7-2023

Design of Bamboo Reinforced Concrete Beams Considering Variability in Tensile Strength of Bamboo

Bibek Bhardwaj

Michael Stoner

Weichiang Pang

Design of Bamboo Reinforced Concrete Beams Considering Variability in Tensile Strength of Bamboo

Bibek Bhardwaj
PhD Student, Glenn Dept. of Civil Engineering, Clemson University, Clemson, USA

Weichiang Pang
Professor, Glenn Dept. of Civil Engineering, Clemson University, Clemson, USA

Michael Stoner
Research Assistant Professor, Glenn Dept. of Civil Engineering, Clemson University, Clemson, USA

ABSTRACT: In recent years, the price of steel has soared, making steel reinforcement in concrete structures unaffordable for households in low-income countries. Seismic activities in low-income households, particularly those in developing countries, pose a significant threat to life and property to unreinforced concrete structures. The application of bamboo as an alternative to steel in reinforced concrete is still in its early stages of development. Unlike steel, bamboo is a natural material, and its structural properties vary greatly based on species, location, age, and geometric properties. Thus, the design of bamboo-reinforced concrete involves more uncertainties than steel-reinforced concrete. This research investigates the structural properties of bamboo and bamboo-reinforced concrete beams through experimental testing and Monte Carlo simulation. Tension tests were conducted on 'Moso' (Phyllostachys edulis) bamboo harvested in Clemson, United States, and the variabilities in the tensile strength and stiffness properties of the Moso bamboo were quantified. A set of tension tests was conducted in conjunction with moisture content tests each week to determine the optimum time for construction application after harvest, given the changes in strength and stiffness over time. It also served to capture the inherent variability of the bamboo material. To test the behavior of concrete reinforced with bamboo, four 25.4 cm × 35.6 cm × 3.66 m (10 in. × 14 in. × 12 ft.) concrete beams with bamboo reinforcement were tested under four-point bending. The interaction between bamboo and concrete was observed during the flexural tests. The findings derived from the tension testing of bamboo samples were utilized in a Monte Carlo simulation to generate an anticipated range of capacities for bamboo reinforced concrete beams. Subsequently, a comparative analysis was performed between the projected beam test outcomes and the actual results obtained. Based on preliminary analysis, applying the current method to estimate the capacity of steel-reinforced concrete beams to bamboo-reinforced concrete may result in an overestimation of the capacity. This could be attributed to the lack of proper quantification of the slip between the bamboo reinforcements and the concrete in the current model.

1. INTRODUCTION

The high price of steel added to environmental concerns over its manufacturing process (Wenceslao et al.) has motivated researchers to seek an alternative reinforcing material, in particular for developing countries. Bamboo is one such material under consideration for its high tensile strength. Bamboo shows the potential to provide a low-cost, readily available, quick-growing, and replenishable alternative to steel as a reinforcement in concrete. However, the applicability of bamboo reinforced concrete (BRC) presents unique challenges, and research about its performance is still in its nascent stages. Bamboo is a natural material; its properties depend on species, climate, age, and geometric properties, among other factors. Tests on bamboo specimens have revealed high variance in their tensile strength (Schneider et al., Mondal et al., Khare et al.). The tests also indicated brittle failure of the test specimens. Bamboo is also susceptible to moisture changes and can shrink or expand based on its moisture content. The shrinking of bamboo while concrete cures can lead to a reduction in bamboo-concrete bonds, which can adversely affect the tensile performance of the assembly (Javadian et al., Ghavami et al.). These issues, among others, must be addressed to present bamboo as a suitable reinforcement in concrete.

Experimental tests on bamboo-reinforced concrete beams have generally indicated that while the bamboo reinforcement in a concrete beam increases its load-carrying capacity when compared to unreinforced concrete, it does not necessarily prevent the propagation of cracking in concrete due to its relatively low modulus of elasticity (Rashid et al., Muhtar et al., Rahim et al., Budi et al., Mali et al., Schneider et al.). Flexural test results also mostly suggest a brittle failure of the bamboo beams (Rashid et al., Muhtar et al., Budi et al., Khare et al., Schneider et al.). Such a behavior has been one of the causes of skepticism related to supplementing concrete with bamboo reinforcement (Archilla et al.). However, it is evident from the literature review that most flexure tests on bamboo-reinforced beams were conducted on small-scale specimens (typically less than 1 m/ 3.28 ft. in length) with just two or three bamboo pieces as flexural reinforcement. Small-scale specimens may not provide sufficient development length for good bonding between bamboo and surrounding concrete. Additionally, as the tensile properties of each bamboo piece vary considerably, utilizing more bamboo pieces per beam helps negate the effects of individual variability, which small specimens cannot achieve.

This research uses experimental tests to quantify the structural properties of ‘Moso’ (Phyllostachys edulis) bamboo and concrete beams supplemented with Moso reinforcements. Tension tests were conducted on Moso bamboo specimens, and the variabilities in the tensile strength and stiffness properties were quantified. The tension tests were conducted alongside moisture content tests each week to determine the optimum time for construction application after harvest, given the changes in strength and stiffness over time. Four 25.4 cm × 35.6 cm × 3.65 m (10 in. × 14 in. × 12 ft.) beams with six bamboo pieces each as flexural reinforcements were tested under four-point bending until failure. The load-deformation behavior of the beams was quantified, and the interaction between bamboo and concrete was observed. The results of the tension tests on bamboo specimens were utilized in a Monte Carlo simulation to generate the range of capacities expected for BRC beams and comparisons were made to the actual beam test results.

2. METHODOLOGY

2.1. Harvesting of Bamboo

The bamboo species utilized in this study was Moso (Phyllostachys edulis), which was sourced from a grove in the Clemson Experimental Forest. The bamboo culms were cut into approximately 2.44 m (8 ft.) lengths for easy transportation. Each culm was divided into between six and eight approximately equal radial segments using a machete. The processed bamboo pieces were stored inside the Wind and Structural Engineering Research (WiSER) Laboratory at Clemson University, where the average temperature was 74° F, and the average relative humidity was 55%.

2.2. Moisture Content tests

2.2.1. Test Setup

The moisture content tests were carried out in accordance with the procedures outlined in ASTM D4442-20 (ASTM international). Parts of specimens from the tension tests (discussed in section 2.3.1) were placed in a vapor-tight container and transported to the oven for drying. The oven temperature was set to 103 °C, although it was noted to fluctuate between 99 °C and 102 °C. The specimens were weighed prior to placement in the oven. The change in mass was monitored at periodic intervals and recorded. The drying process was continued until the change in mass of the specimens was found to be less than or equal to 0.01 g over a minimum period of three hours.

Figure 1: Setup for moisture content tests.

2.2.2. Results for moisture content tests

The nomenclature for bamboo specimens is presented in section 2.3.1. The moisture content of specimens was calculated as per ASTM D4442-20 section 5.5.1 using the following equation:

$$MC = (A - B)/B \times 100 \qquad (1)$$

Where, A = original mass, B = oven-dry mass, MC = moisture content

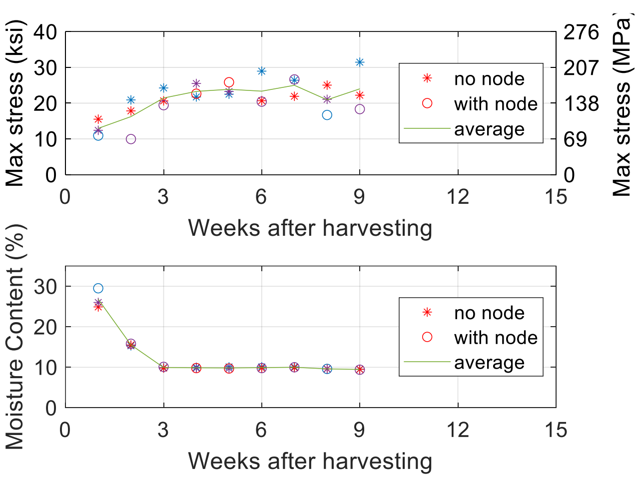

Figure 2: Variation in peak stress and moisture content of specimens over time.

The average moisture content of the specimens after one week of the harvest was determined to be 26.8%. A decrease in moisture content was observed the following week, with an average value of 15.5%. Further, the moisture content of specimens dropped to an average of 9.9% three weeks after harvest, which remained consistent for the remaining weeks.

Figure 2 shows the weekly variation in peak tensile strength (quantified as peak stress from the test) and moisture content of Moso bamboo specimens from the time of harvest. The results indicate that for up to four weeks post-harvest, the average peak stress of the specimens increased with time while the moisture content decreased. The average moisture content and peak stress remained relatively consistent from the fourth post-harvest week. For this study, all subsequent data used in the design procedure for Moso bamboo will be from the fourth-week post-harvest or later.

2.3. Tension tests

2.3.1. Test Setup

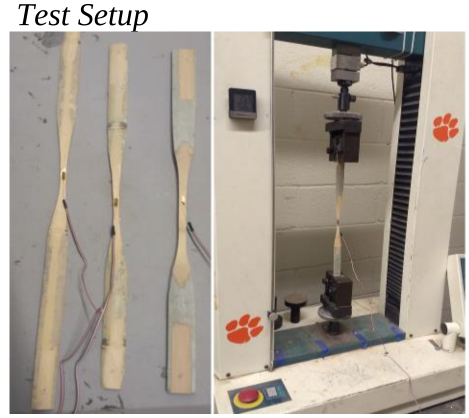

Figure 3: (left) tension test specimens; and (right) setup of tension tests.

The tension tests were performed using a Tinius Olsen Universal Testing Machine (UTM) as shown in Figure 3. The bamboo strips were cut into approximately 45.7 cm (18 in.) lengths. V-grips were employed to clamp the specimens at both ends. Each specimen's central section was ground into a dog-bone shape to ensure failure in the neck region (Figure 3).

Three tests were performed each week, starting from week one to week nine after harvest. For each week's three specimens, one had a node in the neck region. The dimensions of the neck region were measured at three different locations, and strain gauges were installed near the center of the neck region. The tests were conducted at a loading rate of 0.635 mm/min (0.025 in./min) and a sampling rate of 10 Hz.

The specimens were named based on the week of testing after the harvest and specimen number. For example, a specimen named 4-3N indicates that it was tested four weeks after harvest and was the third specimen tested in that week, while the letter "N" indicates that the specimen had a node in the neck region.

2.3.2. Results

Figure 4 shows the stress-strain relationship for Moso bamboo specimens. The results show that the specimens exhibited a relatively linear relationship between stress and strain up to the point of failure. The failure mode of the specimens was observed to be brittle, characterized by a sudden break at the neck region (Figure 5). All specimens with nodes in the neck region failed at the nodes. However, the presence of a node was not necessarily indicative of a weaker specimen (Figure 2 and Figure 4).

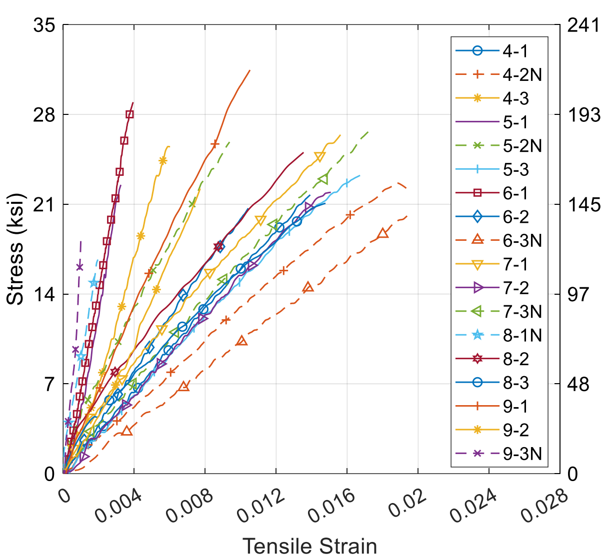

Figure 4: Stress vs strain plots for the tension test specimens.

The peak stress and strain values varied considerably among the specimens. The peak stress values ranged from 115 MPa (16.7 ksi) to 216 MPa (31.5 ksi), with an average of 161.4 MPa (23.4 ksi) and a coefficient of variation (CV) of 0.156. The peak strain of the specimens varied from 0.0010 to 0.0196, with an average of 0.0011 and a CV of 0.540. Subsequently, the modulus of elasticity ranged from 7170 MPa (1040 ksi) to 126,532 MPa, with an average of 26,516 MPa (3846 ksi) and a CV of 1.114. A negative correlation between peak strain and modulus of elasticity was observed for the test specimens, with a coefficient of correlation (ρ) of -0.8 (Figure 14).

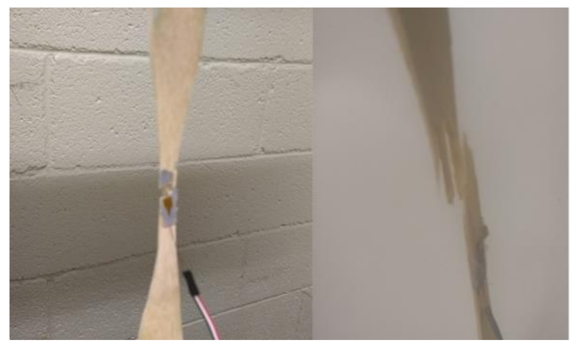

Figure 5: Failure in tension test specimens.

2.4. Beam Tests

2.4.1. Design

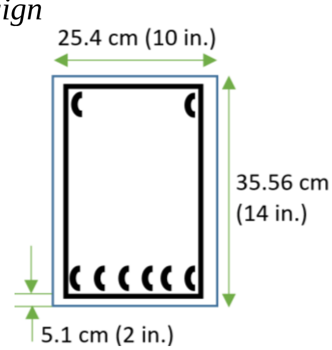

Figure 6: Cross section of a typical beam

The design methodology for the bamboo-reinforced concrete beams followed the same approach as that for a singly reinforced under-reinforced concrete beam with steel reinforcement. The design was carried out using a deterministic approach. Figure 6 shows the cross section for the beams. A four-point bending condition was used with 76.2 cm (30 in.) between the two applied point loads (Figure 7). The peak strength of the bamboo was considered as the yield strength, and the 5th percentile yield strength was determined from the tension test data to be used for design. Table 1 shows the summary of the design values.

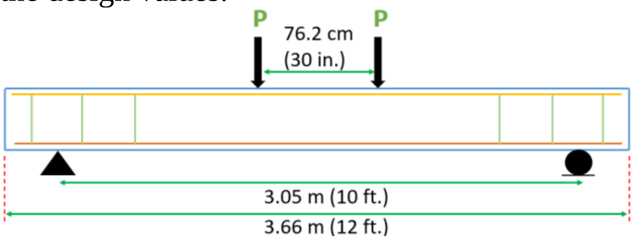

Figure 7: Layout for four-point bending test.

Table 1: Design values for bamboo-concrete beams

Design feature	Description
Effective length (L)	3.05 m (10 ft)
Beam width (b)	25.4 cm (10 in.)
Beam height (h)	35.6 cm (14 in.)
Clear cover (cc)	5.1 cm (2 in).
Effective depth (d)	39.5 cm (12 in.)
Number of tension bamboo	6
Area of each tension bamboo	2.6 cm^2 (0.4 in^2)
Total area of bamboo	15.5 cm^2 (2.4 in^2)
Compressive strength of concrete (f'_c)	27.6 MPa (4 ksi)
Yield strength of bamboo (f_y)	117 MPa (17 ksi)
ϕ	n/a
Depth of compression block (a)	3.05 cm (1.2 in)
Ultimate moment capacity (M_n)	50.8 kN-m (37.5 k-ft)
Tensile stress of concrete (f_t)	3.27 MPa (474 psi)
Cracking moment (M_{cr})	17.5 kN-m (12.9 k-ft)
Shear strength of beam (V_c)	78.8 kN (17.7 kip)

2.4.2. Construction

Four plywood formworks with interior dimensions of 25.4 cm × 35.6 cm × 3.65 m (10 in. × 14 in. × 12 ft.) were constructed. The bamboo strips were cut to the appropriate lengths, and their cross-sectional area was measured at various locations. As notching bamboo pieces has shown to improve bond performance (Budi et. al), notches were made on the bamboo pieces at roughly 5.1 cm (2 in.) spacing (Figure 8). The bamboo reinforcements were secured using rebar wires and positioned over 5.1 cm (2 in.) rebar chairs to provide clear cover. Three stirrups were added near the ends of the beams as shear reinforcement (see Figure 7). The concrete for the beams was poured into the formworks using a concrete truck.

Figure 8: (left) Construction of bamboo cage; and (right) Notches in the bamboo pieces.

2.4.3. Test setup

Figure 10 shows the setup for the four-point flexure test. The bamboo beams were positioned on top of two W-shaped supports spaced 10 feet apart. A 35-kip hydraulic actuator was utilized for load application. A spreader beam was used to establish a four-point bending setup.

2.4.4. Results

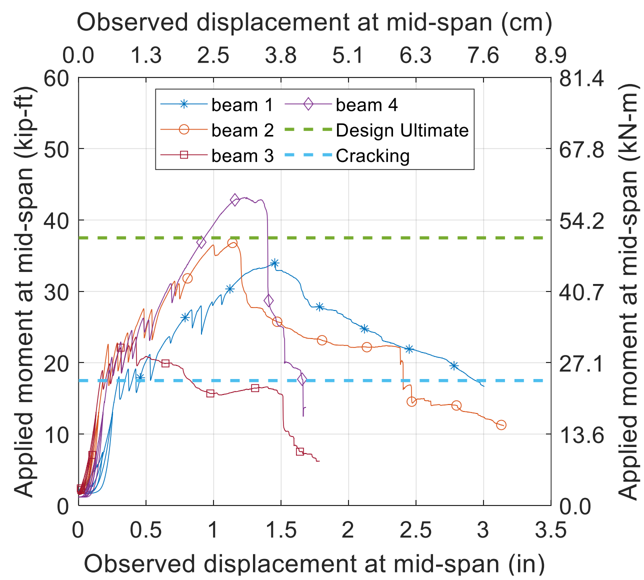

Figure 9: Applied moment vs. observed displacement at mid-span for bamboo beams.

Figure 9 shows the plot of applied moment vs. observed displacement at midspan for the beams tested. The sudden decrease in strength indicates concrete cracking on the tension side, with cracks initiating close to the expected cracking moment. The ultimate moment capacity of the four beams ranged from 32 kN-m (23.6 kip-ft) to 58.6 kN-m

(43.2 kip-ft), with an average of 46.6 kN-m (34.4 kip-ft) and a coefficient of variation (CV) of 0.24. The beams exhibited a ductile failure mechanism. Concrete is well known for exhibiting brittle failure; the tension tests performed on bamboo specimens also demonstrated a brittle failure mechanism. The ductile failure mechanism of the beams could be attributed to three possible factors. First, the dimensions of the bamboo specimens used in the tension tests were smaller than those employed in the beam specimens, providing more opportunity for load distribution among the fibers of the larger bamboo pieces. Second the bamboo pieces could likely have failed under different levels of strain and third, the tension test specimens did not account for the confinement effect on concrete, which may have affected their behavior in the beam specimens.

Figure 10: Setup for test and post failure cracks on beam

Figure 11: Engagement on bamboo and concrete, observed post failure.

Figure 12: Splitting of tension bamboo.

Preliminary post-failure analysis of the beams revealed good engagement between bamboo and concrete, as shown in Figure 11. Splits in some bamboo pieces suggests that the bamboo was sufficiently engaged to cause failure in the bamboo (Figure 12).

2.5. Monte Carlo Simulation

2.5.1. Variables

Table 2 presents this study's independent and correlated variables. The compressive strength of concrete was determined through nine 10.2 cm × 20.3 cm (4 in. × 8 in.) cylinder tests. The distribution of bamboo area was derived from measurements taken on the bamboo pieces used in the concrete beams. All other design variables were considered deterministic.

Table 2: (top) Independent; and (bottom) correlated variables considered for simulation.

Variable	**Distribution**	**Mean**	**CV**
f'_c	Normal	49 MPa (7.12 ksi)	0.09
A_b	Normal	2.45 cm^2 (0.38 in^2)	0.18
f'_c = compressive strength of concrete A_b = area of bamboo			

Variable	**Distribution**	**Mean**	**CV**
ϵ	empirical	0.0111	0.54
E	lognormal	27.3 GPa (3962 ksi)	1.00
ϵ = yield strain of bamboo E = Modulus of Elasticity of bamboo Coefficient of correlation = -0.80			

2.5.2. Approach

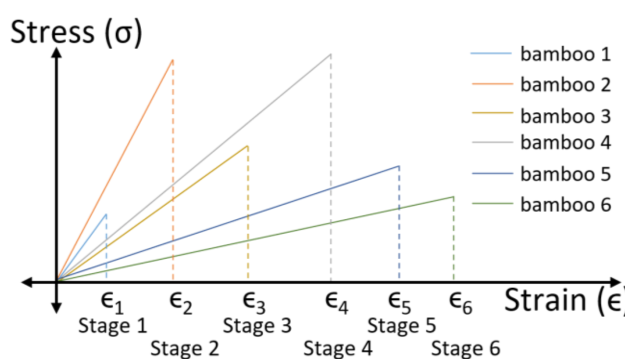

Figure 13: Approach for Monte Carlo simulation

For each simulation, the variables specified in section 2.5.1 were randomly generated based on their respective distributions. Strain compatibility was assumed for this simulation (i.e., no slip between bamboo and concrete). Additionally, it was assumed that the bamboo pieces had no residual strength beyond peak strain. The simulation comprised of six stages, each associated with the failure of one of the six bamboo pieces. The compressive strain in concrete was also checked at each stage assuming a linear distribution of strain over the depth of the beam. The stress at each stage was determined by multiplying the modulus of elasticity by the strain at that stage. Figure 13 provides a visual representation of this concept.

The moment capacity at each stage is given as:

$$M_{ni} = \sum_{k=1}^{6} (A_{bk}\varepsilon_i E_k)(d - a_i / 2) \qquad (2)$$

Where, M_{ni} = moment capacity at stage i, A_{bk} = Area of bamboo piece k, ϵ_i = strain at stage i, E_k = Modulus of elasticity of bamboo piece k, d = effective depth, a_i = depth of compression block at stage i calculated using the following equation:

$$a_i = \frac{\sum_{k=1}^{6} A_{bk}\varepsilon_i E_k}{0.85 f_c' b} \qquad (3)$$

Where, f'c = compressive strength of concrete, b = width of the beam

2.5.3. *Preliminary simulation results*

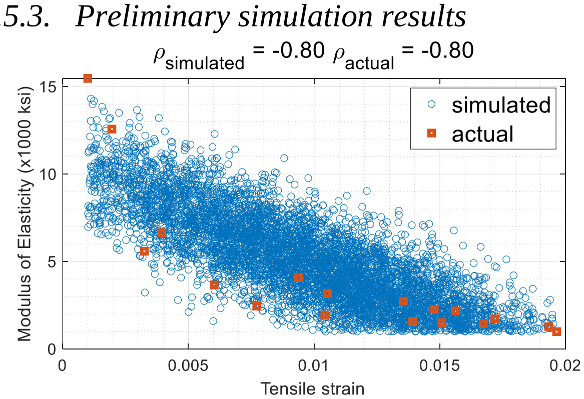

Figure 14: Correlation between modulus of elasticity and peak strain for tension test specimens

Figure 15 displays the results of a sample Monte Carlo simulation and Figure 16 presents a preliminary distribution of peak moment capacity based on one thousand simulations. The results indicate that the simulation's average peak moment capacity was higher than the actual tests. This discrepancy could be attributed to the design approach of the bamboo beams, which was based on the design of steel-reinforced concrete beams with the steel values substituted by bamboo values. These results suggest that a different approach may be necessary when designing bamboo-reinforced concrete.

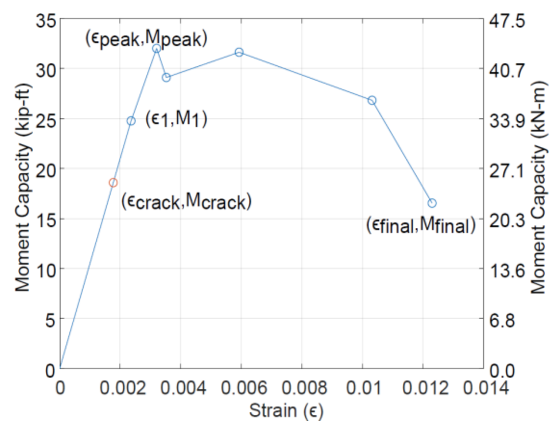

Figure 15: Sample simulation result

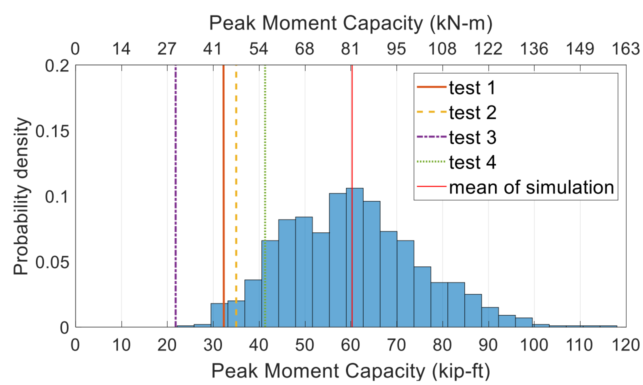

Figure 16: Distribution of peak moment capacity, observed from 1000 simulations.

3. CONCLUSION

Tension tests were performed on Moso bamboo specimens, and concurrent moisture content tests were also conducted. The results showed a strong correlation between higher moisture content and lower peak strength of the bamboo. Over four weeks, the moisture content decreased and stabilized at approximately 10%, while the average peak stress of the specimens also stabilized. The tension tests demonstrated significant variability in both peak stress and strain, and the presence of nodes in the specimens did not strongly predict lower peak strength. Four 25.4 cm × 35.6 cm × 3.66 m (10 in. × 14 in. × 12 ft.) bamboo beams were tested, with each beam incorporating six bamboo pieces as tension reinforcement. Four-point flexural tests on the bamboo beams indicated significant variability in their ultimate moment capacity. A Monte Carlo simulation was carried out based on the variability in the compressive strength of concrete, bamboo dimensions, and bamboo properties. Preliminary analysis suggest that bamboo-reinforced concrete cannot be designed in the same manner as steel-reinforced concrete, and an updated design methodology for bamboo-reinforced concrete is being researched which will be presented at the ICASP14 conference.

4. REFERENCES

Archila, H., Kaminski, S., Trujillo, D., Zea Escamilla, E., and Harries, K. A. (2018). "Bamboo reinforced concrete: a critical review." Materials and Structures, 51, 1–18.

ASTM (1992). "Standard test methods for direct moisture content measurement of wood and wood-base materials." ASTM West Conshohocken, PA.

Budi, A. S. and Rahmadi, A. (2017). "Performance of wulung bamboo reinforced concrete beams." AIP conference proceedings, Vol. 1903, AIP Publishing LLC, 020010.

Ghavami, K. (2005). "Bamboo as reinforcement in structural concrete elements." Cement and concrete composites, 27(6), 637–649.

Jaimes, W. and Maroufi, S. (2020). "Sustainability in steelmaking." Current Opinion in Green and Sustainable Chemistry, 24, 42–47.

Javadian, A., Wielopolski, M., Smith, I. F., and Hebel, D. E. (2016). "Bond-behavior study of newly developed bamboo-composite reinforcement in concrete." Construction and Building Materials, 122, 110–117.

Khare, L. (2005). Performance evaluation of bamboo reinforced concrete beams. The University of Texas at Arlington.

Mali, P. R. and Datta, D. (2020). "Experimental evaluation of bamboo reinforced concrete beams." Journal of Building Engineering, 28, 101071.

Muhtar, M., Dewi, S. M., et al. (2017). "Bond-slip improvement of bamboo reinforcement in concrete beam using hose clamps." IMC 2016 Proceedings, 1(1).

Rahim, N., Ibrahim, N., Salehuddin, S., Mohammed, S., and Othman, M. (2020). "Investigation of bamboo as concrete reinforcement in the construction for lowcost housing industry." IOP Conference Series: Earth and Environmental Science, Vol. 476, IOP Publishing, 012058.

Rahman, M., Rashid, M., Hossain, M., Hasan, M., and Hasan, M. (2011). "Performance evaluation of bamboo reinforced concrete beam." International Journal of Engineering & Technology, 11(4), 142–146.

Schneider, N., Pang, W., and Gu, M. (2014). "Application of bamboo for flexural and shear reinforcement in concrete beams." Structures Congress 2014, 1025–1035.