed varying the cracking models and making use of the meshes described in item 2.5. Figures 7 and 8 present the results. It can be seen that the results of the numerical models employing the Rotating cracking criterion are closer to the experimental result than the results of the models using Fixed, with shear retention factor 0.01, due to its fast approximation with the peak force and a convergence in the final stretch of the softening regime. Furthermore, a lesser influence is noted with mesh refinement using the Rotating cracking model, since, the force versus displacement curves with 1.25 and 0.625 mm meshes show a similar behavior in the softening regime. The results in Figure 7 strengthen the importance of providing an adequate finite-element mesh. A poor mesh (2.5 mm size) has affected not only the peak load obtained but also the softening response. By reducing the element size four times, (0.625 mm) the result approximates to the experimental response.

Therefore, the Rotating crack model and a mesh with 0.625 mm elements are adopted for the subsequent models. Furthermore, it is observed that the numerical models present lower stiffness in the linear phase compared to the experimental one, which implies a higher peak displacement.

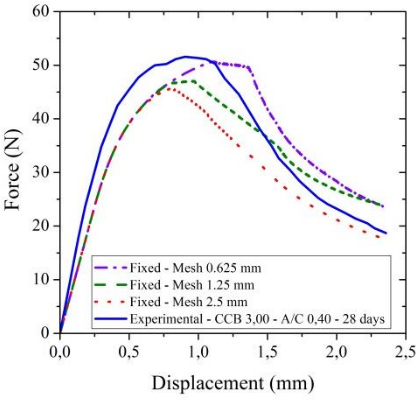


Figure 7. Force versus displacement curves using the Fixed cracking model

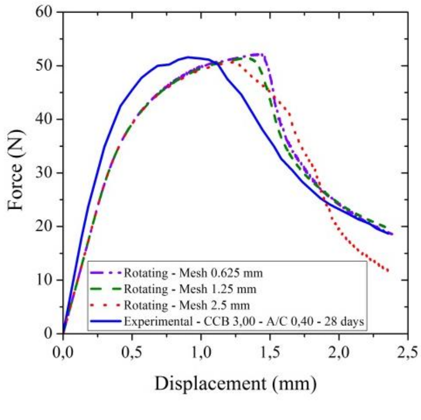


Figure 8. Force versus displacement curves using the Rotating cracking model

As there was a difference in stiffness of the numerical solution compared to the experimental one in the linear section, a new analysis is performed by changing the modulus of elasticity of the material. According to Andreola [2], the average value of the modulus of elasticity to compression, presented in Tab. 1, has a coefficient of variation of 2.9%. Thus, to avoid an arbitrary choice, a new analysis is performed using 2760 MPa, the value of the modulus of elasticity to bending, obtained experimentally by Andreola [2]. Figure 9 presents the new results.

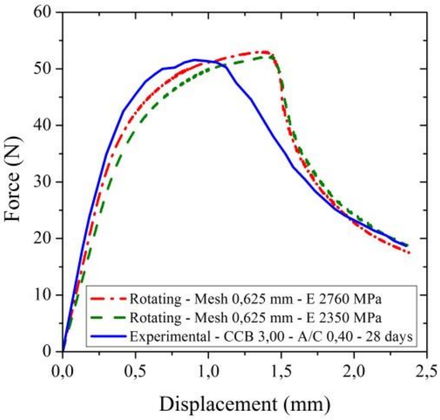


Figure 9. Force versus displacement curves using the Rotating cracking model with different modulus of elasticity

Therefore, the numerical model obtained results that are closer to the linear section of the curve with increasing modulus of elasticity. Furthermore, it is verified that between displacements of 1.7 and 2.5 mm there was a convergence between the numerical and experimental responses.

3.2 Influence of the tensile constitutive laws

Next, it is evaluated which of the tensile laws (exponential, Hordijk and multilinear) represents better the behavior of the material law, obtained experimentally. To elaborate the multilinear law, the experimental tensile curve was considered as a base, adopting points that overlap the experimental trajectory and calibrating in order to have the same fracture energy of the exponential and Hordijk models. It is presented in Fig. 10 the tensile stress versus crack width curve of the models used and in Fig. 11 the numerical load-displacement results of the simply supported beam are presented.

Comparing the numerical and experimental results it is noted that using the exponential tensile law results in a higher peak load deflection than the other models, but a better convergence of the results in the softening regime in the section from 1.7 to 2.35 mm. On the other hand, the Hordijk and multilinear laws present a peak load displacement closer to the experimental result, however, a lower stiffness in the softening section.

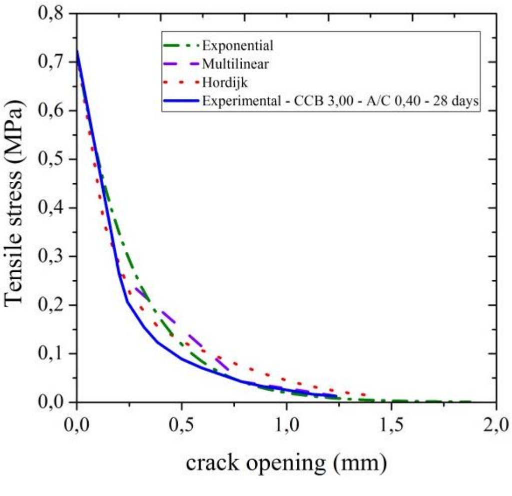


Figure 10. Tensile stress versus crack opening curves of the numerical models

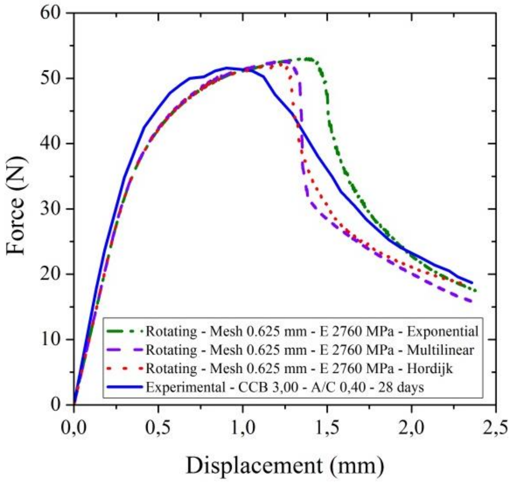


Figure 11. Force versus displacement curves with Rotating crack model and different tensile laws

4 Conclusions

With emphasis on the results obtained, it was verified that the Rotating cracking model presented a better behavior of the numerical curve compared to the experimental one, especially in the softening regime where it presented a good convergence of the results and less influence with mesh refinement, than in the case of cracking under the Fixed criterion. Moreover, as the value of the modulus of elasticity was increased considering its variation of 2.9%, a better approximation of the numerical result to the experimental one is noticed in the linear and beginning of the non-linear section of the curve, before the peak force. Finally, analyzing the exponential, Hordijk and multilinear tensile laws, all presented satisfactory numerical results, where the maximum error of the peak load, compared to the experimental, was 2.8%, this value observed with the use of the exponential law, and each one with its own particularities of behavior regarding the softening of the material.

Acknowledgements. The authors are partially supported by the Brazilian funding agencies CNPq, and FAPERJ. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior — Brasil (CAPES) — Finance Code 001.

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