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Characterization of Constitutive Response of Natural Fibers Reinforced Concrete under Flexural Loading

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Abstract

Concrete is strong in compression and weak in tension, which results in a low toughness and ductility in plain concrete members under flexure. The traditional solution is to use steel reinforcement bars, but other solutions can include the use of distributed fibers in the concrete mix. To transition to a bio-based circular economy, natural fibers such as abaca and coconut are currently being explored. Proper design requires understanding their tensile behavior under flexural loading. Experiments on concrete prisms with natural fibers under third-point loading have been carried out. These are compared and fitted with an analytical moment-curvature response incorporating a quad-linear tension model, enabling strain compatibility analysis for structural design. While experiments on larger scale and on reinforced concrete members have not been carried out yet, the current results provide a foundation for the analytical modelling of members with natural fibers in bending.

Keywords: analytical model; circular economy; constitutive model; experiments; natural fibers; sectional analysis; quad-linear model; tensile strength; toughness.

1 Introduction

The significant disparity between the high compressive strength and brittleness of concrete in tension, leads to the characteristic low toughness of flexural concrete members due to their low tensile response. From a sustainability point of view, a large volume of concrete in tension is not used and instead a significant amount of steel rebar is used to carry the tensile forces. Traditional use of

fiber reinforced concrete improves the strength and ductility of concrete. However, recent results have shown that by hybrid use of rebars and fibers, significant contribution of fibers in the service load levels is undeniable and can significantly improve the overall flexural ductility and strength of structural concrete.

To achieve a bio-based circular economy, natural fibers are currently explored as an alternative [1]. Proper design of natural fibers concrete for

applications in structural calculations requires proper knowledge of their contribution under tension and compression as required in any flexural loading.

2 Model for fiber reinforced concrete

2.1 Sectional model

To simulate the full flexural response of fiber reinforced concrete (FRC) with any property or dosage, a cracked-hinge based moment-curvature model is used, which is applicable for inverse analysis for characterizing the constitutive stress-strain model of FRC. The models as shown in Figure 1 comprise of parameterized tension and compression models normalized with the elastic modulus (E) and the cracking strain (ε_{cr}).
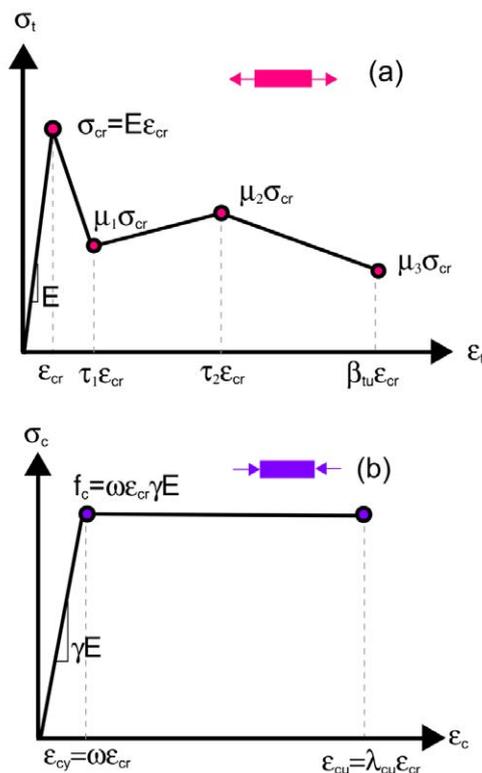

Figure 1 Parametrized constitutive material models for FRC (a) Quad-linear Tension Model (b) Bilinear Compression Model

At each strain increment in the tension zone, equilibrium through strain compatibility is satisfied and the neutral axis is solved with a closed-form equation for all possible stages of stress

distribution along the depth. The parametric approach enables development of dimensionless closed-from equations for the entire moment-curvature response which can be scaled for any rectangular section.

This method was first developed by Soranakom and Mobasher [2]. The theory and validation of this approach has been provided in the referenced work including the algorithm for converting moment-curvature to load-deflection.

The tensile properties of the concrete matrix dominate the flexural performance in FRC. The quad-linear tension model first proposed in [3] allows for much more precise control for simulating the flexural response of the beams enabling improved inverse analysis of the material properties.

2.2 Applications

The proposed analytical model is applicable for design as well as inverse analysis. The procedure for inverse analysis requires sequential fitting of the experimental load-deflection data with the simulated response. This curve fitting approach requires input model parameters that could idealize the materials' response and its parameters. This approach does not depend on any empirical conversion factors but rather provides the exact response that would fit the experimental data minimizing any error in characterization of the material models.

The variable parameters in the proposed model enable it to accurately fit any flexural experimental data of FRC. This approach is particularly beneficial for natural fibers, which are not laboratory-synthesized and whose properties are challenging to characterize. By extracting material properties directly from flexural performance within the matrix, the method ensures reliable calibration. Furthermore, the procedure is capable of accommodating combinations of different fiber types and their collective material response. The extracted material models can then be effectively applied to the design and simulation of hybrid beams incorporating both rebars and fibers, facilitating more precise and optimized designs.

3   Experiments

3.1   Introduction to experiments

To apply the model to natural fibers, first experimental results are obtained using coconut fibers and abaca fibers, including a set of experiments with polypropylene fibers as the control [4]. To extend the model developed for steel fiber reinforced concrete, experiments in third-point bending are carried out [5]. In addition, to quantify the properties of the natural fiber materials, tensile tests are carried out on the fibers.

3.2   Natural fiber properties

For the control specimens, a polypropylene fiber TUF-Strand-SF from Euclid® [6] was used with l_f = 50 mm, and E = 9.5 GPa.

The abaca fibers used in these experiments are obtained from the Santo Domingo de los Tsachilas province in Ecuador. The purchased fibers have a length ranging from 1.5 m to 2 m; these were then cut a length, l_f = 100 mm, for the considered concrete mixes. A longer natural fiber length was considered in comparison to the control polypropylene fibers ($l_{f(natural\ fiber)}$ = 100 mm vs. $l_{f(polypropelene)}$ = 50 mm) to maximize strain energy in the sample [7]. The diameter of the abaca fibers is relatively small (Ø = 0.2 mm) as compared to the control fibers. As a result, the aspect ratio ($L/Ø$) of the abaca fibers is 500.

The mechanical properties were determined in a uniaxial tension using a loading rate of 0.5 mm/min. The displacement was measured in the clamps and not on the fiber. Figure 2 shows the stress-strain diagram results for the abaca fiber. The average mechanical properties of abaca fibers are: maximum axial strain of 0.05, and elastic modulus of 15.3 GPa (standard deviation = 6 GPa). A large scatter on the results for the elastic modulus (8 GPa - 26 GPa) is observed, as expected for an organic material.

The coconut fibers for this study were obtained from the coastal area of Ecuador (province of Manabi) and had lengths that between 100 and 150 mm, as such, the fibers were not cut further. The diameter of the coconut fibers is small (Ø =

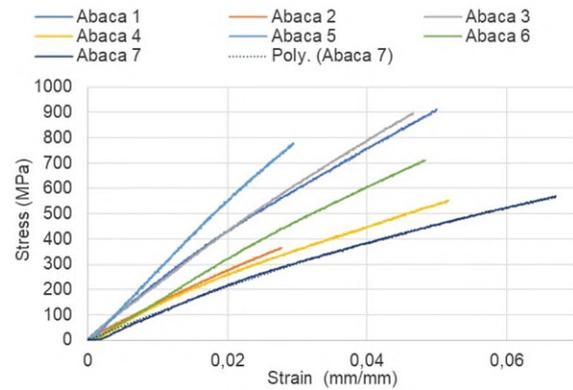0.18 mm), so that the aspect ratio ($L/Ø$) of the coconut fibers is 555.

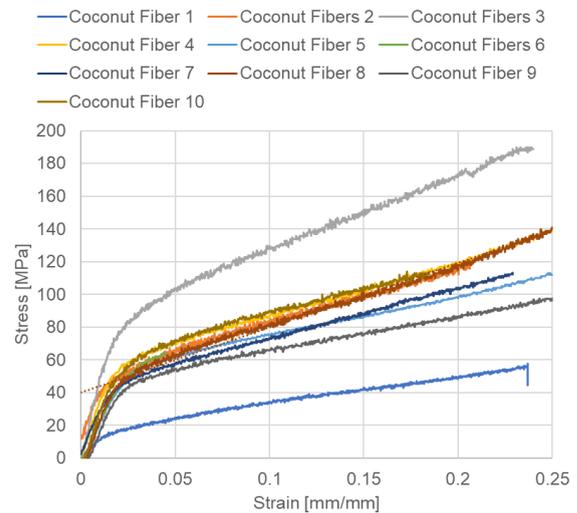Figure 2. Test results of 7 abaca specimens, L=100mm.

Figure 3. Test results of coconut fibers

Figure 3 shows the stress-strain diagrams obtained based on the uniaxial tension tests. The mechanical properties of the Manabi province coconut fibers are: maximum approximate axial strain of 0.22, and elastic modulus of 5.8 GPa with a standard deviation of 1 GPa. The tensile behavior of the coconut fibers is nonlinear, and shows a large scatter on the properties as well.

3.3   Description of series of experiments

The series of experiments includes the determination of the concrete compressive strength, the concrete tensile strength, and the dynamic modulus.

Of interest to this article is the determination of the concrete tensile strength. In total, 18 concrete prisms of size 152 mm (b), 152 mm (h) and clear span of 456 mm (L), divided in 6 sets with three specimens each were tested in a displacement-controlled manner using a third-point loading method [5] to determine the splitting tensile strength, post-peak behavior, deformation energy, and toughness of specimens. The 6 sets result from the following variables: fiber type (abaca, coconut, polypropylene) and aggregate type (normal, recycled). Of interest to this article are the tensile tests on specimens with the different fiber types and normal aggregates.

3.4   Load-displacement response

Figure 4 shows the load-displacement diagram for control aggregate series with polypropylene, abaca, and coconut fibers. The first observation is that all mixes show post-peak behavior to a certain extent, with only two prisms of control aggregates and coconut fibers not being able to reach a displacement of 3.5 mm.

The second observation is that while the post-peak load in all mixes with polypropylene fibers remains roughly constant, we can observe a gradual decrease in the mixes with abaca fibers after the peak. The post-peak strength of the mixes with coconut fibers is markedly lower than the post-peak strength of the mixes with polypropylene fibers, and the displacement post-peak in these mixes is smaller as well.

Table 1 summarizes the mechanical properties obtained from the tested concrete mixes: f_{cm} the concrete compressive strength (for reference), f_p the peak stress obtained in the third-point loading flexural test, and f^D_{600} the residual stress at $l/600$, with l the specimen length. For the experiments for which not all specimens reached performance criteria (coconut fibers), the standard deviation is not reported.
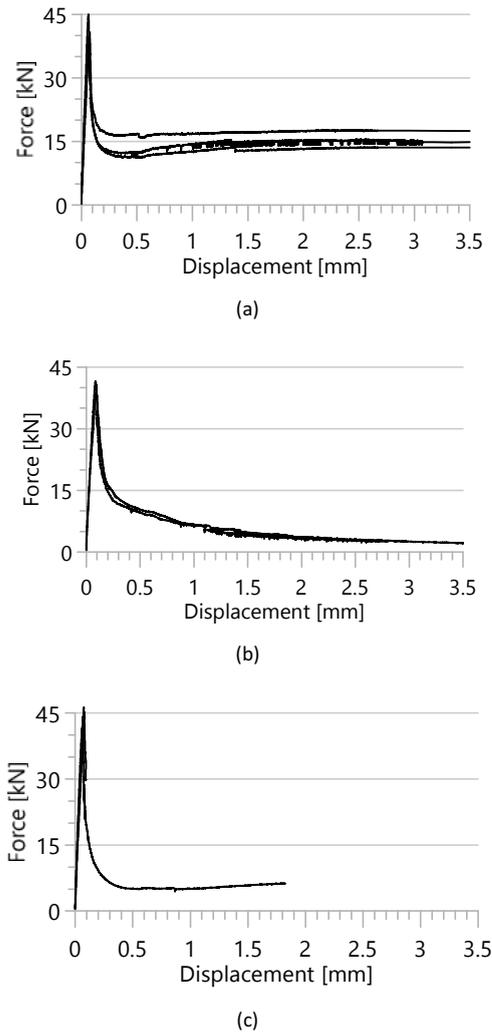

Figure 4. Load-displacement results for:(a) Control aggregate + polypropylene fibers; (b) Control aggregate + abaca fibers; (c) Control aggregate + coconut fibers.

Table 1. Summary of mechanical properties of tested mixes

Mix	f_{cm} [MPa]		f_p [MPa]		f^D_{600} [MPa]	
	AVG	STD	AVG	STD	AVG	STD
C + PPF	22.7	3.3	5.25	0.35	1.8	0.27
C + AF	22.5	0.6	5.05	0.23	0.91	0.03
C + CCF	28.1	3	5.29	-	0.65	-

C=Control,   PPF=Polypropylene fiber,   AF=Abaca fiber, CCF=Coconut fiber, AVG = Average, STD = Standard Deviation

4 Quad-linear model for natural fiber concrete

4.1 Methodology

An inverse analysis procedure was conducted to calibrate the values of the parameters defining the quad-linear stress-crack opening rule outlined in the previous subsections. The calibration procedure was performed starting from the data of each Natural Fibers Reinforced Concrete under flexural loading. Particularly, the best fit was calibrated for the load–deflection curves across intervals of 0.0 < deflection < 4.0 mm.

Table 2 reports, for each mixture, the adopted values of the quad-linear stress-strain model obtained from the inverse analysis.
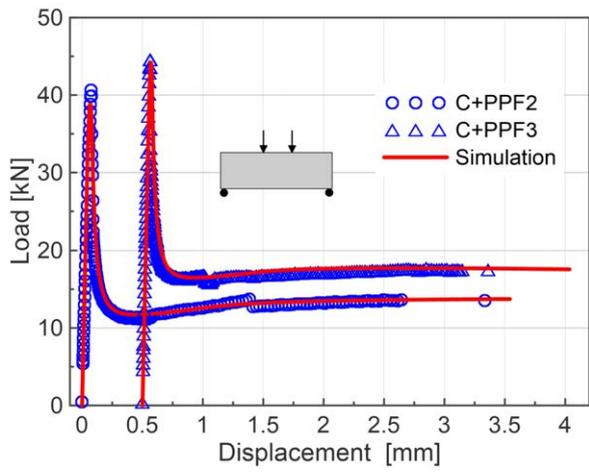
4.2 Results

The comparisons between the numerical simulations and the experimental data are presented in Figure 5. For each mixture, the blue line represents the experimental result, while the red line describes the analytical-based simulations. For all specimens, good accuracy of the simulated results was obtained. This demonstrated that the adopted stress-strain response employed in the Mobasher's model [8-10] allow obtaining load-deflection numerical responses in very good agreements with the experimental data. The adopted tension model for each fiber type is shown in Figure 6.

Table 2. Parameters of the Stress-strain relations obtained through the inverse analysis.

Specimen	f_c [MPa]	E [GPa]	$\varepsilon_{cr} \times 10^{-6}$ [-]	τ_1 [MPa]	τ_2 [MPa]	β_{tu} [-]	μ_1 [-]	μ_2 [-]	μ_3 [-]
C + PPF2	29	26.9	145	3	70	250	0.125	0.16	0.16
C + PPF3	23	24.0	180	2	50	200	0.15	0.17	0.16
C + PPF4	25	25.0	167	2	60	200	0.12	0.167	0.15
C + Coco 2	26	25.5	165	3	80	140	0.046	0.07	0.04
C + Abaca 1	26	25.5	135	7	120	270	0.12	0.03	0.02
C + Abaca 4	26	25.5	135	6	120	220	0.12	0.02	0.02

From both experimental and numerical views, it can be observed that the post-cracking behavior of FRC mixes can generally be divided into three stages. In the first stage, the descending (softening) branch is quite steep, reflecting a brittle response of all FRC mixes. The second stage is characterized by either a continuing softening trend, a plateau, or in some specimens by a rehardening phase. These alternatives stem from the activation of fiber bridging mechanisms which depends on the type and mounts of fibers as well as on the surrounding concrete cover. Finally, in the third stage, fiber debonding occurs, leading to complete failure of the specimens.

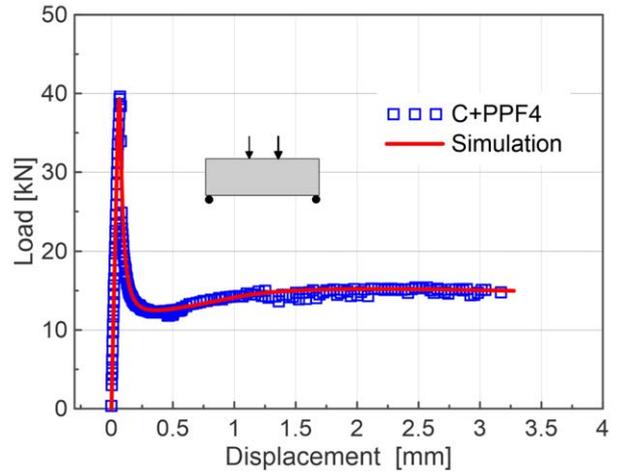In this context, the results indicate that FRC reinforced with polypropylene fiber (PPF) exhibit notable (in comparison to Coco and Abaca) toughness due to the bridging action of these fibers.

It is worth to mention that the initial softening (i.e., Phase 1) is less pronounced and extended in PPFRC, and during Phase 2, a clear rehardening mechanism arises, which is predominantly influenced by the fiber content. Moreover, substituting PPF fibers with an equivalent volume of natural fibers (i.e., Coconut or Abaca) results in reduced toughness among all types, as no marked rehardening is observed. Particularly, Coco-FRC mixes show the lowest toughness among all tested materials.
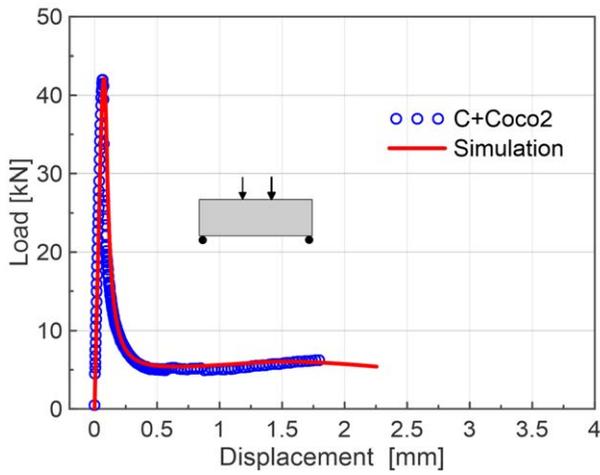
Overall, the findings emphasize that the shape of the stress-strain response curves in FRC is significantly influenced by type and amounts of fibers used.
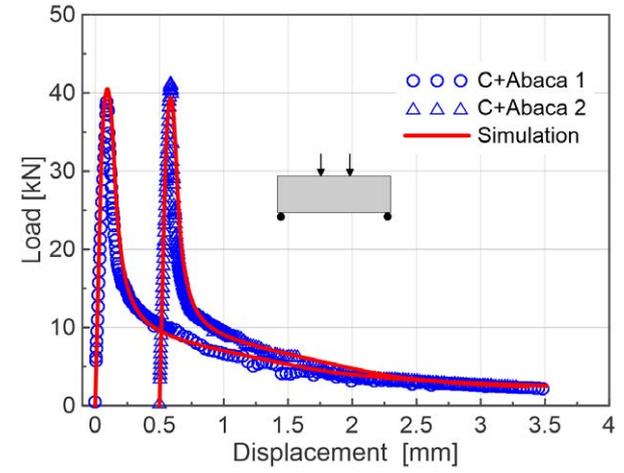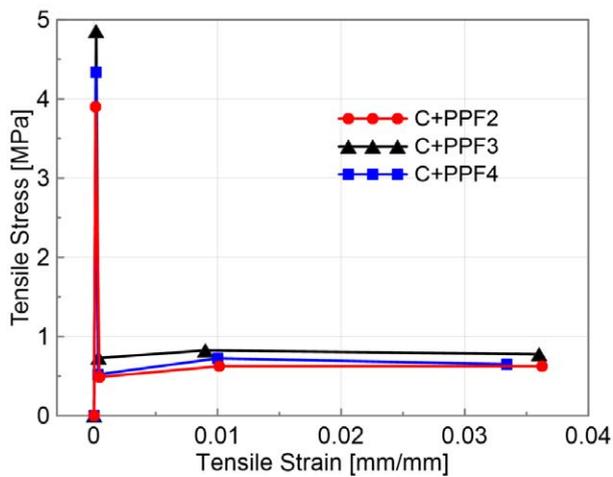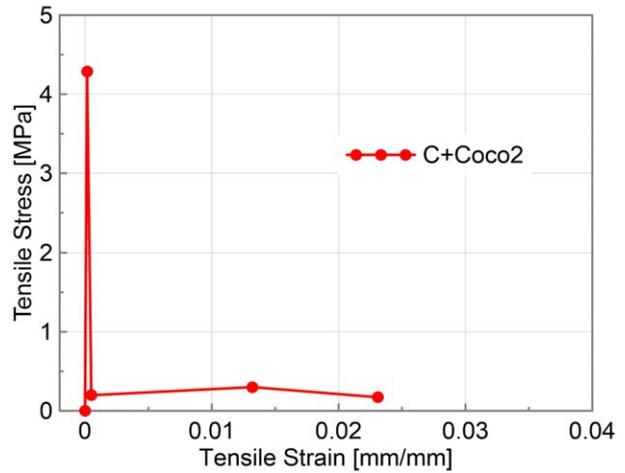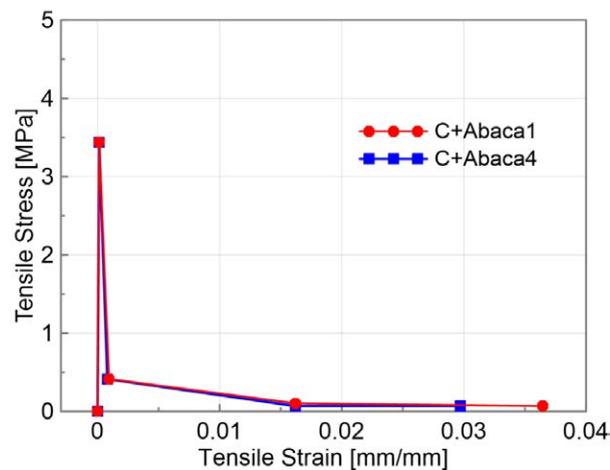
Figure 5. Experimental and numerical load–deflection curves for the fifth mixtures.

(c)

Figure 6 Tensile stress-strain model from inverse analysis for each fiber type

5 Discussion

While full-scale structural experiments on hybrid sections with natural fibers and steel reinforcement have not yet been conducted to show the expected level of improvement, it is expected that the current characterization results will provide a basis for predetermination of the expected improvements in the full-scale tests of concrete mixes with natural fibers for structural purposes.

In addition, these results demonstrate the first application of the method of inverse analysis as applied to flexural tests with natural fibers. As such, the results both confirm the applicability of the method to a broad range of fiber types, and also show relative consistency in the inverse-calculated results of the natural fibers. The latter results indicates that generalized parameters of natural fibers can be derived following the procedure applied in this article. This input information can then serve to prepare full-scale structural experiments, and, ultimately, assist designers with the dimensioning of hybrid natural fiber-reinforced concrete structural elements.

6 Conclusions

This paper shows the initial results of a series of experiments of natural fiber concrete beams tested in flexure, and the modelling of these elements using a quad-linear tension model for the inverse analysis to develop the constitute equations for stress-strain and model the moment-curvature and load-deflection response of the members.

Based on the findings reported in this paper, we can conclude the following:

- Abaca natural fibers show potential for structural applications as a result of their contribution to the post-peak behaviour of the members tested in flexure.
- The quad-linear tension model used in the inverse analysis results in a good match between the experimentally and analytically determined load-deflection diagram.
- The parameters of the stress-strain diagram obtained from the inverse analysis of each experiment separately show consistency among experiments using the same fiber type, indicating that generally applicable stress-strain results can be derived.
- The calculated stress-strain relationships for polypropylene, coconut and abaca fibers are plotted and confirm the aforementioned consistency.

While full-scale experiments are necessary as a proof-of-concept, the presented results in this paper are a first step towards using hybrid natural fiber-reinforced concrete mixes in design practice.

Acknowledgements

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