Applicability of inverse analysis to obtain the tensile behavior of bamboo bioconcretes

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Abstract. In view of the difficulties in obtaining tensile laws in the experimental field, it is of the utmost importance to adopt alternative tools to overcome this problem. Thus, this work is a brief manual for obtaining tensile laws using numerical modeling, which describes the steps for obtaining them, from defining the fixed parameters of the numerical model to characterizing the material's tensile mechanical behavior. The DIANA® software was used to run the numerical simulations, and the numerical model calibration was based on average results of experimental curves. The target material for this study is a new bamboo bioconcretes developed by researchers at COPPE/UFRJ. The results show that the tensile laws developed through inverse analysis using numerical modeling are highly accurate compared to experimental responses, and that the calibration of the numerical model makes a significant contribution to the quality of the results.

Keywords: tensile behavior, inverse analysis, numerical modeling.

1 Introduction

With its many structural applications, concrete is one of the most important materials in the construction sector. In this respect, advances in its understanding and the adoption of new technologies aimed at predicting its mechanical behaviour are indispensable. The concrete tensile strength test is one of the main mechanical tests in its hardened state. However, despite its importance, it is commonly avoided by researchers, as it can be influenced by a number of variables such as the way the grips are attached, the concentration of stresses, the lack of load alignment and flaws in the specimens [1].

To overcome this difficulty, inverse analysis also known as retroanalysis is a powerful tool. Through it, it is possible to obtain the material's tensile stress-strain curve using the results of other experimental tests that are simpler to perform, for example the bending test on prismatic specimens [1].

During the experimental programme developed by Andreola [2], the mechanical behaviour of bamboo bioconcrete was assessed. This new material was produced with different mixtures varying the water/cement ratio (W/C) and bamboo cement composite (BCC). However, due to the difficulties faced in carrying out direct tensile tests, mentioned above, the author obtained a small number of results to characterise this new material.

In view of this, it is of the utmost importance to also determine the tensile constitutive laws of these bamboo bioconcretes by means of numerical modelling and inverse analysis techniques, in order to contribute to the predictability and reliability of the results, and also to have the security to define the application of the material.

In view of the above, this article aims to briefly describe the procedures required to obtain tensile constitutive laws using numerical modelling and inverse analysis techniques, to determine the tensile constitutive laws of bamboo bioconcrete, and finally to compare them with experimental results.

2 Procedures for obtaining the constitutive law of tensile by inverse analysis

Considering the possibilities of inverse analysis procedures mentioned by Andrade [1], this work chooses a manual technique, by trial and error, with the use of a numerical method, by simulating a computer model. The step-by-step process is described below.

Firstly, the numerical model of the bending test is created, reproducing the characteristics of the experimental geometry. Next, it is assigned the known mechanical properties of the material and the parameter to be obtained, the tensile law, is estimated. The calculation is then processed to obtain the numerical result. The experimental bending curve is then compared with the result of the numerical model's bending curve. After this, it is checked whether the error between the curves is within the established limits, and it is also analysed whether the behaviour between them is in good agreement. If the error is within the expected limit, the constitutive law of the material in tension is obtained from the law assigned to the numerical model, otherwise another attempt is made to estimate a new tensile law for the model.

Figure 1 shows the aforementioned procedure in schematic form.

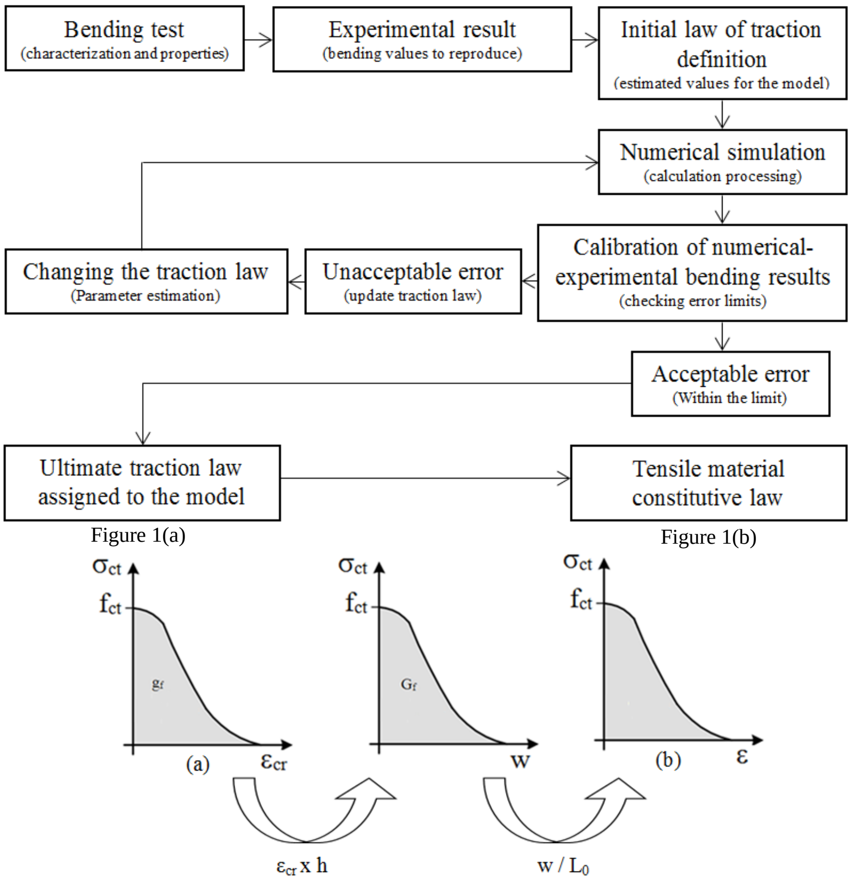


Figure 1. Process of drawing up a tensile law by inverse analysis

2.1 Stopping criteria for inverse analysis simulations

When carrying out numerical simulations, each assignment of input values to the model generates new responses, which can vary considerably, making it necessary to assign stopping criteria. In order to define the numerical bending curve that best fits the average experimental curve for each test considered, the following propositions are observed and compared: existence of overlap in the elastic linear section, maximum tolerance of 3% for the ratio between peak forces and 5% for the ratio between the areas measured below the force versus displacement curve. The criteria and values adopted are based on the works by Araujo et al. [3] and Barros et al. [4]. Figure 2 illustrates the procedure for choosing the most appropriate numerical curve to the experimental one.

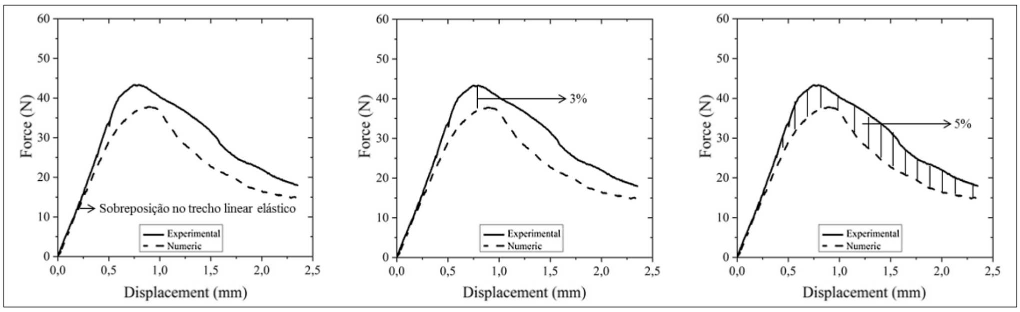


Figure 2. Stopping criteria adopted for inverse analysis simulations

3 Material characterisation

Bamboo bioconcrete consists of cement paste, bamboo particles and a viscosity modifying additive. For the bamboo to reach the dimensions it is used for, crushing and sieving processes are required. The final characterisation of the bamboo particles is shown in Figures 3(a)-(b). These materials are part of the master's thesis developed by Andreola [2].

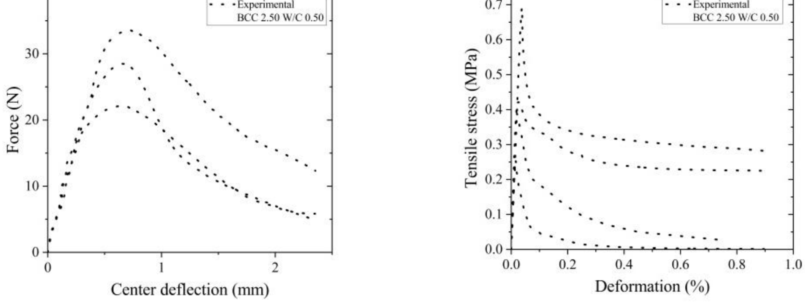
(a) (b)

Figure 3. Bamboo particles used in the composition of bioconcrete: (a) particles retained on the #1.18 mm sieve; (b) fine particles passing the #1.18 mm sieve. Adapted from Andreola [2]

3.1 Experimental results

3.2 Three-point bending strength and direct tensile strength

Looking at Figure 4(a), it can be seen that after the peak load there was no sudden rupture of the material, but rather post-cracking behaviour with a gradual reduction in load and increase in deformation. In this way, the bamboo particles acted as reinforcement and crack control. On the other hand, looking at Figure 4(b), it can be seen that there was linear elastic behaviour until the peak stress was reached, followed by a sharp deformation. The characteristics of the behaviour observed were that of ductile materials, in which the bamboo particles acted as reinforcement and also prolonged the deformations in the direct tensile strength.



(a) (b)

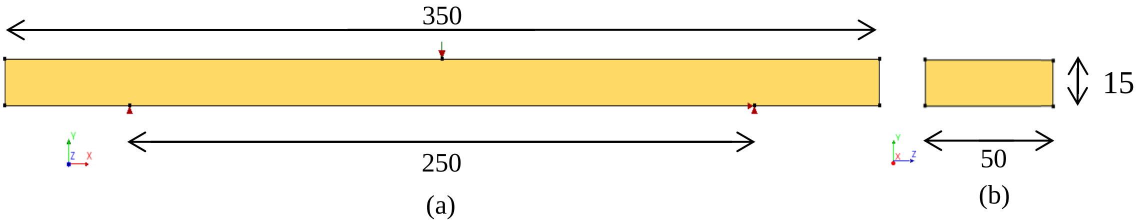
Figure 4. Experimental curve ranges of BCC 2.50 W/C 0.50 bamboo bioconcrete: (a) three-point bending; (b) direct tension test. Adapted from Andreola [2]

4 Numerical modelling

DIANA® software, which is based on the Finite Element Method (FEM), was chosen to carry out the numerical simulations. This computer code offers an extensive library of constitutive models for concrete, cracking models and finite element types.

4.1 Geometry and boundary conditions of the numerical model

Figure 5 shows the geometry of the numerical model and the boundary conditions adopted to reproduce the experimental bending test, carried out by Andreola [2]. On the right support, a restriction on translations in the x and y directions was added, and on the left translations in the y direction were prevented. The load was applied in the form of a prescribed displacement, with a total displacement of 2.35 mm being imposed. This value was applied in 1000 increments of 0.001.



Unit: mm

Figure 5. Numerical model: (a) geometry details; (b) cross section

4.2 Finite elements and meshes

The geometry of the numerical model, a bamboo bioconcrete prism, is discretised by plane isoparametric quadrilateral elements, called CQ16M, shown in Figure 6. This element is made up of eight nodes and uses a quadratic approximation function for its displacement field, using a reduced integration scheme with 2×2 Gauss points.

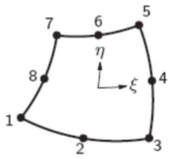
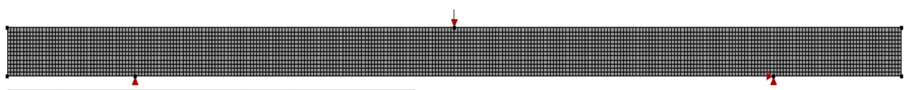


Figure 6. Finite element type CQ16M [5]

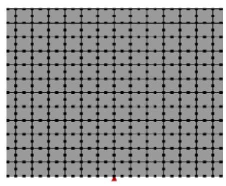
In studies carried out by Andrade [6], using the same numerical model as this research, it was found, through a mesh convergence analysis, that the 1.25 mm dimension led to the best results, both in terms of reproducing the mechanical behaviour and in terms of computational cost. Therefore, this dimension is used in all the numerical simulations in this work.

The magnification shown in Figure 7(b), shows a good regularity in the distribution of the mesh, without the presence of adaptive elements. This behaviour continues throughout the numerical model.



Solid elements	Interface elements	Vertical elements	Nodes
3360	-	12	10665

(a)



(b)

Figure 7. Numerical model: (a) mesh detailing; (b) magnification of a section of the geometry

4.3 Mechanical properties of the material and modelling parameters

Table 1 summarises all the necessary material information and modelling parameters to characterise the bamboo bioconcrete numerical model.

Table 1. Mechanical properties of bamboo bioconcrete and complementary modelling parameters

	Bamboo bioconcrete
	BCC 2.50 W/C 0.50
Linear material properties	
Modulus of elasticity (MPa)	1667
Poisson's ratio	0.2
Mass density (T/mm³)	2.4×10^{-9}
Total strain based crack model	
Crack orientation	Fixed
Tensile behavior	
Tensile curve	Multilinear*
Poisson's ratio reduction model	Damage based
Compressive behavior	
Compression curve	Ideal
Compressive strength (MPa)	2.25
Shear behavior	
Shear retention function	Constant
Shear retention	0.01

*Multilinear: tensile stress versus total strain curve assigned by the user in the numerical analysis.

4.4 Equation solution method and convergence criteria

The system of equations generated by DIANA®, version 10.4, was solved using the Modified Newton-Raphson equation solving method. The analyses were carried out with displacement control, and the convergence criterion was met when the energy norm reached values less than or equal to a tolerance of 10^{-4}.

5 Results and discussions

5.1 Determination of tensile constitutive law of bamboo bioconcrete BCC 2.50 W/C 0.50

To determine the tensile constitutive law of the bamboo bioconcrete BCC 2.50 W/C 0.50 by inverse analysis, the points that make up the final multilinear tensile diagram shown in Table 2 are applied to the material properties of the numerical model and graphically represented in Figure 8.

Table 2. Points on the final tensile diagram of bamboo bioconcrete BCC 2.50 W/C 0.50

Pontos	ε (%)	σ (MPa)
1	0.00000	0.0000
2	0.02579	0.4300
3	9.25000	0.2950
4	17.00000	0.2200
5	28.00000	0.1500
6	42.00000	0.0800
7	67.00000	0.0400
8	130.00000	0.0005
h = 1.25 mm		

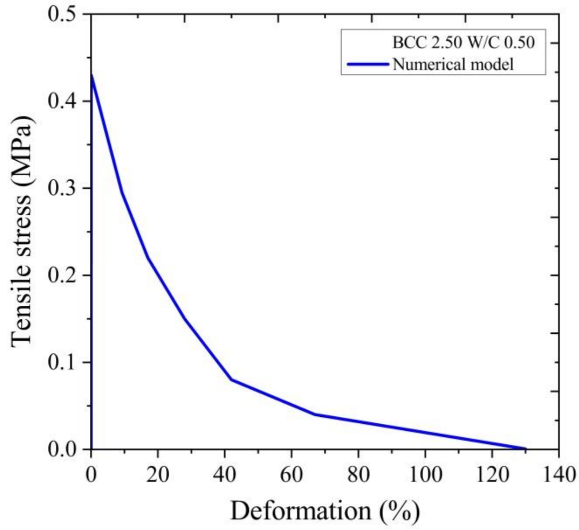


Figure 8. Graphical representation of the final tensile multilinear diagram BCC 2.50 W/C 0.50

With all the material data in Tables 1 and 2, the calculation of the numerical bending model is processed.

The numerical result together with the average experimental curve and the experimental curves are shown in Figure 9. Analysis of the result shows that the numerical curve compared to the average experimental curve shows overlapping behaviour in the linear elastic section and the start of the non-linear section, before the peak force. The peak force shows a slight difference, with a relative error of 2.3%. In the softening regime the curves also overlap throughout the entire section. The area ratio under the curves shows a relative error of 0.08%. All the behaviour and error values are in accordance with the simulation stop criteria, which means that the multilinear tensile law assigned to the numerical model is capable of successfully reproducing the tensile behaviour of BCC 2.50 W/C 0.50 bamboo bioconcrete.

Once we have the multilinear tensile law that best fits the numerical curve to the average experimental curve, we find the tensile softening law for the material σ(w). This is done by multiplying the crack deformation values (ε_{cr}) by the bandwidth (h). Figure 10 shows the result.

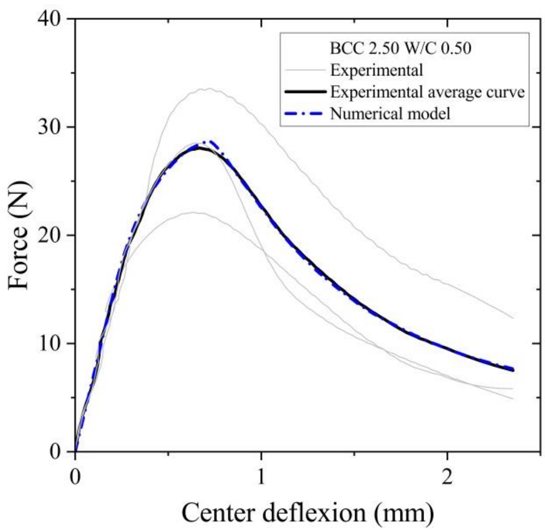


Figure 9. Force versus displacement curves BCC 2.50 W/C 0.50

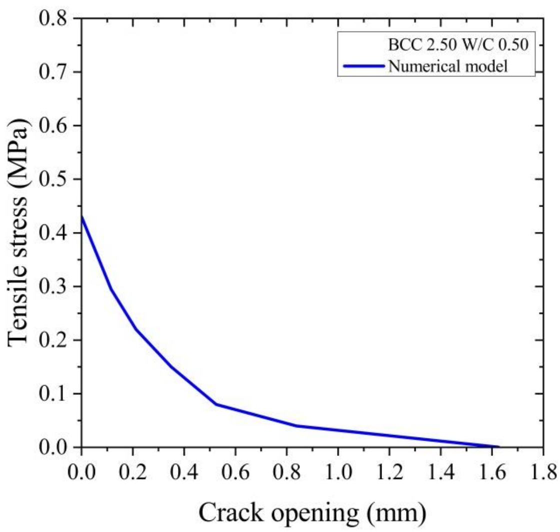


Figure 10. Tensile stress versus crack opening curve BCC 2.50 W/C 0.50

Knowing the law σ(w) and the initial length (L_0) of the tensile test specimen, which is 200 mm, the numerical tensile law of the BCC 2.50 W/C 0.50 bamboo bioconcrete is found by, dividing the crack opening values (w) by L_0. This law is shown in Figure 11.

Comparing the numerical tensile curve to the experimental curves shows excellent conformity, with the numerical curve falling within the experimental range throughout its behaviour, both linear and non-linear. The difference between the average peak stress of the experimental tensile laws, which has a coefficient of variation of 42%, and the peak stress value of the numerical tensile law results in a relative error of 2%. This shows that the numerical method produced satisfactory results.

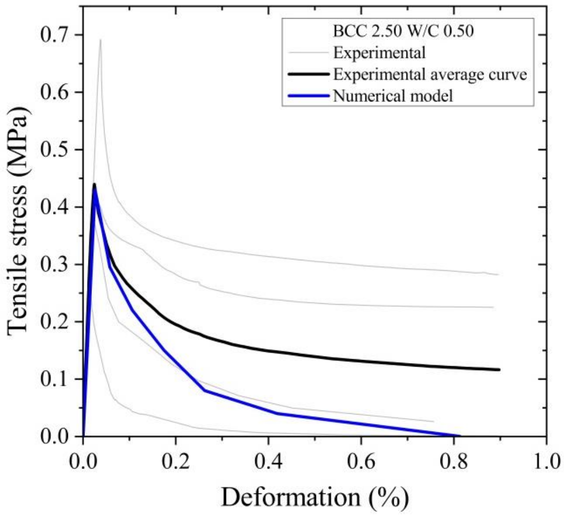


Figure 11. Tensile curves BCC 2.50 W/C 0.50

6 Conclusions

This article reports on a brief manual of inverse analysis for obtaining tensile laws. It proved capable of characterising materials with great precision, since the results of the tensile laws found using the numerical model are close to the experimental values, with good representation of the behaviour along the entire curve.

Despite the small range of experimental bending results, the calibration of the numerical model curve based on the average experimental curve made a significant contribution to the success of the results.

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